ACCELERATED QUALITY AND RELIABILITY SOLUTIONS

LEV M. KLYATIS
EUGENE L. KLYATIS

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TO MY WIFE, NELLYA KLYATIS
L. M. K.

TO MY MOTHER, NELLYA KLYATIS
E. L. K.

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PREFACE

The primary goal of this book is to describe accelerated quality and reliability solutions of the physical essence of engineering problems during the design, manufacturing, and maintenance stages. Therefore, the book integrates Quality Improvement and Accelerated Reliability/Durability/Maintainability/Test Engineering concepts. It introduces a complex technique which consists of five basic components:

(1) physical simulation of field input influences;
(2) useful accelerated reliability testing;
(3) accurate prediction of reliability, durability, and maintainability (RDM);
(4) accelerated quality development and improvement in manufacturing and design;
(5) safety aspects of risk assessment.

This is a true simulation of field situations, therefore it is accurate.

We hope that this book will become a good reference for practicing engineers and academics who are engaged in product and technology management, research, testing, development, and improvement and want to achieve the results rapidly and with high quality. At the same time, our complex techniques and solutions that follow are also applicable to other economic sectors:

a) service: insurance, repair, banking, medical, real estate, brokerage, etc.;

b) processing: chemical, food, bio, pharmaceutical, etc.;

c) high technology: software development, microelectronics, telecommunication, etc.

Readers of this book will be able to find new methods of developing complex solutions in order to eliminate rapidly the problems of product quality and reliability. Some actual results given in Chapter 4 demonstrate the dynamics of complaints over a three-year increase in the product's sales as a result of improved competitiveness in the market.

Naturally a specific product will need a particular solution, but the basic methodology will be similar. Our methodology was successfully tested for different products, from farm machinery and the automotive industry to electronics and aerospace.

There are separate publications (including books) on simulation, testing, prediction, quality management, and other quality and reliability (maintainability, durability, serviceability, etc.) solutions (analysis, improvement, development, etc.) as well as on safety risk. But in real life the above areas are connected with each other and depend on each other.

This is the first book which has combined physical simulation with useful accelerated reliability testing, accurate prediction of reliability, durability, maintainability with accelerated development and improvement of product quality, and safety risk.

Therefore, our methodology opens new unique opportunities for more effective integrated solutions of high quality and RDM, development and improvement of the design and production as well as problems of safety, and accuracy of prediction.

Simulation is the basic component of experimental testing, and research. Simulation of input influences on the actual product, especially physical simulation, is a specific area which has a very limited discussion.

Chapter 1 "Accurate Physical Simulation of Field Input Influences on the Actual Product" contains the strategy, basic concepts, criterion, and methodological aspects for the development of accurate physical simulation of these influences as well as the system of control of this simulation. For this goal, the methodology of substitution of artificial media for natural technological media, and a description of how the climate influences reliability, are included.

This chapter will be useful not only for industrial engineering, but also for the researchers who provide laboratory experimental research for any devices or technologies and use laboratory equipment, as well as testing and research for safety risk solutions and assessment. First, one needs to simulate the field environment, then to provide the experimental research. The quality of the research depends on how accurately real life conditions have been simulated. This chapter will help readers to more accurately simulate the field conditions.

Chapter 2 "Accelerated Reliability Testing Performance" includes a general analysis of different approaches to accelerated testing methods as well as the specifics of useful accelerated reliability testing (UART) methodology. It also includes the basic concepts of UART on the basis of the above physical simulation, which makes it possible to obtain accurate initial information for quality and RDM accurate prediction, and a decrease in safety risk. This chapter contains also the technology of step-by-step UART as well as the basic modern components for UART methodology implementation (accelerated multiple environmental testing, vibration testing, etc.).

Chapter 3 "Accurate Prediction of the Reliability, Durability, and Maintainability on the basis of Accelerated Reliability Testing Results" includes solutions to previously inaccessible problems.

The proposed methodology of simulation and UART is predetermined by the distributions of RDM and expenses during the above testing and is identical to these distributions during the field usage time. In this case, the chapter includes concepts and basic principles of accurate RDM prediction for different situations, which are illustrated by practical examples.

High product quality can be achieved during the design stage by utilizing accurate physical simulation, UART, accurate prediction of RDM. But these results may decrease during the manufacturing and usage processes.

On the other hand, some of the design mistakes can be recognize only during the manufacturing or by users. Moreover, the specifics of usage can affect the quality of the product for users. Therefore, most completely quality problems can be solved if one analyzes them during one connected complex design + manufacturing + usage as integrated in each other. Here is the potential for improvement and development of quality integrated in RDM.

To solve the above problem, the book includes Chapter 4 "Practical Accelerated Quality Development and Improvement in Manufacturing and Design " which contains a modern practical strategy of accelerated quality improvement through a complex approaches during the design, manufacturing, and usage. The above strategy was used effectively in several companies for increasing their competitiveness in the market. This chapter will be especially useful for practical engineers and managers, for improvement of the quality situation, then the situation of the industrial companies in the market and, as a result, the companies financial situation.

The above four components narrowly connect to safety of machinery and risk assessment and reduction. Therefore, Chapter 5 "Basic concepts of Safety Risk Assessment", includes basic principles, assessment of a machine's limit, risk estimation, evaluation, and management as well as hazard analysis. The chapter also includes practical safety aspects of risk control and assessment, and, as an example, the current situation with transportation problems.

The strategy of engineering concepts in the author's new system of reliability, durability, and maintainability (RDM) solutions integrated with quality (Q) during the design, manufacture, and usage consists of:

- Combined accurate physical simulation of the field input influences (and other aspects of field situation) during design and manufacture.

- Development and improvement of useful accelerated reliability testing (UART) on the basis the above simulation.

- Methodology of constant quality, reliability, durability, and maintainability (QRDM) improvement and development through useful accelerated reliability testing (UART).

- Strategy of the above methodology and its realization.

- Strategy of the development, improvement and use of the equipment for the above methodology implementation along with its practical realization.

- Strategy of accurate prediction of QRDM on the basis of UART results.

- Strategy of the constant system of high quality improvement and development during the design, manufacturing, and use.

- Strategy of the realization of the above system.

- Tactical concepts of usage development an engineering system of high QRDM for a particular area of the industry or for a particular company.

The above approach can dramatically improve the company's financial situation by changing its reputation in the market and , as a result, increasing its volume of sales.

The book contains a component of the above approach (system).

Figure A illustrates the complex solution described in this book.

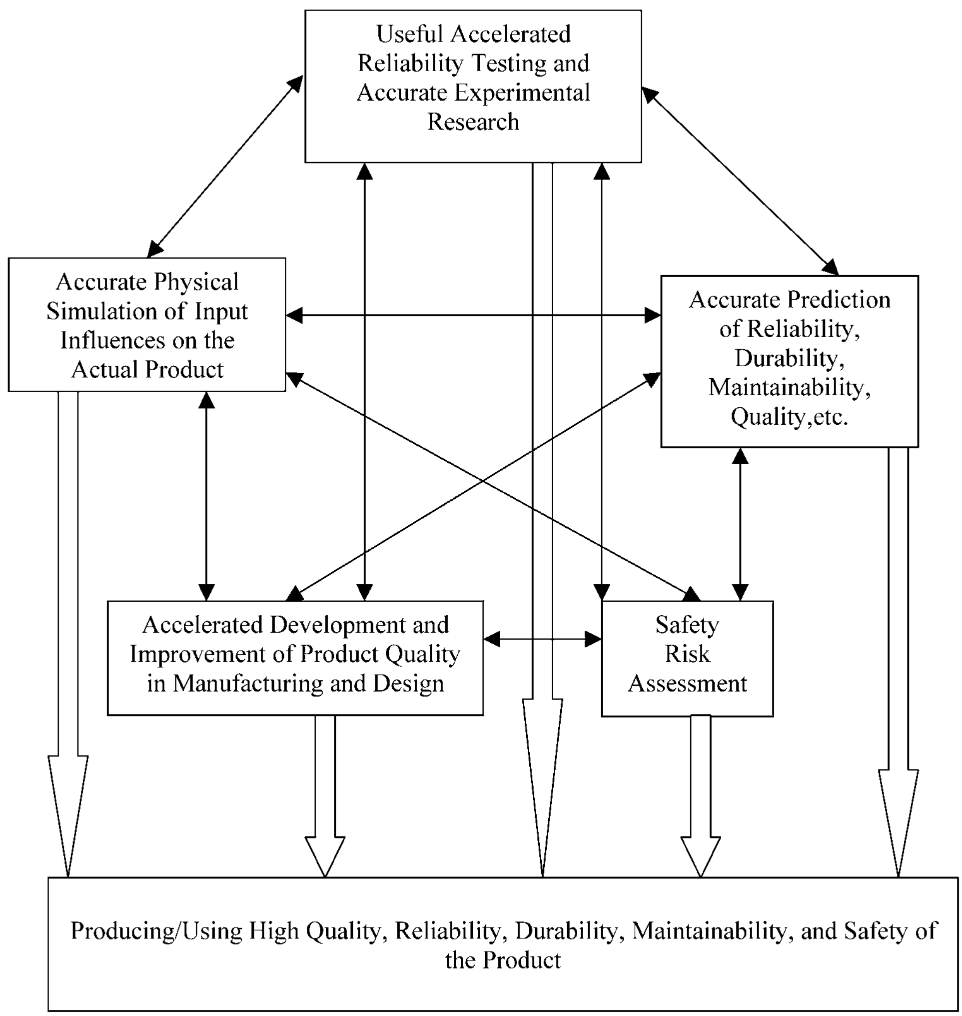

Figure A Complex solution of high quality, reliability, durability, maintainability, and safety of the product.

We wish to express our thanks to Dr. V.A. Ivnitski, Dr. J.M. Galanternik, Dr. A. Prutkovsky, Dr. J.M. Abdulgalimov, Dr. A.G. Reznikov, R.J. Kuper, and Dr. J.M. Shehtman for help provided in various stages of this project.

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INTRODUCTION

In the last few years, global competition in the market place has become much complicated. Currently cheaper products do not sell well, because customers generally prefer the product which has higher quality and reliability, which more comfortable and cheaper in use (less time and cost for maintenance, etc.).

Therefore, the manufacturer and user need a more accurate prediction of quality and reliability (durability, maintainability, etc.) over a longer period of time, increasing the warranty period, decreasing the number of complaints, etc. This requires accelerated solutions of new problems which may arise as well as a new scientific-technical basis.

In accordance with the above requirements, this book describes accelerated quality and reliability solutions on the basis of an integrated methodology complex, i.e. combination of problems which earlier one solved separately. The complex solutions of problems more accurately reflect the field situation, and, therefore, are more effective and help to solve previously inaccessible problems.

Simulation is an essential aspect for the solution of the above problems; without it there cannot be any laboratory experimental research and testing. The current literature is mostly related to software simulation. Simulation of input influences on the actual product, especially physical simulation, is a specific area which is minimally described in the literature. This problem of solution is described in this book.

The above complex relates not to engineering problems only, but also to the safety of medicines, software projects, etc.

For example, Dr. Graham[1] testified that up to 139,000 Americans may have suffered heart damage as a result of taking Vioxx. Of these, said Dr. Graham, 30 - 40% have died[1]. A study in 2004 by the Standish Group, a technology consultancy, estimated that 30% of all software projects are cancelled, nearly half come in over budget, 60% are considered failures by the organizations that initiated them, and nine out of ten come in late. A 2002 study by America's National Institute of Standards (NIST), a government research body, found that software errors cost the American economy $59.5 billion annually. Worldwide, it would be safe to multiply this figure by a factor of two[3]. There are many more examples proving how wrong the currently used testing and prediction technology is in many areas of real life.

Testing is an important aspect of economics, quality, reliability, maintainability, and other aspects of industrial products, because it helps to obtain initial information for the evaluation, prediction, development, improvement, and solution of many other problems during the design, research, manufacturing, and maintenance stages.

Accelerated testing can help to obtain this information quickly, thus rapidly solving the above problems. Moreover, accelerated testing can help to show the direction for more quickly finding the reasons for the above problems and rapidly eliminating them[4]. This results in saving time and cost. Therefore, professionals require access to literature on this subject, but, unfortunately, they cannot find fundamental books apart from Wayne Nelson's book [9]. This does not have answers to all of the many questions of engineering, especially those of practical engineers/researchers. As has been written by this book reviewer "...Nelson's focus is, primarily, statistical. Klyatis and Klyatis has more emphasis on engineering and physics. The books on HALT/HASS are, again, complementary, not competing".

Useful accelerated reliability testing (UART) enables the evaluation and prediction of reliability, durability, maintainability, availability (RDMA), etc. measurements of the system correlated to the field RDMA measurements within a field testing duration. The above correlation offers solutions to previously inaccessible problems, such as:

- rapid finding of the components that limit the product's quality, reliability, maintainability, warranty period, etc.;
- rapid finding and elimination of the reasons for the above limitation;
- obtaining the information for accurate reliability and maintainability prediction;
- reduction of the time needed to market a new product;
- obtaining dramatically longer warranty periods and a lower cost of use;
- and many other problem solutions.

ART effectiveness depends on how accurate the above simulation is.

ART can give more or less accurate information resulting in different levels of effectiveness and improvement. Consequently, accelerated testing can be more or less efficient depending on its application.

Frequently the designers and producers, as well as users, do not know how long their product will work after the warranty period (sometimes during the warranty period), and cannot accurately predict the optimal maintenance, durability, etc. of the product over a longer period. One of the basic reasons is that testing, especially ART, is not presently used as a key factor for improving product quality. Now, one uses not more than 10 - 15% of the possible benefits from accelerated testing. UART, described in this book, can dramatically increase the percentage of these benefits, especially when it is source of information for RDMA prediction.

One of the basic advantages of the book is how one can accurately predict RDMA.

After UART, one can evaluate the test subject under test conditions or predict the test subject's characteristics under field conditions. Of greatest interest is how the test subject's characteristics will react during usage by customers, e.g. in the field.

Often it is a problem for industrial companies to find reasons for the complaints they receive and then to quickly remedy this situation and improve the quality, and, as a result, to eliminate complaints during the manufacturing process. Therefore, it often takes years before these companies can increase the product's quality. As a final result, this product is not adequately competitive in the market, even though it was provided with all of the above described complex of simulation, testing, and prediction. This book shows how one can solve shortly this problem.

Now the connection of safety risk and field simulation, especially the simulation of the traffic-crash situation, is not sufficient. This is one of the reasons for the low effectiveness of crash protection and the high cost of traffic crashes. To take one example of the risk aspect: considering the total losses in monetary values, it is estimated that the US traffic crashes in 2000 cost $231 billion[4]. Therefore, in this book there is special information (Chapter 5) devoted to this area.

Basically, the above advantages are the reasons why the authors prepared the current book which comprises the successful results of many years of work on the concepts and strategy of accelerated development and the improvement of product quality, reliability, and maintainability.

One of the main goals of this book is to show how one can fill the current vacuum in the accurate prediction of quality, reliability, and maintainability, different aspects of UART which are still under-developed, as well as accurate physical simulation of the field for accurate laboratory experimental research, and accelerated development of a practical complex quality system integrated with reliability. Figure C shows in this book proposed quality, reliability, durability, and maintainability as components of one integrated system.

There is another important aspect of usage quality development and its improvement technology. When the well known authority in quality Josef M. Juran was interviewed by Scott M. Paton, the results were published in the magazine Quality Digest[7]. The leading question was why the quality and services of the U S product were inferior to those of the Japanese. His answer was: it is true for the West in general not only for the USA.

Joseph Juran said that one of the basic reasons for this problem was (and is) that many CEO's believe that they are too busy to take personal responsibility for the quality demands and instead they delegate it to others. Unfortunately, that method hasn't worked well.

Leadership at the top level of corporations is an essential factor in getting out of that steep slope, especially when one needs financial investment in the development of some areas.

The same is true in the quality and reliability (durability, maintainability) areas.

Figure B illustrates a comparison between different aspects of Japanese and Western product quality (mostly in automotive and electronics). The testing and know-how for achieving high quality (1) are on an equal level in both (Japan and Western countries).

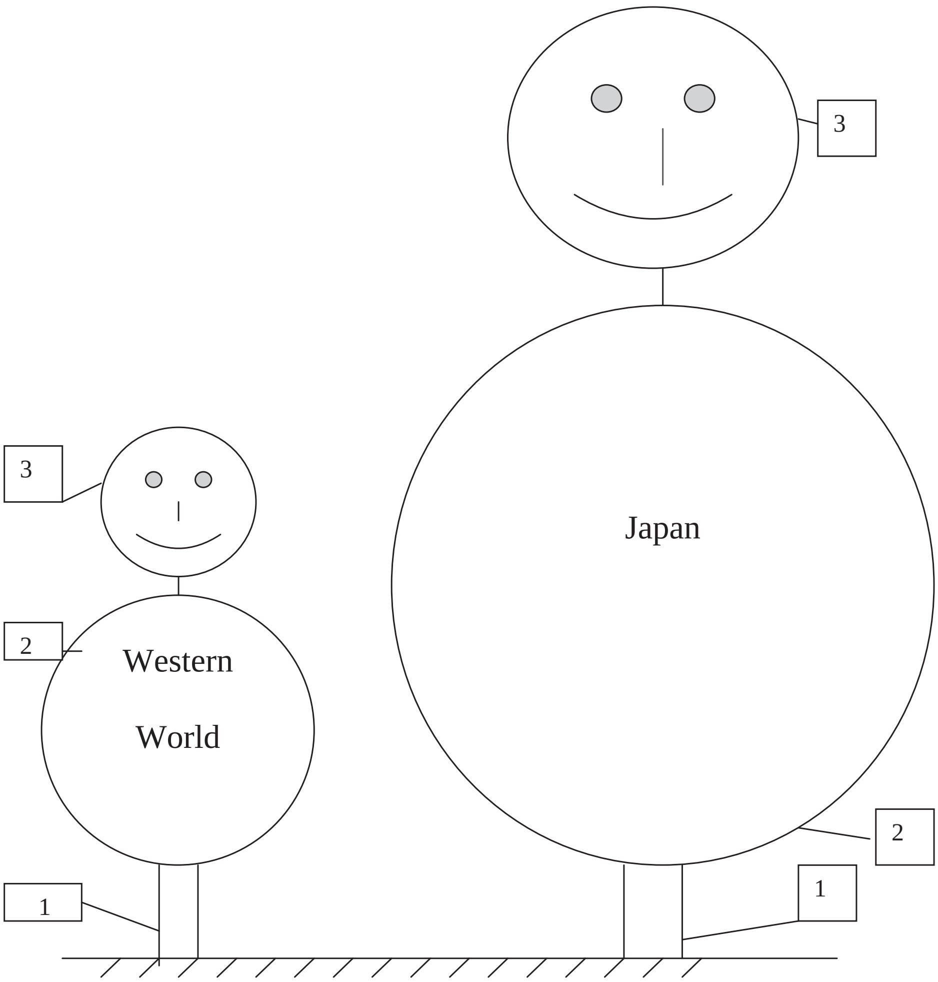

Figure B Different aspects of quality within the general quality system: 1 is testing, especially AT, know-how for achieving high quality, etc.; 2 are corporate culture attitudes to the job, engineering culture, participation of the top management in quality changes, analysis and quality of manufacturing, etc.; 3 is the final product quality.

In Japan the attitude to the job, and participation of top managers in quality process, design and manufacturing areas are much greater, i.e. in the speed of implementing know-how. Therefore, 2 (corporate culture towards quality, engineering culture, etc.) is well developed in Japan. As a result, their product quality (3) is higher.

Therefore, Western companies lose more money on product development, including quality, reliability, and testing, especially during the manufacturing process. For this reason, often their product, for instance cars, is not competitive with those of the Japanese in the world market.

Hence, this is the situation in the automotive market. Japanese companies continue to gain a greater share of this market. In the first quarter of 2004[2] General Motors increased its American market volume sales by 5%, Chrysler by 2%, Ford decreased by 1.3%. At the same time, Toyota increased its volume of sales by 12% and Nissan increased it by 33%. For the last 10 years (from 1995 to 2005) Ford's U S market decreased from 25.6% to 17.9%[3].

Results of studying why customers do not buy the General Motors cars[10] show that 58 % do not buy the cars because of poor workmanship, 56 % do not buy because reliability/durability is low. This is one of the basic reasons why sales are slowing down. As a result, the financial situation of the above and other companies is deteriorating. One can see from table A the financial situation of "Big Three" in comparison with 3 Japanese companies which produce higher quality products[8].

Unfortunately, the corporate management is unwilling (or cannot) to understand that they must change the strategy for quality and reliability in the improvement and development of the product.

This must be done rapidly, and this book shows the way it can be done (see Figures A and C).

On the other hand, by using of accurate physical simulation of field input influences, useful

Table A. Comparison of major business indicators in billions of US $ [8].

Indicator	General Motors	Ford Motor	Daimler/ Chrysler	Toyota Motor	Honda Motor	Nissan Motor
Sales	193.452	170.839	192.753	165.684	78.198	71.172
Profit	3.691	3.487	3.346	11.133	4.448	4.825
Assets	479.125	305.126	242.287	211.145	78.235	73.744
Market value	20.147	23.147	47.039	140.890	49.944	48.768

accelerated reliability testing technology, accurate prediction of quality, reliability, and maintainability, Western companies have the opportunity to use faster and less expensive methods and equipment, and, therefore, surpass the quality and reliability of the Japanese product. An added advantage is that the Japanese companies have not yet used the methodology (system) of accelerated and integrated quality and reliability solutions described in this book.

Therefore, American (and other Western) companies now have the opportunity to rapidly solve their problems, including the improvement of product quality and reliability during design, manufacturing, and use.

If Japan and Korea had been the first to use this system of benefits such as those presented in the current book (as it was, for example, in Deming's approach) Western companies would have lost a unique opportunity to be ahead of Japan.

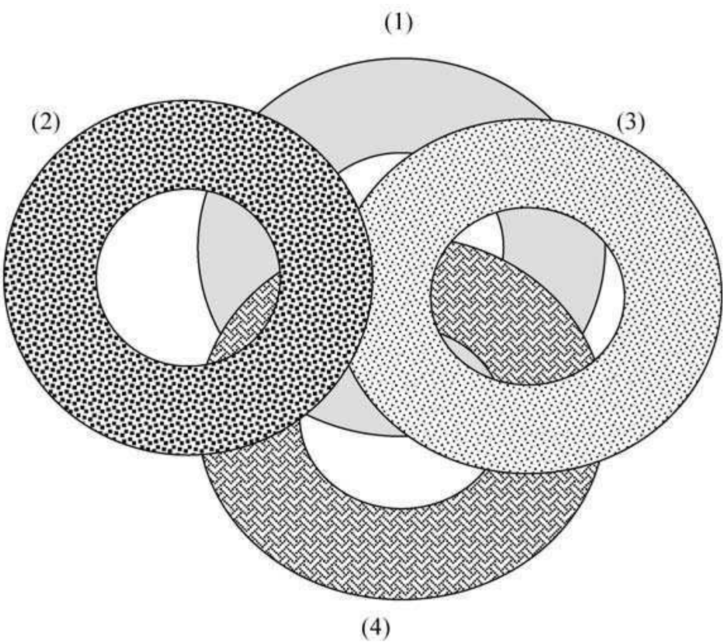

Figure C. Quality, reliability, durability, and maintainability as components of one integrated system: (1) is quality, (2) is reliability, (3) is durability, (4) is maintainability.

This book is directed to the engineers and managers engaged in the research, design, development, testing, manufacture, and management of solutions for quality and reliability problems, engineering teachers and students. It can also be used by professionals who are involved with service, software, pharmaceutical, biological, and other areas which need solutions for simulation, testing, reliability, safety, and other complex problems.

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CHAPTER 1. ACCURATE PHYSICAL SIMULATION OF FIELD INPUT INFLUENCES ON THE ACTUAL PRODUCT

1 INTRODUCTION: THE GROWING IMPORTANCE OF SIMULATION FOR ACCELERATED DEVELOPMENT AND IMPROVEMENT OF PRODUCT QUALITY

1.1 GENERAL

Experiment is considered to be an essential, integral part of scientific development.

Experiment is also one of the basic components of knowledge. Therefore, the theory and practice of simulation in its new and wider sense, make possible the concentration of information and are the basis of experimentation. This gives directions for conducting experiments, and shows the regularity of their results, which has a specific, as well as a very important value. Quality is one of the goals of these experiments which make it possible for development and improvement problem solving.

The common goal of the theory of simulation is the establishment of the methodology whose purpose is to direct and to regulate the processing of information about subjects (systems) which exist outside of our consciousness, and their mutual interconnection within and outside of the exterior environment.

Simulation simplifies obtaining general information and also correctly provides the necessary experiments and processing of their results. This can be provided with the help of both the theory and the practice of simulation (modeling).

The model is a natural or artificial object which corresponds to the studied object or to any of its facets. In general, simulation (modeling) is a reflection of a real situation in order to study its objective regularity.

1.2 ELEMENTS OF HISTORY OF PHYSICAL SIMULATION DEVELOPMENT

The study of simulation was created more than four hundred years ago. Leonardo da Vinci began to work on the development of simulation from the middle of the 15th Century. He wrote: "Somebody mentioned that small models do not represent to a similar effect as a large model. I want to show that this is wrong…"[1]. He created the common analytical regularities and described many examples. For example, he established the ratio between square, power, and the quantity of wood which is removed by different sizes of augers, used for wood drilling.

Similar problems arose often in the 16th and 17th Centuries. Galileo Galilei wrote in his work

"Speaking about two new sciences" that much attention was given to the science of simulation in the 17th Century when the Venetians began to build larger galleys. Galileo Galilei established that " ... Fatigue of similar bodies does not preserve the same ratio as between body sizes".

In 1679 Marriott was engaged with the problems of the theory of mechanical simulation in his treatise about the collision of bodies, and developed the ideas of Leonardo and Galileo.

At the end of 17th Century Newton completed these theories in his work "Mathematical introduction of natural philosophy". It was the first major scientific formulation of the conditions of simulation in relation to mechanical motion. He described the movements of the material bodies and established the law of the similarity of these movements. The direct theorem of similarity and the basic principles of similarity which were formulated by Newton, are the basis of the modern science of similarity which shows the conditions of similar mechanical systems and the criteria which are characteristic of the movement of the systems (1st theorem of similarity).

Newton opened the way for the implementation of similarity and a model for a description of theoretical regulations. To this analogous similarity, as it is now called, is related, for example, the creation of a natural mechanical model for the description of luminous phenomena, the mathematical model for description of gravitation, etc. Newton's works on the theory of similarity and modeling did not last long and what followed was development and practical implementation. Although there were many experiments on models of arcs and testing of different hypotheses of their work at the beginning of the 18th Century in France and other countries[2].

The famous Russian inventor I.P. Kulibin was one of the first to use static similarity in his development of the project of an arch bridge over the river Neva with a span of 300 m. He provided the research using wooden models at 10% of the natural scale, with a weight of more than a ton, which were built and tested in Petersburg in 1775 - 1776. It was the first project to take into account that a change of the linear size by k times changes the original weight by k^3 times, and the square of the cross-section of the elements – by k^2 times. He established that the physical models in $1/k$ natural value had tensions based on its original weight of k times less than the original tensions. It is possible that the similarity of influence of its own weight in the model can carry an additional load. The working load which acts on the bridge must be less in k^2 times more. These levels of advances were checked and approved by L. Eelier.

J. Fourier's work, "The analytical theory of heat conductivity" was published in 1882 and in this it was shown that the components of an equation, which is described as a physical phenomenon, always have the same dimensional representation. This property was called "Fourier's right".

Bertrand has established the common properties of a similar mechanical movement, and shown the methods of similarity for complicated mechanical movements, as well as having formulated the requirement for the presence of the criterion of similarity. He showed in 1878 how one could find the mathematical dependence for physical quantities when the equation for the connection for these quantities is unknown. The mathematical dependence between these quantities must be a dependence between dimensionless complexes which are composed from these quantities.

Shortly thereafter, there were some works published such as the connection of the theory of similarity to different mechanical phenomena. For example, Koshee published the laws of sound phenomena in all geometrically similar bodies from the equation for the movements of elastic bodies.

Gelmgolz obtained the conditions of similarity for hydraulically phenomena. Philips established the laws of bridge vibrations, not only for static, but also for dynamic loading.

Even after the methods of similarity were obtained practical implementation was not easy.

Here is one example of physical simulation. In 1870 a big ship was built called "Captain", was launched by the Admiralty of England. Earlier research showed that this ship could be overturned by even minimal waves, but the lords of the Admiralty of England did not believe in the research of scientists with their toy model. The "Captain" overturned as it left for the open sea and 523 sailors perished. There is a memorial desk in London which serves to forever memorialize the ignorance of the lords of the Admiralty of England[2].

Ignorance on the part of executive personnel of the process of simulation continues to the present day.

There are many examples in which ignoring accurate simulation continues even now in aerospace and other areas. The result is the existence of very expensive crash disaster research stations and not enough reliability, maintainability, and availability (RAM) of many other types of technical products. These problems can be solved if the modern research results of similarity are employed along with accelerated reliability testing as well as accurate RAM prediction.

Often the low level of a professional's knowledge which only considers traditional approaches is the major obstacle to the use of other, especially new, approaches.

During the last Century the following science of similarity was developed in two basic directions:

1. Analysis of equations which describe mathematically the studied phenomena;
2. Analysis of the dimensionless physical quantities that characterize these phenomena.

The first direction was called *analysis of equations.* The second direction was called *analysis of dimensionless.*

In the 20th Century Reynolds, Nusselt, and other researchers proposed methods for the establishment of similarity and criteria processing of research results related to the problems of hydromechanics.

Now research into complicated, nonlinear, and non - homogeneous systems provides the next basic problems in the development of the theory of similarity. The above is about the development of a common theory of similarity.

Now the meaning of similarity (modeling) includes a wider content than previously. In modern scientific meaning the words "simulation" and "modeling" also include informational modeling, and many other types.

Above is a description of the history of the physical simulation of the test (research) subject, but there is a large area of physical simulation which is less developed and which was not fully described earlier. This is the physical simulation of the field input influences in the laboratory.

This type of simulation relates to laboratory experimental work with the actual test subject, as well as accelerated laboratory testing of the actual product that is used by most of the industrial companies as well as the university research centers during the development, improvement, and control of the quality of products. This is the physical simulation of field input influences on the actual product. For these goals one uses different types of test chambers (temperature/humidity//vibration/input voltage, temperature/humidity/vibration, temperature/humidity, etc), vibration equipment, dynamometers, and many others. The technique of this simulation is not sufficiently developed.

Below, this type of physical simulation will be described, as well as its development.

1.3 SIMULATION FOR ACCELERATED QUALITY DEVELOPMENT AND IMPROVEMENT THROUGH ACCELERATED RELIABILITY TESTING AND EXPERIMENTAL RESEARCH

As was mentioned earlier, accelerated testing as practiced today usually offers a minimum of all the possible benefits. One basic reason for this situation is that most companies and research centers cannot accurately simulate the basic combination of real life input influences on the actual product. As a result, they cannot provide successful accelerated reliability testing (ART) for obtaining accurate initial information for quality, reliability, maintainability, and availability evaluation and prediction in the field, and the solving of other problems such as accelerated experimental laboratory research, accelerated development and improvement of the product's quality, reliability, maintainability, availability, effectiveness, etc.

Experimental research (ER), especially in engineering, also offers only a minimum of possible benefits, because usually it isn't possible to accurately simulate in the laboratory the real life input influences on the research subject. Therefore, the experimental results are often different from field results.

The basic reason for the above situation is that there are insufficiently developed techniques and equipment for this simulation.

Unfortunately, literature in experimental research as well as in the accelerated testing area is for the most part about theory of experiments, statistical models, models for reliability analysis of Accelerated Life Testing (ALT), selecting the best distribution, research and test plans, analysis of results, computer simulation for providing a computer test without an actual product, censored data, etc. Such information is often insufficient for increasing ways to help practical engineers and managers as well as researchers in their problem solving, because it does not show how one can directly provide the above work with a high level of field simulation.

One of the advantages of this book is demonstrating how to fill this vacuum. This method can aid the development of practical experiments and accelerated testing which have developed slowly over the past 40 - 50 years. There are objective and subjective reasons for this situation.

Experiments and testing include the techniques and equipment for obtaining initial information for solving different problems of design, quality, reliability, etc. Success of the above problem solving often depends on how accurately this initial information reflects real life. When testing/research of the product is under artificial conditions of use, such as in a laboratory situation, computer, etc., it is necessary to simulate a real life situation. The above types of testing are in fact accelerated testing.

Depending on the level of real life simulation, the ratio of these experiments and testing results to field results can vary from 0% to 95 - 99%, whereas, in the accelerated testing area the level of field simulation is usually determined by the level of similarity of the testing results to the field results.

Usually, current complicated products such as computers, automobiles, aerospace and aircraft industry products, etc. include mechanical, electronic, plastic, and other possible components which work together. Simpler products (components) (subsystems of systems) also work in combination with other components. The interactions among subsystems of systems (components of complicated products), as well as interactions between different field input influences, can result in the overlooking of significant degradation and failure mechanisms.

If the specialists want to provide accurate simulation, they must to take into account these simulation processes, and this book describes the above processes for accelerated development and improvement of product quality.

The modern level of simulation as well as experimental research (ER) and accelerated reliability testing (ART) technology of the actual product is based on the application of a combination of various fields of knowledge: physics, mathematics, mechanics, electronics, chemistry, psychology, health care, and others. Simulation does not need a general understanding of these areas, instead it requires specific knowledge in greater depth.

Success in solving ER and ART problems often depends on the level of knowledge of the professionals involved in these areas. Now advanced companies throughout the world foster future development through special research/testing centers. For example, the new Clemson University International Center for Automotive Research plans to create an innovative automotive and transportation cluster unlike any other in the United States[3]. The automotive research center will be home to a new graduate engineering center, state-of-the-art research/testing facilities and private industry R&D operations. The corporate partners are BMW, IBM, and Microsoft. The effectiveness of the above centers, as well as other innovative technical-organizational solutions will depend on how well they can use accurate simulation of the field situation for accelerated research/testing provision.

A more detailed example comes from the Talford-Jones, Inc. experience. "Without [simulation] we couldn't have justified such a major investment in tooling to make our Reflex bumper system with a vertical honeycomb energy absorber a reality", said Bill Cherry, President, Talford-Jones Inc.[4].

2 THE STRATEGY FOR DEVELOPMENT OF ACCURATE PHYSICAL SIMULATION OF FIELD INPUT INFLUENCES

2. 1 BASIC CONCEPTS

Physical simulation of real life input influences [chemical and mechanical (dust) pollution, radiation, features of road, etc.] means physical imitation of the above influences on the natural test subject. Therefore, in the laboratory (artificial conditions) artificial input influences are active instead of those of the field. These input influences are in physical contact with the test subject.

Therefore, one can study under artificial conditions the physical essence of the actual processes.

Basic concepts of accurate physical simulation of field input influences in the laboratory for providing ART and ER include:

- Maximum simulation of field conditions;
- Simulation for testing 24 hours a day, every day, but not including:
  - idle time (breaks, etc.);
  - time with minimum loading which does not cause failures;
- Accurate simulation of each group of field conditions [multi-environmental, electrical, mechanical, etc. (Fig. 1.2)] simultaneously and in combination;
- Use of each of the above groups of field conditions as a complex simultaneous combination of different types of influences (Figure 1.2);
- Simulation of simultaneous combination of each type of complex influence that accurately simulates the field conditions [for example, pollution is a complex which consists of chemical air pollution + mechanical (dust) air pollution, and both types of this pollution must be simulated simultaneously];
- Assurance similitude of the degradation mechanism as a basic criterion for accurate simulation of field conditions;
- Consideration of system interactions among components;
- Reproduction of the complete range of field schedules and maintenance (repair);
- Maintenance of proper balance between field and laboratory conditions;

- Corrections of simulation system after analysis of field degradation and failures, and comparison of this with degradation and failures during ART.

These concepts are demonstrated in more detail in A, B, C, D, E, F, G, and H.

A. Simulation of simultaneous combination of real life input influences

For better understanding of the basic concepts of accurate physical simulation of field input influences, one needs to understand what kind of field influences will be simulated in the laboratory and what is intended by the physical simulation of these influences.

Different types of input influences are active on the "in the field" subject while it is working as well as during its storage (Figure 1.1). These are temperature, humidity, pollution, radiation, road features, input voltage, and many others ($X_1 \ldots X_N$).

The results of their action are output variables (vibration, loading, tension, output voltage, and many others ($Y_1 \ldots Y_M$). The output parameters lead to the degradation (deformation, cracking, corrosion, etc.) and failures of the product.

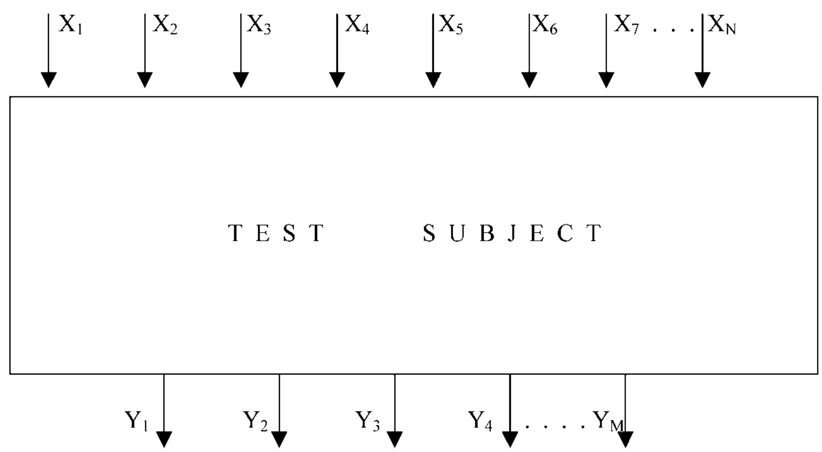

Figure 1.1 Scheme of input influences and output variables of the actual product.

One needs to simulate the input influences ($X_1 \ldots X_N$) in the laboratory for accelerated reliability testing (ART) of the product. ART is initial information of the accurate prediction of reliability, maintainability, durability, etc. This book considers physical simulation of the above influences on the actual product, e.g. those which preserve the physical essence of the actual product processes (direct physical contact with the product).

Accurate physical simulation is a situation in which the physical essence of output variables in the laboratory is different from those in the field by no more than the given limit of divergence.

For example, the mean of output variables (loading, tensions, voltage, amplitude and frequency of vibration, etc.) for the product in the laboratory differs from these variables in the field by no more than a given limit (3%, 5%, 7%, etc.).

This means that:

$$Y_{1\ FIELD} - Y_{1\ LAB} \leq \text{Given limit (for example, 3\%, 5\%, or 7\%)}$$

$$\vdots$$

$$Y_{M\ FIELD} - Y_{M\ LAB} \leq \text{Given limit (3\%, 5\%, or7 \%)}$$

What does one need in the laboratory for accurate physical simulation of the field input influences? The first concept of accurate simulation is the simultaneous combination of field input influences as they act in real life. What is meant by simultaneous combination? For an answer to this question let us consider the scheme of field simultaneous combination influences, for example, on automobiles (cars, trucks, etc) (Figure 1.2). As we can see from this figure, most of the field influences act simultaneously, so for the accurate simulation of real life one must simulate these influences simultaneously.

Current accelerated testing does not accomplish this. For example, one must simulate separately environmental, mechanical, electrical, and other input influences. Moreover, for example, for simulation of environmental influences one must separately simulate chemical and mechanical dust pollution from radiation. The above is separate from the simulation of the air and gas pressure, separate from the temperature and humidity, as well as from other environmental influences, etc. For simulation of road features one usually simulates only the profile, etc.

How can one combine the results of these separate simulations for accurate accelerated reliability testing? How can one use the results of the testing after the above simulations for obtaining initial information on the accurate prediction of reliability, durability, maintainability, etc? There are no answers to these questions.

Let us consider how weather factors affect people's feelings for a better understanding of how important the simulation of the simultaneous combination of real life input influences is on the product's reliability and maintainability. The connection between the reliability of the industrial products and input influences is similar to the connection between people's filling and the weather. When somebody asks another person: "Do you like today's weather, it is 80 °F?", the correct answer must be: "This is not a proper question", because people's feeling about the weather do not depend on temperature alone. The humidity is also an important factor. Normally, if the temperature is 80 °F and the relative humidity is 80 – 90%, usually people do not feel comfortable. If the temperature is the same, but the relative humidity is 40 – 50%, most people feel more comfortable. For a full description of the dependence of people's feelings on the

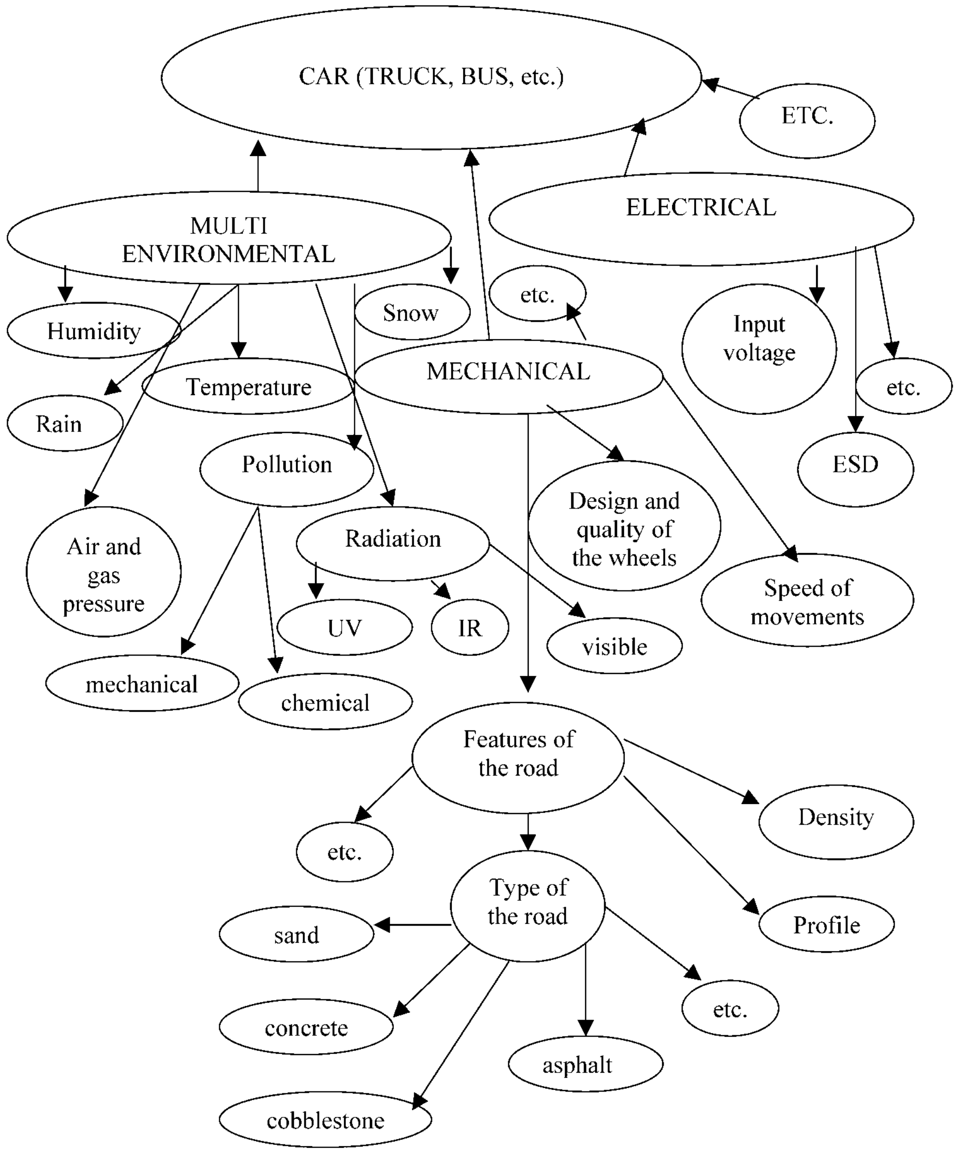

Figure 1.2 Scheme for the field simultaneous combination of influences (example with automobiles).

weather we also need to take into account air pollution, air pressure, the speed and direction of wind, and other factors. The reasons are: people's feelings are the result of a simultaneous combination of many factors of the weather's actions (input influences) and interactions. People's feelings influence their capacity for work and reliability.

The situation for equipment is similar. The temperature, or the temperature and humidity, or the temperature and vibration, etc. are only a small part of real life input influences. Therefore, their separate simulation in the laboratory for product testing (accelerated testing) cannot help to obtain accurate initial information for reliability, as well as solving maintainability, evaluation and other problems (rapidly finding the reasons for degradation and failures, etc.), because this is based on an inaccurate physical simulation of real life. Therefore, the field reliability, durability, and maintainability of the test subject are usually several times different from results obtained using accelerated testing technique and equipment.

One needs to use the above mentioned simultaneous combination of field input influences for accurate physical simulation of real life

B. Maximum simulation of field conditions (complete range of field loads) including all of these, not stresses only

One has to simulate not only stresses (higher and lower than blue line), but also the maximum

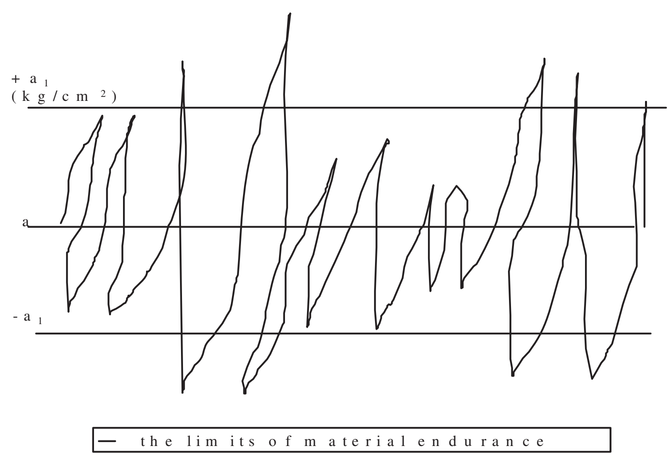

Figure 1.3 An example of a loading oscillogram in the field (upper of $+a_l$ and under of $-a_l$ are stresses).

complexity of field conditions (Figure 1.3).

C. Simulation for testing 24 hours a day, every day

This does not include idle time (breaks, etc.) and time with minimum loading that does not cause failures.

D. Simulation of the complete range of field schedules and maintenance (repair)

E. Assured similitude of the degradation mechanism as a basic criterion for accurate simulation of field conditions

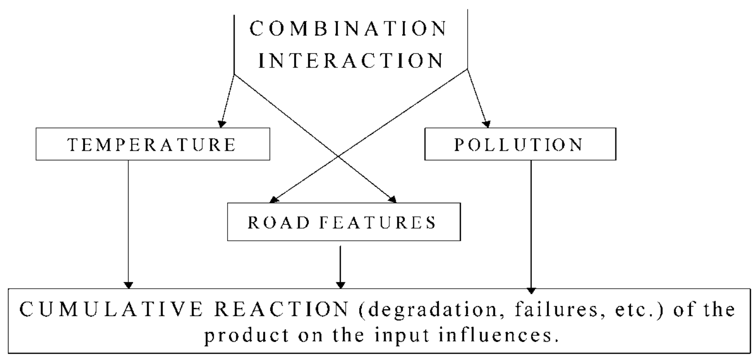

Figure 1.4 Example of cumulative reaction of the product on the input influences.

F. Consider the cumulative reaction of the product on the input influences (Figure 1.4)

The above is especially important for understanding why partial separate simulation of field input influences, without taking into account the cumulative field reaction of the test subject, cannot yield the correlation of field degradation (or failures) to the degradation under laboratory conditions. The above relates to accelerated reliability testing as well as to any experimental research in the laboratory.

G. Consider the system interactions amongst its components (Figure 2.9)

For accurate physical simulation of field input influences one has to take into account that in the field each subsystem (unit) and sub subsystem (detail) may act in a series along with interactions with all other subsystems and sub subsystems of the complete product. Therefore, for accurate simulation of field conditions, one must simulate exactly the full hierarchy of these connections and interactions. It is especially important if one wants to simulate input influences for ART or any experimental research on a separate unit or detail.

H. Corrections of the simulation system after an analysis of the field degradation and failures, and in comparison to the degradation and failures during ART

When one simulates the field conditions in the laboratory, one cannot consider all the possible field situations of the research or test subject. Therefore, at the end of research and testing one has to compare the field and laboratory results (degradation, failures, reliability, etc.) and correct the simulation conditions. Perhaps this will be important for correction of the finished work, as well as being useful for future testing and research on the same or analogous subjects.

2. 2 ACCURACY OF THE SIMULATION

Accuracy means the data are accurate within a given limit or the degree to which data correctly reflect the real-world object or event being described.

Of great importance for ART and any research is the accuracy of the simulation input processes. The authors' experience shows that in general the most accurate simulation of input processes occurs when each statistical characteristic [mathematical expectation μ, variance D, normalize correlation $\rho(\tau)$, and power spectrum $S(\omega)$] of all the input influences differs from the operating condition measurements by no more than 10%[5].

In specific situations one has to calculate and use for this goal the following statistical criteria comparing the reliability during ART to operating conditions.

The reliability function distribution after ART is labeled $F_a(x)$. In operating conditions it is $F_0(x)$.

The measure of the difference is[6]:

$$\eta\ [\ F_a(x),\ F_0(x)\ ] = F_a(x) - F_0(x)$$

The function $\eta\ [F_a(x),\ F_0(x)\ ]$ has the limitation η_A (maximum of difference), such that when

$$\eta\ [\ F_a(x),\ F_0(x)\ ] \le \eta_A$$

it is possible to determine the reliability of ART results. But if

$$\eta\ [\ F_a(x),\ F_0(x)\ ] > \eta_A$$

it is not recommended.

Often in practice one does know the theoretical functions of $F_a(x)$ and $F_0(x)$. Therefore, one can construct graphs of the experimental data $F_a(x)$ and $F_0(x)$ and determine the difference:

$$D_{m.\ n.} = \max\ [F_{ae}\ (x) - F_{oe}\ (x)]$$

where F_{ae} and F_{oe} are empirical distributions of the reliability function observed by testing of the product under operating conditions and by accelerated testing.

Also, one can find $D_{m,\ n}$ from experimental graphs of $F_{ac}(x)$ and $F_{oc}(x)$.

One counts the number:

$$\lambda_0 = \frac{\sqrt{mn}}{(m + n)\ (D_{m,n} - \eta_A)}$$

where n is the number of failures observed in operating conditions; and m is the number of failures observed in the laboratory.

The correspondence between comparable distribution functions is evaluated with probability:

$$P[\ \sqrt{mn}/(m + n)(D_{m,n} - \eta_A) \geq \lambda_0\ ] < 1 - F(\lambda_0)$$

If $[1 - F(\lambda_0)]$ is small, not more than 0.1 typically, then:

$$\max\ [F_{ac}(x) - F_{oc}(x)] > \eta_A$$

and the distribution function for ART does not correspond to the distribution function in the field. It means that one needs to develop the system for physical simulation of field input influences in the laboratory (methods or equipment, or both).

The main conclusion from the above criteria is that they give the possibility of comparing the reliability changes during the time of service life in the field. The second conclusion may be to determine the limitation of the reliability function between testing under operating conditions (field) and laboratory conditions. The level of accuracy of the reliability evaluation depends on this limitation.

The choice of influences for ART may be evaluated by analysis of work specific to the test subject in operating conditions. Therefore, it is very important to evaluate the influence of the regional statistical characteristics of operating conditions which one needs for a physical simulation in the laboratory for ART or experimental research. This would represent characteristics close to the operating conditions characteristics.

The solution to this problem is theoretically very complicated. Therefore, the author does not give it here. The following describes the principal steps of this solution.

Accurate simulation of input processes offers the possibility for the calculation of the acceleration coefficient. Without this coefficient one cannot accurately calculate predictable reliability in the field after ART. Without accurate simulation of field input influences in the laboratory, one cannot accurately predict reliability, durability, and maintainability in the field.

Why does one usually does not accurately simulate the field input influences? Because:

- Only part of the field conditions are simulated simultaneously (Figure 1.2). For example, for electronic product testing one simulates simultaneously maximum input voltage plus temperature plus vibration plus humidity (seldom). As a result, one does not take into account the connections and interactions between different parameters of the field conditions;
- Simulation of each parameter from the above part is not correct. For example, one simulates stresses only for measuring acceleration;
- The entire step-by-step ART technology is not used, but only several steps at a time.

2. 3 DEGRADATION (FAILURE) MECHANISM OF THE PRODUCT AS A CRITERION FOR AN ACCURATE SIMULATION OF FIELD INPUT INFLUENCES

How can one evaluate the accuracy of physical simulation? For this goal different types of criteria have been used. Professionals often use the correlation of ART results to field testing results, and reliability indexes such as time to failure, types of failures, etc. For these criteria a long time is required, especially if one wants to evaluate a product's durability. Another negative aspect of this method is that ultimately the destruction of the product occurs. Also professionals need to know earlier the accuracy of the field simulation to be sure that the criterion was used correctly, or whether an earlier correction of the criterion was necessary.

Therefore, for this purpose one often uses the comparison of output variables (loading, tension, etc.) in the field and in the laboratory. Sensor measurements of tension and load were easy to determine with outputs that were simple, short, and frequently used. Using this method doesn't require a long time, but practice shows that when this method is used, the primary output parameters (tensions, loads, etc.) are not sufficient to characterize the simulation process. There is often good correlation between tensions, loads, etc. during the field and laboratory testing, but insufficient correlation between the time to failure and other reliability indexes in the field and in the laboratory.

Experience shows that a better method is a comparison of the degradation (or failure) mechanism (process) during ART/experimental research with this process during field testing.

This is difficult since changing of the equipment is required followed by a destructive failure analysis of part of the system.

The physical (chemical, mechanical, etc.) mechanism of degradation approach to accelerated qualification is the basic criterion for accurate simulation of real life processes by AT, because it offers the possibility to compare the results of testing in the field and in the laboratory, and to quickly correct the simulation process if the simulated process is incorrect.

The degradation (failure) mechanism during AT must be approximately similar to the degradation mechanism during field testing:

$$D_L \approx D_F$$

where D_L is the degradation mechanism during AT; and D_F is the degradation mechanism during field testing.

The degradation mechanism helps to set a stress limit,. which means the limit after which the degradation mechanism (physical, mechanical, electrical, chemical, or other) during laboratory testing is different from the degradation mechanism in the field. Often one uses for the above goal only the meaning "physics-of-degradation" which is not correct. Chemical degradation, for example, chemical corrosion as well as changing of the chemical structure of plastics, etc., has a different mechanism. The same is true for mechanical degradation, for example, mechanical wear or electrical degradation. Therefore, the type of degradation (physical, or chemical, or mechanical, or electrical) depends on the type of process and the subject of testing (research), (Figure 1.5) .

Each product has different parameters for the degradation mechanism, and one must evaluate the limit for each parameter.

Many professionals understand that AT only stresses simulation. But often they do not want to understand the following axiom of stress testing: more stress means greater accelerations and lower correlation of AT results with field results.

In real life the mechanical, chemical, and physical types of degradation mechanisms often are connected with each other. Each type of degradation mechanism can be evaluated through the degradation parameters. If sensors can be employed to evaluate these basic parameters, one can measure their rate of change during a particular time, compare field and laboratory testing, and can determine how similar the ART conditions are to real life conditions. If these processes are

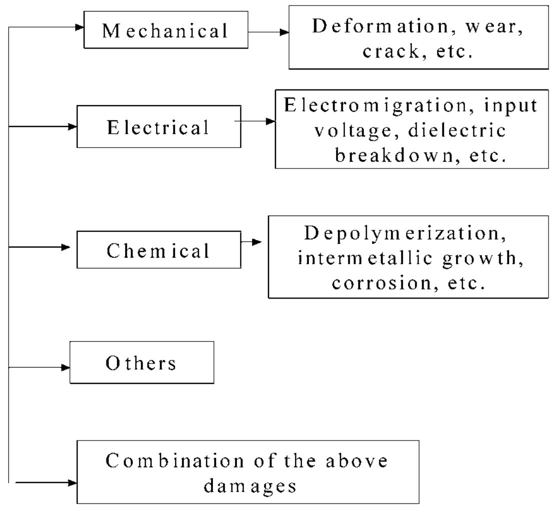

Figure 1.5 Types of degradation mechanisms and their parameters during product testing[3].

similar, then there may be sufficient correlation between ART results and field testing results.

How is it possible to make a practical comparison between the parameters of degradation mechanisms in the field and in the laboratory? Let's take as an example metallic sample deformation. In Figure 1.6 we can see that the mean of deformation during the laboratory testing is within the ±10% confidence interval (between upper and lower confidence limit) of the field deformation. This means that there is a sufficient correlation between accelerated testing results and field results (usually in practice, the confidence interval ±10% is a good measure of this goal). The comparison process of the field and laboratory results has a statistical character. One can read about this in more detail in section 8 "Technology of step-by-step accelerated testing".

What is the connection of physical simulation with Accelerate Reliability Testing? This is a very complicated process. Let us show the essence of the above process with the following example. Degradation and failures in the field (and in the laboratory if there is accurate simulation of the field influences) are a result of the complex [climatic (environmental), mechanical, electrical, etc.] of factors influencing the machinery's reliability.

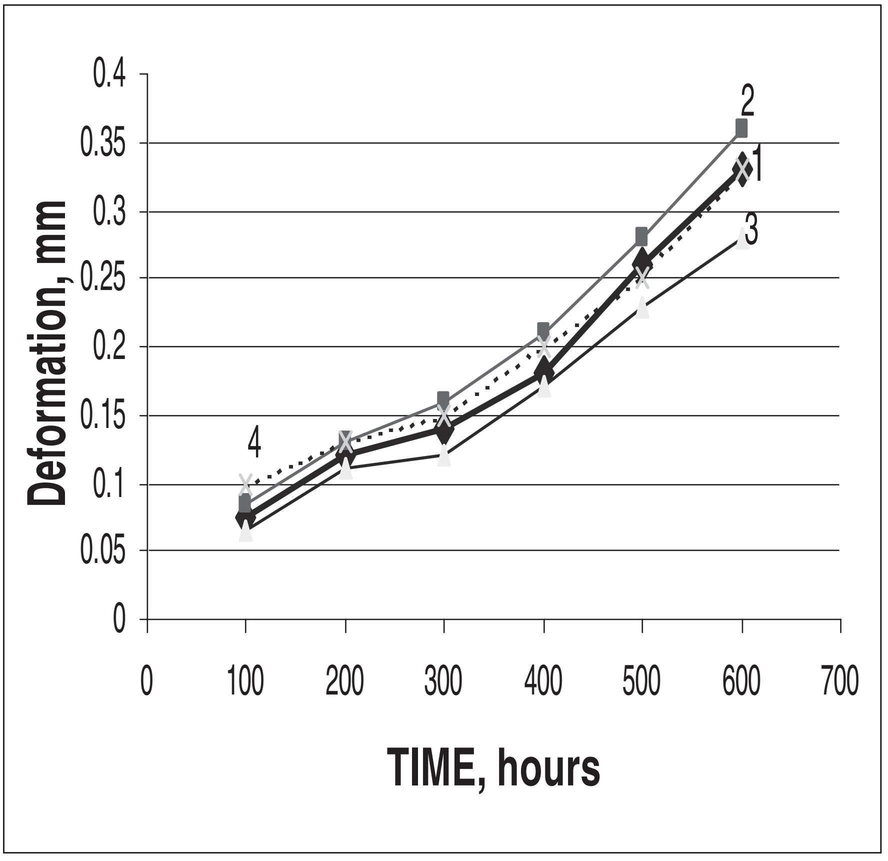

Figure 1. 6 Deformation of a metallic sample over time[7]: 1 is the mean deformation in the field; 2 is the upper confidence limit in the field; 3 is the lower confidence limit in the field; 4 is the mean deformation in the laboratory (accelerated testing conditions); the value of confidence interval is ±10%.

The scheme (Figure 1. 7) shows an example of three stages of the influence of climatic factors on automotive reliability. Of course, these factors in real life exert a simultaneous influence over mechanical, electrical, etc. groups of influences.

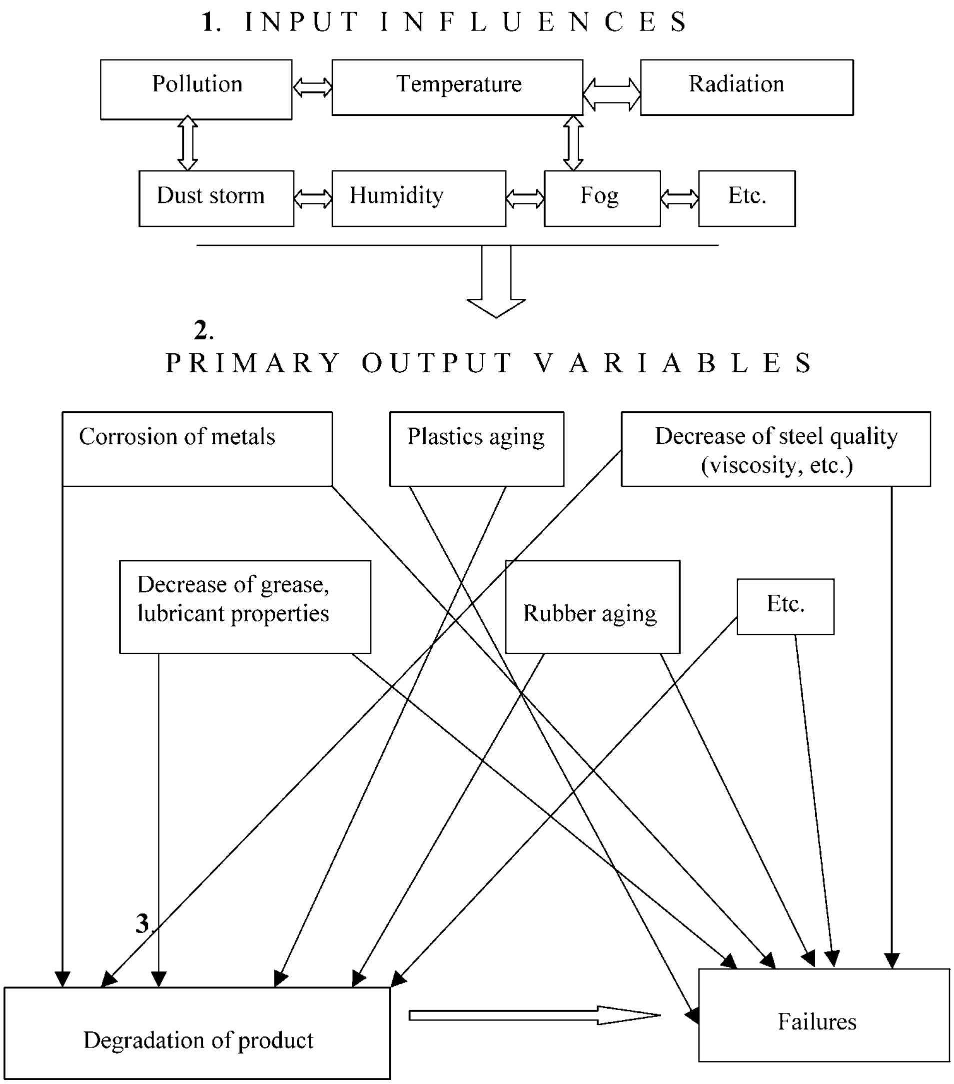

Figure 1. 7 Example of a scheme of complex influences of the basic climatic factors on automotive reliability[3].

2.4 OBTAINING ACCURATE INITIAL INFORMATION FROM THE FIELD

For accurate simulation of field input influences one must obtain for each test subject:

- input influences which affect product reliability (the range, character, speed, and limit of value changing, etc. of temperature, humidity, input voltage, radiation, pollution, air pressure, features of the road, etc.) under various field conditions wherever the product is employed, as it acts in the field;

For example, concerning the temperature one needs to obtain for each of the climatic zones where the test subject is used the information shown in Figure 1.8:

- output variables (load, tensions, vibration, corrosion, output voltage, etc.) the range, character, speed and limit of value changes under various field conditions;

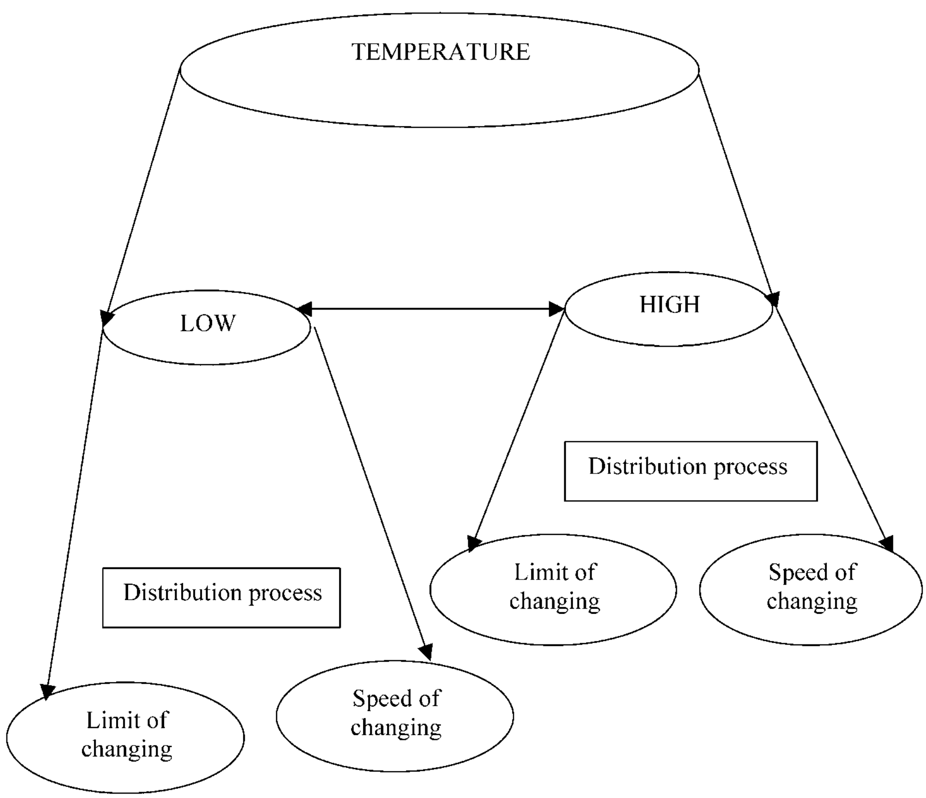

Figure 1. 8 A study of temperature as input influence on the test subject.

speed and limit of value changes under various field conditions;

- scheme of the mechanism of degradation for the components of the test subject (types and parameters of degradation, value of parameters of degradation, dynamic and statistical characteristics of these parameters which change during usage time, etc.). As an example, one can see the types and parameters of degradation from Figure 1. 5;

- the distribution percentage of the test subject when working under different usage conditions, for example, tables 1. 1 and 1. 2 shows these time distributions for a fertilizer applicator.

Table 1.1 The distribution of farm work for a fertilizer applicator[7].

Phase	Distribution of work	Time, %
1	Distribute fertilizer	46.0
2	Moving of applicator with fertilizer	24.0
3	Moving of applicator without fertilizer	30.0

Table 1. 2 Distribution of work in different agricultural conditions[7].

Phase	Conditions	Time. %
1	Stubble	54.0
2	Plowed ground	32.5
3	Fallow ground	11.0
4	Clover	2.5

If the applicator is used in different climatic regions, this may also change the distributions;

- analysis of the above information as a probability (random) process. Most of the field input influences and output variables have a probability (random) process, because they change during usage, and the character of this change is random. Therefore, one has to evaluate as a minimum the mathematical expectation, standard deviation (or variance), correlation (normalized correlation), and power spectrum, as well as the distribution of input influences and output parameters;

- the scheme of the test subject as a system which consists of subsystems and sub subsystems with their connections and interactions (an example was shown in Figure 1. 4).

2. 5 A METHODOLOGY FOR SELECTING A REPRESENTATIVE INPUT REGION FOR ACCURATE SIMULATION OF THE FIELD CONDITIONS

2. 5. 1 Introduction

Accelerated testing of products is increasingly popular because, for example, parts are lasting longer and field testing under nominal operating conditions is expensive. Usually accelerated testing involves reproducing the effects of maximum stresses experienced in the field by stressing items at a higher level and/or a faster rate so that data about failure, or successful operation, can be collected more quickly. Therefore the main motivation for accelerated testing is to reduce test time. Second is the reduction of testing cost. Consequently, accelerated testing is usually testing that reproduces the operating conditions of the field with some kind of acceleration to obtain faster and less expensive results.

For example, wear of a mechanical part will be influenced by many factors such as metal fatigue, corrosion and so forth. Typically it will be difficult to include let alone control all these factors during wear evaluation. Therefore one strategy is to select a subset of factors, however if this is haphazard then the test design will be flawed and the results produced will not be useful.

It is impossible accurately to simulate all the field conditions in the laboratory, because often around 100 parameters can influence the reliability of the test subject. Failure to control output parameters (corrosion, wear, deformation, etc.) during degradation evaluation can result in a larger scatter.

Usually the test subject is used under different field conditions: variation in environment, load, and different physical-chemical and other influences. In practice one cannot test the test subject in all the above conditions. Therefore, to solve the problem requires a strategy: one or several field conditions out of a multitude of real field conditions should be chosen for their physical simulation in the laboratory.

The following methodology describes how to help solve this problem by identifying a representative region using stochastic modeling of the degradation processes.

The approach aims to establish representative regions of input processes that correspond to part of the field influences, such as air temperature, humidity, pollution, radiation and so on, based on estimates of the output processes, such as measures of the output parameters of degradation including tension, vibration, corrosion, and so on. The representative region approach is based on evaluation of statistical characteristics of input (or output) processes, and thus presents the possibility of determining one region with sufficient characteristics and statistical information about the multitude of regions that exist and to simulate its characteristics in the laboratory.

The methodology has been motivated by and applied successfully to real accelerated tests[6,7] and is based on the theory of random processes described in publications by, for example, Corn[8], Lourie[9], Ventcel[10] and others.

It is clear this work must be carefully performed to have the desired results. A full description of the methodology is given in the next section and is followed by an illustration of its application to an accelerated test.

2. 5. 2 Methodology for Selecting a Representative Region

The methodology can be summarized in the algorithm presented below. The details of each step will be explained in the following sub sections.

2. 5. 2.1 *Algorithm*

The algorithm for selecting a representative region for accelerated test is:

Step 1

Identify the type of process exhibiting a random rate and establish whether it is a stationary process through the following steps:

A. Characterize the process in terms of its mathematical expectation, standard deviation, correlation and power spectrum.

B. Evaluate whether the process is ergodic by assessing whether the important correlation tends to zero as time tends to infinity.

C. Use the Pearson criterion, or equivalent, to assess whether the process exhibits Normality.

Step 2

Measure the divergence between the basic characteristics of the process evaluated in different regions.

Step 3

Select and measure a characteristic in a representative region (usually length)

Step 4

Identify the representative region as the one with minimal divergence.

2.5. 2. 2 *Selection of process and its characterization*

We assume there is an interval [O, *T]* in the oscillogram that characterizes the changes in loading or wear (or another physical parameter, *X*) of a product during use. We then divide the interval [0,*T*] of the oscillogram into smaller intervals of length T_p and for each evaluate mathematical expectation (μ_X), correlation function ($\rho_X(\tau)$, power spectrum ($S_X(\omega)$)and their accuracy, for example, using Lourie method[9]. Thus the periodicity of the process can be checked to ensure that it is appropriate to use one interval realization of the process as being representative of all realizations of the same duration. Periodicity can be assessed formally by checking that the correlation function tends to zero by $\tau \rightarrow 0$ to analyze the ergodicity of the process. However it is also appropriate to combine this information with judgment relating to the particular problems and the physical essence of process being studied.

To check the hypothesis about Normal character of process, we assume that using one realization of the specified interval length T_p is sufficient to characterize the entire process because it is ergodic. From the correlation function we can identify the value of τ for which the correlation is (statistically) zero. That is, $\rho_X(\tau_0)$. For the interval $[0,\tau_0]$ in the oscillogram we measure the values at equi-distant points $t_1, t_2, t_3 \ldots t_n$. The usual goodness-of-fit tests, such as Pearson, can be used to assess whether these values are Normally distributed.

2. 5. 2. 3 Length of representative region T_R .

If is established that the process is Normal, we can begin to evaluate the length of representative region, T_R, which has to be enough large for evaluating the correlation function ($\rho_X(\tau)$) and the mathematical expectation because the accuracy of μ_X.

At the *m*th point of the interval representing T_R it is divided into *n* equally spaced sub-intervals of length $\Delta t = T_R/n$ and the observed values of the oscillogram noted at the times are denoted by $x(t_i)$. Hence the correlation function can be estimated using

$$\hat{\rho} = \frac{1}{m-n}\sum_{t_i=1}^{n-m}\left[x(t_i+m)-\mu_X\right]\left[x(t_i)-\mu_X\right] \qquad (1.\ 1)$$

To calculate the preliminary values of T_R we need to know the frequency ranges in the oscillogram where the parameters are changing. The row of full low frequency periods, denoted by $T_1, T_2, T_3 \ldots T_n$ and each of which have random rate, are marked at equal intervals from each other. The mean, denoted by T_M can be evaluated by

$$T_M = \frac{T_1 + T_2 + \ldots + T_n}{n}$$

where $n \geq 3$

The lowest frequency of process rate is given by $f_L = 1/T_M$ and the value of τ_{max} can be selected using the condition $\tau_{max} \approx 1/f_L = T_M$ [8]. The value of T_R can be established from τ_{max}. Typically $T_R = 10\tau_{max}$ because the error associated with the estimation of μ_X and $\rho_X(\tau)$ should be no more than 5%.

To estimate Δt it is usual to consider the highest frequency changes of the process which we denote by f_m and in practice $\Delta t = 1/0.6 f_m$.

2.5. 2. 4 Comparison of values between different regions of the oscillogram

Since stationary Normal processes can be characterized by their expectation (μ), variance (σ^2) and normalized correlation structure ($\rho_N(\tau)$), we evaluate these for the entire oscillogram over the range [0,*T*] and *k* different regions of the oscillogram of length T_R, where $k = T/T_R$. For example, we denote the vector of the characteristics of the *i*-th region as $[\hat{\mu}_i, \hat{\sigma}_i, c|\rho_{Ni}(\tau)|]$ where *c* is a normalization constant. For the entire oscillogram the equivalent vector will be written as $[\hat{\mu}, \hat{\sigma}, c|\rho_N(\tau)|]$ where

$$\hat{\mu} = \frac{\sum_{i=1}^{k} \hat{\mu}_i}{k}, \quad \hat{\sigma} = \frac{\sum_{i=1}^{k} \hat{\sigma}_i}{k}, \quad \hat{\rho}_N(\tau) = \frac{\sum_{i=1}^{k} \hat{\rho}_{Ni}}{k}, \quad k = \frac{T}{T_R} \tag{1. 2}$$

The divergence between any two regions, say $\underline{a_i}$ and $\underline{a_j}$ may be estimated as a weighted linear combination of the squared differences between their expectations, variance and correlations. For example,

$$\Delta(\underline{a_i}, \underline{a_j}) = p_1(\hat{\mu}_i - \hat{\mu}_j)^2 + p_2(\hat{\sigma}_i - \hat{\sigma}_j)^2 + p_3 \max[\hat{\rho}_{Ni}(\tau) - \hat{\rho}_{Nj}(\tau)]^2 \tag{1. 3}$$

where the weights, p_1, p_2, p_3 sum to one and are selected using the method least squares to minimize the sum of squared deviations between the corresponding components of the two vectors. Hence higher weights will be given the bigger differences between the corresponding statistics. If there is no difference between any of the components within the vector then all will be equally weighted (i.e. 1/3). Note also we suggest using the maximum deviation between the correlations as a measure of the most extreme difference between the two correlations. This only uses a selection of information in the correlation structure. To overcome this, it may be preferred to use the estimated spectral power function ($\hat{S}(\omega)$) instead of the correlation function. In this case, the deviations between the two regions would be written as

$$\Delta(\underline{a_i},\underline{a_j}) = p_1(\hat{\mu}_i - \hat{\mu}_j)^2 + p_2(\hat{\sigma}_i - \hat{\sigma}_j)^2 + p_3[\hat{S}_i(\omega) - \hat{S}_j(\omega)]^2 \quad (1.\ 4)$$

where again $p_1 + p_2 + p_3 = 1$.

2. 5. 2. 5 Choice of representative region

The representative region is selected as the one, from the k considered, that has the minimum divergence from the whole range considered. That is, the representative region will be denoted by the vector $\underline{a_R}$ and is the one which minimizes the following function written first for the correlation structure and second for the power spectrum,

$$\min \Delta_1(\underline{a_R},\underline{a}) = \min\left\{p_1(\hat{\mu}_R - \hat{\mu})^2 + p_2(\hat{\sigma}_R - \hat{\sigma})^2 + p_3 \max_{\tau}\left[\hat{\rho}_{NR}(\tau) - \hat{\rho}_N(\tau)\right]^2\right\}$$

or (1. 5)

$$\min \Delta_2(\underline{a_R},\underline{a}) = \min\left\{p_1(\hat{\mu}_R - \hat{\mu})^2 + p_2(\hat{\sigma}_R - \hat{\sigma})^2 + p_3 \max_{\omega}\left[\left(\hat{S}_R(\omega) - \hat{S}(\omega)\right)\right]^2\right\}$$

Thus the region of length T_R that satisfies the above condition is selected to be simulated during accelerated testing as this provides a representative selection of the oscillogram of reduced length (i.e. (0, T_R) rather than (0, T) and this will facilitate more efficient testing.

2. 5. 3 Example of Selecting a Representative Region

The following example illustrates the application of the proposed methodology to a real accelerated test. The data to be analyzed are from the oscillogram that was written by a tension sensor on a truck with a mobile computer. The curve of the oscillogram consists of the 20 separate regions, each of equal length 800 mm, and reflects the influence of the field on the sensor. The estimates of the expectation and standard deviation over all regions of the oscillogram are $\hat{\mu} = 1.58\text{mm}$ and $\hat{\sigma} = 5.98\text{mm}$. The statistical characteristics of tension changing on 19 regions are summarized in Table 1. 3. Note that the values of the estimated parameters are shown in mm (1 mm = 2 MПa) and the data for region 15 have been excluded since it exhibited very different characteristics from the other regions as it represented an atypical field experience. Figure 1.9 shows the correlation function for regions 10, 11 and 12.

Table 1.3 Statistical characteristics of variable tension process[7].

Number of region	μ_i	σ_i^2	σ_i	$\lvert\mu_i-\mu\rvert$	$\lvert\sigma_i-\sigma\rvert$	$\max_\tau \lvert\rho_{Ni}(\tau)-\rho_N(\tau)\rvert$	$\max\lvert S_i(\omega)-S(\omega)\rvert$
1	-0.72	68.3	8.26	2.3	2.28	0.23	0.024
2	2.22	45.3	6.73	0.64	0.75	0.26	0.024
3	2.79	35.6	5.9	1.21	0.08	0.11	0.005
4	1.12	21.6	4.65	0.46	1.33	0.13	0.08
5	1.04	33.2	5.76	0.54	0.22	0.15	0.007
6	3.66	30.2	5.49	2.08	0.39	0.18	0.023
7	-1.21	42.7	6.5	2.79	0.52	0.15	0.011
8	3.48	27.8	5.27	1.9	0.71	0.24	0.008
9	1.47	56.4	7.5	0.11	1.52	0.15	0.012
10	2.21	26.6	5.16	0.63	0.82	0.17	0.015
11	1.5	51.4	7.17	0.32	1.19	0.24	0.012
12	1.71	39.4	6.8	0.13	0.82	0.16	0.010
13	0.08	24.8	4.98	1.5	1.00	0.19	0.023

Table 1.3 Statistical characteristics of variable tension process[7] (continuation).

14	-0.19	30.8	5.55	1.77	0.43	0.15	0.013
16	1.03	34.0	5.84	0.55	0.14	0.23	0.020
17	5.0	22.2	4.7	3.42	1.28	0.27	0.027
18	4.6	18	4.24	3.02	1.74	0.20	0.012
19	-0.95	35	5.92	2.53	0.06	0.19	0.003
20	0.82	38.4	6.2	0.76	0.22	0.18	0.018

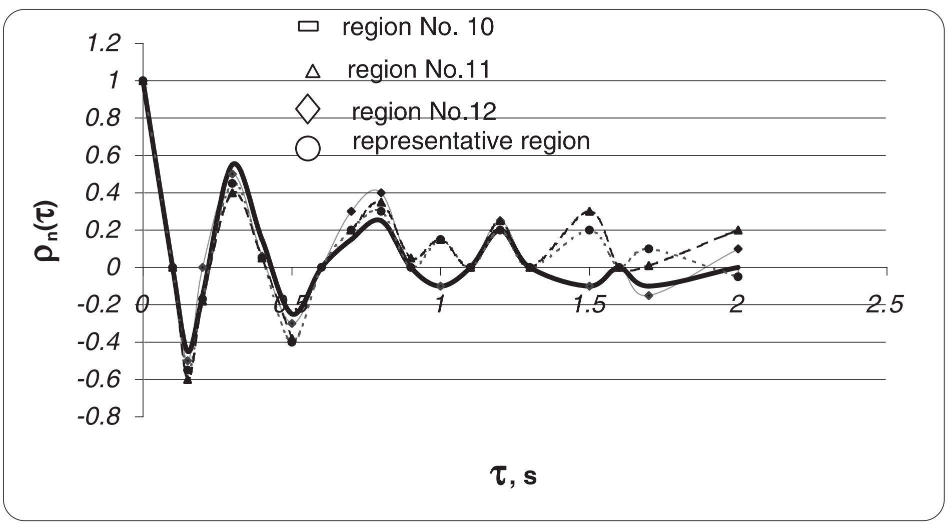

Figure 1. 9 The correlation functions of regions 10, 11, 12, and the representative region.

To illustrate the process used to assess Normality of the data, consider the data for region 6. Since the first time the estimated correlation tends to zero is 0.1s, we set $\tau_0 = 0.1\text{s}$. In the region $(0,\tau_0)$ we obtained 225 observed values occurring at a random rate. These data: 33, 30, 55, 46, 55, 42, 29, 38, 42, 48, 40, 41, 38, 37, 35, 32, 32, 40, 43, 46, 28, 20, 31, 48, 44, 36, 30, 30, 37, 38, 40, 32, 34, 36, 36, 36, 38, 34, 25, 33, 41, 39, 34, 28, 38, 44, 54, 41, 25, 33, 49, 45, 40, 37, 37, 37, 36, 34, 31, 26, 36, 35, 43, 33, 25, 30, 33, 39, 33, 38, 29, 30, 32, 40, 42, 44, 39, 36, 26, 27, 46, 39, 30, 31, 34, 38, 33, 36, 44, 40, 28, 28, 36, 38, 36, 39, 35, 38, 38, 36, 35, 37, 39, 38, 31, 32, 34, 39, 38, 42, 39, 28, 31, 44, 42, 39, 37, 36, 37, 27, 30, 43, 42, 36, 35, 38, 37, 32, 36, 40, 36, 38, 37, 30, 37, 40, 38, 34, 31, 33, 32, 31, 43, 38, 24, 30, 35, 40, 37, 34, 44, 39, 28, 28, 36, 36, 38, 37.

The estimated mean and standard deviation for region 6 are 36 and 5.56 respectively. Dividing the range of the data into 11 equal classes, we can compare the observed frequency with that expected under a Normal distribution as shown in Table 1. 4. Further the usual Chi-squared goodness-of fit test[11] gives a test statistic of $\chi^2 = 9.14$ and since this statistic has a Chi-squared distribution with 8 degrees of freedom, the p-value is found to be 0.34. This suggests that the Normal distribution is a suitable model for the data.

Table 1. 4 Frequencies and probability for the groups in region 6.

Groups	1	2	3	4	5	6
Frequency	1/225	5/225	18/225	25/225	35/225	57/225
Probability	0.0078	0.0238	0.0628	0.1227	0.1875	0.2127

Continuation

Groups	7	8	9	10	11
Frequency	47/225	22/225	9/225	3/225	3/225
Probability	0.1816	0.1167	0.0564	0.0205	0.0067

We check the Normality of data from region 8 in a similar manner. Again 225 sample values are analysed. Table 1. 5 shows the probabilities observed over 10 equal sized classes and the mean and standard deviation for the data set are 36.68 and 5.25 respectively. The Chi-squared goodness-of-fit test statistic is 6.9 and has Chi-squared distribution with 7 degrees of freedom, giving a p-value of 0.43. Again this provides evidence that the Normal distribution is a suitable model for the data. This is indeed the case for analysis of all 19 regions.

Table 1. 5 Frequencies and probability for the groups in region 8.

Groups	1	2	3	4	5
Frequency	5/225	9/225	27/225	44/225	47/225
Probability	0.0221	0.0493	0.1146	0.1878	0.2242

Continuation

Groups	6	7	8	9	10
Frequency	55/225	45/225	8/225	3/225	3/225
Probability	0.1952	0.1958	0.0579	0.0189	0.0046

Further checks on the expectation and variance of the process suggest that it is not stationary. For example, consider the results presented in Table 1. 3 for the mean, variance and standard deviation which show that there is a considerable spread in the estimates. However the same is not true for the correlation. In contrast, the estimates across regions show that the maximum deviations in normalized correlation are almost equal and so this suggest the process does reduce to stationary.

Analysis of the power spectrum over the interval of ω from 9 to 25 s^{-1} covers most of the spectral density as shown in Figure 1. 9, whereas the correlation function for regions 10, 11, and 12, shown in Figure 1. 9, appears to have a periodical component. Therefore, the correlation should take in a larger interval, such as from 0 to 10 s.

Table 1. 3 shows the modulus of mathematical expectations, standard deviations, correlation and spectral functions and the divergences from the different regions based on the characteristics of the whole oscillogram. The divergences presented in Table 1. 3 are substantial. An alternative way of examining the deviations between each region and the whole oscillogram could be to superimpose the corresponding functions on the same graph.

Taking the small influence of the tension expectation value into account gives estimates of p_1 = 0.1; p_2 = 0.5; and p_3 = 0.4 and so we can calculate the divergence of Δ_1 and Δ_2 . The results are presented in Table 1. 6 . We can see that regions 3 and 19 are closer in their characteristics to the whole oscillogram than any of other regions. Criterion Δ_1 is closer for region 3, and criterion Δ_2 is closer for region 19. The power spectrum shows frequency is the most important factor, because it characterizes the dispersion distribution (amplitude of oscillation) by frequencies, i. e. a very important technical characteristic. Therefore, we can select region 19 as the best representative of input influences.

Table 1. 6. Divergences measured between characteristics of 19 regions.

REGIONS

Divergence measure	1	2	3	4	5	6	7	8	9
$\Delta_1(\underline{a}_i, \underline{a})$	12.55	4.85	0.96	7.27	1.75	2.37	3.48	4.76	8.21
$\Delta_2(\underline{a}_i, \underline{a})$	12.59	4.93	0.72	7.07	1.45	2.57	3.32	4.12	8.09

Continuation

Divergence measure	10	11	12	13	14	16	17	18	19	20
$\Delta_1(\underline{a}_i, \underline{a})$	4.84	6.94	4.75	5.91	2.93	1.68	6.82	9.8	1.31	1.9
$\Delta_2(\underline{a}_i, \underline{a})$	4.76	6.46	4.51	6.07	2.85	1.56	6.82	9.48	0.17	0.49

The purpose of this chapter is to describe an approach to the methodology of selecting a representative region from the multitude of input influences based on input (output) influence simulation. The result leads to successful accelerated testing.

The concept of representative region selection is then extended to real life analysis techniques to establish the characteristics of the critical input (or output) processes. This leads to the possibility of determining one from multitude regions which is most characteristic for all statistical population of field varieties.

Seven basic steps describe the methodology. The associated procedures are measures of the representative short region with minimal divergence resulting from the multitude of input influences (or output variables) under field conditions. The whole process is illustrated by a practical example. The solution is shown for normal processes by use of the Pierson criterion, but could be use with other types of random rate.

The described methodology is useful in substantiation of accelerated testing regimes as well as leading to successful accelerated testing, and helps to obtain accurate preliminary information for reliability prediction, predictive maintenance, and solving other problems of reliability.

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3. CLIMATE AND RELIABILITY

3. 1 INTRODUCTION

Most mobile products such as machinery and equipment for automotive, off-highway and construction, railroads, aircraft and aerospace, farmers and the lumber industry, ship building, gas and petroleum industries, etc. are used outdoors and exposed to the elements.

Outdoor use subjects them often to unfavorable influences from environmental factors. Most of these influences are atmospheric: high and low air temperatures, daily and yearly fluctuations of these temperatures, solar radiation, humidity, pollution (mechanical and chemical), rain, wind, etc. Other unfavorable influences on the machinery are from atmospheric phenomena such as fog, snowstorms, frost, ice on the ground, dust-storms, water-storms, etc. Because of the unfavorable influences of the above environmental factors, the quality of construction materials deteriorates, leading to deterioration of machinery reliability and effectiveness.

The above factors influence not only the machinery, but also the people who control these machines, as well as the objects of the machines' influence (working the land, roads, agricultural products, food, etc.). The changes in human conditions and the deterioration of the land and roads also influence machinery reliability. Therefore, the reliability of machinery must be described as a complex system "operator-machinery-object of machinery actions". The successful functionality of the above system depends on also on the operator's actions.

The environment (climate) is characterized by a wide range from arctic to subtropical. The nature and character of the environmental factors which influence the internal material and reliability of machinery are very complicated. The reliability and effectiveness of machinery that is used outdoors mostly depends on a level of correspondence, and suitability of its design for use under given climatic conditions.

The guarantee of optimal reliability for different environmental conditions requires development of environmental accelerated testing along with a generalization of the accumulated experience-proved design and testing of machinery which has been designed for specific environmental conditions[20].

Electronic and plastic products are the most sensitive to environmental actions.

3. 2 THE CLIMATE CHARACTERISTICS AS EXTERNAL CONDITIONS OF MACHINERY USE

3. 2. 1 The Classification and Characteristics of World Climate for Technical Goals

World climate has a large range. The formation of territorial climate depends on the following factors: regimes of solar radiation, circulation of atmospheric components, moisture-rotation, physical-geographical specifics (relief, surface, etc.), people's influences on the climate (development of water tanks, hydroponics, etc.). The characteristics of these factors are determined by the geographical location (its geographical width, the distance from the ocean, lakes, etc.).

The world territory of climatic characteristics consists of six basic microclimatic regions (Table 1. 7)[1]

Table 1. 7 Classification and characteristics of world climatic regions for technical goals[1].

REGION	CHARACTERISTICS
Temperate	A territory where the median of annual absolute maximums air temperature is equal to or less than 40 °C, the median of annual absolute minimum temperature is equal or less than –45 °C.
Cold	A territory where the median of the annual absolute minimums of the air temperature is less than –45°C.
Tropical, humid	A territory where the combination of air temperature is 20 °C or higher, and relative humidity 80% or higher, exists for 12 hours or more during the day for a continual period of more than 2 months a year.
Tropical dry	A territory where the median of the annual absolute maximums of the air temperature is higher than 40 °C and which is not related to the microclimatic region with a humid tropical climate.
Temperate-cold marine	Waters of seas and oceans whose location is more than 30° north of 30° south.
Tropical marine	Waters of seas and oceans whose range is between 30° north and 30° south.

For the determination of the character and intensity of the influence of climatic factors on the interior area of materials and machinery reliability, one must consider the characteristics and some specifics concerning the distribution of these factors within a given region.

3. 2. 2 The Characteristics of the Radiation Regime

The electromagnetic radiation of the sun (radiant energy) is called solar radiation. The solar radiation that reaches the earth's surface consists of wavelengths between 295 and 3000 nanometers. A nanometer is one billionth (1 multiplication 10^{-9}) of a meter.

This terrestrial radiation is commonly separated into three main wavelength ranges[2,3]:

- wavelengths between 295 and 400 nm (6.8% of the total radiation) are known as the ultraviolet (UV) portion of the solar spectrum. Ozone in the stratosphere absorbs and essentially eliminates all radiant energy below 295 nm. Extremely sensitive instruments may detect radiation below 295 nm, but this amount is considered negligible by most experts. Ultraviolet (UV) according to ASTM G 113-94. *Termino*logy *Relating to Natural and Artificial Weathering Tests of Non-metallic materials*, is radiation for which the wavelengths of the components are shorter than those for visible radiation;

- wavelengths between 400 and 800 nm (55.4% of the total energy of radiation) are the visible (VIS) portion of the solar spectrum;

- wavelengths between 800 and 2450 nm (37.8% of the total energy of radiation) are known as the infrared (IR) portion of the solar spectrum.

The spectral range for the UV portion and its sub components is not well defined. However, the CIE (Commission Internationale de l'Eslairage) E-2.1.2 committee makes the following distinction: UV-A = 315 to 400 nm; UV-B = 280 to 315 nm; UV-C < 280 nm.

Visible light (the radiation the human eye can detect) is between 400 and 800 nm, making up just over half of the solar spectrum. About 40% of the radiation from the sun is contained in the infrared portion of the solar spectrum beyond 800 nm.

The defined break between the UV and VIS portion of the spectrum may be different depending on the source of information. Some consider the break to be at 400 nm, some at 385 nm and others at 380 nm. While this might be considered a trivial point, it must be understood when calculating radiant dosages for exposure, whether in outdoor or artificial conditions. The variance between a break at 385 nm and a break at 400 nm could be more than 25%, which could be extremely important when attempting to estimate the service life of a material, (see Table 1.8).

Irradiance can be defined as the radiant flux incident on a surface per unit area, commonly expressed in W/m^2. For this parameter it is necessary to indicate the spectral range in which the measurements were taken or for which the values were calculated, such as 295 – 3000 nm (total solar) or 295 – 400 nm (total UV). If we turn our attention to narrow wavelength intervals, we obtain the spectral irradiance, measured in $W/m^2/nm$. Most radiant exposures are measured in either kJ/m^2 or MJ/m^2 to convert this energy into numbers to which we can more easily relate (see Table 1.9).

Table 1.8 Global solar spectral irradiance at sea level* (in accordance with CIE Pub. 85, Tab. 4).

Spectral range	nm	Irradiance, W/m^2
UV-B	280 - 315	2.19
	280 - 320	4.06
UV-A	315 - 380	49.43
	315 - 385	54.25
	315 – 400	72.37
	320 – 400	70.50
Total UV	≤ 380	51.62
	≤ 385	56.44
	≤ 400	74.56
Total UV + VIS	≤ 780	658.53
	≤ 800	678.78
IR	780 – 2450*	431.87
	800 – 2450*	411.62
Total	≤ 2450*	1090.40

* limit of CIE Pub. 85, Tab. 4

The terms used for measuring solar radiation can be thought of a similar to a bathtub being filled with water. Irradiance would be the rate the water is coming out of the faucet, and radiant exposure would be how much water is in the tub at any specific time. Spectral irradiance, which defines the wavelength range, would be the quality of the water used to fill up the tub[3].

The ratio between direct and diffuse radiation reaching the earth's surface is strongly influenced by atmospheric conditions Water vapor (humidity) and pollution will increase the amount of radiant energy found in the diffuse component. A desert climate has a much higher percentage of radiant energy in the direct component than a subtropical climate. This occurs because there is much less water vapor in the desert than in subtropical climate. By contrast, the

Table 1.9 Terms, definitions, and units.

Term	Definition	Units
Irradiance	The radiant flux incident on a surface per unit area	W/m^2
Spectral Irradiance	Irradiance measured as a function of wavelength	$W/m^2/nm$
Radiant Exposure	Time integral of irradiance	J/m^2
Spectral Radiant Exposure	Radiant exposure measured as a function of wavelength	$J/m^2/nm$

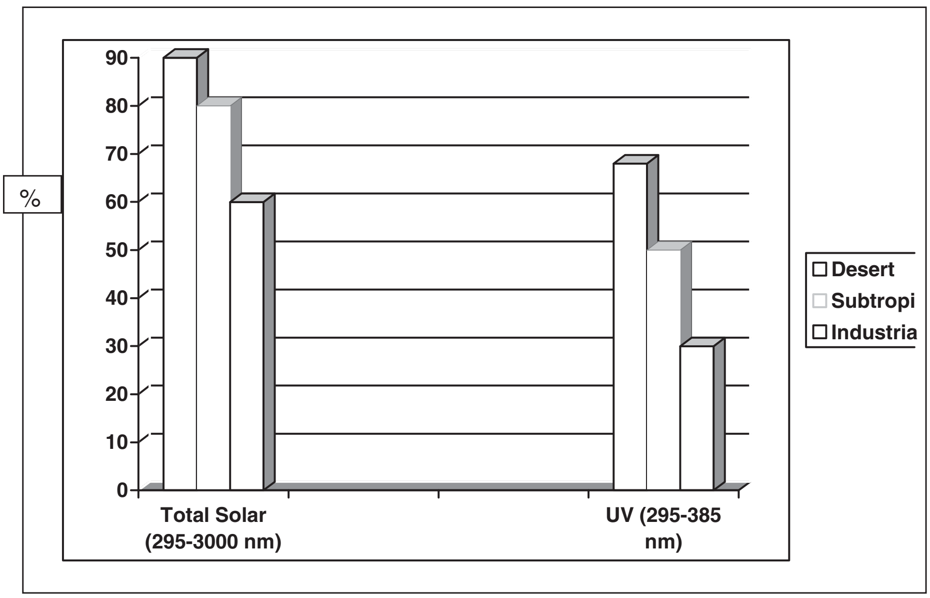


Figure 1.10 Direct solar area.

location with higher levels of pollution has dramatically reduced amount of direct radiant energy.

Based on Rayleigh's Law, shorter wavelengths of radiation are more likely to be scattered than long wavelengths. Therefore, the percentage of UV in the direct components will always be less than that of total solar radiation. This difference can be seen in graphs comparing the percentage of direct irradiance between total solar radiation (including all regions of the solar spectrum) and UV only (Figure 1.10)

The discussion of direct and diffuse radiation is important when considering radiant energy received at different orientation to the sun[3]. Because of the high level of vapor in a subtropical climate such as south Florida, about 50% of the UV radiation is diffused on clear days. Many days in Florida are not clear which results in an even greater percentage of radiation in the diffuse component. A desert climate such as central Arizona would have a greater percentage of UV radiation in the direct component (as much 75%).

Most of the active part of solar radiation strikes the earth's surface as parallel rays which one calls direct solar radiation (S). Most of this radiation strikes in the southern regions. The part of solar radiation which is dispersed by the air molecules and aerosols and then strikes the earth's surface, is called dispersed radiation (D). The direct and dispersed solar radiation are related to short-wave radiation (the length of the wave is 0.17 - 4 μm). The sum of direct and dispersed radiation is evaluated as total solar radiation (Q). The distribution of the annual sum of solar radiation on the earth is analogous to the distribution of direct solar radiation.

The solar radiation is redistributed in the atmosphere and on the earth's surface. The part of solar radiation that reflects from the atmosphere and the Earth's surface is called reflected high-frequency radiation (R). The other part of radiation which is absorbed by the earth's surface is called absorbed short-wave radiation. The quantity of absorbed and reflected radiation depends on color, structure, moisture, and other attributes of surface where the solar rays fall. The characteristic of reflection capacity of the surface is called albedo (A) (%). Albedo is the ratio of the amount of radiation reflected by a surface to the amount incident upon it. It is the ratio of reflected radiation from the surface (R) to the total of radiation which comes to this surface (Q):

$$A = \frac{R}{Q} \cdot 100$$

If the surface reflects more of the radiation, then A will increase.

The value of albedo (%) of some materials and surfaces is shown in table 1. 10.

The albedo surface of the territory changes during the year and depends on the appearance of the snow, paint, and influences of other factors. The albedo of desert areas has an insignificant change.

Table 1.10 The value of some albedo materials[1].

Type of material	%
Snow: fresh dry clear moisture	 80 - 95 50 – 55
White new paint	75
Limestone	50 – 65
Light sandstone	18 – 40
Light dry sand	30 – 35
Steel painted in red color	34
Black sands, shale	8 – 15
Coal	9

In addition to short-wave radiation to the land surface, there is also a long-wave radiation to the earth's atmosphere which is called oncoming radiation E_a. The self-radiation E_s emanates from the ambient heat which warms up the solar radiation at the earth's surface. The difference between E_a and E_s is the effective radiation E_{ef}.

The basic characteristic of the action of solar radiation is its radiation regime. The radiation regime B of a region is evaluated by measuring the amount of change during the year and the geographical distribution of radiation balance[1]:

$$B = (S + D)(1 - A) - E_{cf} = S^1 + D - E_a - R - E_s$$

where: S, S^1 are direct solar radiation corresponding to perpendicular rays and horizontal surface; D is dispersed radiation; A is albedo of the surface; E_{ef} is effective radiation; E_a is the long-wave radiation of the earth's atmosphere; R is short-wave radiation reflected from the earth to the atmosphere; E_s is long-wave radiation from the earth's surface.

The intensity of solar radiation depends on geographical latitude, height of the sun, and clarity of the atmosphere.

3. 2. 3 The Characteristics of the Air Thermal Regime

The thermal regime of outdoor air is characterized by its distribution and changes of temperature. The main source of heat for the lower layers of the atmosphere is caused by the warmth of surface action (land, water, plant, etc.). On the other hand, active surfaces obtain their warmth from the sun.

Temperature changes during the year in each of the earth's regions depend on the quantity of solar energy which reaches the surface. They also depend on other factors such as atmospheric circulation, sea courses, surface of locality, the fundamental composition of the surface, and other factors[6].

The median values of air temperature are its basic characteristics, but maximum low and maximum high air temperatures also influence machinery's reliability. This may be characterized by median values of minimal $t_{min.\ m.}$ and maximal $t_{max.\ m.}$ temperatures; absolute (external) values of minimal $t_{min.\ abs.}$ and maximal $t_{max.abs}$ temperatures.

The highest air temperature on the earth (+58 °C in the shade) has been registered in Libya, the lowest (–88.3 °C) in Antarctica.

3. 2. 4 Daily Variations of Air Temperature

Machinery's reliability is influenced not only by low and high air temperatures, but also by changes in speed over a length of time. It can be evaluated by the days temperature variations (amplitudes).

There is a difference between the average values for the warmest month and the coldest hour of the day (periodical variations) or the difference between the mid-maximal and mid-minimal daily air temperature over the period of a month (non-periodical variation).

The greatest daily air variations of temperature are specific to regions with a high elevation of continental climate, The lowest are for regions with a low continental climate (the regions of ocean and sea influences).

Most influence on the machinery's materials and tensions in the machines components affect the maximal daily amplitudes.

3. 2. 5 Air Humidity and Rains

The content of air humidity depends on many factors: distance from the ocean and sea, air temperature, time of year and day, quantity of rain, etc. Therefore the air humidity depends on the region, time of day, etc.

Variations in the value of the humidity depend on the geographical situation of the region.

Most of the worlds rain (12,660 mm/year) is in East India , the lowest amount falls in the Sudan.

Frequent damage to the copper windings of electric arc furnace (EAF) transformers has been observed in a climatic region with high relative humidity[4]. Such damage is caused through the accumulation of heat inside the transformer, and for simulating electricity and heat flow in an EAF transformer has been developed. The model has been validated by testing the operation of an EAF transformer in the Ahvaz Steel Making Plant. The results of the analysis indicate that the simulation model can be applied in controlling the hot spot temperature of the transformer. This provides an appropriate means of increasing the reliability of an EAF transformer and preventing further damage to its cooper windings.

3. 2. 6 Characteristics of Wind Speed

Wind speed and direction depend on the character of the air mass circulation near the earth, as well as on differences of air pressure, time of year, time of day, surface relief, and other factors.

Atmospheric circulation influences climate and weather, and depends on the transfer of air masses. Weather changes depend on the motion of cyclones and anticyclones. The important characteristics of the wind that affects machines that work outdoors as well as buildings, bridges, etc., are the speed and variability that influence air pressure. Changes of air direction have often influenced weather changes or the appearance of a storm. As a result, air speed influences machinery's reliability.

3. 2. 7 Atmospheric Phenomena

Atmospheric phenomena such as fog, dew, frost, ice on the ground, storms, and dust storms exert the most influence on machinery's reliability. The atmosphere actions such as gases and pollutants, especially in the form of acid rain, may cause entirely new reactions. In highly industrial areas acid rain is the primary element driving the weathering process that affects a wide range of materials.

Blowing dirt and dust may have effects on the weathering process without reacting with the actual molecular structure of the materials. These effects include the screening of ultraviolet radiation from materials by dirt, which absorbs the ultraviolet portion of the spectrum. Semi-permanent varnishes can form on the surface of materials in certain climates. Mold, mildew, and other microbiological agents may play a significant role in material degradation, particularly in tropical and subtropical climates, although they may not be generally thought of as weathering factors.

3. 2. 8 Characteristics of Environmental Factors in Combination

Outdoor machines act under a complex of environmental factors. Therefore, for the development of machinery's reliability, not only are the characteristics of separate environmental factors important, but also their combinations in time and space.

The different combinations of environmental factors in the time zones for each region are best studied on complex weather-climatic graphs. For example, one builds weather-climatic graphs of changes during the year according to basic environmental factors for each climatic zone that exerts an influence on the materials, properties and reliability of machinery. These graphs make it possible to predict common weather situations for each month.

These graphs also allow for an analysis of environmental factors that exert an influence on machinery reliability.

3. 2. 9 Biological Factors

The biological factors that influence technical products are mould, insects, and rodents. These factors also have an influence on reliability especially in tropical regions (mostly during machinery storage) and for ships in water.

Mold is related to the lowest plant forms that lack the property of photosynthesis, and it forms as a result of its interconnection with materials in which it secretes the products of metabolism that consists of different acids, which in turn decompose insulating materials and plastics. The most favorable condition for mold development is relatively humid air 50 - 85% and temperature 20 – 30 °C. If the humidity is lower and the hygroscopic nutrition is absent, the mold is unable to develop. The production of mold can also be accelerated by its fast speed of development and huge variety (about 40,000 species).

Some types of insects, especially termites, feed on electrical conductor insulation and cause machinery failures. The same is true of the actions of rodents.

3.3 THE INFLUENCE OF CLIMATIC FACTORS AND ATMOSPHERIC PHENOMENA ON THE PROPERTIES OF THE MATERIALS AND ON THE SYSTEM "OPERATOR-MACHINE-SUBJECT OF THE MACHINE INFLUENCE"

Not all climatic factors and atmospheric phenomena influence the products reliability. For example, the following factors have no influence on product reliability: the form and compositions of clouds, the time of the first frost, the temperature of upper layers of the soil, etc.

The most important influences on technical vehicles are solar radiation, high and low air temperatures and temperature variation, humidity, changes in wind speed, fog, air pollution (chemical, dust storms, etc.), etc.

The changes in a material's properties also depend on the intensity and the duration of the influence of the above factors and their adverse combination.

Climatic factors are especially the reasons for failures for products that are used outside. There is a need for changing the physical and chemical properties of the materials which are utilized in the design (metals, plastics, electronic, etc.). As a result there is a decrease in the reliability of the machines. This is a reason for a consideration of the climatic factors which influence materials.

3. 3. 1 Influence of Solar Radiation

The result of solar radiations action on the elements of metallic machinery is an increase in the temperature of these elements and of the air entering these elements (car body, the speed controller, etc.). More complicated processes occur in plastics which result in their aging more rapidly.

Furthermore, solar radiation is the basic factor of the thermal regimes interface between the atmosphere and the earths surface. Therefore, the influence of low and high air temperatures on the properties of materials is a result of the influence of solar radiation on the thermal regime of the air.

Photochemical reactions are usually accelerated at elevated temperatures. In addition, temperature determines the rate of subsequent reaction steps. These secondary reactions can be qualified using the Arrenius equation.

A general rule of thumb assumes that reaction rates double with each 10 °C rise in material temperature. However, this may not be seen in physical measurement or changed appearance. Also, thermo chemical reactions that may be initiated at higher temperatures may not occur at all or at a very low rate at lower temperatures.

The temperature of metallic parts of equipment is a function of the ambient temperature, metal solar absorptivity, solar irradiance, and surface conductance. Therefore, in the presence of sunlight, the surface temperature of an object is usually considerably higher than the temperature of the air.

Solar absorptivity in both the visible and infrared regions is closely related to color, varying from about 20% for white surfaces to over 90% for black surfaces; thus, material of different colors will reach different temperatures on exposure. This surface temperature dependency on color can have secondary (non-thermo chemical) effects on materials as well. For example, as a result of different surface temperatures, mildew and other biological growth will form and accumulate at different rates on materials of different colors. White, or lighter colored materials, tend to "grow" more mildew than darker colored materials.

Much higher temperatures are obtained on painted or coated metal surfaces than in the bulk of a plastic material because the thermal conductivity and heat capacity of metals are generally higher than plastic substrates. Ambient air temperature, evaporation rates, and the convective cooling from the surrounding air during exposure all play a role in the temperature of a material, and therefore, influence degradation rates.

Thermal influence of solar radiation

The intensity of solar radiation is evaluated by the quantity of heat in joules that falls on 1 cm^2 (J/cm^2) on an absolutely black surface which for 1 min is perpendicular to the rays. By absolute black surface, one means a surface that absorbs all solar radiation.

The quantity of energy E that irradiates an absolute black surface of whatever object is evaluated by the law of Stephan-Boltzman[5]:

$$E = \sigma F T^4 \qquad (1.\ 6)$$

where: σ is the coefficient of proportionality or a constant of radiation; F is the surface of the objects; T is the absolute temperature of a radiated surface.

The action of Stephan-Boltzman's law can be extended to natural "gray" surfaces. By more accurate calculation of a natural surfaces radiation capacity in formula (1. 6) one introduces the relative coefficient of radiation δ. Then formula (1. 6) become

$$E = \delta\sigma F T^4$$

Warming of a body by solar radiation depends on the intensity of solar radiation, outdoor temperature, and the reflective capacity of a body surface. Reflective capacity depends on the color and roughness of a surface: more radiation is reflected by a body with a smoother surface.

If the body becomes warm, it becomes a source of radiation. One can track the regularity of surface heat exchange in the example of the metallic housing heat exchange. In matte black housing, that has no inner source of warmth (for example, the body of an excavator which is not working) the radiation energy can be shown by the scheme in Figure 1. 11. The housing walls are thin, therefore the temperatures of the external and the internal wall surfaces are equal.

The upper cover of the housing absorbs the warmth of the solar radiation and well as inside of the housing (σT^4_s). The lower wall of the housing (bottom) absorbs warmth from the upper cover and radiates it both inside and outside (σT^4_D). By placement of the housing on the ground the bottom of the wall radiates its warmth and can receive warmth from the ground (σT^4_S).

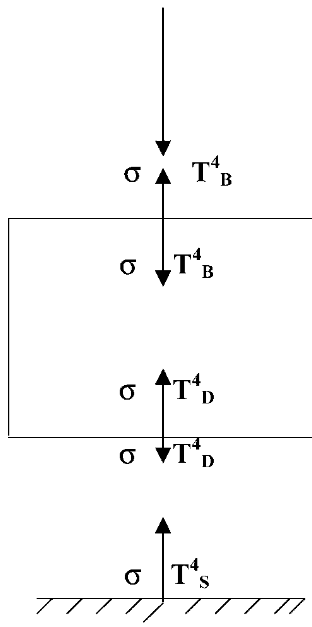


Figure 1. 11 Scheme for the definition of the balance of housing wall radiation[1].

According to the temperature equilibrium of the system, the following mathematical dependencies are correct[1]:

$$\sigma T^4_B = \sigma/2\cdot(T^4_D - T^4_S); \qquad \sigma T^4_D = 1/2\cdot(1.6 + \sigma T^4_B).$$

where: T_B is the temperature of housing cover; T_D is the temperature of the housing bottom; T_S is the ground temperature; and σ is the constant of radiation.

The temperature of the body surface is determined by the difference between the absorbed warmth and the radiation inside and outside the body. This is the warmth balance of the body. It can also be the warmth balance of the surface and the warmth balance of the body.

Thermal balance of the surface

In general, the bodys surface absorbs heat or radiates it to the environment, or both processes may act simultaneously. The heat quantity Q which is absorbed by the surface consists of:

1) heat from all types of radiation (short-wave, long-wave, and reflected) Q_E;

2) the heat from environmental heat exchange; self heating of the surface radiation Q_A;

3) loss of heat as a result of evaporation Q_v and condensation Q_K;

4) and also as a result of heat conductivity inside of the body Q_L.

The quantity of heat which is necessary for evaporation is deducted from the body, but the quantity of heat which is necessary for condensation must be added to it. In general, the quantity of heat Q which passes through the body surface can be estimated from the formula:

$$Q = Q_E + Q_S - Q_A - Q_v + Q_K \pm Q_L$$

Air is a heat insulator , therefore an insignificant quantity of heat can be diverted from the surface or brought up to it when the air is motionless. This situation can be changed when the air is kept in motion.

There is a heat exchange between the body surface and the outside air. The character of heat changing depends on separate types of heat transfer. Corresponding to this are surfaces that absorb solar radiation or radiate warmth, or intermediate surfaces (Figure 1. 12). By absorption of solar radiation without evaporation, the resulting heat is transferred directly to the heating surface. Some part of this heat is then radiated to the outside air, another part is transferred inside the body. The heat absorption is usually greater than its radiation and is absorbed by the body. Therefore, the surface temperature is increased (curve a).

The following equation can be used to determine thermal equlibrium:

$$(Q_E - Q_A) - Q_S - Q_L = 0$$

By absorption of rays with simultaneous evaporation, part of the heat is transformed into evaporation, therefore the temperature of the surface and, as a result, its radiation decreases compared to its clear absorption (curve δ). The condition of the thermal equilibrium for this

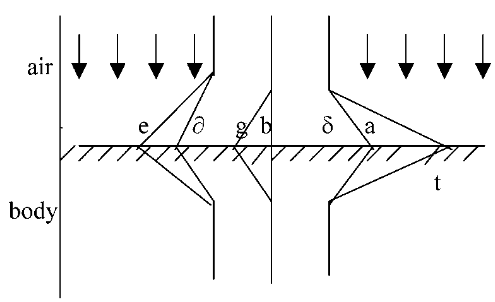


Figure 1. 12 Changing the surface body temperature by different types of radiation[1]: a is the absorption of rays; is the absorption of rays with simultaneous evaporation of moisture from the surface; b is radiation; g is radiation with the formation of dew or hoar-frost on the surface; ∂ is clear evaporation without influence of radiation; e is under normal temperature.

surface is:

$$(Q_E - Q_A - Q_v) - Q_S - Q_L = 0.$$

Surfaces with clear radiation react if the absorption of rays is equal to zero or approaches zero. Heat comes to the surface from the outside air and within the body (curve b). The heat equilibration in this case is:

$$-Q_A + Q_S + Q_L = 0.$$

The particles of moisture in the air after contacting a colder surface, transfer part of the heat to the surface, and form dew or hoar-frost. During this time rising surface heat as well as its radiation and cooling ability are weaker (curve g). The equilibrium condition is as follows:

$$-(Q_A - Q_K) + Q_S + Q_L = 0.$$

Clear evaporation without the action of rays occurs when the absorption and radiation are equal, for example, radiation is reduced to zero with special insulation. The heat which is necessary for evaporation comes from the air. The condition of equilibrium is:

$$-Q_v + Q_S + Q_L = 0.$$

A surface with normal temperature that equals its environment occurs when the heat conductivity of a body is not sufficient to eliminate heat from the surface or when the body is cooling to a degree that the surface temperature decreases as a result of evaporation. When the heat from evaporation has to come from the air, as well as the condition of warmth equilibrium:

$$-Q_v + Q_S = 0.$$

Action of solar radiation on plastics

More and more, plastics are included in the design of modern machines and equipment. The trends in the development of these products show that in the future there will be a wider use of plastics in different areas of industry.

Complicated photochemical processes react on plastics, rubber, and their combinations under the action of solar radiation. These processes decompose chemical structures. As a result, there is a change in the quality of both materials and products.

Solar radiation, especially its ultraviolet part, often destroys numerous, very strong bonds in the molecules of plastics. Therefore, the aging of products is accelerated, followed by failures.

The aging process of plastics is accelerated by warmth, moisture, air oxygen, radiation of high energies, and other factors. The rate of the aging of plastics under solar radiation depends on its intensity, the percentage of ultraviolet radiation in the solar spectrum, and the absorption capability of plastics.

Research results describe how the break down of molecular connections and the aging processes of plastics are activated by the intensity of radiation when it is more than 16.8 kilo joules (kJ)[6].

It is known that there are two simultaneous processes in the aging and destruction of plastics. There is a breaking of bonds in the molecules resulting in the formation of molecular fragments which can then form new bonds between the atoms and molecular fragments. As a result, in the process of aging the plastic is changed in its mechanical and electrical properties, color, etc.

The influence of solar radiation on the properties of plastics can be evaluated by putting plastic specimens in the radiation chambers or under specialized outdoor conditions. For example, for the second type of specimen testing it would be advisable to use stations provided by ATLAS[7] which is a division of the Weathering Services Group in the different climatic areas of the USA and Europe.

A complex of climatic factors acts on plastics under natural conditions. These influences can be provided in the laboratory by the use of accelerated evaluation of these factors on material destruction.

The changing of frictional and dielectric properties of materials exerts an influence on the reliability of the machinery. For example, the braking time[8] for one brake design (KSP-1) by friction braking without radiation was 4.0 s, after radiation for 15 hours it was 4.6 s, and after radiation for 30 hours it was 5.5 s. As a result of the aging of the friction straps the friction coefficient of the plastic decreases and the braking time increases.

One can decrease the aging process of plastics by changing the ray absorption capability (increase its degree of stability in light as well as making it heat-proof) and injecting these materials with special stabilizers that decrease the processes of destruction.

3. 3. 2 Influence of High Temperatures

The temperature of materials is raised as a result of the direct influence of solar radiation, and heat exchange between air and liquids that heat up to higher temperatures. This heat is given off when the equipment is working. The sources of heat in working equipment (machinery) are the engine, the units of friction where heat arises as a result of the action of friction and is transferred from mechanical energy to thermal, and electrical conductors which exude heat when the current passes through.

High temperatures have the greatest influence on the properties of plastics and technical liquids. High air temperature influences the elasticity of rubber. If the temperatures increases from 0 to 50 °C, the relative stretching of rubber increases from 400 to 560% at a voltage 5 Mpa[1].

Heat dissipation from semiconductor devices elevates the operating temperature of these devices[9]. Unfortunately, most electronic devices are prone to failure at elevated temperatures, and the reliability of each device is affected by its operating temperature. Virtually all the failures of mechanisms are increased by higher temperature.

Most common failures are due to the increased operating temperature resulting from:

1. Thermal coefficient of expansion (TCE)

2. Creep in the bonding materials

3. Corrosion

4. Electromigration

5. Diffusion in the devices

One can see in this publication[9] the effect of the operating temperature on the failure rates of some typical electronic devices. These curves clearly show a very strong dependence of reliability on operating temperature.

A common industry practice is to maintain average device temperatures (also called junction temperatures) below 100 °C which is the worst operating conditions[10]. However, in systems requiring very high reliability, junction temperatures as low as 85 °C may be desirable. This maximum allowable junction temperature is generally suggested by the manufacturer of the component on the basis of its power dissipation and reliability requirement. In an electronic system, the cooling technique and the system cooling configuration are based on the maximum allowable component temperatures, heat dissipation rates, and environmental specifications[9].

The surface elements of the machinery that are painted in dark colors, increase the temperature up to 80 °C as a result of the influence of direct and scattered radiation. If the engine components are heated to high temperatures, forced cooling may be used to maintain the normal working of engines.

The greatest quantity of heat generated by the units of friction is given off by braking devices. In these devices plastic brackets with high frictional properties are widely used under normal and slightly increased temperatures. But the frictional properties of these materials are decreased by an increase in the temperature of these materials, in the heat which is caused by braking, and the heat of the suns radiation. The plastic materials which bind soften under the action of high temperature, and the liquid fractions come to the surface and result in the destruction of the plastic[1].

Insulation materials of electrical conductors (cables, wires, bindings of electrical machinery and apparatus, etc.) absorb the heat from the environment (sun radiation and hot air) and heat that is emitted from the conductors. Insulating materials of many different types of plastic, rubber, and paint are used. The process of aging of these materials depends on the action of high temperatures, sun radiation, humidity and air oxygen. Heating and aging of insulation plastics rapidly decrease their electrical strength and reduce their longevity. Therefore, in insulation design one can often use inorganic fillers, thermosetting plastics, and other devices such as varnishes for binders, impregnates, and coated compositions, etc. The life of these insulators decreases under high temperatures (100 – 180 °C).

The viscosity of combustible liquids, grease, solvents, etc. decreases under the action of high air temperatures. Decrease in viscosity destroys the quality of grease, because it decreases the thickness of the oil films between the surface of the treads. This accelerates abrasion which wears out the surface treads.

Increasing the temperature decreases the viscosity of technical liquids that are used in hydraulic and braking fluids. It increases the wear on the details of the hydraulic engines, cylinders, and apparatus, resulting in a leakage of liquids from the hydrosystem, which then transports from a space with high pressure to a space with lower pressure.

The process of oxidation and aging of liquid oils in technical liquids is intensified under high temperatures. This aging depends on the evaporation of less dense fractions from oils and other liquids. As a result their structure is changed.

3. 3. 3 Influence of Daily and Yearly Fluctuations of Air Temperatures and Rapid Changes of Other Climatic Factors.

Low and high temperatures exert opposite influences on composition of the materials. Also, rapid changes of temperatures (during one day or several hours) increase the negative effect on the machinery.

Additional tensions can occur in the elements of the metalwork through rapid changes of air temperature which are induced by the different speeds caused by the thermal expansion of these elements[11].

Most of the thermal tensions arise in thin elements, which have flexible contours, because the change in length increases compared to those of thick elements.

There is irregular cooling or warming of the machines massive details as a result of rapid changes in air temperature. This leads to additional tensions in the materials. Most tensions arise through rapid cooling of the details. Relative elongation or compression of discrete layers of the material is evaluated by the following equation[1]:

$$\varepsilon_t = \alpha_t(t_2 - t_1)$$

where: α_t is the coefficient of linear widening; t_1 is the temperature in first layer; t_2 is the temperature in second layer; $t_2 = t_1 + (\partial t/\partial l)\Delta l$ (Δl is the distance between the layers).

Additional tensions (thermal) in the material can be calculated by using the following equation[1]:

$$\sigma_t = \varepsilon_t E$$

where: E is the module of the materials elasticity.

The dependence of the materials specific electrical conductivity on its temperature can be evaluated from the equation[12]:

$$\sigma_e = \sigma_{eo} e^{at} \approx \sigma_{eo}[1 - \alpha t],$$

where: σ_{eo} is the specific electrical conductivity by t = 0 °C; and α is the thermal coefficient.

Rapid changing of the above temperatures decreases the service life of electrical machines, especially electric motors.

Dielectric permeability of air depends on air pressure, humidity, and temperature. Low and high temperatures together with the corresponding changes in air humidity influence the tension between the breakdown of air clearance under the same air pressure (Table 1. 11).

Rapid changes of temperature, humidity, and air pressure are adverse to the workings of electrical devices where the air is an insulator (path of current flow devices of electrical cranes, excavators, etc.). As a result of rapid changes in temperature, the protective paint cracks.

Varying thermal expansion causes these materials (paint and steel) to laminate. As a result, there is scouring and removal of paint layers from metallic surfaces.

Considerable pressure in air chambers decrease the work of carburetors in engines and oil transformers.

Table 1. 11 Correction coefficients for tensions of the breakdown of air clearance[1].

Pressure, MmHg	Temperature, °C					
	-40	-20	0	20	40	60
845	1.07	0.99	0.93	0.87	0.82	0.77
1013	1.25	1.17	1.10	1.03	0.97	0.91
1182	1.43	1.34	1.26	1.19	1.12	1.05

3. 3. 4 Influence of Water (Moisture), Air Humidity, Fog, and Dew

Water is one of the substances in our environment that is everywhere, whether in the form of humidity, rain, dew, snow, or hail. All materials used outdoors are exposed to these influences.

There are two ways in which water affects materials. Water absorption by synthetic materials and coating from humidity and direct wetness are examples of physical effects. As the surface layers absorb moisture, a volume expansion is produced that places stress on the dry subsurface layers. Following a drying out period, or desorption of water, the surface layers will lead to a volume construction. The hydrated inner layers resist this construction, leading to surface stress cracking. This fluctuation between hydrated and dehydrated states may result in stress fractures.

The freeze-thaw cycle is another physical effect. Because water expand when it freezes, absorbed moisture in a material causes expansion and stresses that cause peeling, cracking, and flaking in coatings. Rain, which periodically washes dirt and pollutants from the surface, has an effect on the long-term rate of deterioration that is determined more by its frequency than its amount. When rain strikes an surface, evaporation processes cool the surface rapidly, which may cause physical degradation of a material. Frozen rain, or hail, may also cause physical degradation of materials because of the strong kinetic energy associated with its impact.

Water also can be directly involved in the degradation reaction in a chemical sense. The chalking of titanium dioxide (TiO_2) in pigmented coatings and polymers is one good example. While the structure of a polymer is changed by radiant energy, the actual release of material on the surface is enhanced, if not caused, by the cyclic action of chemically absorbed moisture.

Contact with water in any phase can accelerate the rate of oxidation. Moisture also may act as a pH adjuster, especially when considering the effects of acid rain, which may cause an etching of many paints and coatings.

The amount of air humidity which exerts a negative influence on materials depends on the percentage of moisture (Table 1. 12). If there is more moisture in the air (more than 90%), it either decreases the quality of materials, penetrates inside these materials or constitutes the film of moisture on the materials surface. If the content of moisture in the air is less than 50%, the moisture from the materials evaporates in the air and results in internal changes to the materials: they become fragile and cracks appear.

Table 1. 12 Characteristics of the influence of air humidity on the internal aspects of materials and the working conditions of equipment.

High humidity	Low humidity
Corrosion of metals	Cracks appear and micro destruction of the insulation materials
Saturates the mineral oils, technical liquids, and fuel oil	———
Changes the consistency of grease with the formation of an emulsion	Grease becomes more solid
Decreases the volumetric resistance of insulation materials	Sealing materials dry out
Decreases the surface resistance of insulation Increases the dielectric	Plastic details deform
Permeability of the air	———
Growth of mold	———

Hygroscopic materials absorb moisture from the air, for example, in insulating materials which are produced from cotton or paper. Moisture can penetrate inside materials (capillary condensation) or penetrate into a polymer structure (intermolecular interval), and also through the cracks and large pores in the material.

When the air temperature is increased, the speed of penetration of the material increases. Moisture, which penetrates the material, decreases its solid resistance (Figure 1. 13). The dependence of specific electrical conduction of the dielectric on the volume of moisture is evaluated in the following equation[12]:

$$\sigma_e = \sigma_{eo} e^{x(z - zo)},$$

where: σ_{eo} is specific electrical conduction at t = 0 °C; z is the absolute moisture of material; x is the coefficient which depends on the material used.

Moisture may settle on the materials surface forming a film. As a result, the surface resistance of materials decreases enormously (Figure 1. 13). Most decreases in surface resistance of insulators are the result of the pollution of the film by gas and dust.

There are favorable conditions for atmospheric corrosion of metals from moisture settling on the metallic surface. This type of corrosion induces 50% of the common loss of metals. One can see in [2] more detail about atmospheric corrosion.

Air moisture reacts with liquid mineral oil which surrounds the product. The result is a decrease in the lubricating and anticorrosive qualities of internal oils. As a result of the interconnection of consistent greases (lubricants) moisture forms as well as aqueous emulsion.

Therefore the quality of the lubricating materials is diminished.

Low air humidity causes a drying of materials which may dry out and buckle. If the moisture is decreased by the insulation of the electrical winding, the resistance of this insulation increases. The drying out of this insulation may cause cracks and, as a result, flaking and destruction of insulation may occur.

3. 3. 5 The Characteristics of Complex Influences of Basic Climatic Factors

As has been show previously, in real life different climatic factors (Figure 1. 14) act simultaneously and in combination on the reliability of the product. Moreover, the effect of their action depends on the interconnection between these factors. Often unfavorable combinations influence product reliability. Most unfavorable combinations of influences are factors such as low temperature of air and wind, high air temperature, and low humidity, etc.

One can study the effect of the combination of different factors of influence on the interiors of materials and equipment by using methods of passive experiments under field conditions and active experiments of accelerated actions in the test chambers or under field conditions.

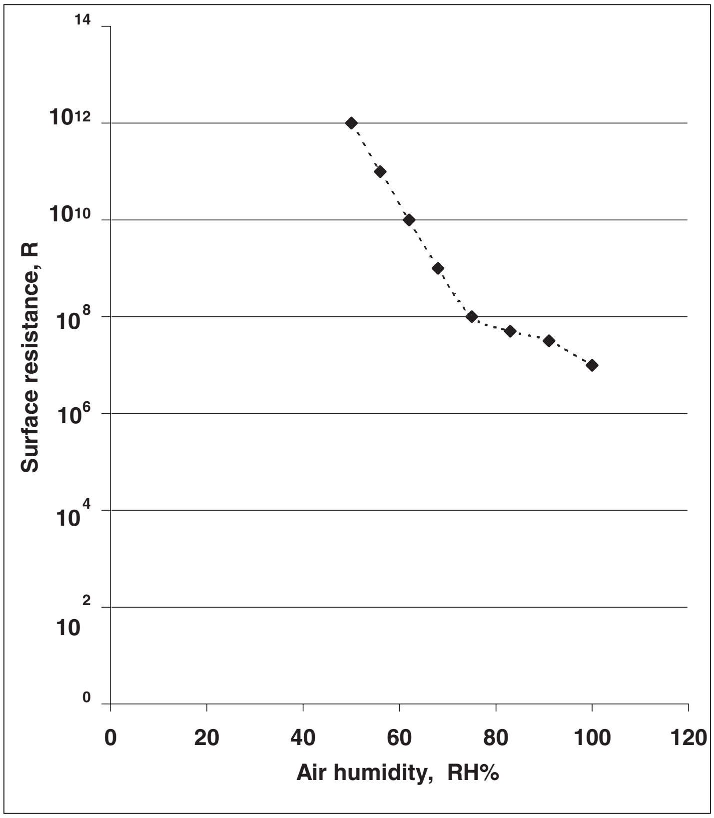


Figure. 1. 13 Dependence of surface resistance (R

Figure. 1. 13 Dependence of surface resistance (R) on the insulation of ceramic details from air humidity RH[13].

When considering the roles that solar radiation, temperature, moisture, and secondary effects play on products, we must realize that these factors work together to degrade materials. For example, if one simulates only one of these factors, it is very unlikely that the degradation incurred will look anything like that of a material exposed to outdoor conditions, where all factors play a role in the degradation process[18].

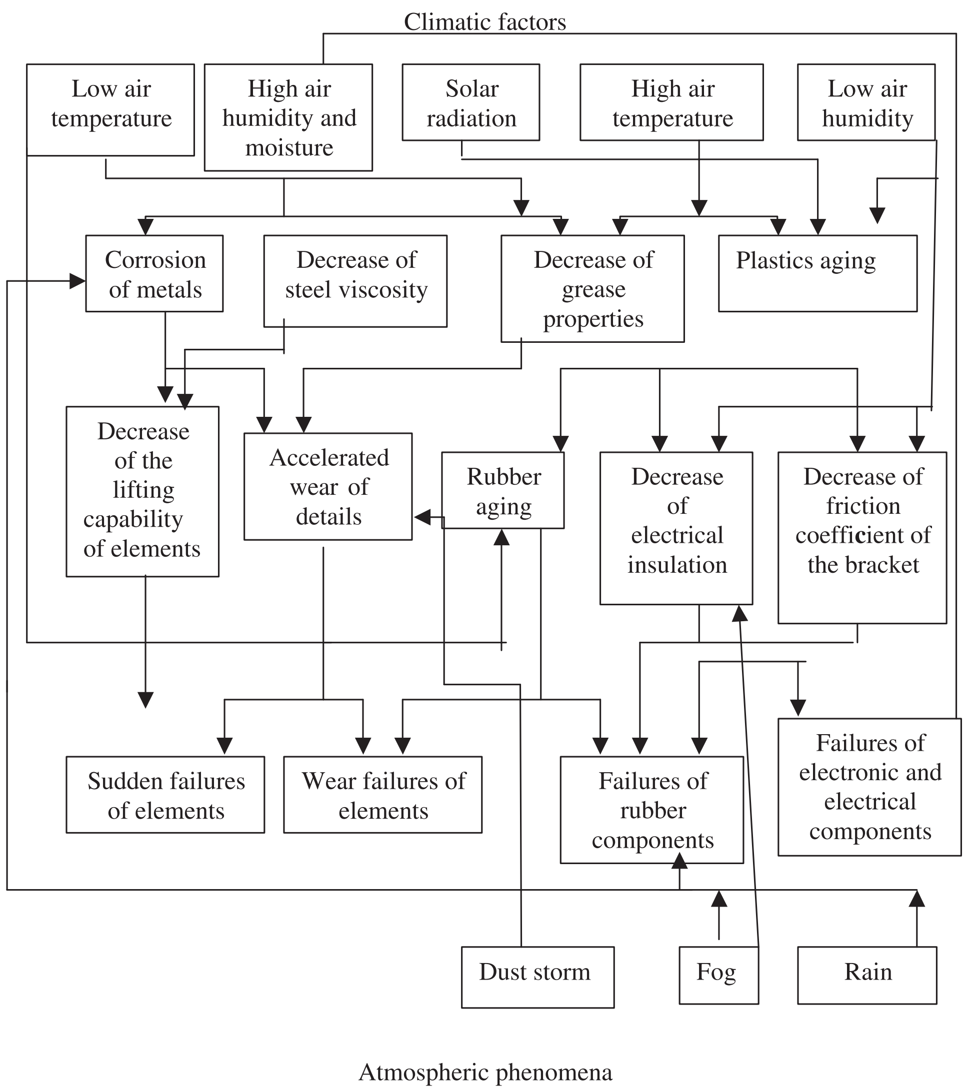


Figure 1.14 Scheme of complex influence of basic climatic factors and atmospheric phenomena on the properties of materials and machinery reliability.

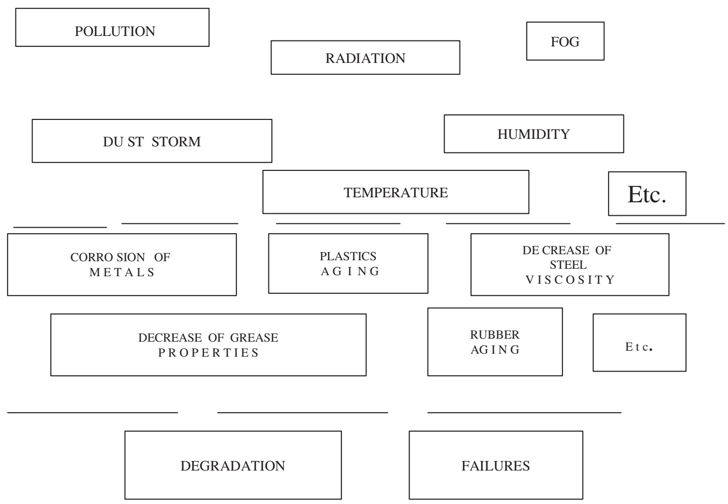


Figure 1.15. Basic scheme of complex influences of basic climatic factors on machinery reliability.

The synergic effects of the main climatic factors (see Figure 1.15) vary, depending on materials being exposed. Even small changes to a product formulation, such as the addition of stabilizers, flame retardants, fillers, etc., will change the degradation characteristics of that material. The use of recycled material, impurities in the polymer matrix, and the characteristics of product processing are additional variables in weathering performance. While there are literally thousands of publications that examine the durability characteristics of pure polymers, stabilizers, and specific aftermarket products, the study of a material's durability to weathering is not an exact science. It is safe to say that a complete understanding of the effect of weathering factors on every material will never be achieved.

People have used the first method for many years. There are special stations to achieve this goal in different climatic areas. For example, ATLAS[7] has a division (Weathering Services Group) which has three primary facilities in the United States and internationally (ISO/IEC Guide) and also dozens of sites around the world, providing the widest range of climatic and environmental conditions for materials and product tests.

Static weather testing capabilities include direct exposure using fixed or variable angles, and backed or unbacked racks; under glass exposure for interior materials; and black box exposure for paints and coating materials. As an example, table 1. 13 shows average monthly UV and total radiant exposure for Phoenix, Arizona and for Southern Florida[7], table 1.14 shows annual climatological data of ATLAS stations in different sites of the world.

Table 1. 13 Average monthly UV and total radiant exposure for Phoenix, Arizona and Southern Florida (MJ/m^2)

MONTH	Phoenix (AZ) 34 °South		Southern (FL) 26° South	
	UV*	Total	UV*	Total
January	20.1	490	20.0	505
February	19.8	546	22.5	545
March	24.7	633	26.5	618
April	33.3	755	28.0	612
May	38.6	786	28.0	609
June	36.8	770	25.7	543
July	35.1	745	24.7	532
August	32.5	756	24.0	543
September	29.3	711	22.3	540
October	25.8	705	21.7	555
November	19.2	582	18.0	490
December	18.3	525	18.6	496
Annual TOTAL	333.5	8004	280.0	6588

*Below 385 nm wavelength

Table 1. 14 Annual climatological data, domestic and international remote sites.

Location	Latitude	Longitude	Elevation (m)	Average ambient temperature (°C)	Average ambient RH (%)	Rainfall (mm)	Total radiant energy (MJ/m^2)
Louisville, KY	38° 11' N	85° 44' W	149	13	67	1092	5100
Jacksonville, FL	30° 29' N	81° 42' W	8	20	76	1303	5800
Prescott, AZ	34° 39' N	112°26' W	1531	12	65	1093	7000
Lochem, The Netherlands	52° 30' N	6° 30' E	35	9	83	715	3700
Hoek van Holland, The Netherlands	51° 57' N	4° 10' E	6	10	87	800	3800
Sanary, France (Bandol)	43° 08' N	5° 49' E	110	13	64	1200	5500
Singapore (Changi Airport)	1° 22' N	103° 59' E	15	27	84	2300	6030
Melbourne, Australia	37° 49' S	144° 58' E	35	16	62	650	5385
Townsville, Australia	19° 15' S	146° 46' E	15	25	70	937	7236
Ottawa, Canada	45° 20' N	75° 41' W	103	6	73	1910	4050
Sochi, Russia	43° 27' N	39° 57' E	30	14	77	1390	4980
Dhahran, Saudi Arabia	26° 32' N	50° 13' E	92	26	60	80	6946

One cannot control climatic factors with passive experiments only. The aging of polymeric materials is influenced by atmospheric phenomena such as solar radiation, high and low air temperatures, humidity, ozone, and tension of the material. As a result, there is a decrease of mechanical strength, electrical resistance, and friction coefficient, etc. Figure 1.16 shows the changing moment of friction for the braking of a steel couple against the press-mass as a result of the atmospheric aging of the press-mass.

It is impossible to evaluate the influence of each climatic factor on the changing of a material's properties of atmospheric aging if the specimen is exposed to only one climatic area However, it

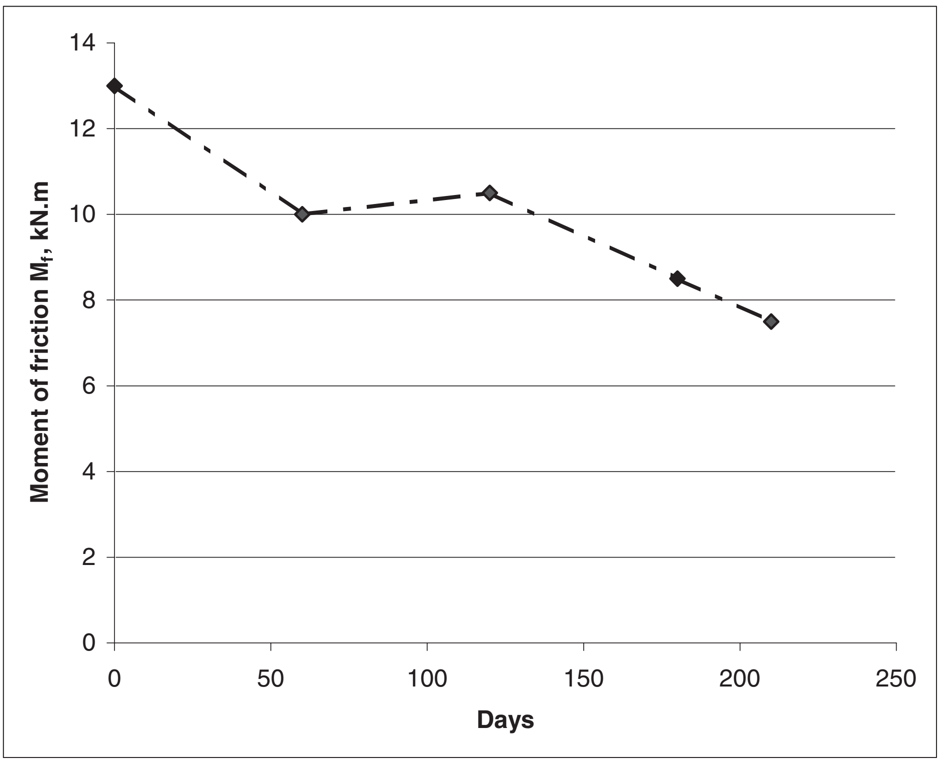


Figure 1.16 The dependence of the moment of friction in the frictional braking 35567 press-mass bracket from the duration of atmospheric aging[8].

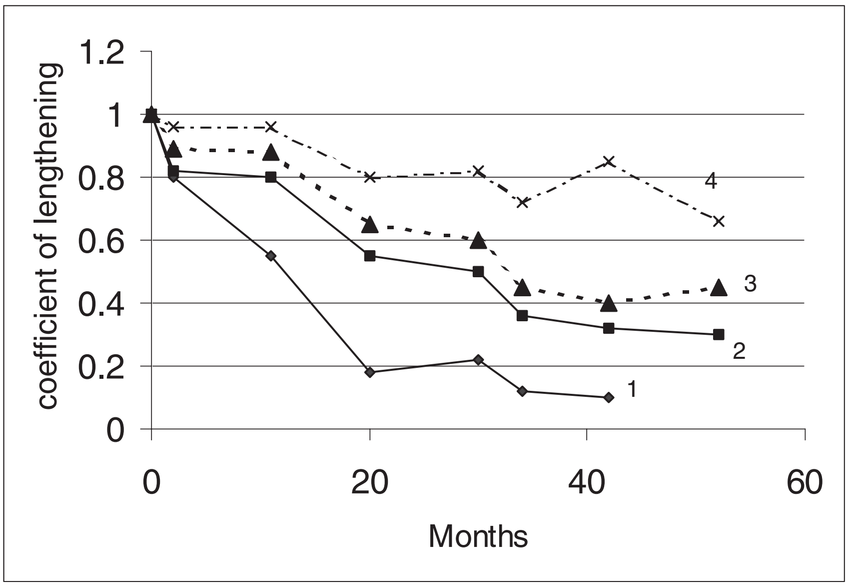
is possible to establish the common character and intensity of the complex influence of climatic factors on the property of the same materials by their disposition in different climatic areas. One can see from Figure 1. 17 how polyamide strength changes during 12 months of atmospheric aging under different climatic conditions. It is evident how different climatic conditions influence the above indexes. An analogous influence on these conditions is the relative prolongation of polychloride plasticity (Figure 1. 17 a) and how long it takes before cracks appear caused by deformation of the rubber (Figure 1. 17 b).

Some plastics are changed through the actions of climatic factors, thereby volatile substances from within the plastics escape into the environment. This changes the original quality of the plastics.

The aging of paints is caused by the actions of acids, CO_2, etc. There are processes of atmospheric aging of inorganic materials, such as ceramics. As a result, there are decreases in their electrical resistance with increased electrical losses. The change of quality of the above materials is less than plastics and rubber.

As we can see from Figure 1.17, the aging of materials with time decreases their characteristic value. The character of the above decrease depends on the influence of the original quality and intensity of climatic factors. The aging of materials is always an irreversible process.

The method of active experiments offers the possibility for selecting approaches of input influences and a different intensity for each influence. Moreover, accelerated testing in the test chambers allow researchers to control the input influences on the studied product. Test chambers must be complicated to reach this goal. The technique will be described in the following chapter.



a)

Figure 1.17 . Changes in the material characteristics in different climatic areas:
(a) coefficient of the relative prolongation K_2 of a plastic specimen with a thickness of 1 mm[10] ;
1 is the initial value; 2 is the mean latitude; 3 is the subtropical humid; 4 is dry subtropical.

b)

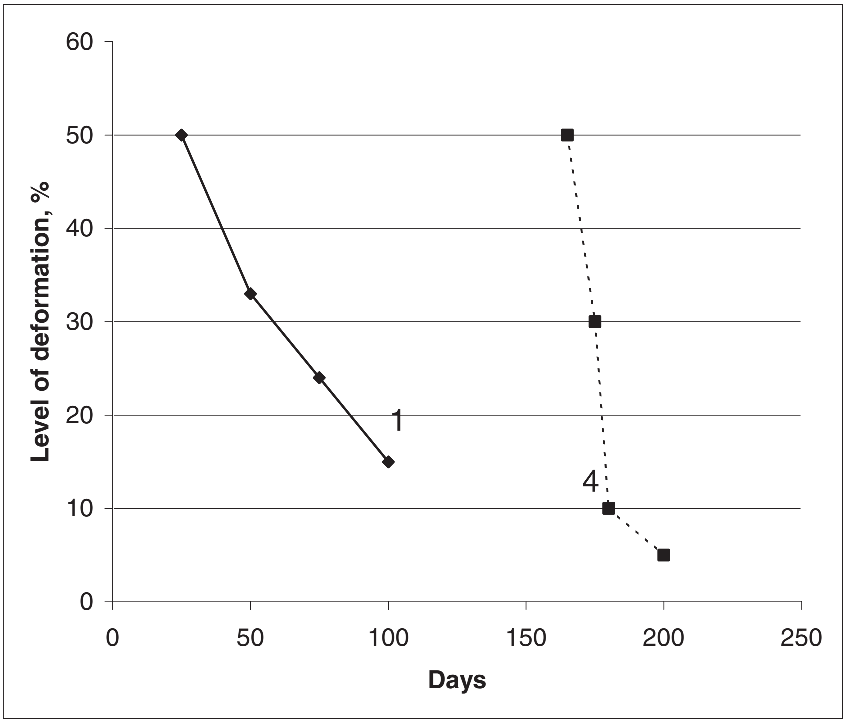


Figure 1. 17 (continuation). Changes in the materials characteristics in different climatic areas: b) is the influence of the deformation level on the base of natural caoutchoucs (rubber) depending on the time until the cracks appear during outdoor aging[10]; 1 is the initial value; 2 is the mean latitude; 3 is subtropical humid, 4 is dry subtropical.

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4 THE SYSTEM OF CONTROL FOR PHYSICAL SIMULATION OF THE RANDOM INPUT INFLUENCES*

4.1 PRINCIPLES FOR SIMULATION OF RANDOM INPUT INFLUENCES

Usually input influences on a product, especially a mobile product, have a random character in real life. Therefore, one can obtain the most accurate information in test results if testing is based on the physical simulation of the random character of real life input influences.

The above problem can be solved by the use of electronic control devices. The types of these devices can differ. For example: • a generator of random signals which is based on the two basic components – generator for random signals like "white noise" and formatting filter; • a programmed controller; • etc.

Usually the generator of random noises is used for research on the corresponding processes and for solving statistical problems on computers, etc. There are problems with formatting of the stationary random signals with their basic technical characteristics and parameters to the given corresponding accuracy (0.1 - 2.0%). One can obtain the stationary (Gaussian) noise on an equable spectrum with the use of background noises of diode valves, silicon stabilitrons, photoelectric cells, or teratrons. Often one can include the scheme for the automatic control of strengthening, which makes it possible to control the mean level at its absolute value, for guaranteeing the stationary output voltage.

The above generators can also be used for solving the former stated problem. For this goal it is necessary in the common scheme of the device to include the formatted filter which offers the possibility to obtain from "white noise" the random voltages along with their statistical characteristics (mathematical expectation, variance, correlation function, and power spectrum) in a sufficiency similar to the correspondence characteristic of real life. Then the random electrical signals can be transformed, with the help of special devices, to correspond with the mechanical or other influences on the natural test subjects.

One must simulate the representative statistical characteristics of real processes, therefore different methodological approaches are required. One of them was developed by Lourie and Enikeev at the Saint-Petersburg Agricultural University and consists of the following. For providing "white noise" one can use the modernized generators such as GBP or GS-1 (GS-191). The calculation of the formatted filter can be used to determine its gear function $W_m(S)$, and its design in order to construct an electronic model of the system with the same gear function. For determining $W_m(S)$ one takes as the basis that the power spectra of the stationary random signals can be represented as fractional-rational functions, i.e. as the ratio of two polynomials that also include degrees of frequencies. The assemblage of the electronic model of the above filter can be made from the standard blocks of an analogue computer, but the problem

*Information here is taken from result of research carned out with Dr. J. M. Galanternik and Dr. A. G. Reznikov.

with these generators is instability of their characteristics which may influence testing quality. This defect can be eliminated by using a digital block of computers. But in this case, the real processes are approximated and the simulated processes differ from the actual. Also the reliability of these devices is lower.

Another methodological approach is the use of generators with pseudo-random signals and formatted filters which are designed for parallel switching on aperiodical links of the first order. The generators of pseudo-random signals are mounted with the help of digital systems for execution of any mathematical and logical operations. The basic device of this generator is the calculating device which uses the ratio:

$$x_n = f(x_n - 1) \qquad (1.\ 7)$$

where: n = 1, 2, 3, ...; and x is the number (or signal) for a particular value of the argument n.

By calculation of the ratio (1. 7) each previous number will be the starting point for the calculation of the subsequent number. The first number is given by the researcher.

The above method helps to obtain only a pseudo-random sequence. The basic problem is the presence of the non-periodical L piece. It means that the first subscript L in the consecutive numbers $(x_1, x_2, \ldots, x_L)$ in correspondence with algorithm (1. 7) will be different, and that the number $[(L + B) - 1]$, where B is an arbitrarily given number, coincides with one which was obtained earlier, x_L $(1 \leq x_i \leq L)$, and after that the succession of numbers $x_i, x_{i+1}, \ldots, x_L$ will be periodically repeated. Therefore, in the design of similar generators of random signals for a specific problem it is necessary to select the algorithm of their design taking into account the value of L so that the periodicity of numbers does not influence the accuracy of the research results.

By this method the effective generation of random sequences can be obtained from the digital device, a shift register (Figure 1.18). This generator can create the binary pseudo-random noise sequence with any stroke frequency. The maximum length of periods which can be obtained using the linear row of reverse connection is $(2^n - 1)$ from the period of stroke frequency. For a signal of reverse connection, one uses the signal which is obtained from the output of the summarizer by module 2 (Figure 1. 18), the output of which is connected with two categories of the shift register.

The analogical noise from the digital binary sequence is created with the help of the shift register with a displacement of the constant component and restriction of the working levels of bistable which stay on the output of the shift register. This forms the pseudo-random voltage with the rectangular form $x(t)$.

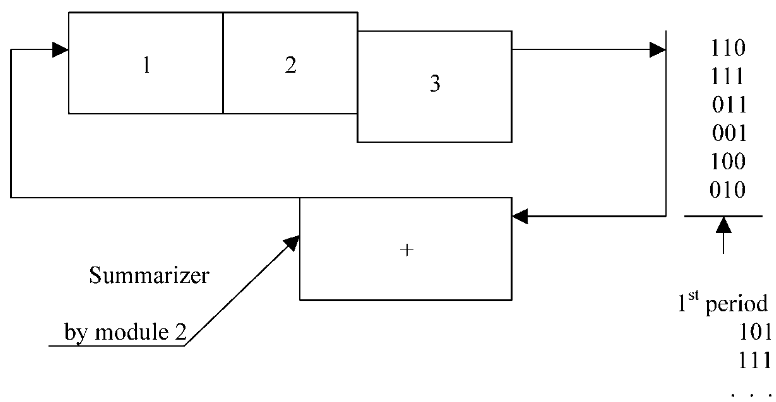

Figure 1. 18. Structural scheme of the shift register for obtaining pseudo-random noise: 1, 2, and 3 are modules.

If the stroke advance pulse enters the register through each Δt second, its function $x(t)$ is the periodical function of the time with the periodical of repetition $(2^n - 1)\Delta t$. The period of autocorrelation function is the same.

Each sequence with the length $(2^n - 1)$ includes three important properties of the pseudo-randomness which makes it possible to change random sequences:

1. During each period of maximum length, the shift register travels through all possible conditions, except for the condition in which all digit places are written as zeros. Each period consists of $P = 2^n - 1$ numbers, between which there are $(2^n - 1)$ ones and 2^{n-1} zeros.

2. In each period of time 50% of the series (sequences which have only zeros or ones) have the length 1, 25% have the length 2, etc. For each series of zeros there is a corresponding series of ones of equal length.

3. The autocorrelation function is periodical and has only two values.

For intervals of observation shorter than the length of one period of the shift register, the laws of distribution of probabilities of the first and a second arrangement, which is obtained by processing of the pseudo-random signal of the rectangular form and with the maximal length, are identical to analogous laws of distribution for the binary random noise process which is formed by an independent sampling of the results of true random tests. There are also additional positive properties:

• the pseudo-random noise signal is formed by the reliable digital scheme;

• the output signal practically doesn't undergo environmental influences;

• the digital-analogous noise generator forms the pseudo-random numbers in digital form, in an exemplary fashion, which binomial or Gauss's distribution, and analogous noise also.

The basic components of the generator of pseudo-random sequence (GPRS) are a synchronizer, a shift register, and a summarizer by module 2.

Usually the method of construction of the formatted filter is a collection of included non-periodical sections of an analog computer, but for solving our problem this is not optimal, because for simulation there is a need for previous approximation of the autocorrelation function. Besides, it is necessary to repeat theoretical calculations on the filter if the statistical parameters of the simulated random process have to be changed.

As the basis of the construction of the above formatted filter, which is used for problem solving, one needs to find the interpreted theorem of Kotelnikov for the frequency area: if $S(\omega)$ is the spectrum of the function $f(t)$ (this function can be one from the realizations of the random process) which is equal to zero outside the interval of time from t_1 to t_2, so $S(\omega)$ is determined according to the sequence of the spectrum values from the points which stay $1/(t_2 - t_1)$ Hz from each other. Therefore, the block-scheme of the formatted filter is the rack of narrow full page filters which overlap all diapason of the simulated frequency spectrum. If one changes the coefficient of transparency of each filter, one will obtain in the output the random signal with a correspondence power spectrum which, after Fourier transformation, corresponds to the particular correlation function.

The narrow full page filters are T-figurative transistor RC-filters. If one feeds as input into this formatted filter the binary pseudo-random sequence of the normalized level of process with the even spectrum, it is possible to obtain as output the stationary random process with the Normal distribution.

It was shown earlier how to obtain the random process by the Normal law of probabilities distribution which is determined by mathematical expectation, variance, and correlation function.

For more accurate physical simulation of input influences of real conditions it is necessary to obtain stationary random process with the unspecified law of probabilities distribution. In this case, the class of simulated laws must also include laws which are too complicated for analytical description.

For more accurate simulation of real conditions, it is necessary that the control apparatus can be formatted by non-stationary random processes.

In conclusion, we can state that the basic function of the random process synthesizer is formatting of the random process with discrete or continuous changes over time according to the law of probabilities distribution. This problem can be solved by the following methods:

1. Formatting of the given law of distribution from Normal with the help of a non-linear functional transformer, i.e. the law obtaining "full and promptly".

2. Formatting the law of distribution by the control method for momentum functions of the initial Normal process, i.e. the law obtaining "little by little".

Competence of the first method is theoretically validated in many publications in the area of the theory of random processes where it is written that non-linear transformation of the Normal process leads to the synthesis of non-Normal laws. Non-linear functional transformation can be executed by a combination of simple linear electrical filters with pulse characteristics which approximate Lagger's polynomials:

$$L_n(t) = (-1)^n e^t \frac{d^n}{d_t^{(n)}} (t^n e^{-t})$$

and a combination of the multiples together with the summarizers.

Competence of the second method determines that practically all the laws of distribution can be given and repeate with enough accuracy with the help of the limited number of momentum functions (it is enough to give the mathematical expectation, variance, correlation function, the coefficients of asymmetry and excess, and to control them).

If one uses the method of averaging by a closed curve with multiple ensembles for determination of the moment functions, one can obtain the experimental laws of probabilities distribution of the values for each moment of the basic law of distribution.

If one takes into account the above and a large diversity of random process types, the obtained solutions can be formulated as a synthesis of the devices which transform the stationary process with the Normal law of distribution into the stationary and non-stationary processes arbitrarily.

The problem with the generation of non-stationary random processes can be solved in two steps. First, one can add to the generator of random signals (GRS) the elements which provide the generation of the Normal non-stationary process using the given law of changing of non stationary parameters of variance and mathematical expectation. Then it can solve the problem of changes during the time of the laws of distribution in a flash value of the amplitudes.

For the solving of these steps it is necessary to determine the laws of the changes of the non-stationary statistical parameters during this time.

Two approaches are possible using the methods given in these laws. The first, is the consideration of the law of the parameter changes as the deterministic function of the time period. In this case the given apparatus is very complicated, because in advance it is difficult to establish the limit of the functions which may be needed for the generation of a particular type of this process. Second is the possibility of changes during the time of the non-stationary parameters such as a random process with particular statistical characteristics. If one interprets the changes over the time (for example, mathematical expectation and variance of the process), each value of the random process which characterizes the changing of the mathematical expectation and variance can be established as the mean of the sum of the random values of the basic process.

Here, in correspondence with the central limited theorem we obtain the values which are distributed by Normal law.

Therefore, one can conclude that changes in the mathematical expectation and variance are random process with the Normal law of distribution which is practically stationary in character.

Hence, changes during the time of the non-stationary parameters of the generated process in each particular situation will be the results which are taken from the normally distributed general population. As a result, the law for changing the above parameters can be given by mathematical expectation, variance, and autocorrelation function.

On the output of the formatted filter with constant parameters is formed by the stationary Normal random process. For obtaining the non-stationary normal process one can add to this filter the devices which reform it into a parametric filter with random changes of parameters. Devices which change the electrical parameters of the filters can be developed as follows. For variance changing there is sufficient input to add to the generator's scheme regulator of the amplitude of the formatted filter's input signal. For a varying the values of the mathematical expectation it is necessary add regulator with a constant component of the output voltage. In general, these regulators must provide smooth changes of the mathematical expectation and the variance.

Expansion of these functions into the Kotelnikov series and use of the known apparatus of their re-establishment by discrete values is aided by a special simple narrow stripe filter, which allows for discrete changes of the values of the regulated parameters in the points of reading. The interval between these points is established according to the width of the power spectrum, mathematical expectation, and variance.

If one uses this process in the register of the GPRS for each moment of time, the number will be written in the binary code and results in the central limited theorem, then one can obtain a new collection of numbers by summing more than 7 - 10 numbers. This will be sampling from the general population which is distributed by Normal law. If one uses the property of non-correlation of the values of pseudo-random sequence which is shifted in value by more than $1/f_T$ (f_T is the stroke frequency of the GPRC), one can obtain the sampling of numbers with normal distribution. If each sampled number corresponds to a particular condition of the regulator and establishes each time the number of summed evenly distributed numbers in the register of GPRC (depending on the width of the power spectrum of corresponding non-stationary parameters), the non-stationary random process with mathematical expectation or variance by Normal law changing over time can be obtained as output from the formatted filter.

If as a regulator one uses the register's divisors and switches the arms with the help of the digitally controlled computer's scheme in correspondence with the numbers which are obtained by the above algorithm, one can obtain a simple, stabile, and reliable scheme for changing the non-stationary parameters.

It is necessary to build an easily tunable non-linear converter to obtain an arbitrary law of distribution. The above converter can help obtain whatever non-linear characteristic is desired.

4.2 THE MECHANISMS FOR CONTROL OF SIMULATION OF THE FIELD RANDOM INPUT INFLUENCES

The scheme developed by the authors' vibration equipment with a system of control is shown in Figure 1. 19. This is the equipment for random vibration which consists of a generator of random signals (GRS) and an electrohydraulic vibrator which includes an electrohydraulic converter, vibro-platform, etc. (see[1, 2, 3] for details).

The GRS provides physical simulation of input influences as a random character of electrical signals, the electrohydraulic converter transforms electrical energy into mechanical energy, and the vibro-platform develops the given character of random vibration. This equipment is useful for simulation of many types of input influences.

We will show the simulation of low frequency random processes and simulation of the representative statistical characteristics of real processes for many types of mobile equipment such as automobiles, farm machinery, off-highway equipment, aerospace research stations, etc.

They can be useful for stationary equipment too.

For this goal the GRS should have the following specific advantages:

1.Providing the range of simulated input influences with frequencies from 0.01 *Hz* to 30 - 50 *Hz*.

2. Statistical parameters of signals from the output of the generator must be easily reconstructed for the possibility of changing the regimen of accelerated testing often.

3. Unaltered ability and stability of the voltage level on the output of the generator, because the parameters of random signals must be similar to parameters of "white noise" (i.e. to noise with a constant power spectrum in a given range of frequencies). This enables preservation of the given testing regime for the required time.

4. Simplicity and reliability in use, and adaptation to maintenance by users.

With the help of the GRS one can simulate the random character of different types of input influences for different types of test subjects.

To generate a stationary random process which is given by mathematical expectation, variance, and power spectrum (or correlation function) one may use the generator shown in Figure 1. 20, as follows:

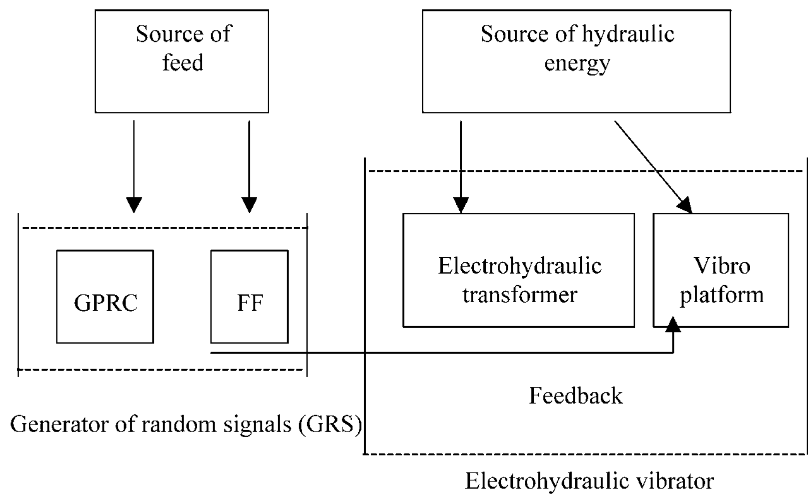

Figure 1.19 Scheme of equipment for random vibration.

1. Divisor R_1 is set up in the arbitrary mean position for providing whatever value of mean power of the signal in the output of the generator of m-sequence.

2. The mathematical expectation is a Normal stationary ergodicity process which is proportional to the constant component of the signal in the output of the generator, and with variance proportional to the mean power of the process.

3. The divisor R_n may be used to make the value of the constant component of the signal in the output of the generator equal to zero.

4. One can recalculate the initial power spectrum to the amplitude-frequencies characteristics of the formatting filter.

5. If one includes the spectroanalyzer in the output of the summarizer, one can regulate the divisors $R_2, R_3, \ldots, R_{n-1}$ so the amplitude-frequency characteristic of the formatting filter, which is controlled with the spectroanalyzer, will be equal to the given characteristic.

6. If one regulates the divisor R_1 for controlling the mean power of the process in the output of the generator with the help of the power measurer, one can obtain a value which is equal to the given variance (with re-count of unity of transference of the working mechanism of vibration equipment to the unity of power).

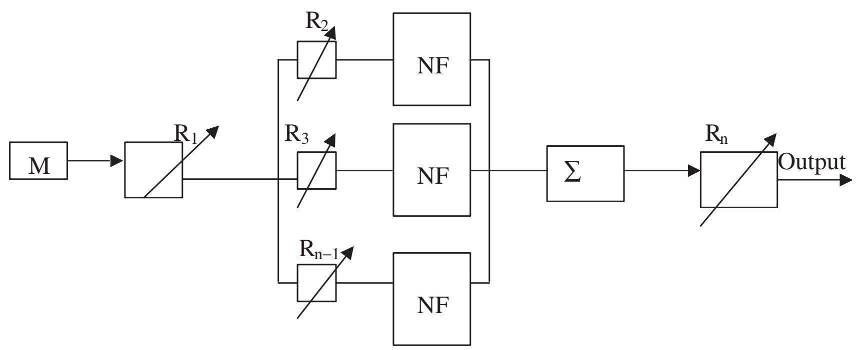

Figure 1. 20 Scheme of the generator which is used to generate a Normal stationary random process: M is the generator of m-sequence; $R_1, \dots, R_n$ are resistive divisors; NF are narrow strip filters; Σ is the summarizer.

If one performs, with the help of the control block, the operations which are analogous to regulated stationary signals of the generating process, one can obtain a wide class of non-stationary random processes, for example, a non-stationary process with statistical characteristics which changes over time by the given Normal law.

The generator of non-stationary random processes consists of a control block whose input connects with the output of the generator of bar impulses of a primary noise source. The output from the control block is connected to the controlled input of the formatting filter, non-linear functional transformer and resistive divisor of the voltage, which input is connected to the output of the pseudo-noise sequence of the primary source of the noise. The output from this resistive divisor of voltage is connected to the input of the formatting filter. The control block includes the generator of the pseudo-noise sequence. Its input is connected to the output of the generator of bar impulses of the primary noise source and input of the counter of bar impulses. Its output is connected to the input of the summarizer's interrogation. The summarizer's inputs are connected to the shift register of the generator of pseudo-noise sequence, and its output – and to inputs of the digital-analog transformer which is controlled by resistive divisors of the generator.

Figure 1.21 shows a block-scheme of the described generator of non-stationary processes. Non-linear functional transformer 10 consists of consistently connected orthogonal filters 11 with a characteristic impulse which is described by Lagger's function, controlled divisors of voltage, 12, block of multiples, 13, and a summarizer, 14. The generator works as follows.

Output voltage from the generator does through resistive divisor 4 of the voltage, which controls the process of variance in the device output, and forms the input of formatting filter 5 the strip of clarity of which is determined by the coefficient of transmission of controlled divisors of voltage, 6, which stays on the input of the narrow-strip filters 7. One selects the frequencies of the adjustment and its strips so that there will be on overlap of the given frequency range. Output voltages of all narrow-strip filters are summarized in the summarizer, 8, which is the constant component of the output which is regulated by controlled divisor 9 of the voltage. The output voltage from the formatting filter (FF) 5 moves to the non-linear functional transformer, 10. Its structure gives the possibility of synthesizing whatever non-linear characteristics are required by the sufficient number of orthogonal filters, 11. The output voltage of each of the orthogonal filters is regulated by the controlled divisors of voltage, 12, that correspond to selection of the coefficients of the row of decomposition for the non-linear characteristic of the transformer.

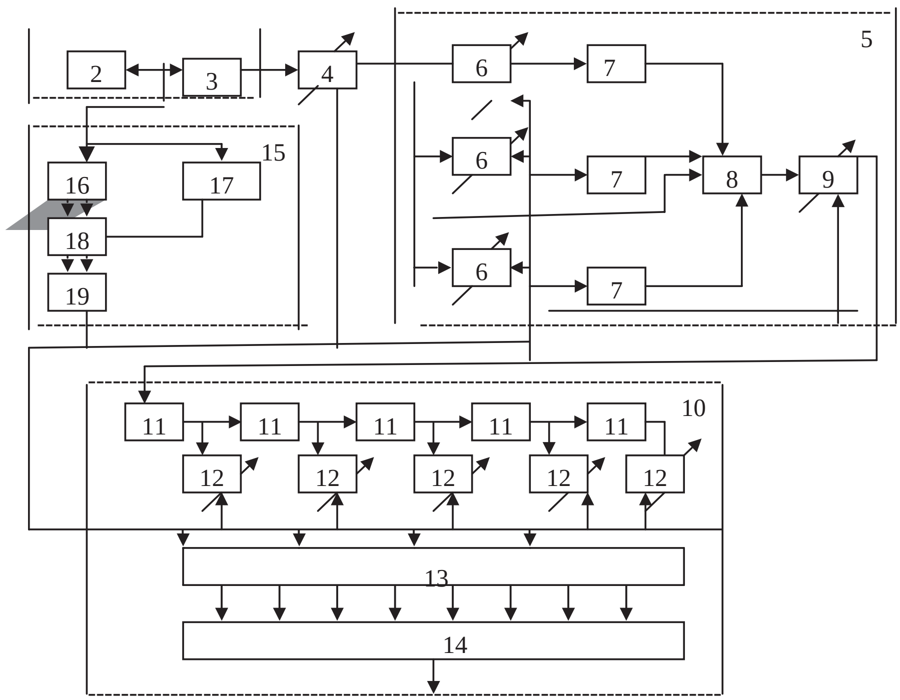

Figure 1.21 Block-scheme of the generator of the non-stationary random processes: 2 is the generator of stroke impulses; 3 and 16 are generators of pseudo-noises; 4 is the resistive divisor of voltage; 5 is the formatting filter; 6, 9, and 12 are the controlled divisors of voltage; 7 are the narrow-strip filters; 8, 14, and 18 are summarizers; 10 is the non-linear functional transformer; 11 are orthogonal filters; 13 is block of multiplying factors; 15 is the control block; 17 is the counter of stroke impulses; and 19 is the digital-analog transformer.

The controlled divisors of voltage 4, 6, 9, and 12 are regulated by changing the output signal of control block 15, to the input which moves the signals from the generator of stroke impulses 2.

The generator, 16, makes evenly distributed numbers and is connected through digital outputs of its shift register to summarizer 18. This output for a sufficient amount of stroke summarizing time creates a random number in correspondence with the Normal law of distribution (counter 17). The output information from the summarizer is transferred to controlled voltage with the help of digital - analog transformer 19.

The limit of change of the mathematical expectation, variance, and autocorrelation function is regulated by changing the arm of the controlled voltage divisors with the necessary switch. The given changes during the time of the correspondence parameters of random process are regulated by the output voltage of control block 15, which influences the same divisors.

Test results from the above generator show that with its help in the laboratory over a given time one can format practically and real power spectrum (or autocorrelation function).

The formatting filter creates the strip of filtration frequencies from 0.01 Hz to 50 Hz. It consists of 10 analogous resonance active RC-filters, input and output cascades.

The input cascade builds on the silicon transistor and has the function of a buffer which allows the output of the generator of pseudo-random sequence to correspond to the input of the filter.

Each of the 10 filters is designed on the principle of including it in the chain of the amplifier with a negation inverse connection of symmetric double *T*-figurative *RC*-bridge and has a strip of filtration with levels 0.7 to 2 *Hz*.

For more reliability one uses the scheme of a triple cascade amplifier of constant current which provides amplification by a factor of 30 - 400 times. Symmetrical double *T*-figurative *RC*-bridges are included in the chain of the inverse connection.

The necessary program of GRC work can be carried out by even a slightly qualified operator within seconds. One advantage of the generator is its high reliability and less expensive outlay.

For accelerated testing of complicated equipment such as an engine, harvester, whole car, etc. it is necessary to simulate simultaneously several different non-stationary processes – through each location of input influences. For this goal it is necessary to use a multi-channel generator of random processes.

Current multi-channel generators of random processes include a beat generator which is connected to a multi-digital generator of pseudo-random process and blocks of formatting of the statistical characteristics. A basic disadvantage is that the width of the spectrum of output signals depends on the number of output channels.

To eliminate of this disadvantage, Figure 1.22 shows a multi-channel generator which consists of a block of lateness for which the number of inputs is equal to the number of digits of the register of the generator of pseudo-random sequence, and the number of outputs is equal to the number of output channels. The inputs of lateness are connected to the corresponding digital outputs of the generator of pseudo-random sequence, and the outputs are connected to corresponding blocks of formatting of the statistical characteristics.

If one uses for preliminary points of noise, the generator of pseudo-random m sequence on the basis of the dislocation shift register with the summarizer of module 2 in the chain of inverse connection, then into the multi-channel of random processes one can introduce the multi-input block of lateness.

This block includes a collection of summarizers of module 2 of which inputs and outputs are brought to the cross-field. Also to the cross-field are brought the outputs from each digit of the generator of the pseudo-random sequence. All outputs are dependent on the number of digits of the register and the number of channels of the pseudo-random processes, and are connected to the cross-field with the inputs and outputs of the summarizers of module 2. The outputs of the cross-field are connected to the inputs of the blocks of collection of statistical characteristics, the outputs of which are outputs of the multi-channel generator.

The output of generator 1 (Figure 1. 22) is connected to the stroke width of generator 2 of the pseudo-random m-sequence. The stroke pulses produced by the generator 1 move the information into the register which includes the summarizer of module 2 in the chain of inverse connection.

The outputs of each digit of the register connect to the cross-field of lateness block 3, where it is connected to the summarizer of module 2 so that movements during the time between sequences of the outputs are approximately equal to each other, i.e. evaluate by a value of $\Delta t2^{n}$ $^{1}/N$, where Δt is the period of stroke pulses; n is the number of digitals of generator of m-sequence of the shift register; and N is the number of output channels.

With each output from the lateness block by field of stroke pulses on the generator 1, a pseudo-random sequence of the signals is formed which is transformed with the help of blocks 4 into a random process with given statistical characteristics.

4.3 EXAMPLE OF PHYSICAL SIMULATION OF RANDOM INPUT INFLUENCES ON THE TRAILER

This is a brief example of the use of the methodological approach described earlier. To solve this problem for a trailer it is necessary to simulate different types of input influences: the features of the road, speed of test subject movement, speed and direction of the wind, etc.

To deal with road features, from previously described methods the processes $z(t)$ of the profiles of the road and vibration $f(t)$ of the trailer hitch on the three types of road – town road, field, and cobblestone – were approximated and simulated. The values of the components for calculation of the formatting filters of the processes $z(t)$ and $\varphi(t)$ are given in table 1.15. The experimental and theoretical graphs $\rho_z(\tau)$ and $\rho_\varphi(\tau)$ are shown in figures 1.23 and 1.24.

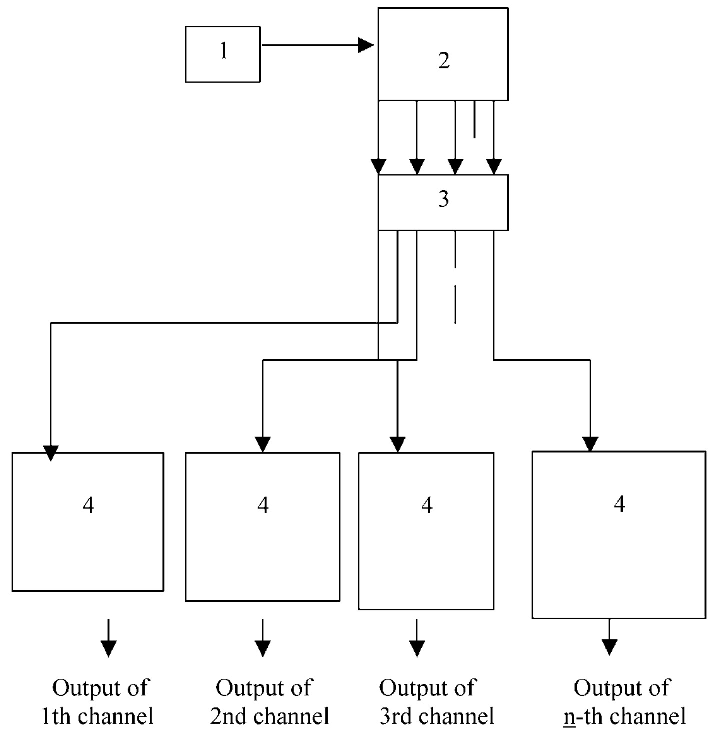

Figure 1.22 Block-scheme of the multi-channel generator of random processes: 1 = generator of stroke pulses; 2 = generator of pseudo-random sequence with the shift's register; 3 = block of lateness; 4 = blocks of the statistical characteristics formatting.

It is necessary to know, for the simulation of a random process, the range through which its variance changes in different conditions of use, in order to carry out subsequent simulation (physical or computer) in the laboratory. To correspond with the reduction of the intensity, the coefficients α of the correlation functions, their periodical components β, and variance D, the values of constant of time of the formatting filters and coefficients of the differential equations which have to be set up on the analog computer (Table 1.15) can be calculated.

The correspondence between the process that is obtained from the output of the formatting filter, and the input influence in real life can be obtained as follows. The first step is to check the accuracy of the composition of the formatting filter and its calculation of the values of α, β, and D of the correlation function of a simulated process. For this goal in the scheme of composition on the analog computer of formatting filter, to the one from integrators one gives the initial condition that it is equal to 50 wt or 100 wt and provides the start of the solution. As a result,

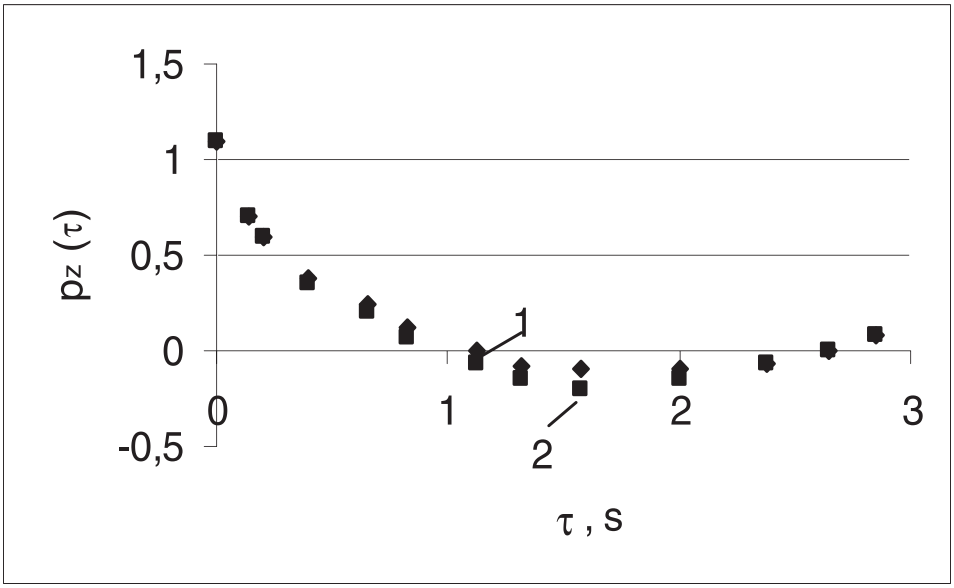

Figure 1.23 Experimental and theoretical correlation functions of the road profiles: ♦ experimental, ■ theoretical.

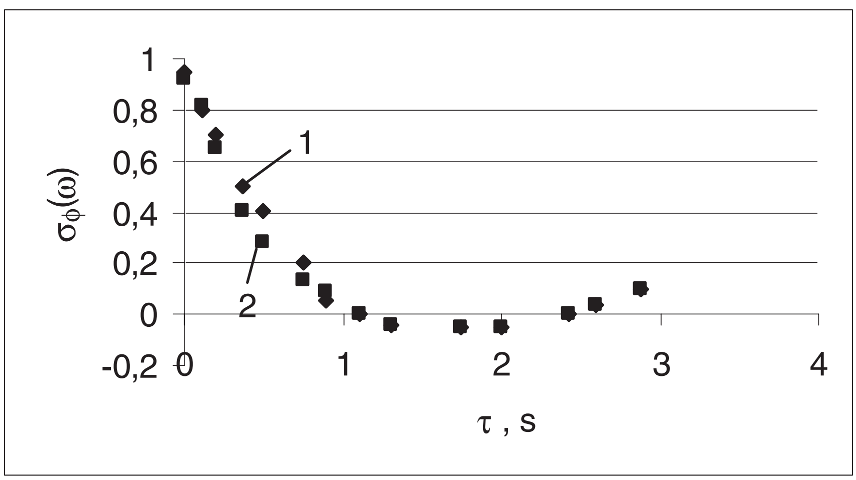

Figure 1.24 Experimental and theoretical correlation functions of the trailer hitch vibration: ♦ experimental; ■ theoretical.

Table 1.15. The values of α, β, and D that are necessary for calculation of the formatted filters of processes *z(t)* and *φ(t)*.

Type of road	Process	α, 1/s	β, 1/s	D_1, $sm^2/degree^2$	D_2, $sm^2/degree^2$	D_3, $sm^2/degree^2$
Town road	$z_1(t)$	1.1	2.24	1.32	2.82	5.05
	$z_2(t)$	1.3	1.3	1.32	2.82	5.05
	φ(t)	0.6	1.2	-	7.08	-
Field	z(t)	1.15	1.5	1.21	3.15	6.1
	φ(t)	0.6	1.2	-	7.08	-
Cobblestone	z(t)	3.6	5.2	1.4	3.04	-
	φ(t)	0.6	0.7	-	4.8	-

one will obtain from the output of the simulated process the correlation function which is identical to the approximated value.

Table 1. 16 The values of the time constant of formatted filters and coefficients of differential equations that are set up on the computer.

Type of road	Process	α_1^1	α_0^1	α_1	α_0
Town road	$z_1^1(t)$	2.21	6.26	1.4	0.4
	$z_2(t)$	2.66	3.44	1.54	-1.22
	$\varphi(t)$	1.2	1.75	1.66	0.25
Field	$z(t)$	2.4	3.7	1.54	-0.74
	$\varphi(t)$	1.2	1.75	1.66	0.25
Cobblestone	$z(t)$	7.25	40.0	2.78	-2.46
	$\varphi(t)$	1.21	0.85	1.33	0.35

Figure 1. 25 shows the correlation functions $\rho_z(\tau)$ of the road profiles' (1) processes and trailer hitch vibration (2). The formatting filters were calculated using values α, β, and D of these processes. The correlation functions ■ and ▲ were obtained from the output of formatting filters by giving the initial conditions and starting without supported loading for stretching. The close alignment of both correlation functions will give the possibility for true calculation and collection of the formatting filters.

The experimental data have shown that by the use of the generator GS – 1 there is more spread of variances and mathematical expectations in the field and in the laboratory. Therefore, it does not give the possibility for successful correlation of these data.

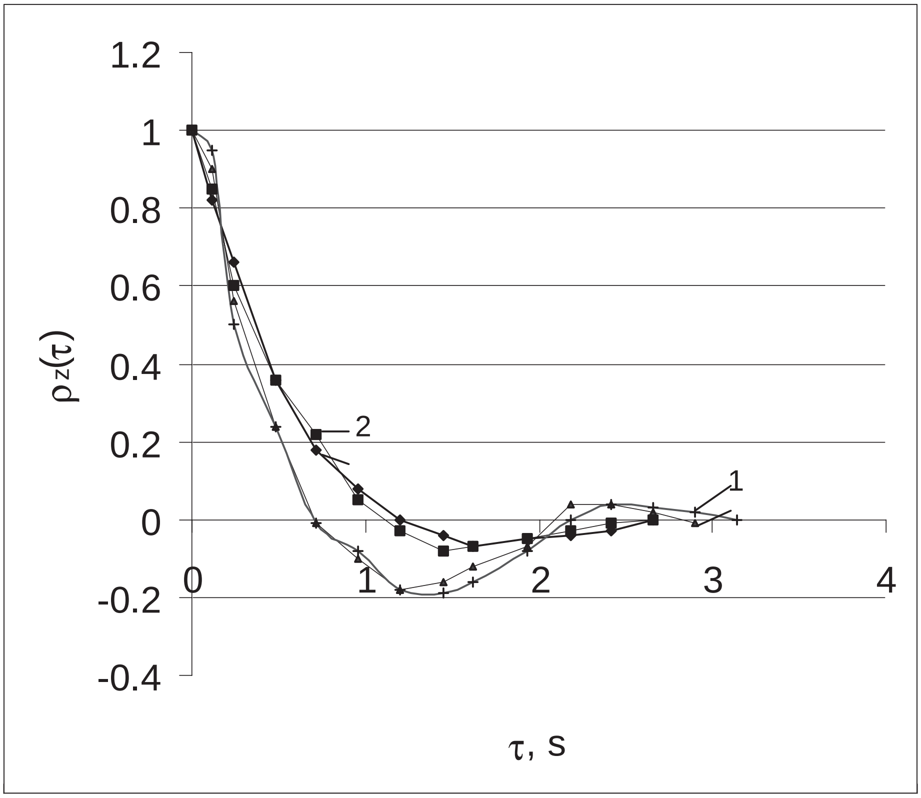

Figure 1. 25 The correlation function of the road profiles processes z(t) (1) and trailer hitch vibration (2): ♦ and + are experimental, ■ and ▲ are the output of the filters.

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5 SUBSTITUTION OF ARTIFICIAL MEDIA FOR NATURAL (TECHNOLOGICAL) MEDIA

5.1 BASIC CONCEPTS

In accelerated testing it is both an important and a difficult problem to find equivalent substitute artificial media for natural media. The natural (technological) medium is the product with which the machinery comes into contact during its work (waste, fertilizer, sand, soil, different chemical products, food, etc.) in food processing, truck usage, etc. Often the natural technological medium cannot be used for AT, because it changes its quality rapidly. In practice, when one wishes to simulate accelerated testing of a truck, one is unable to reproduce the actual field conditions in the laboratory in a satisfactory fashion. For example, the result of natural media action on the truck may be corrosion, wear, etc. rather than more degradation and a decrease in reliability as observed in the field. For fertilizer applicators the natural medium is fertilizer, etc. Therefore, we must use these natural media for accelerated laboratory testing to accurately simulate their characteristics.

One of the basic reasons for the inability to change a natural (technological) medium in the laboratory after a limited number of times (the number is different for various media) is that this medium loses and/or changes its chemical/physical/mechanical qualities. Therefore, one must often change worn groups of natural media. In practice then it may be very difficult, or too expensive, or impossible to use the natural medium. Therefore, for laboratory testing of many types of product one often substitutes an artificial medium for the natural medium.

But how does this artificial medium perform as compared to the natural medium? For example, how does the corrosive-abrasive influence compare with the natural media? For several years the authors and their colleagues have studied this problem and developed principles that lead to a satisfactory solution.

The basic principles of approach for the solution of the above problem are based on acceptance of the structure and composition of the artificial media which simulate with enough accuracy the wearability mechanism which sufficiently accurately reflects the wearability mechanism of the machinery work in contact with natural technological media[1,2,3,4].

The research is based on a diagnostic of the wearability mechanisms in technological masses, simulated in artificial media.

For the criterion of the similarity of the artificial media to a natural media based on the wearability capacity one can use the similarity of the rows of the materials' wearability after testing in the above media. The basic steps of establishing equality between these two media are:

- Test samples of materials that consist of the product components (steel or plastic, etc.) and which comes in to contact with the natural medium.

- Obtaining a series of measurements of the amount of wear on these samples resulting from to the natural media and various artificial media.

- Establishing a correlation of this wear (or fatigue, etc.) between the natural and artificial media to determine if a particular artificial medium can effectively replace the natural medium.

The authors showed, as an example of the problem solving, experimental research to search for natural media substitutes for waste applicator. The methodological process for the above requirement included five basic steps[1]:

- Manufacture the test specimens from different steels (determinate sample size and configuration) to test them in both a technological medium (waste) and in artificial media.

- Study the effects of various natural media and the selection of an artificial medium, then identify identical results for physical-mechanical and chemical properties.

- Determine the conditions and regime for testing metallic specimens in natural and artificial media.

- Provide metallic samples from different types of steel for testing natural and artificial media.

- Analyze wearability rows of materials as a result of specimen testing in the above media.

For the first step one uses research on physical-mechanical properties and chemical composition of technological mass in real life. For waste it is necessary to evaluate moisture, strawness, content of abrasive particles, N, P, and K, etc. After that one must evaluate possible compositions of artificial media which could simulate this technological mass for accelerated reliability testing of the product.

For the second step one chooses a selection of materials, producing from them the specimens for testing in technological mass and artificial media, to study the hardness of the materials, and the roughness of the wear surface. For clarity of this experiment, the index R_z of the roughness of the wear surface must be no more than 10 millimicrons. Besides, it is necessary that not less than six or seven types of materials should be tested. The group of materials must be homogeneous, for example, different types of steels.

For the third step one must evaluate testing regimes of specimens for different types of materials (for example, steels) in technological mass and artificial media. The testing regimes must have minimum divergences from real life regimes of work. For this goal, one must analyze the work regimes of machinery components (the speed of movement of the wear surface, distribution of the time of use between processes of work and breaks, and other factors).

The research results of other scientists must also be analyzed to evaluate the influence of different regimes on the wear of machinery components. Then must equal the required regimes of testing of the steel specimens in technological masses and artificial media.

The fourth step must provide the required regimen on the special test device for testing steel (or other studied material) (Figure 1.26) specimens in technological masses and artificial media for obtaining wearability lines for technological mass ξ_1 as well as these lines for different artificial media $\xi_2 \ldots \xi_i$, i. e.

$$\xi_1(W_{11}, W_{21}, \ldots, W_{j1});$$

$$\xi_2(W_{12}, W_{22}, \ldots, W_{ji});$$

$$\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\xi_i(W_{1i}, W_{2i}, \ldots, W_{ji}),$$

where: W_{ji} is absolute value of wearability of the j-th tested material and i-th line.

For the above goal the following simple device for testing mechanical wearability properties of materials was developed (Figure 1.26).

The fifth step involves analysis of obtained lines of wearability, as a result of testing, and taking up the solution of how identical the wearability mechanism is in technological masses and artificial media. The basic criterion of how identical the wearability mechanism of materials is in technological masses and artificial media is their similarity, which can be expressed by the following equation:

$$\xi_1(W_{11}, W_{21}, \ldots W_{j1}) \approx \xi_1(W_{1i}, W_{2i}, \ldots Wji)$$

If the lines of wearability differ, one must evaluate the level of divergence by formula (1.8), shown later. For substantiation of the necessary artificial medium, it is necessary also to analyze the regularity of the wearability process and the condition of the surface of wear.

Let us show the above technology on the example of waste.

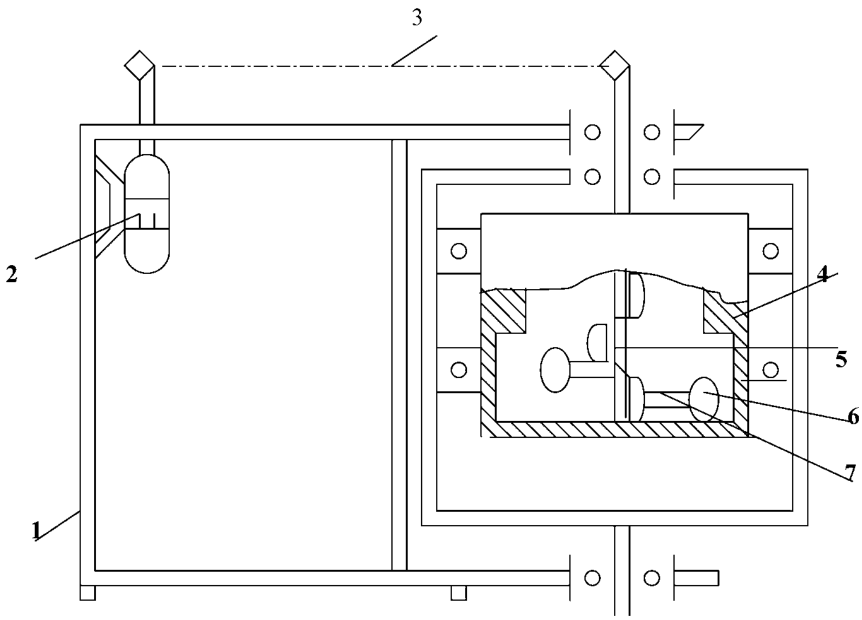

Figure 1. 26 Device for testing wearability of materials[1]: 1 = frame; 2 = motor; 3 = transmission chain; 4 = tube; 5 = shaft; 6 = samples for testing; 7 = bracket for holding samples.

5. 2 EXAMPLE OF USE

As a result of research, the following friction coefficient was obtained (Table 1.17).

Table 1.18 includes the value of wear for each medium after 375 hours of testing. The value of wear is measured by loss of mass. The weight of each sample of steel was checked every 75 hours of testing. Table 1.18 shows that artificial medium 4 (quartz sand 60.44%, turf 21.36%, and water 18.2%) is similar to natural waste across all steel samples. The wearability of medium 7 is very different from the natural medium (waste), therefore it was decided that this medium would be removed from the next experiments. The following lines of wearability (Table 1.19) were built on the basis of the obtained results of the above media. In these lines the values of wearability were changed for the above types of steel.

Table 1. 17 Friction coefficient of different media by steel.

Number	Media composition	Friction coefficient
1	Waste (moisture W = 65 %)	0.98
2	Waste (moisture W = 70 %)	0.90
3	Quartz sand (dry) with sizes of samples from 0.1 mm to 0.4 mm	0.60
4	Quartz sand (moisture W = 5%)	0.80
5	Quartz sand (moisture W = 10%)	0.62
6	Quartz sand 60.44%, turf - 21.36%, water - 18.2%	0.92
7	Polymer granules (dry)	0.50
8	Polymer granules (wet)	0.44
9	Polymer granules (wet) and quartz sand (6%)	0.47

Here ξ_w, ξ_1, ξ_2, ξ_3, ξ_4, ξ_5, ξ_6 are raws of wearability of steels that were obtain as a result of their testing in a natural medium and six compositions of artificial media. The analysis of the lines of wearability showed that the mechanism of wear of the studied steels is different with different media.

The level of divergence of the lines of wearability may be evaluated by the formula:

$$R_i = \frac{n_{mn}}{n_{um}} \tag{1.8}$$

where: n_{mn} is the number of materials in line ξ_i which it is necessary to displace to obtain an analogy with another line (ξ_i); n_{um} is the total number of tested materials.

Table 1. 18 Total corrosive-mechanical wear of the steels by waste and artificial media, g/m^2

Media	S 1020	5140	T 5140*	1045	E 1045*	1070	E 1070*	W108	LW 108*
Waste	**156.6**	**136.5**	**105.8**	**143.9**	**115.9**	**138.0**	**165.4**	**122.0**	**130.1**
Art. Medium 1	133.3	153.7	142.3	144.0	176.1	137.3	167.7	127.1	170.1
Art. Medium 2	279.7	280.8	253.6	275.0	313.6	307.3	323.7	280.9	361.0
Art. Medium 3	139.4	100.9	112.3	101.2	150.2	110.3	138.1	86.9	153.1
Art. Medium 4	**135.3**	**145.0**	**110.1**	**145.5**	**122.4**	**142.8**	**162.8**	**129.0**	**139.8**
Art. Medium 5	253.4	260.6	188.8	285.4	183.4	389.5	358.6	281.0	236.7
Art. Medium 6	101.8	98.8	91.5	102.7	87.5	89.5	88.5	90.9	75.9
Art. Medium 7	2.0	15.4	0.6	22.3	1.4	0.9	4.4	1.2	7.2

* *shows that the steel is heat-treated*

If the lines are fully equal, $R_i = 0$, but when they are fully, divergence $R_i = 1$.

So, R_i is a measure of the divergence of the wearability of steels after testing in artificial media as compared to the level of steel wearability after being tested in a natural medium. In other words, how different the mechanism of wearability in artificial media is from that in natural media. Table 1.20 shows the coefficients of inverse R_i, of lines ξ_1, ξ_2 . . . ξ_6 to line ξ_w .

Table 1.19. The lines of wearability of the studied steels.

ξ_w	5140*	1045*	W108	1020	W108*	5140	1070	1045	1070*
ξ_1	W108	1020	1070	5140*	1045	5140	1045*	1070*	W108
ξ_2	5140*	1045	1020	5140	W108	1070	1045*	1070*	W108
ξ_3	W108	5140	1045	1070	5140*	1070*	1020	1045*	W108
ξ_4	5140*	1045*	W108	1020	W108*	1070	5140	1045	1070*
ξ_5	1045*	5140*	W108*	1020	5140	W108	1045	1070*	1070
ξ_6	W108*	1045*	1070*	1070	W108	5140*	5140	1020	1045

From table 1.20 we can see that the mechanism of wearability in waste is closest to that of the fourth artificial medium (0.22).

Table 1.20 The values of inverse coefficients (R_I) in the ratio of materials' wearability ξ_1, ξ_2 . . . ξ_6 and ξ_w.

Compared lines	ξ_1 and ξ_w	ξ_2 and ξ_w	ξ_3 and ξ_w	ξ_4 and ξ_w	ξ_5 and ξ_w	ξ_6 and ξ_w
Coefficient of inversion	0.89	0.89	1.00	0.22	0.89	0.89

In table 1. 21 one can see that the results of the abrasives indexes shows the relative capability of medium wear. The abrasives index R_a is defined as $R_a = \frac{W_{ji}}{W_{j1}}$, where: $W_{j\,i}$ is the absolute value of wearability for the j-th material and the 1st line.

Table 1.21 The indexes of abrasives R_a of line ξ_i in ratio to line ξ_w.

The rows of wearability	S1020	5140	T 5140*	1045	E 1045*	1070	E 1070*	W108	LW 108*
ξ_1 - ξ_w	1.06	1.13	1.34	1.00	1.44	0.99	1.01	1.04	1.31
ξ_2 - ξ_w	2.23	2.06	2.40	1.91	2.71	2.23	1.96	2.30	2.77
ξ_3 - ξ_w	1.11	0.74	1.06	0.70	1.30	0.80	0.83	0.71	1.18
ξ_4 - ξ_w	1.08	1.06	1.04	1.01	1.06	1.03	0.98	1.06	1.07
ξ_5 - ξ_w	2.02	1.91	1.78	1.98	1.58	2.82	2.17	2.30	1.82
ξ_6 - ξ_w	0.81	0.72	0.86	0.71	0.75	0.65	0.54	0.75	0.58

An analysis of the characteristic line values shows that the spread in values of wearability for the materials for all obtained rows of steel wearability also shows that the closest characteristics are in waste and the fourth artificial medium. (Table 1.22).

Table 1. 22 The spread in values of wearability.

Line	W	1	2	3	4	5	6
Characteristic of line	1.56	1.34	1.42	1.76	1.48	1.96	1.35

The final conclusion regarding the similarity of the wear mechanisms of steels in different artificial media and waste was made after an analysis of the corrosive-mechanical results for various steel wear in these media. The following functions were determined to relate the artificial media and waste.

Analysis of the research results shows that the value of corrosive-mechanical wear of steels in waste has a linear character in time. The data from the fourth medium also have a linear dependence between time and the value of corrosive-mechanical wear in these steels (Figure 1.27). For other media this dependence does not have a linear character. Therefore, we can make a conclusion that the fourth artificial medium may be recommended for use instead of waste for accelerated testing.

Table 1. 23 The calculated functions of corrosive-mechanical wear of steels by waste and artificial media.

		artificial media				
STEEL	WASTE	1	2	3	4	5
1020	1.4+0.34t	15.9+0.34t	0.96+0.9t	-0.9+0.38t	-7.2+0.37t	-6.6+0.7t
5140	10.7+0.34t	20.6+0.38t	10.0+0.75t	0.2+0.28t	-3.3+0.41t	-15.0+0.74t
5140*	4.8+0.28t	16.0+0.37t	-2.0+0.7t	2.4+0.3t	-1.4+0.31t	-9.0+0.5t
1045	6.6+0.37t	20.7+0.36t	11.4+0.74t	0.7+0.28t	-11.4+0.42t	0.97+0.96t
1045*	4.6+0.29t	27.6+0.43t	6.7+0.86t	0.91+0.69t	-4.2+0.34t	0.96+0.87t
1070	9.0+0.35t	17.6+0.35t	6.7+0.88t	-1.3+0.3t	-5.2+0.4t	-21.1+1.08t
1070*	17.7+0.4t	21.6+0.42t	1.01+0.89t	0.82+0.38t	-2.3+0.46t	-7.0+0.98t
W108	-0.5+0.32t	0.81+1.2t	0.98+0.88t	-0.6+0.24t	-2.5+0.35t	-11.0+0.78t
W108*	8.4+0.33t	29.0+0.43t	1.02+0.99t	0.89+0.8t	-3.3+0.39t	0.93+0.97t

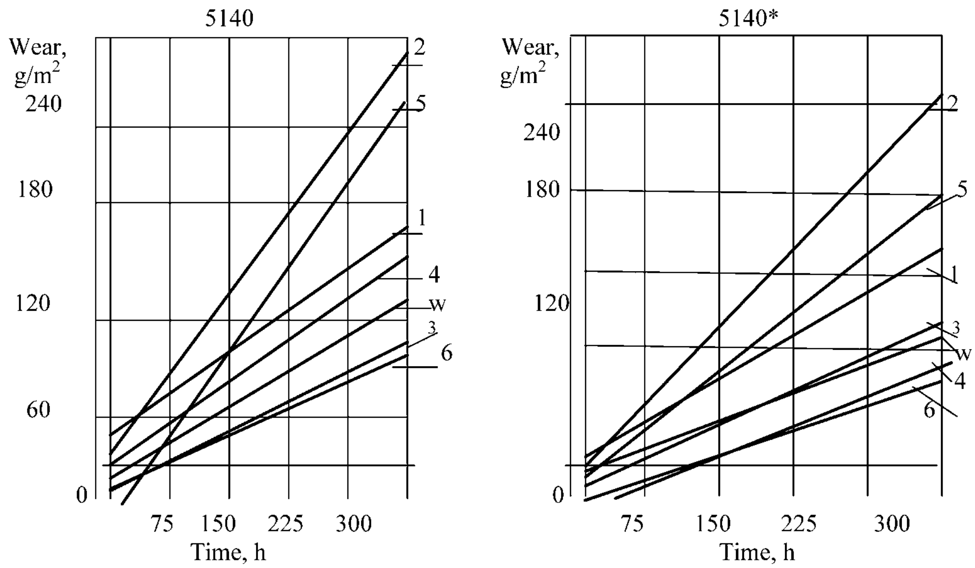

Figure 1.27 Dynamic wear of steels 5140 and 5140* by corrosive-mechanical wear in waste (W) and artificial media.

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CHAPTER 2. USEFUL ACCELERATED RELIABILITY TESTING PERFORMANCE

6 GENERAL REVIEW OF ACCELERATED TESTING METHODS

There are in practical use three basic directions for accelerated testing (AT).

1. Field testing of the actual test subject with more intensive use than under normal conditions

For example, a car is usually in use for no more than 5 - 6 hours per day. If one uses it 18 - 20 hours per day, this represents true accelerated testing and research on this car, because the intervals between usage are less than normal (4 - 6 hours instead 18 - 20), and the results of this type of testing are more accelerated than under normal field conditions.

2. Laboratory [or specific field (proving grounds, etc.)] testing of the actual test subject on the basis of physical simulation of field input influences

For example, if the actual car is studied or tested with the simulation of field input influences using special equipment (vibration test equipment, test chambers, proving grounds, etc.), the difference between the results of this direction of testing and the results of testing under normal field conditions will be greater than in method 1. In this direction of testing there is physical simulation of the field input influences on the actual test subject. The accuracy of the test results depends on the accuracy of the simulation of these input influences.

The higher simulation of field input influences enables one to obtain the highest level of accelerated reliability testing, therefore, the most accurate correlation between test results and field results.

3. Laboratory testing with computer software (mathematical) simulation of the test subject and field input influences.

The difference between the results of this direction of testing and the results of testing under normal field conditions will be greater than in method 2 (and certainly more than in method 1). In this case, the simulated product is different from the actual product, and the simulated field input influences are different from the actual field input influences. The basic reason is that currently one cannot accurately simulate on the computer both the test/research subject and the field influences. At present, this direction is in the early stages of development and is more popular with professionals in the software development field. But people can see in this approach what they want to see, their dream. For example, "... thanks to computer technology, engineers can perform extremely sophisticated virtual tests in much less time and for much less cost than if they performed the corresponding physical tests"[1].

This book includes direction 2, therefore the following review relates to this direction.

The following example illustrates the current situation with emphasis on the importance of accelerated testing. An established company produces many types of servo-motors. This company has developed several types of new products on a similar basis and has begun producing these without a full testing program (including AT) for quality evaluation, and saved $15,200 and several weeks time.

However, after producing thousands of this product, at a cost of millions of dollars, customers began to return rejected products. These were tested to find the reasons for rejection, but it was too late. The result was that when the company reduced the testing of the product and saved several weeks of production time and $15,200 in testing, the company lost:

- almost $200,000 for the correction of the rejected products;

- potential customers for future products, because it could not find customers who bought small quantities of products through other selling agencies, who failed to get the necessary help to correct the wasted product;

- its reputation on the market as a company, that produced a high quality product was destroyed.

For larger companies these losses would be even greater.

Is it possible to count how much money production companies lose through product rejection and repair during the warranty period when they offer the same warranty period as a higher quality company in the world market?

Companies do this because they do not want to lose their market share, but this problem can be solved in a much cheaper way if they use accelerated testing.

The more complicated a product is the greater are its losses. Phillip Coyle, the former director of the Operational Test and Evaluation Office (Pentagon) said that if during the construction of a complicated apparatus such as a satellite, one tries to save a few pennies in testing, the end results may be a huge loss of thousands of dollars due to faulty products which have to be replaced because of this mistake.

When Boeing wanted to produce a sensor system for satellites with minimum expenditure and time, the specialists in this company decided not to carry out the subsystem testing until it was mounted with more complicated components, then to test the entire block. In the end, however, this approach required more expenditure and time than planned. The subsystems that were not tested had failures that led to the failure of complete blocks, which then had to be dismantled and regrouped[2]. The above approach makes the problem of finding the cause of failures more complicated, therefore, more time and cost are necessary.

Just to improve on the above situation it is not sufficient to use only accelerated testing, it must be a high level of this testing, e.g. accelerated reliability testing.

There are several approaches to accelerated testing, and it is important to differentiate among them, because each approach requires specific techniques and equipment. The effectiveness of these approaches sometimes depends on the product (how simple or complicated it is) and sometimes depends on how complicated the operating conditions of the product are (one or several climatic zones of usage, inside or/and outside usage). For example, electrode testing needs simpler techniques and equipment than engine testing. Devices or vehicles which are used indoors do not need solar radiation testing. For testing devices which are used for a short time in a year or a long time in a year, one needs different approaches for greater effectiveness, etc.

In general, there are two basic approaches to accelerated testing. Let us describe them shortly.

First there is *use-rate acceleration.* Many products are not in continuous use, and one can capitalize on this by accelerating the use rate and/or reducing working time with a minimal loading which has no influence on the product degradation (failure). For example, a toaster might be designed for 10 years failure-free operation, assuming twice-a-day usage. If the toaster is run 100 times daily, one can accumulate the equivalent of 10 years of field operation in about 75 days. Or a truck might be in use usually not more than two hours a day, and 25% of the time it may have a minimum loading. If it is tested for 24 hours a day with a maximum field loading, one can accumulate the equivalent of 10 years of field operation in 5 - 6 months.

This approach assumes life can be adequately modeled by cycles of operation (year or number of cycles) an assumption that does not hold, for example, for failures caused by corrosion and other results of action of environmental factors. This part of accelerated testing can be performed by stress acceleration.

Product stress acceleration. This test involves increasing the stress factors. Acceleration (stress) factors are factors that accelerate the product degradation process in comparison with normal usage. There are many types of accelerated factors: higher concentration of chemical pollutions and gases; more air pressure; higher voltage; higher temperature, fog, and dew; a higher speed of change of input influences, etc. This approach is often used, but it can be useful if the stress is no more than the given limit. Usage of this approach is simpler and more effective for materials and simple components, but this type of AT is used for entire equipment too.

Highly Accelerated Life Testing (HALT), Accelerated Aging (AA), and Highly Accelerated Stress Screening (HASS) relate to this approach to testing.

HALT is a process that utilizes a high step stress approach in subjecting products to varied accelerated stresses to discover the design limitations of the product. HALT is intended to discover the stress limits of a product and identify the product's weaknesses. HALT usually includes two stress parameters: vibration and step stress temperature.

Vibration: Chamber technology for HALT is:

- Repetitive shock vibration which is 6 degrees of freedom (3 linear and 3 rotational) multi-axis and quasi-random;

- Broadband energy exists from 2 Hz up to 10,000 Hz (broadband vibration is vibration that contains energy over a broad frequency range);

- 35 Grms minimum vibration table output with no load.

Thermal: The goal is to force rapid thermal change rates on the product. It is additionally important that the chamber has sufficient air velocity to produce the desired rapid thermal rates of change as measured on the product and to maintain thermal stability:

- High rate of change (minimum air temperature average of 45 °C/minute);

- Thermal range from –80 °C to +170 °C;

- Thermal step stress begins at ambient temperature(defined as 20 °C to 30 °C);

- The step increments are a maximum of 10 °C

HASS: High stress levels can be used in order to reduce the reliability stress screening (RSS is a reliability screening process using environmental and/or operational stresses as a means of detecting flaws by precipitating them as detectable failures) time as much as possible, however the specification of the components must not be exceeded unless decided by the management. For consumer products this decision may be taken by the manufacturer after potential safety issues and potential lifetime reduction have been considered. For equipment supplied under contract, approval from the customer and if relevant from the component suppliers must be obtained before the RSS is started.

Combined stresses, such as for example combined temperature change and vibration or bumps are especially efficient for precipitating flaws as failures. Before the RSS with high stress levels is started the operational limits for the assemblies must be determined, and it must be proven, for example by repeating the RSS cycle a large number of times, that the planned RSS cycles only reduces the life time of the assemblies by an insignificant amount, even with repeated RSS because of repair of precipitated failures.

By choosing an appropriate RSS cycle with high stress levels, the number of fault-free RSS cycles can often be reduced to one.

The screening process under consideration is to be performed at the subsystem level of the system manufacturer. The planning comprises a number of main steps.

STEP 1 – Specify the maximum allowable fraction of weak assemblies. This step is performed by looking at the requirements for the end product in which the printed board assembly (PBA) is to serve. In the present case, no other parts of the end product contribute to early failures. Therefore, the acceptable fraction of weak assemblies, remaining after reliability screening is the same for the end product and the PBA.

STEP 2 – Evaluate the actual fraction of weak assemblies. Calculations steps 1 and 2 are required. In the present case, there are two rogue component classes: Ics and power transistors. Previous experience shows that about 1% of the ICs and about 0.5% of transistors fail early. The fraction of early failures has to be reduced by an order of magnitude before the PBA is mounted into the end product.

STEP 3 – Consider the stress conditions. First the flaws are identified. They are expected to be induced by the assembly process:

- For the ICs, the following phenomena may appear:
  - partial damage of the internal dielectric barriers due to ESD in the production handling;
  - formation of cracks in the plastic encapsulation due to a difficult manual production process.
- For the transistors the following phenomena may appear:
  - formation of cracks in the plastic encapsulation due to a difficult manual production process.

Based on the information in tables of relations between the sensitivity of flaws and stresses, a combination of constant high temperature, low/high temperature cycling and constant operational stress was selected as the most cost-effective stress condition.

Developers and users of the above approaches, especially AA, claim that after several days of testing they can obtain results equivalent to several years in the field.

The above approaches can be used by anybody for reliability and durability testing, but one has to be careful with a high level range of acceleration, as well as when using a combination of field influences and other aspects of accelerated testing.

Most equipment can simulate only part of the basic field input influences that occur in real life, because many environmental influences (temperature, humidity, chemical and dust pollution, sun radiation, etc.) act simultaneously with many mechanical, electrical, and other influences.

Most current equipment simulates these actions separately, so users implement these parts of environmental influences separately. Chemical pollution is also simulated separately from mechanical pollution such as dust. As a result, this equipment cannot provide accurate accelerated environmental testing. The same is true of mechanical and other types of testing. Therefore, ART can be provided mostly in the present only theoretically, but not practically. We will describe how one can overcome this obstacle and develop equipment for the practical implementation of ART to obtain good results.

In principle, the companies that design and manufacture equipment for AT and ART can make test chambers with simultaneous combinations of many environmental, mechanical, electrical, and other types of field simulation by building together, in one complex, many current types of testing equipment. Although these companies produce all the equipment necessary for the above types of simulation, they combine only a few of the possible influences. Of course, the combinations will be different for testing different products, Otherwise this equipment would be so expensive and complicated that users would not buy it.

To solve this problem some professionals who work in the area of accelerated testing development use HALT, Accelerated Aging, and other types of accelerated stress testing with a high level of stress to rapidly obtain their test results. Some people think that in a few days they can obtain test results that compare adequately to a few years in the field. For example, "When a 10-year life test can be reduced to four days, you have time to improve reliability while lowering cost"[3].

This direction is simple: large stress and a short time to obtain the results. It is very easy because one does not need accurate simulation. Therefore, the equipment for these types of AT is much simpler and cheaper. For example, HALT needs only vibration equipment and a temperature chamber.

A negative aspect of this approach is that one cannot obtain the physics (or chemistry, etc.) of the product degradation mechanism through these testing conditions which will be similar to the physics of degradation (or the chemistry) mechanism in the field. Therefore, this approach cannot obtain sufficient correlation between AT results and field results. If one measures the time to failure during AT, it is still impossible to know accurately the time to failure in the field. Moreover, the product may be destroyed during AT or show failures in the laboratory which do not occur in the field.

This approach is used at present in the aerospace, aircraft, and electronic industries[3] and often without success.

Most high level professionals in these areas (in Lucent Technologies, Bell Labs, etc.) monitor the stress level very carefully and use as a criterion of simulation the physics of degradation mechanism. For AT of electronic equipment they often use a minimum of three parameters of the regime in the test chambers simultaneously. These parameters are temperature, multi-axis vibration, and input voltage.

A second negative aspect of this approach is that in testing the whole product or its units that consist of different details, each detail has a different acceleration coefficient. As a result, one cannot estimate the acceleration coefficient of the whole product (car, computer, etc.) or unit.

Therefore, if we know the time to failures of different components of whole product during accelerated stress testing (AST), we cannot estimate the time to failures and other reliability indexes of the whole product or unit during real life, because the ratios of acceleration coefficient (the ratio between AT time and field time) of the failures of test subject elements vary too widely.

This is similar to the situation where , as is shown in this book, different subunits will interact with each other and cause some subunit failures to disappear, but other new subunit failures to appear. We have non-linear combinations. For example, for different details of caterpillar elements[4] the ratio of failure acceleration varied from 17 to 94. In this case it is impossible to find the reliability indexes for whole caterpillar. One of the conclusions of this research was that

"This confirms the practical impossibility of selecting the regime of AST that will give the ratio of loading of all details and units of the complete device which will correspond to field"[4].

This was known almost 50 years ago. Kyle and Harrison wrote 40 years ago that the ..."Absence of tensions with small field amplitude by AT gives an error in the estimation of the ratio of the number of work hours in the field and on AST conditions, for evaluation of details under high tension and fluctuation of load"[5]. This approach is one of the basic reasons why they cannot obtain sufficient correlation between AT results and field results.

There are various types of standard test chambers for environmental accelerated testing: a) climate chambers (cold, heat, and humidity); b) heat shock (separate cold and heat chambers alternate between test subjects); c) cold, heat, and vibration; d) cold, heat, and gas pressure; e) solar radiation; f) corrosion (heat and destructive gas); etc.

There is specific test equipment for environmental testing that is more popular in different areas of industry. For example, the automobile industry has five such types of equipment. First, test chambers for simulation of tropical conditions. This type of equipment provides the possibility of regulating temperature and humidity within the limits of +20 °C and 30% to 55 °C and 97%. This equipment often has an additional aerodynamic pipe for the generation of wind with a speed equal to automobile speed (1 – 100 mph), and separate uses of the devices to simulate solar radiation, thermal atmospheric radiation (0 – 1,100 Kkal/m^2.hr on the floor level) and for protection (0 – 80 °C). As shown above, these test cannot accurately simulate true tropical conditions, because they cannot simulate the real life simultaneous combination of conditions founds in the tropics. Therefore, they cannot give accurate information for the evaluation and prediction of test subject quality and reliability.

Second, equipment for testing in low temperatures. Usually this equipment simulates the temperature from +10 °C to 40 °C and air humidity to 95%. This type of testing is used to check the starting quality of an engine under conditions of low temperature, and to analyze of the operational characteristics and oil systems, lubrication, protection, etc. of automobiles at low temperatures.

Of course, in real life low temperature acts in combination with other input influences, therefore even the above type of testing cannot give accurate initial information for the evaluation of product quality.

Third, weather test chambers. These have a regulation system of temperature (from –40 °C to +55 °C), and humidity (from 30% to 99%). The chambers have a device for the simulation of thermal radiation from the atmosphere (0 – 1,200 Kkal/m^2.h at floor level) and from the road surface (0 – 80 °C); snow (15 kg/m^2.hr), rain (200 mm/hr), pollution, UV radiation, etc.

Usually the chamber has an aerodynamic pipe and a device for power absorption. This multi-functional equipment helps to determine the operational characteristics of automobiles under conditions of different types of weather. An example of these test chambers is show below (WEISS TECHNIK test chambers). Unfortunately, they are very seldom used in the industry.

Fourth, low pressure chambers. These simulate changes of pressure during the moving of automobiles at high altitudes or at sea level. Usually under these conditions the air pressure is from 0.3 to 0.5 of atmosphere.

Fifth, chambers which simulate temperature and vibration (or temperature + vibration + input voltage).

The electronics of automobiles usually have the following types of environmental testing:

- storage at high temperature;
- ALT by high temperature;
- dynamic long-term testing under temperature and vibration;
- thermo shock testing, etc.

The test equipment for the automotive industry usually includes a volume from 0.5 to 500 m^3.

Accelerated life testing (ALT) is the method for determining or estimating the projected life of a product when exercised in a customer-type environment[27].

Accelerated environmental testing (AET) of electronics and other types of products has the same negative aspects as AET for automobiles which was shown above.

Weathering testing, which was included in many standards, is now popular.

What is weathering? Weathering[6] is the adverse response of a material or product to climate, often causing unwanted and premature product failures. Consumers spend billions of dollars per year to maintain products that inevitably degrade and to replace products that fail. Materials that fail as a result of exposure to outdoor environments account for a significant portion of this total cost.

The three main factors of weathering are[6]:

- solar radiation (light energy);
- temperature;
- water (moisture).

Solar radiation is radiant energy that comes from the sun and is made up of photons that travel through space as waves. Their energy *(E)* is proportional to their frequency *(v)* according to the following equation, where h is Planck's constant, c is the velocity of light in a vacuum, and λ is wavelength:

$$E = hv = hc/\lambda$$

The relationship in this equation shows that shorter wavelengths are associated with higher photon energy. This is an important concept when we later discuss how materials degrade as a result of solar radiation. The solar radiation that reaches the earth's surface consists of wavelengths between 295 and 3000 nanometers. A nanometer is one billionth (1×10^9) of a meter.

Other areas of industry also have specific types of AT. For example, accelerated testing of farm machinery can be:

- in the field;
- on special experimental proving grounds;
- on special test equipment in the laboratory;
- or any combination of the above testing.

It can be complex testing of entire machines, or testing of details, units, or combinations of details (units).

Usually, complex testing of entire machines is performed mostly in the field. The details and units, or their combination, are tested in the proving ground and on laboratory equipment. One can also test new (modern) details and units, which are components of entire machines, in the field.

Depending on the method of loading, laboratory accelerated testing can be realized with:

- periodical and constant amplitude of loading;
- block-program stepwise loading;
- maximum stress of loading;
- maximum simulation of basic field loadings in simultaneous combinations[6].

One must take into account that in the field the input influences on the equipment, especially mobile, have random (probabilistic) character. Therefore, to implement accurate accelerated testing one must simulate the random character of these influences.

For example, during the use of farm machinery their working parts, clearances, matting, and other parameters are changed. This influences the quality and quantity of the loss of farmer's product. Therefore, one must take this into account when performing accelerated testing on farm machinery. The established testing techniques for the accelerated testing of farm machinery, as well as other areas of machinery, throughout the world have not dramatically changed for the last 30-40 years. Currently the following types of accelerated testing of farm machinery are in use:

1. Accelerated testing with a continuous flow of farm products through the machine.

2. Accelerated testing of tillage working parts in an abrasive medium.

3. Field testing with special organization (moving machinery being tested through different climatic zones, working 24 hours per day, reducing time for repair, etc.).

4. Accelerated stress testing of farm machinery with the use of universal test equipment and proving grounds.

5. Combined testing which consists of combinations of the above.

1. Accelerated testing with a continuous flow of farm products through the machine

After the requisite amount of field testing has been completed in order to evaluate the machines working quality, the basic working parts of farm machinery such as mixers, fertilizer spreaders, manure applicators, loaders, feed distributors, sprayers, dusters, pumps, coolers, milk pasteurizers, and other products can be rapidly tested with the simple simulation of field conditions. The simulation is effected by passing through the machine, under test conditions, a continuous flow of the actual technological product (material) or of a product which is similar in its physical and mechanical properties. An uninterrupted flow is maintained by connecting a number of machines together, e.g. feed distributor and conveyors.

A variation of this method is to use a closed-cycle test rig, with the rig playing the role of the conveyor mechanism by maintaining a continuous supply of process material to the machine.

Accelerated testing of both tillage and planting machines is carried out by combining the operation of the machines under farm conditions with simulation of the trials on the testing grounds. In all these variations of accelerated testing, the machines can be run for a longer period than the normal farming season, and by using a two-shift system for the simulation tests the working parts and other parts of the machine that would require three years testing under normal field conditions can be reduced to the equivalent of a one-year load. These testing-ground trials are simple and inexpensive as ordinary traction equipment can be used, and there are no special installations involved. Furthermore, since less time is taken up in servicing the machines, hourly output can be increased by 30 - 40%. However, the negative aspects of the above techniques are:

- it is only possible to test separate parts of farm machines, such as working parts or the conveyors;

- there is also no simulation of vibration, or of the influences of environmental factors, and there are numbers of other aspects for which it is impossible to test for accurate simulation of real life input influences;

• their combinations and simultaneous actions cannot be simulated.

Finally, under current conditions it is not possible to test for accurate reliability evaluation and prediction.

2. Accelerated testing of tillage working parts in abrasive media.

Accelerated testing of tillage attachments can be carried out either on circular testing rigs or on testing-grounds where an abrasive medium is available. The rate of wear on parts such as ploughshares and hoe blades depends on the composition of the abrasive medium. Experience has shown that, on sandy testing-grounds, the rate at which attachments for tillage machines are tested can be increased roughly fourfold.

3. Field testing with special organization (moving tested machine through different climatic zones, working 24 hours per day, reducing the time for repair, etc.)

The moving of machines could be from southern zones, where the agricultural season begins early, through central zones to northern zones, where the agricultural season begins later.

Another asset of this type of testing is that the same testers are given the opportunity to observe the performance of the machine on different varieties of crops in different soils and climatic conditions.

The effectiveness of the above method also depends on how large on area of the country is involved. When the country is not very small and the system is well organized, not only can the machine be tested in areas with different soils and climates, but it also can accomplish two or more standard years work in a single year and thus yield highly reliable performance indexes.

4. Accelerated stress testing with use of universal and specific test equipment and proving grounds (used for automotive, off-highway, and other industries too).

This method is used extensively for tractors and farm machinery as well as automobiles on concrete and other tracks. Normally a number of tracks are laid down in one particular section of the proving ground which is equipped with a drainage system.

The procedure for testing using the above conditions is based on the principle of a substantial increase in the frequency with which maximum working loads are imposed. For accelerated environmental stress testing, increasing temperature, humidity, and/or air pressure, etc. makes sense.

Accelerated testing of tractors, tanks, auto, farm machinery and other mobile products is carried out on specially equipped proving grounds designated for:

• accelerated testing of wheeled machine frames by running them, under various conditions, along a race-track set with obstacles;

- investigation of the coupling properties of wheeled machines, tool-carriers and wheeled truck tractors on a concrete track;

- testing of tractors, agricultural machines, and others in abrasive media (in bath).

To improve working conditions and make more rational use of testing time and a higher level of testing conditions, one can use an automatic system of control. Usually the above system includes the following basic components:

- a component (system) for driving a machine automatically along the ground on the proving track and operating its attachments;

- a system of remote control over the units operating schedule;

- a system for prevention of damage.

Accelerated stress testing can also be used on the laboratory equipment[6] (universal and specific). There are different types of vibration equipment, dynamometers, test chambers, etc.

When these techniques are used for the accelerated testing of tractor and harvester engines, the permissible limits of wear on such components as cylinder and piston or con rod and crank assemblies can be rapidly determined. The wear on the engine parts is accelerated by artificially increasing the dust content of the intake air and by introducing solid particles into the crank-case oils.

The substantiation of the testing regimen is similar to that described in[6] step-by-step accelerated testing, beginning with the analysis of field input influences on the actual product which must be simulated in the laboratory, but the specifics of stress testing need special techniques which will be described later using the example of tractors.

5. Accelerated testing with accurate physical simulation of real life input influences on the actual product

This type of accelerated testing is more successful for farm machinery, as well as for other areas of industry. A basic specific result of this type of testing is accurate simulation of a real life combination of input influences on the product. The advantage of this approach is that it helps to rapidly find the reasons for degradation and failures of products, and so to eliminate them.

One can use these test results for rapid and accurate evaluation and prediction of product quality and reliability, as well as for successful and rapid solution of other quality and reliability problems at a reduced cost. The strategy, basic principles, step-by-step technology, as well as use of accelerated vibration and corrosion testing, and substitution of artificial media for natural technological media for this type of accelerated testing were described in[4]. All of this is useful for farm machinery testing. Specific techniques and equipment for this will be described later.

7 SPECIFIC ACCELERATED RELIABILITY TESTING TECHNOLOGY

7.1 INTRODUCTION

Reliability testing is the cornerstone of a reliability engineering program. It provides the most detailed form of reliability data, because the conditions under which the data are collected can be carefully controlled and monitored. Furthermore, reliability testing can be designed to uncover particular suspected failure modes and other problems.

The basic goal of accelerated reliability testing (ART) technology is to describe how one can obtain rapid, objective and accurate initial information about the virtual (factual) values of quality, reliability, maintainability, availability, and other measurements for product evaluation and prediction, in comparison with technical requirements. The basic desirable results of ART are the reduction in time and cost of product development, rapid finding of reasons for product degradation and failures, rapid elimination of these reasons, and, therefore, a rapid increase in product quality, reliability, durability.

The importance of ART technology as a component of customer satisfaction and product differentiation throughout all industries cannot be overstated.

ART is fundamental to a product's success for all customers, industrial, and service companies, as well as academia and military equipment suppliers.

The customer expects a product that functions according to its specifications indefinitely, at no extra cost, especially for maintenance and repair.

The company that develops a reputation for poor quality and reliability pays a heavy penalty in the marketplace. The cost of repair or replacement for failed products, post delivery, can make the difference between profit and loss. Therefore, it is critical that the tools of quality and reliability engineering be available to, and used by, all members of an organization which has a role to play in any part of the product's life cycle.

They do this because they do not want to lose their market share, but this problem can be solved in a much cheaper way if the companies concerned use accelerated reliability testing.

Unfortunately, professionals frequently want to use ART, but in practice this cannot be done[5, 6, 7, 8]. Some understand this, others do not, but everybody involved in design, evaluation, prediction, quality development and improvement processes particularly wants to accomplish this. How can this situation be improved?

First, one must analyze and understand the current actual situation regarding the development of ART and the reasons why frequently one cannot put ART into practice.

Why not in practice? Because theoretically there are many approaches to ART usage, but they cannot be used practically. Often some authors do not differentiate between AT (accelerated testing) and ART which are completely different processes (see 7.3).

Other authors have written books on reliability, but the testing chapters are called "Accelerated Testing" or "Experimentation and Testing" without the word "reliability", because they do not recommend how it should be done in practice. Therefore, many authors have written books about reliability evaluation, failures and reliability analysis and studies, models and data analysis for steps of varying stress, accelerated degradation, analysis of failures distributions (Weibull, Exponential, Normal, etc.), etc., but not in relation to ART.

How can one practically analyze the above without obtaining accurate initial information in these matters?

From a practical viewpoint, it is only possible after prolonged field testing. However, field testing is too expensive and not very effective for accelerated evaluation and improvement of the product.

It is very important that the testing problem solving is closely connected with reliability, maintainability, durability, availability (RADM), etc. problem solving, especially prediction, because not every type of testing allows for accurate RADM prediction.

In order to improve the above situation, below will be described the complex approach for the development of ART which consists of the following basic integrated components:

1. Improvement of the strategy of accurate physical simulation of the field input influences on the actual product (see Chapter 1);

2. Analysis of the influences of climate on reliability (see Chapter 1);

3. Improvement of the techniques for accurate physical simulation of the field input influences on actual product (see Chapter 1);

4. Improvement of appropriate equipment for ART (see Chapter 2);

5. Improvement of ART performance as a specific area of accelerated testing (se Chapter 2);

6. Improvement of the techniques for accurate prediction of reliability, durability, and maintainability on the basis of ART results (see Chapter 3);

7. Accurate establishment of the cost effectiveness of ART as the sum of the phases of design, manufacture, and use (Chapters 2 and 4).

7.2 ANALYSIS OF DIFFERENT APPROACHES TO ACCELERATED RELIABILITY TESTING

Many people, including professionals in the reliability area, think that testing is always a useful action.

They think that accelerated reliability testing (ART) is especially useful because it offers initial information for reliability evaluation, prediction, development, improvement, etc. But in real life ART is often not useful in practice. The following analysis explain this situation.

The use of different accelerated reliability testing (ART) approaches for reliability problem solving can be shown in the following three categories[9]:

1. useful;
2. minimally useful or useless;
3. harmful.

To understand the situation better, one has to analyze the real field input influences (Figure 1.2) which act simultaneously and in combination. But practically one uses mostly separate simulation of different input influences (Figure 2.1) for ART and other types of accelerated testing. The below example shows this for environmental testing. We can show similar examples for mechanical, electrical, and other groups of testing. This situation has an influence on the level of testing usefulness.

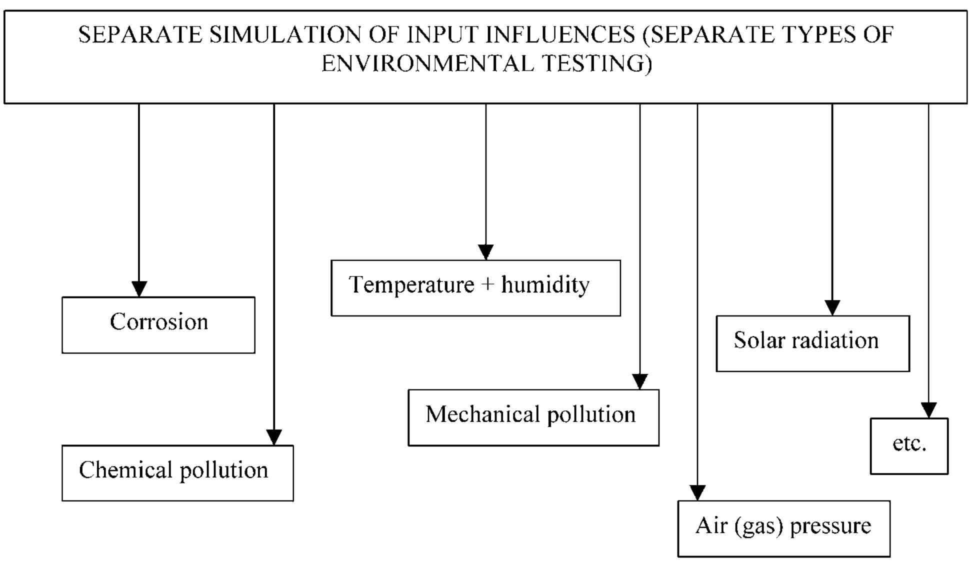

Figure 2.1 Example of current types of environmental testing.

ART is useful when methods and equipment offer the practical possibility for accelerated evaluation and prediction of product reliability and quality with a high level of accuracy.

Accuracy implies the conditions or quality of being correct and exact. The level of accuracy of test results depends on the accuracy of the simulation of the real life influences (temperature, humidity, pollution, radiation, road features, input voltage, etc.) on the test subject.

Accuracy of simulation is the situation in which output variables (loading, tensions, output voltage, amplitude and frequency of vibration, corrosion, etc.) in the laboratory are different from those under field conditions by no more than a given (upper) limit of divergence. As a result, degradation and failures during ART are correlated to those in the field, and accelerated prediction, development and improvement of reliability and quality are obtained with minimum time and cost.

Currently used methods and equipment for ART are seldom useful, because they do not correspond to the desired accuracy.

The basic problems with implementing "classical" ALT relate to the second and sometimes the third groups.

Accelerated reliability testing is minimally useful or useless if:

- one simulates high stresses instead of real life input influences. For example, establishment in the test chamber of temperatures from −100 °C to +150 °C that change the physics of degradation process for many types of test subject in comparison with the physics of degradation process in the field, etc. This does not offer accurate simulation of real life;

- one simulates independently one or a part of full field input influences. Therefore, separate accelerated laboratory testing is provided, or testing with a combination of only a portion of the above influences (temperature, humidity, vibration, corrosion, braking, electrical, etc.) which affect reliability, without connection and interaction with each other. This contradicts real life where all (or most) of input influences act simultaneously and in interactions with each other;

- one uses separate steps or several steps of full ART technology;

- one does not take into account the influence of the operator's reliability on the test subject reliability;

- the above testing results will most likely be incorrect (see[10,11], and other), because of a low correlation (or no correlation) of the accelerated testing results with field results as combined environmental issues are not addressed, and/or not all of the field environmental issues are adequately addressed;

- as a result of the above, the practical methods and equipment of ART offer the minimum possible benefits for reliability evaluation and prediction; longer time is needed for product development and improvement with greater expenditures than planned earlier, because after testing one does not know exactly the reasons for degradation and failures in the field. This is one of the basic reasons why one can often see the constant rapid modernization of design and manufacturing technology and slow modernization of reliability testing techniques and equipment. Therefore, often there are practical combinations of a high level of modernized design and manufacturing technology with testing which is similar to that used 30 - 40 and more years ago. As a result, a high level of reliability evaluation, analysis, and prediction techniques does not offer the expected results, because initial information (practical test results) does not correspond to the required level, and is plagued by problems of reliability, maintainability, and availability (RAM) performance.

Reliability testing is harmful when in addition to the above:

- it shows incorrect reasons for degradation and failures;
- changes in the design and manufacturing process for product improvement do not increase reliability and quality;
- moreover, more time and cost are needed for this work.

The additional basic reasons for the above situation are:

- poorly qualified professionals who are involved in ART;
- following incorrect directions in establishing conditions for ART;
- not enough literature and courses available for increasing a professional's knowledge in implementing the practical approaches to effective ART technology.

The basic negative results in the last two groups of using practical ART are found by users where often the predicted quality and reliability, cost and time of maintenance, etc. are different from reality. But manufacturing companies also have losses, because they do not effectively improve this situation for better market competitiveness. In this case, cost increases may not have beneficial results.

How can one eliminate the above situation? The basic goals of the text above and below are the principles and descriptions of useful theoretical approaches and practical tools for solving this problem.

Useful accelerated reliability testing (UART) of the actual test subject enables measurement of reliability indexes (times of failures, time between failures, etc.) correlated to the field reliability indexes within the duration of field testing. This makes possible the direct evaluation and prediction of field reliability and maintainability during service life. UART makes it possible to rapidly increase reliability and improve the robustness of a product. This type of testing requires accurate physical simulation of the whole complex of field input influences leading to degradation and failures of the product. As a result, the problems of accelerated development and improvement of product reliability and maintainability have been successfully solved.

The above type of ART is practically very seldom implemented, because usually one cannot simulate the simultaneous combination of real life input influences with high accuracy.

One of the basic problems is also the cost of accelerated testing, especially accelerated reliability testing (ART). Often we read and hear that ART is very expensive. This occurs when the professionals consider ART as a goal, but not as resources for obtaining initial information for accurate evaluation and prediction of product reliability, for accelerated improvement and development of product reliability. Therefore, one usually takes into account only the cost of the design process, but if one also takes into account manufacturing and usage processes cost, especially the cost of maintenance, the conclusion about the cost of ART will be different and it will not appear to be as expensive. This is especially important in the military area.

Many publications and standards in accelerated testing (often as part of a reliability assurance program, especially in applied statistics) describe the strategy for analyzing AT data and other problems on the basis of information obtained after AT and using single testing equipment. Of course, these results also will be different from the actual field situation. The standards usually reflect only past achievement, therefore they cannot also point the way for improvement of the current situation in ART.

As a result of poor strategies for testing and reliability, often in the field the reliability and maintainability of equipment, especially for the military area, are several times lower than predicted during the design and manufacturing phases.

Thus, conclusions from the above analysis of reliability testing are:

1. There are practical situations in which different testing approaches cannot be used for practical improvement of product reliability and maintainability. They are minimally useful or useless, or harmful, because money is spent without any increase in product quality and reliability.

2. The proposed approach can help to increase the level of testing of systems reliability, maintainability, and availability (RAM), especially for the military, which is more interested in increasing RAM and decreasing the total cost of ownership including three phases: design, manufacture, and utility.

3. This also helps to increase the warranty period, and to predict the RAM performance of the systems more accurately.

Use of the above approach requires teams that consist of professionals who have knowledge not only of testing and evaluation technology, but also of the technology of product use, economics, applied statistics and other areas of mathematics, reliability, fatigue, physics, chemistry, etc.

7. 3 BASIC CONCEPTS OF USEFUL ACCELERATED RELIABILITY TESTING

The basic principles of ART can be seen from the following definitions:

- Accelerated testing (AT) is testing in which the deterioration of the test subject is accelerated to a degree that is more than expected in normal actual service.

- Accelerated Reliability Testing (ART) (of the actual test subject) enables measurement of reliability indices (times of failures, time between failures, etc.) correlated to field reliability indices within a field testing duration. The above correlation has a wide range, from low to high.

- *Useful (accurate) accelerated reliability testing* (UART) is testing which provides a high level of correlation between ART results (degradation, failures, etc.) and field results.

So, as we can see from these definitions, the basic principle of UART is high correlation of ART results with field results. This requires more responsibilities and makes ART more complicated, because it needs more accurate simulation of field situations in the laboratory.

As mentioned earlier, UART can offer the following benefits for rapid solutions for: finding of the components that limit the product's quality, reliability, warranty period, etc.; finding the reasons for limitation of the above; elimination of these reasons; improvement and development of product quality and reliability, and, as a result, a longer warranty period and lower cost of usage; reduction of time and cost of product development and improvement; reduction of the time to market of a new product; a more competitive position in the market; accurate prediction and decrease of cost of maintenance; solving many other problems of product economics, quality, reliability, durability, etc.

But currently no one achieved more than 10 - 15% of the above possible benefits, because practically they do not provide UART.

On the other hand, the complexity of UART needs more deep though by the manufacturers and users of test equipment. Moreover, usually management, especially top managers, think that investment in UART during the design and manufacture processes seldom give the necessary profit. Often we read in the literature and guidelines that "testing is expensive and time-consuming", especially UART, because it needs expensive equipment, complicated techniques, high level professionals in different areas of sciences (physics, electronics, mechanics, chemistry, mathematics, etc.), information for accurate prediction during the life-time, and much though, but does not guarantee high reliability and quality of the product during required life-time.

There are two basic reasons for this situation:

- the current level of ART is not sufficiently developed to overcome the above obstacles;

- top managers are not sure that investment in the development of ART will give enough technical and economical benefits.

Life-cycle costs (LCC) consist of all costs associated with design, manufacture, and usage.

The results of analysis [1],[8,12,13,] show, that usually life cycle costs consist of the design phase 8 - 11% (including concept 1 - 2%), the manufacturing phase 18 - 30%, and usage phase 59 -

- 74%.

If we add dramatically increasing the warranty period and, as a result, the corresponding improvement in the market situation (increase in product sales), the economic situation of the companies that develop and use ART in their areas of industry will be going up.

Figure 2.2[12] shows how a company loss its profit through poor reliability of a product.

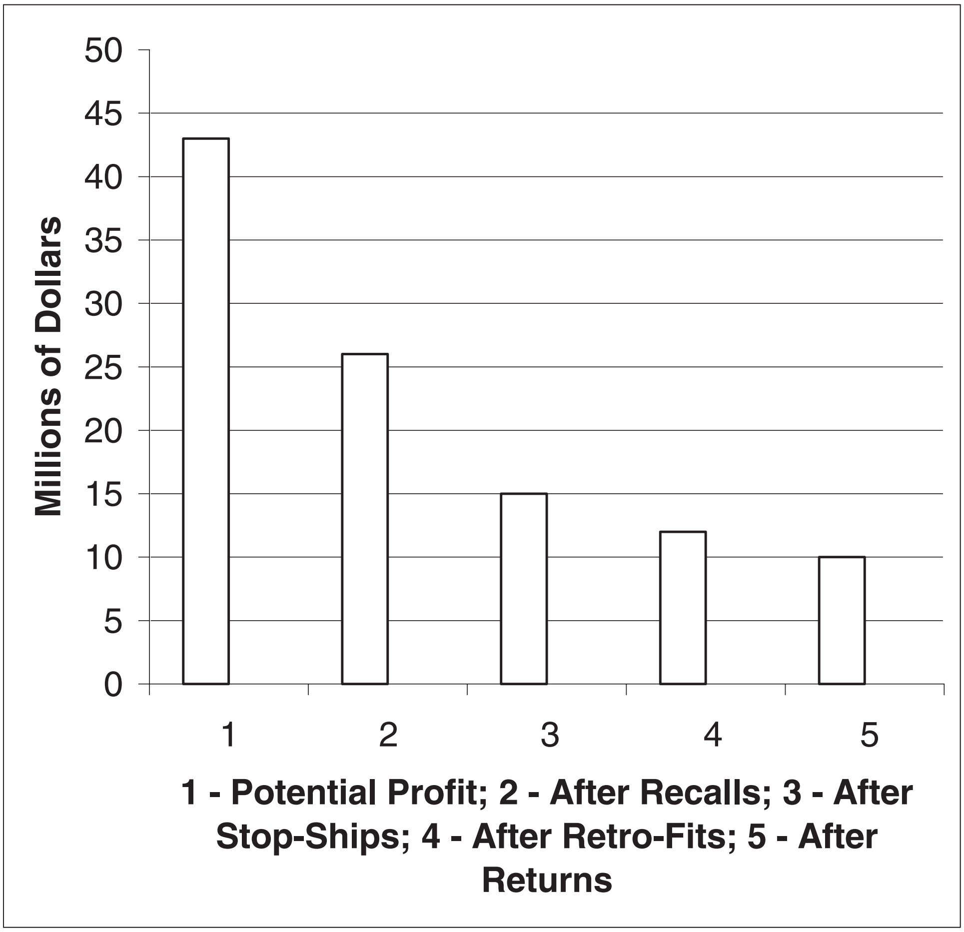

Figure 2.2 Effect of poor reliability on company profits[12].

The basic proposed UART concepts consist of the seven basic components mentioned in section 7.1:

1.Improvement of the strategy of the accurate physical simulation of the field input influences on the actual product. The improved strategy consists of using:

- Corrected basic concepts (see 2.1);

- Obtaining and analysis of all field input and output conditions which affect product reliability, as their range, character, speed, limit and distribution will increase the accuracy of initial information from the field;

- Accuracy of simulation. This means:

  - • One must simulate not only stresses, but also the maximum range of field conditions;

  - • Simulation of the complete range of field schedules and maintenance/repair;

  - • Consideration of the cumulative reactions of the product on the input influences.

- Degradation (failure) mechanism of the product as a basic criterion for an accurate simulation of field input influences;

- A methodology for selecting representative input regions (from the multitude of input influences) for accurate simulation of the field conditions. This leads to the possibility of determining one field region that is a typical system characteristic of a wide variety of field influences. This methodology is described by four basic steps: 1) selection of a process and its characterization, 2) length of representative region, 3) comparing values between regions of the oscillogram, and 4) choice of the representative region.

2. Analysis of the climatic influences on reliability

The following short description of analysis helps to correct the aforementioned deficiencies, because it helps to take into account how and what influences of different climatic zones must be simulated for ART:

- The climate characteristics as external conditions of machinery use;

- The classifications and characteristics of world climate for understanding how they influence the product degradation, for accurate simulation for ART;

- The characteristics of thermal regimes, radiation regimes, air humidity and rains, wind speed, fog and dew, atmospheric phenomena, characteristics of environmental factors in combination, biological factors, influences of solar radiation, fluctuations and rapid changes, characteristics of complex influences of basic climatic factors, and other.

3. Improvement of the technique for accurate physical simulation of the field input influences on the actual product:

- Techniques of accurate simulation in the laboratory of each real life input influence;
- Techniques of simultaneous combination of a selection of the numerous above influences which take place in the field (Figure 1.2) which are necessary for each product;
- The system of control for physical simulation of the random input influences;
- Techniques for providing special field testing in addition to the accelerated laboratory testing;
- Testing which takes into account the connections and interactions of the product components;
- Accurate substitution of artificial media for natural technological media.

The combination of the above improvements forms a new direction in the improvement of physical simulation of field input influences as a basis for providing successful ART.

This new direction consists of two basic steps:

1. Introduction to the description and development of physical simulation;
2. The strategy for creating accurate simulation which allows for obtaining UART results with sufficient correlation with field results.

4. Improvement of appropriate equipment for UART

As was mentioned earlier, testing equipment on the current market is not suitable for UART, because it does not correspond to the above needs of improved testing techniques.

Therefore, it is of prime importance that present equipment must be developed for this goal. For example, if one mechanically combines all present testing equipment only for accelerated environmental testing [humidity, temperature, chemical and mechanical pollution, all three parts of radiation (ultraviolet, infrared, and visible), air and gas pressure, wind, snow, rain, etc.], one also needs to design as well to consider overall cost problems which, of course, is quite expensive.

This particular system applies only to multi-environmental accelerated testing which is a component of UART.

So, how about entire UART which is more complicated?

It seems this direction is not effective, and we must look for an alternative: not a mechanical combination of current equipment only, but the development of new, less expensive equipment with more functional possibilities.

An example of how this direction has developed can be shown in new equipment for combined vibration testing. The authors and their colleagues have created models for this new vibration equipment which is based on theoretical and experimental research results. The new vibration equipment has unique features such as working heads which provide assigned random values for the acceleration amplitude and frequency. Vibration can be provided for both mobile and stationary products, and delivered by the universal vibration equipment as well as equipment designed for special products. The design is simpler than much modern electrodynamic and electrohydraulic equipment, with no deterioration of performance, and it also extends the functional applications to a wider range of markets. To this equipment it is easy to add other elements (such as transmission, engine, or other auto accessories) for simulation of simultaneous influences of vibration, braking, and other types of testing. The equipment has the following possibilities:

a) the ability to simulate different physical-mechanical qualities of roads which cannot be done with the current vibration testing equipment;

b) it can simulate torsion swing in the simultaneous combination of linear and angular vibration, that cannot be provided by current equipment;

c) it can make the connection between vibration testing and dynamometer testing.

5. Improvement of accelerated reliability testing performance as a specific area of accelerated testing

This includes:

- Entire technology of step-by-step accelerated reliability testing (see section 8);

- Providing accelerated laboratory testing technology as a simultaneous combination of multiple environmental (including corrosion testing), mechanical (including vibration testing), electrical and other components of UART;

- Providing a combination of the above accelerated laboratory testing and special field testing (see section 7.4).

6. Improvement of the techniques for accurate prediction of reliability, durability, and maintainability on the basis of UART results

UART is not the goal, but is the source for obtaining initial information for the accurate prediction of reliability, maintainability, availability, their improvement, etc. This improvement consists of:

- Development of techniques for product reliability prediction on the basis of UART results;

- Performance of prediction of system reliability from UART results of the components;

- Durability prediction taking into account expenses of time, costs, and losses;
- Basic principles of maintenance prediction (time between maintenance intervals, their volume, and cost).

7. *Accurate establishment of the cost effectiveness of UART as the sum of the stages of design, manufacture, and use*

The process of UART development is going very slowly. The basic reason for this is not only the fault of the company producers' test equipment, but also that of the company users. Combined test equipment is more complicated, therefore more expensive, and company users want to save money by purchasing simpler and cheaper test equipment. This, however, is wrong. It leads directly to lower quality testing, incorrect evaluation and prediction of the product's reliability, and, as a result, requires more time and raises the cost of improvement and development during manufacture and use. Especially this leads to higher maintenance cost (often several times more than predicted).

But UART offers the possibility to reduce the time and cost of product development, and saves money, especially in the manufacture and usage stages, but most companies do not understand this.

In[12] was written that: "Many reliability efforts fail because they are not justified financially. When faced with a large investment years before a product is launched it is difficult to convince financial management that this investment will produce the required level of return. The financial justification for reliability efforts is much easier when all system costs are considered rather than focusing on warranty costs".

So, the life-cycle cost consists of all costs associated with the design, manufacture, and usage. Therefore, for greater accuracy in establishing how UART is cost effective, one must develop the methods of taking into account the cost of complaints, increasing the warranty period, adjusting the time and cost of maintenance, etc. And, more important, to include these methods in the standards, and use them in practice. This is the effective way for rapid implementation of UART in practice.

7.4 RELIABILITY (DEPENDABILITY) AND LIFE CYCLE COSTING

As was mentioned earlier, life cycle costing consists of many contributory elements and often means a process of economic analysis to assess the cumulative cost of a product over its life cycle. This costing is the process of economic analysis to assess the total cost of acquisition, ownership, and disposal of a product[14]. It can be applied to the whole life cycle of a product or to parts or combinations of different life cycle phases.

Acquisition costs are generally visible, and can be readily evaluated before the acquisition decision is made and may or may not include installation cost.

The ownership costs, which are often a major component of lifecycle cost (LCC), in many cases exceed acquisition costs and are not readily visible. These costs are difficult to predict and may also include the cost associated with installation. Disposal costs may represent a significant proportion of total LCC. Legislation may require activities during the disposal phase that for major projects, e.g. nuclear power stations, involve significant expenditure.

An important objective in the preparation of LCC models is to identify costs that may have a major impact on the LCC or may be of special interest for that particular application. Equally important is to identify costs that may only influence the LCC to a very small extent.

The more common types of decisions to which the life cycle costing process provides input can include, for example[14]:

- evaluation and comparison of alternative design approaches and disposal option technologies;
- assessment of economic viability of project/products;
- identification of cost contributors and cost effective improvements;
- evaluation and comparison of alternative strategies for product use, operation, test, inspection, maintenance, etc.;
- evaluation and comparison of different approaches for replacement, rehabilitation/life extension or retirement of aging facilities;
- allocation of available funds between the completing priorities for product development/ improvement;
- assessment of product assurance criteria through verification tests and their trade-off;
- long-term financial planning.

There are six major life cycle phases of a product[14]:

- concept and definition;
- design and development;
- manufacturing;
- installation;
- operation and maintenance;
- disposal.

The appropriate life cycle phases, or parts, or combinations of these phases, should be selected to suit the special needs of each specific analysis. In general terms, the total costs incurred during the above phases can also be divided into acquisition cost, ownership cost, and disposal cost.

The LCC concept includes general elements, and a breakdown into cost elements. As far as general elements are concerned, an LCC model as with any other model, is a simplified representation of the real world. It extracts the salient features and aspects of the product and translates them into the cost estimating relationship. In order for the model to be realistic, it should:

- represent the characteristics of the product being analyzed (intended use environment, maintenance concept, operating and maintenance support scenarios, and any constraints or limitations);

- be comprehensive in order to include and highlight all factors that are relevant to LCC;

- be simple enough to be easily understood and allow for its timely use in decision making, and future update and modification;

- be designed in such a way as to allow for the evaluation of specific elements of the LCC independent from other elements.

LCC modeling includes:

- cost breakdown structure;

- product/work breakdown structure;

- selection of cost categories;

- selection of cost elements;

- estimation of costs;

- presentation of results.

Sometimes it may also include environmental and safety aspects, uncertainties and risks, and sensitivity analysis to identify cost drivers.

In order to estimate the total LCC, it is necessary to break down the total LCC into its constituent cost components. These components are individually identified so that they can be distinctly defined and estimated. Identification of these components and their corresponding scope depends on the purpose and scope of the LCC study.

Estimation of costs for use as the parameters of a cost component may be done by the:

- engineering cost method;

- analogous cost method;

- parametric cost method.

If one uses the engineering cost method, the cost attributes for the particular cost components are directly estimated by examining the product element by element, or part by part.

If one uses the analogous cost method, cost estimations are based on experience from a similar product or technology. Historical data, updated to reflect cost escalation, effects of technology advances, etc. are utilized. This method is easily applied to elements of the product for which there is some experience and actual data.

The parametric cost method uses parameters and variables to develop a cost estimating relationship. These relationships are usually in the form of equations where, for example, person hours are converted into costs.

LCC estimation includes the following steps[14]:

1. Obtain data for all the basic cost components in the LCC model for all product options, subsystems, and support option combinations;

2. Perform LCC analysis of product operating scenarios defined in the analysis plan;

3. Report analyses with a view to identifying optimum support scenarios;

4. Examine LCC model inputs and outputs to determine the cost components that have the most significant impact on the analyses.

5 Categorize and summarize LCC model outputs according to any logical groupings, for example, fixed or variable costs, recurring or non-recurring costs, acquisition, ownership or disposal costs, direct or indirect costs which may be relevant to users of the analysis results.

6 Conduct sensitivity analyses to examine the impact of assumptions and cost element uncertainties on LCC model results. Very important here are major cost contributors and assumptions related to product usage and to the time value of money.

7 Review LCC outputs against the objectives defined in the analysis plan to ensure that all goals have been fulfilled and that sufficient information has been provided to support the required decision. If the objectives have not been met, additional evaluations and/or modifications to the LCC model may be required.

7.5 USEFUL ACCELERATED RELIABILITY TESTING (UART) AS A COMBINATION OF ACCELERATED LABORATORY TESTING AND SPECIAL FIELD TESTING

Useful accelerated reliability testing gives the possibility of obtaining directly the data for evaluation and prediction of product reliability, and for rapid solution of different problems of product development and improvement. The methodology and equipment developed during the design process must be used then during the manufacturing process. Usually one cannot provide /UART/ only in the laboratory. There are some real life situations that cannot be simulated in the laboratory. Therefore, for UART one must combine laboratory testing with special field testing (Figure 2.3).

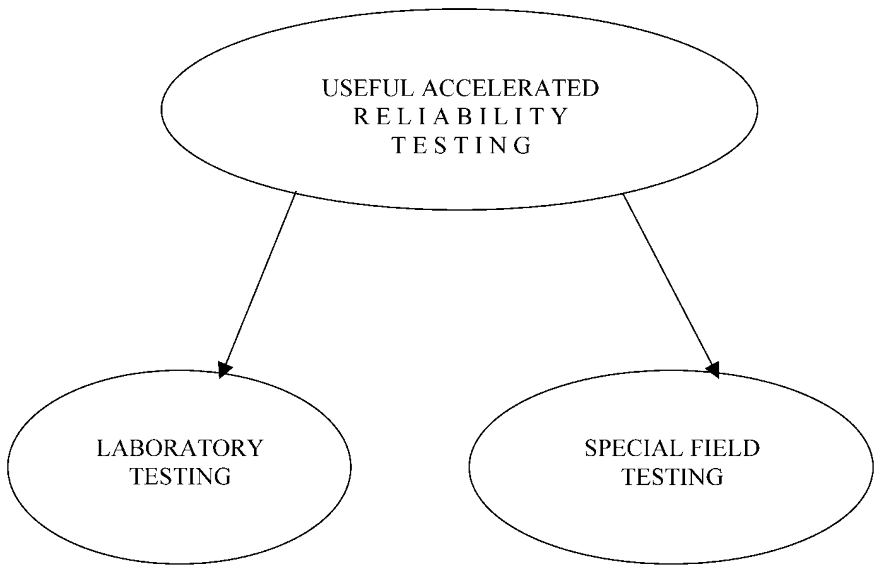

Figure 2. 3 Basic components of UART.

Figure 2. 4 shows an example of special field testing. This testing offers the possibility to evaluate the stability of product functions which may be dependent upon the level of product wear during laboratory testing.

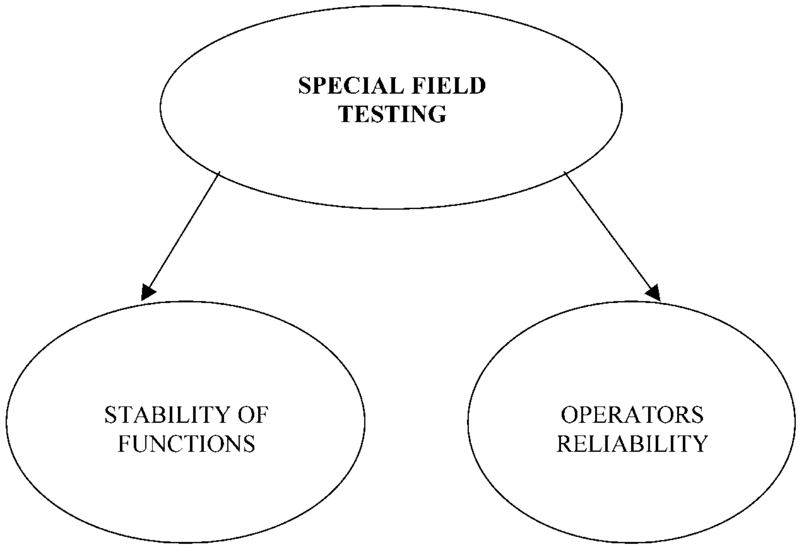

Figure 2. 4 Example of special field testing.

Adding to this complex problem is the operators (drivers) reliability as influenced by a variety of factors. An example for solving this problem is shown in Figure 2. 5, which demonstrates[15] that the operators reliability may be stipulated as a series of interactions of biomedical, social, and psychological factors. The system "operate-product-traffic" (OPT) especially is the usual method for reliability testing of a product as a completed system.

Ability, knowledge, skill, experience, and modes of activity play a major role in determining an operators reliability This function is further determined by sociologically obtained personal traits, character, and environmental factors, such as the peculiarities of the operators state of health.

It is obvious that the reliability of the OPT system depends on the operators health under acute pathological conditions (like sudden death, coma, acute pain, etc.). The percentage of such causes of accidents is, however, extremely insignificant. The more significant cause is reduced capacity for work resulting from disease. In a three-year analysis of 8,000 professional drivers it was found that complaints of being unwell had a great deal to do with a statistically reliable increase

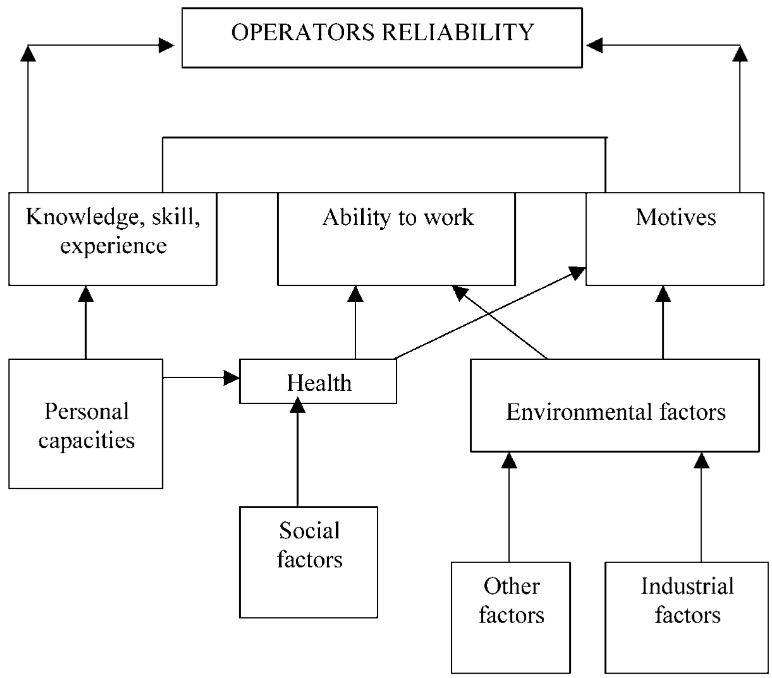

Figure 2. 5 The factors of operators reliability.

in the number of registered rule violations and accidents. For example, for drivers complaining of irritability, headache, disturbing dreams, and sleepiness, accidents were registered from 1.5 to 1.8 times more frequently as compared with drivers who did not have that kind of complaint.

If the rate of accidents involving drivers who have not fallen ill during the whole period of observation (less than three days) is set equal to "1", then for drivers who were ill 7 - 9 days a year this index goes up to 1.6 and for those who stayed away from work for 15 - 19 days it reached 2.6.

The influence of a certain disease on accident probability depends to a great extent on the diseases severity, its peculiarities, treatment, conditions and strain in the work situation, etc. For example, accident probability among professional urban drivers, suffering from hypertensive disease is 2.5 times higher than for healthy drivers. In the case of back pain, such as lumbago, it is almost 3 times higher, and for neuroses it is 7.4 times higher[7,15].

A series of methods are known to prevent and remove such conditions, including functional music, physical exercise, and stimulation of bioactive points. One method of fighting monotony is based on the moderate intermittent effect of touch on the driver's forehead skin. A portable device which has been tested under laboratory conditions showed the effect of non specific activation of the cerebral hemispheres on the agitation of the brains reticular structures when tested in field conditions. The 65.2% of drivers who were subjected to monotony or falling asleep while driving gave a positive assessment, 21.7% did not feel any effect and 13% found it difficult to answer[15].

The results of research show that many aspects of an operator's reliability can be studied in the laboratory. For example, let us look at the National Advanced Driving Simulator (NADS) at the

University of Iowa[16] NADS is the world's most sophisticated research driving simulator which offers easy experimental setup, product integration and data collection. It is a large motion base, capable of physically moving 64 feet in two directions, and providing users with true, realistic motion experience, whether accelerating, turning or braking. Its computer image generation system features 15 LCD projectors that provide a 360-degree horizontal field of view and incorporates a database of driving scenes spanning more than 2,500 square miles of terrain.

Four vehicle cab types are available for use, as well as multiple secure participant briefing rooms and medically equipped facilities for medical studies. It can also work with researchers on many aspects of research planning, development, execution, and analysis efforts.

This highly realistic driving simulator provides a powerful tool for the evaluation of driver behavior in a wide range of complex situations that would otherwise be difficult, costly and often unsafe to obtain under actual roadway driving conditions. Representative traffic scenarios can be examined safety with experimental repeatability and configurability, and comprehensive data collection capability.

The level of fidelity allows researchers to implement virtually any experiment that they would consider in a real vehicle on any roadway. It can also help to investigate the driver-vehicle-traffic environment system with an eye to improving products and highway designs, and reducing the causes of crashes – in addition to reducing fatalities. Tables 2. 1 and 2. 2 show the specification of two units of NADS.

Table 2. 1 Design specifications of the NADS Visual Subsystem[16].

Element	Performance
Polygons (at 60 Hz)	>15,000
Total pixels	> 5 M
Transport delay	≤ 50 ms (at 60 Hz)
Contrast ratio	25:1
Luminance	5 fl
Field of view	360 deg H x 40 deg V
With high resolution inset	28 deg H x 7 deg V
Forward inset – high resolution	ArcMin/Line Pair
Forward and side area resolution	7.0 ArcMin/Line Pair
Rear area and rear-view mirror resolution	15.0 ArcMin/Line Pair

Table 2. 2 Design specifications of the NADS motion subsystem[16].

Elements	Performance
X – Y Platform	
Displacement	± 32 ft
Velocity	± 20 ft
Acceleration	± 20 ft/s^2
Motion Base	
Z (heave)	± 20 ft
Z (velocity)	± 5 ft/s
Z (acceleration)	± 25 ft/s^2
Pitch	± 25 deg
Pitch rate	± 45 deg/s
Roll	± 25 deg
Roll rate	± 45 deg/s
Yaw (turntable)	± 330 deg
Yaw rate	± 69 deg/s
Pitch, roll, yaw accelerations	± 120 deg/s^2
High frequency vibration displacement	± 0.2 in
High frequency envelope	3 Hz – 20 Hz
High frequency vibration acceleration	± 1000 lbf
Noise (multi-axis)	< 0.02 g rms

The NADS can help to study the following aspects of driver reliability:

- Driver reaction to tread separation scenarios.

A study was conducted in collaboration with the Vehicle Research and Test Center for the National Highway Traffic Safety Administration (USA) to conduct an investigation of the response of non-expert drivers and resulting vehicle motions, to simulated tire failures under various scenarios (e.g. vehicle under steer gradient). The objectives were to evaluate how vehicle under steer gradient, prior knowledge of an impending tire failure, receipt of instructions on how to respond to a tire failure, driver age, and failed tire location affected drivers' responses and the likelihood of control loss following simulated tread separation on one of the rear tires during simulated traveling at high speed.

- The influence of alcohol on driver performance and behavior.

The NADS concentrated on impairment associated with various levels of BAC ranging from 0.02% to as high as 10%, various environmental conditions and roadway situations, and a host of in-vehicle tasks.

- Driver distraction relating to wireless voice communications devices.

The first study investigated how different wireless phone interfaces – such as hand-on (manual) dialing, headset with voice dialing, and hands-free with voice dialing – affect driving behavior under different levels of driving demand. A second study investigated how distraction caused by wireless phone usage varies based on the actual content, length, and intensity of the phone call.

- Driver-assisting in vehicle technologies

The goal is to develop a NADS driving simulation environment within which various driver-assisting in-vehicle technologies can be effectively tested, comparing driver performance with and without the assertive technologies. The use of high-identity driver simulation is proposed to ensure maximum driver immersion without the risks associated with the driving situations necessary to exhibit the potential benefits of the driver-assisting technologies.

- Crash avoidance metrics partnership.

This measured last-second braking and steering of drivers in the NADS for comparison with test track data collected by the Collision Avoidance Metrics Partnership (CAMP).

- And various others.

Therefore, basic principles of practical accelerated reliability testing strategy consist of the following:

1. Simultaneous combination of simultaneous different groups of field influences (environmental, mechanical, electrical, etc.) on the actual product with less expensive equipment.

2. Providing each type of the above simulation as a complex simultaneous combination of different types of simulation. For example, the environmental testing of the products includes simultaneous combination of temperature, humidity, radiation, pollution, and other input influences.

3. Providing simulation of each type of input influences as a complex process that accurately simulates the field conditions. For example, pollution simulation is a complex process which accurately simulates chemical and mechanical field conditions.

The necessary combination of simulations for a specific product depends on the type of product and the conditions in which it is used.

7. 6 ACCELERATED LABORATORY TESTING TECHNOLOGY WHICH PROVIDES SIMULTANEOUS COMBINATION OF ENVIRONMENTAL, MECHANICAL, ELECTRICAL, AND OTHER TYPES OF TESTING

Most of this book (Chapter 1 and Chapter 2) describes accelerated laboratory testing. Figure 2. 6 shows an example of how we can combine four types of laboratory testing (environmental, mechanical, electrical, and corrosion in a simultaneous combination) for effective reliability problems solving. Of course, one has to ultimately combine all the different types of input influences. So, one is start by first combining two, then three steps, then proceed to all basic types of input influences for the product.

To implement this basic strategy, different types of testing equipment have been developed.

These are typically several times less expensive than equipment on the worldwide market[17,18,19,20]

Each of the above three types of testing in the Figure 2.6 is a complex of special type of testing. For example, mechanical testing consists of different types of testing that interact with each other (Figure 2.7). This combination of input influences act simultaneously and simulates real life. Of course, for each product one has to determine the necessary groups of testing.

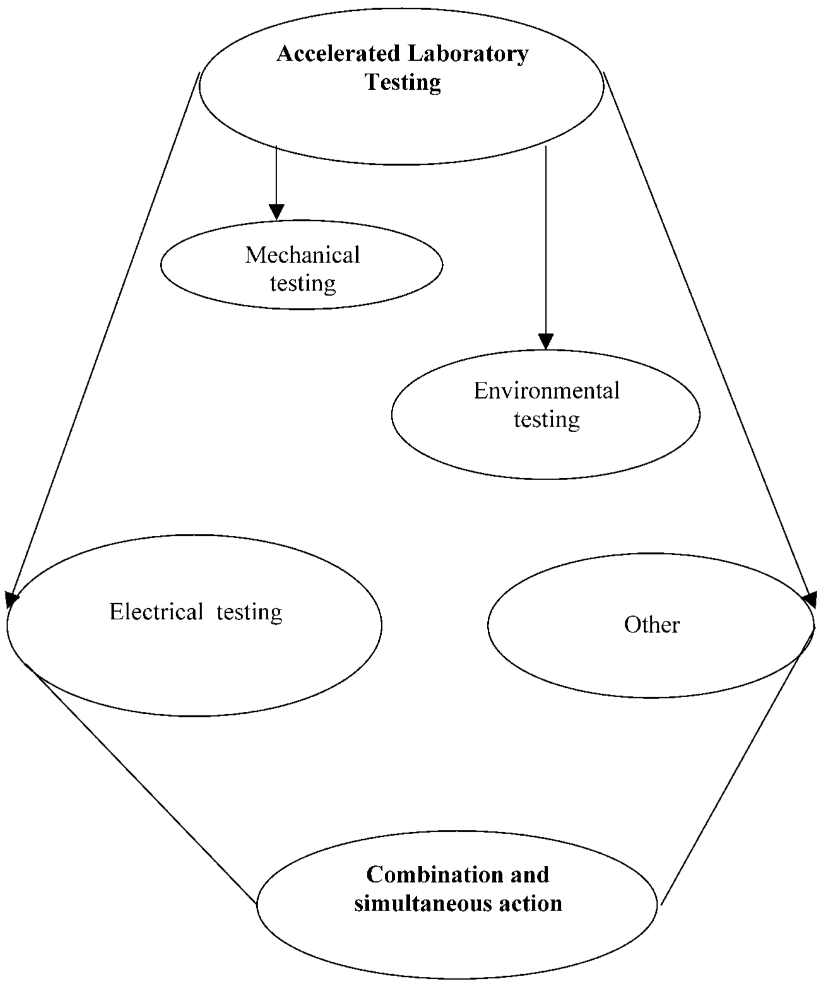

Figure 2. 6 Example of accelerated laboratory testing.

7.7 EQUIPMENT FOR ACCELERATED RELIABILITY TESTING

The strategy involved in equipment development is very important for implementation of the above methodology. We have seen recently in the market that more and more industrial companies that produce testing equipment go in the direction of simultaneous combination of complex input influences. First, we consider one from advanced company Weiss Technik (Germany), and look at the technical characteristics of one series of these types of equipment. Weiss Technik has subsidiaries in the United Kingdom (Weiss Technik Ltd.), in Japan (Weiss

Enet Industrietechnoek BV), Weiss Technik Italia S r l, Weiss Technik Belgium BVBA, and in the USA (Weiss Environmental Technology, Inc.).

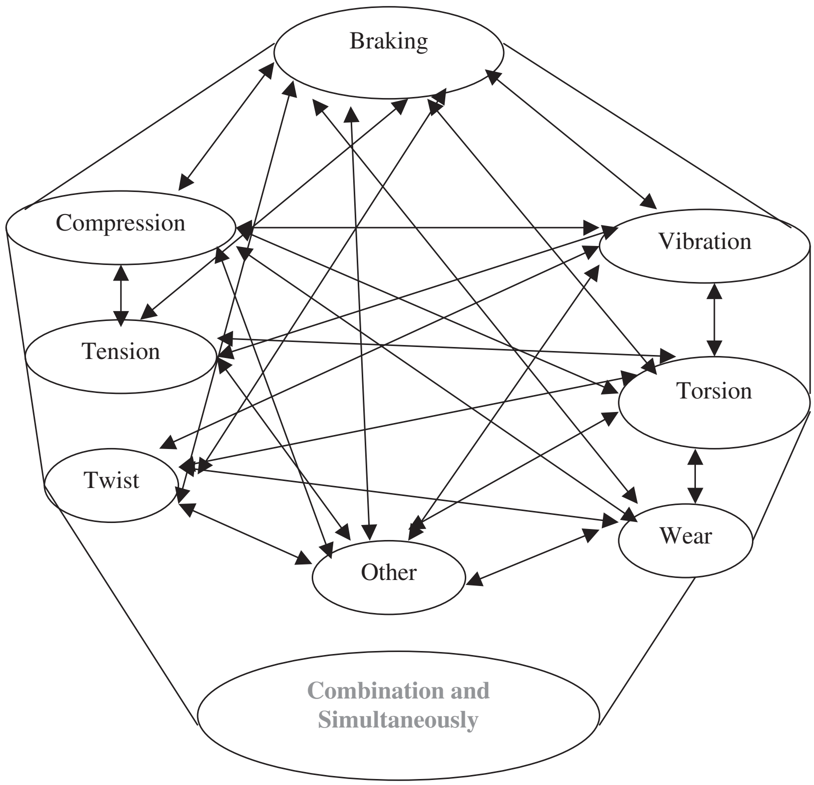

Figure 2. 7 Different types of mechanical testing.

Weiss Technik, especially after joining Atlas, has also test chambers for simultaneous effects of UV radiation, temperature, humidity, and (acid) rain, and their diurnal variations are decisive factors for the premature aging of polymer materials. There are also other test chambers that combine different test equipment; for example, climate test chambers with a road simulator and a solar (full spectrum sunlight) simulator.

So, the advanced companies are going step-by-step in the direction described in this book, towards simulation of simultaneous combinations of basic field input influences. Some test chamber data are shown in table 2.30.

Table 2. 3 Technical data from vibration test chambers[17].

Test space contents	Liters	600	600	1150	1150	2156
Test space dimensions	Height mm	950	950	950	950	1100
	Width mm	800	800	1100	1100	1400
	Depth mm	800	800	1100	1100	1400
Outside dimensions	Height mm	2150	2150	2150	2150	2300
	Width mm	1225	1225	1525	1525	1825
	Depth mm	2860	2860	3210	3210	3560
Chamber width (incl. touch)	mm	1500	1500	1800	1800	2100
Height (up to bottom side of test space floor) min/max	mm	660/1380	660/1380	660/ 1380	660/ 1380	660/ 1380
	mm	680	680	980	980	1280
Largest shaker port diameter	mm	600*600	600*600	900*900	900*900	1200* 1200
Largest slip-table port						
Performance for temperature tests						
Temperature range	°C	40…+180	-70…+180	-40+180	-70+180	-40… +180
Change rate as per IEC	Cooling K/min	5.5 5.0	5.0 5.0	5.5 5.5	4.5 5.5	6.5 6.0
Heat compensation	at +20°C W	5000	5000	5000	5000	5000
	at -20°C W	5000	5000	2000	5000	5000

Notes:

Temperature fluctuation	K		±0.1 to ±0.8 in time, ±0.5 to ±2.0 spatial				
Performance for climate tests			only WK/V				
Temperature range	°C		+10 … +95				
Dew point range	°C		+4 … +94				
Humidity range	% r. h.		10 … 95				
Humidity fluctuation	% r. h.		± 1 to 3 in time				
Temperature fluctuation	K		±0.1 to ± 0.3 in time, ±0.5 to ±1.0 spatial				
Heat compensation	W		500				
Calibration values			+23 °C/50% rh and +95 °C/50% r. h.				
Electrical connection			3/N/PE AC, 400 V ±10 %, 50 Hz				
Max. connected load	kW	11	16	23	26	26	34
Max. current consumption	A	19	29	33	38	38	50
Sound pressure level – 1 m from the front	dB(A)	68	71	75	76	76	77
Cooling water consumption max	m^3/h	2.2	2.7	3.3	3.8	4.1	6.6
Weight	kg	1000	1075	1450	1600	2100	2500

This company has produced a Cold-Heat Climate test chamber with a Road Simulator and Sunlight Simulation[21] which can be used for accelerated reliability testing. This equipment can be used for ART if includes for multiple component testing of complete vehicle bodies under realistic operational conditions in combination of vibration with the environmental influences of temperature, humidity, solar radiation. This combination includes:

Test space volume 480 m^3

Temperature range –40 … + 90 °C

Climate range +10 … +80 °C

Dewpoint temperature range: +5… +59 °C*

* limited by sunlight simulation.

The authors of this book solve the problem of simultaneous combination of different types of equipment for ART by another approach. This is based on the principle of reproducing the complete range of operating schedules and maintaining the ratio of high to small loads[22].

As a result, one hour of pure work performed by the test subject with a faithfully reproduced stress schedule is identical in its degradation effect to one hour of pure work under normal field testing.

One must simulate real life input influences and build the corresponding equipment in the laboratory in order to create less expensive test equipment with no loss of quality. As a result, the combination of many types of test equipment will also be much cheaper. Therefore, there is a practical possibility for accurate simulation of real life input influences with sufficient correlation of the physics of degradation mechanism during AT and field testing. As a result, initial information will be obtained for accurate prediction of the product reliability, durability, and fatigue. The ratio of failures (acceleration coefficient) for different subunits (details) varies from 10 to 18. It is simple to modernize this direction to obtain acceleration coefficients of 50 and more.

Therefore, this approach gives the possibility for accurate ART. But there are some problems:

1. Requirement of accurate simulation in the laboratory of the basic field input influences simultaneously and in combination;

2. Comparison of the degradation process of product during the field and laboratory testing.

For accelerated environmental testing this approach includes the simulation of simultaneous combinations of the following influences: humidity, temperature, pollution (salt spray + dust), radiation (ultraviolet + infrared + visible), air and gas pressure, wind with periodical rain, snow, and others.

Let us show how we can create test equipment several times less expensive than currently available. Examples of such vibration equipment are shown in Figures 2.8 and 2.9.

To obtain this goal we have developed computer controlled wheeled electromechanical vibration equipment[23]. This equipment is based on theoretical and experimental research results and is used for vibration testing of electronics, car trailers, trucks, farm machinery, or their components, etc. This equipment provides vibration of mobile products as a result of road influences, but does not simulate only the road profile as current vibration equipment does. This equipment for vibration testing is also 3 - 5 times less expensive than worldwide, and has more functional possibilities. It is very important that the equipment has possibilities for connecting with other types of testing (dynamometer and others). This will be shown in more detail later.

The authors and their colleagues developed new equipment for simulation of simultaneous combination of different influences for the engine accelerated testing (Figure 2.8).

Also developed was other inexpensive equipment for the simultaneous combination of salt spray and sun radiation chambers, different types of universal and specific equipment for different product testing, etc.

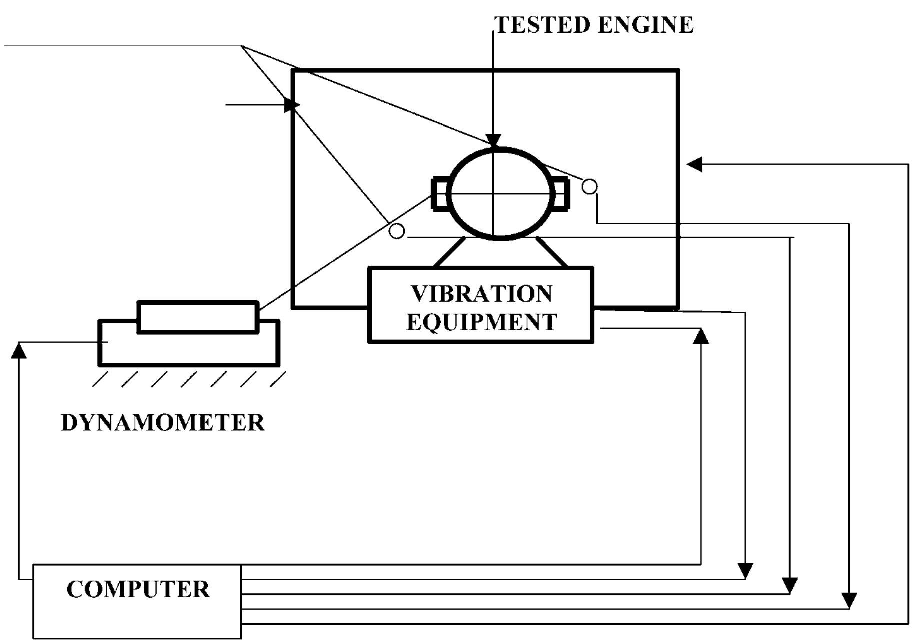

Figure 2. 8 The scheme of new equipment for engine combination testing.

Figure 2.9 shows a scheme of test equipment for fertilizer applicators which combine vibration equipment, equipment for technological process simulation, drive simulation, and equipment for mechanical and corrosion process simulation. All the equipment is computer controlled.

As a result of the use the above five steps of this strategy, there is sufficient correlation of the field results to the accelerated testing results[7,22].

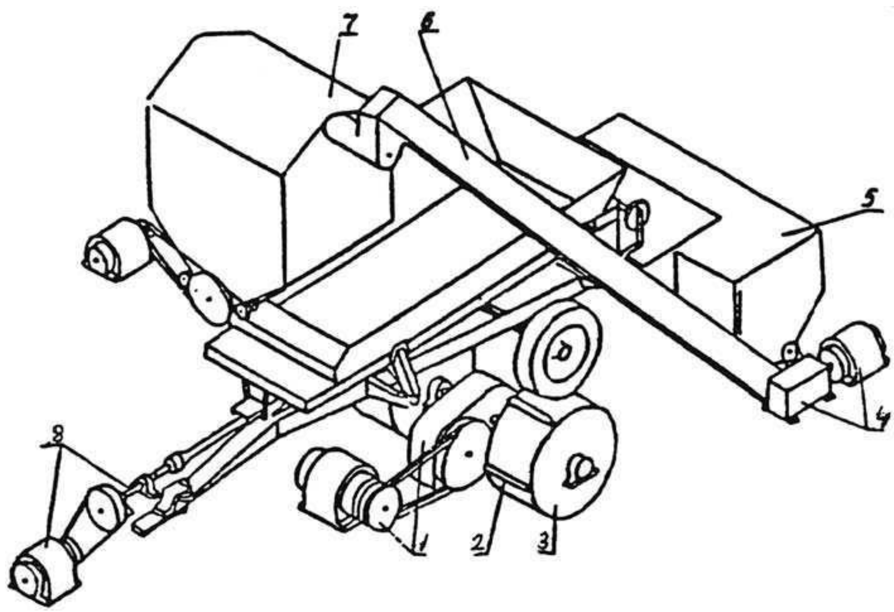

Figure 2. 9 Scheme of test equipment for fertilizer applicators: 1, 2, 3 is a simulation mechanism for vibration simulation, 4, 5, 6, 7 is a mechanism for technological process simulation of fertilizer application work; 8 is a simulation mechanism of drive.

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8 TECHNOLOGY OF STEP-BY-STEP USEFUL ACCELERATED RELIABILITY TESTING

Many industrial companies use separate steps, or several steps combined, but seldom full accelerated testing technology from the first to the last step. This is one of the basic reasons which these methods and equipment for AT often give low return benefits. The following UART technology can help to eliminate this problem.

It comprises the 11 basic steps that link with each other[11].

8.1 Step 1: COLLECTION OF THE INITIAL INFORMATION FROM THE FIELD

This step is very important, because it helps to convey the kind of input influences that act on the specific product in the field. To determine how they act, select the input influences that must be simulated in the laboratory for accurate UART. Without this knowledge one cannot substantiate accurate ART parameters and regimes.

For this goal it is necessary to obtain:

- input influences which affect product reliability, durability, maintainability, etc. (the range, character, speed, and limit of value changing, etc. of temperature, air pollution, humidity, full complex of radiation, input voltage, air pressure, features of the road, etc.) under various field conditions wherever the product is employed, as it acts in the field.

- input influences on the product in single steps and in simultaneous combinations including interaction, as they act in the field. An example is shown in Figure 2.10.

The basic meaning of this hierarchy is that the complete product as a test subject (system) in real life consists of N units (subsystems) that act in series with interactions. The subsystems (units) also consist of K subsubsystems (details/components) that also act in series with interactions.

Therefore, each subsystem and component in real life may act in series with interactions to all other subsystems and components of the complete product.

As a result, the system (complete product), its subsystems (units), and components (details) provide their functions and the system works. If one wants to simulate real life influences on the components accurately in the laboratory during AT, one must simulate accurately the full hierarchy of these connections and interactions, but usually AT does not take this into account.

Therefore, one cannot accurately simulate the field input influences, and AT results differ from real life results.

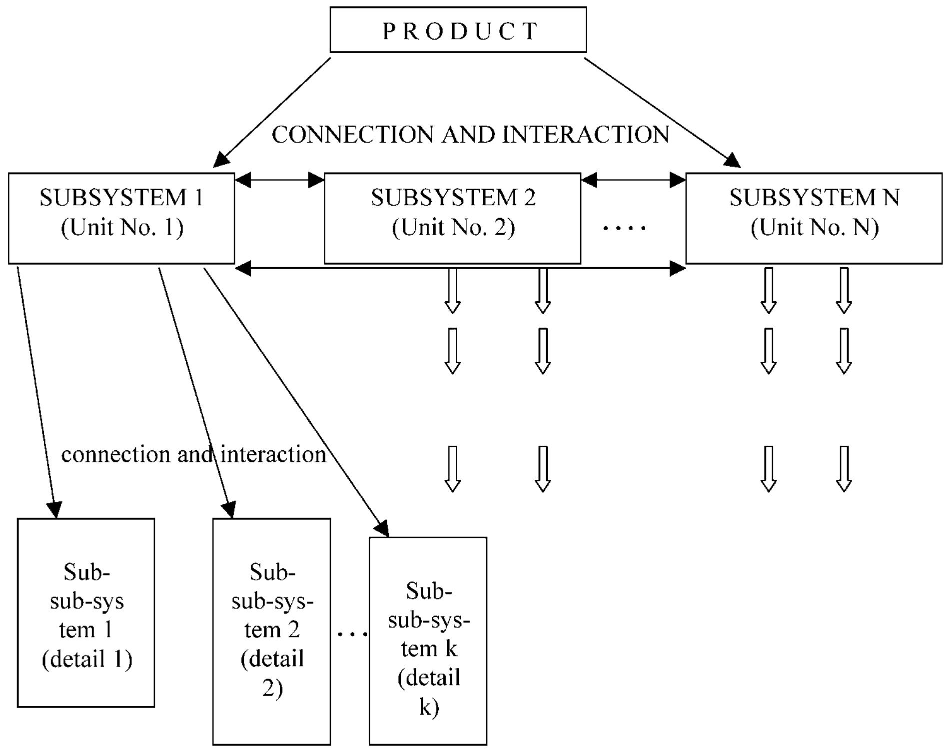


Figure 2.10 The full hierarchy of the complete product and its components as a test subject[1].

- output variables (vibration, corrosion, loading, tension, wear, resistance, output voltage, decrease of protection after deterioration, etc.) the range, character, speed, and limit of value changes under various field conditions including climatic areas (see section 2). With a new product these studies can be brief, using additional data from any prototypes. There will be variations depending on the facilities of the researchers, the goals of the research, conditions of experiments, the subject of the study, etc.

- mechanism of degradation of the components or test subject (parameters of degradation, value of parameters of degradation, dynamic and statistical characteristics of these parameters which change during the usage time, etc. (see section 1.3 in detail).

- input influences and output parameters, data collection and analysis. What types of input influences impact enough on the degradation and failure process. If we are certain that one or several influences does not impact the product degradation (failure) it can be eliminated from the following consideration, but we must know this exactly. This possibility was described in detail by Parker[2] for electronic equipment.

- the percentage of distribution of the test subject when working under different usage conditions. This is important , because most products are used in different conditions, with different loads, etc. These conditions depend on the changing values of each output parameter. Moreover, the results lead to the distributions that are needed for the programming and understanding the ART results.

An example of these distributions for fertilizer applicators is shown in Chapter 1 (Tables 1.1 and 1.2). If the fertilizer applicator is used in different climatic regions, this may also change the distributions.

- the scheme of the test subject as a system which consists of subsystems (units) and subsubsystems (details) with their connections and interactions (see Figure 2.10)

8.2 Step 2: ANALYSIS OF THE ABOVE INFORMATION AS A RANDOM PROCESS WITH AN EVALUATION OF THE STATISTICAL CHARACTERISTICS OF THE STUDIED PARAMETERS

Most of the field input influences and output parameters have a probability (random) character, because they change during usage and the character of this change is random[3].

Therefore, one has to evaluate as a basic minimum the mean, standard deviation, correlation (normalized correlation) or power spectrum, as well as the distribution of input influences and output parameters. Figure 2.11 shows an example of ensembles of experimental normalized correlation and power spectrums of tension data registered by sensor 1 for the car's frame point for different field or operating conditions. One can use probability distribution too for more detailed evaluation of the above processes.

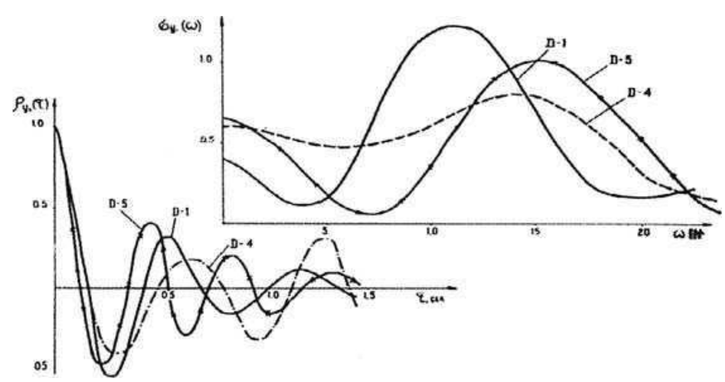


Figure 2.11 Ensembles of normalized correlation and power spectrum of frame tension data of the car's trailer.

8.3 Step 3: ESTABLISHING CONCEPTS AND STATISTICAL CRITERIA FOR THE PHYSICAL SIMULATION OF THE INPUT INFLUENCES ON THE PRODUCT SELECTED FOR USEFUL ACCELERATED RELIABILITY TESTING

The field input influences must be accurately simulated in the laboratory with a limit of stresses to give higher correlation between accelerated reliability testing results and field results, and for the accurate prediction of field reliability, durability, and maintainability after ART. In general, the most accurate physical simulation of the input influences processes occurs when each statistical characteristic $[\mu \; D \; \rho(\tau) \; S(\omega)]$ of all input influences differ from the field condition measurements by no more than 10%.

In specific situations one has to calculate and use the statistical criteria for this goal of comparing the reliability measured in an accelerated reliability testing to the field reliability (see section 1.2), but all these methods have an acceleration coefficient. The similarity of the degradation process in the field and in the laboratory will determine the practical limit of stress (acceleration coefficient) (Figure 2.12).

The first method of AT can be to decrease to a minimum the breaks between work time. This type of testing can be accelerated if the product is tested 24 hours a day, every day, and it does not include idle time, or time with minimum loading, etc. This method is based on the principle of reproducing the complete range of operating conditions and maintaining the proportion between heavy and light loads. The author's experience shows that this has the following basic advantages:

a) maximum correlation between field and laboratory testing results;

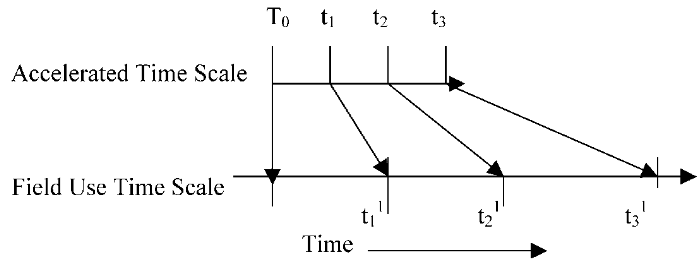
b) one hour of pure work performed by the product which faithfully reproduces its stress schedule is identical in its destructive effect to one hour of pure work under normal operating conditions;

c) there is no need to increase the pace of testing in terms of the size and proportion of stress in this method.

This is accelerated testing, because the result of testing in the laboratory is faster than in the field by more than 10 - 18 and more times. This method is especially useful for a product which works for short periods of a time.

Specialists who use this method know that reproducing a complete range of operating conditions is not so easy, but gives successful correlation accelerated testing results and field results.

- Test conditions consist of several parameters (temperature, humidity, vibration, radiation, and others).



$$\text{Acceleration Coefficient} = \frac{t_1^{I}}{t_1} = \frac{t_2^{I}}{t_2} = \frac{t_3^{I}}{t_3}$$

Figure 2.12 Accelerated coefficient describing.

If it is necessary faster and simpler to obtain the accelerated testing results, one can use the stress methods of accelerated testing. However, the correlation between laboratory test results and field results will be less. More stress means less correlation. Less correlation means less

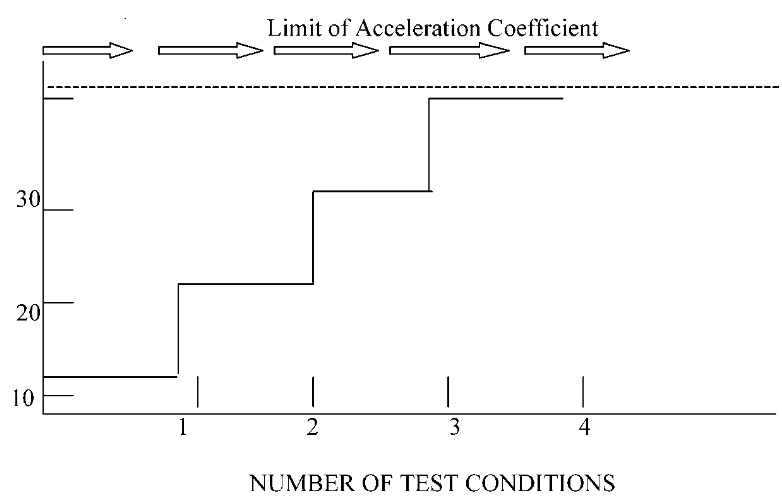


Figure 2.13 Example of stress limit (acceleration coefficient).

accuracy of simulation and greater problems with accurate evaluation and prediction of product reliability and durability in the field. Less correlation brings about more problems with finding the reasons for failures (degradation) and eliminating them as well.

Therefore, in the case of accelerated coefficients one must decide specifically for specific products which way will be more effective.

As shown above, acceptance of the method of how fully it is necessary to simulate real life input influences simultaneous combination and also depends on the testing goal. Therefore, if it is necessary to have independent simulation, for example, for vibration testing of the product, one must know that after this testing it isn't possible to evaluate accurately the reliability or durability of that product. The same is true of simulation of temperature testing. This is not environmental testing, because simulation of only one parameter out of the combination of possible field environmental influences is used on the product.

There is a third popular use of the basic AT method – accelerated stress testing which is often used for electronic product, aircraft, airspace[2,3,4]. It has a smaller acceleration coefficient than HALT, and is more practically substantiated, but also has a high acceleration coefficient (usually around 25 - 30). This method is often used, but without finding *directly* the initial information for reliability evaluation or prediction.

Acceleration (stress) factors are factors that accelerate the product degradation process in comparison with normal usage. There are many types of acceleration factors: higher concentration of chemical pollutions and gases; more air pressure; higher voltage; higher temperature, fog, and dew; a higher speed of change of input influences; shorter break time between work cycles, etc.

There is also a widely used AT method that employs simulation with only a minimum number of field combinations of input influences. For example, a temperature/humidity environmental chamber for environmental testing[5]. It is known that these are only some of the many environmental influences on the product.

These types of testing cannot give accurate information about the reliability of the product under accelerated testing actions given minimum correlation between accelerated testing results and field testing results.

One has to be careful with a high level range of acceleration, as well as a combination of the field influences and other aspects of AT or ART.

8.4 Step 4: DEVELOPMENT AND USE OF THE TEST EQUIPMENT WHICH SIMULATES THE FIELD INPUT INFLUENCES ON THE ACTUAL PRODUCT

This is a special design effect that is the result of the analysis of the combination of field input influences on the product ($X_1^1 \ldots X_M^1$) (Figure 1) and how they can be simulated in the lab.

There is also universal and specific test equipment. Universal test equipment can be used on many different types of products. Usually these types of test equipment are used in design and manufacturing by special companies. For example, all types of mobile product and parts of the stationary machinery in the field vibrate. Therefore, they need vibration testing and for this goal vibration equipment. The same is true for test chambers which simulate environmental influences, and combinations of environmental influences with other types of influences.

The level of test equipment is very important as it exerts an influence on the level of accelerated testing results. For example, in the market the company using the test equipment can buy single axis and multi-axis vibration test equipment (VTE). For mobile products single-axis VTE cannot simulate real life vibration. The modern solution in this area is multi-axis VTE.

Vibration input can be generated in up to three or six degrees of freedom. It is 1 - 3 linear (vertical, lateral, and longitudinal) and from 1 to 3 angular (rotational) (pitch, roll, and yaw).

This VTE provides random vibration as in real life. The user can control the motions of each actuator independently or in groups to determine the degree-of-freedom control.

Environmental accelerated testing (EAT) can also be used in different levels of real life environmental simulation. The temperature/humidity equipment is only a low level of environmental influence simulation in the laboratory. A higher level EAT simulates combined temperature, humidity, pollution, radiation, air, gas, or/and water pressure, etc. Equipment for measuring these influences of simulation can also be at different levels. For example, pollution simulation can be a mechanical (dust) simulation (low level) or a high level simulation using a combination of mechanical (dust) and chemical (chemical conditions of the environment) simulation. High level simulation provides more accurate simulation of field conditions.

Many varieties of the product (or group of similar products) have a specific design and need specific testing equipment for the simulation of field input influences in order to provide for the technological process of their use. For this simulation process one needs specific test equipment. Many industrial companies design, manufacture, and use their own specific test equipment. Both universal and specific equipment may be required to work as a simultaneous combination if one wants to obtain accurate initial information in the results of ART.

8.5 Step 5: DETERMINING THE NUMBER AND TYPES OF TEST PARAMETERS FOR ANALYSIS DURING USEFUL ACCELERATED RELIABILITY TESTING

The types of simulation methods depend on the specifics of product use and the limits of the facilities of the test company. One cannot simulate in the laboratory all the various operating conditions and their input influences.

The basic objective is to determine the minimal number and types of test parameters to enable comparison of the laboratory and field testing results which are sufficient for accurate reliability, durability, and maintainability prediction.

Therefore, it is necessary to establish the partial (basic) area of each influence which can be introduced into all varieties of operating conditions to set a minimum acceptable test conditions this is:

$$E > N,$$

where: E is the number of field input influences $X_1 \ldots X_a$ (Figure 1) ; N is the number of simulated input influences $X_1^1 \ldots X_b^1$ (Figure 1).

And allowable error simulation input influences $M_1(t)$:

$$M_1(t) = X_1(t) - X_1^1(t)$$

where: $X_1(t)$ are input influences of the field; $X_1^1(t)$ are simulated input influences.

The authors recommend the following approach for choosing the area of influences which introduce all basic varieties of the field:

1. Establish the type of studied random process. For example, the stationary process is determined by the dependence of the normalized correlation using the difference in variables only.

2. Establish the basic characteristics of this process. For a stationary random process we have the mean, standard deviation, normalized correlation, and power spectrum.

3. Define an area's ergodic, the possibility to make judgments about the process from one realization. This is when the correlation approaches zero if the time $\tau \to \infty$.

4. Check the hypothesis that the process is normal. Try the Pearson or other criteria.

5. Calculate the length of the influence area.

6. Select the size of divergence between basic characteristics of different areas.

7. Minimize the selected measure of divergence and find the area of influence which introduces all possibilities of the field.

If one cannot simulate the simultaneous complete combination of the field input influences, one cannot obtain results after laboratory testing that can be used as accurate initial information for reliability, fatigue, and durability problem solving.

The number and types of field input influences which have to be simulated in the laboratory depend on the result of the analysis of the action of the field influences on the product degradation (failure) mechanism, which shows how the influences are linked with the product degradation.

8.6 Step 6: SELECTING A REPRESENTATIVE INPUT REGION FOR USEFUL ACCELERATED RELIABILITY TESTING

The content of this step can be seen in section 2. 5.

8.7 Step 7: PROCEDURE FOR USEFUL ACCELERATED RELIABILITY TESTING

The preparation should consider the following:

- the schedule of the product's technological process including all areas and conditions of use (time of work, storage, maintenance, etc.) in each condition.
- sensor disposition.
- what kind of input influences and output variables occur under each field condition to be analyzed.
- the measurement regimes of speed, productivity, output rate, etc.
- typical measurements of conditions and regimes in the field, and their simulation by accelerated reliability testing, compared to the field.
- establishment of the value of testing.
- execution of the testing.
- the schedule for checking the testing regimes.
- obtaining test results and analyzing the data.

8.8 Step 8: USE OF STATISTICAL CRITERIA FOR COMPARISON OF ACCELERATED RELIABILITY TESTING RESULTS AND FIELD RESULTS

As it was shown above, the degradation mechanism is a criterion of comparison between the field results and accelerated testing results. For calculation of this comparison one need use the applied statistic comparing the desired reliability with the results. For this goal we will use the term "statistical criteria".

Use of these criteria can help one to decide whether to use one's current ART technique or whether it is necessary to develop this technique until the measure of the difference reliability function distribution in ART and in the field is no more than the fixed limit.

The statistical criteria that are shown below must be used on the two stages of testing:

- during ART for a comparison of the output variables or lab degradation process with the degradation process in the field;

- after ART for comparison of the reliability indexes (time to failure, failure intensity, etc.) with field reliability indexes. Addition information might be generated as this step by analysis of failed and not failed test subjects.

The difference between the field and laboratory testing results for both situations should be no more than a fixed limit. The limit for fixed parameter differences in the field and in the laboratory depends on the level of desired accuracy such as 3%, 5%, or 10% maximum difference.

One criterion was shown above. One can use also one or any of the following basic criteria for correlating results of ART with field testing:

$$[(C/N)_L - (C/N)_f] \leq \Delta_1$$

$$[(D/N)_L - (D/N)_f] \leq \Delta_2$$

$$[(V/N)_L - (V/N)_f] \leq \Delta_3$$

. . . .

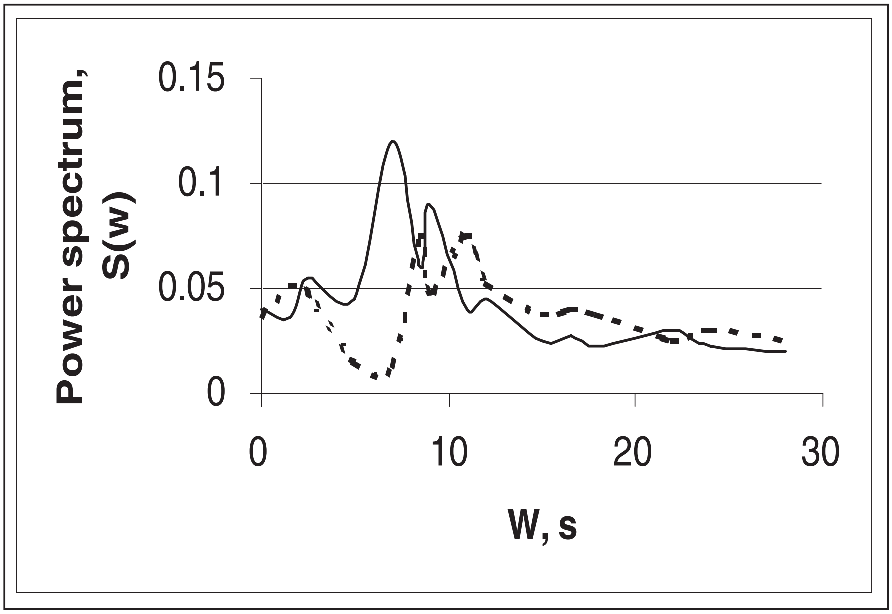
$$[(F/N)_L - (F/N)_f \leq \Delta_I$$

where:

$\Delta_1, \Delta_2, \Delta_3 \ldots \Delta_i$ are divergences calculated from the results of the laboratory and field testing;
L and *f* are laboratory and field conditions;
C, D, V and *F* – are measures of output parameters: corrosion I;
D is destruction of polymers, rubbers, wood, etc.;
V *is vibration or tension; etc., failures;*
N is the number of equivalent years (months, hours, cycles, etc.) of exposure in the field (*f*) or laboratory (*L*).

For example, Figure 2.14 shows normalized correlation data for $\rho(\tau)$ and power spectrum S(w) of a car's trailer frame tension data from the field and from simulation after using the above criteria.

The authors describe in Tables 2.4 and 2.5, and also the implementation of criteria for correlating results of machinery ART for the field and the laboratory[6,7]. The result of the implementation of these criteria for AT for a car's trailer is shown in the Table 2 and Table 3[8].



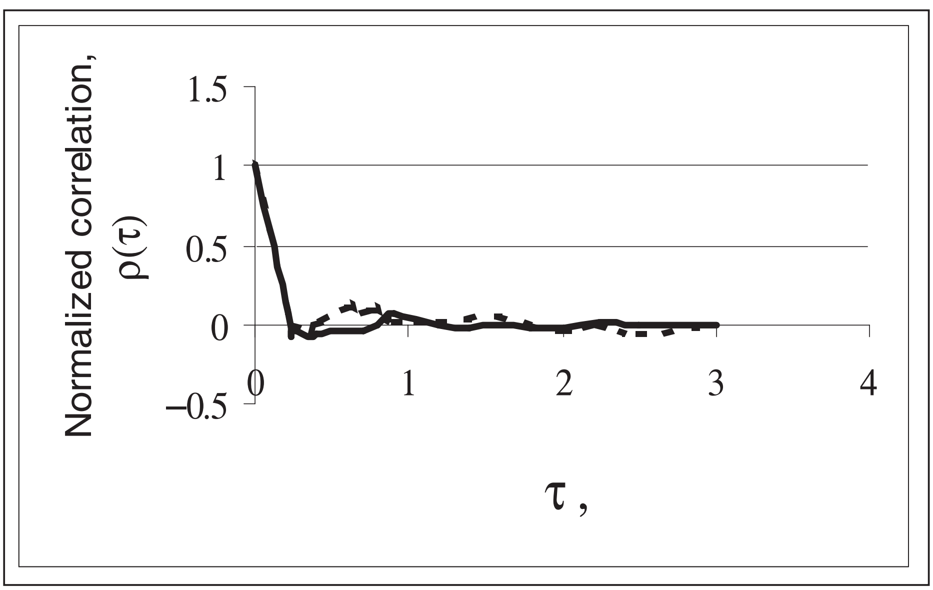


Figure 2. 14 Normalized correlation ρ(τ) and power spectrum S(w) of the car's trailer frame tension data: _______ field; ------------ accelerated testing (laboratory).

Let us show a simple example of how we can find this correlation. Figure 2.15 shows experimental distribution of tension amplitudes (frequencies) on the fertilizer applicator axle (sensor 1), the frame (sensor 2), and carrier system (tension 3) during fertilizer distribution in field conditions and in laboratory testing (Figure 2.15).

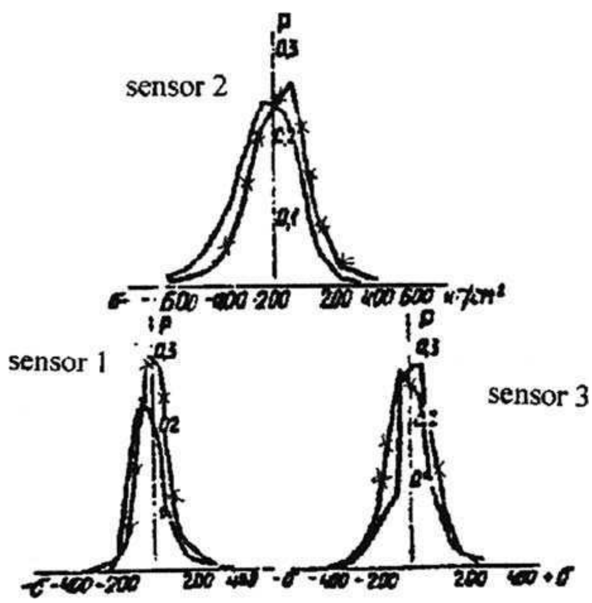


Figure 2.15 Distribution of fertilizer applicator tension amplitudes in the field and in the laboratory (-x- is the field, - is the laboratory).

The results of calculation based on sensor 1 are in Table 2. 4. These comparison data show very little deviation.

Table 2. 4 Results of the calculation of tensions on the wheel axles of the fertilizer applicator.

Class Number	Class frequency		Class accumulated frequency		Accumulated relative frequency		Modulus of congruence accumulated relative frequencies difference Max $\lvert D \rvert$
	N_i	N_j	ΣN_i	ΣN_j	$P_i = \frac{\Sigma N_i}{N_i}$;	$P_j = \frac{\Sigma N_j}{N_j}$	
1	10	16	10	16	0.020	0.040	0.020
2	18	10	28	26	0.070	0.065	0.05
3	20	14	48	40	0.121	0.100	0.021
4	32	32	80	72	0.202	0.180	0.022
5	39	50	119	122	0.303	0.305	0.002
6	84	68	203	190	0.512	0.476	0.037
7	68	72	271	262	0.680	0.655	0.025
8	49	63	320	325	0.808	0.812	0.004
9	30	36	350	361	0.884	0.900	0.016
10	24	16	374	377	0.994	0.940	0.004
11	10	12	394	389	0.969	0.971	0.002
12	12	11	396	400	1.000	1.000	0.000

Here: i is in the field and j is in the laboratory.

$$\lambda = \max|D| \cdot \sqrt{\frac{\Sigma N_i \cdot \Sigma N_j}{\Sigma I + N_j}}$$

If λ is less than 1.36, we can be accept the hypothesis about both samples being linked to one statistical population, i.e. the loading regimes in the field and in the laboratory are closely related to each other. Here $\lambda = 1.36$ is the tabled value of Smirnov's criterion at the 5% level.

Table 2.5 shows an example of using Student's distribution for evaluation of the mean. These results were obtained by sensor 2 in the field and in the laboratory.

In this example, the definition of average is equal to 1.4. Therefore, $1.4 < 1.8$, where: 1.8 is significant from the tables of Student's criterion at the 5% degrees of freedom level (information can be found in books on additional the theory of probability).

Therefore, our hypothesis is true for this example also.

The results of comparison random tension data in the field and in the laboratory are illustrated in Figure 2.16, which shows normalized correlation functions and power spectrums of the car trailer's frame tension data requested by sensor 1. The time of correlation is between 0.1 and 0.12, the time of attenuates is the same, the power spectrum maximum corresponds to frequencies of 8 – 12 s, and the interval of frequencies is substantially the same (from 0 to 16 – 18s). The power spectrum maxima have low velocity. Overall the regime of testing the carrier and running gear systems of the fertilizer applicator in the laboratory is closely related to the test regimes in the field. Also see Figure 2.41 in[5].

Table 2. 5 Part of assembly of fertilizer applicator's tension data.

Digit Number	Field N_i	Laboratory testing n_j	Difference $n_i - n_j$	Definition from average $[(n_i - n_j)\ x]$	Definition from average squared $[(n_i - n_j)\ x]^2$
1	1	1	0	-32.5	1056.25
2	5	4	-1	-33.5	1122.25
3	18	8	-10	-42.5	1808.25
4	20	25	-5	-27.5	756.25
5	121	66	-55	-87.5	7658.25
6	223	174	-49	-81.5	6642.25
7	270	201	-59	-101.5	10302.25
8	217	107	-110	-142.5	20302.25
9	105	40	-55	-97.5	9506.25
10	37	11	-26	-58.5	3422.25
11	13	4	-9	-41.5	1722.25
12	3	1	-2	-34.5	1190.25

$\sum_{ni} = 1033$ $\sum_{nj} = 642$ $\sum_{ni - nj} = 391$ $\sum_{[(ni - nj) - x]^2} = 65489.5$

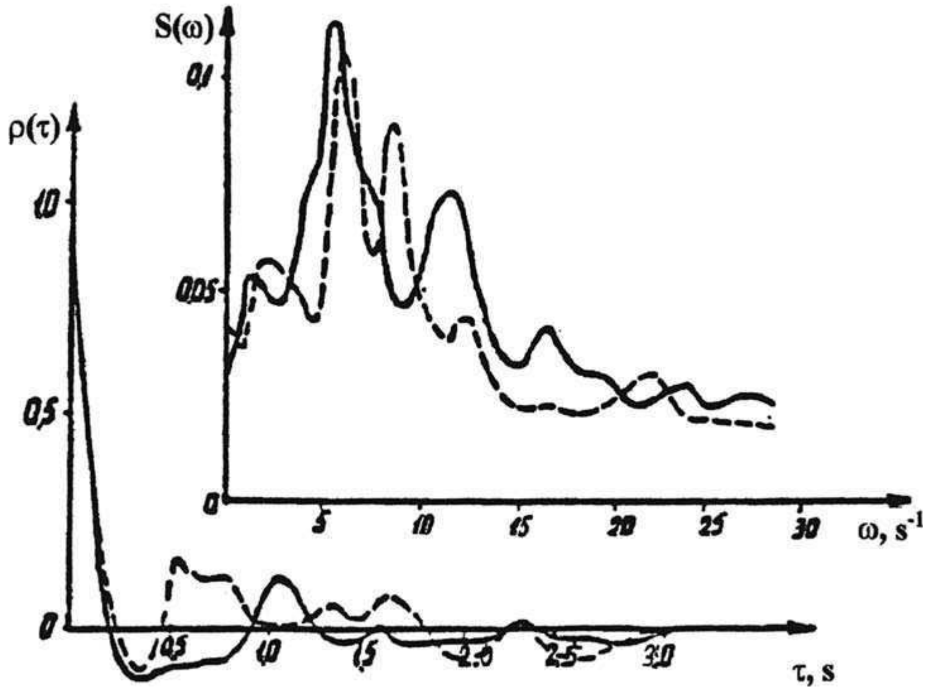


Figure 2.16. Normalized correlations ρ(τ) and power spectrum S(ω) of car trailer's frame tension data: _________ field; - - - - - - - - accelerated (laboratory) testing.

8.9 Step 9. COLLECTION, CALCULATION, AND STATISTICAL ANALYSIS OF USEFUL ACCELERATED RELIABILITY TESTING DATA

This step concerns test data collection during the test time, statistical analysis of this data based on the failure (degradation) type and test regimes, and the reasons for deterioration leading to the ultimate failure of the test subject, counting the accelerated coefficient, etc.

Figure 2.17 shows an example of accelerated loss of paint protection in the test chamber. One can easily find the acceleration coefficient, as is shown below.

The loss of protection quality of paint A (curve 1) for 5 days of ART is the same as for 90 days in he field, and the accelerated coefficient is 18.

Since the paint deterioration data show the importance of collecting and analyzing many data points, most ART are monitored by computer and data automatically collected, as this can then

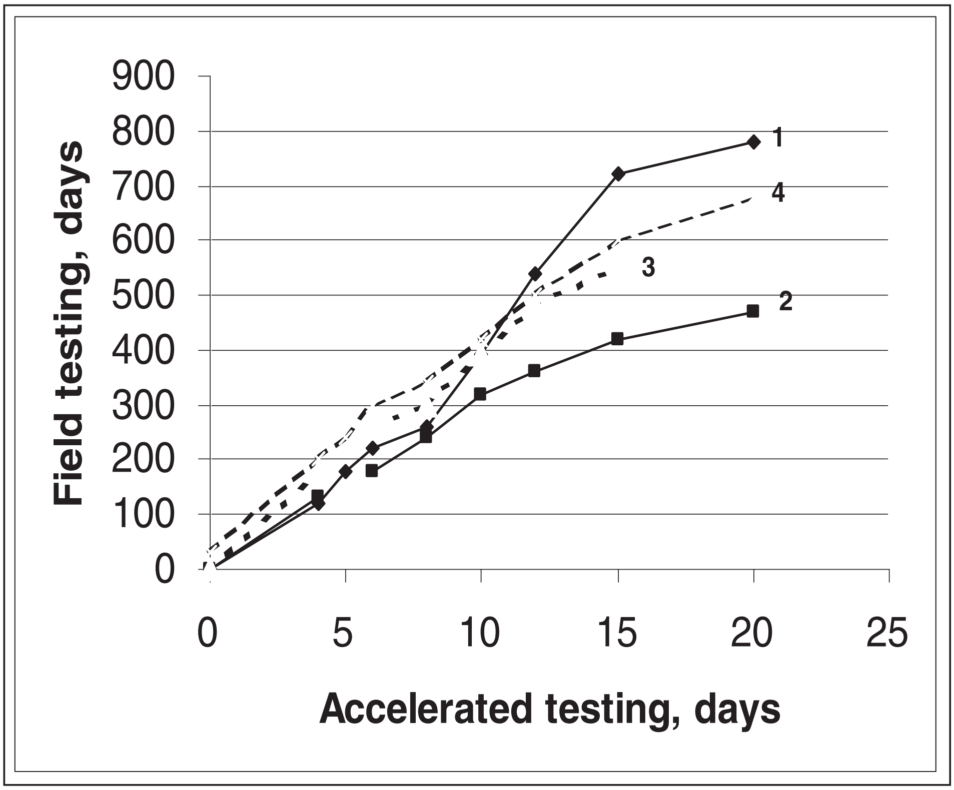


Figure 2.17 Accelerated destruction of paint protection in test chambers (two types of paint)[11]: first type of protection (paint A): 1 = protection quality; 2 = impact strength; 3 = bending strength; second type of protection (paint B): 4 – impact strength.

be easily set up. A second important function of the computer is to ensure the test conditions are maintained, or to monitor deviations from the desired conditions. The importance of this data collection step is discussed by Chan and Parker[2].

8.10 Step 10: EVALUATION AND PREDICTION OF THE DYNAMICS OF THE TEST SUBJECT'S RELIABILITY, DURABILITY, AND MAINTAINABILITY DURING ITS SERVICE LIFE

Accelerated reliability testing is not a goal, it is a source of initial information for quality, reliability, maintainability, and other problems solving. This initial information can be used for evaluation of the above problems in test conditions or prediction of these problems in field conditions. One can read in Chapter 3 how these can be predicted.

8.11 Step 11: USING ACCELERATED RELIABILITY TESTING RESULTS FOR RAPID AND COST-EFFECTIVE TEST SUBJECT DEVELOPMENT AND IMPROVEMENT

If the accelerated reliability testing results have sufficient correlation with the field results, it is UART, therefore, possible to rapidly find the reasons for test subject degradation and failure.

These reasons can be found by analyzing test subject degradation during time of usage, through the location of initial degradation and the development process of degradation. Then it is necessary rapidly to eliminate these reasons. This method is time and cost-effective. Figure 2.18 shows the process of accelerated reliability improvement.

If the above correlation is not close enough, the reasons for test subject degradation and the character of this degradation during accelerated reliability testing usually do not correspond to this degradation in the field. Therefore, the conclusion from accelerated reliability testing may be wrong and increase the cost and time of test subject improvement and development.

In this case, often the designers and reliability engineers think that they have understood the reason for failure (degradation), and change the design or manufacturing process. But after checking the "improvement" in the field they will know how wrong they are. Then they have to look for other reasons for degradation, etc. This process doesn't allow rapid improvement or development of test subject reliability (quality). Moreover, it only increases the cost and time of test subject development and improvement. This is a situation familiar in practice.

The following two examples illustrate the authors' approach to UART for rapid improvement of product quality. This concerned a problem with a harvester's reliability, which designers failed to eliminate from field data testing over several years. A laboratory complex was built that simulated the field input influences on the harvester.

For six months UART of the harvester[9]:

- two specimens of the harvesters were subjected to evaluation for the equivalent of 11 years in the field;

- three variations of one specimen unit and two variations of another unit were tested. The resulting information was satisfactory as a basis for an evaluation equivalent to their service life (8 years).

Elimination of the rapid degradation process was done as follows:

- the design of the harvesters was changed according to the conclusions and recommendations drawn from the test results;

- the specimens incorporating the design changes were then field tested;

- this reduced (3.2 times) the cost and the time (2.4 times) of the harvester's development.

In the field, a reliability increase of 2.1 times was validated. Also confirmation was obtained for the basic components of the harvesters that limited their reliability. Usually this volume of work needs a minimum of two years to compare, So the above improvement was four times faster.

The second example concerned a problem with the reliability of important belts. For several years, beginning with the design stage and continuing through the manufacturing stage, the low reliability of belts limited the reliability of the whole machine. Designers increased the strength of the belt, but couldn't increase reliability by more than 7% for several years. In that time the cost of the belts increased twice. The authors created special test equipment for accurate simulation of the belt field influences. After several months of testing (studying) the reason for the low belt reliability was found, and the designers were given recommendations for improving the machinery design (the reasons for the belt failures was not in the belts, but in the rolls). The field test results showed that the durability of the belt on the updated machine was increased 2.2 times. The cost of this work increased the machine's cost by 1% which included the cost of the test equipment and all the work involved in finding the reasons and thereby increasing the belts' reliability.

If we do not have accurate initial information which generating the results of UART, even the best methods of reliability prediction cannot be useful.

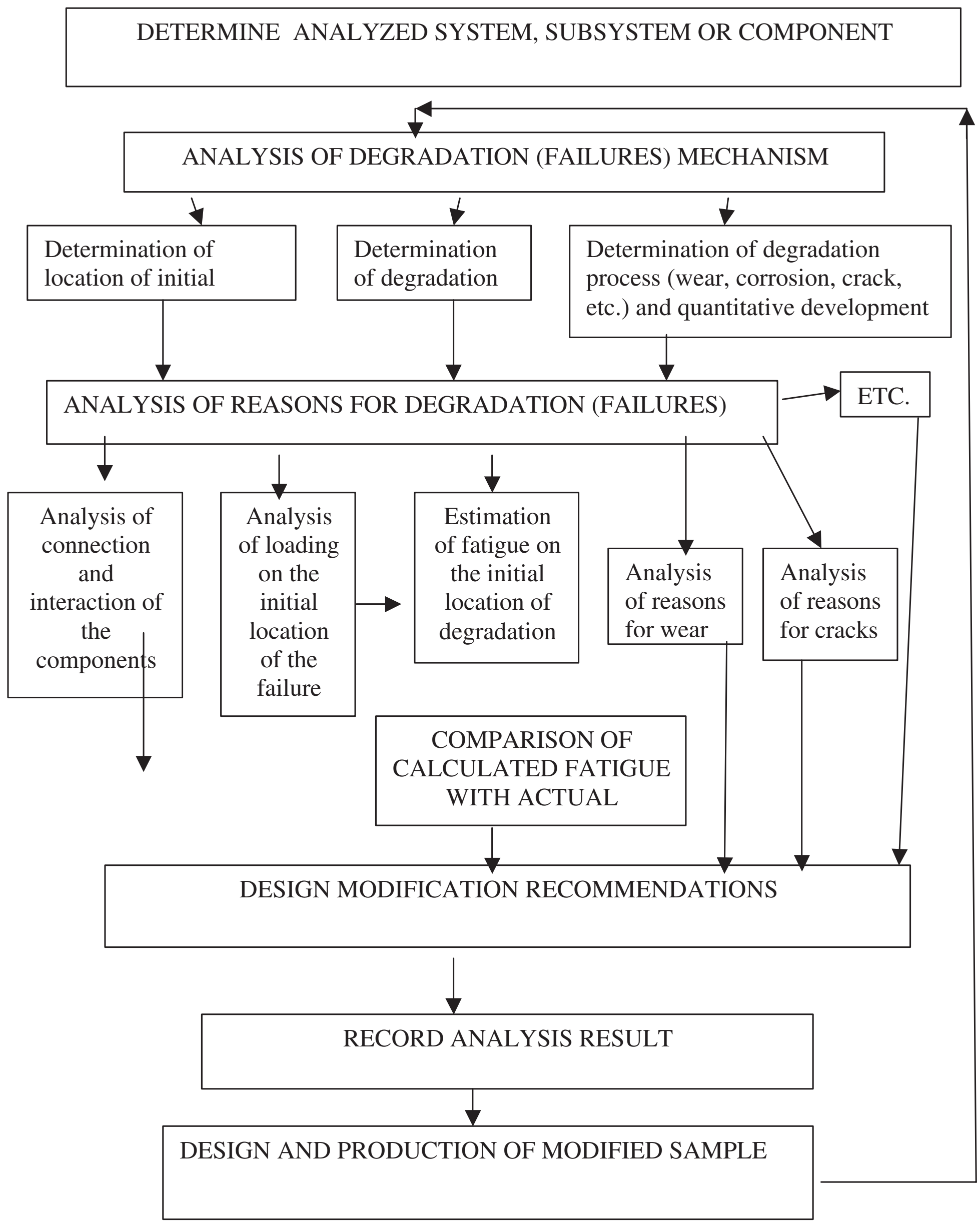


Figure 2.18 Process of rapid reliability improvement.

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9 ACCELERATED MULTIPLE ENVIRONMENTAL TESTING TECHNOLOGY

9.1 INTRODUCTION

Accelerated multiple environmental testing (AMET) is a process in which a product is subjected to environmental simulation. AMET is one of the basic components of accelerated reliability testing.

A randomly selected product can be tested at an extreme range of environmental parameters (temperature, humidity, pollution, radiation, etc.) to confirm continuation of the design and production process compliance. Testing can be used to simulate the environment which the products will encounter in transportation and operation. But people who plan, manage, and make AMET must realize that in real life environmental influences do not act independently on the product, but in combination with other types of influences such as road features, input voltage, etc. Product reliability is a result of interaction of these types of influences.

Unfortunately, most texts, including those of the more highly developed technologies such as electronics, aerospace, etc., make use of and describe mostly the simulation of only one type of real environmental influences – temperature. And more rarely, temperature + humidity. Texts use the following types of separate testing[1,2,3], etc.:

- Thermal Cycling.
- High Temperature Burn-In.
- Thermal Shock.
- Humidity.
- Low Temperature
- Etc.

The above approach is used for reliability or durability testing in accelerated testing techniques such as HALT, Accelerated Aging, etc. For example, HALT means simulation of temperature (usually the range from –100 °C to +150 °C), with additional vibration testing. Developers and users of this approach claim that after several days of testing they can obtain results equivalent to several years in the field. The author has previously described how wasteful the above approach is in practice for many areas of industry[4]. As a results, wrong conclusions are drawn after this testing. For example, in 1998 NASA sent a research station to Mars. The minimal service life of this station after accelerated testing was predicted to be not less than four months, but after three days the station died. HALT and Accelerated Aging can be useful for specific situations only, but not for most industrial products, and especially not for reliability testing of these products.

In the literature we often see in the title "Environmental Testing Chambers", but usually the production companies concerned are referring to the contents of their temperature-humidity test chambers, or corrosion test chambers, very seldom to separate solar radiation test chambers, dust chambers, etc.

The companies then connect these types of testing with the reliability and durability evaluation of their product. This is unsuitable, because, as this book shows, in real life environmental factors act only in simultaneous combinations.

There are several basic reasons for this situation. For example:

1). Some user companies want to reduce expenses for environmental testing and therefore buy cheaper testing equipment. Temperature-humidity test chambers are less expensive than complex test chambers that simulate simultaneous combinations of basic real life environmental influences. But these companies do not take into account total expenditure on the design, manufacture, and usage stages needed for the provision of a high quality product.

2). The representatives of production companies work as volunteers in different organizations for standardization, for example, ISO Test Chambers Working Groups, IEC Environmental Chamber Working Groups, etc. The user companies of the above products rarely send their representatives to these organizations, therefore the standards reflect mostly the producers' interests.

WEISS TECHNIK is a production company that makes complex test chambers such as climate test chambers with road simulators,vibration test chambers, and solar simulators. It produces test chambers for component reliability and for simulation of combined environmental conditions such as UV radiation, humidity, heat, cold, rain (and acid rain), mechanical effects, etc, for example, Climate Test Chamber with Road Simulators and Solar Simulation[5]. Technical data of modern testing equipment which is produced by Weiss Technik was shown earlier.

Technical data:

Solar simulation is realized with 6 lamps:	4, 000 watts.
Climate range (without heat load):	+5 ... +60 °C
Humidity range:	15 . . . 95% rh
Dew point temperature:	+4 . . . +59 °C
Dew point range:	- 40 . . .+80 °C
Temperature constancy:	± 1 K
Test chamber volume:	approx. 200 m^3

One can see from the technical data in Table 2.6 the complex test chamber which is produce by WEISS TECHNIK.

Table 2. 6 Technical data global UV test unit. Model UV 200[6]

Type		UV^{200}
Test chamber volume		approx. 200 liters
Test chamber dimensions	Height	approx. 1,800 mm
Width		approx. 830 mm
Depth		approx. 250 mm
Specimen carrier area		approx. 0.75 m^2
External dimensions*	Height	approx. 1,990 mm
Width		approx. 1,000 mm
Depth		approx. 1,000 mm
Floor clearance		approx. 100 mm
Radiation door	Height	approx. 1,340 mm
Width		approx. 995 mm
Depth		approx. 205 mm
Observation window	Height x Width	approx. 60 x 500 mm
Temperature range without radiation		-20 . . . +80 °C
with radiation		-10 . . . +80 °C
Temperature constancy, over time		≤ ± 1 K
Climate working range		+10 . . . +80 °C
Dewpoint temperature range		+ 9 . . . +40 °C
Humidity range depending on temperature		10 . . . 95% rh

Table 2.6 (continuation). Technical data global UV test unit. Model UV 200[6]

Type	UV^{200}
Humidity constancy	≤ ± 5% rh
Radiation intensity in wavelength range 290 mm to 400 mm	approx. 55 W/m^2
Reservoir for precipitation	approx. 60 liters
Cooling unit	air-cooled
Water supply for humidifier, reservoir 8 liters	dust, water max. 0.5 l/h
Conductivity max.	20 μs/cm
Condensation drain	counterpressure-free, DN 20
Finish	RAL 7035/RAL 5000
Mains connection	400 V/3 Ph + N + PE/50 Hz,
CEE plug,	5 role
Power	approx. 7.0 kVA, fuse 25 A, inert
Weight	approx. 600 kg
Sound pressure level measured in open space at 1 m in front of unit	approx. 60 dB(A)

* without a notebook operating station, without door locks and hinges.

Therefore, it is very important that real life simulation of environmental influences is used for accurate accelerated testing, in order to correct the prediction of product reliability, as well as for the rapid and correct solving of reliability and other quality problems. The authors approach, which will be described below, is based on the careful study of real life environmental influences followed by simulation of them in the laboratory.

Accelerated environmental testing (AET) can be used as a separate type of stress testing as well as part of reliability testing. In addition it can be used in conjunction with other parts of accelerated reliability testing (mechanical, electrical, etc.).

Often in practice, when carrying out fatigue testing of a product (steel specimens, details, etc.) one does not take into account the influence of environmental factors. But corrosion of the above product, which destroys its surface, causes a concentration of tensions. As a result, the product's fatigue ability is decreased.

Often the names of test chambers are misleading in their description and content. For example, "Chamber for durability accelerated testing" are usually labeled chambers of temperature and humidity without condensation. Or "Chambers middle volume for environmental testing" (MU, MG, ML, MSL, MZT, MZH), are only chambers with temperature changes, chambers with changes of temperature and humidity, or the chambers with changes of air pressure, temperature, and humidity.

However, full AMET is not used as frequently as it might be. Full AMET means simulation in a simultaneous combination of different basic environmental factors such as temperature, humidity, pollution, radiation, etc. One reason for this situation is that there is insufficient development in this direction, including the theoretical and experimental foundation.

Also there's not enough practical implementation of the new technique for accelerated testing.

Results formed under laboratory conditions often do not correspond to test results in the field, and information obtained by conventional methods of accelerated testing, including environmental testing, often cannot be used with high accuracy for reliability evaluation and prediction, or for the reduction of the time and cost of the product development, and other reliability problems.

In the laboratory environmental testing can often achieve only a small part of the possible benefits, because usually one uses this to test above environmental influences separately, which is contradictory to real life where these influences act simultaneously.

Simulation in test chambers is physical simulation of field environmental influences on the actual product.

Often, the standards reflect out of date information, therefore it is necessary to develop AMET techniques such as those which act on equipment in order to acquire more accurate simulation of real life environmental influences, especially simultaneously and in combination as they exist in real life.

9.2 THE STRATEGY OF THE ESTABLISHMENT OF ACCELERATED MULTIPLE ENVIRONMENTAL TESTING CONDITIONS

The advanced strategy of AMET is based on the principle of simulation in the laboratory of basic field environmental influences on the actual product: temperature, humidity, pollution, radiation, air, water, and gas pressure, rain, snow, wind, etc. The combination of the types of simulated influences depends on the types of specific field influences on the test subject.

Results of their action on the product include: metal corrosion, destruction of polymers, rubber, and wood; decrease in the protective effects of grease and paint, etc. These results decrease the product's quality and reliability (through different types of degradation, failure, etc.). Therefore, for AMET one must accurately simulate the above input influences.

The principles of obtaining accurate information about field input influences on the product for their simulation are:

1. In real life the product is influenced by a simultaneous combination of input influences.

2. These influences are interconnected.

3. Their action on the product is a result of the interaction of the above influences.

4. The results of their action on the product (degradation, failures, etc.) is a cumulative reaction of the combination of input influences.

For taccurate evaluation of environmental conditions for accelerated testing, one can use the following. The ideal ratio of simulated conditions in the test chambers to natural conditions should be equivalent, but in actual practice it is different. If the influences on the product under operating conditions are different from influences in the laboratory by no more than a fixed limit, the results of the influences in the test chambers correspond to results in the field. Failures in the field should differ from failures in the test chambers by no more than a predetermined limit.

One can read more detail about this aspect in the Palmer's book[7].

The most important aspect of this strategy is finding the optimum conditions for AMET (regimes in the test chambers).

The basic steps of physical simulation of environmental conditions are:

a) analysis of input environmental influences on the product in real life, in accordance with the above principles;

b) analysis of which kinds of influences are important based on the results of their action on the failures (reliability, serviceability, etc.) of the product;

c) development and use of laboratory conditions for the simulation of the necessary combination of influences (important for failures, reliability, serviceability, etc. of the test subject).

The choice of influences for AMET is evaluated by an analysis of the work and storage of the test subject in the field. Therefore, it is very important to evaluate the effect of statistical characteristics of the field region influences which are needed to build physical models of field conditions in the test chambers (different regions have different influences on the product)

9. 3 BASIC ENVIRONMENTAL INFLUENCES ON THE PRODUCT AND THE MAIN SCHEME OF ACCELERATED MULTIPLE ENVIRONMENTAL TESTING

In real life the basic environmental influences act on the product as is shown in the example in Figure 2. 19.

Therefore, in general, accelerated environmental testing in test chambers must include simulation of the following factors (Figure 2. 20). One group of influences such as temperature, humidity, solar radiation, air and gas pressure have to be acted on simultaneously as well as in combination.

Other groups of influences such as rain and snow have to be used periodically. If the test subjects are going to be used indoors, radiation can be removed from the environmental testing program.

The actual program of environmental testing for specific products depends on the type of product and the conditions of its use. That can only be known after an analysis of the field input influences and their resulting actions on the product.

There are field input influences which have no impact on degradation and on the failure process. One can recognize his after special analysis and data collection, then these data which have been obtained for one product can be used for many similar or new products.

Environmental testing, as with other types of testing, envisages all 11 steps of accelerated

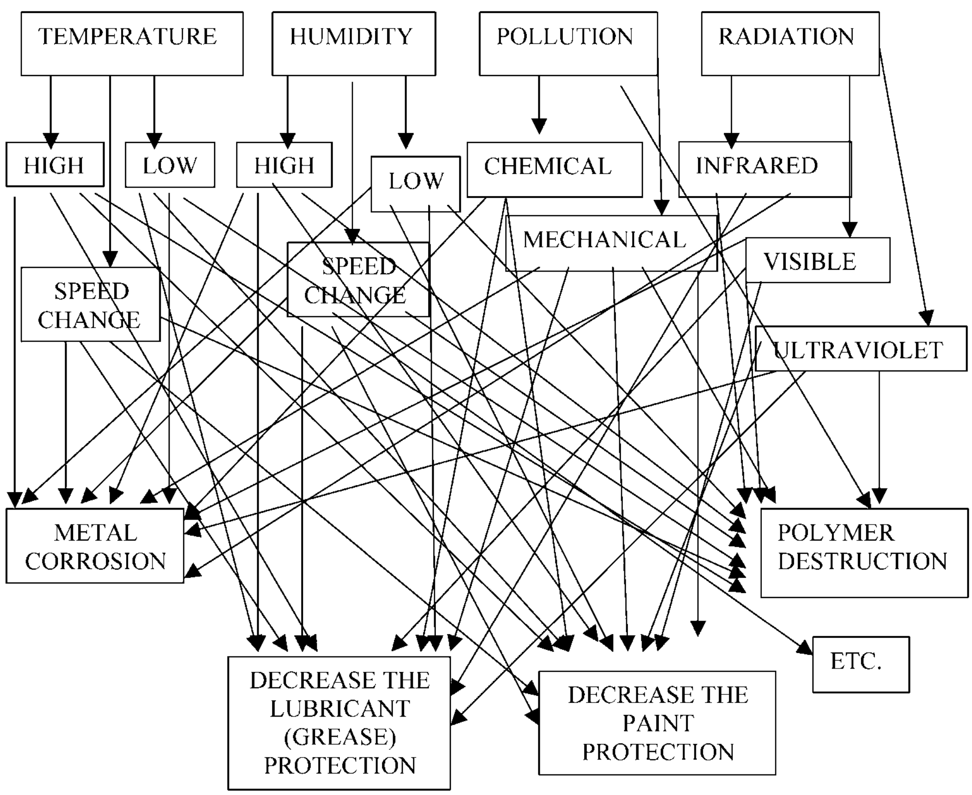


Figure 2. 19 Example of the scheme of environmental factors which influence a product's degradation (failures).

reliability testing technology (see Chapter 2). For example, one needs to study the field input environmental influences in order to accurately simulate them in the laboratory. Many companies and organizations that did not do this have had big problems after AET, because they did not take into account, for example, the speed of temperature change, etc. The example below of temperature (Figure 2.21) shows this principle of studying air temperature in the field.

In this example, the distribution process begins by establishing to which type of distribution the dynamic of temperature process is related (Exponential Distribution, Normal Distribution, Weibull Distribution, Gamma Distribution, etc.). This is followed by a study of he precise distribution process of temperature changes during subsequent simulation in the chamber for product testing.

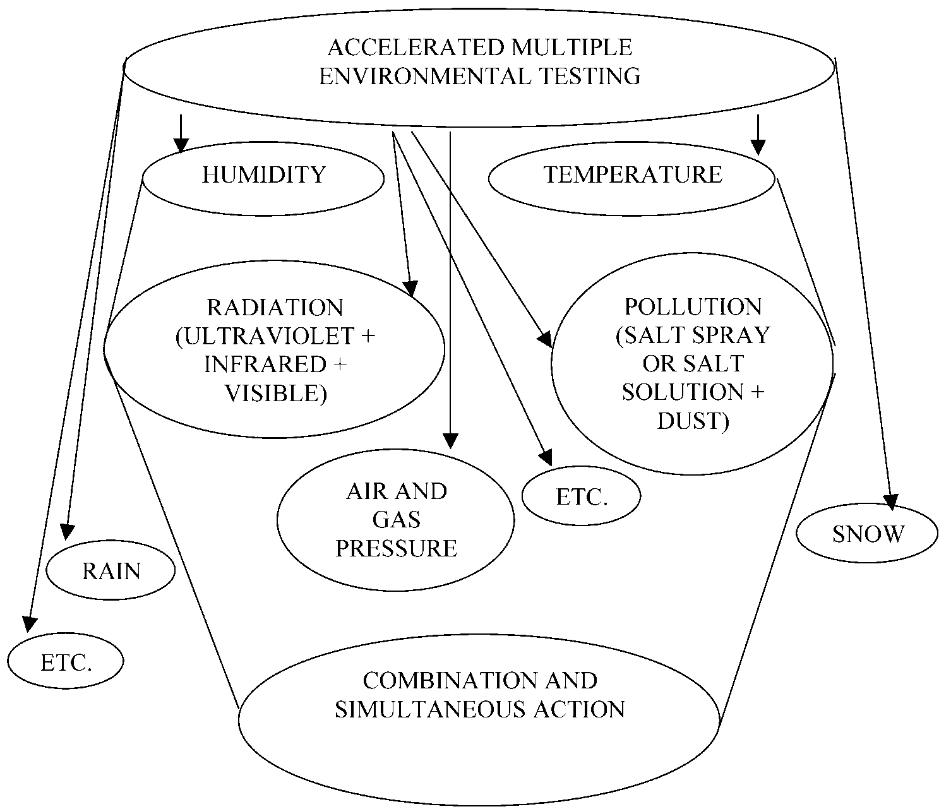


Figure 2. 20 Scheme of complete accelerated multiple environmental testing.

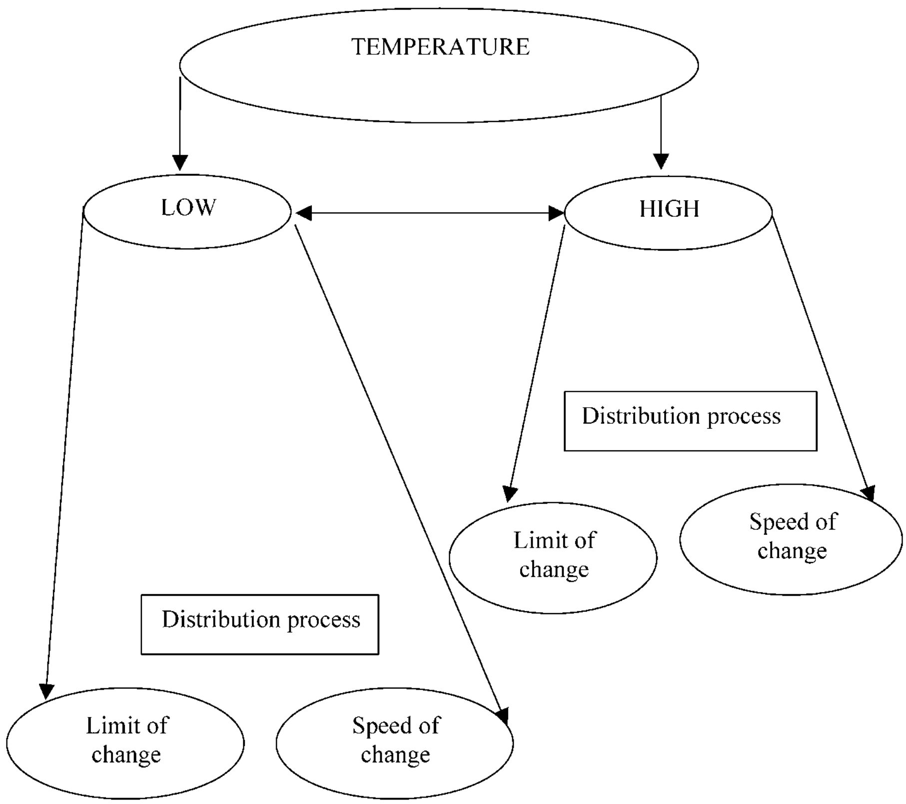


Figure 2. 21 A study of temperature as input influence on the test subject.

For obtaining accurate information after the above simulation, one must use the criteria of the necessary magnitudes. For example,[8]:

C/L, D/L, G/L, P/L, etc.

where C is a measure of corrosion; D is a measure of the destruction of polymers, rubbers, wood, etc.;
G is a measure of grease and paint aging;
P is a measure of decrease in strength;
L is quantity which is equivalent to the number of years of influence in the operating conditions (field).

In test chambers the intensity of the environmental influences may be increased and a ratio between laboratory and field environmental data can be determined.

The types of test chambers can be adjusted to correspond to international or national standards.

9. 4 MECHANISM OF THE INFLUENCES OF SOLAR RADIATION ON THE DESTRUCTION OF POLYMERS AND RUBBER. SIMULATION OF THESE INFLUENCES

Solar radiation action is less studied and described in the literature than other environmental influences such as temperature or humidity. Therefore, we are concentrating on this factor.

9. 4. 1 Influence of Radiation on the Diminution of the Plastic's Quality

Radiation is one of the basic influences on the destruction of polymers in the field.

As was shown earlier, the light from solar radiation on the earth's surface consists of ultraviolet (UV), visible, and infrared (IR) parts of radiation.

Ultraviolet (UV), according to ASTM G 113-94, *Terminology Relating to Natural and Artificial Weathering Tests of Non-metallic Materials*, is radiation for which the wavelength of the components are shorter than those for visible radiation.

In practice, light with a wavelength of less than 290 nm cannot reach the earth, because it is absorbed by the ozone layer. Visible light is weakly absorbed by polymers and has less photochemical activity, but for painted materials, aging continues even under the action of visible light.

Solar radiation has an influence on the light aging of polymer materials and includes primary and secondary reactions.

In polymer materials which one uses in the design of machinery, under solar radiation

A process takes place which causes aging of these materials. At a result of solar radiation action , in organic materials there is a closely related photolithical process of the decomposition of chemical compounds, which leads to a change in the material's properties.

The aging process of polymer materials is accelerated by warmth, air oxygen, high energy radiation, and other factors.

At the basis of polymer aging are two simultaneous processes: destruction which is breaking of

The bonds between atoms of the molecules and the formation of molecular fragments; and structurization, which is formation of new bonds between atom and molecular fragments. Therefore, aging of polymers changes their mechanical and electrical properties, color, etc.

The aging of polymeric materials depends on also water action. This aging is more dependent on the duration than the amount of water (either rain or dew) on the surface. The total duration that a surface is wet is called the time-of-wetness. For example, it makes a great difference if a certain amount of rain falls in a matter of a few minutes in a sudden shower or in the form of drizzle lasting several hours. The depth of penetration into the material, and thus the influence on the weathering behavior, is much greater in the second case than in the first.

Less studied is the influence of solar radiation on the protective quality of paint.

Polymers can be divided into two groups, according to their rate of solar radiation absorption:

1. Polymers which absorb the radiation in the UV field of the spectrum (primary photochemical initiation); and

2. Polymers which do not absorb solar radiation (secondary photochemical initiation).

The destruction of polymers in nature occurs by a process of photo-oxidation caused by the absorption of solar radiation in the presence of atmospheric oxygen.

Biological factors also influence polymer destruction in several climate areas. These factors include fungal formations, insects, and rodents. These factors act especially in tropical areas as a result of their interaction with polymers: the fungal formations excrete a product that disintegrates the polymers. Some types of insects, termites, for example, eat polymeric material.

Solar radiation may result in either of two possibilities:

1. Polymers may absorb radiation in the UV field of the spectrum related to functional groups in their structure (primary photochemical initiation); or

2. Polymers do not absorb solar radiation, because the basic chemical connections in their macromolecules are simple σ - bonds (secondary photochemical initiation).

The basic reason for polymer destruction from solar radiation is the action of UV radiation, which causes film formation, photo-oxidation and chemical changes in pigments, and as a result loss of sheen and change of color.

The action of solar radiation in atmospheric conditions results in an increase temperature because of absorption in the IR field of the solar spectrum. This temperature increase then results in changes in physical-chemical properties, swelling, etc.

These processes occur above 70 °C, but they are accelerated by the simultaneous action of temperature and radiation.

Humidity, air rain, snow, spray, etc. also influence the physical, chemical, and photochemical processes of polymers. Chemical changes in polymers as a result of humidity and of actions of others of the above factors depend on the hydrolysis and photo-hydrolysis processes.

An increase in humidity, temperature, acid, and alkali pollution accelerates hydrolysis.

Basic environmental factors which decrease the light resistance of polymers are solar radiation, temperature, and humidity.

9.4. 2 Chemical Factors in the Destruction of Plastics and Rubbers

The energy of solar radiation is enough to break some types of chemical bonds. In addition, light together with oxygen may create a free radical in organic substances or a type of peroxide which is highly chemically active and could begin different lines of chemical transformations. For example, destruction of polystyrene may begin after three months, and in a year its strength may be decreased by 50%[9].

Destruction of PVC also begins after three months of solar radiation activity: the most destructive radiation is within the wavelength of 220 - 250 nm, and in the presence of pollution the destructive action increases within higher wavelengths.

Rubber deteriorates under the action of atmospheric ozone, oxygen, heat, and solar radiation.

Under atmospheric conditions it loses ductility, and solar radiation accelerates this process by a factor of five or more times.

Light with a wavelength of approximately 300 nm accelerates the oxidation of rubber and destroys vulcanization. The oxygen absorption and chain decomposition under UV radiation at room temperature occurs by an analogous thermal oxidation process at 120-130 °C.

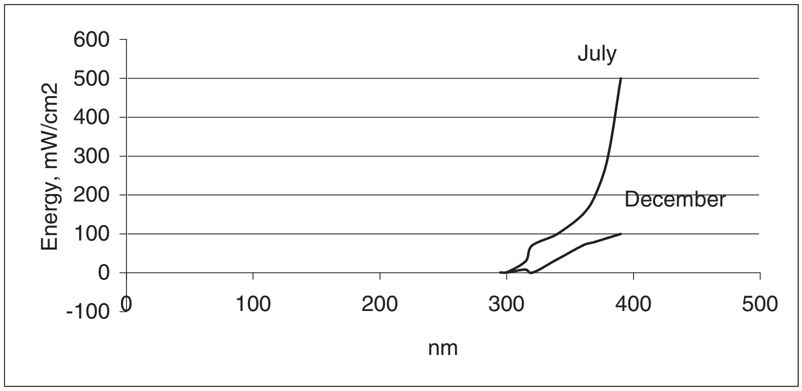
Therefore, the action of solar radiation on polymeric materials results in permanent loss of strength and viscosity.

9.4. 3 Sources of Light for Solar Radiation Simulation

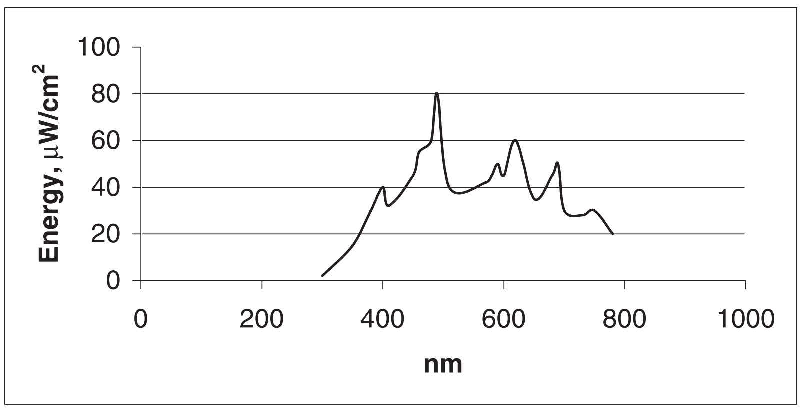
The main objective is a rational distribution of radiant energy in space with a minimum of wattage. Analysis of the spectral composition of artificial light shows that the fraction of UV radiation is substantially different from the fraction in natural solar radiation (Figure 2. 22).

One can see from Figure 2. 22 how different the real sun spectrum of radiation on the earth's surface is from the spectra of the two types of lamps that are often used in sun radiation test chambers. Therefore, customers must be careful when they buy solar radiation test chambers.

They must understand that the UV radiation is only part of solar radiation[9].



a)



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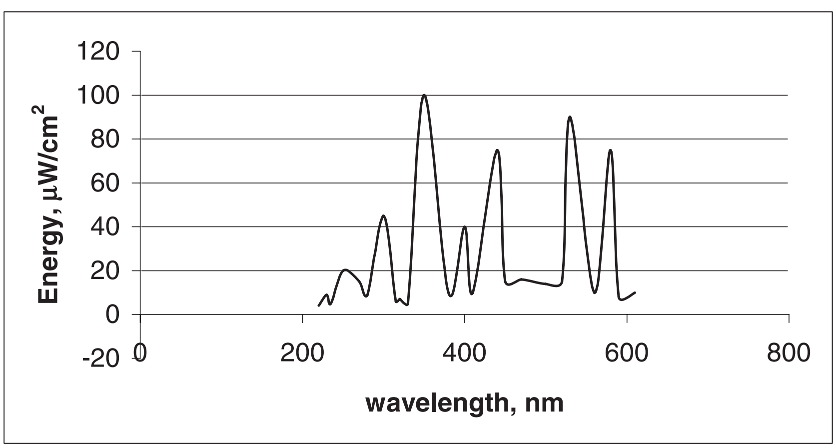

c)

Figure 2. 22 Spectra of radiation: a) sun on the earth's surface; b) Xenon lamp; c) Mercury-tungsten lamp.

Electric lamps provide most of the present day lighting sources. There are fluorescent lamps and gas discharge lamps. The latter type is better for accelerated testing chambers, as they have five times more durability than fluorescent lamps. Their radiation spectrum is also better. Xenon lamps are most preferred for accelerated environment testing of the different types of gas discharge lamps. They have the following advantages:

- have more range of power;
- spectrum of radiation includes UV, IR, and visible areas (in the visible area the spectrum is not far from solar);
- power coefficient of network $\cong 1$;
- can work in wide temperature intervals of the environment without changing characteristics;
- ecologically approved;
- maintain stability under either cooling or vacuum;
- can tolerate a brief overload;
- allow regulation of power by maintaining stability of the special distribution of radiation;
- explosion proof.

It is necessary to provide for testing the high frequencies of UV beams. For this goal a low power UV lamp is included in the apparatus.

9.4. 4 Equipment for Lighting Technology

This technology consists of natural lighting and artificial lighting equipment. Figure 2. 23 shows the classification of equipment for lighting technology.

9.4. 5 Basic Principles of Development of Lighting Module Elements

Influences on the value of solar radiation include geographical location, fall out frequency, quality of cloudy days, etc. Therefore, the lighting module can combine the intensity value of solar radiation, thermal, and flux for light to 15,000 m high and compose 1125 wt/m^2, including density of the UV part of spectrum (the wavelength 280 - 400 nm) 0.001 kal/cm^2/sec (42 v/m^2).

In different climatic areas the intensity of solar radiation on surface soil varies. Therefore, it is necessary to be able to regulate the intensity of the lamp power within allowable limits.

The flux light density shown above must be at a height of 0.5 m from the floor.

In the test chambers a level (to 97 $\pm$ 3%) of humidity must be introduced. Hermetically sealing the lighting module in the work space is necessary to prevent corrosive destruction of the module elements. The height of the lighting module must be considered, because the atomizer for the distribution of pollution and humidity must be mounted on the lateral sides of the chamber. These principles of lighting module development were the basis of the authors work in the design and management of test chambers for accelerated environmental testing.

The technical data of the lighting systems for test chambers are as follows:

1. Power needs, kW no more than 35

2. Illuminated square, m^2 no less than 4

3. Illumination of the 0.5 m from protected pipe 1125kg/m^2.

Environmental conditions in this chamber can be changed if necessary.

9.5 ACCELERATED WEATHERING TESTING

Accelerated weathering simulates and accelerates the effect natural elements have on materials, aiding in service life prediction and faster time to product development and improvement. It includes[10]: artificial light sources for weathering and fading; xenon; fluorescent/UV; metal halide; corrosion equipment; laboratory services.

Not many companies have begun so far to produce equipment for accelerated weathering testing.

Atlas Material Testing Technology is one of the advanced companies not in natural testing, but in accelerated weathering testing. They produce Ci series test chambers for this goal, Si which feature:

- A rotating rack maximizing exposure uniformity over all specimens;
- Narrow band (340 nm or 420 nm) or broad band (300 - 400 nm) irradiance control with optional monitoring as a second wavelength to meet global test requirements;
- Controlled irradiance up to 2 sun levels for higher acceleration rates based on different test requirements;
- Programmable stepped changes in irradiance set points and other test conditions to meet any user defined test program or cycle;
- A black panel thermometer that controls and monitors temperature at specimen levels to ensure test repeatability from one test to the next;

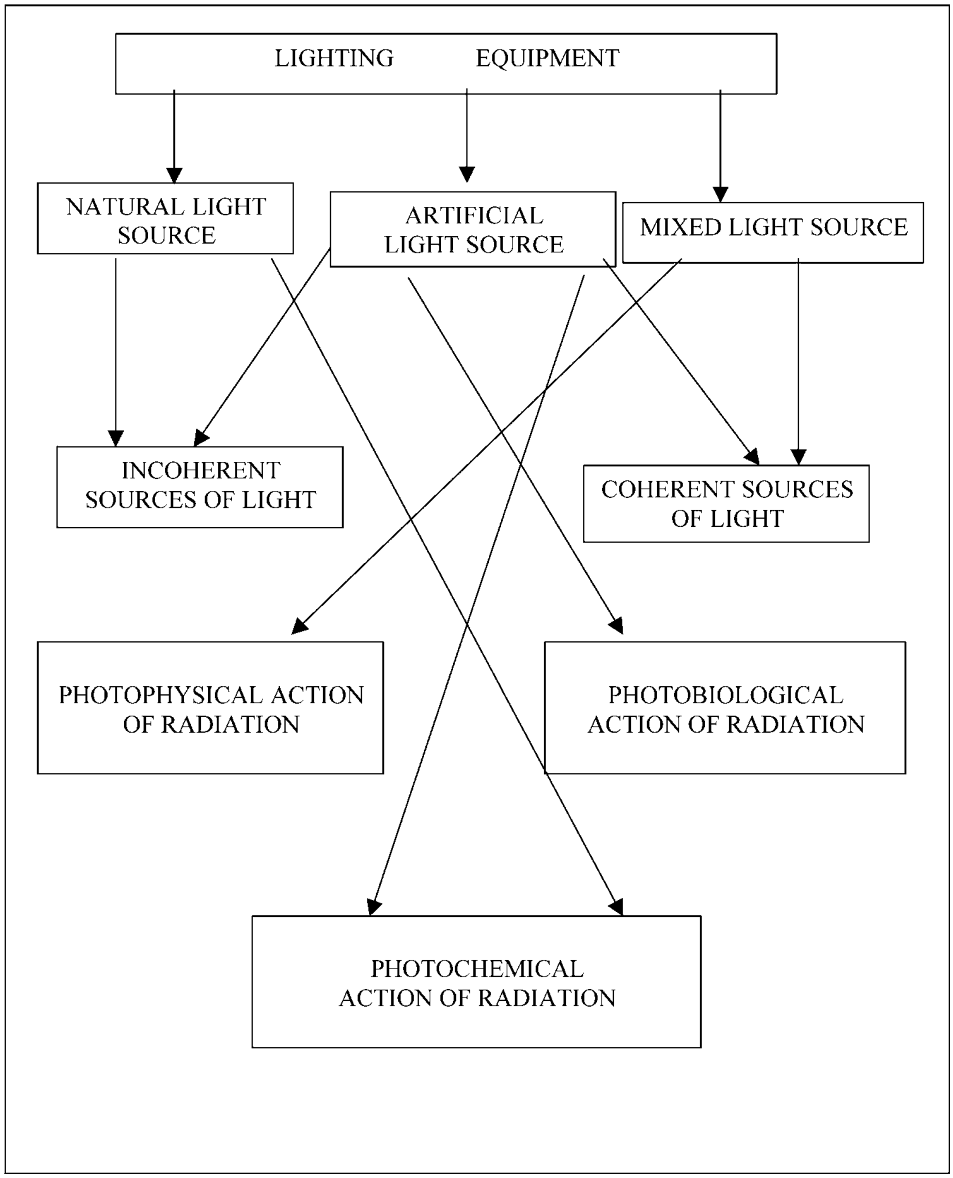

Figure 2. 23 Classification of equipment for lighting technology.

- A black panel thermometer that controls and monitors temperature at specimen levels to ensure test repeatability from one test to the next;

- Simultaneous automatic control of both chamber temperature and black panel temperature closely simulate the material's end use temperature conditions test after test;
- VibraSonic humidity control to replicate user selectable humidity levels to meet stringent global test requirements;
- A smart damper that tightly controls test chamber temperature and humidity levels and compensates for changes in ambient laboratory conditions for accurate and repeatable tests;
- A smart light monitor that verifies the proper interference filters are installed prior to operation, avoiding costly testing errors;
- Water purity meter signals when water quality falls below set point.

Technical characteristics of the test chambers are shown in Table 2.7.

The Ci series meets or exceeds the following standards:

ISO	105 – B02; 105 – B04; 105 – B06; 11341; 3917; 4892 – 2; 12040
MIL STD	810 F
SAE	J1885; J 1960
ASTM	G151; G155; D6695
AATC	TM 16; TM 169
Ford	DVM 0067 MA
GME	60292
GMW	3414
JASO	M 346
VDA	621 – 429; 621 – 430; 75202
VW	PV 1211; PV 1303; PV 3929; PV 3930

Table 2.7 Technical characteristics of Ci series test chambers[10].

	Ci5000 Weather-Ometer	CI4000 Weather Ometer	CI3000 + Weather Ometer
Light Source	12000 W, Water-Cooled Xenon Are Lamp	6500 W, Water-Cooled Xenon Arc Lamp	4500 W, Water-Cooled Xenon Arc Lamp
Irradiance Control	Automatic single point control at 340 nm or 420 nm or 300-400 nm	The same	The same
Light Monitor	SmartLight monitor	The same	The same
Humidity and Temperature Control	Automatic	The same	The same
Humidity Range	Light Cycle: 10 –75% (Dependent on Temp.) Dark cycle: Up to 100%	The same	The same
Dial BPT/BST Control	Optional	The same	The same
Filters	Interchangeable Inner And Ouer	Interchangeble Inner and Ouer	Interchangeable Inner and Ouer
Black Panel or Black Standard Temperature Range	BPT 40-110 °C	The same	The same
Specimen Rack Type	3 Tier	3 Tier	Single Tier

Table 2.7 (continuation) Technical characteristics of Ci series test chambers[10]

Total exposure area	11000 cm^2 (1705 in^2	6500 cm^2 (1008 in^2)	2188 cm^2 (339 in^2)
Electric	400/480 V, 3 Phase, 3 wire, 50/60 Hz, 60 A; or 400 V, 3 Phase, 50 Hz, 65 A	200/250 V, 3 phase wire, 50/60 Hz, 52 A, or 200/250 V, 3 phase, 4 wire, 50 Hz, 42 A	200/250 V, 1 or 3 phase, 50/60 Hz, 47/57 A; or 400/230 V, 3 Phase, 4 wire, 50 Hz, 38 A
HVAC-MJ/h (BTU/h (Max)	64,22 MJ/h (60870 BTU/h, 800 CFM)	41,36 MJ/h, 450 CFM)	26.06 MJ/h, (24703 BTU/h, 275 CFM)
Compressed air	0.11 m^3/min (4 CFM max), @552 kPa (80 psi)	The same	The same
Water Flowrate: Pressure Humidification Specimen Spray Rack Spray	138-345 kPa (20-50 psi); Deionized Water 0.2 1/min; Deonized Water 0.2 1/min The same	The same The same The same The same	The same The same The same The same
Physical Dimension (W x D x H)	160 cm x 130 cm x 198 cm	127 cm x 102 cm x 198 cm	95 cm x 84 cm x 183 cm
Footprint	180 cm x 302 cm including access area	148 cm x 274 cm including access area	115 cm x 240 cm including access area
Floor Weight	936 kg (2060 lb)	700 kg (1540 lb)	404 kg (890 lb)
Minimum Guaranteed Lamp Life	1200 hours	1200 hours	1200 hours
Simultaneous Control of BPT or BST and chamber Temperature	Standard	Standard	Standard

There are other types of modern weathering standards such as Xenotest Beta, Xenotest alpha, etc.

9.6 TRENDS IN THE DEVELOPMENT OF ENVIRONMENTAL TESTING

These trends are the result of an analysis of the negative aspects of current AMET techniques and equipment. The fact is that standard techniques and equipment usually show values from the previous day. Therefore, researchers and designers continue developing the simulation of field environmental conditions (especially physical simulation) to obtain more accurate information for solving different problems of product reliability.

The authors have shown above that one of the basic negative aspects of AMET is inaccurate simulation of real life input influences on the product. In reality the product is influenced by a complex combination of environmental conditions. These influences are interconnected, and their actions on the product and the result of these actions (degradation, failure, reliability, durability, etc.) are a cumulative reaction based on the combination of input influences and their interconnection.

Therefore, if one simulates these individually or simulates only part of the combination of the product's real life environmental conditions, one cannot be sufficiently accurate in obtaining, as a result of accelerated environmental testing, initial information on the real life character of the degradation mechanism.

This information is not sufficient for the evaluation and prediction of real life failures

As a result, it is impossible to obtain the product's reliability evaluation and prediction with high accuracy. This also does not make it possible to rapidly find the reasons for product degradation and failures, in order to achieve accelerated improvement of product quality.

In this case the development of conditions for accurate physical simulation of the environment is very important.

Some industrial companies work in this direction for the market. For example, ESPEC Corporation (Japan, with divisions in the USA, China, and Malaysia) designed[11] an insulated floor system that allows a road vibration simulator to integrate with a drive-in chamber. This floor moves to allow the simulator to adjust for vehicles with different wheelbases, from sub-compact cars to extended-cab pick-ups.

In another case, ESPEC created a drive-in chamber from special fiberglass for corrosion testing with road salt. The system included an undercarriage salt spray capability and an easy-maintenance brine tank made by ESPEC. ESPEC chambers integrate with:

- Single and multi-axis vibration systems;
- Road vibration simulators;
- Salt or rain spray;

- Dynamometers;
- Emissions test stand;
- Test-buck fixtures;
- Light simulation (IR, UV, VS);
- Video recording (for airbag testing and others);
- Measurement and data acquisition systems).

The authors have developed conditions for accurate physical simulation of AET . Also several techniques and equipment were developed for a complex of climate chambers, a type of "sandwiches" which simulate simultaneous combinations of four basic environmental parameters (Figure 2.24): temperature, humidity, pollution, and solar radiation. These test chambers are for AMET of separate specimens, details, units, and complete machinery. The chambers have a system for simulation, regulation, and control of environmental parameters. The chambers also have ventilation and cooling systems, waste water, an aggressive evaporation drainage system, a sprinkler system, and a power and alarm system.

The chamber is constructed so that it can be moved readily to the hard-to-react places.

Brief technical data

1.	Temperature range, °C	from −10 to +60 ±1
2.	Humidity range, %	from 40 to 97 ± 3
3.	Temperature changing velocity, °C/min	0.7
4.	Sun radiation range	spectral range 280 – 400 nm (42 W/m^2)
5.	Pollution	sprinkling with salt water, ammonia solutions, etc. and dust.

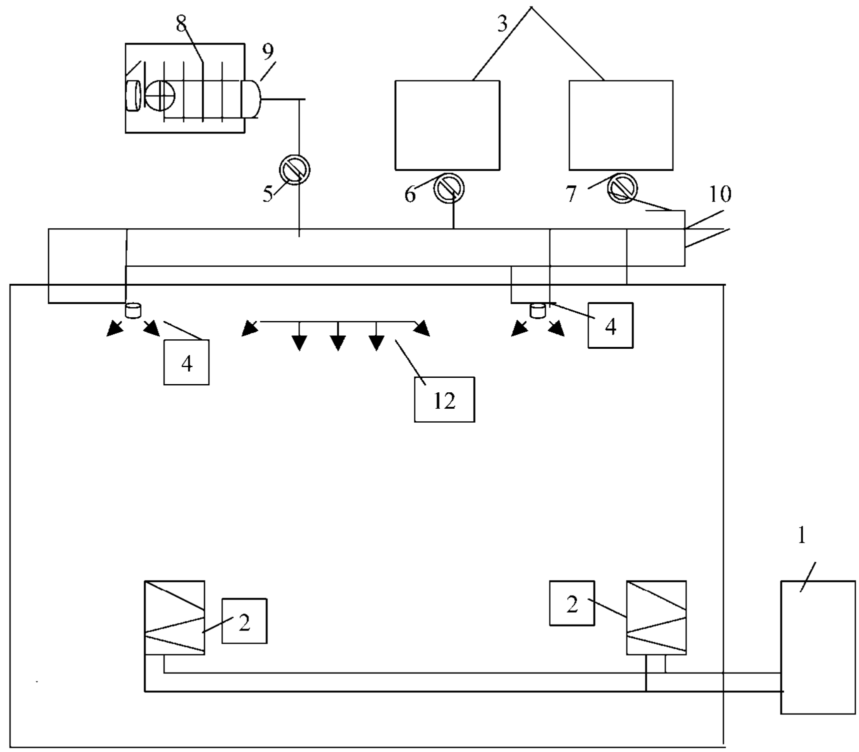

Figure 2. 24 Scheme of test chamber for simultaneous combination of temperature, humidity, pollution, and radiation (1 – system of control; 2 – heat exchanger; 3 – compressor; 4 – sprayer; 5, 6, and 7 – valves; 8 – capacities; 9 – receiver; 10 and 11 – pipe-lines; 12 – lamps).

There is a small stress and acceleration coefficient of time for failures which is greater (2 - 3 times) than time for failures of the optimum life regimen of temperature, humidity, pollution, and sun radiation in the field. The temperature, humidity, and concentration of pollutants are little bit higher than in real life. The basic reason for this is the necessity for compressing work time (take off the time of breaks with minimum time loading which has no influence on the product reliability, etc.). One has to be very careful with the accelerated coefficient, because the basic criterion is similar to the degradation mechanism in both field and laboratory conditions.

The accuracy of the simulation of real life multi-environmental influences depends on the accuracy of the initial information for success in obtaining solutions to quality and reliability problems, therefore work along these lines must be continued.

9. 7 ACCELERATED CORROSION TESTING

9.7. 1 Introduction

It has been established that corrosion is one of the most important factors causing deterioration, loss of metal, and ultimately the decrease of product reliability. A typical set of corrosion cost amounts is shown below[12].

The cost of metallic corrosion in the USA is valued at billions of lost dollars and has increased over the following 20 year period:

- 1975: $82.5 billion of which $33.0 billion are completely avoidable;

- 1995: $296.0 billion of which $104.0 billion are completely avoidable.

In 2004 corrosion alone was estimated to cost the USA Department of Defense $10 - $20 billion annually[13].

Factors determining if a corrosion reaction can occur are:

- thermodynamics;

- kinetic rates;

- time constant:

- cell development:

  - cathodic reaction;

  - electrical continuity.

Failures of electronic products[12] are: 80% due to materials and manufacturing defects and 20% due to corrosion.

Corrosion can be of various different types such as aerobic, anaerobic, atmospheric, fretting, pitting, etc.

There are many types of corrosion, and the specific type of corrosion depends on types of test subject. For example, there are the following types of corrosion for electronic industry products:

- Galvanic corrosion;

- Grevice corrosion;

- Tarnishing;

- Atmospheric corrosion;
- Fretting corrosion;

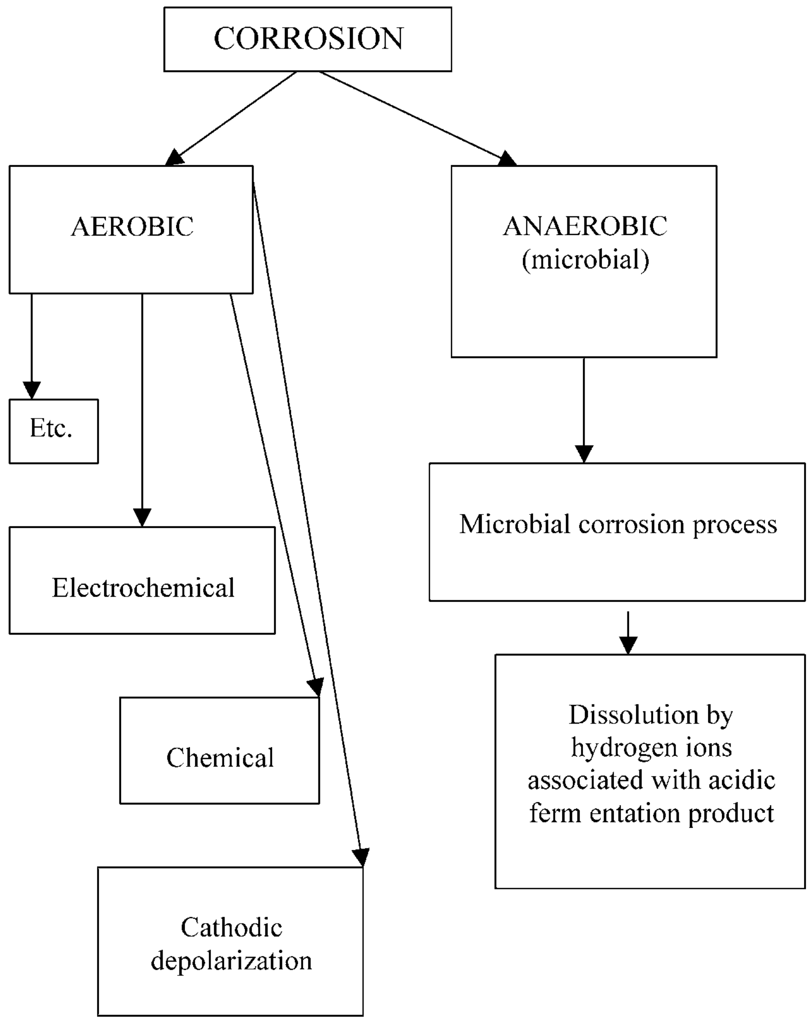

Figure 2.25 Basic types of corrosion.

- Electrolytic corrosion.

Types of acceleration factors include:

- Temperature;
- Relative humidity (% RH);

- Concentration and types of flowing mixed gases;

- Particles;

- Voltage; and

- Combinations of the above with variations of time and sequence.

The process of atmospheric corrosion occurs widely. This type of corrosion is usually an electrochemical process and as such depends on the presence of an electrolyte. The usual electrolyte associated with atmospheric corrosion is water resulting from rain, dew, melting snow, or high ambient humidity which may be contaminated, as will be described later.

Since an electrolyte is not always present, atmospheric corrosion is considered a discontinuous process which takes place during a period of time of sufficient wetness. The absorption of water on the metallic surface may be the result of high relative humidity of the atmosphere, of the chemical and/or physical properties of the corrosion products, of the properties of products deposited from the air, or a combination of all three. Industrial atmospheres often contain suspended particles of carbon, carbon compounds, metal oxides, sulfur compounds such as sulfuric acid, sodium chloride, nitrates and ammonia. When these substances combine with moisture or when because of their hygroscopic nature, they form an electrolyte on the surface, corrosion is initiated. Then hygroscopic salts that are deposited or formed by corrosion continually absorb moisture from the atmosphere, and the metal surface becomes or remains wet.

Such absorption occurs above a certain relative humidity, called the critical relative humidity, which corresponds to the vapor pressure above a saturated solution of the salt present. The amount of water on the surface then has a direct effect on the corrosion rate. The more water present, the greater the corrosion rate will typically remain.

In many locations dust is the primary air contaminant that helps drive corrosion. When in contact with metallic surfaces and combined with moisture, dust can promote corrosion by forming galvanic or differential aeration cells that, because of their hygroscopic nature, form an electrolyte on the surface.

This is particularly true if the dust contains water-soluble particles or particles in which electrolytes such as sulfuric acid may be absorbed.

During long-term exposure in a temperate climatic zone, temperature appears to have little or no effect on the corrosion rate. However, the overall effect of temperature on the corrosion attack may be increased as the result of an increase in the rate of electrochemical and chemical reactions as well as increases in the diffusion rate. Consequently, under constant humidity conditions, a temperature increase may promote corrosion.

The electrolyte film on the surface may contain various materials deposited from the atmosphere or originating from the corroding metal. Oxygen is a natural constituent of air and is readily absorbed from the air into the water film on the metal surface thus promoting any oxidation reactions[14]. Therefore, the metal corrosion process depends on temperature, humidity, chemicals in the air and dust pollution. The corrosion process is typically treated as a random rate, because the field input influences (temperature, humidity, pollution, etc.) often have a random character.

The study of corrosion processes and corrosion testing in the literature primarily relates to the corrosion of metallic materials. The corrosion process of a material may be different from the corrosion process of a product created from this material, because the corrosion of the product may be strongly influenced by the loading, friction, and the interconnection between different parts of the product, etc.

The level of corrosion and the depth of the corrosive cavern directly influence the decrease in product reliability for many materials and situations. The reasons for paint destruction and lubrication (grease) decreases are often primarily environmental factors that may be in combination with mechanical factors. Corrosive influences are often evaluated by the mass of material removed, by the size of the invaded surfaces, by the depth of the corrosion cavern and/or by measurements of the process intensity.

For the last one hundred years, some industries have used accelerated corrosion testing to evaluate products as well as their protective coatings.

The authors have developed techniques for accelerated corrosion testing (ACT) and implemented them. This leads to the benefits of rapid product improvement, lower warranty costs, lower life cycle costs, and improved reliability. This technology will be demonstrated through examples of mobile and stationary products.

9.7. 2 Current Accelerated Corrosion Testing

9.7. 2.1 Field weathering tests

The first step in developing ACT is to study the field input influences (climatic conditions) on the product and results. For this goal there exist special test centers representing the different types of climate. One famous company in this area is ATLAS[10,15]. This company has a division (Weathering Services Group) which has three primary facilities in the United States and an additional 15 sites around the world, providing the widest range of climatic and environmental conditions for material and product tests. South Florida Test Service (SFTS) founded in 1931 and located in Miami, Florida, is the company headquarters. The subtropical site has an outdoor capacity of over one million specimens and a modern accelerated weathering laboratory. An alternative Florida site, SFTS Everglades Test Site, is primarily geared toward special projects such as testing full car enclosures, test houses and automotive component evaluation. DSET Laboratories founded in 1948 and located in Phoenix, Arizona, provide a desert environment ideal for testing materials under high UV, high temperature and low humidity conditions (see Table 2.8). Outdoor accelerated testing is a key benefit of this site for many clients.

A laboratory site at Louisville, Kentucky, located in the Ohio River Valley near several coal-fired power plants, is exposed to a constant supply of industrial pollutants, including NO_x, CO, and O_3. These acid rain compounds, combined with a northern climate temperature characterized by hot, humid summers and winters with multiple freeze/thaw cycles, produce an environment that is specific for testing materials such as PVC siding (ASTM D3679).

The Lochem site (The Netherlands), North Sea Corrosion Test Centre (The Netherlands), and Bandol Region (France) were established to provide outdoor exposure testing for European companies and institutes performing independent weathering testing for products specifically used in that region. The North Sea Corrosion Test Centre (NSCTC), located in Hoek van Holland, is the European reference site for corrosion testing. It is situated in an industrial zone on the Rotterdam port of the North Sea, where conditions accurately reflect much of western Europe. The combined influence of acid rain, sunlight, marine air, and industrial pollution provide a reliable representation of the consequences of these parameters on material durability.

Weathering can be defined as the adverse response of a material or product to climate. The factors that influence products, and therefore the degree of weathering, are:

- Solar radiation (primarily ultraviolet wavelengths);

- Heat (the temperature of the material);

- Moisture (dew, rain, humidity); and

- Pollutants (aerosols, acid rain, ozone, etc.).

Because some of these factors vary widely over the earth's surface, the weathering of materials is not always an exact science. Material performance varies with changes in climatic conditions and chemistry. Static weathering tests may be applied for exterior materials and for interior materials. Static weather testing capabilities include direct exposure using fixed or variable angles; backed or unbacked racks; exposure under glass for interior materials; custom test house; vertical north or south exposure; bumper fascia testing; full or partial enclosure; and black box exposure for paints and coating materials at a variety of latitudes.

Table 2.8 Climatological data[15].

	Phoenix, Arizona		Miami, Florida	
Latitude	33° 54′ N			25° 52′ N
Longitude	112° 8′ W			80° 27′ W
Elevation:	610 m (2000 ft) above MSL*			3 m/10 ft above MSL*
Temperature: °C/°F	Summer	Winter	Summer	Winter
Average High	39/102	20/68	26/79	34/93
Average Low	24/75	8/46	13/55	23/73
Relative Humidity: (Annual Mean)	37%			78%
Annual Precipitation:				
Rain	255mm/ 10 in			1685 mm/66 in
Annual Solar Radiant Exposure				
Total	8004 MJ/m²			6500 MJ/m²
UV	333 MJ/m²			280 00 MJ/m²
Distance from ocean				27 km (17 miles)

*Mean sea level

The exposure of materials (specimens) are: unbaked exposure rack, backed exposure rack, vertical south exposure rack, tracking IP/DP Boxes (GM 9538P), etc.

9. 7. 2. 2 Current techniques for accelerated corrosion testing

The commonly used standard methods for metal corrosion include ASTM B 117 (salt spray), ASTM DG85 (modified salt spray), etc. While the test procedures may have remained constant over the years, the coating industry has undergone significant changes, especially during recent years[16,17]. Additional changes in corrosion testing include:

1). Environmental regulations to reduce the level of volatile organic content have resulted in the increased use of waterproof coatings. These coatings have shown good service performance, while performing poorly under salt spray testing.

2). For mobile machinery, the widespread use of two-sided, precoated sheet metal and longer consumer warranties (up to 10 years) have driven the need for improved corrosion protection.

3). The growth of powder coating as a finish has replaced some traditionally painted and/or electroplated finishes.

4). Shorter times from research and development to market hardly allow for long-term testing. ACT may be a solution to all of these industry changes. ACT chambers for accelerated corrosion testing may involve any of the following environments[15, 17, 18, 19, 20, 21, 22, 23]: ambient temperature, salt spray (or electrolyte solution) or fog, humidity, dry-off (high temperature); and total immersion. A salt solution may be sprayed into the test chamber using the injector principle through a nozzle located in the top of the test chamber. This may be combined with changes of temperature or humidity. The procedure for a typical lternating climate test[17] is given in the following example. In this example a test cycle lasts seven days and consists of the following conditions:

- Day 1 is 24 hours (per SS DIN 50021) salt spray mist testing;

- Days 2 to 5 are cycles (per KFW DIN 50017) for consideration of water alternating climate;

- Days 6 - 7 are 48 hours at ambient temperature 18 °C to 28 °C as specified in DIN 50014, clause 5.

The test period is as agreed; preferably lasting for 4 to 6 cycles, which corresponds to 4 to 6 weeks.

The test chamber is made from special glass fiber reinforced plastic laminate and is fitted with all supply and drainage connections to support the various conditions. Some companies produce test chambers for ACT which also provide an SO_2 gas dosing device corresponding to industry standards. Chambers may also have a special air ventilation system, a demineralization cartridge, air compressors, a precipitation collector, precipitation measurement and display of data.

A second type of cyclic corrosion testing[20] uses a different approach. In this approach parts are exposed to a constant environment of 35 °C and 100% RH with a 5% (by weight) sodium chloride (NaCl) solution sprayed for a pre-determined period. In the CASS (ASTM B-368) test, a derivation of the standard salt fog, 25 g/l copper chloride is added to the solution, and the ambient environment is maintained at 49 °C. The standards and parameters of test chambers are related to accelerated corrosion testing of metals and their combinations. Most companies apply the accelerated corrosion testing to whole machines (equipment) or their components. To reduce corrosion in the field they need many test components for ACT with corresponding testing equipment. Conditions required for ACT of metals also need improvement. These typically require larger chambers and special test conditions. The accelerated environments of ACT often need adjustment for the available testing equipment, as may the test conditions.

9.7. 3 Development of the Technique of Accelerated Corrosion Testing

Development and substantiation of the accelerated corrosion testing conditions for components and whole machinery are shown by examples of various steels as well as automobiles and their protection.

One result of ACT is to estimate the expected life in the field. It is necessary to solve the following problems in order to establish the conditions of ACT[29]:

- Find the impact of environmental conditions on various products.
- Determine the physical-chemical processes that cause product deterioration under the action of environmental factors.
- Study the parameters that characterize the above processes.
- Establish of the intensity of possible environmental influences and determinate the evaluation methods.
- Find the limit of the physical-chemical mechanism of the deterioration processes in the field.
- Determine the optimal conditions of ACT for a particular product with similar degradation mechanisms to those in the field.
- Check the correlation of established conditions of ACT results with the field results.

Practical establishment and application of ACT conditions leads to the following brief description.

9. 7. 3. 1 Accelerated corrosion testing of metals and metallic components

The following approach for corrosion testing can be applied. The magnitude of metal corrosion is usually a function of the wetting of the metallic surface. The maximum rate of corrosion should occur when the moisture film is drying. This situation will be considered for steel and protection provided by grease and/or paint.

Establishing the limits of environmental influences on steel corrosion and protection (grease and paint)

How can one establish the environmental parameters on the corrosion of the product in the test chambers? Let us show the approach as it refers to an example of 1020 steel.

The basic environmental factors in our example will be temperature, humidity, and chemical pollution using wettings with a KCl solution.

Interaction of environmental influences for steels, greases, and paints is depicted in Figure 2.26.

The limit of the basic environmental factors is determined as a result of their action on the 1020 Steel, Polyurela - thickened grease, and a standard pain DBU 4273W. The following problems must be addressed[24]:

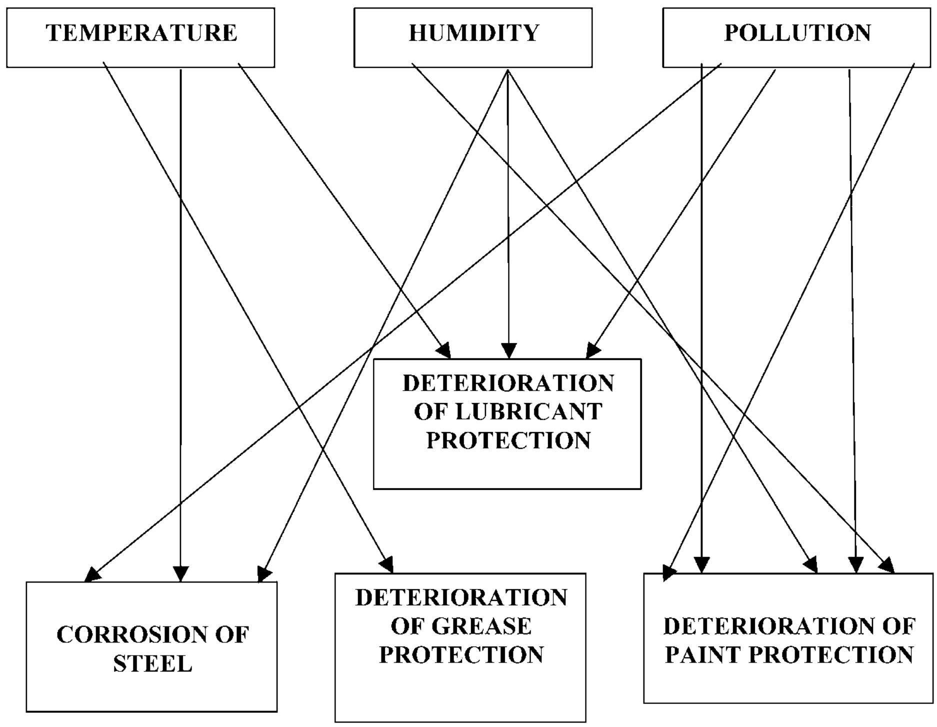

Figure 2. 26 Influence of basic environmental factors on the deterioration of steels, greases, lubricant, and paints.

1. Establishment of the limits of environmental stress influences on the paint DBU-4273W.
2. Determination of necessary humidity conditions in the test chamber to evaluate or estimate the speed of the atmospheric corrosion of the 1020 steel under a film of moisture.
3. Determination of the necessary temperatures for the test chamber to evaluate or estimate the speed of atmospheric corrosion of the 1020 steel under a film of moisture.
4. Determination of the time interval necessary for the evaluation of experimental dependence of "corrosion of 1020 steel on the duration of wettings by 0.01 Normal solution of KCl" applied during selected conditions of temperature and humidity.

Establishment of required temperature in test chamber[24].

Special research with grease has shown[25] that its protective quality is determined by the temperature required to cause a flow down from the surface. The grease first melts and then flows down. Our investigation was conducted at a relative humidity of 50% with temperatures of 30 °C (85 °F), 35 °C (95 °F), 40 °C (104 ° F), and 45 °C (113 °F).

The results obtained are shown in Figure 2. 27. After six days and nights at temperatures of30 °C and 35 °C, the electrical resistance of the metal had not changed.

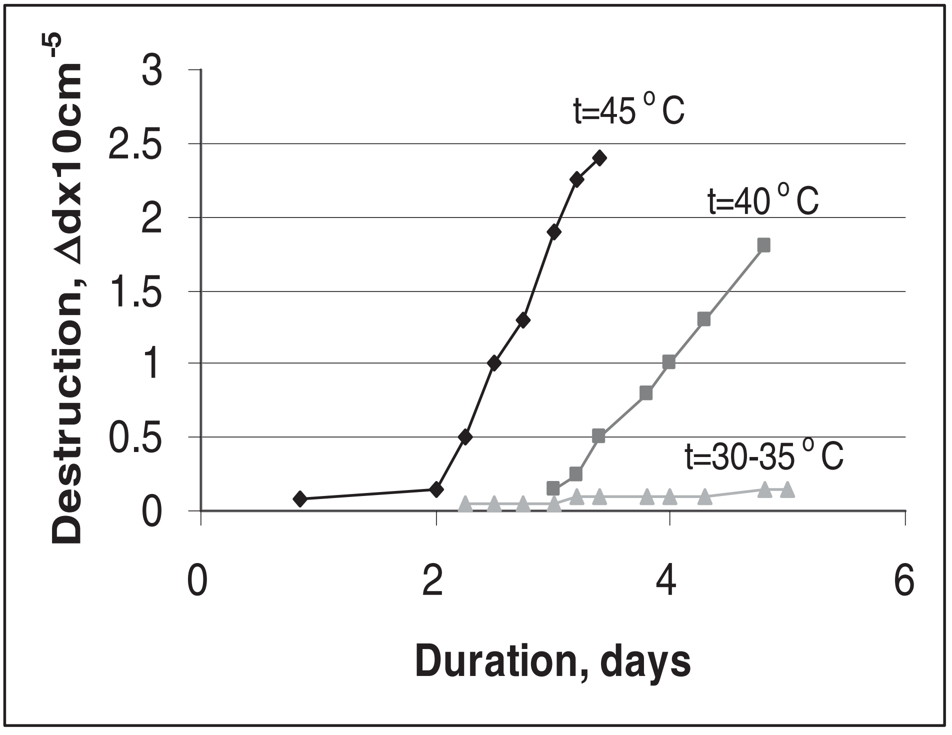

Figure 2. 27 Dependence of Iron corrosion with protective grease as a function of different temperatures.

We conclude that the surface properties (no oxidation) had not changed.

The indications of oxidation, as shown by an increase in the resistance of metal, appear first at a temperature of 40 °C after only 72 hours and at 45 °C after 48 hours. A trace of grease appears at the top of the electrolyte coats, resulting in a slower process of evaporation of solutions from the surface of the specimens.

Two opposing forces are acting on the grease element which is under the coating of water solution of the electrolyte. One force is exerted by the liquid, from one side, and from another side the force of cohesion with neighboring elements attracts the grease element. If the temperature increases, the fluidity of the grease increases too, but the force of cohesion is weakened. After that the grease element tears away from the common mass and floats up to the surface of liquid.

The thickness of the protective coat is continuously decreased, and the corrosion process begins. Results of testing with specimens of 0.005 mm thickness of greased coat confirm these findings.

The experiment took place at a temperature of 45 °C without change of humidity and indications of oxidation were not found until the sixth day. Therefore, to avoid destructive corrosion of the metal under the coat of grease in accelerated testing "wetting – drying", the temperature in the test chamber must be no higher than 35 °C (95 °F) for the particular grease studied.

Establishment of necessary humidity in the test chamber [24]

An electrochemical method of studying steel corrosion is based on representing atmospheric corrosion by a model that employs many short-circuited microelements of the system on the metal surface[3] in contact with a corrosive film.

Corresponding to this, one measure of the steel deterioration can be estimated from the electrical current which is generated by the micro-corrosion elements on the surface of the metal with a film of electrolyte solution.

In our experiments the test object was to create a battery with metal plates and exploit the different work potentials.

The micro-cathode consisted of 40 copper plates, and the micro-anodes consisted of 40 plates of 1020 steel. The thickness of the plates was 0.5 mm. These batteries were studied at relative humidity values of 50%, 60%, 70%, 80%, and 90% across a temperature range of 5 to 35°C in intervals of 5°. The thickness of the electrolyte solution film was 100 μk . The duration of the corrosion process was fixed by the availability of current in the battery, and the anode destruction was measured by the area under the curve of the graph of current versus time.

It is apparent that with the increasing consumption of the anode's material the reaction time increases. The common corrosive effect depends entirely on the time duration of the moisture on the wetted surface. The mean rate of corrosion is constant while the surface is wetted. The reason is that the speed of oxygen diffusion to the cathode does not depend on the relative humidity when under a thick, wet film.

The access of oxygen depends on the thickness of the electrolyte coat. This confirms the observation that the corrosion current increases when the humidity is high.

It is necessary to develop a test plan with long periods between the use of the sprinkler system, for stability of the environment in the test chamber.

The dependence of "corrosion vs. temperature" shows that the increase in corrosion C is not proportional to the increase in temperature (Figure 2.28). The curves are maximum in the interval 10 °C – 15 °C. The effect of increasing the speed of the reaction by 15 °C is less than the effect of slowing the reaction rate.

This is quantified by equation 2.1. The results of these experiments are in Table 2. 9.

Table 2.9 The influence of humidity and temperature on the corrosion speed under a dried film of wet.

Relative humidity, %	Temperature, °C	Value of corrosion, $C\cdot10^{-1}$	Time, hour	Speed of corrosion, $V_k\cdot10^{-1}$ mg/cm^2 per hour
50	5	0.14	0.81	0.17
	8	0.21	0.67	0.31
	12	0.25	0.55	0.45
	15	0.26	0.46	0.56
	20	0.21	0.32	0.66
	25	0.17	0.24	0.71
	30	0.12	0.17	0.70
	35	0.07	0.11	0.64
60	5	0.16	1.01	0.16
	8	0.25	0.85	0.29
	12	0.29	0.67	0.43
	15	0.30	0.55	0.55
	20	0.25	0.40	0.64
	25	0.21	0.31	0.69
	30	0.15	0.21	0.70
	35	0.12	0.17	0.70

Table 2.9 (continuation) The influence of humidity and temperature on the corrosion speed under a dried film of wet.

70	5 8 12 15 20 25 30 35	0.22 0.32 0.37 0.38 0.33 0.27 0.20 0.14	1.39 1.16 0.88 0.71 0.54 0.41 0.30 0.21	0.16 0.28 0.42 0.54 0.62 0.66 0.67 0.66
80	5 8 12 15 20 25 30 35	0.35 0.50 0.60 0.61 0.52 0.41 0.31 0.23	2.21 1.80 1.37 1.11 0.82 0.60 0.45 0.35	0.16 0.28 0.44 0.55 0.63 0.68 0.68 0.67
90	5 8 12 15 20 25 30 35	0.80 1.17 1.36 1.30 1.01 0.81 0.58 0.41	4.73 4.03 3.01 2.21 1.58 1.19 0.86 0.63	0.17 0.29 0.45 0.58 0.64 0.68 0.67 0.65

The character of the curve $\nu_k = f_2$ *(t, W = 90 %),* which is based on experimental results, shows that the value of ν_k changes very slowly across the intervals of temperature from 20 °C to 35 °C. Therefore, this low dependence is enough to determine the optimal temperature, which is t = 30 °C here. Therefore, the optimal parameters of a test chamber regime for this material are: t = 30 °C, W (humidity) = 90%.

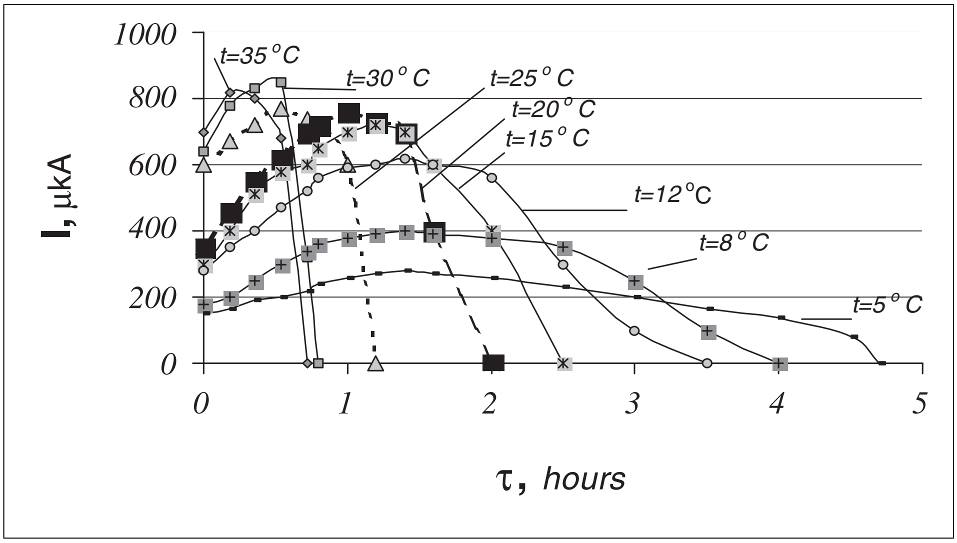

Figure 2.28 Dependence of corrosion current on the conditions of Fe – Cu batteries drying at a humidity of 90%.

As a result of experimental research, the dependence of the length of corrosion current time in the circuit of the model on the conditions of drying is shown in Figure 2.29.

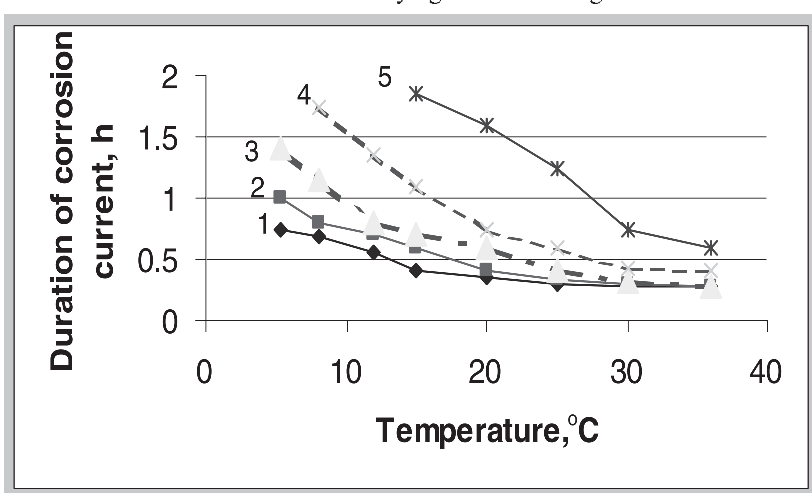

Figure 2. 29 The dependence of corrosion time versus different surface drying conditions of the batteries (humidity is: 1 = 50%, 2 = 60%, 3 = 70%, 4 = 80%, 5 = 90%).

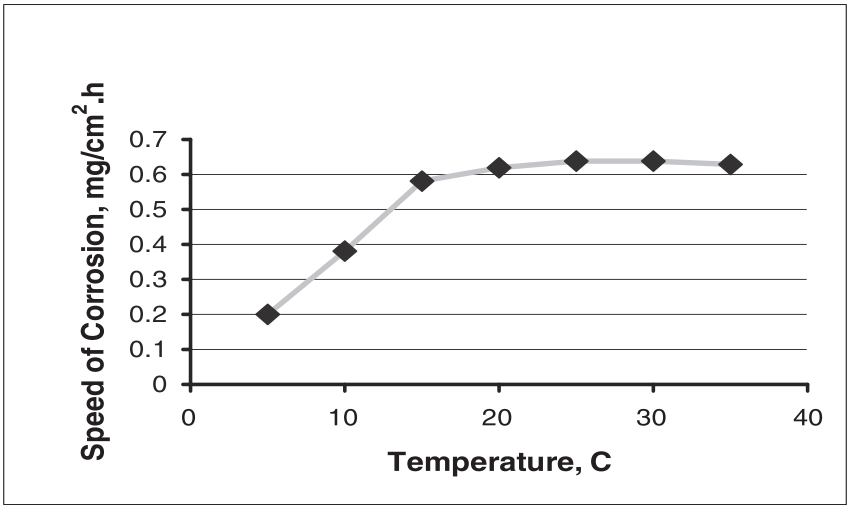

Figure 2. 30 Dependence of the duration of corrosion speed versus the temperature at 90% humidity.

Determination of the dependence of "steel corrosion versus the number of wettings" [24,27].

Corrosion is a degradation process and we should compare the field and laboratory results in order to evaluate the acceleration coefficient over the time interval. This experiment used specimens of 1020 steel of size 50 × 80 mm and thickness 1.6 mm. The dependence of the amount of the corrosion versus the number of wettings with 0.01 Normal KCl solution is the outcome of this experiment.

The micro-corrosion was used to determine the drying time of the surface. The time between wettings was selected as 55 minutes. The specimens changed places after each 10 wettings. The level of corrosion was determined by the loss of mass. The product of corrosion was eliminated by an agreed-upon method. The results of experiments are approximated by the curve in Figure 2.31.

The dependence of steel corrosion on the number of wettings for $N_w > 100$ is well approximated by the equation

$$C = 0.546\ N_W^{0.97} \qquad (2.\ 1)$$

where C is the quantity of metal corrosion, g/cm^2; N_W is the number of wettings (N_w is more than 100) of the corroded surface; 0.97 is the experimental coefficient.

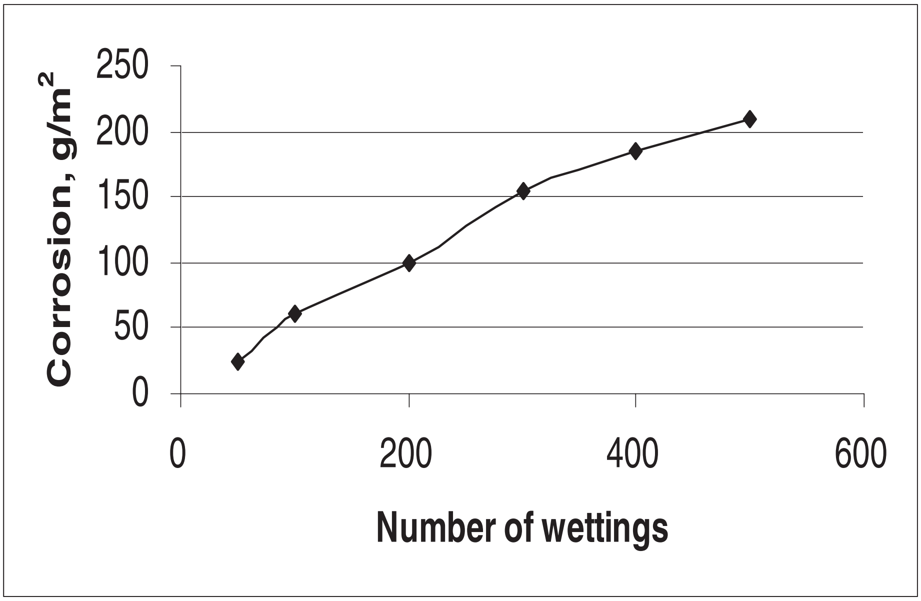

Figure 2. 31. Dependence of 1020 steel corrosion values on the number of wettings.

By filling in equation 2. 1 with the accumulated steel corrosion in any region, the required number of wettings to simulate this accumulated corrosion in the test chamber will be obtained for the particular region. If one knows the interval between two wettings and how many years are required to simulate this, one can determine how long the testing time in the chamber should be. The ratio of this time to one year (365 days) will show the testing acceleration coefficient. For example, see Table 2. 10.

Table 2. 10. Example of calculating the acceleration coefficient (the time between wettings is one hour).

How many years (days) are required to simulate	How long the test time in the chamber should be (days)	Acceleration coefficient
1 year (365 days)	13.77	26.50
2 years (730 days)	30.42	24.00

Table 2.10 (continuation) Example of calculating the acceleration coefficient (the time between wettings is one hour).

3 years (1095 days)	43.80	25.05
4 years (1460 days)	61.34	23.80
5 years (1825 days)	72.85	25.05
6 years (2190 days)	87.25	25.10
7 years (2555 days)	106.41	24.01
8 years (2920 days)	154.50	18.90

Checking the laboratory accelerated corrosion versus field conditions [24]

The following is an example of this. The sample plates will be 1020 steel of size 50 × 80 × 1.6 mm; and coated with grease to a thickness of 0.5 mm. Additional sample are the same plates of 1020 steel with paint DBU-4273W protection; glass-plates with Iron coated with grease to a thickness of 0.2 mm; specimens of 5140 steel and 1045 steel of the same size.

The test conditions are: t = 30 °C, W = 90%. From formula (2.1) there are 456 wettings with a 0.01 N solution of KCl. The wetting was done for 0.9 minutes at intervals of 1 hour. The results of laboratory testing (a degradation mechanism) and real life correspond only for variant 1 (Table 2.11). The variants $(\sigma_l^2 - \sigma_c^2) \leq \Delta_{l\sigma}$ and $(\mu_l^2 - \mu_c^2) \leq \Delta_{l\mu}$; where $\Delta_{l\sigma}$ and $\Delta_{l\mu}$ are the permissible square of standard deviations and mathematical expectation (mean) between the expected value for real life and for test chamber conditions. I this expression, μ is the mathematical expectation; σ is the standard deviation; σ_l is the standard deviation in real life; and σ_c is the standard deviation in the test chamber.

Table 2. 11 Possible outcomes.

Example	Standard deviation	Mathematical Expectation	Variants
1	$\sigma_l^2 = \sigma_c^2$	$\mu_l = \mu_c$ $\mu_l \neq \mu_c$	1 – 1 1 – 2
2	$\sigma_l^2 \neq \sigma_c^2$	$\mu_l = \mu_c$ $\mu_l \neq \mu_c$	2 – 1 2 – 2

The experimental results using 1020 steel for one year in real life conditions were a mean corrosion μ of 198.4 g/m^2 with a standard deviation σ_l^2 of 203.0 g^2/m^4. The hypothesis of normality which was checked by the Pearson criterion does not contradict the experimental data (P = 0.62 for $\chi^2 = 3.56$). The necessary number of wettings for the test chamber was calculated from equation (2.1) by $\underline{C}$ = 198.4 g/m^2. The value of the mathematical expectation calculated was 179.1g/m^2 and the variance was 250.0 g^2/m^4, as shown in Table 2. 12.

The level of similarity of the test chamber conditions to the natural real life conditions is measured by the degradation (corrosion) mechanism and through comparison of mathematical expectations as well as standard deviations (variances) of both above distributions.

Table 2. 12. Corrosion in real life and in the test chamber (calculated from equation 2. 1) for one year (number of wettings is 8,760).

Where	Mean of corrosion, g/m^2	Standard deviation of corrosion, G^2/m^4
In real life	198.4	203.0
In test chamber	179.1	250.0

Hypothesis checking provides:

$$H_0 \{ \frac{\sigma_M^2}{\sigma_N^2} = 1 \}$$

The alternative hypothesis is:

$$\sigma_m^2 > \sigma_n^2$$

In this case for the sampling ratio $\frac{S_m^2}{S_n^2}$ (where S_m^2 and S_n^2 are estimations of the standard deviations for the corrosion model and the natural results) one can use percentage points of the F-distribution (Tables of Mathematical Statistics) as a limiting value of this ratio.

The level of importance α = 1% is found from the above tables with 1%, ∞, 49 yielding a number of 1.523. These tables can be found in different handbooks on the theory of probability.

The actual ratio of standard deviations derived from the data was 1.232.

$$\frac{S_m^2}{S_n^2} = 1.232.$$

Since 1.232 < 1.523, the hypothesis that $\sigma_m^2 = \sigma_n^2$ does not contradict the experimental data.

Typical engineering estimations usually suggest that the deviations from the model should be no more than 8-10%. If we adopt this measure, $\delta = |m_n - m_m| = 15$ g/m^2 with a level of importance equal to 1%, and the critical value of accepted statistics is equal to 2.33. From the data we obtain a value of $V = 1.84$, which is less than 2.33. Therefore, the suggested hypothesis does not contradict experimental data.

Using the known ratio for standard deviation, it is possible to check the null hypothesis H_0 $(m_n^* - m_m^* = \delta)$. With the help of the limiting values of the statistic one has the following relationship[8]:

$$V = \frac{\eta - \delta}{\sqrt{\lambda_m S_m^2 + \lambda_n S_n^2}}, \qquad C = \frac{\lambda_1 S_1^2}{\lambda_1 S_1^2 + \lambda_2 S_2^2}$$

where:

$$\lambda_n = \frac{1}{N_n}; \quad \lambda_m = \frac{1}{N_m}; \quad \eta = m_n{*} - m_m{*}; \quad \delta = |m_n - m_m|;$$

and n_n and m_m are values for the field results and test chamber results.

The final evaluation of the correspondence of the recommended conditions in the test chamber to real life can be established by the results of standard fatigue testing of metallic specimens. The experimental results (Figure 2.32) show fatigue testing on the "Shenck" test machine for those specimens (see Figure 2.32, ■), where after 5.10^6 cycles corrosion destruction of 5140 steel the fatigue decreases from 18 kg/mm^2 to 14.8 kg/mm^2 on testing in test chambers. After field testing (♦) the fatigue of the same specimens decreases from 18.6 kg/mm^2 to 13.8 kg/mm^2 .

Similar results are obtained when testing 1045 steel specimens (see Figure 2. 32 , ∗ and ×).

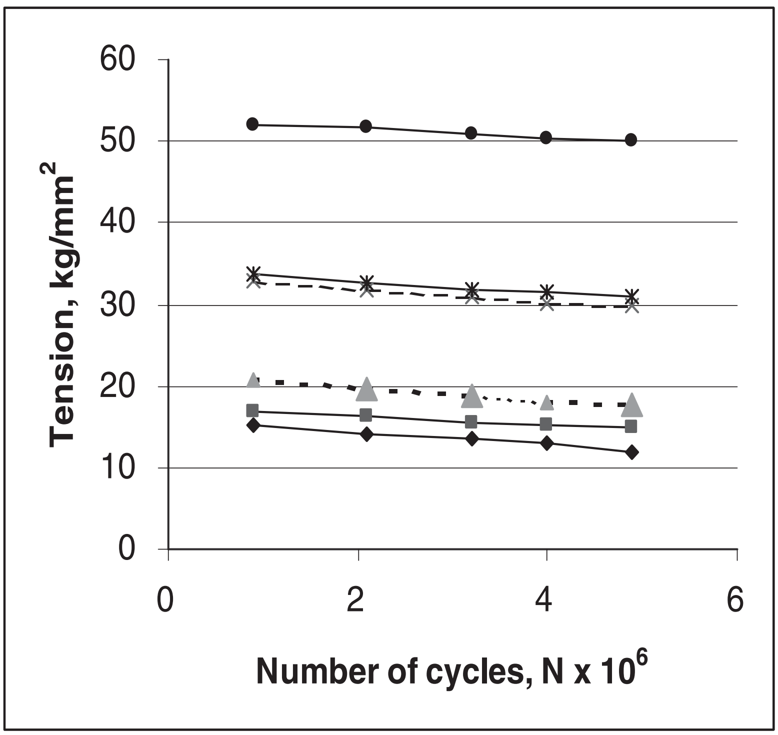

Figure 2.32. Results of the fatigue testing of steel specimens: • is 1045 steel before exposure; ∗ is 5140 steel after testing in test chambers; **x** is 1045 steel after field testing; Δ is 5140 steel before exposure; ■ is 5140 steel after testing in test chamber; ♦ is 5140 steel after field testing.

9.7. 4 Accelerated Corrosion Testing for the Complete Product

If we want to use accelerated corrosion testing for complete products such as whole (especially mobile) machinery and its major components, or mobile machinery, we have to take into account other influences besides the prior studied factors on the corrosive destruction of this machinery in real life. This mechanical damage to protective films during surface drying is affected by other influences such as road salt in the winter, impact of sand dust thrown up by wheels, any mechanical wear or even solar radiation, etc. And we must simulate these factors correctly.

Thus, it is becoming more common for mobile product life testing to include in the corrosion test conditions the combination of motion from special road or off-road simulation with a bath or spray of a saline solution[26]. One such program includes the following list of conditions during one day:

- 6 hours in corrosive test chamber (salt spray or fog, with humidity, and high temperature);
- movement through a bath or spray of 5% salt solution;
- motion via simulating a 40 mile drive along a dust road, combined with simulating 14 miles of macadam road and 3 miles of cobblestone road;
- repetition of movement through the bath or spray with 5% salt solution.

The equivalency of corrosion destruction of the automobile by accelerated testing and by field will testing be[26]:

$$D_f = D_a + D_s (N)$$

where:

D_f is the maximum depth of designed corrosion for a life-time in the field, in mμ;
D_a is the maximum depth of corrosion life testing, ignoring the time of stress influences, in mμ;
D_s is the maximum depth of corrosion for the time of testing in a regime of stress influences of moving cycles with use of the corrosive test chamber, in mμ.

If we take into account that corrosion depth has a constant speed, then

$$\lambda_f T_f = \lambda_{s.r.}(T_{s.r.} - T_s) + D_s (N)$$

where: T_f is the life-time of automotive components under given conditions, such as the normative index of corrosive endurance of the test subject, in years;
$T_{s.r.}$ is the common duration of special road testing, in years; T_s is the duration of testing stress regimes, in years;

λ_f, $\lambda_{s.r.}$ are the speeds of distribution of atmospheric corrosion in given field conditions and accelerated testing conditions, *mμ*/year; *N* is the number of cycles of accelerated stress corrosive influences;

D_s *(N)* is dependence of corrosion depth on the number of accelerated stress testing cycles.

One can use these values of time T_f, and $T_{s.r.}$ for basic types of studied components from actual use experience, for new components – for technical conditions, prototypes, and estimates of accelerated testing duration. For the measurement of the value of corrosion influences on accelerated testing in order to obtain corrosive results there are identical to field testing, one has to evaluate the function D_s *(N)* which measures the correlation of corrosion depth to the number of cycles of the accelerated influences.

As a research result of averaging the common most probable dependency of automobile component corrosion depth found from a number of accelerated testing cycles in correspondence with the above methodology, it can be shown that

$$D_s^0\,(N) = 11.2 \cdot N^{0.7}$$

The dispersion of the evaluated function of deviation:

$$D_d = 536\ m\mu^2$$

The confidence interval of function D_σ^0 *(N)* on each fixed level of argument N_I can be evaluated as the confidence interval of its mathematical expectation evaluation in given experiments by *n* = 8 random observations and the obtained common variance of their deviations. If we use Student's criterion, for counting this interval we use the following equation:

$$T_\beta = D_s^0\,(N_I) \pm t_\beta\sqrt{}D_d/n$$

where: index β is determined by the confidence probability of the calculated interval of function D_s^0 values; t_β is evaluated by the Student's distribution density tables for the accepted value β and $n - 1$ degrees of freedom.

In Figure 2. 33 is shown the common approach for building this interval for 99% probability.

Now one can calculate the necessary number of influence cycles for corrosion testing of automobiles as well as their components, and other types of mobile products, from the following formula:

$$11.2\cdot N^{0.7} - k_1N - k_0$$

where: $k_1 = T_c/365 \cdot \nu_{s.r.}$; $k_0 = \nu_f T_f - \nu_{s.r.} T_s$

This approach has been used for accelerated corrosion testing to evaluate different types of components in the automotive industry, farm machinery, off-highway equipment, food technology, and others so the above illustrates the modern essential of accelerated corrosion testing.

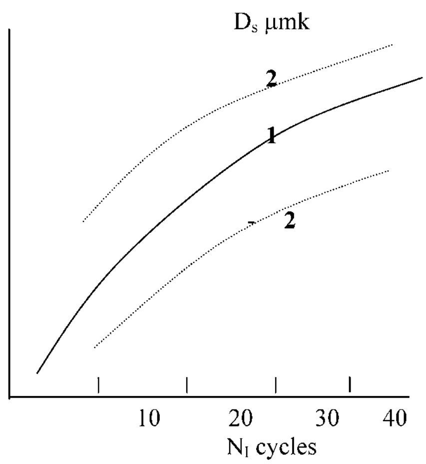

Figure 2. 33. Statistical-probability generalization of the data about the corrosion depth by dependence on the cycles number of stress influences combined with the used corrosion chamber and normalized road motion: 1 = approximated mathematical expectation of function D_D^0 *(N)*; 2= the limit of its 99% confidence probability intervals; T_c is the duration of one cycle of stress influences by testing, in days; and ν_f, $\nu_{s.r.}$ are speeds of corrosion development under given climatic conditions, *mμ*/year.

9.7. 5 Anaerobic Microbial Corrosion of Steel

Anaerobic microbial corrosion of steel is a major cause of deterioration (destruction) of piping and other structures related to the nuclear and fossil fuel electric power generating companies, armaments, gas pipelines, and industries related to pulp and paper, oil fields, ships, and off-shore[14].

The cost to the oil industry[27] has been estimated at $1.4 billion per year and the gas pipeline industry has estimated that over 70% of their corrosion cases were caused by micro-organisms.

Although micro-organisms have clearly been implicated in this corrosion, the mechanism and method of measurement of the degradation process are not clear and no studies have conclusively shown that corrosion initiation and progression is the direct result of microbial activity.

Therefore, before carrying out accelerated corrosion testing for the action of the micro-organisms, one has to study step 1 "Obtaining initial information from the field" (see section 8, Chapter 2). After one understands the degradation mechanism, it is possible to simulate the conditions in the laboratory for accelerated testing of these products.

Now the major principles of the anaerobic microbial corrosion of steel will be described briefly. Under anaerobic conditions two mechanisms appear to be of principal importance to the microbial corrosion process: cathodes depolarization and dissolution by hydrogen ions associated with acidic fermentation products. Cathodes depolarization involves utilization of hydrogen molecules which encourages oxidation of elemental metals to the ionic state as shown in Table 2.13.

Table 2. 13. Cathodes depolarization theory for microbial corrosion of metals using iron and sulfur reducing bacteria[27].

Process	Reaction
Metal dissolution	$4\ Fe^{\circ} \rightarrow 4\ Fe^{+2} + 8\ e$
Hydrogen reduction	$8\ H^{+} + 8\ e^{-} \rightarrow 8\ H \rightarrow 4\ H_2$
Water dissociation	$8\ H_20 \rightarrow 8\ H^{+} + 8\ OH^{-}$
Microbial activity	$SO_4^{-2} + H_2 \rightarrow S^{-2} + 4H_2O$
Corrosion product 1	$Fe^{+2} + S^{-2} \rightarrow FeS$
Corrosion product 2	$3Fe^{+2} + 6OH \rightarrow 3Fe\ (OH)_2$
Summary reaction	$4Fe + SO_4^{-2} + 4H_2O \rightarrow 3Fe(OH)_2 + FeS + 2(OH)^{-}$

The concept of the corrosive metabolite theory, where microbial metabolites such as organic acid fermentation products cause corrosion, was proposed by Iverson[28] and Pope[1]. This mechanism is illustrated in Table 2. 14. Hydrogen ions associated with organic acids catalyze the dissolution of metals and serve as electron acceptors for metal oxidation. For those organisms producing acids and utilizing hydrogen, such as Desulfovibrio and Clostridium the two mechanisms are additive.

Table 2. 14. Microbial metabolite corrosion by acetic and butyric acids[1].

PROCESS	REACTION
Production of acids	Organic matter → Hac + Hbu
Dissociation of acids	Hac → H^+ + Ac; Hbu → H^+ + Bu-
Metal dissolution	$4Fe° \rightarrow 4Fe^{+2} + 8e^-$
Hydrogen reduction	$8H^+ + 8e^- \rightarrow 8H \rightarrow 4H_2$

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10 ACCELERATED VIBRATION TESTING

Accelerated vibration testing can be used as one of the components (Figure 2.7) of accelerated mechanical testing, which is a unit of accelerated reliability testing, as well as an independent type of accelerated testing. It depends on the goal of testing. This type of testing goes as far back as 1915[1].

The equipment for vibration accelerated testing must be accurate in order to simulate real life input influences on the actual product. This is one of the basic criteria for the use and development of the above equipment as a component of accelerated reliability testing.

10. 1 ANALYSIS OF THE CURRENT SITUATION

The vibration of a product is an output parameter. The input influences for mobile products shown in Figure 2.34 consist of the features of the road (type of road, profile, density, hardness, moisture, etc.), design and quality of the wheels, coupling of the wheels with the surface of the road, stability of the surface due to weather changes, speed of test subject's movements, speed and direction of the wind, etc. The types of road may be concrete, asphalt, cobblestone, or dirt road, etc. Most of these surface influences have a random character and are related to each other. This influences the stiffness, inertia, elastic, and damper qualities of the product. The result of this interconnection is vibration of a mobile product on a particular surface, under specified conditions. Therefore, the mobile product should be treated as a dynamic system which vibrates as a result of these interconnections.

There are two generations of field vibration physical simulations: proving grounds and laboratory testing equipment. Both were developed in the 20 th century and continue to be developed in the 21 st century. Large companies and test centers can use and develop both generations.

One of the most well known proving grounds in the USA is the Nevada Automotive Test Center (NATC)[2]. NATC since its founding in 1957 has evaluated, tested, and certified more than 1,500 vehicle systems and millions of components for commercial, military, and public utility applications. With more than 3,000 miles of test courses plus access to nearly 1 million acres ranging from 12,000 foot mountain passes to live sand dunes, NATC can test and evaluate wheeled and tracked vehicle systems over outdoor terrain or by use of road simulators.

Usually these test centers have many different test chambers and other test equipment, but basically they consist of different types of road simulation in the form of proving grounds.

The negative aspects of this approach include: 1) it is often too expensive for middle-sized and small companies to use the proving grounds; 2) the vibration process cannot be controlled; there is a dependence on outside weather; and 4) it is not convenient for separate divisions and departments of large companies.

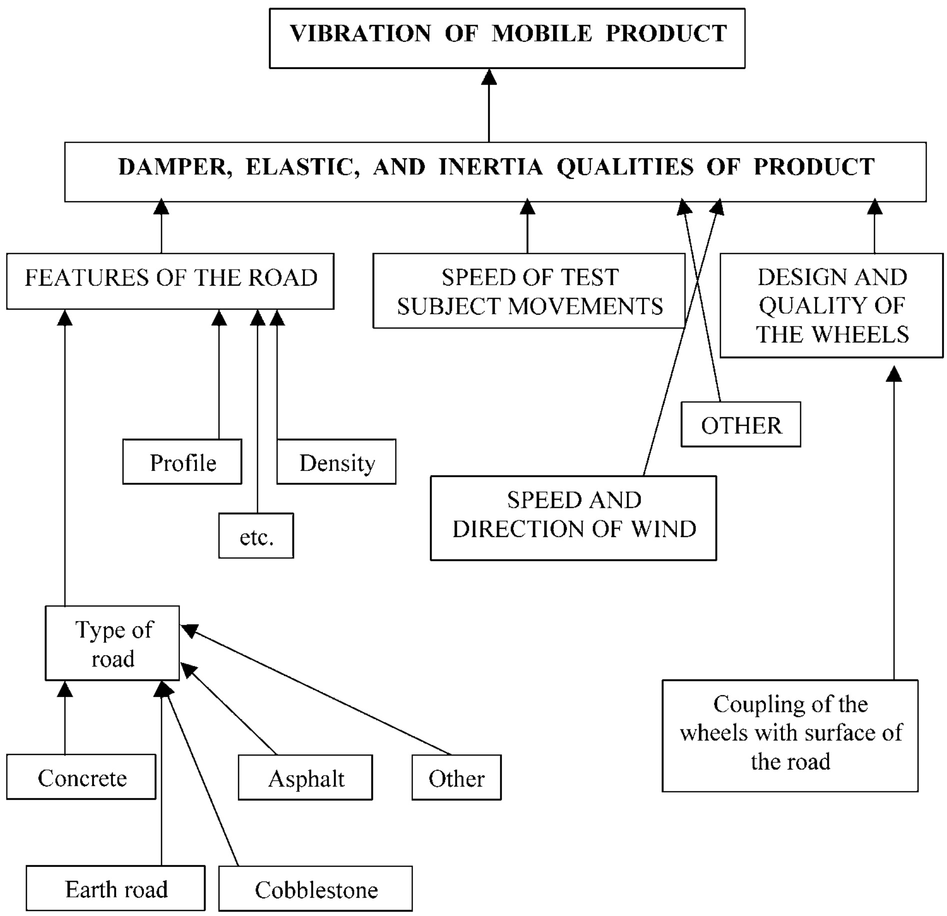

Figure 2.34 Vibration of a mobile product as the result of input influences.

The vibration test equipment (VTE) that simulates these (Figure 2.34) input influences can be part of the complex equipment for accelerated reliability testing, as well as part of simpler test equipment that combines of vibration with environmental or other influences (for example, temperature and humidity). There may be separate specialized vibration equipment for special test goals. These include, for example, vibrofatigue evaluation.

Therefore, basic trends for use and development of this VTE approach of testing include the following factors: more accurate simulation of real life mechanical influences on the product; reduction of the cost of simulation; vibration testing of the product and the connection of the vibration testing with other types of mechanical testing, and electrical, environmental, and other types of testing.

Initially vibration testing was developed with simple uni-axial shakers. Today multi-axial servohydraulic, electrodynamic, and pneumatic shakers have eliminated most of the negative aspects of this test method and the proving grounds.

Many middle-sized and small manufacturing companies, university research centers, and first time user companies still prefer to use low cost single axis vibration systems. For this goal companies such as VTS[3], MRAD Corporation, IST[4], TEAM[5], etc. design and manufacture simple shakers. Mechanical shakers cost less than other varieties. Their moving elements consist of three or four counter-rotating eccentric weighted shafts driven by an electric motor.

The amplitude of motion is precisely adjusted with a lead screw. Easy access to all adjustments is through removable panels. This type of shaker often has self-contained coil springs to isolate the shaker and test load from its base. The shaker can be operated on any floor capable of carrying dead-weight loading. There are no air bags to accidentally deflate during operation. The IST low cost single axis systems are designed for sinusoid wave or random vibration.

Spectrum control has the capability of notching discrete frequencies to minimize the bending of the core of the board undergoing screening. The TEAM horizontal vibration system is completely self-contained, and requires only a sinusoid curve or random test controller, electrical power, and cooling water to operate. The T-Film shaker can do sine testing over a frequency band from 5 Hz to 2,000 Hz. At low frequencies the shaker is stroke limited. At intermediate frequencies it is velocity limited and at high frequencies it is acceleration limited. Higher harmonic distortion occurs at high frequencies.

The simple shakers also have some negative aspects. These includes problems with low levels of vibration correlation in comparison to field vibration. Therefore, in the 1950s the companies designing vibration equipment began to produce more servohydraulic, electrodynamic, and pneumatic equipment with control systems to solve this problem. This equipment is more expensive, therefore middle-sized and small companies continue to use simple shakers wherever possible.

Any laboratory vibration testing equipment has a large negative aspect compared with track testing. This is a much lower quality of road simulation (see Figure 2.35). The use of servohydraulic equipment for vibration testing in the laboratory with block-programmed control began in the1950s. The accuracy of simulation was much lower (Figure 2.35) than on the proving ground, but the lab simulation was much cheaper.

The companies that designed servohydraulic equipment during the next 50 years continued to improve their equipment. Each step of improvement (including the system of control) made this equipment more expensive. But the quality of road simulation improved slowly, because the principles were unchanged. Therefore, this approach has not proved useful for some users of this type of equipment. The basic negative aspect (simulation of profile instead of road simulation) was not improved. In 2004 the companies (MTS Systems Corporation[6], IST, and others) continued to improve the profile simulation instead of road simulation. The description of this situation can be seen in Figure 2.34.

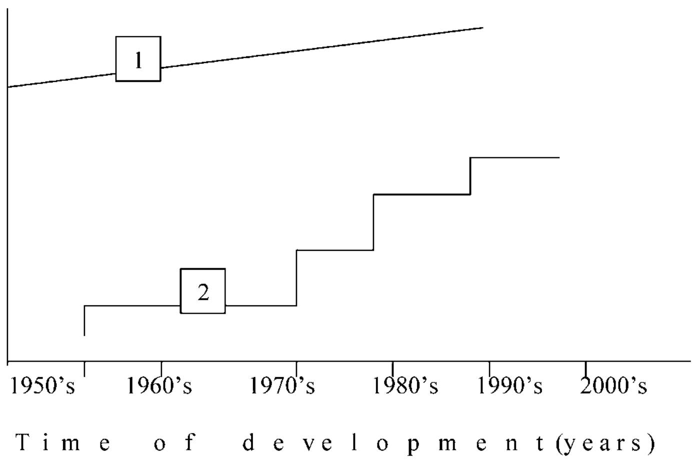

Figure 2.35. Development of vibration testing quality: 1– proving ground; 2 – vibration equipment in the laboratory.

Therefore, accurate simulation of road vibration is still one of the basic trends of the vibration testing technique development.

There are two basic aspects of vibration testing equipment (VTE) in the technical area. The first is the type of vibration i. e. electrodynamic, electrohydraulic, or pneumatic. The second involves the system of control: block-programmed or different types of computer control (analog, digital, etc.) (Figure 2.37).

Many companies in the world produce electrohydraulic VTE. Carl Schenck, Instron, and MTS Corporation are the largest and most famous companies in the world which design and manufacture this type of vibration equipment. The range of their product frequency is usually 0.1 -100 Hz, with an amplitude of 0.1 mm to 90 mm. Carl Schenck and MTS Corporation have been producing electrohydraulic equipment since the 1950s (Figure 2.36).

The modern solution of vibration testing is a Multi Axis Simulation Table (MAST) system that is designed for vibration testing of a wide range of test specimens. Vibration input can be generated in up to six degrees of freedom: three linear – vertical, lateral, and longitudinal, and three angular – pitch, roll, and yaw.

Similar types of multi-axis simulation table (MAST) have been produced and developed by the MTS Systems Corporation[6], Carl Schenck, Instron Structural Testing systems (IST), and others.

Recently they also developed a test control transducer called a Spinning Wheel Integrated Force Transducer (SWIFT).

Now IST has developed[4,7] several standard design MAST tables: MAST 9710, MAST 9720, MAST 9730, and MAST 35. All can give vibrations in six degrees of freedom, maximum angle – pitch, and angle – yaw ±8.5°, maximum angle – row ±6.8°, operating frequency range 0.1 – 50/ /60 Hz, stroke is ±16 mm.

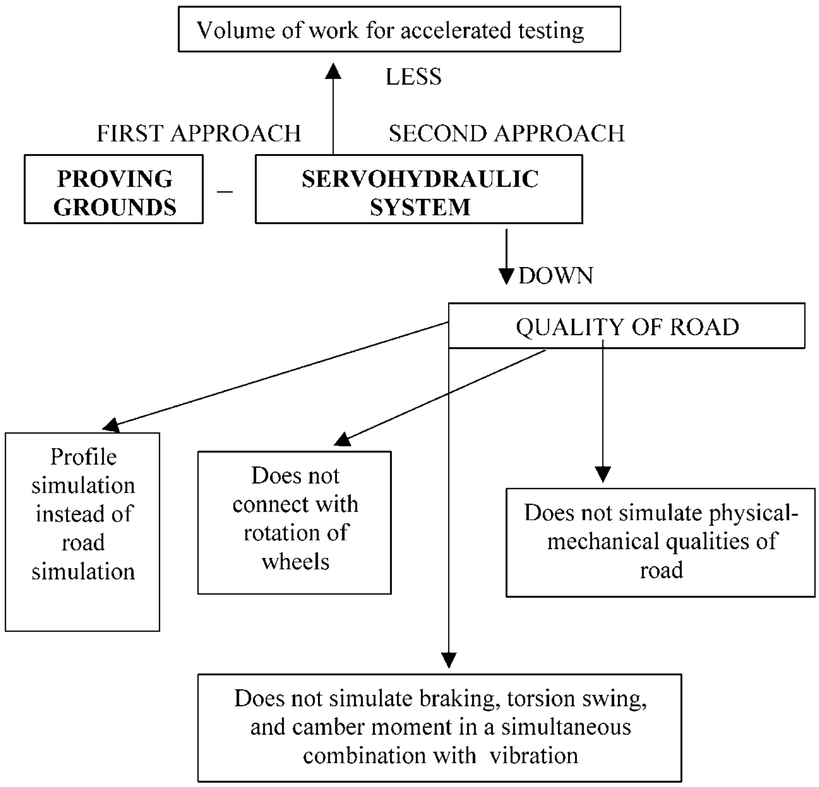

Figure 2.36 Two general directions of vehicle accelerated vibration testing development.

The maximum payload of the first and second models is 450 kg (990 lbs), and of the third model is 1000kg . The first model table has a mass of 300kg (660 lbs), and the second and third have masses 545 kg (1200 lbs)[4].

As was shown above, one of the basic negative aspects of the present electrohydraulic and electrodynamic vibration testing (and other types of testing) is insufficient methodology for real life simulation of input influences in the laboratory.

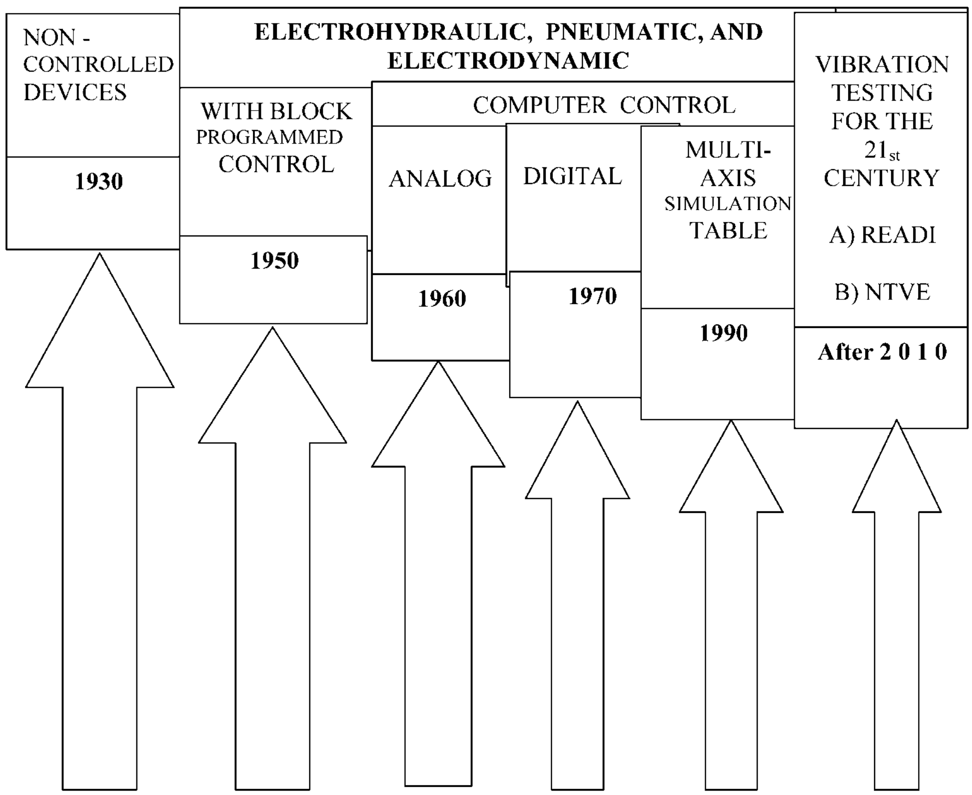

Figure 2.37 Stages of basic vibration testing equipment development.

Usually it consists of three basic steps: profile of the road and load (acceleration, tension, etc.) data of the test subject; signal processing and analysis; and laboratory test setup.

The first step is to collect vehicle load, moment, or motion data. Multiple passes of each road surface are collected to ensure a representative sample of usage. Data are stored in a time history format to retain important frequency, amplitude, and phase information between channels. The second step consists of time based editing or analysis; statistical analysis and amplitude based editing; fatigue analysis and cycle based editing; frequency analysis and digital filtering. The test setup involves considerations of: motion or load simulation; fixed, semi-fixed, active, or inertial reaction; direct, matrix or degree-of-freedom control; load or stroke feedback; simulation frequency passband; and fatigue correlation assessment.[4]. The complete test system includes a mechanical test fixture, servocontrols, specimen, and instrumentation[4].

This approach was satisfactory 20 or more years ago. Today there is better developed equipment, especially in the areas of load simulation, load feedback, and other criteria for real life simulation. First, we cannot simply use the load or acceleration correlation of the field and laboratory as a criterion of the quality of the simulation, i. e road simulation for vibration testing.

Rather, the objective criterion has to be the results of testing. In general we cannot always use failures for this testing goal, because this requires a longer time. For this goal the best criterion at present is a mechanism of product degradation which can be evaluated rapidly. The basic result of vibration testing is typically mechanical degradation. The measurable parameters of the mechanical degradation mechanism can usually be through deformation, crack, wear, or creep measures be they detector direct or indirect.

The second negative aspect of electrohydraulic and electrodynamic types of vibration equipment is that they cannot accurately simulate the "machine - road" combination of moving wheeled vehicles. The field vibration acts simultaneously with the effect of rotation of the test subject's wheels. This situation creates a unique problem in the VTE where there are no braking, torsion swings, and camber moments simulated as they act in real life. The following conditions are also not well simulated by simple VTE: 1) physical-mechanical quality of roads and fields, and surface including density, hardness, wear possibility, moisture, etc. that are features of asphalt, concrete and different types of soil surfaces; 2) fluent movement of the test subject's wheels across any road obstacles; 3) impact influences on the wheels and structures. Profile simulation makes some attempt to include these effects, but typically not road simulation.

Therefore, the market does not reflect the real situation with vibration testing equipment. Currently it includes only a small part of the required equipment. One can understand the real situation from Figure 2.38. Designers and researchers continue to work in order to eliminate these negative test aspects[8,9,10,11].

Laboratory vibration testing is accelerated testing which is typically operated under stationary conditions of the test vehicle. This makes it possible to use this technique to find some of the reasons for failures more quickly. To improve the understanding of this testing, this equipment may be combined with video tapes of the system's response under stress. The new crash simulator developed by MTS[12] is available for viewing in a short video which was shown at the1999 SAE Congress, Detroit.

The basic principles and use of this method were developed by the authors more than 20 years ago [[13], pp. 125 – 128]. At that time, high speed video was not available, but a speed movie was used to illustrate this idea. The authors described in detail and with examples how use of both high speed movies and accelerated testing made it possible for better understanding of the reasons for the degradation process. This knowledge helps to eliminate these reasons rapidly, thus accelerating improvement of product quality. The authors showed how[14] one can rapidly find the reasons for truck degradation and failure and remove them.

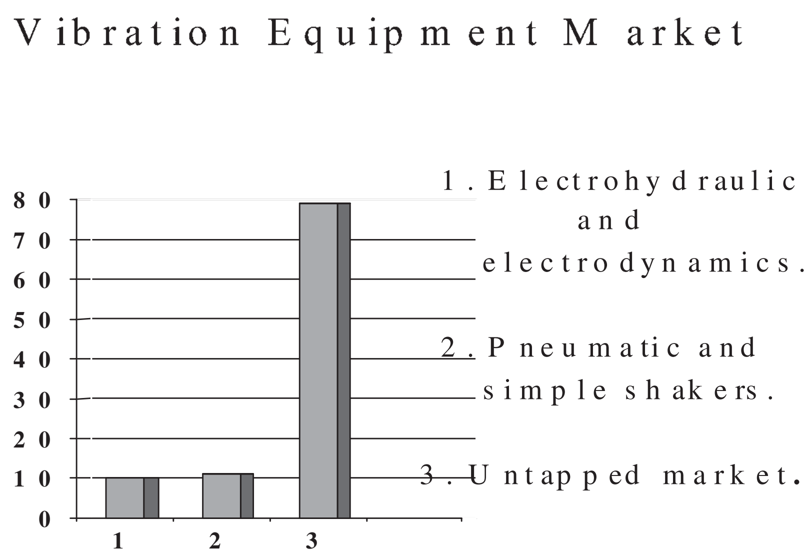

Figure 2.38. The situation with vibration testing equipment in the market.

One of the world leaders in electrodynamic (electromagnetic) vibration test systems is Ling Dynamic Systems (LDS). For over 40 years Ling Dynamic Systems has been at the forefront of this technology[15]. The frequency range of their electrodynamic vibration test systems can be from 5 to 13000 Hz, and the range of displacement runs from 1 to 75 mm. This type of vibration equipment is used for testing high speed products such as aircraft, aerospace, and many types of electronic systems. Recently electrodynamic vibration equipment has been developed to put test items through their paces in the two horizontal axes as well as the vertical axis[15]. The major disadvantages of electrodynamics shakers are the same as described above for servohydraulic equipment, which also includes its inability to produce a multi-axis simultaneous vibration[16].

Ling Electronics[17] produces electrodynamic vibration equipment which is selectively arrayed on the stroke, frequency, cross-axial and rotational restraint requirements of the vertical test system. These are combined with a pneumatic load support system to provide a low cost system, capable of good performance from 5 to 2000 Hz. Support structures for test samples may be required for attachment to the shaker body and/or the system reaction mass. These structures often have an impact on the performance of the shaker. Test equipment employing six degree of freedom has come into use during the last 10 years. Team Corporation[5] has produced the CUBE™ testing system. This system has the ability to perform multi-axis testing over a wide range of features and frequencies. This flexibility, coupled with the small size of its module, has made the CUBE the system of choice for the car seat testing application. The CUBE's design which incorporates high-performance exciters into a compact, six-degree-of-freedom testing system, makes it a flexible system to apply to a variety of test situations. Already under consideration are applications to test instrument panels and entire vehicles. Many other smaller companies produce analogous vibration systems.

Unholtz-Dickie (Germany) has developed a feature to solve the age old problem of keeping unwanted water and foreign particles from entering the slip table recirculating oil. Contaminants increase the oil replacement frequency, require additional maintenance and decrease reliability.

The below table 2. 15 shows the T2000 series electrodynamic test equipment.

There is very effective implementation of the testing equipment and methods with this equipment, which is the result of collaboration between test engineers, reliability engineers, product designers, and specialists from companies who produce testing equipment. The authors' experience[13,14,19] and the experience of other specialists confirm this. A good example of collaboration is shown in Meier, Otto, Pielemeir, and Jeyabalan work[10].They are based in the Ford Motor Company, and describe how in collaboration with Bill Woyski, John Davis, and Bob

Table 2.15 System performance and configuration[16].

SYSTEM MODEL	SA 160-T2000--64	SA 160 E-T2000-44	SA 1120-T2000-44	2XSA 1120-T2000-64HS
Sine Force (pk)	15,000 lbf (67 kN)	15,000 lbf (67 kN)	20,000 lbf (89 kN)	25,000 lbf (111 kN)
Random Force (rms)	15,000 lbf (67 kN)	15,000 lbf (67 kN)	20,000 lbf (89 kN)	22,000 lbf (98 kN)
Half Sine Shock[1] 4 ms vs Payload lb ms	50 g: 500 lb 100 g: 200 lb 160 g: 70 lb 30 g: 800 lb 50 g:500 lb 70 g: 100 lb	50 g: 500 lb 100 g: 200 lb 160 g: 70 lb 30 g: 800 lb 50 g: 500 lb 70 g: 100 lb	50 g: 800 lb 100g: 300 lb 250 g:60 lb 30 g: 1,200 lb 50g: 800 lb 100 g: 160 lb	50 g: 1,100 lb 100 g: 520 lb 300 g: 70 lb 30 g: 1,500 lb 50 g: 520 lb 100 g: 180 lb
Usable Frequency Range				

Table 2.15 (continuation) System prformance and configurations.

Maximum acceleration Sine (pk) Random (rms) ISO 5.344	120 g (1177 m/s^2) 90 g (882 m/s^2)	120 g (1177 m/s^2) 90 g (882 m/s^2)	80 g (1765 m/s^2) 100 g (981 m/s^2)	200 g (1961 m/s^2) 170 g (1667 m/s^2)
Maximum velocity (pk) Sine Sweep[3] Shock	50-70 in/s 107 in/s	50-70 in/s 107 in/s	70-80 in/s 143 in/s	80 in/s 160 in/s
Shaker Displacement (pk-pk)[8.15]	2.0	inches	(51	mm)

Armature weight — 100 lbs (45 kg)

Armature diameter — 17.5 inches (445 mm) overall dia, with 16 inches (406 mm) dia, outer bolt circle

Armature resonance (f_R) (typical) — 2,250 Hz

Shaker body isolation standard — 4 Hz with air mounts and damping tanks

Electrical Requirements Total	140 KVA	140 KVA	210 KVA	270 KVA
Acoustic Noise (2m) Amplifier	<75 dBA	<75 dBA	<80 dBA	<80 dBA

Notes:

1. Shock ratings based on symmetric pre & post pulses (+12, - 24 %). All UD shakers are rated for shock pulses at three times the random force rating. However, the actual system's performance depends on the size of the power amplifier, pulse shape, pulse duration and weight of the test load. All the indicated numbers represent the actual system performance, not a hypothetical maximum. Extensive shock performance curves are available for each system on request.

2.Usable frequency range dependent on the test level and payload.

3. Maximum sine sweep velocity varies for high and low field setting.

Tauscher from TEAM Corporation they developed an effective vehicle vibration simulator (VVS) for subjective vibration testing. The authors described how they made the first multi-axis, fully integrated vibration test system to be used for automotive applications. Initially, the vibration simulator had been used to study vehicle ride and truck idle quality. In 1993 a project was started to develop a Vehicle Vibration Simulator so that the reliable quality process could be applied to vehicles. The results of these studies demonstrated that Ford VVS has the potential to become an extremely valuable tool for the vibration engineer.

It has been shown to provide a more consistent and repeatable environment for human subjective testing of vehicle vibration, and to allow blind evaluation of different vehicles (eliminates brand bias). The authors are confident that the full potential of VVS will eventually be demonstrated through the application of more studies, including:

- Simulation of transmission shift;

- Basic research on vibration perception;

- Seat and steering wheel component evaluations and comfort studies;

- Vehicle ride and harshness evaluations for metric development.

The environmental test program for the Cassini spacecraft included a force-limited vertical-axis random vibration test. The flight limit applied loads were achieved at a number of critical locations on the spacecraft, and the instrument responses were similar to those observed during the component random vibration tests[20]. According to the author force limiting has been used extensively in the vibration tests of many of the instruments and subassemblies on the Cassini spacecraft, especially in the vertical axis random vibration test of the complete spacecraft; semi-empirical force limits were used in a number of the Cassini vibration tests.

Semi-empirical force limits require only the acceleration specification and data from a low-level vibration pretest and are, therefore, much simpler to develop than previously described force limits based on analytical models and measurements of the mounting structural mechanical impedance; with piezoelectric, three-axial force transducers the acceleration of the center of gravity (CG) may be accurately measured in vibration tests, according to Newton's second law.

The capability of accurately measuring CG acceleration with force transducers provides a convenient means of limiting the quasi-static acceleration, commonly used for design purposes, to a fraction of the design limit.

More accurate simulation of real life input influences is a basic *technical trend* of developing and using vibration testing. But the selection of test equipment also relates to the *economical* aspects of the situation. There are dozens of companies in the USA and abroad that design and manufacture equipment for vibration testing.

But the paradox is only about 40 - 45% of the current market (needs) has been filled with current mechanical shakers, electrohydraulic, electrodynamic, and pneumatic types of equipment for vibration testing (Figure 2.38). The remaining 55 - 60% is an untapped or potential market for improved capable equipment. The economic trade - off and perceived benefits strongly influence when older equipment is replaced with modern equipment. There are two basic reasons for this situation. First, the multi-axis equipment, especially in six degrees of freedom, that provides the stochastic process, may appear to be too expensive for some companies, universities or research centers.There are products that would benefit from fatigue testing, durability testing, reliability testing, or special vibration testing with the simultaneous combination of vibration, or even combined with other conditions (environmental, electrical, mechanical, etc.). It is very expensive for most companies.

The second reason is that the present worldwide equipment cannot adequately simulate the real life input influences. Therefore, accelerated testing does not appear to have sufficient correlation with real life results, and users cannot obtain accurate information for fatigue, durability, or reliability evaluation and prediction of the product in the field. Thus, we often hear and read more about the negatives of accelerated testing than about the possible benefits of accelerated durability or accelerated reliability testing. This is complicated by the fact that often field failure costs are poorly estimated, thus it is difficult to persuade management of the possible benefits.

One can solve this very important problem only when the technical benefits are better understood and the true cost savings can be documented. Such improvements will lead to less expensive equipment and wider use.

This is the basic problem with all improvement trends of the 21st century.

10. 2 DEVELOPMENT OF ACCELERATED VIBRATION TESTING

The authors and their colleagues created a model for new technology vibration equipment (NTVE) 15 years ago. This technology is based on theoretical and experimental research results on electronics, car trailers, trucks, and farm machinery, etc. Improved vibration testing technology has unique features such as working heads which provide assigned random values for acceleration amplitude and frequency. The system of control consists of a computer with a peripheral network system, and sensors for vibroacceleration and tension. Vibration can be provided for both mobile and stationary products, as delivered universal vibration equipment as well as dedicated equipment for special products. It covers wheeled and unwheeled applications acting in 1 – 3 linear and 1 – 3 angular axes (six degrees of freedom). The design of this VTE is simpler than many modern electrohydraulic and electrodynamic equipment systems with no deterioration of performance, and it also expands the functional applications to a wider range of markets. Table 2.16 presents the specifications.

This equipment is easy to mount for operation and to add other elements, such as transmission, engine, or other auto accessones.

The scheme of computer controlled VTE for the car with test subject is shown in Figure 2.39.

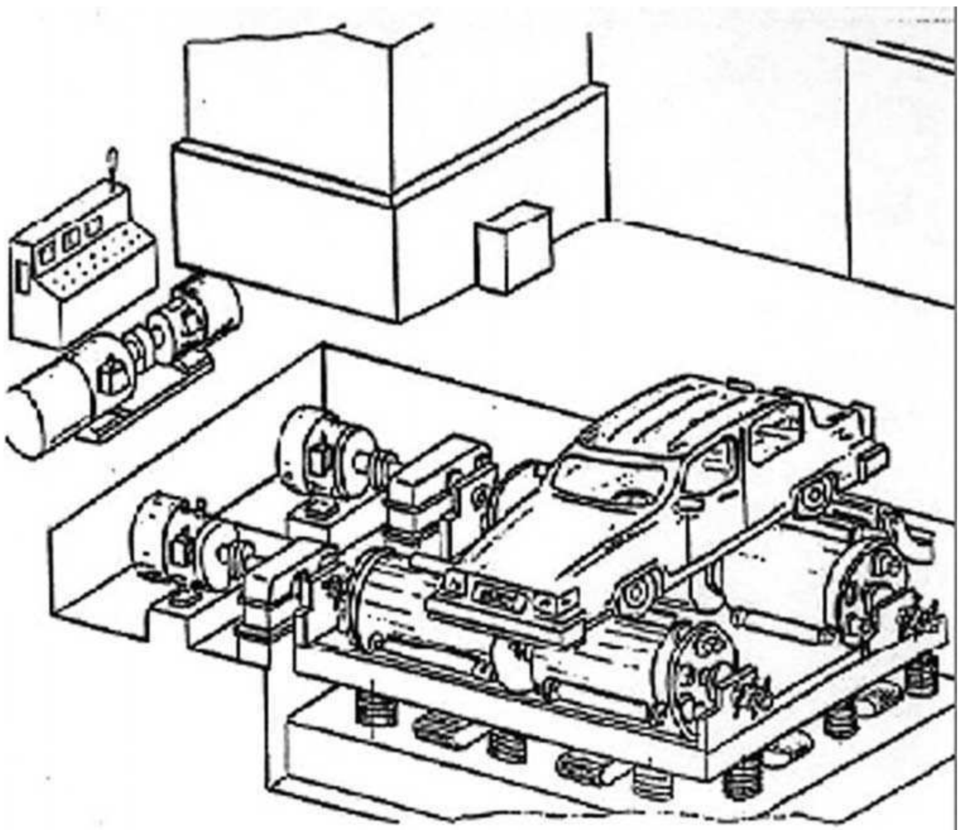

Figure 2.39 Scheme of vibration equipment for the car with test subject.

The new computer controlled VTE for whole car trailers is shown in Figure 2.40. This equipment act in three linear axes.

Figure 2.40 Vibration computer controlled equipment with test subject – a car trailer.

Table 2.16 Example of typical specification for new vibration equipment.

Names of indexes	Test subject	
	With wheels	Without wheels
Weight of test subject, tons	up to 30	from 0.001 to 2.00
Weight of vibration equipment, tons	38	from 0.002 to 4.00
Axles excited	3 linear	3 linear + 3 angular
Table sizes		from 20” × 20” to 100 × 100
Frequency of vibration of the tested product, Hz	0.1 – 80*	0.1 – 200*

Table 2.16 (continuation) Example of typical specification for new vibration equipment

Amplitude of vibration of the tested product, mm	from 0.1 to ± 90 (wheel swing axles)	from 0.1 to ± 90 (table)
Necessary power, kW	120	from 1.6 to 105

*Can be more if necessary.

This technology is used on electronics, car trailers, trucks, farm machinery, etc. Tables 2.17 and 2.18 show part of the car trailer testing results.

Table 2.17 The frequency of vibroaccelerations of the car's trailer axle.

Type of road	Field			Under laboratory conditions		
	linear speed, mph	minimum frequency, Hz	maximum frequency, Hz	linear speed of drum, mph	minimum frequency, Hz	maximum frequency, Hz
Town road	37.50	26	248	5.60	16	324
Highway	50.00	36	224	5.60	24	357
Field	12.50	28	221	4.05	26	362
Cobblestone	12.50	30	271	3.08	23	314

Table 2.18 Results of comparative testing of the car trailer in the field and the laboratory.**

Type of testing	Linear speed, mph	Tension at the most loaded point of the trailer frame, kg/cm^2	%
empty trailer			
town road	37.50	272.00	100.00
laboratory	5.60	251.00	92.00

Table 2.17 (continuation) Results of the comparative testin on the car trailer in the field and the laboratory**

full trailer			
highway	37.50	442.00	100.00
laboratory	5.60	424.00	96.00
field	12.50	318.00	100.00
laboratory	4.00	312.00	98.10

** The mathematical expectation is shown. The normalized correlation and power spectrum would have a difference similar to that of frequency and amplitude.

The difference of the tension in the laboratory (new vibration technology) as compared to the field is no more than 8 %.

Figure 2.41 shows that the characteristics of random process for the new vibration equipment are also similar to these characteristics in field conditions.

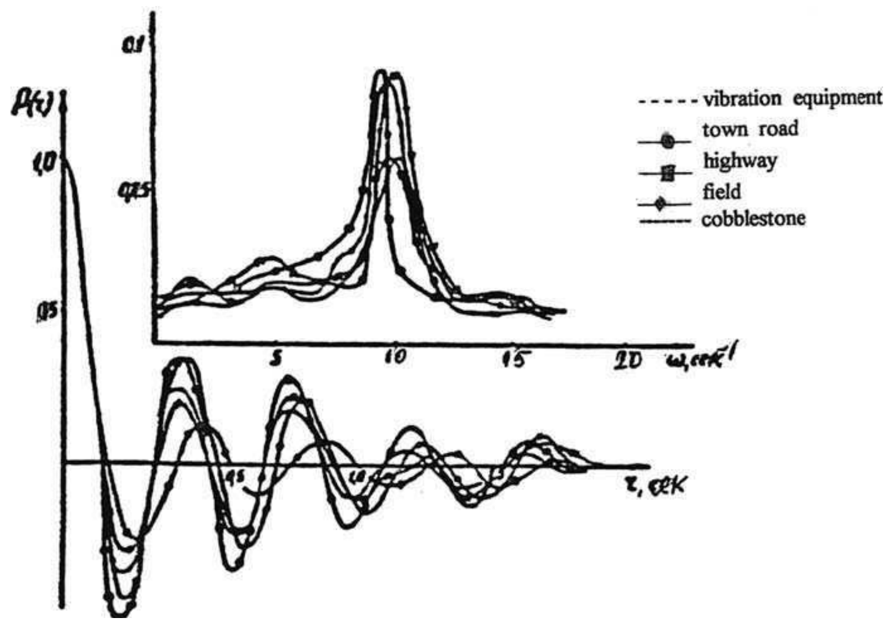

Figure 2.41 Normalized correlation and power spectrum of frame tension data for the car trailer's in field conditions and with the new vibration equipment.

The results of testing show that this direction gives the possibility to eliminate some of the negative aspects of the current vibration equipment.

For example, this equipment has the following possibilities:

- It has the ability to simulate different physical-mechanical qualities of roads, which cannot be done with the current vibration testing equipment.

- It can simulate torsion swing in the simultaneous combination of linear and angular vibrations which cannot be provided by current equipment.

- It can bridge the connection between vibration testing and dynamometer testing.

This equipment is easy to mount, to control the speed and to add other elements, such as transmission, engine, clutch, fans or power system with their simultaneous vibration requirements. The design of this equipment is much simpler than current electrodynamic and servohydraulic equipment, therefore it is several times less expensive.

The second type of new vibration equipment is similar to the above design, but is simpler and less expensive. It can be applied to many types of stationary and mobile products such as mechanical, electrical, electronic, etc., and to more complicated products.

Therefore, this equipment can satisfy a large part of the 55 - 60% untapped needs.

Another vibration testing model for the 21_{st} century is possibly Model READI (Rules for the Exchange and Analysis of Dynamic Information) (Figure 2.42)[11]. The READI is used to describe the physical process that controls field vibration data and how to use this data to define realistic laboratory test environments. This model is a subset of the more general area known as vibration testing. Vibration testing can be defined as " *the art and science of measuring a structure's response while exposed to its dynamic environment and simulating this environment in a satisfactory manner to ensure that the structure will either survive or function properly when exposed to this dynamic environment*" [11]. The results show the following situations: numerical simulations were performed in order to investigate the test scenarios previously described.

Viscosity damped lump parameter models were employed in the field and laboratory simulation simulations. Test items and vehicles were modeled by four DOF systems, and two field environments were studied.

The process for operating this system includes the following. First, the test item is absent from the field and the background field data consists of the bare vehicle interface accelerations.

Second, the test item is attached to the vehicle in the field at two interface points. Field interface forces and test item interface and external accelerations compose the field data in this case.

In the laboratory environment, multiple exciters are used to generate and control the test item inputs. The pseudo-inverse technique is employed to define the test item laboratory inputs.

The major conclusions obtained in the numerical simulations with READI include: blind application of the bare vehicle interface data to define the test item laboratory inputs without accounting for the vehicle's interface driving and transfer point FRFs leads to significant errors; field external force effects must be accounted for in the laboratory in addition to interface force effects in order to obtain reasonable simulation results; when using the pseudo-inverse technique with random type signals, acceleration CSDs (Cross Spectral Densities) must be accounted for in addition to acceleration ASDs (Auto Spectral Densities). This is because motions are always correlated independently of whether the input forces are correlated or uncorrelated. The results of experimental investigations showed that the pseudo-inverse technique is feasible when working with experimental random signals as long as the correspondence equation is used in the force estimation process. This requirement is independent of forces being correlated or uncorrelated since motions are always correlated. The solutions for the input forces were obtained by a method where by the number of motions used was larger than the number of unknown input forces. As pointed out earlier, this solution for the input forces helps to reduce the effects of measurement noise in the force estimation process and it improves the numerical conditioning of the inverse problem, since the inverse of the beam's FRF matrix is required.

10.3 SYSTEM OF CONTROL FOR VIBRATION TESTING

In order to implement in practice the current vibration testing technology as well as the above new technology for vibration testing, one needs a corresponding control system.

As an example of the current system of control of vibration testing, below is a brief description of the shaker vibration control system 8500 of the Vibration Research Corporation[16]. A major advantage of this design is that there are no notifications required for a PC and no special skills needed to install and maintain the system.

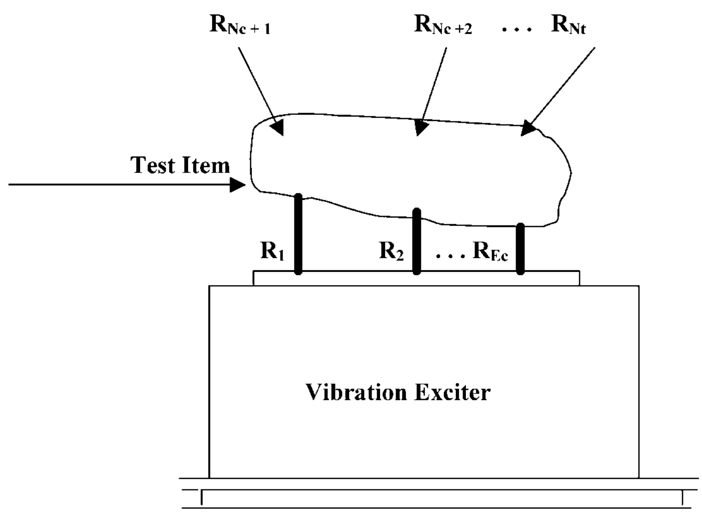

Figure 2.42 Test item attached to a vibration exciter in the laboratory environment[11].

All VibrationVIEW software packages include a System Check mode which provides a manually controllable wave output and oscilloscope, and spectrum analysis plots of the accelerometer inputs. This test mode is used to calibrate the system and verify operation of the controller, amplifier, shaker, and accelerometers. The VibrationVIEW program may be installed on any number of machines, using (optional) Net VibrationVIEW, and used to view test data and create test reports from virtually anywhere.

A variety of remote monitoring and control options are available. The controller can be monitored or controlled via networks and the web with a built-in web page and e-mail server. Other applications can control the VibrationVIEW program through any easy-to-use file-based interface. External TTL logic level inputs and outputs may also be used to start and stop tests.

Calibration of the 8500 system hardware can be done in the customer' calibration laboratory using their calibration instruments with the VR661 System Hardware Calibration software. The eight inputs on the back of the 8500 can be set up as analog DC monitor inputs. This allows the user to monitor, plot graphs, and store data from up to eight analog signals, including shaker current and voltage. Software allows scanning to desired units, +/- 10 volt range. It also features high and low trip points which can be set by the user.

8500 technical specifications are as follows:

HARDWARE:

Front end signal processing box:

Low-noise design with a dedicated high speed processor for signal processing. Front BNC connectors for four accelerometer connections. Front panel status LEDs. Rear panel connectors drive output and COLA output, connection to ethernet port, and and a terminal block of digital 1/) lines.

Input channel expansion:

Can be expanded from 1 to 16 total analog inputs by adding signal processing boxes. Each box processes four inputs. Additional boxes connect to the PC via a network switch.

Output channels: One analog output (drive) standard; COLA (Constant Output Level Amplitude) optional.

INPUTS:

Analog channels: 1 to 16 simultaneous channels. Each can be control, monitor, or disabled. All are configurable single ended or differential with 200 K Ohm impedance. Setup allows per channel selection of transducer sensitivity, coupling (AC or DC) accelerometer constant current supply (4 mA), TEDS

	transducer interface, and a unique DC offset that allows measurement to true DC with constant current type accelerometers.
Electronics per channel:	Different amplifier, configurable as differential, single ended, AC or DC, anti-aliasing filters, and 24-bit analog to digital converter (ADC)
Filtering:	An analog multiple pole filter plus a digital filter.
Frequency range:	Capability of up to 20,000 Hz analysis frequency (sample frequency up to 52,000 Hz).
Voltage range:	+/– 10 Vpeak.
Resolution:	24-bit.
Dynamic range:	120 dB input signal separation.
Phase match between channels:	Within +/– 0.5 degree from DC to 10,000 Hz.
Signal-to-noise ratio:	> 100 dB (from DC to 1,000 Hz measured with half-full-scale sine wave).
Channel cross-talk:	< –110 dB.
Total harmonic distortion:	< –105 dB.
Digital input and output:	Rear pluggable terminal block enables the digital level signals (8 inputs and 8 outputs) to be interfaced with the product and other systems. Used for remote start/stop/ /pause/continue and other functions such as close/open control loop, manual/auto schedule, and enable/desible aborts.

OUTPUTS:

Analog channels:	One drive channel standard. One COLA output optional.
Drive channel:	24-bit digital to analog converter (DAC), anti-imaging filter, and optional emergency stop shutdown circuit, and transient power failure prevention shutdown circuitry.
Filtering:	Analog multiple pole filter plus a digital filter.
Frequency range:	Capability of up to 20,000 Hz output frequency (52,000

	sample per second).
Voltage range:	+/−10 Vpeak.
Resolution:	24-bit.
Total harmonic distortion:	<−100 dB.

The structural scheme of the control system for new vibration equipment is shown in Figure 2.43[9].

The computerized control block of the system consists of a processor (1); an external memory (EM) (2); a block of real storage (RS) which includes a random access memory (RAM) and read-only memory (ROM); and a buss (4) for control commands and data transmission. In addition, the system for control functions uses an adapter (24), an expansion card (23) (with modules and interfaces of input (20) and output (22) signals blocks), and an analog-to-digital converter (14) (ADC) with a normalized amplifier (15).

The adapter makes it possible to join the expansion card to the computer and ensures the conformity of information exchange between different level channels.

The expansion card block (230 is able to use several blocks of input and output signals (22) from the controlled subject (5) and ADC for transformation of analog signals to digital forms from sensors of the controlled subject.

The mechanical part of the equipment consists of vibrodrums (13) with height controlled simulators (7) of the road profile. Each simulator with a control mechanism is mounted inside the drum, separate from the other simulators. The signals for changing the simulators are transferred from the computer by a group of cable connections through the current collector. The position of each simulator is determined by a feedback sensor (8) which connects with the axis of the simulator.

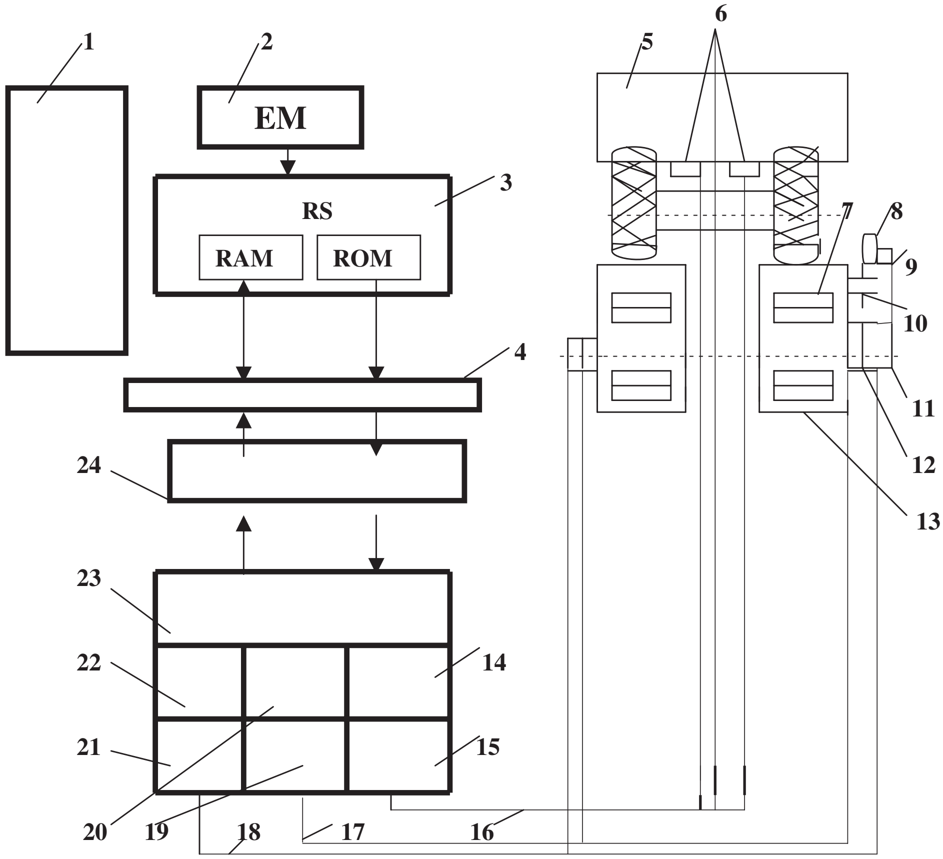

Figure 2.43 Structural scheme of drum vibration equipment control system [21]:
1 = computer processor; 2 = external memory (EM); 3 = block of real storage (RS); 4 = control command and data transmission buss; 5 = test subject; 6 = loading measurement sensor; 7 = controlled simulators; 8 = feedback sensor; 9 = feedback sensor signal transformer; 10 = feedback sensor roller; 11 and 12 = feedback sensor current collectors and controlled simulator filters; 13 = vibration drum; 14 = analog-to-digital converter (ADC); 15 = normalized amplifier; 16 = group sensors collection cable with ADC; 17 = output control signal interface with control mechanisms of simulator position; 18 = feedback sensor interface with input signals; 19 = output signal interfaces; 20 and 22 = input and output signal blocks; 21 = input signal interfaces; 23 = expansion card; 24 = adapter.

The deformation and vibration of the test subject are measured with sensors that are mounted on the test subject. Analog signals are received and transferred by a cable connection to the amplifier, then converted in the ADC to digital form.

The test equipment is operated in real time. For simulation of the random rate of loading (or product degradation) it is necessary to have individual control of each simulator position.

The scheme of the simulator road influences position control is shown in Figure 2.44.

It is necessary to define numerical characteristics for the program used in preparing the control for the test equipment. The program may be composed by the of random signal generators which possess in their composition the following characteristics:

1. Probability distribution of the random input influences on the test subject;
2. Mathematical expectation of the distribution, m;
3. Variance D or standard deviation α;
4. Power spectrum $S(\omega)$ of the input influences or normalized correlation $K(\tau)$.

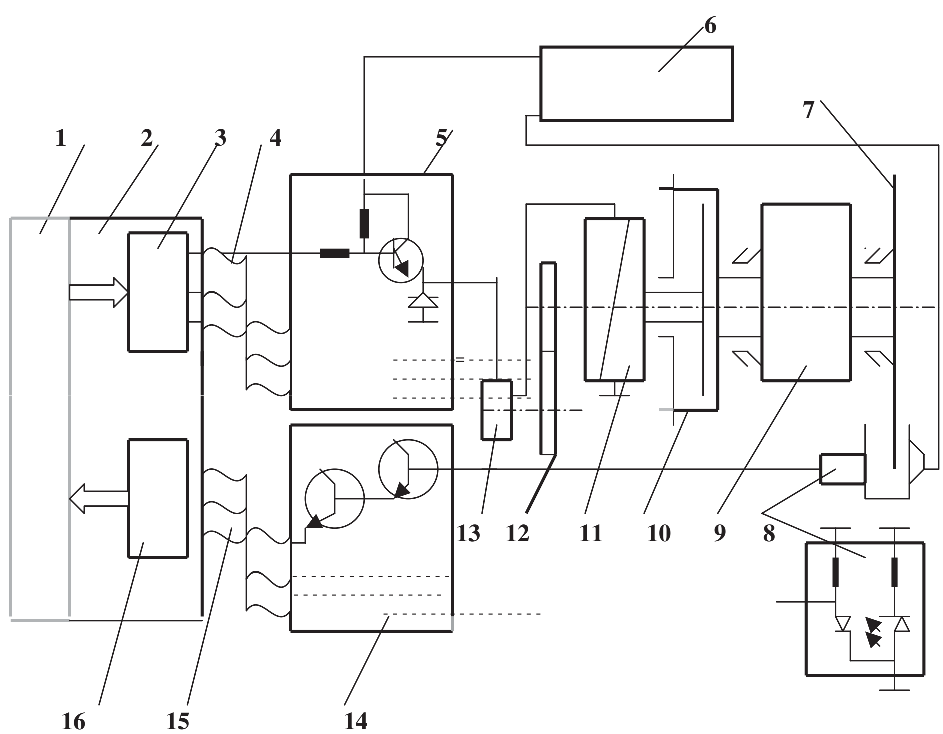

Figure 2.44. Scheme of simulator road influences position control[21]:
1= computer; 2 = block of expansion; 3 = output signal block modules; 4 = block output signal group collection cable; 5 = control signal interface block; 6 = power supply unit; 7 = simulator position sensor disk; 8 = simulator position sensor recorder; 9 = controlled simulator; 10 = electromagnetic clutch coupling disks; 11 = electromagnetic coupling coil; 12 = simulator controlled drive mechanism; 13 = current collectors; 14 = feedback signal interface block; 15 = block input signal group collection cable; 16 = input signal module block.

Transfer degradation of the signals is shown in Figure 2.45.

Forgiven *m* and *D*, one builds the graph of distribution density *f(b)* and *F(a)* of the continuous

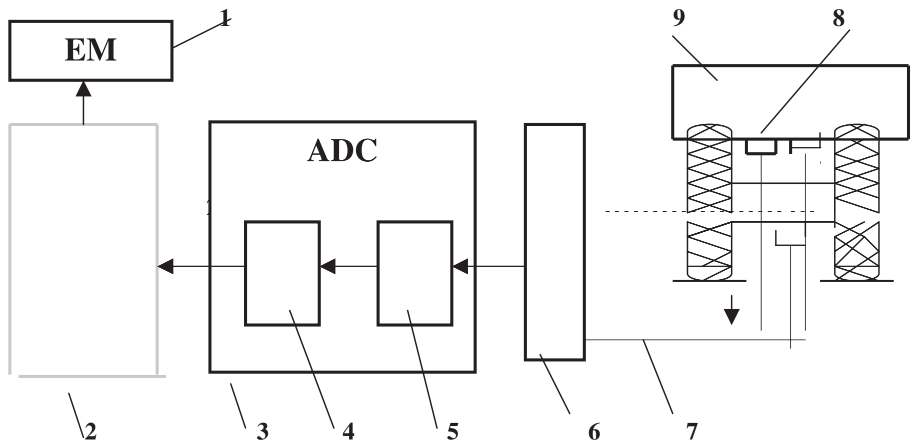

Figure 2.45 Scheme of transfer degradation of the signal from test subject to the computer: 2 = external memory; 2 = computer; 3 = ADC; 4 = ADC module digital unit; 5 = ADC module analog unit; 6 = normalized amplifier; 7 = group connection cable; 8 = degradation sensors; 9 = test subject.

random process of input influences that are transformed to the height h of working heads over the vibration drum surface or to angle of turn, a, of the simulator's blade. These characteristics reflect the distribution of input influences. The turn angles are provided in real and continuous numbers. Therefore, the continuous random quantity *f(a)* must be transformed to discrete points, *n*, in groups over the input influences range. For this goal the characteristics of distribution density may be represented by a histogram as shown in Figure 2.46.

It is necessary to calculate the number of points, *n* in each group.

Often the profile and other input influences follow a normal probability distribution.

In this case in order to find the sequence of generated random signals η_{2i-1}, η_{2i} we use a set of random numbers generated from the normal sistribution[19] $\xi_i (i = 1, 2, 3, \ldots)$:

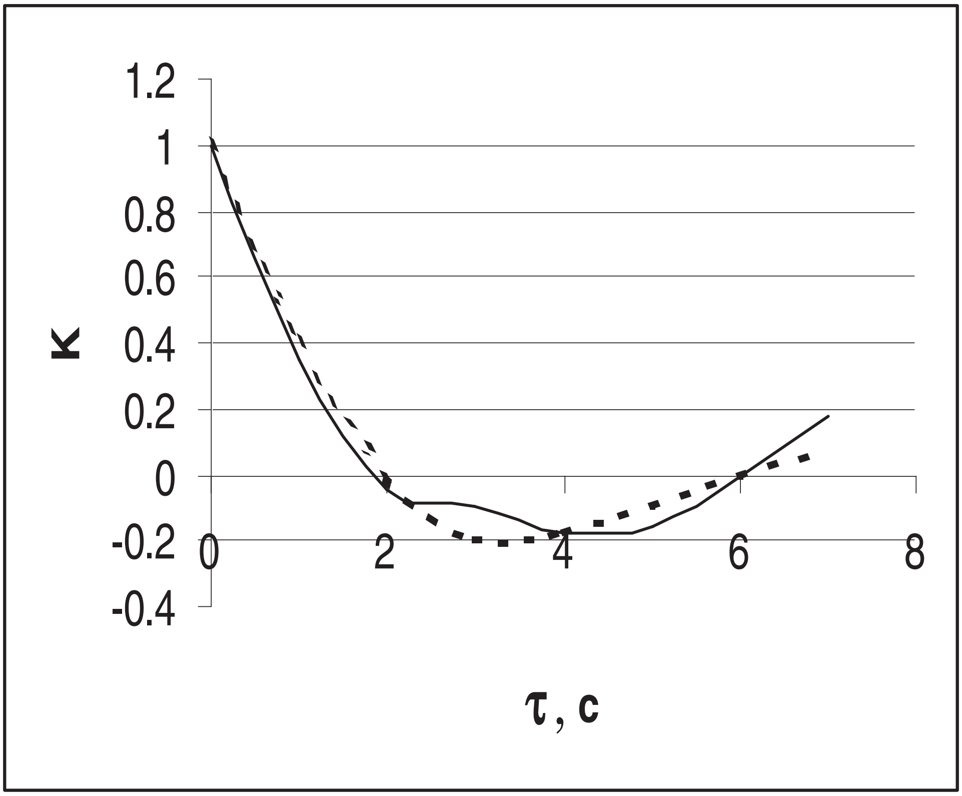

Figure 2.46 Load correlation of test subject: (calculated directly __________ ; approximated – --------------).

$$\eta_{2i-1} = (-2\ln \xi_i)^{0.5} \cos (e^9\xi_i)$$
$$\eta_{2i} = (-2\ln \xi_i)^{0.5} \sin (e^9 \xi_i) \quad (2.2)$$

To prepare a program it is necessary to provide a predetermined power spectrum. For example, the power spectrum of input influences on the mobile product's wheels may be described as:

$$S(\omega) = D/2\pi \left[\frac{\alpha}{\alpha^2 + (\omega + \beta)^2} + \frac{\alpha}{\alpha^2 + (\omega - \beta)^2} \right] \quad (2.3)$$

where: α and β are parameters that are determinable from random signals of real life input influences, ω is the circular frequency of the input influence.

This characteristic of the power spectrum corresponds to results of the expansion into Fourier series of the correlation function $K(\tau)_p$. This is:

$$K(\tau)_p = De^{-\alpha(\tau)} \cos \beta\tau, \qquad (2.4)$$

where $\underline{\tau}$ is the parameter of time.

It is necessary to provide the frequency of decomposition of the power spectrum's characteristic in order to compile of a digital program for vibration equipment control. For this goal the power spectrum $S(\omega)$ is speed out on the n harmonics – regions of equal width $\Delta\omega$. The variances D_k of each harmonic and α_k wave amplitude, corresponding to each selected regions are calculated. The frequency of these waves is equal to the mean of the frequencyof the wave for the region under consideration.

The variance D_k is equal to the sum of the variances of all the harmonics of the spectral decomposition. The wave amplitude of each harmonic is calculated by the use of the following formula:

$$\alpha_k = (2D_k)^{0.5} \qquad (2.5)$$

As a result, we have an equation for the evaluation of the control program numerical series $y(t)$, for obtaining the given power spectrum:

$$y(t) = \alpha_1 \cos(\omega_1 t) + \alpha_2 \cos(\omega_2 t) + \ldots + \alpha_n \cos(\omega_n(t) \qquad (2.6)$$

where: ω_n is the circular frequency of each region of spectral decomposition; and t is an interval of time from the start of calculation which one can use to determine the next digital value of the program.

By combining the results of calculation from (2.2) and (2.6) one may obtain a digital version of the test equipment's control whose characteristics depend on the real life of the test subject.

The computer control system also provides control of the test subject technological process, periodic calculation of the indexes of work through requested periods of time, and evaluation of changes in these indexes that give the possibility to evaluate any deterioration in time, the technical conditions, or vibration distribution on the test subject, etc.

To obtain the correlation function one can use the equation:

$$K(\tau) = D^{-1} (T - \tau)^{-1} \sum_{1}^{T-\tau} n_0 (i) n_0(I+\tau) \qquad (2.7)$$

where: n_0 (i) is the centralized value of random magnitude of the degradation at time of moment *i*; $n_0 (i+\tau)$ is the same with time displacement of τ.

Figure 2.46 shows an example of how to obtain the correlation function from formula (2.7) based on experimental data of variable input influences on the test subject.

This method may find the deviation from theoretical characteristics if τ is large.

Therefore, one must choose the parameters α and β to approximate this curve, where α measures the degree of decrease of the elementary branch, and β is the frequency of branch waves. Different methods may be used for approximation of this correlation function. One possibility is use the method of least squares to evaluate α and β, so that the deviation of the sum of the squares which may be calculated by using formulas (2.4) and (2.7), has a minimal difference:

$$\sum_{i=0}^{i=\tau} [k(\tau_I)_p - K(\tau_I\}]^2 = \min$$

After one finds, the quotient derivative separately for α and β and makes each equation to zero, two equations with two unknowns α and β will be obtained. These are:

$$\sum_{=0}^{i=\tau} [K(\tau_I)_p - e^{-\alpha\tau} \cos\beta\tau_I](-\tau_I e_i^{-\alpha\tau} \cos\beta I) = 0$$

$$\sum_{i=0}^{i=\tau}[K(\tau_i)_p - e^{-\alpha\tau} \cos\beta\tau_I](-\tau_I e_i^{-\alpha\tau} \sin\beta\tau_I) = 0$$

One can construct an approximate characteristic correlation function based on the solution of these equations.

Next will be shown, as examples, a typical system of control specifications for vibration testing of a complete product (truck) and of components of a complete product (see Table 2.19).

Table 2.19 Typical specifications of drum vibration equipment system of control for whole product (truck) testing

Speed of central processor, short operations in second	1 million
1. Capacity of ROM	24 K
2. Capacity of RAM	4 K
3. Number of the clutch control command	48
4. Number of angle sensors	27
5. Number of acceleration sensors	64
6. Number of degradation sensors (deformation, wear, etc)	88
7. Frequency range of measured acceleration, Hz	from 0.5 to 200
8. Number of digital - analog transformers	3
9. Channel of connection with outside computer	1
10. Mass, kg	30

<u>The system of vibration control (SVC) consists of:</u>

- block of controlled computer (CC);
- block of analog signals transformation (ADC);
- system of vibration influences sensors;
- 3 blocks of control with electromagnetic clutches;
- 3 blocks of turn angle transformation;
- 27 sensors of turn angles.

The control program includes:

- program of vibration equipment control in real time:

a) program of selection and control of vibration testing regimes corresponding to regime of use in the field;

b) program of correction and selection of the regimes for obtaining necessary statistical characteristics of vibration as a random process from each vibrosensors;

- prepared program of controlled file of SVC which provides special road simulation;

- control program with database of product components degradation during accelerated testing

- database degradation information for components from the field;

- test programs of SVC with built-in means;

- service programs checkout for the vibration equipment.

The SVC must be able to function in a temperature range of –40 °C to +50 °C, and a vibration range of 0.1 to 500 Hz, with acceleration of no more than 15 m/s^2, with multiple road loads of acceleration ranging from 80 to 100m/s^2, and duration from 2 to 20 ms.

The second new implemented type of vibration equipment covers separate components of trucks.

The working head of this equipment is a table with slots for attachment of the test subjects.

The vibration is transferred to the table through an elastic system. The table can be shaken in 1 - 3 linear and 1 - 3 angular axes (six degrees of freedom). This equipment also provides a random rate of vibration and is 3 - 5 times less expensive than worldwide.

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11. ACCELERATED DYNAMOMETER TESTING

Accelerated dynamometer testing is one of the components of accelerated reliability testing (ART). It's also often used as a separate braking testing systems for engines, electromotors, transmissions, etc.

The hydraulic dynamometer was invented over 120 years ago and has been continually developed to meet the ever changing needs of customers. This type of testing is seldom used for ART, because, as was mentioned earlier, ART is in development. As a second goal, separate dynamometer testing (or in combination with one or two other types of testing) is a traditional type and its development is geared to improving design and the system of control.

11.1 PRODUCT OVERVIEW ON THE MARKET.

Most of these types of testing equipment (Magtrol, Inc[1], Froude Hoffman Gmbh[2], Burke Porter Co.[3], Kistler Instruments[4,5], MTS[6], and others) absorb power with a braking system which provides frictionless torque loading independent of shaft speed. For example, the Hysteresis Brake Magtrol, Inc.[1]) provides torque by the use of two basic components – a reticulated pole structure and a special steel rotor/shaft assembly – fitted together, but not in physical contact.

The role structure of the unit is energized, and the drag cup can spin freely on its shaft bearings. When a magnetizing force from the field coil is applied to the pole structure, the air gap becomes a flux field and the rotor is magnetically restrained, providing a braking action between the pole structure and the rotor.

Magtrol Dynamometers.

The Hysteresis Braking System of the dynamometer is complemented by Magtrol's rugged yet highly accurate torque and speed sensors. To complete the motor test system, Magtrol offers Dynamometer Readouts and Controllers, Single and Three Phase Power Analyzers, and easy-to-use motor testing data acquisition and analysis of software (Figure 2.47).

When completed, the motor test system delivers a full range test of critical motor performance characteristics, including breakdown, locked rotor and pull-up torque. From basic manually operated dynamometers to comprehensive PC based motor test systems, Magtrol will exceed customer expectations for performance. The motor test system selected in dependence on:

- What type of motor has to be tested?
- What is the maximum torque, speed, and power of the motor?
- Which motor test parameters does one needs to test?
- How can one plan to control the dynamometer and collect motor test data?

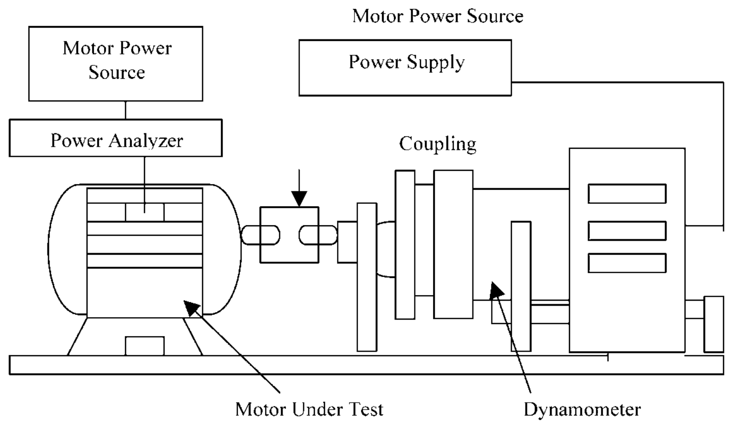

Figure 2.47 The scheme of the Magtrol Dynamometer Test System.

Load Cell Dynamometers

- 15 models with maximum torque from 2.5 oz.in to 500 lb.in;
- Features Hysteresis Brake to provide precise torque loading independent of shaft speed;
- Motor testing from no load to locked rotor;
- English, Metric or SI torque units of measurement are available;
- Custom dynamometers for special torque and special requirements.

Customized base plates, riser blocks and shaft modifications can be provided.

Engine Dynamometers

These dynamometers have been designed to address the severe, high vibration conditions inherent in internal combustion engine testing, and can be controlled either manually or via a PC based controller. For a small engine test stand there are controllers, readouts, and software. This type of dynamometer is suited for emissions testing as set forth in the clean air regulations. The features include:

- High speed capabilities;
- Large, rugged stainless steel shaft;
- Additional front shaft;

- Additional front shaft bearing for greater support;
- Specially reinforced load cell;
- Blower cooling to maximize heat dissipation.

High Torque Dynamometers

These dynamometers are designed for performance testing of gear motors, as well as other high torque, low speed motors. The dynamometer consists of two hysteresis brakes, a precision gear box with virtually no backlash, an extremely accurate in-line torque meter, and a high resolution speed encoder. This type of dynamometer can be used in an open or closed loop system and can provide a full load at low speeds down to a locked rotor. The torque provided by the brake is frictionless, although there is a drag torque reading it does prevent capturing free-run data.

Dial Weight Dynamometers

This dynamometer uses the combination of a hysteresis brake and gravity to ensure constant, reliable results. The brake torque rise is directly proportional to the applied current. The calibrated weight system provides readings in standard engineering units through the use of multiple torque range scales provided on each size dynamometer.

Customized Motor Test Systems

These systems are PC based, turn-key motor test systems custom designed and built to meet customers' specific requirements. The CMTS Configuration is as follows:

- Programmable dynamometer controller;
- Power analyzer;
- Customized software;
- Motor power supply (AC and/or DC);
- Computer and printer;
- GPIB cards and cables;
- Test console;
- Motor fixturing;
- Couplings.

Froude Hofmann Gmbh – Froude Consine for engine test systems.

Froude Consine provides a range of standard in-cell products to complete the test cell installation. This includes engine and roller dynamometer test stands, engine oil and water conditioning modules, throttle actuators, shut down actuators and engine start systems. Froude Consine manufacture a wide range of electrical and hydraulic dynamometers designed to absorb power from automotive, marine, industrial and gas turbine engines. There is guaranteed torque and speed measurement accuracy.

Fundamental to all Froude Consine vehicle test systems are chassis dynamometers, computer control systems, and selected peripheral equipment. There are chassis dynamometers to suit a wide range of applications and sizes, including 20 inch diameter twin roller, 48 inch diameter (latest emission spec.) and up to 3 meter roll arrangements.

Motor/generator power devices may be configured in-line, belt-driven or between the roles. Burke E. Porter Machinery Company[3] produces a Electric Roll/Brake Test system which:

- Performs engine loading;

- Estimates the use of clutches;

- Results in energy savings in generating a portion of its own power; and is

- Capable of performing the following tests: engine (emissions & performance), brake, transmission, speed control, park brake, powertrain testing, vibration analysis, etc.Kistler Instrument[5] also produces a rotating wheel dynamometer (RWD CT) which can operate over the full speed range of cars and light trucks. The complete system consists of up to four wheel dynamometers, one control unit and optionally a data acquisition system. This system can easily be mounted on a vehicle without modifications of the wheel hub or the suspension strut.

Adapters ensure that the unit can be easily fitted to any car under test. The dynamometer, which contains sensors, an angle encoder, and signal conditioning equipment, transforms the signal coordinates from the rotating to the fixed system. The output signals are passed through slip-rings to data logging equipment in the body of the vehicle.

The working principle that quartz force sensors measure three orthogonal force components. The sensors are preloaded, in pairs, by a high-strength bolt. The outer flanges that are bolted together transmit the force via the adapter to the standard hub of the car. The center bore of the RWD CT contains the electronics which consists of:

- Charge amplifier;

- Angle encoder;

- An analogue calculator for coordinate transformation;

• Slip-rings for signal transmission.

The electromagnetic angle encoder in the RWD L determines the angular position of the wheel.

The built-in analogue calculator transforms the forces and moments from the rotational to the fixed coordinate system of the cat by using the output from the angle encoder. The same calculator derives the three components of the moments from the force signals.

A holding arm attached to the suspension strut keeps the stationary part of the angular encoder steady in order to define the reference point for the angular position of the wheel. It also holds the stationary part of the slip ring assembly and carries the cables. The signals are transmitted by slip rings to the stationary part of the RWD L system and to the control unit. The RWD L outputs directly the following signals: force components F_x, F_y, F_z moments M_x, M_y, and M_z, and the sine and cosine of the angular position of the wheel.

Rockwell Automation test systems[7] are used for different types of test stands, such as:

•Aircraft Test Stands

- Gear boxes,
- Helicopter rotors,
- High-speed components.

• End and Line Transmissions Test Stands

- Front/rear wheels,
- Transfer cases,
- Manual/Automatic.

• Chassis Dynamometer Test Stands

- Vehicle performance,
- Vehicle emission.

• Hot Engine Test Stands

- Engine performance,
- Engine efficiency.

• Drive Train Test Stands

- System efficiency evaluation,
- Inertia/road-load simulation,
- Synchronize wheel speed and position.

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12. ACCELERATED TESTING OF FARM AND OFF-HIGHWAY MACHINERY

12.1 INTRODUCTION.

As was mentioned earlier, ART is a combination of accelerated laboratory testing and special field testing. Accelerated laboratory testing needs universal and specific test techniques and equipment. And as section 8, step 4 of "Technology of step-by-step UART " said different varieties of a product need specific testing equipment for simulation of field input influences.

Farm machinery and off-highway machinery are special types of machinery and for accelerated testing they require a combination of universal testing techniques and equipment plus specific testing techniques and equipment[5,6,7,8,10]. The above specifics depend on the precise type of machinery used. For example, most farm machinery:

- is used for a short time during the year (harvesters, soil-cultivating machinery, fertilizer applicators, seeders, cotton pickers, sprayers, and others);
- is used in specific climatic zones (cotton in one climatic zone, beets in another, etc.);
- is used in direct contact with the technological product such as grain, manure, sand, concrete, fertilizer, milk, fruits, vegetables, etc.;
- one can often check the effectiveness of farm machinery improvement on the following year's seasonal yield of field work alone.

To this group of machinery (with regard to the use of testing equipment) off-highway machinery can be related too.

12. 2 SOME ASPECTS OF ACCELERATED STRESS TESTING TECHNIQUE

As was shown above and elsewhere[1], this type of testing cannot give accurate initial information for reliability problem solving, but it is simple, so can be used for a long time. It can be more or less useful depending of the goal and level, therefore, below will be described the methodology of this type of testing to make it more useful.

12.2. 1 General Procedure for Statistical Analysis of Stress on the Machine's Components

Usually statistical analysis of stress on components of farm machinery is applied to the information provided by oscillograms (or anything else), which record the stress at specific points.

These stress oscillograms, which take the form of random process curves, are analyzed in order to obtain component-stress data in concise numerical form.

Oscillogram analysis is based on the following assumptions:

- deviation of the curve from the sinusoid curve does not noticeably affect the fatigue characteristics of the component;

- a variation of up to 40 - 50 cycles/sec in the stress frequency, which is characteristic for components of tractors and agricultural machines, has no appreciable effect on the fatigue of the components.

By processing initial information for analysis, the experimental curve (for example, oscillogram) is smoothed out to fit selected extreme points. The smoothing-out is effected either by plotting a transformed curve on the oscillogram or by omitting certain intermediate extreme points from the analysis.

In oscillogram analysis with only a small amount of experimental data, the ordinates of the extreme points on the curve are measured directly at some arbitrarily selected level.

When a considerable volume of experimental data are available, analysis is speeded up by using the method of set divisions, whereby the entire range of the curve is split up into several equal divisions, each of which is given a serial number. In the analysis, the occurrence of extreme points in a particular division is ascertained. The curves are analyzed often with the aid of a specially scaled ruler. The first step is to mark on the oscillogram the extreme points to be included in the subsequent analysis. The extreme points of the curve are then plotted in sequence in the squares of a correlation table. The distribution of the maximum and minimum of the recorded process is than obtained by adding up the figures in the vertical columns and horizontal lines, respectively, of the correlation table.

In analysis of the stress-distribution curve, it is necessary to establish which of the known theoretical laws of distribution applies to that particular curve. This entails establishing the degree to which the empirical distribution corresponds to the theoretical distribution. A stringent evaluation of this correspondence is made by means of the accuracy-of-fit tests devised by Pearson, Smirnov, Kolmogorov, Weibull, and others.

Analysis is confined to these maximum stresses which exceed the endurance limits of the components. Since these limits are often unknown, the procedure is to take the endurance limits of the materials of which the components are made, and apply corrective coefficients.

12.2. 2. An Example of Analysis of the Loadings on the Frame of a Tractor Prototype and Accelerated Fatigue Testing on the Proving Ground

As an illustration of accelerated stress testing methods, research on tensions and accelerated proving ground testing of frame fatigue can be used. The goals of these studies are: to characterize of tension in quantitative terms, to evaluate the durability of the frame system, and to develop recommendations for increasing the durability.

Tension sensors were attached to points in the areas of maximum expected tensions (connections between frame and trailer, sites of changing the cross-section of welded parts, the sites of failures in the field and proving ground).

The choice of sensors was governed by the following considerations:

- it is necessary to study which zones of these details are subjected to the greatest variation in tensions (taking into account their concentration); and

- the tensions of the basic details of frame must be studied.

Measurements of the tractor's tensions were studied under the following conditions:

- variations of the field regimen which is typical for this type of tractor;

- motion over cobblestone proving grounds without a plough, at a speed of 7.8 km/h;

- motion over a concrete track proving ground, without a plough, at a speed of 7.8 km/h.

On the basis of the oscillogram processing obtained from preliminary studies[2] nine sensors were accepted for more detailed research. Five additional sensors were used to record an oscillogram solely when the tractor was put through a series of 180° turns.

As a criterion for evaluation of the tensions of frame details one used the parameters of distribution of rows of tension amplitudes which were obtained as a result of statistical processing of the oscillograms.

To evaluate the tensions, these parameters were compared with characteristics of fatigue resistance of the design elements (where the sensors were located) as roughly determined from the experimental data quoted in the literature.

Table 2.20 Amplitudes of variable tensions in the details of tractor (prototype of challenger 30) frames which are fixed on the proving ground.

Sensors number	Pass over 20 pairs of obstacles (H = 160 mm) on concrete track. Amplitudes of tensions, kg/cm^2			Pass over 40 pairs of obstacles (H = 160 mm) on coblestone track. Amplitude of tensions, kg/cm^2		
	A_{max}	A_{av}	A_{min}	A_{max}	A_{av}	A_{min}
1	X			X		
2	720	645	520	870	705	610
3	375	320	215	-	-	-
4	505	435	375	-	-	-
5	780	645	545	900	725	630
6	785	650	445	800	675	575
7	750	600	460	815	610	435
8	910	775	615	710	610	435
9	680	585	470	-	-	-
10	1,240	1,020	850	1,450	1,076	760
11	530	420	360	535	420	370
12	1,190	855	640	-	-	-
13	720	520	455	840	815	770

Table 2.20 (continuation) Amplitudes of variable tensions in the details of tractor (prototype of Challenger 30) frames which are fixed on the proving ground.

14	695	560	410	800	600	515
<u>15</u>	970	770	615	1,030	835	740
16	805	705	590	850	660	525
17	930	655	505	765	540	445
18	690	550	490	600	490	385
<u>19</u>	995	795	665	1,000	730	630
20	570	485	385	615	490	420
21		X			X	
22	830	690	575	435	350	300
23	935	620	435	-	-	-
24	70	540	465	-	-	-
<u>33</u>	1,270	1,120	975	795	655	520
34	1,180	960	675	1,210	935	715

Notes:

1. "X is tension less than 300 kg/cm^2.

2. " – " is test not recorded for technical reasons.

3. Sensors, which are accepted for more detailed study are underlined; the sensors, that accepted for the schedule of 180° turns are bold-underlined.

4. During processing of the oscillograms the greatest curve-span corresponding to passage over two obstacles was taken into account.

5. The average amplitudes (A av) are shown in the table as parameters of amplitude distribution rows and cannot be used for analysis of the level of tensions as comprehensive characteristics.

6. "H" is heighlight of the obstacles.

Tables 2. 21 and 2. 22 show basic characteristics from more detailed research (basis number of cycles is $2 \cdot 10^6$). The values of the breaking limits are taken from the literature. Determination of the breaking points of the frame's components was guided by the following considerations:

- for the types of welded joints in use, the coefficients of tension concentration "k" (with high-grade welded seams) range from 2.3 to 3.4;

- some units and details have been made from steel with "k" ranging from 1.5 to 2.5;

- the breaking point of details is equal to the breaking points of the materials, divided by "k".

For welded joints made from another group of steels (1020, 1041, etc.) with continuous longitudinal and transverse seams, the endurance limit is:

$$\sigma_{-1k} = \frac{\sigma'_{-1k}}{k_1} = \frac{1650}{2.4} = 685 \text{ kg/cm}^2 \quad (2.8)$$

For welded joints made of the same steel, but with longitudinal seams only, the endurance limit is:

$$\sigma_{-1k} = \frac{\sigma'_{-1k}}{k_2} = \frac{1650}{3.3} = 500 \text{ kg/cm}^2 \quad (2.9)$$

As a result of variable tensions in excess of the endurance limit of the details, fatigue cracks in welded and cast details of the frame may occur after sufficient repetitions.

Table 2. 21 The amplitudes of variable tensions in details of the tractor frames which registered when the tractor with plough was turned sharply through 180° to left or right on packed earth.

Sensor No.	18	19	20	33	45
Endurance limit	685	685	685	685	685
Amplitudes of tension, A max (kg/cm^2)	410	440	395	300	665
Average amplitudes (A av)	395	600	365	x	570
Minimal amplitudes (A min)	360	540	385	-	470
The volume of amplitudes distribution row	5	5	5	5	5

Note: The average amplitudes (A av) were determined as the arithmetical averages of the maximum (A max) spreads.

Analysis of the data in tables 2.21 and 2.22 shows that:

1. The greatest amplitudes of variable tensions in the field are obtained by moving the tractor with the plough along a dirt road with dried ruts; over a field in which transverse furrows have been left by previous plouging; along the cobblestone road; and while it is making turns. Driving with the plough attached along a cobble stone road carriers a particularly high risk of destructive effect.

2. The maximum amplitudes of variable tensions recorded under certain operating schedules and on the proving ground exceeded the endurance limits of the details of the tractor's frame at positions where the following sensors were placed:

Sensor	Nos. 10 and 15	frame's longeron
	Nos. 23 and 24	front engine support
	Nos. 25 and 28	the spring replacle
Nos. 29, 32, 33, 34, 35, 0-13, 42, 43, 45, 0-11		trailer of the caterpillar.

When the amplitudes of variable tensions exceed the endurance limits on some regimens only, the answer to the question about the necessity for additional steps to increase the frame's strength may be found after a long period of testing on the proving ground[3].

Usually position-finding predictions of durability of the above components one made on the basis of calculations based on the hypothesis of summarizing damage and other assumptions.

However, for the frame of a tractor with semi-rigid suspension, the calculation is very difficult in proportion to increasingly high speed of deformation. Therefore, the characteristics of fatigue resistance taken from the literature require additional corrections.

3. A comparison between the loading strain imposed by motion along a concrete track on the proving ground with obstacles 160 mm high and that imposed by motion along a cobblestone track with obstacles 140 mm high shows no substantial difference in the level of amplitude of variable tensions recorded in most of the details studied (except for the readings given by sensor No. 15, which was attached to the rear end of the outer longitudinal member).

On the basis of experience, the ratio of the number of passes over obstacles to the number of turns was set at 3.5:1. While on the proving ground the speed of the tractor testing was systematically controlled.

To analyze the proving ground testing results as a criterion of durability evaluation, the time is measured for cracks to appear in the longeron brackets of the frame and in the junction plates of the crawler body caterpillar's trailer.

Like with variation of durability in real life, it is impossible from the testing results of only two specimens to obtain an exact quantitative evaluation of the service life of the frames.

It is possible merely to identify a tendency towards: greater or lesser durability of the design under test.

Table 2. 22 The amplitudes of tension in the tractor frame's details (prototype of Challenger 35) registered in the field and on the proving ground.

Type of road and regimens of loading	Length of run, m	Speed, km/h	Tests No.	S E N S O R No. 6 10 34 38 Endurance limit of details, kg/cm^2 685 800 800 1600
Field:				
Tillage: Stubble	500	5.8	1	X 520 375 315 27; 375 x x
	500	7.8	2	X 530 365 300 37; 395 325 300 29 x
With plough	400	5.8	3	370 335 305 690 450 400 40 425 360 315 32 x
Across furrow	400	7.8	4	x 560 400 300 28; 410 310 300 12; x
Going ahead by	-	6.7	5	x 535 315 300 4; x x
Bite deeper plough	-	7.8	6	x 370 325 300 5; x x
Lowering and raising of	-	5.6	7	x 740 500 385 510; 370 x; 360 x
plough		7.6	8	x 550 500 420 8; x x
Field with transverse furrows	400	6.8	9	565 505 460 35; 960 765 630 40; 890 645 540 x 710 530 460 40; 845 640 545 40; 895 625 520 x
Cobblestone road	1,000 1,000	5.8 9.6	11 12	640 390 320 40; 960 625 485 40; 925 625 520 x 520 430 390 39; 1,020 775 700 40; 890 780 x

Table 2.22 (continuation) The amplitudes of tension in frame's details of tractor (prototype of Challenger 35) registered in the field and on the proving ground.

Without plough:				
Dirt road	1,000	5.8	13	455 x; 555 360 310 30; x 405 355 360 22
with				
dried rut	1,000	9.6	14	405 350 315 8; 515 405 320 40; 490 415 340 14;
180° turns	-	6.7	15	440 405 355 3; 820 715 620 6; 490 405 335 3; x
Cobblestone				
road	1,000	9.5	16	350 x; 480 390 350 40; 765 625 570 40; 600 470
On Proving grounds:				
Height of				
Obstacles, mm:				
160	200	5.8	17	785 650 455 19; 970 770 615 16; x; 980 960 575
140	400	5.8	18	800 675 575 40; 1,030 835 740 40; 1,100 845 670

The average for one hour of the above testing consisted of performing 420 turns or 1,200 passes over obstacles.

Table 2. 23 shows data on the types of failure that occurred in certain units and details of the tractor's frame, as revealed by accelerated testing on the proving ground.

Table 2. 23 Results of proving ground testing of the prototype of Caterpillar 30.

Serial No.	Nature of damage	Time taken for damage to appear: Number of passes / number of turns	
		Specimen 1	Specimen 2
1	**Damage to spring box** Cracks in lower welded seams of front brackets		
	a. Right (length of crack up to 130 mm)	54,100 / 37,050	150,00 / 24,810
	b. Left (length of crack up to 40 mm)	—	117,300 / 24,810
2	**Damage to lift links of caterpillar trailer** Cracks to wall of rear crossbar of right lift link (length of crack up to 10 mm)	38,000 / 37,050	—
3	**Damage to bracket securing the frame longerones to the body of rear axle** Crack in bracket of left longeron in area of end of welded seam (length of crack up to 20 mm)		117,300 / 24,810

A rough prediction of service life can be made from the results of the accelerated proving ground testing if one uses the accelerated coefficients between measurements of durability of the same units or details in the field and measurements in accelerated testing. It was established that in testing one prototype of Caterpillar 30, one hour of work under loading in the field corresponds to between from 23 to 36 passes over obstacles on the proving ground, i.e. the conversion factor ranges for obstacles are from 1:23 to 1:36.

For another prototype the ratio was from 1: 33 to 1:37. Therefore, the conversion factor is from 1:23 to 1:37 for prediction of durability.

12.2. 3 The Method of Evaluation of Accelerated Stress Testing Results on the Example of the Trailer Prototype

This method will be discussed in the calculation of the durability of the heaviest loaded elements on the trailer's frame. This calculation was based on readings from four sensors (two on a standard production model and two on a prototype) located in the areas where cracks may occur during proving ground testing (Table 2. 24).

Table 2. 24 The conditions of research[2].

Trailer	Sensor No.	Location of the sensor
Manufactured	18	Bottom shelf of third member of frame in area of welding to the left longeron member
	29	Bottom shelf of left inner longeron member of the body in area of welded seam of locking-mechanism plate
Prototype	17	Bottom shelf of front cross member of rear bogie in area of welding to right longeron member
	25	Bottom shelf of third cross member of frame in area of welding to right longeron member

The number of passes over obstacles on proving ground proving track until failure of the trailer's details counted.

Fatigue resistance under variable tensions is determined by the conditions in which damage accumulates. In this calculation it is assumed that in each cycle of identical parameters, the damage will increase by exactly the same amount:

$$D_n = \frac{n}{N} \tag{2. 10}$$

where:

D_n is accumulated damage;

n is number of loading cycles;

N is the number of cycles until failure.

When $n = 1$, the accumulated damage is equal to unity. Hence the damage for one cycle is:

$$D = \frac{1}{N} \tag{2. 11}$$

The number of cycles until crack formation is:

$$N = \frac{N_0 \cdot \sigma_{-1k}^{\ m}}{\sigma^m} \tag{2. 12}$$

where: σ^m is a variable representing tensions in the cycles studied; $\sigma_{-1k}^{\ m}$ is the endurance limit of the component in a symmetrical cycle; N_0 is the number of cycles until a fracture occurs in the fatigue curve (basic number of cycles); m is the cotangent of the angle (in the logarithmic coefficients) of inclination of the left branch of the fatigue curve.

$$\sum_{j=b}^{K} \sigma_j^{\ m} \cdot n_j$$

It is proved that $D_n = \dfrac{n}{\sigma_{-1k}^{m} \cdot N_0}$ (2. 13)

For example, where statistical analysis of the oscillograms yields the tensions amplitude spectrum for passing over 80 obstacles on the track of the proving ground, the damage caused by passage over one obstacle will be:

$$\Delta D = \frac{D_n}{80} \qquad (2.\ 14)$$

Thus the number of passes over obstacles will be:

$$n = \frac{80 \cdot \sigma_{-1k}^{m} \cdot N}{\sum\limits_{j=b}^{k} \sigma_j^{m} \cdot n_j} \qquad (2.\ 15)$$

Table 2. 25 shows the value selected for the fatigue resistance characteristics (taking into account the quality of the welded seams) together with the results of the calculation. The fatigue resistance characteristics of the details are derived from the data given in the literature. The value of N_0 is taken as equal to $2 \cdot 10^6$, $m = 4$.

Comparison of the calculated values durability of the details with those obtained from the proving ground shows satisfactory agreement between the calculated number of passes over obstacles and actual test results at the proving ground.

This fact indicates that, for a rough prediction of the service life of frame members with welded joints of the types considered, it is feasible to apply the calculation procedure selected and the assumption on which it is based (linear accumulation of damage, discrete distribution of tension amplitudes, systematization of amplitudes by the "consolidated spans" method, etc.).

Table 2. 25 The fatigue resistance characteristics.

Trailer	Sensor N_0	Fatigue resistance characteristic of details		Number of passes over obstacles until failure, on the proving ground		
		Effective coefficient of concentration, K	Endurance limit σ_{-1k}	Actual		
				For each specimen	Average	Calculated
1	2	3	4	5	6	7
Standard model	18	253	590	12,000 83,120 100,600	65,000	15,000
	29	2.8	590	48,320 45,520	47,000	48,000
	17	253	720	105.440 131,520 43,840	94,000	87,000
	25	253	590	250,160 105,440 156,360	171,000	232,000

The distance covered in field operation until failure occurs is calculated by the same formula as a number of passes over obstacles; the only difference is that, for each operating schedule, the experiment yields a tension spectrum relating to a particular length of run. The distance covered in operation until failure (assuming that the trailers are used only on roads of a single type and at the same speed) is calculated by the formula

$$n' = \frac{\sigma_{-1k}^{m} \cdot N_0}{\sum_{j=b}^{k} \sigma_j^{m} \cdot n_j} \qquad (2.16)$$

Assuming that the series of the amplitude distribution of the tensions (obtained from the road of limited length) changes in real life in proportion to the distance covered on a given type of the road throughout the service life of the trailer, the distance covered in operation until cracks appear can be calculated by the formula:

$$n'' = \frac{1}{\frac{a_1}{n_1} + \frac{a_2}{n_2} + \dots + \frac{a_i}{n_i}} \qquad (2.17)$$

where: *n* is the distance covered in different combinations of roads surfaces until cracks appear; a_1 is the ratio of the distance traveled on a particular type of road in proportion to the total distance covered by the trailer; n_1 is the distance traveled until cracks appear when the trailer is run on only one type of road.

Table 2.26 The results of proving ground trials on the trailers.

Trailer model N0.	Number of specimens	Average number of passes over obstacles before testing stopped	Range of dispersion of time before testing stopped
1	3	3,470	1: 2.6
2	3	87,300	1: 1.5
3	3	208,500	1: 1.7

The criterion adopted for evaluating the durability of the tractor trailer models being tested was the length of time that elapsed before development of extensive cracks caused the trials to be broken off.

12.3 SPECIAL EQUIPMENT FOR ACCELERATED TESTING OF FARM MACHINERY

12.3. 1 Equipment for Testing Fertilizer and Manure Applicators

The scheme of the test equipment for fertilizer applicators was shown in Chapter 2 (Figure 2.19). We will now show several designs of this type of equipment in more detail and the technologica process of their work. The specific advantage of the equipment shown below is that it can be produced by the company building the applicators.

Figure 2. 48 shows the scheme of equipment for testing manure applicators. It consists of a frame 1, body 2, spreading units 3, bunker 4, downhill elevators 5, protuberant planks 6, fastened to the chains of the machine's elevators 7, wheels 8, pneumatic tires 9, mounted to the body 2 with stilts 10 and axles 11, scraping elevators 12, scraper 13 with different heights, the units of fastening 14 - 18, reducing gear 19, bearings above the main shaft 20, shafts 21 and 22 of elevators 7 and spreading units 3, device for vibration, and a system of control for pneumatic wheels. Units of fastening 8 to spreading units 3 are made like circular plates and mounted on the frame 1 with roll 23 and have a groove 24 for bearing supports and stops 25 that are needed for fixing the wheels when necessary. The system of control of the pneumatic wheels 8 consists of pipelines 26 which make contact with the tires 9, control valve 27, pressure valve 28, compressor 29, and pressure manometer 30. The vibration device consists of a driving electric motor 31, shafts 32, mounted on the prop 33 which on one side connect with frame 1 and on the other side connect with buffers 34, eccentric device 35. The frame is supported with the help of a shaft on the bearing 37 also. Electric motor 38 is used to drive the working heads, and the loading on the spreading units is simulated by loading devices 39.

The system of elevator driving 7 and spreading units 3 includes chain transmissions 40 and 41 also.

Driving the elevators 5 and 12 is by means of electric motors 42 and 43. For simulation of the corrosive mechanical influences of manure a special manure substitution material 44 is used.

The work principle of the above equipment is that by rotating the fastening unit 18 on the rolls and moving the bearing's supports along the groove 24, one obtains the necessary angle of driving shift 41 and fixes the unit of fastening 18 with stop 25. Switching on compressor 29 allows air to enter pressure valve 28, then control valve 27, which distributes the air through pipelines 26 between the wheels. The tires 9 of wheels 8 are filled out and simultaneously the protuberant planks 6 of distributor 7 elevators are pushed to the bottom of the body, while regulating loading by changing the pressure in the tires 9 to the required pressure with valve 28 and changing of axles 11 of wheels along the stilts 10. After that the electric motors 31, 38, 42, and 43 are switched on to drive the working heads, the vibration system, and the elevators 5 and 12.

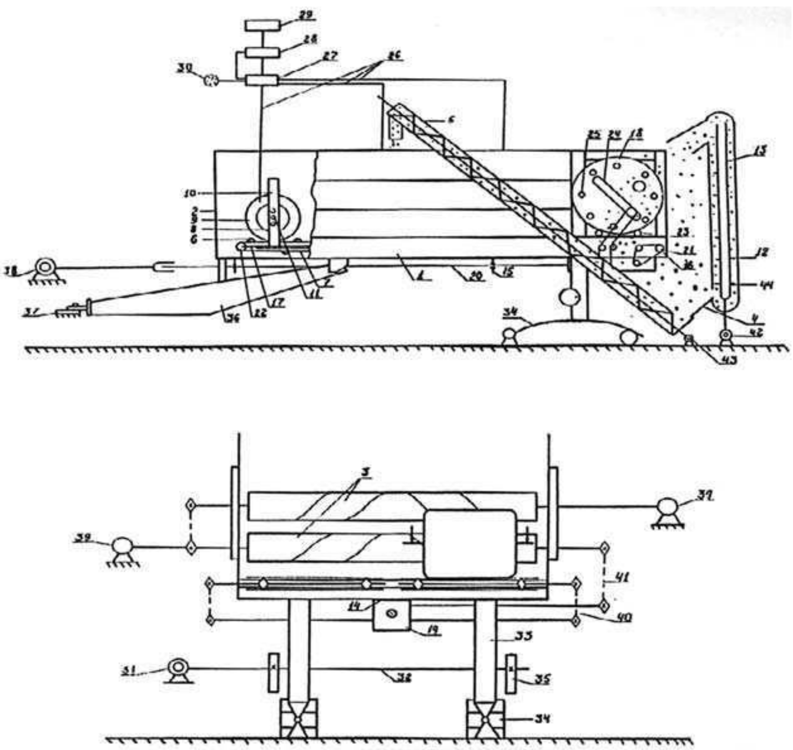

Figure 2. 48 Scheme of equipment for accelerated testing of manure applicator's distributors: 1 = frame, 2 = body, 3 = spreading units, 4 = bunker, 5 = downhill elevator, 6 = plank, 7 = elevator of test subject, 8 = wheel, 9 = pneumatic tire, 10 = stilt, 11 = axle, 12 = scraping elevator, 13 = scraper, 14 to 18 are units of fastening, 19 = reducing gear, 20 = main driver shaft, 21 = 22 shaft of test subject elevators , 23 = roll, 24 = groove, 25 = stops, 26 = pipeline, 27 = control valve, 28 = pressure valve, 29 = compressor, 30 = manometer of pressure, 31, 38, 42, and 43 are electric motors, 32 = shafts, 33 = prop, 34 = buffer, 35 = eccentric device. 36 = beam, 37 = bearing, 39 = loading device, 40, 41 = chain transmission, 44 = substitution material.

The scraper elevators give different quantities of substitute material 44 on the driving chain transmissions 40 and 41, and downhill elevators 5 transfer to the body 2 the substitution material, which is moved by protuberant planks 6 of the applicator in bunker 4. Electric motor 31 is rotated by shaft 32 with eccentric device 35, with the help of buffers 34, and induces vibration of the test subject. Then the system of control through control valve 27 takes out the air from the tires 9 and wheels 8 in turn until loading is completed. After that all systems are stopped and the cycle is repeated.

Another design of testing equipment for testing working heads and drives of manure applicators consists of (seeFigure 2.49 and Table 2.27): frame 1, body 2, where the test subjects are mounted, elevators 3, spreading units 4, driving chain elevators 5 spreader units, drive shafts of spreading units 6, reducing gear 7, common drive shafts 8, cardan shaft 9, barriers 10 which are mounted diagonally across the body 2 with regulated screws 17, bunker 11 which is mounted on the back of body 2, horizontal 12 and inclined screws 13, direct trough 14, electric motor 18 for driving the transmission elements and working heads, electric motors 19 and 20 for driving horizontal 12 and inclined screws 13, hinge support 23 of frame 1, and support 24 which join with beam 25, the vibration system, and the system of the load in addition to spreading units 4, the system of alarm control. The special vibration system, which can be made by the company that produce the applicators, consists of electric motor 26, reducing gear 27, drive chain 28 for driving the shaft with eccentric 29, and buffer 30 at support 24. The load system in addition to spreader units 4 consists of hydraulic pump 31 which is mounted on the free end of the high spreading unit, hydraulic drives 32, manometer 33, throttle 34, and oil tank.

The system of control and alarm consists of the programmer microprocessor controller 36, programmer apparatus and adjustment 37, control cupboard 38, alarm sensors 39 which are mounted on the shaft 21 of the elevators 3 and inclined screw 13. The whole equipment is mounted on the support plate 22. The equipment also has moisturizing system 40 of substitution material 15.

The testing equipment works as follows. The necessary clearance between the barriers 10 and the bottom of body's 2 adjusted by regulated screws 17. The body 2 is filled with substitution material 15. Then the program controller 36 runs a program to turn the electric motors 20, 19, 18, and 26. The substitution material 15 is moved by elevators to spreading applicators 4 and bunker 11.

The height of substitution material 15 is practically equal to the clearance between the barriers and the bottom of the body 2. The changing displacement of the barriers gives the possibility of obtaining the necessary loading on the elevator and minimizes the depth of the substitution material 15 which is delivered to the bunker 11. This gives the possibility of returning the substitution material 15 in the body 2 of low productivity testing. The material 15, after moving through spreader units 4 and bunker 11, reaches the horizontal screws 12 and then the inclined screws 13, and they return material 15 to the body 2 with help of the direct trough 14.

The material 15 which comes in on the chain elevators through the windows in the post of body 2 comes to the screws 12 also.

The necessary loading on the spreader units 4 is simulated with a hydraulic system of uploading in the following way. The hydraulic pump 31 which connects with one end is rotated from high spreader unit 4. It takes the oil from oil box 35 and turns it back through the throttle 34, which creates the pressure on the exit of hydraulic pinion pump 31.The value of this pressure is shown by manometer 33. This pressure makes it difficult to rotate the shafts of gear pump 31, and this increases the resistance for rotation of spreading units 4, i. e. of loading for torsion moments. The value of torsion moments depends on the pressure generated.

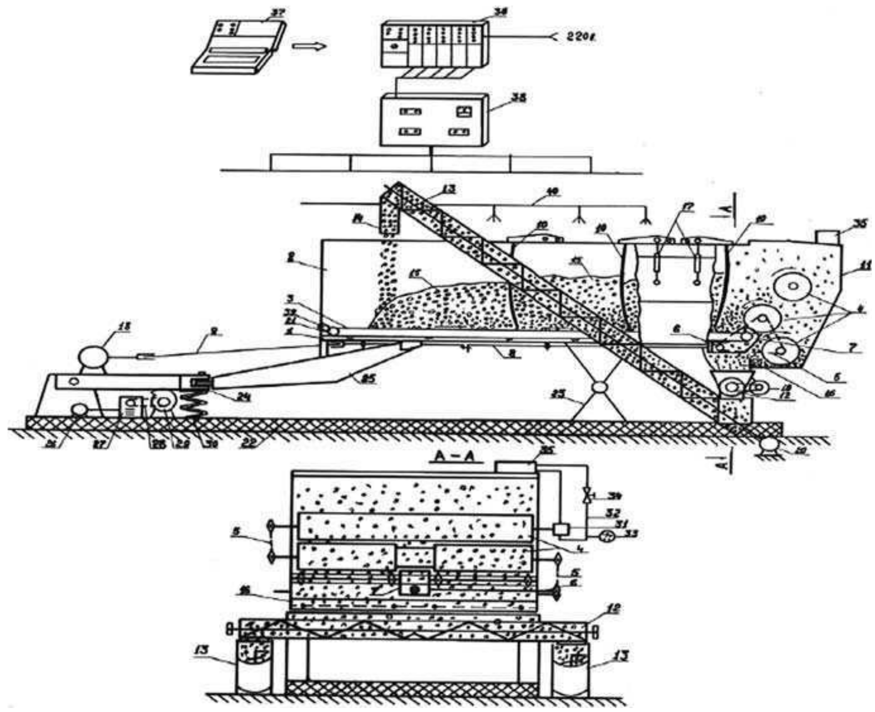

Figure 2.49 The scheme of equipment for testing the working heads and drives of manure applicators: 1 = frame, 2 = body, 3 = elevators, 4 = spreader units, 5 = chain drivers, 6 = driver shaft of spreading units, 7 = reducing gear, 8 = common driver shaft, 9 = cardan shaft, 10 = barriers, 11= bunker, 12 = horizontal screw, 13 = inclined screw, 14 = direct trough, 15 = substitution material, 16 = oven-door, 17 = regulated screw, 18 = electric motor, 19 = electric motor, 20 = electric motor, 21 = drive shafts of elevator, 22 = support plate, 23 = hinge supports, 24 = support, 25 = beam, 26 = electric motor, 27 = reducing gear, 28 = drive chain, 29 = eccentric, 30 = buffer, 31 = hydraulic pinion pump, 32 = hydraulic drives, 33 = manometer, 34 = throttle, 35 = oil box, 36 = programmer microprocessor controller, 37 = apparatus for programming and adjustment, 38 = control cupboard, 39 = alarm sensors, 40 = system of moisturizing.

If one moves the oven-door 16 up or down, can change the loading on the lower spreading unit.

The control of this equipment is provided by a microprocessor programmer controller.

One cycle of work with the above equipment depends on the time that the body takes to become empty of manure (fertilizer) simulation material, and the work of the equipment then stops. Then the cycle is repeated. The break between cycles depends on the specific conditions of test subject use. Alarm sensors 39 are used for stopping the testing equipment through controller 36 under certain conditions. For example, if the elevator is destroyed the sensors 39 will give a signal to the controller 36 which stops the testing equipment.

Table 2. 27 Technical specifications of equipment for testing the working heads and drive of the manure applicators (Figure 2.49).

INDEX	VALUE
1. Total power of electric motors, kW :	84.00
- electric motors with inclined screws,	15.00
- electric motors with horizontal screws,	11.00
- electric motors with vibration system,	3.00
electric motor with transmission which	
contents elements and working heads.	55.00
2. Rotations, min^{-1}:	
- common drive shaft,	960.00
- horizontal screws,	350.00
- inclined screws,	350.00
- eccentric	3.00
3. The system of uploading of spreading units:	
- oil box volume, l	50.00
- manometer pressure, Pa	0 – 25.0
- throttle nominal pressure, Pa	20.00
4. Limit of regulation, mm	
- clearance between the barriers and bottom of body,	90.00 – 400.00
- height of oven-door,	20.00 – 150

Table 2.27 (continuation) Technical specifications of equipment for testing the working heads and drive of the manure applicators.

5. Number, pieces :	
- barriers,	3
- horizontal screws,	2
- inclined screws,	2
- oven-doors	2
6. Diameters of screws, mm	256.00
7. The sizes of equipment, mm:	
- length:	9900.00
- width	4300.00
- height	3500.00

12.3. 2 Regimen for Accelerated Testing of Manure Applicator Working Heads, and their Drives

First, the comparison of the field and the laboratory loading processes is based on their statistical characteristics. Earlier it was established by the authors and their students that laboratory loading corresponds to field loading if the difference between their statistical characteristics is no more than 10%.

Results of analysis of statistical characteristics (all three statistical parameters) of loading for the common drive shaft (sensor 6) shows that the third and fourth regimens in the laboratory correspond to the field (the divergence is no more than 10%). The same holds is true for sensors 4, 2, and 1 for the third, fourth, and fifth regimens in the laboratory (see Table 2.28).

We have to take into account that in τ_k for all sensors the difference is more than 10%. The basic reason for this is the low value of this characteristic.

In Figure 2. 50[4] one can see the graphs of normalized correlation for the shaft of the bottom spreaders unit in the field (F) and in the first to fifth (1 – 5) regimens in the laboratory using testing equipment.

Table 2. 28 Statistical characteristics of loading processes for components of manure applicators[4].

Studied Component	Names of parameters	VALUES OF PARAMETERS					
		Field	Testing equipment (regimen numbers)				
			1	2	3	4	5
Common drive shaft (sensor 6)	Mathematical expectation $\bar{X}$ (H · M)x10^{-1}	20.2	11.1	15.6	19.3	21.2	21.4
	Standard deviation, σ^2_x (H · M)^2 x 10^{-2}	181.1	101.9	138.3	186.0	191.0	101.0
	Time of correlation, τ_k, c	0.09	0.15	0.04	0.10	0.08	0.10
Shaft of spreader units (sensor 4)	$\bar{X}$	50.9	27.3	39.6	48.2	54.6	48.0
	σ^2_x	1152.6	617.8	878.1	1090.4	1238.8	1071.1
	τ_k	0.05	0.15	0.09	0.07	0.02	0.06
Shaft of milling unit (sensor 2)	$\bar{X}$	24.4	17.8	20.2	22.8	25.7	22.7
	σ^2_x	497.3	352.1	431.0	460.1	515.0	464.2
	τ_k	0.08	0.19	0.17	0.09	0.03	0.07

Table 2.28 (continuation) Statistical characteristics of loading processes for components of manure applicators.

Shaft of bottom spreading unit (sensor 3)	$\bar{X}$	12.9	11.2	13.1	-	-	-
	σ^2_x	22.9	185.0	231.3	-	-	-
	τ_k	0.05	0.11	0.07	-	-	-
Shaft of upper spreader unit (sensor 1)	X	21.1	165.0	17.7	20.1	22.2	20.2
	σ^2	191.3	141.6	160.0	182.5	201.2	180.4
	τ_k	0.10	0.48	0.25	0.13	0.05	0.14
Drive shaft of conveyer (sensor 5)	X	260.0	129.5	189.5	229.6	268.1	267.8
	σ^2_x	1785.8	880.4	1312.8	1566.1	1833.4	1824.4
	τ_k	1.13	1.21	1.19	1.15	1.05	1.13

12.3.3 Special Test Equipment for Accelerated Testing of Other Farm Machinery

Equipment for accelerated testing of hay mowing machines

The principal scheme of this equipment is shown in Figure 2.51. It can be used to testing the cutting apparatus of other machinery also.

The equipment consists of the following basic units:

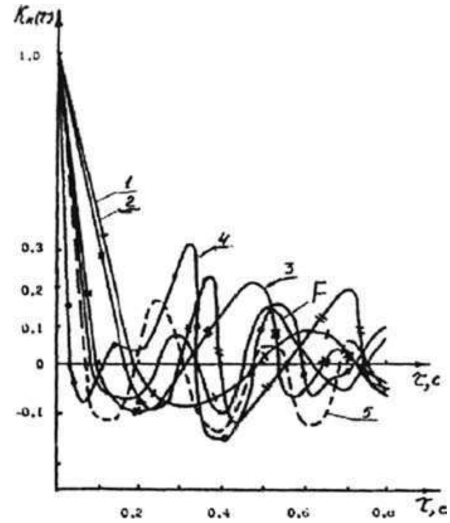

Figure 2.50 Normalized correlation functions of shaft of milling unit loading processes: F – field; 1, 2, 3, 4, and 5 are numbers of the regimens in the laboratory (using testing equipment).

- the frame with mechanisms for simulating the influences during the movement of the test subject (5, 6);
- mechanism of simulation of the wear and fatigue loading on the cutting apparatus (2, 3, 4);
- mechanism which creates a bending moment in the cantilever of the pinned bar;
- mechanism 1 for removing heat from the cutting apparatus.

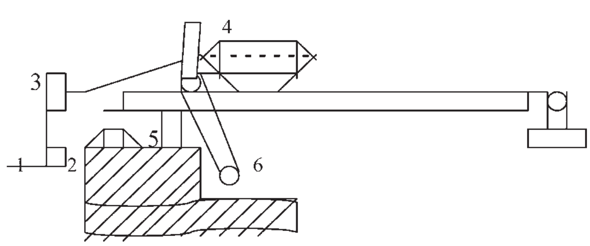

Figure 2. 51 Principal scheme of equipment for accelerated testing of hay mowing machines.

The output influences on the hay mowing machine when cutting green mass are simulated as follows. The circled electromagnet with a clearance of 5 mm is mounted inside of the moving reciprocating segment of the cutting blade. There is strong magnetic field, therefore in the gaps between segments vortex currents arise which are interconnected with the magnetic field, and as a result cause braking of the segments. Hence, resistance of the grass to cutting is simulated. The second electromagnet is pivoted. The high, horizontal magnetic circuit is moved to the back of the blade. The force of attraction of the electromagnets acts on the blade, simulating the reaction of the grass on the cutting blade.

In addition to fatigue loadings, the force of wear acts on the blade segments, simulated by a special eccentric mechanism which consists of shaft 11 with mounted eccentrics 2 which have a special C-shape. These special form eccentrics affect the cutting edge.

The mechanism hoisting the cantilever of the pinned bar before the obstacle is removed automatically.

A moisturizing mechanism removes the heat of interconnection of the magnetic field and vortex current and also simulates corrosive action on the details of the cutting blade mechanism.

In another variation, to simulation loading on the cutting blade apparatus of the testing equipment the mechanism of effort of cutting is mounted on the frame, the cantilever of the pinned bar, and the cutting apparatus is moistured.

After a given period of cutting simulation, the turning regime is started (by raising and then lowering the cutting beam.

Equipment for accelerated testing of other machines

For accelerated testing of a harvester's working heads and elevators one can use the following testing equipment (Figure 2.52).

For accelerated testing of farm machinery transmission one can use the equipment shown in Figure 2.53.

Figure 2.54 shows the scheme of test equipment for measuring the hopper sterns and elevators.

All previously shown test equipment is automatically controlled.

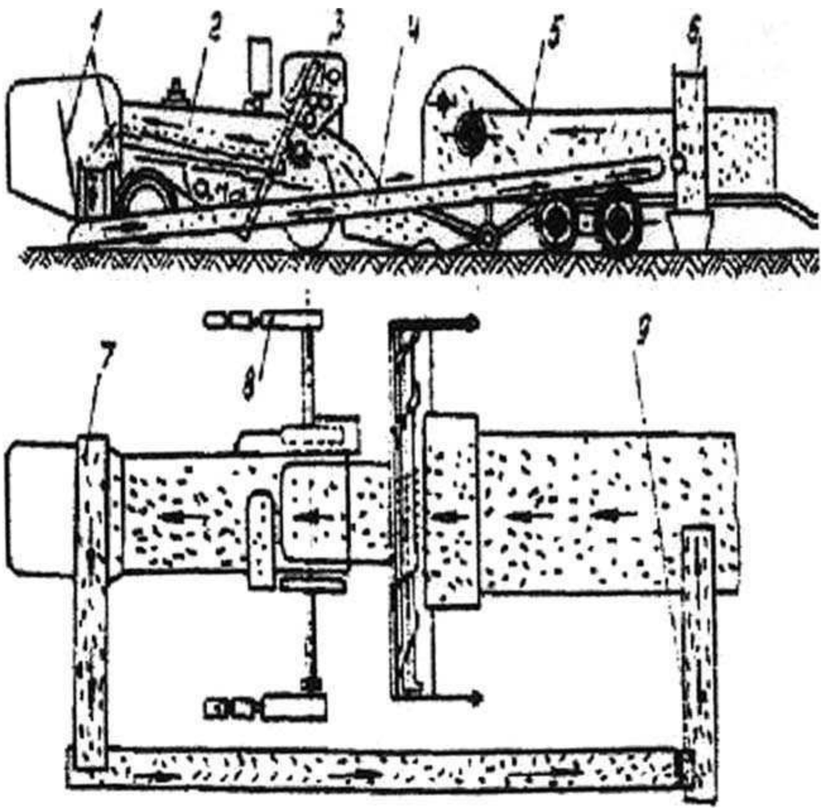

Figure 2. 52 The scheme of equipment for accelerated testing of harvesters: 1= the roll down descs, 2 = harvester; 3 = hopper for measuring grain, 4 = elevator, 5 = storage, 6 = front elevator, 7 = back elevator, 8 = upload device, 9 = magnetic share, 10 = grain simulator, 11 = straw simulator.

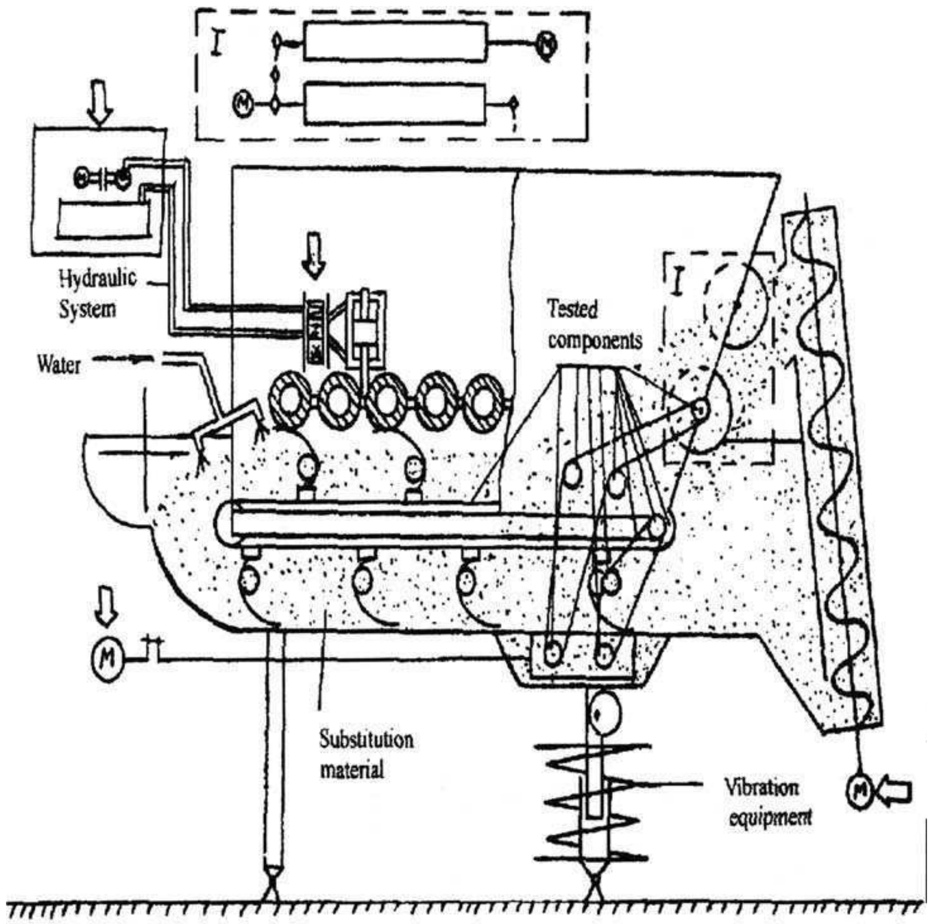

Fig. 2.53. The scheme of equipment for accelerated testing of transmissions.

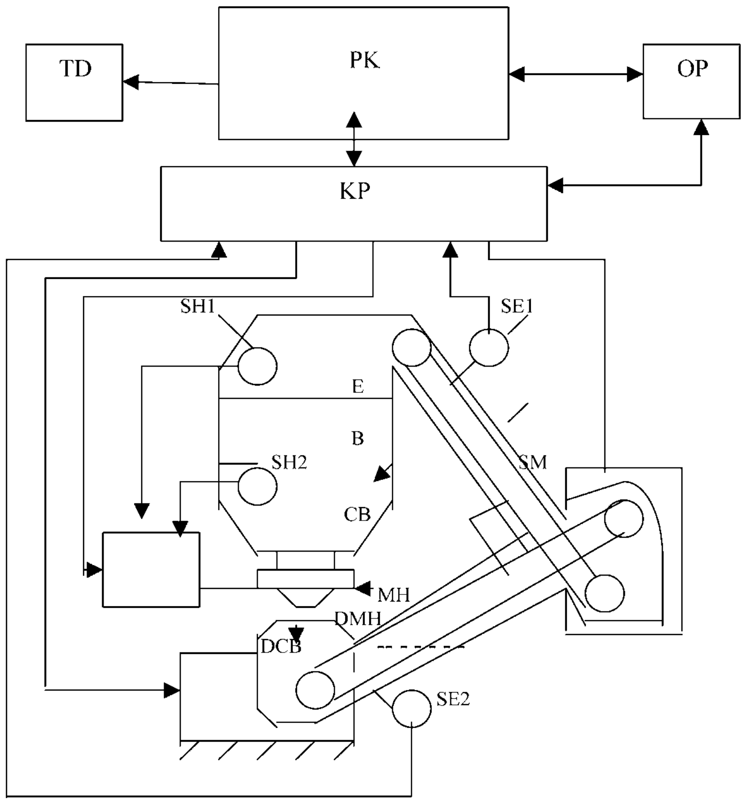

Figure 2. 54. The structural scheme of equipment for measuring hopper sterns and elevators: PK = programmer controller; TD = typed device; OP = operator's panel; CP = control panel; B = bunker; SH1 and SH2 = heigh sensors; SE1 and SE2 = elevator sensors; E = elevator; SM – substitution material; DMH = drive of measuring hopper; MH = measuring hopper; CB = conveyor belt; DCB = drive of conveyor belt.

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13 DETERMINATION OF THE NUMBER OF TESTED PRODUCTS

13. 1 SOLUTION

One important problem in accelerated testing is determining the number of test samples needed (number of experiments). In general, the results of experiments can be shown as a polynomial of power *d* which contains C^{d}_{k+d} coefficients. For a definition of these coefficients, the number of experiments *N* have to be taken in order to satisfy the equation[1]:

$$N > C^{d}_{k+d} \qquad (2.18)$$

Table 2.29 shows the minimum number of experiments needed from the number of studied factors *k* and power *d* of polynomial.

Table 2. 29 Minimum necessary number of experiments.

K	D		
	1	2	3
1	2	3	4
2	3	6	10
3	4	10	20
4	5	15	35
5	6	21	56
6	7	28	84

The number of tested products for each experiment depends on the required accuracy of the experimental results as defined by the formula [2.18]:

$$n = t^2_\alpha \sigma^2 / \Delta^2 \qquad (2.\ 19)$$

where: t_α is the coefficient which characterizes probability that the divergence should not exceed Δ (by $t_\alpha = 2$ the probability $\alpha = 0.95$ and by $t_\alpha = 3$ the probability $\alpha = 0.997$); σ is the standard deviation of the parameter in its general totality; and Δ is the maximum divergence between the selected and the average which corresponds to the given probability α.

This equation is correct when the output parameters have the Normal law of distribution.

It is necessary to find the connection between the number of tested products and the accuracy of the information that is obtained as a result of testing, in order to solve the problem of defining the optimal number of tests.

Therefore, to estimate the number of experiments needed one can use equation [2.18]:

$$N_1 \geq \frac{t^2_\alpha \sigma^2}{\Delta^2} C^d_{k+d} \qquad (2.\ 20)$$

It is necessary to conduct parallel experiments to evaluate the required number of repetitions of the experiment. Practice shows that three or four parallel experiments are enough for one regime of testing.

Then[2]:

$$N_2 = \frac{t^2_\alpha \sigma}{\Delta^2} (C^d_{k+d} + m) \qquad (2.\ 21)$$

where *m* is the number of parallel experiments.

For example, using formula (2. 21) for each regime (experiment) with each new group of test subjects, one can derive the common number of test subjects using the planning the matrix established from formula [2.18]:

$$N_3 = \frac{t^2_\alpha \sigma^2}{\Delta^2} (2^k + m) \qquad (2.\ 22)$$

The provision of parallel experiments for one testing regime significantly reduces the number of multifactor experiments.

If there is an increase in the number of factors and the number of levels to be studied the number of experiments needs to be increased. Table 2.30 shows the number of experiments that are necessary to determine the basic influences and interconnections for some of the factorial experiments[1].

Planning by testing using Normal distribution with known and unknown variance by lognormal distribution, and also the determination of testing values for Weibull distribution, binomial distribution, Poisson distribution, exponential distribution, and gamma distribution is described in detail in the literature[1,2,3,4,5].

Table 2. 30 Determination of the number of experiments by the multifactor influence.

Influence	Number of factors						
	2	3	4	5	6	7	8
Basic (linear)	2	3	4	5	6	7	8
Interconnections of two factors (temperature + vibration)	1	3	6	10	15	21	28
Interconnection of three factors (temperature + input voltage + vacuum)	-	1	4	10	20	35	56
Interconnection of four factors (temperature + input voltage + vacuum + salt spray)	-	-	1	5	15	35	70
Common number of experiments ($N = 2^k$)	4	8	16	32	64	128	256

Let us consider the random magnitude X with Normal distribution and with the known variance σ^2, but with unknown general mean X_0 and experimental estimation $X_{ex} = \overline{X}$.

If given the absolute error and confidence probability α^*, one can find the volume of testing *n*.

The volume of testing we can determine from formula [2.22]:

$$N = (U_a\sigma/\varepsilon)^2 \qquad (2.22)$$

where: U_α is quantile of Normal distribution $U_\alpha = Z_\alpha$.

The values $Z^*_\alpha\sqrt{n}$ for different α^* and n are published[6]. If one knows the value of ε, σ, and α^*, one can determine the unknown n.

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14 TRENDS IN THE DEVELOPMENT OF ACCELERATED RELIABILITY TESTING TECHNOLOGY

14. 1 ANALYSIS OF THE CURRENT SITUATION

How can practical engineers and managers make use of the evaluation, prediction, and analysis of product durability, reliability, failures, degradation, etc. after using current techniques and equipment for accelerated testing?

Where can they obtain accurate initial information in these matters?

From a practical viewpoint, this is only possible after prolonged field testing. However, field testing is too expensive and not very effective for the accelerated evaluation and improvement of the product.

If one does the above after accelerated laboratory testing, the test results for most types of products will differ from field reliability testing, because one does not take into account the following:

• accurate physical simulation of field input influences in the laboratory: all basic types of field input influences on the product, simultaneously and in combination, as they act in the field, and the character of change of these influences in the field;

• the influence of the operator's reliability on the product reliability;

• changes in the technological process of the product use during its working time, etc.

As a result, there is a low correlation between the accelerated testing results (degradation, failures, etc.) and the field reliability test results. Therefore the above laboratory testing cannot give initial information for accurate prediction of the field durability, reliability, maintainability, minimum or zero reduction of time and cost of reliability improvement and the development process in practice. As a result, it is not accurate to prefer reliability testing rather then ordinary AT.

There are many types of ordinary laboratory accelerated stress testing (HALT, HASS, etc.) with high levels of stress that have the above and other negative aspects that do not offer accurate an prediction of the test subject's reliability. Therefore, they cannot be as useful for rapid improvement and development of the industrial product, because rapid testing does not imply rapid improvement.

From a practical and useful viewpoint, this is possible only after field testing, but long term field testing is too expensive and takes too long.

For many fields of industry the following groups of input influences are active: environmental [temperature, humidity, pollution (chemical and mechanical), radiation (ultraviolet, infrared, and visible rays), air and gas pressure, rain, snow, etc.]; features of the surface, speed and directions of the wind; input voltage, etc. Most of these influences act simultaneously and in combination.

The results of their action on product reliability also depend on the connections and interactions of these influences and of the product's components.

Therefore, for accurate reliability prediction one needs to simulate the entire range of the above influences, connections and interactions.

Usually, one does not simulate the above complex in the laboratory, and separate accelerated laboratory testing is provided (temperature-humidity, vibration, corrosion, braking, electrical, etc) or testing with a combination of a part of the above influences which affect reliability[7]. Of course, this is traditional accelerated testing (AT), but not accelerated reliability testing (ART).

During the described testing one has not taken into account the influence of the operator's reliability on the reliability of the test subject. Also, one does not know changes in the stability of the product's technological functions have fenced their reliability.

Consequently, one cannot accurately analyze and predict field reliability, maintainability, etc. without providing ART.

Therefore, the current situation is as follows: industrial companies need to provide separately the different types of above accelerated testing of the product (vibration testing, corrosion testing, dynamometer testing, etc.), and after that to evaluate, analyze, predict, etc. the durability, reliability, maintainability, etc. for the laboratory testing conditions, but not for field conditions,, because these testing conditions are other than the field conditions. Of course, the results will be incorrect[1,2], because of low correlation (or no correlation) of the accelerated testing results with field results.

The above approach is not very productive, but it represents the current situation regarding the use of accelerated testing.

Often in the literature and standards one can find that vibration testing, or dynamometer testing, or corrosion testing, etc. or any combination of two or three of the above types of testing leads to durability and reliability prediction[6]. This appears not only in out dated literature, but also in current literature. For example, "For *durability* testing applications[3], the Series 353 High

Frequency MAST provides the relatively high stroke and force required for event-based control, or control that can reproduce specific force-time events". This means that the Multi-axis Simulation Table (MAST) for vibration testing in six degrees of freedom can be used for durability testing.

There are many other examples of negative aspects of the current situation.

As will be shown below, this situation depends not only on the companies that produce testing equipment, but also on the companies that use it. Industrial companies use the above and other testing equipment for simulation of one or several of many field input influences on the product.

They want to obtain from this single set of testing data the information for reliability, maintainability, and durability evaluation, prediction, and other problem solving. Of course, the results of these evaluations and predictions will be different from those in the field, because the above information does not reflect accurately the field situation. There are many practical examples of the current situation in which the data from ART are prevented from reaching a high correlation between ART results and field results.

Many publications and standards in Accelerated Life Testing (ALT) (often as a part of reliability assurance programs, especially in applied statistics), describe the strategy for analyzing ALT data and other problems, on the basis of information obtained after accelerated testing using single testing equipment. Of course, these results also will be different from the actual field situation.

The standards usually reflect only past achievement, therefore they cannot also point the way for improvement of the current situation in ART.

One needs to develop ART in order to improve the above situation. But one cannot do this immediately, it needs long-term development. One must be sure that the development process is going step-by-step in the correct way. Consequently, it is very important that the correct direction of development is used. Therefore, the trends in development of ART are very important.

How can that be done? The author has analyzed the practical experience in different countries and areas of industry, and literature in development and improvement of ART and, as a result, has generalized the following trends.

14. 2 TRENDS IN DEVELOPMENT

To determine these trends, we have to answer the following question: How can one improve the above situation and realize ART which gives initial information for the accurate prediction of field reliability, rapid and cost-effective solutions as well as other possible quality and reliability problems?

The basis of ART is accurate physical simulation of field input influences on the actual product. Therefore, at present, there are the following trends in the development of Accelerated Reliability Testing Technology (ARTT):

1. Development of the strategy of the above accurate physical simulation of the field input influences on the actual product, including:

- basic concepts;
- obtaining accurate initial information from the field;
- accuracy of simulation;

- degradation (failure) mechanism of the product as a criterion for accurate simulation of field input influences;

- a methodology for selecting representative input region for accurate simulation of the field conditions.

2. Analysis of the climatic influences of climate on reliability, for simulation only components that decrease the product reliability and durability:

- the climate characteristics as external conditions of machinery use;

- development classifications and characteristics of world climate for technical goals;

- the characteristics of influences on the product reliability and durability of thermal regimes air humidity and rains, wind speed, fog and dew, atmospheric phenomena, characteristics of environmental factors in combination, biological factors, influences of solar radiation, fluctuations and rapid changes, characteristics of complex influences of basic climatic factors, etc.

3. Development of the technique for accurate physical simulation of the field input influences on the actual product for the realization of ART:

   - techniques of accurate simulation in the laboratory of each real life input influence which decreases the product's reliability and durability;

   - techniques of the simultaneous combinations necessary for each product selected from the numerous influences which take place in the field;

   - the system of control for physical simulation of the random input influences;

   - techniques for providing special field testing in addition to accelerated laboratory testing;

   - testing which takes into account the connections and interactions of the product components;

   - substitution of artificial media for natural technological media.

4. Development of appropriate equipment for ART.

   Testing equipment on the current market is not suitable for ART, because it does not correspond to the above needs of testing techniques' development. Therefore, it of prime importance that the present equipment must be developed for this goal. For example, if one mechanically combines the present testing equipment only for accelerated environmental testing [humidity, temperature, chemical and mechanical pollution, all three parts of radiation (ultraviolet, infrared, and visible), air and gas pressure, wind, snow, rain, etc.], one also needs to design as well as to consider overall cost problems. Of course, this is quite costly.

This particular system applies only to multi-environmental accelerated testing which is a component of ART. How about ART which is more complicated? It seems this way is not effective, and we must look for another way: not a mechanical combination of current equipment, but the development of new, less expensive equipment with more functional possibilities. As an example of how this trend has developed, these now new combined equipment for ART of electronic devices, and equipment for combined vibration testing, etc. and 15 - 20 years ago this was not apparent.

The process of testing equipment development is going very slowly. The basic reason for this is not only the fault of companies producing test equipment, but also of the user companies combined test equipment is more expensive, and user companies want to save money by purchasing simpler and cheaper test equipment. But this is wrong. It leads directly to lower quality testing, and, as a result, requires more time and raises the cost of product's improvement and development during its manufacture and use. ART offers the possibility to reduce the time and cost of product development, and saves money, especially in the manufacture and usage stages, but some companies do not understand this.

5. Development of accelerated reliability testing performance which consists of:

   - entire technology of step-by-step ART (see 6);

   - providing accelerated laboratory testing technology as a simultaneous combination of multiple environmental, mechanical, electrical, and other components of ART;

   - providing a combination of the above accelerated laboratory testing and special field testing.

6. Development of techniques for accurate prediction of reliability, durability, and maintainability on the basis of ART results:

ART is not a goal, it is a source for obtaining initial information for accurate prediction of reliability, maintainability, availability, their improvement, etc.

The above development consists of:

- development techniques for product reliability prediction on the basis of ART results;

- durability prediction taking into account expenses of time, cost, and losses;

- basic principles of accurate prediction of maintainability (intervals between maintenances, their volume, cost, etc.).

- performance of prediction of system reliability from ART results from the components.

7. Accurately establishing the cost effect of ART as the sum of the stages of design, manufacture, and maintenance.

The process of ART development is going very slowly. The basic reason for this is not only the fault of companies producing test equipment, but also that of the user companies. Combined test equipment is more expensive, and companies using it want to save money by purchasing simpler and cheaper test equipment. This, however, is wrong. It leads directly to lower quality testing, incorrect evaluation and prediction of the product's reliability, and, as a result, requires more time and raises the cost of improvement and development during manufacture and use. ART offers the possibility to reduce the time and cost of product development and improvement, and saves money, especially in the manufacture and usage stages, but most companies do not understand this.

Dodson and Johnson wrote[5]:" Many reliability efforts fail because they are not justified financially. When faced with a large investment years before a product is launched it is difficult to convince financial management that this investment will produce the required level of return. The financial justification for reliability efforts is much easier when all system costs are considered rather than focusing on warranty costs."

So, life-cycle cost consists of all costs associated with the design, manufacture, and usage of a product. Therefore, for greater accuracy in establishing how ART is cost effective, one must develop methods to take into account the cost of complaints, increasing the warranty period, adjusting the time and cost of maintenance, etc.

8. Improvement of the RMS culture.

The basic goal of ART is improvement of quality, reliability, durability, maintainability, supportability, availability, and other related disciplines.

One of the basic components of the above is reliability, maintainability, and the supportability of (RMS) culture.

Robert J. Kuper described[8] a Strategic Plan – Top Priorities of the above use in many areas (US Army, as well as other Armies, industry, professional societies, academia, etc.), which consists of:

• Changing the RMS Culture – people, processes, products & services;

• Core competency enhancement program;

• World class tools, best practices & methods;

• Target big payoff technologies

- probabilistic technology/methods
- quantitative life cycle reliability & safety
- diagnostic/prediction technology.

• New life cycle model: RMS focus on technology and engineering systems;

• Fill in the voids in "Total Systems RMS":

- Network reliability, arise systems, human reliability, integrated HW/SW reliability.

• Focus on real time quantitative life cycle cost, logistics, and supportability;

• Physics of failure – predictive engineering focus;

• Focus on life cycle cost consequences of all RMS activity;

• RMS program visibility: "Eliminate Stovepipes":

- Early RMS intervention – Use of advanced Maintainability & Supportability for requests & concepts;
- Contracting for RMS: business case, "Progressive Assurance";
- RMS engineering as the key linkage in the Systems Engineering Processes;
- RMS backs decision making: life cycle Trade-offs'

• Continuous Reliability (RMS) growth & Trade-off analyses;

• Totally Integrated Life Cycle System: tools & processes:

- Concepts now being developed & deployed: develop & introduce a totally integrated RMS physics-based design and an RMS analytical tool set with an over reaching probabilistic analysis of a capability of managing uncertainty in all aspects of program and decision-making for the technological maturation, design, development, production, and life cycle support and life cycle costs and trades, Advanced Technology solutions;
- Enhanced Technology Base Processes: RMS Descriptions for TRLs;
- Discloses the System Engineering/RMS deficiencies;
- Yields reduced cycle time, higher RMS early in the design, reduced T & E, better M & S and data utility. Reduced: Log tail, O & S costs, and life cycle costs.

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CHAPTER 3. ACCURATE PREDICTION OF RELIABILITY, DURABILITY, AND MAINTAINABILITY ON THE BASIS OF USEFUL ACCELERATED RELIABILITY TESTING RESULTS

15 INTRODUCTION

There are many publications in reliability prediction area[9,10,11,12,13,14,15,16,17,18,19,20] (look references 20.4), because this problem is very important for the theory and practice of reliability, especially when using product reliability prediction for the provision of high quality products.

Most of these publications relate to electronic.

Traditional methods of reliability prediction utilize failure data collected from the field to estimate the parameters of the failure time distribution or degradation process. One can then estimate reliability measures of interest such as the expected time to failure or quantity/quality of degradation during a specified time interval and the mean time-to-failure (or degradation).

Reliability prediction models that utilize accelerated degradation data are performed rather than those models that utilize degradation data obtained under normal conditions, because often the degradation process is essentially very slow and requires a long period to compared to that observed at normal conditions.

In one of the publications mentioned[2] there is a broad description of reliability prediction that emphasizes the procedure used by Bellcore for both hardware and software. In this publication the background of reliability prediction consists of:

1. Outputs from the reliability prediction procedure:

   - Steady state failure rate;
   - First year multiplier;
   - Failure rate curve;
   - Software failure rate.

The output from a reliability prediction procedure is various estimates of how often failure occurs. In the hardware arena the estimates of interest are the steady-state failure rate, the first year multiplier, and the failure rate curve. The steady-state failure rate measures how often units fail after they are more than a year old. One measures the steady-state failure rate in FIT (failures per 10^9 hours of operation). A failure rate of 5000 FIT means that about 4% of the units that are over a year old will fail during the year. The first year multiplier is the ratio of the failure rate in the first year to that in subsequent years. Because one generates a failure rate curve, one is able to provide the failure rate as a function of the age of the equipment. For software one needs to know how often the system fails in the field as a result of faults in the software.

2. About history of hardware procedure:

   - 1975 - Reliability Estimation Procedure for general trade products (hardware only);
   - Reissued every 1.5 to 2 years.

   Before AT&T was divested, the first reliability estimation procedure was developed for use with products bought from outside vendors.

3. Scope of procedures – hardware:

   - Devices;
   - Units;
   - Simple serial systems;
   - Design considerations for complex systems.

Scope of procedures – software:

- Systems;
- Modules.

The Bellcore hardware reliability prediction is aimed at electronic equipment only.

It provides predictions at the device level, at the unit level, and for simple serial systems, but it is primarily aimed at units. Units are replaceable non-repairable assemblies or plug-ins. The goal is to provide the user with useful information on how often units will fail and have to be replaced.

The software prediction procedure estimates software failure intensity. It applies to systems and modules.

There are many uses for reliability prediction. For example, it can be used as input to life-cycle cost studies. Life-cycle cost studies determine the cost of a product over its entire life. Required data include how often a unit will have to be replaced. Inputs to this process include the steady-state failure rate and the first year multiplier.

The Bellcore Reliability Prediction procedure consists of three methods:

1. Parts Count - The predictions are based solely on adding together the failure rates for all the devices. This is the most commonly used method, because laboratory and field information that is needed for the other methods is usually not available.

2. Incorporating laboratory information - Device or unit level predictions are obtained by combining data from a laboratory test with the data from the Parts Count Method. This allows suppliers to use their data to produce realistic predictions of failure rates and is particularly suited for new devices for which few field data are available.

3. Incorporating field information - This method allows suppliers to combine field performance data with data from the Parts Count Method to obtain accurate reliability predictions.

Mechanical Reliability Prediction[13] (look references 20.4) uses various stress factors under operating conditions as a key to all proposed models for different devices. The number of such factors that have to be included in any calculation may appear to be excessive but tailoring methods can be used to remove factors that have little or no influence, or for which no data are available. This situation may occur more often in testing mechanical devices (bearings, compressors, pumps, etc.) than for electronic.

The problems found with all attempts to predict the reliability of mechanical systems are[10]:

1) the lack of specific or generic failure rate data;

2) the lack of information on the predominant failure modes;

3) the lack of information on factors which influence the reliability of the mechanical components.

16 CRITERIA OF ACCURATE PREDICTION OF RELIABILITY AND MAINTAINABILITY BY RESULTS OF USEFUL ACCELERATED RELIABILITY TESTING

Usually one uses the results of accelerated reliability testing[5] as a source for obtaining initial information to predict the reliability and maintainability of machinery under field conditions.

But one must be sure that the prediction will be correct (if possible, with a given accuracy). For this goal one could use the following solution.

The problem is formulated as follows: there is the system [results of use the current equipment in the field] and its model [results of accelerated testing of the same equipment]. The quality of the system can be estimated by the random value φ using the known or unknown law of distribution $F_S(x)$. The quality of the model can be estimated by the random value ϕ using the unknown law of distribution F_M. The model of the system will be satisfactory if the measure of divergence between F_S and F_M is less than a given limit Δ_g.

After testing the model one obtains the random variables φ_1: $\varphi_1^{(1)}, \ldots \varphi_1^{(n)}$. If one knows $F_S(x)$, by means of $\varphi_1^{(1)}, \ldots, \varphi_1^{(n)}$ one needs to check the null hypothesis H_0, which means that the measure of divergence between $F_S(x)$ and $F_M(x)$ is less than Δ_g. If $F_S(x)$ is unknown, it is necessary also to provide testing of the system. As results of this testing one obtains realizations of random variables φ: $\varphi^{(1)}, \ldots, \varphi^{(m)}$. For the above two samplings it is necessary to check the null hypothesis H_0 that the measure of divergence between $F_S(x)$ and $F_M(x)$ is less than the given Δ_g. If the null hypothesis H_0 is rejected, the model needs updating, i.e. to look at more accurate ways of simulating the basic mechanism of machinery use for useful accelerated reliability testing.

The measure of divergence between $F_S(x)$ and $F_M(x)$ is functional as estimated by multi-functional distribution and depends on a competitive (alternate) hypothesis. The practical use of the obtained criteria depends on the type and form of this functional. To obtain exact distributions of statistics on the condition that the null hypothesis H_0 is correct is a complicated and unsolvable problem in the theory of probability. Therefore, here the upper limit s are shown for studied statistics and their distributions are found, so the level of values will be increased, i.e. explicit discrepancies can be detected.

Let us consider the situation when $F_S(x)$ is known.

First, we will take as the measure of divergence between the functions of distribution $F_S(x)$ and $F_M(x)$ the maximum of modulus difference:

$$\Delta[F_M(x), F_S(x)] = \max_{(x)<\infty} / [F_M(x) - F_S(x)] /$$

We understand that H_0 is the hypothesis that the modulus of difference between $F_N(x)$ and $F_S(x)$ is no more than the acceptable level Δ_g, i.e.

$$\bar{H}_0 : \max_{(x)<\infty} [F_N (x) - F_S (x)] \leq \Delta_g$$

where: $F_N(x)$ is the empirical function of distribution.

Against H_0 one checks the competitive hypothesis:

$$\bar{H}_1 : \max / F_N (x) - F_S (x) / > \Delta_g$$

The statistic of the criterion can be given by the formula:

$$\bar{D}_n = \max_{(x)<\infty} / F_N (x) - F_S (x) /$$

Practically it can be calculated by the following formula:

$$\bar{D}_n = \max_{1\leq m \leq n} \{\max [\frac{m}{n} - F(\eta_m)], \max [F(\eta_m) - \frac{m}{n}]\}$$

It is very complicated to find the distribution of this statistic directly[2]. The $D_n \to \Delta_g$ as $n\to \infty$. Therefore, it is necessary to look for the distribution of random value $\sqrt{n}(D_n - \Delta_g)$.

Let us give the upper estimation which can be useful for practical solution of our problem:

$$\bar{D}_n = \max_{(x)<\infty} [F_n (x) - F_S (x)] = \max [F_n (x) - F_M (x) + F_M (x) - F_S (x)] \leq \max_{(x)<\infty} \{/F_n(x)/$$

$$F_M(x)/ + /F_S - F_M(x)/\} \leq \max_{(x)<\infty} /F_n (x) - F_M)/ + \max_{(x)<\infty} /F_M(x) - F_S(x)/$$

If hypothesis H_0 is true:

$$\max_{(x)<\infty} / F_M (x) - F_S (x) / \leq \Delta_g$$

Therefore

$$\bar{D}_n \leq \max_{(x)<\infty} / F_n (x) - F_M (x) / + \Delta_g$$

or

$$\sqrt{n} (\bar{D}_n - \Delta_g) \leq \sqrt{n} \max_{(x)<\infty} / Fn (x) - F_M (x) / \qquad (3.1)$$

Here: if *F (x)* is the probability of work without failure, then *n* is the number of failures.

Let us mark $\max_{(x)<\infty} /F_n (x) - F_M (x) /$ as D_n. This random value $\sqrt{n}D_n$ limited by $n \to \infty$ follows Kolmogorov's law[1]. Therefore

$$P \{\sqrt{n} (\bar{D}_n - \Delta_g) < x \} \geq k (x)$$

or

$$P \{\sqrt{n} (\bar{D}_n - \Delta_g) \geq x \} < 1 - k (x)$$

where: *K (x)* is the function of the Kolmogorov distribution.

As a result of research, was obtained the next right of use of the Kolmogorov's criterion:

First, one calculates the number $\sqrt{n} (\bar{D}_n - \Delta_g) = \lambda_0$.

Then:

$$P \{ \sqrt{n} (\bar{D}_n - \Delta_g) \geq \lambda_0 \} < 1 - k (\lambda_0)$$

If the difference $1 - k(\lambda_0)$ is small, then the probability $P\{\sqrt{n} (\bar{D}_n - \Delta_g) \geq \lambda_0 \}$ is also small. This means that an improbable event occurred, and the divergence between F_n (x) and F_S(x) can be considered as a substantial, rather than a random character of the studied values and Δ_g

Therefore, the conclusion is $\max_{(x)<\infty} / F_S(x) - F_M(x)/ > \Delta_g$.

If the level of value of this criterion is higher than $1 - k(\lambda_0)$, hypothesis H_0 is rejected. If $1 - k(\lambda_0)$ is large, it does not exactly confirm the hypothesis, but by a small Δ_g we can practically consider that the testing results do not contradict the hypothesis.

Let us take now as a measure of divergence between $F_S(x)$ and $F_M(x)$ the maximum difference between $F_S(x)$ and $F_M(x)$ by Smirnov[4] criterion, i.e.

$$\Delta[F_M(x), F_S(x)] = \max_{(x) < \infty} [F_M(x) - F_S(x)]$$

In this case the hypothesis H_0 becomes:

$$H_0: \max_{(x) < \infty} [F_n(x) - F_S(x)] \leq \Delta_g$$

The statistic of the criterion is[4]:

$$D^{+-}_n = \max \left[\frac{m}{n} - F(\eta_m)\right]$$

By analogy to the previous solution, the upper value is:

$$\bar{D}^+_n = \max_{(x) < \infty} / F_n(x) - F_M(x) / + \Delta_g$$

or

$$\sqrt{n}(\bar{D}^+_n - \Delta_g) \leq \sqrt{n} \max_{(x) < \infty} / F_n(x) - F_M(x) / \cdot \sqrt{n}\, D^+_n$$

The random value $\sqrt{n}D^+_n$ in limit has a Smirnov's distribution, therefore

$$P\{ \sqrt{n}(\bar{D}^+_n - \Delta_g) < x \} \geq 1 - e^{-2x2}$$

or

$$P\{ \sqrt{n}(\bar{D}^+_n - \Delta_g) > e^{-2x2}$$

As a result, the following rule for use of the criterion was obtained:

One calculates the value $\sqrt{n}(\bar{D}^{+}_{n} - \Delta_g) = \lambda_0$. Then

$$\{\sqrt{n}\,(\bar{D}^{+}_{n} - \Delta_g) \geq \lambda\} < e^{-2\lambda o2}$$

If $e^{-2\lambda o2}$ is small, therefore the probability $P\{\sqrt{n} \cdot (\bar{D}^{+}_{n} - \Delta_g)\} \geq \lambda_0$ is also small, and if we describe it as analogous with the above:

$$\max\,[\,F_M(x) - F_S(x)\,] > \Delta_g$$

In consideration of the alternate hypothesis H^{-}_{1} everything will be analogous to hypothesis H^{+}_{1}, because if the minuend and subtrahend exchange places, that will not change the final result.

Second, let us consider checking the hypothesis H_0 by using the alternate hypothesis $H_1[\varphi(F)]$ with only the weight function

$$\varphi(F) = \begin{cases} \left(\dfrac{1}{F_S(x)}\right) & \text{if } F_S(x) \geq a \\ 0 & \text{if } F_S(x) < a \end{cases}$$

Let us take as a measure of divergence between $F_S(x)$ and $F_M(x)$

$$\Delta[(F_S(x), F_M(x)] = \max_{F_S(x) \geq a} \frac{/\,F_M(x) - F_S(x)/}{F_S(x)}$$

The statistics of the criterion can be expressed by the formula

$$R_n\,(a, 1) = \max_{F_S(x) \geq a} \frac{F_n(x) - F_S(x)}{F_S(x)}$$

For this practical calculation the following formula can be used:

$$\bar{R}_n(a, 1) = \max\left\{ \max_{F(\eta_M)\geq a} \frac{\frac{m}{n} - F(\eta_m)}{F(\eta_M)}, \quad \max_{F(\eta_M)\geq a} \frac{F(\eta_M) - \frac{m}{n}}{F(\eta_M)} \right\}$$

As stated earlier, the upper value for this statistic was found to be

$$\bar{R}_n(a, 1) = \max_{F_S(x)\geq a} \frac{/\, F_n(x) - F_S(x)\, /}{F_S(x)} \leq \max_{F_M(x)} \frac{F_n(x) - F_M(x)}{F_M(x)} \cdot \max_{F_S(x)\geq a} \frac{F_M(x)}{F_S(x)} +$$

$$+ \Delta_g \leq \bar{R}_n(a, 1)\ 1/a + \Delta_g \qquad (3.2)$$

Hypotheses H_0 and H_1 then become:

$$H_0: \max_{F_S(x)\geq a} \frac{/\, Fn(x) - F_S(x)\, /}{F_S(x)} \leq \Delta_g$$

$$H_1: \max_{F_M(x) > a} \frac{/\, F_n(x) - F_S(x)\, /}{F_S(x)} > \Delta_g$$ we obtain (3.2), because

$$\max_{F_M(x) > a} \frac{/\, F_n(x) - F_M(x)\, /}{F_M(x)}$$ is a statistic of $R_n(a, 1)$.

Therefore, the random value $\sqrt{n}(R_n(a,\ 1)\ -\ \Delta_g$,limited by $n \rightarrow \infty$ follows the law of distribution[3]

$$L(x) = \frac{4}{\pi} \sum_{k=0}^{\infty} \frac{(-1)^k}{2^{k+1}}\ e - \frac{(2k+1)^2\, \pi^2}{8x^2}$$

From here

$$P\{\sqrt{n}\, a\, [\, \bar{R}_n (a, 1) - \Delta_g\,] < x$$

or

$$P\{\, \sqrt{n}\, [\, \bar{R}_n (a, 1) - \Delta_g\,] \geq x\,\} < 1 - 4\,(\lambda_0)$$

As a result, there is the following rule of criterion use:

A) One calculates the actual number $\sqrt{n}\, a\, [\, \bar{R}_n (a, 1) - \Delta_g] = \lambda_0$

B) In that case:

$$P\,\{\, \sqrt{n}\, a\, [\, R_n (a, 1) - \Delta_g\,] \geq \lambda_0\,\} < 1 - L\,(\,\lambda_0)$$

C) If $1 - L\,(\,\lambda_0)$ is small, therefore the probability $P\,\{\sqrt{n}\, a\, [\, R_n (a, 1) - \Delta_g\,]\, \geq \lambda_0$ will also be small. This means that the difference between $F_n(x)$ and $F_S(x)$ is significant.

Then we will take the maximum difference as a measure of divergence:

$$\Delta\,[\, F_M (x), F_S(x)\,] = \max_{F_S (x) \geq a} \frac{F_M(x) - F(x)}{F_S(x)}$$

This problem can also be solved by the method analogous to the previous solution. The rule of use of this criterion is as follows. One calculates the actual number

$$\sqrt{n}\, a\, [\, R^{+}_n (a, 1) -\!- \Delta_g] = \lambda_0.$$

Then

$$P\,\{\, \sqrt{n}\, a\, [\, R^{+}_n (a, 1) - \Delta_g\,] \geq \lambda_0\,\} < 2\,[1 - \Phi\,(\frac{\lambda_0 \cdot \sqrt{a}}{\sqrt{1 - a}})]$$

If $2 \left[1 - \Phi \left(\frac{\lambda_0 \cdot \sqrt{a}}{\sqrt{1-a}} \right) \right]$ is small, it means that hypothesis H_0 is rejected and then by analogy to previous solutions.

The same applies to the competitive hypothesis H_1.

All are analogous with weight function

$$\psi [F_S(x)] = \left\{ \begin{array}{ll} \frac{1}{1 - F_S(x)} & \text{by } F_S(x) \leq a \\ & \text{by } F_S(x) > a \end{array} \right\}$$

Let us now consider the variant when $F_S(x)$ is unknown.

In this case one provides a testing of the system. As a result, one obtains realizations of the random value φ of system quality $\varphi^{(1)}, \ldots, \varphi^{(m)}$, and can use these realizations to build empirical functions of the distribution $\tilde{F}_m(x)$. By means of the empirical functions of distribution $F_n(x)$ and $F_m(x)$ it is necessary to establish whether the studied random value relates to one class or not, i.e. will the divergence between the actual functions of distribution $F_n(x)$ and $F_S(x)$, by a certain measure be less or more than the given tolerance Δ_g.

Let us take the measure of divergence in the Smirnov criterion as a measure of divergence between functions of distribution[4]:

$$\Delta [F_M(x), F_S(x)] = \max_{(x) < \infty} [F_M(x) - F_S(x)]$$

In this case the null hypothesis H_0 looks like:

$$H_0: \max_{(x) < \infty} [F_n(x) - \tilde{F}_m(x)] \leq \Delta_g$$

The alternative hypothesis H^+_1 looks like:

$$H_1: \max [F_n(x) - F_m(x)] > \Delta_g$$

The statistic of criterion can be expressed by the formula:

$$D_{m,n} = \max_{(x) < \infty} [\, F_n(x) - \tilde{F}_m(x)$$

Its upper estimation is:

$$D^{+}_{m,n} = \max \{\, F_n(x) - F_S(x) - \tilde{F}_m(x) + F_M(x) + F_S(x) - F_M(x) \,] \leq \max_{(x) < \infty} [\, F_n(x) - F_S(x)] +$$

$$+ \max_{(x) < \infty} [F_M(x) - \tilde{F}_m(x)\,] + \max_{(x) < \infty} [\, F_S(x) - F_M(x)\,]$$

If hypothesis H_0 is true:

$$D^{+}_{m,n} \leq D^{+}_{n} + \bar{D}^{-}_{m} + \Delta_g$$

where

$$\bar{D}^{+}_{n} = \max_{(x) < \infty} [\, F_n(x) - F_S(x)] \quad \text{and} \quad D^{+}_{m} = \max [F_M(x) - F_m(x)]$$

Statistics $\bar{D}^{+}_{m}$ and D^{+}_{m}, as was shown earlier, have equal distributions. Therefore,

$$\bar{D}^{+}_{m,n} - \Delta_g \leq D^{+}_{n} + D^{+}_{m}$$

Therefore,

$$\sqrt{\frac{mn}{m+n}}\,(D^{+}_{m,n} - \Delta_g) \leq \sqrt{\frac{mn}{m+n}}\,D^{+}_{n} + \sqrt{\frac{mn}{m+n}}\,D^{+}_{m}$$

Let n and m approach infinity, so that $\frac{m}{N} \to k$. Then

$$\lim_{n \to \infty} \sqrt{\frac{mn}{m+n}} (\bar{D}^{+}_{m,n} - \Delta_g) \leq \sqrt{\frac{1}{1+k}} \lim_{n \to \infty} \sqrt{n}\, D^{+}_{n} + \sqrt{\frac{k}{k+1}} \lim_{n \to \infty} D^{+}_{m}$$

Let us mark the random variable $\lim \sqrt{n}\, D^{+}_{n}$ through V_2. V has Smirnov's function of distribution [1] $F_V(x) = 1 - e^{-2x2}$. Then from the assumption that m and n are large enough

$$\sqrt{\frac{mn}{m+n}} (\bar{D}^{+}_{m,n} - \Delta_g) \leq \sqrt{\frac{1}{k+1}} V_1 + \sqrt{\frac{k}{k=1}} V_2 = \xi \qquad (3.3)$$

The variances of ξ and V $(D_\xi = \frac{1}{k+1} DV_1 + \frac{k}{k+1} DV_2 = DV)$ are equal. Let us find

the mathematical expectation of V

$$\mu_v = \int_0^\infty [1 - F(x)]\, dx = \int_0^\infty e^{-2x2}\, dx = \frac{\sqrt{\pi}}{2\sqrt{2}}$$

Therefore, $\mu_v = \frac{\sqrt{\pi}}{2\sqrt{2}} [\sqrt{\frac{1}{k+1}} + \sqrt{\frac{k}{k+1}}]$. Let us find the maximum of $\frac{1+\sqrt{k}}{\sqrt{k+1}}$

$$\left(\frac{1+\sqrt{k}}{\sqrt{k+1}}\right)^1 = \frac{½\, k^{-1/2} (k+1)^{1/2} - (1+k^{1/2})^{1/2} (1+k)^{1/2}}{k+1} = 0$$

or $k + 1 = (1 + \sqrt{k})\sqrt{k} = \sqrt{k} + k$ and $k = 1$, i.e. maximum μ_ξ is reached when $m = n$.

In this case

$$\mu_\xi - \frac{\pi}{2\sqrt{2}} \cdot \frac{2}{\sqrt{2}} = \frac{\pi}{2}$$

One must take into account that $D_\xi = D_v = ½$

Now let us find the distribution of random variable ξ which is the upper estimation for our normalized statistic $\sqrt{\frac{mn}{m+n}}\,(\bar{D}_{m,n} - \Delta_g)$. Let us find the distribution of the random variable

$$\xi = a_1V_1 + a_2V_2$$

$$F_{a1v1}(x) = P\{a_1v_1 < x\} = P\{V_1 < \frac{x}{a_1}\} = 1 - e^{-2x2/a1,2}$$

$$F_{a1v2}(x) = 1 - e^{-2x2/a2,2}\ ;\ a_1 = \frac{1}{\sqrt{k+1}}\ ;\ a_2 = \sqrt{\frac{k}{1+k}}$$

Let us mark $\frac{2}{a_1^2}$ through A; $\frac{k}{a_2^2}$ through B.

By the formula of convolution[5]

$$F_\xi^1(x) = \int_0^x Fa_1v_1(x-y)\,dFa_2v_2(y) + \int_0^x (1 - e^{-A(x-y)2})\,2By\,e^{-By2}dy =$$

$$= \int_0^x 2By\,e^{-By2}\,dy - 2B\int_0^x ye^{-A(x-y)2-By2}\,dy = 1 - e^{-2Bx2} - 2Be^{-Ax2}\int_0^x ye^{2Axy\,-\,y2(A+B)}\,dy = 1 -$$

$$e^{-Bx2} + \frac{A^2x^2}{A+B}\int_0^x e^{-(y\sqrt{A+B}\,-\,\frac{Ax}{\sqrt{A+B}})2}\,y\,dy = 1 - e^{-2Bx2} - \frac{2Be^{-ABx2/A+B}}{A+B}$$

$$[\int_0^x e^{-(y\sqrt{A=B}\,-\,\frac{Ax}{\sqrt{A+B}})2}\,y\,dy = 1 - e^{-2Bx2} - \frac{2Be^{-ABx2/A+B}}{A+B}\qquad [\int_0^x e^{-(y\sqrt{A+B})-Ax/\sqrt{A+B})2}\,.$$

$$\cdot \left(y\sqrt{A+B} - \frac{Ax}{\sqrt{A+B}}\right) d\left(y\sqrt{A+B} - \frac{Ax}{\sqrt{A+B}} + \right.$$

$$+ \frac{Ax}{\sqrt{A+B}} \int_0^x e^{-(y\sqrt{A+B} - \frac{Ax}{\sqrt{A+B}})2} d\left(y\sqrt{A+B} + \frac{Ax}{\sqrt{A+B}}\right)\Big] = 1 - e^{-Bx2} + \frac{2B}{A+B} e^{-ABx2/A+B} \Big[$$

$$\Big[\int_{\frac{-xA}{\sqrt{A+B}}}^{\frac{xB}{\sqrt{A+B}}} e^{-u2} dy + \frac{Ax}{\sqrt{A+B}} \cdot \int_{-xA/\sqrt{A+B}}^{xB/\sqrt{A+B}} e^{u2} dy \Big] =$$

$$= 1 - e^{-2Bx2} + \frac{2B}{A+B} e^{-ABx2/A+B} \Big[1 - \frac{e^{-A2x2/A+B} + e^{B2x2/A+B}}{2} +$$

$$+ \frac{Ax\sqrt{\pi}}{\sqrt{A+B}} + \Big[\Phi\left(\frac{\sqrt{2}\,Ax}{\sqrt{A+B}} + \Phi\left(\frac{\sqrt{2}\,xB}{\sqrt{A+B}}\right)\right]\Big] = \frac{Ax\sqrt{\pi}}{\sqrt{A+B}} \Big[\Phi\left(\frac{\sqrt{2}\,Ax}{\sqrt{A+B}}\right) +$$

$$+ \Phi\left(\frac{\sqrt{2}\,xB}{\sqrt{A+B}}\right)\Big] = 1 - e^{2Bx2} + \frac{2B}{A+B} e^{-ABx2/A+B - B/A+B} \left(e^{-Ax2} + e^{-Bx2}\right) + \frac{2ABx\sqrt{\pi}}{A+B} \cdot$$

$$\cdot \Big[\Phi\left(\frac{\sqrt{2}\,xB}{\sqrt{A+B}}\right) + \Phi\left(\frac{\sqrt{2}\,xA}{\sqrt{A+B}}\right)\Big] \qquad (3.4)$$

After substituting in (3.4) the values of $A = \frac{2}{A_1^2}$ and $B = \frac{2}{A_2^2}$; $a_1 = \sqrt{\frac{1}{k+1}}$; $a_2 = \sqrt{\frac{k}{k+1}}$;

$A = 2(k+1)$; $\quad B = \frac{2(k+1)}{K}$, we obtain the expression for the function of distribution of estimation ξ

$$F_{\xi}(x) = 1 - e^{-4(k+1)x2/k} + \frac{2}{k=1} e^{-2x2} - \frac{1}{k=1}\left(e^{-(k+1)x2/k}\right) + \frac{x\sqrt{\pi}\,2\sqrt{2}}{(k+1)\sqrt{k}} e^{-2x2}\,[$$

$$\cdot[\Phi\left(\frac{2x}{\sqrt{k}}\right) + \Phi(2x\sqrt{k})]$$

Thus, we have found the distribution ξ . From (3.3) it follows that

$$P\left\{\sqrt{\frac{mn}{m+n}}\,(\bar{D}^{+}_{m,n} - \Delta_g) > x\right\} \leq 1 - F_y(x)$$

As a result, we obtain the following rule of criterion use.

To calculate the actual number

$$\sqrt{\frac{mn}{m+n}}\,(\bar{D}_{m,n}^{+} - \Delta_g) = \lambda_0 \qquad (3.5)$$

where: n is number of failures in accelerated (laboratory) testing;
and m is number of failures in the field.

Therefore,

$$P\left\{\sqrt{\frac{mn}{m+n}}\,(\bar{D}^{+}_{m,n} - \Delta_g) \geq \lambda_0\right\} \leq 1 - F_{\xi}(\lambda_0)$$

If $1 - F_{\xi}(\lambda_0)$ is small, the hypothesis H_0 is rejected by analogy to the previous calculations.

In this case $\xi = V$ if $k = 0$ or $k = \infty$.

If we take as a measure of divergence between distributions of functions a functional

$$\Delta[F_S(x), F_M(x)] = \max_{x<\infty} / F_M(x) - F_S(x) /$$

and make the actions analogous to previous, we obtain the rule of use for the criterion in the following form. First, we calculate the following number $\sqrt{\frac{mn}{m+n}}\,(\bar{D}^{+}_{m,n} - \Delta_g) = \lambda_0$.

Then

$$P\left\{ \sqrt{\frac{mn}{m+n}}\,(\bar{D}^{+}_{m,n} - \Delta_g) \geq \lambda_0 \right\} \leq 1 - F_x(\lambda_0)$$

If $1 - F_x(\lambda_0)$ is small, it means that the hypothesis H_0 is rejected, and then is analogous to previous actions.

For finding the distribution of random variable k one can use the following dependence

$$F_k(z) = \sum_{k=-\infty}^{+\infty} \sum_{L=-\infty}^{\infty} (-1)^{k+I+1} \cdot \frac{2i^2 a^2}{k^2 b^2 + I^2 a^2}\, e^{-\frac{2k^2 I^2 z^2}{k^2 b^2 + I^2 a^2}} \Big\{ 1 -$$

$$- \tfrac{1}{2} \left(e^{\frac{-2k^4 z^2 b^2}{a^2 (k^2 b^2 + a^2 I^2}} + e^{\frac{-2 I^4 z^2 a^2}{b^2 (k^2 b^2 + I^2 a^2)}} + e^{\frac{z\sqrt{\pi}\sqrt{2}\,k^2 b}{a\sqrt{k^2 b^2 + I^2 a^2}}} \right) \cdot$$

$$\cdot / \Phi\left(\frac{2 z k^2 b}{a\sqrt{k^2 b^2 + I^2 a^2}}\right) + \Phi\left(\frac{2 z i^2 a}{b\sqrt{k^2 b^2 + I^2 a^2}}\right) / \Big\} \qquad (3.6)$$

where

$a = \frac{k_1}{\sqrt{k+H}}$; $b = \frac{\sqrt{k_1}}{\sqrt{k_1+1}}$ in the function of Kolmogorov's distribution

$$F_\xi(k) = \sum_{k=-\infty}^{\infty} (-1)^k e^{-2k2x2}$$

Conclusion[5]:

a) The engineering version of the obtained solution is that the upper estimation of the statistical criteria of correspondence, for some measures between the functions of distribution of studied characteristics of reliability, maintainability, etc., were created in laboratory conditions and in field conditions. This can be useful for reliability and maintainability prediction as well as for solving other engineering problems (accelerated reliability development and improvement, etc.);

b) The mathematical version of the obtained solution is that approximate criteria as modifications of Smirnov's and Kolmogorov's criteria by divergence ($\Delta_g < 0$) were obtained for comparison of two empirical functions of distribution by measurement of Smirnov's divergence:

$$\Delta[F_S(x), F_M(x)] = \max_{(x)<\infty} [F_M(x) - F_S(x)]$$

and Kolmogorov's:

$$\Delta[F_S(x), F_M(x)] = \max_{(x)<\infty} / F_S(x) - F_M(x)$$

In Smirnov's criterion by zero hypothesis:

$$\max_{(x)<\infty} [F_M(x) - \tilde{F}_m(x)] < \Delta_g$$

By competitive hypothesis:

$$\max_{(x)<\infty} [F_M(x) - \tilde{F}_m(x)] > \Delta_g$$

If $\Delta_g = 0$, we have Smirnov's criterion. An analogous situation applies for Kolmogorov's criterion.

The difference between both versions is that in the measure using Smirnov's criterion one takes into account only the regions (the oscillograms of loadings, etc.) where $F_S(x) > F_M(x)$ and one looks for maximum differences only for them. In measuring with Kolmogorov's criterion one takes into account the maximum differences for all regions by modulus. The consideration of both criteria makes sense because Smirnov's criterion is easier to calculate, but does not give the full picture of divergences between $F_S(x)$ and $F_M(x)$; Kolmogorov's criterion gives a fuller picture of the above divergence, but is more complicated in calculation.

Therefore, the choice of the better criterion for a specific situation must be decided according to the specific conditions of the problem to be solved.

Let us show the solution obtained by a practical example. In the field 102 failures ($m = 102$) of details of car trailer transmissions were obtained. After accelerated testing in the laboratory 95 failures were obtained [($n = 95$), Δ_g is 0.02].

In the field one builds the empirical function of distribution of the time to failures $F_m(x)$ *by* the intervals between failures, and one builds by intervals between failures during laboratory testing of the empirical function of distribution time to failures $F_M(x)$. As we can see, this is last variant to be considered

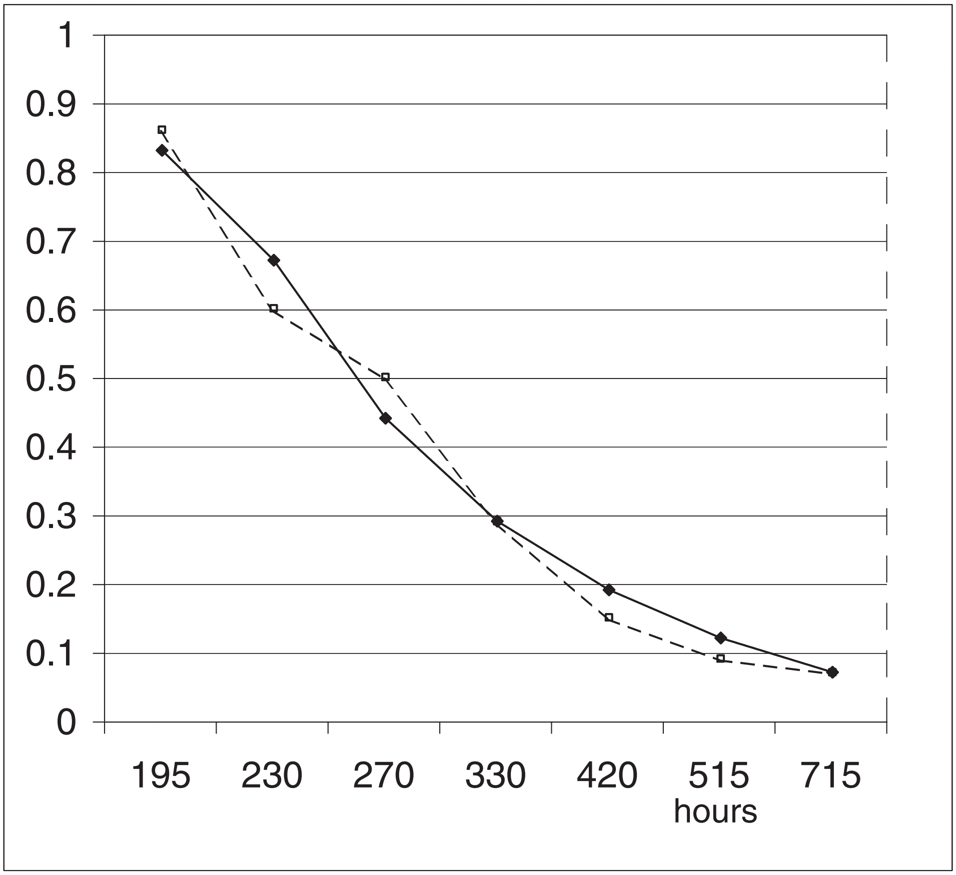
If we align the graph $\tilde{F}_M(x)$ (Figure3.1)and the graph $F_m(x)$, we will find the maximum difference between $\tilde{F}_M(x)$ and $F_m(x)$.

For this goal we can draw the graph $F_m(x)$ on the transparent paper and it is simple to find the maximum difference $\bar{D}^{+}_{m,n} = 0.1$. In correspondence with[3] we have $\lambda_0 = 0.98$.

$$\text{The}\quad k = \frac{m}{n} \approx 1, \text{ therefore } F_x\text{:}$$

$$F_x(x) = 1 - e^{-2x2}\,[1 + x\sqrt{2\pi} \cdot \Phi(x)]$$

After substitution of $\lambda_0 = 0.98$, we obtain $F_x(0.98) = 0.6$. Therefore, $1 - F_x(0.98) \approx 0.4$. *So,* $1-F_x\ (0.98)$ is not small and the hypothesis H_0 can be accepted. Therefore, the divergence between actual functions of distribution of time to failures of the above transmission details for the tested car trailer in field conditions and in laboratory (accelerated testing) conditions by Smirnov's measure is within the given limit $\Delta_g = 0.02$(Figure 3.1). This gives the possibility for accurate prediction of reliability and maintainability of the car trailer transmissions using the results of this accelerated testing.



---------------- in the field ; ———— in the laboratory

Figure 3.1 Evaluation of the correspondence between functions of distribution of the time to failure of a car trailer's transmission details in the field and in the laboratory (accelerated testing conditions).

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17 DEVELOPMENT OF TECHNIQUES FOR PRODUCT RELIABILITY PREDICTION ON THE BASIS OF USEFUL ACCELERATED RELIABILITY TESTING RESULTS

The problem to solve here is the accurate prediction of product reliability if one takes into account the influences of the complex input factors on reliability.

The typical situation in practice for engineering is a small sample size (from 5 to 10 specimens of each component) with only 2 - 5 possible failures included. Usually it is assumed that the failures of the system components are statistically independent.

The proposed approach is very flexible and useful for many different types of product such as electronic, electromechanical, mechanical, and others.

17.1 BASIC CONCEPTS OF RELIABILITY PREDICTION

The best methodology of reliability prediction cannot be useful for practical engineers if it is not connect with techniques and equipment for obtaining accurate initial information for this prediction. Useful accelerated reliability testing can give this information if this is successive step-by-step testing as shown in Chapter 2.

The basic concept of accurate reliability prediction consists of the following basic steps:

1. Building an accurate model of real time performance.
2. This model will be used for testing the product and, as a result, to study the degradation mechanism over time and compare it with the real life degradation mechanism of this product. If these degradation mechanisms differ by more than a fixed limit, one must improve the model's real time performance.
3. Making real-time performance forecasts for reliability prediction using these testing results as initial information.

Each step can be performed in different ways, but reliability can be predicted accurately if the researchers and engineers use the above concept.

Step 1 can be executed if one understand that in real life the reliability of the product depends on a combination of different minimum numbers of input influences, such as temperature, vibration, and input voltage (for electronic), etc. which are interesting in connection and interaction. In this case the simulation of real life input influences will be complicated as in real life. For example, for a mobile product one needs to use multi-axis vibration.

In order to solve the step 2 one has to understand the degradation mechanism of the product and parameters of this mechanism. The results of the product degradation mechanism include data on the electrical, mechanical, chemical, thermal, radiation, etc. effects. For example, the parameters of the mechanical degradation mechanism are deformation, crack, wear, creep, etc. In real life different processes of degradation act simultaneously and in a combination. Therefore, useful accelerated reliability testing includes simultaneous combination of different types of testing (environmental, electrical, vibration, etc.)[6], with the assumption that the failures are statistically independent. The degradation mechanism of the product in real life must be similar to this mechanism during accelerated testing.

In order to solve the step 3 the reliability prediction technique has to be developed. For solving this problem the aspects that must be considered involve specific manufacturing and field conditions.

17. 2 PREDICTION OF THE RELIABILITY FUNCTION WITHOUT FINDING THE ACCURATE ANALYTICAL OR GRAPHICAL FORM OF THE FAILURES' DISTRIBUTION LAW

The problem was solved for two types of conditions: a) prediction of consisting of points expressions of reliability function of the systems elements; b) prediction of the reliability functions of the system with predetermined accuracy and confidence area[14] (look 20.4).

Problem a) can be solved with grapho-analytical methods on the basis of failure hazard or frequency if we have the graph f(t) of the empirical frequency of failures. Guided by the failure frequency graph, one can discover the reliability function:

$$p(t) = \int_0^t f(t)dt = 1 - S_f \qquad (3.7)$$

where:

$\int_0^t f(t)dt = S_f$ is the area under the curve f(t) which was obtained as a result of reliability testing.

The reliability function of a system which consists of different components (details) is:

$$P(t) = \Pi P_j (t) = \Pi (1 - S_{fj}) \qquad (3.8)$$

For example, as a result accelerated testing of belts t = 250 (Figure 3. 2), the area is S_f = 1.12, and probability P(t) = 0.82.

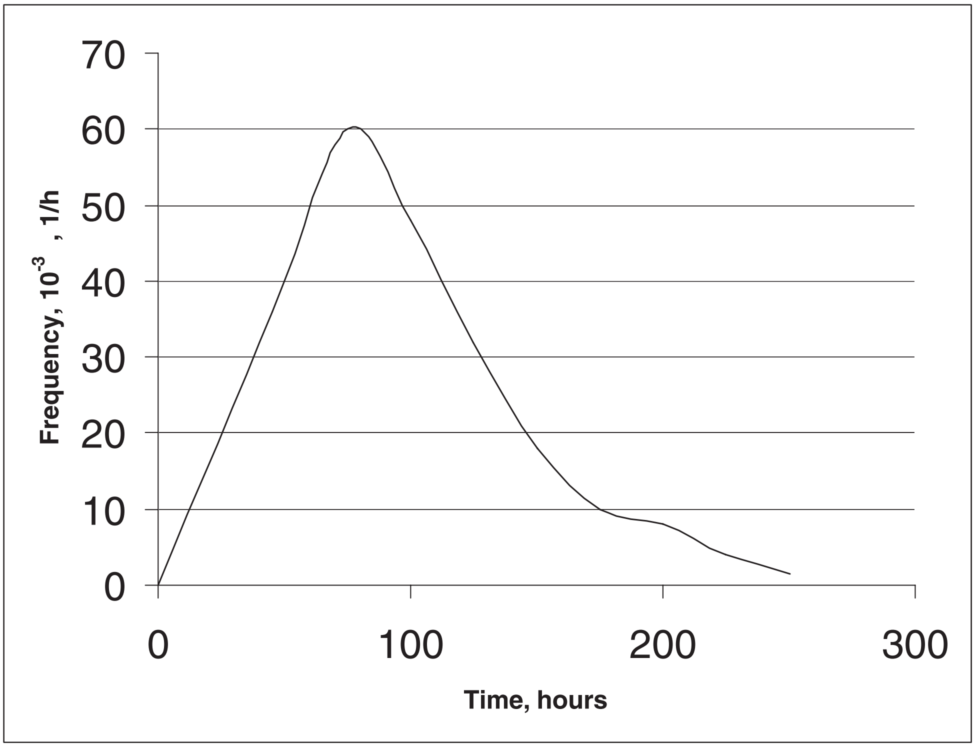

Figure 3. 2. Graph of frequency of failure of the belts.

In variant b) one needs to calculate the accumulated frequency function and the values of the confidence coefficient found in the equations:

$$Y(x) = \sum_{m}^{n} C_n^m p^m (1 - P)^{n-m} \qquad (3.9)$$

$$Y(x) = \sum_{m=0}^{k} C_n^m p^m (1 - P)^{n-m} \qquad (3.10)$$

and evaluate the curves that are limited to the upper and lower of the confidence areas.

Where $C_n^m p^m (1 - P)^{n-m}$ is the probability that based on an event will be in *n* independent experiments' *m* times. The values of η and $\acute{\eta}$ are found in the tables of the books on the theory of probability if the confidence coefficient is: $\lambda = 0.95$ or $\lambda = 0.99$.

Figure 3.3 shows the area of reliability function *P(t)* of belts if $\lambda = 0.95$. If one uses this type of graph, it is possible to evaluate the actual reliability of details, units, and machines (equipment) for whatever time and accuracy are needed.

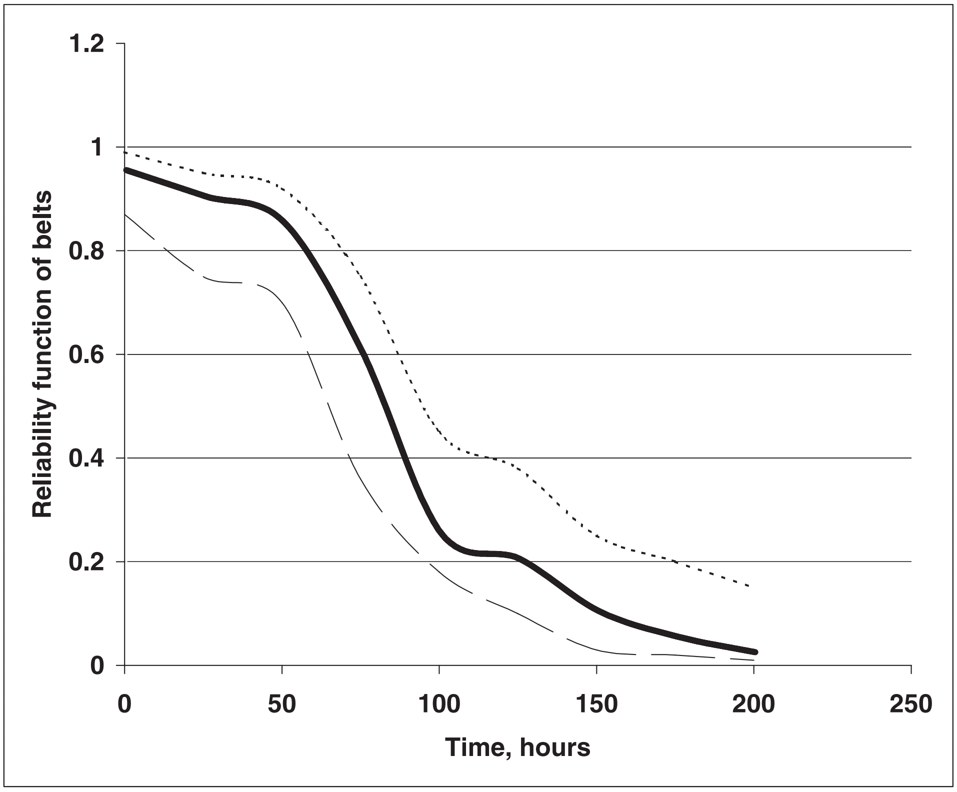

Figure 3. 3 Area of possible value P(t) of the belts reliability.

— is mean of reliability function;

. . . is upper confidence level;

— — is lower confidence level.

17.3 PREDICTION USING THE MATHEMATICAL MODELS WITH INDICATION OF THE DEPENDENCE BETWEEN PRODUCT RELIABILITY AND DIFFERENT FACTORS OF MANUFACTURING AND FIELD

These factors (influences) should be evaluated as the results of accelerated testing.

The solution of this problem is possible using mathematical models which best describe the dependence between the reliability and the series of factors shown above:

$$z_i^{(\tau)} = f_i^{(\tau)} (v_1; v_2; \ldots; v_\theta, \qquad (3.\ 11)$$

$$\tau = 1, 2, \ldots, n$$

where:

θ is the number of all factors;

n is the number of reliability indexes which most completely characterize the I-th model of the product;

$f_i^{(\tau)}$ *(v)* is the function which gives the possibility of finding the optimum value of this functions indexes, by changing the level of factors influencing the products reliability.

A large volume of statistical information is necessary to build this function, which one can obtain by experiments with fixing values of factors for estimation of reliability indexes.

This is a difficult problem which requires large expenditures for its solution.

The prediction of reliability indexes of a product which will be manufactured in the future is more readily obtained by results of accelerated testing of its specimens. In this case, one part of the input influences (mechanical, environmental, etc.) can be used to obtain results of product accelerated testing. Another part (influences of manufacturing specifics, conditions of operator's specific, etc.) must be taken into account when studying the results of mathematical modeling.

In this case, the connection between evaluation of $Z_{ij}^{(\tau)}$ of the τ-th quantified reliability index of the *i*-th model of product in j-th conduction of use, which needs of prediction, and the mean value of this index $Z_i^{(\tau)}$, which can be obtained as a result of accelerated testing of μ specimens of the product, is described with functional dependence:

$$Z_{ij}^{(\tau)} = G^{(\tau)} (Z_i^{(\tau)}; U_i(t); a_I^{(\tau)}; a_{ij}^{(\tau)}), \qquad (3.\ 12)$$

$$\tau = 1, 2, \ldots, n,$$

where $U_i(t) = F_{mi}(t)$ and $F_{ij}(t)$ are the most important lack of correlated common factors of manufacture and field;

$a_i^{(\tau)}$ and $a_{ij}^{(\tau)}$ are unknown parameters of mathematical model (3. 12) which are characterized by the group of manufacture and field factors;

$$F_{mi}(t) = F_{m1}(t); F_{m2}(t); \ldots; F_{mn}(t);$$

$$F_{ij}(t) = F_{i1}(t); F_{i2}(t); \ldots; F_{in}(t);$$

$m = 5$ and $i = 6$ are the numbers of the most important lack of correlated common factors of manufacture and field.

The mean value $Z_i^{(\tau)}$ which is a result of accelerated testing of μ specimens (usually not more than 2 - 3 specimens) can be evaluated as:

$$Z_i^{(\tau)} = \mu^{-1}\sum_{k=1}^{\mu} Z_{ik}^{(\tau)} \quad (3.\ 13)$$

The results of accelerated testing are independent of factors that cannot be simulated in the laboratory. Therefore, in model (3. 12) the variable can be divided into:

$$Z_i^{(\tau)} = K_{if}^{(\tau)} (F_{ni}(t); F_{fi}(t); a_j^{(\tau)}; a_{ij}^{(\tau)})\ Z_i^{(\tau)} \quad (3.\ 14)$$

where: $K_{if}^{(\tau)}$ are the recalculated coefficients of the quantitative values quantitative index of future product reliability concerning the indexes of means indexes which have been obtained by accelerated testing of specimens.

These coefficients depend on manufacturing and field conditions, which themselves depend on time and the values of unknown parameters. The value of these coefficients is different for different products and different indexes of reliability, because the levels of most important factors of manufacture by different companies and in different field conditions are not the same.

The values of recounting coefficients may be more or less than 1 for different reliability indexes.

Therefore, the coefficients are functionals:

$$K_{ij}^{(\tau)} = F^{(\tau)} \{f[F_{ni}(t); a_i^{(\tau)}; a_{ij}^{(\tau)}]\}, \quad (3.\ 15)$$

where: $F[F_{ni}(t); F_{fi}(t); a_I^{(\tau)}; a_{ij}^{(\tau)}]$ is the function which evaluates the level of influence on the product reliability of the basic lack of correlated generalized factors of the field and manufacturing conditions.

The most important factors are characterized by ponderable levels P, Q and actual levels X_i and Y_i.

Let us consider the function of the impact of the statistical problem of product reliability prediction if we take into account the weak dependence of these factors on time:

$$K_{ij}^{(\tau)} = F^{(\tau)} \{f[X_i; P; Y_i; Q; a_i^{(\tau)}; a_{ij}^{(\tau)}]\}, \quad (3.\ 16)$$

where $X_I = (x_{i1}, x_{i2}, \ldots, x_{im})$, and $Q = (q_1, q_2, \ldots, q_i)$ are means of specific ponderabilities of the manufacturing and field factors.

The values of the actual levels and the mean of the ponderabilities of manufacturing and field are the most important factors. A special chapter will discuss reliability prediction studying and dependence on specific manufacturing and field conditions (operating conditions) of different companies.

Let us build a specific influence function which can help to determine:

- the level of the combined impact of all the most important lack of correlated and generalized factors of manufacture and field action;
- the level of impact of individual groups of factors (the group of manufacturing factors and group of field factors) on product reliability;
- the level of impacts of individual factors of the group of most important factors.

The functions $f(X_i; P; Y_i; Q; a_i^{(\tau)}; a_{ij}^{(\tau)})$ for all quantities of reliability indexes appear to be equal, because the form of influence for different factors of manufacturing and field is identical for all reliability indexes. But the values for any reliability indexes may be different. The difference should be taken into account with unknown parameters $a_i^{(\tau)}$ and $a_{ij}^{(\tau)}$ which have specific values for each quantity of reliability indexes, for each model of product, each set of field conditions, and for each production company.

Let us give for this function the following requirements:

- it must always be positive;
- the maximum value must be less than or equal to 1.00 to give the possibility of simplifying the mathematical model by calculating the functional (3.17).

In addition, the practical requirement is that the reliability of the specimen used in the accelerated testing is usually higher than after manufacture of this product, but the time for maintenance is usually less.

Therefore, the coefficients of recalculating the mean time to failure and the mean time of maintenance are characterized by the following dependence:

$$K_{ij}^{(1)} = f(X_i); P; Y_i; Q; a_i^{(1)}) \qquad (3.\ 17)$$

$$K_{ij}^{(2)} = 1/f(X_i; P; Y_i; Q; a_i^{(2)}) \qquad (3.\ 18)$$

If we take into account the lack of correlation of separate factors and groups of factors, we obtain the following equation (after manipulation):

$$f(X_i; P; Y_i; Q; a_i^{(\tau)}; a_{ij}^{(\tau)}) = C_n\Sigma_{k-1}{}^{m}\, \alpha_x\, (a_i^{(\tau)})^{1-xik} + C_f\Sigma_{k=1}{}^{l}\, \beta_k(a_{ij}^{(\tau)})^{1-yjk}, \qquad (3.\ 19)$$

where $C_n = 1 - b_n$, and $C_f = 1 - b_r$ are normalized coefficients which relate to the mean specific ponderabilities b_n and b_r of different groups of factors. For this the authors' research gives the following results: $b_n = 0.47$ and $b_r = 0.53$.

The input of normalized coefficients is necessary, because if ponderability of group of factors (or a separate factor) is greater, the decrease in the product reliability which depends on this group (factor), must be more. It means that the quantity of influence function must be less.

By analogy, normalized coefficients α_k and β_k were included:

$$\alpha_k = (1 - \rho_k) / (m - 1)$$
$$\beta_k = (1 - q_k) / (l - 1) \quad (3.20)$$

One can find the unknown parameters $\alpha_I^{(\tau)}$ and $\alpha_{ij}^{(\tau)}$ for prototypes, because it cannot be determined for future or modernized products. For example, $\alpha_{ij}^{(\tau)}$ can be evaluated if we compare the τ-th index of reliability of the i-th model of the product which is obtained as a result of accelerated testing of μ specimens and as a result of studying of υ specimens in the field.

Unknown parameter $\alpha_I^{(\tau)}$ is evaluated by sum of parameters $\alpha_{ij}^{(\tau)}$.

$$\alpha_I^{(\tau)} = N^{-1}\Sigma_{j=1}^{N} \alpha_{ij}^{(\tau)} \quad (3.21)$$

where N is the number of regions where previous model is used.

Therefore, for prediction of time to failures the following equation can be recommended:

$$T_{oijf} = T_{oi} [C_n \Sigma_{k-1}^{m} \alpha_k(\alpha_i^{(i)})^{1 - xik} + C_f \Sigma_{k=1}^{i} \beta_k(\alpha_{ij}^{(1)})^{1 - yjk}] \quad (3.22)$$

For prediction of time to maintenance:

$$T_{bijf} = T_{bi} / [C_n \Sigma_{k=1}^{m} \alpha_k(\alpha_I^{(2)})^{1 - xik} + C_f \Sigma_{k=1}^{i} \beta_k(\alpha_{ij}^{(2)})^{1 - yik}] \quad (3.23)$$

where T_{oi} and T_{bi} are the mean times to failure and the times to maintenance. It is obtained a result of accelerated testing of μ specimens.

17. 4 PRACTICAL EXAMPLE

As a result of short field testing of new Self-Propelled Spraying machines Ro Gator 554 and John Deere 6500 the mean time to failure and mean time for maintenance were obtained (Table 3.1).

Table 3. 1. The results of short field testing of prototypes of self-propelled spraying machines.

Index	Prototype of Ro Gator 554		Prototype of John Deere 6500	
	Prestige Farms (Clinton, NC)	Continental Grain Co. (NY)	Prestige Farms (Clinton, NC)	Continental Grain Co. (NY)
Mean time to failure, h	104	73.80	104	171.10
Mean time for maintenance, h	1.04	1.47	1.82	1.97

Now let us take as the prototypes the Finn T-90 and T-120. The results of field testing of four specimens of these machines can be seen in table 3. 2.

Table 3. 2. Testing results of prototypes of the studied machines.

Conditions of machines used, No. of model	Time to failure, hours	Mean time for maintenance, hours
1	2	3
Murphy Family Farms		
Finn T – 90	21.9	3.02
No. 287	29.04	2.70
No. 261	53.62	2.87
No. 290	47.81	2.24
No. 291	37.92	2.71
Mean		
T – 120	49.32	2.90

Table 3.2 (continuation) Testing results of prototypes of the studied machines

1	2	3
No. 0.59	49.32	2.90
No. 030	56.20	1.86
No. 063	67.41	3.81
No. 218	58.37	3.17
Mean	57.80	2.94
Caroll & Foods		
Finn T – 90		
No. 316	40.92	2.83
No. 358	1.72	3.20
No. 1001	37.67	1.95
No. 1005	58.21	2.61
Mean	39.63	2.65
T – 120		
No. 714	58.72	4.12
No. 1105	80.54	2.80
No. 4516	62.98	3.64
Mean	67.41	3.52

The values of normalized coefficients α_k, β_k, and q_k were obtained in correspondence with the mean specific ponderabilities of the most important manufacturing and field factors, using equations (3. 19) (table 3. 3).

Table 3. 3. Normalized coefficients corresponding with the most important manufacturing and field factors.

Normalized coefficient	1	2	3	4	5	6
ρ_k	0.2325	0.2225	0.2125	0.175	0.1575	-
α_k	0.1920	0.1940	0.1970	0.206	0.2110	-
q_k	0.2325	0.2250	0.2075	0.130	0.1125	0.0925
β_k	0.1540	0.1550	0.1590	0.174	0.1780	0.1820

The unknown parameters $\alpha_I^{(\tau)}$ and $\alpha_{ij}^{(\tau)}$ were obtained using equation 3.11, and tables 2 and 3. 3 (Table 3. 4).

Table 3. 4. Unknown parameters $\alpha_i^{(\tau)}$ and $\alpha_{ij}^{(\tau)}$

Unknown parameters	Finn T-90			T-120		
	Marphy Family Farms	Caroll & Foods	Prestige Farms	Marphy Family Farms	Carrol & Foods	Prestige Farms
$\alpha_i^{(\tau)}$	0.42	0.47	0.445	0.19	0.23	0.21
$\alpha_{ij}^{(\tau)}$	0.45	0.75	0.60	0.56	0.80	0.68

The coefficients of recalculating for new machines were obtained (Table 3. 5) using the above equations and Tables 3. 3 and 3. 4.

The mean time to failure and mean time for maintenance of the new machines Ro Gator 554 and John Deere 6500 were predicted for when they will be manufactured by series, using equations (3. 22) and (3.23) and tables 3. 1 and 3. 5 (Table 3. 6).

Table 3. 5. Coefficients of recalculating for the studied machines.

Coefficients of recalculating	Ro Gator 554		John Deere 6500	
	Prestige Farms Grain Co.	Continental	Prestige Farms Grain Co.	Continental
Mean time to failure, hours	0.64	0.66	0.43	0.45
Mean time for maintenance, hours	0.41	1.25	1.29	1.18

Table 3. 6. Predicted mean time to failure and mean time for maintenance of studied machines.

Indexes of reliability	Ro Gator 554		John Deere 6500	
	Prestige Farms	Continental Grain Co.	Prestige Farms	Continental Grain Co.
Mean time to failures, h	57.12	59.01	59.67	61.61
Mean time for maintenance, h	2.17	1.93		33

18 PREDICTION OF SYSTEM RELIABILITY FROM ACCELERATED TESTING RESULTS OF THE COMPONENTS

18. 1 INTRODUCTION

This problem often appears when the testing of a system as a whole either has high cost or may be impossible in a short period of time, especially at the beginning of development.

It is assumed that the system consists of *N* components for which failures are statistically independent and for each of which the Weibull life-time distribution is used with scale parameter β_i and shape parameter α_i, $i = 1, \ldots, N$. For each component the test results are obtained using sensors to provide the data.

On the basis of this data the authors offer the algorithm for calculating the lower confidence bounds (LCB) with a given confidence level of system reliability prediction.

There are a lot publications in this area, but apparently no one has previously discussed the multi-variate Weibull model. For these components there are not only well developed algorithms for calculating point and interval reliability estimates, but corresponding software such as SuperSMITH/99 developed by Wes Fulton.

The initial information for rapid reliability prediction can be obtained as a result of accelerated testing of the product. The accuracy of reliability prediction often depends on how accurately the actual degradation (failure) process is simulated in accelerated testing. The results of the product degradation (failure) process include data on the mechanical, chemical, physical, electrical, thermal, etc. effects as described above. UART includes simultaneous combinations of different types of testing, with the assumption that the failures are statistically independent. Ignoring this fact gives a lower estimation of system reliability. Techniques which could take into account the failure dependence would require more additional information.

In this chapter only series systems are considered, but the proposed methodology can be extended also to systems with arbitrary series-parallel structures.

18. 2 CONFIDENCE BOUNDS FOR SIMPLE WEIBULL MODEL

Let us consider first of all the simple Weibull model and algorithm for calculating the LCB for reliability function $R_i(t)$, $i= 1, \ldots, N$, of each component separately (index **i** will be dropped in this section for simplicity).

If we use the Weibull model for the life time τ of the component, we can write the reliability index for this component as

$$R(t) = \exp\left\{ -\left(\frac{t}{\alpha}\right)^{\beta} \right\}, \quad t > 0, \qquad (3.24)$$

where t is a variable generally given in terms of time or cycles; α is the scale parameter, and β is the shape parameter of the Weibull distribution.

Expression (3.24) can be transformed into the following:

$$R(t) = \exp\{-\exp(\frac{Lnt - u}{b})\}, t. 0, \quad (3.25)$$

where $U = ln\ a$ and $b = 1/\beta$ are the share and scale parameters of the random variable $x = ln\ \tau$, t will be held fixed in the future. Assume n units are tested and let $t_1, t_2, \ldots t_\tau$ be failure data and $t_{\tau+1}, t_{\tau+2}, \ldots t_n$ be censored data (either failure or time censoring).

The methodology of calculating the point and interval estimations of reliability function R(t) applied to the simple Weibull model has been developed in many publications[11,etc.] and can be described as follows.

Denote by $\bar{a}$ and $\bar{b}$ estimates of the parameters ($u = ln\ \alpha$ and $b = 1/\beta$) for which the distribution of the ratios

$$B = \bar{b}/b \text{ and } U = (\bar{u} - u)/b$$

Is independent of the unknown parameters. Here, the distribution of the random variables is determined only by the estimation method and the test plan (that is, by the numbers n and r).

The indicated estimated types include maximum likelihood estimates, the best linear estimates, and the best linear invariant estimates, as well as the linear estimates in[15].

Tables of the coefficients for calculating the estimates $\bar{u}$ and $\bar{b}$ by censored samples are presented in the indicated papers. For the estimates of the types indicated above, one can introduce the function

$$L(\varepsilon, \nu), \varepsilon\ \theta\ R^1, \text{ such that } P\{L(\varepsilon, \nu) < \nu B - U\} = \varepsilon \quad (3.26)$$

That is, $L(\varepsilon, \nu)$ is the $(1 - \varepsilon)$ –th quantile of the distribution of the random variable $\nu B - U$.

The function $L(\varepsilon, \nu)$ decreases with increasing value of ε (for fixed ν) and increases with increasing value of ν (for fixed ε). This form is independent of the parameters u and b and is determined only by the form of the estimates $\bar{u}$ and $\bar{b}$ and the test plan (that is, by the numbers n and r).

We denote

$$L^*(\varepsilon, \nu) = \exp\{-\exp[-L(\varepsilon, \nu)]\} \qquad (3.\ 27)$$

Extending its definition by its continuity property to the set

$$\{(\varepsilon, \nu);\ \varepsilon\ \theta\ [0.1],\ \nu\varepsilon\ R^1\},\ \text{setting}\ L^*(o, \nu) = 1\ \text{and}$$

$$L^*(1, \nu) = 0\ \text{for all}\ \nu\varepsilon R^1$$

Tables of values of $L^*(\varepsilon, \nu)$ for different forms of the estimates $\bar{u}$ and $\bar{b}$ are presented in the previously sited publications[15,etc.].

For example, for the linear estimates by Johns and Lieberman present tables of the function

$L^*(\varepsilon, \nu)$ for $\varepsilon = 0.5, 0.75, 0.8, 0.9$ and for censoring $\delta = r/n$,

Table 3. 7 The component values of σ for given value of δ.

δ	σ_b^2	σ_{ub}	σ_u^2
0.1	9.473	22.183	60.508
0.2	4.738	7.374	16.477
0.25	3.735	4.926	10.497
0.3	3.065	3.438	7.186
0.5	1.716	0.936	2.510
0.6	1.373	0.447	1.612
0.7	1.12	0.145	1.447
0.8	0.928	-0.049	1.253
1.0	0.608	-0.257	1.109

which is close to the values of 0.25, 0.5, 0.75, and 1. For large volume samples, $n > 30$, the normal approximation of the function

$$L(\varepsilon, \nu) = \nu - z_\varepsilon \sigma / \sqrt{n}, \quad (3.28)$$

Where σ depends only on ν and δ and is written in the form

$$\sigma = \sqrt{\sigma_u^2 - 2\nu\sigma_{ub} + \nu^2\sigma_b^2} \quad (3.29)$$

is presented in the same article. In the last equality, the values of σ_u^2, σ_{ub}, σ_b^2 can, depending on δ, be determined by table 3. 7.

For maximum likelihood estimates and complete samples of volume n = 8, 10, 12, 15, 20, 25, 30, 40, 50, 75, and 100[5] presents tables of the values of the function L* as a function of

$$\varepsilon \text{ and } \bar{R} = \exp\{-\exp(-\nu)\}$$

for $\underline{\varepsilon}$ = 0.75, 0.9, 0.95, 0.97, 0.98 and $\bar{R}$ = 0.5 (increasing from 0.5 to 0.98 in steps of 0.02).

For the best linear unbiased estimates, the tables of values of the function $L^*(\varepsilon, \nu)$ are presented by Mann and Shafer. A good log χ^2 – approximation for the function $L(\varepsilon, \nu)$ is presented by Johns and Lieberman in the form

$$L(\varepsilon, \nu) = -\ln \frac{m\chi_\varepsilon^2(1)}{1}, \quad (3.30)$$

where: and m are chosen so that the means and the variations of the quantities $W(\nu) = U - \nu B$ and $\ln[m\chi^2(1)]/1$ are identical.

Having calculated the estimates $\bar{u}$ and $\bar{b}$ by the results of tests of i-th type components ($i = 1, \ldots N$), one can write the expression for the lower confidence bound (LCB) of level q for the component's function reliability $R_I(t)$ in the form

$$R_{iq} = L^*_I(q, \bar{\nu}_I), \qquad \bar{\nu}_I = \frac{u - \ln t}{B_i} \quad (3.31)$$

Therefore, to calculate the LCB for function reliability of any type of component with given confidence probability q it is necessary:

- to calculate estimates of the Weibull model's parameters $\bar{u}$ and $\bar{b}$, $I = 1, \ldots N$; (using one of the above mentioned methods);

- to calculate the value $\bar{\nu}_I - (\bar{u}_i - \ln t)/\bar{b}_i$ and the value of the function $L_i(q, \bar{\nu}_I)$, as mentioned above;

- to use the expressions (3.26) and (3.29) for given values of confidence probability q.

18. 3 MULTI-VARIATE WEIBULL MODEL

Let us consider a system with a series connection of N components the failures of which are independent of each other.

If the Weibull model is valid for each of N components, then the function of system reliability $R(t)$ for given (hold fixed) value of time t could be represented as

$$R(t) = \exp\{-\sum_{i=1}^{N} (\frac{t}{\alpha_i})_I^{\beta}\} \qquad (3.\ 32)$$

or, if we denote $u_i = \ln \alpha_i$ and $b_i = 1/\beta_i$, $i = 1, .. N$, as

$$R(t) = \prod_{i=1}^{N} \exp\{-\exp(\frac{\ln t - u_i}{b_i})\},\ t>0. \qquad (3.\ 33)$$

Our goal is to give the algorithm for calculating LCB (Low Confidence Bounds) $R_q(t)$ with confidence level q for system reliability function $R(t)$ if we have N independent censored samples

$$t_{(1)}^{(i)} \le t_{(2)}^{(i)} \le \ldots \le t_{(ri)}^{(i)},\ I = 1, \ldots N,\ r_i \le n_i \qquad (3.\ 34)$$

where:

n_i is the sample size of the i-th type component, and r_i is the number of failures of the i-th type component.

On the basis of data (3. 34) we can calculate the estimations $\bar{u}_i$, $\bar{b}_i$ for unknown parameters U_i and b_i, $i = 1, \ldots N,$ using one of the methods described in the previous section and it is simple to calculate the point estimation of reliability function as follows:

$$\bar{R}(t) = \prod_{i=1}^{N} \exp\{-\exp(\frac{\ln t - \bar{u}_i}{\bar{b}})\} \qquad (3.\ 35)$$

For calculating the LCB $R_q(t)$ of confidence level q $(q = 0.8 - 0.95)$ it is necessary to use the general methodology developed in[7]. In accordance with[6], the general methodology is necessary to solve the next nonlinear external task:

$$R_q(t) = \min_{y \varepsilon S_q} \prod_{i=1}^{N} L^*_I \, [1 - e^{-y_i}, \; -\overline{\ln} \ln(1/R^{`})] \qquad (3.\ 36)$$

where

$$S_q = \{y \varepsilon R^N; \; y_i \geq 0; \; \Sigma y_i = \ln \frac{1}{1-q} \},$$

and $\bar{R}^{`}$ is the value of the statistic $\underline{R(t)}$ determined by expression (3. 36) after calculation of the estimated parameters $\bar{u}_i$ and $\bar{b}_i$, $i = 1, \ldots N$.

This is denoted by

$$g_i(y_i) = -\ln L^*_i \, [1 - \exp(-y_i), -\ln \ln(\bar{1} / R^{`}(t))] \qquad (3.\ 37)$$

For S_q as shown in[8], isolate the two situations most frequently encountered in practice, in which the expression for $R_q(t)$ can be written in explicit form.

A. If the functions $g_i(y_i)$ are identical for all $i = 1, \ldots N$ (which is satisfied when the elements are tested according to the same plan (n, U, r) and estimates of the same type are used for the unknown parameters) and are convex upward on $(0, \ln 1 / (1 - q)]$, then

$$\bar{R}_q(t) = \{L^*[1 - (1 - q)^{1/N}, \; \ln \ln(1/ R'(t)]\} \qquad (3.\ 38)$$

B. If all the functions $g_i\,(y_i)$ are convex downward on $[0, \ln 1/(1 - q)]$, then

$$\bar{R}_q(t) = \min_{1 \leq I \leq N} L^*_i \, [q, -\ln \ln(1/R'(t)] \qquad (3.\ 39)$$

where, as also was mentioned above, $R'(t)$ is the observed value of statistic $\bar{R}(t)$ determined by expression (3.35).

If the convexity conditions are not satisfied for the functions $g_I(y_i)$ on the interval $[0, \ln 1/(1 - - q)]$, then they can be replaced by convex approximations $g_i(y_i)$ such that the error Δ of equation (3.33) is no greater than

$$\Delta^* = \exp\left(-\sum_{j=1}^{N} \Delta_i\right) \qquad (3.40)$$

where

$$\Delta_i = \max_y \left| \bar{g}_i(y) - g_i(y) \right|, i = 1, \ldots N.$$

Our calculation investigations showed that most practical situations (that is, for components having a very high level of reliability and relatively small sample sizes) take place in case *B*.

Calculation of LCB by use of equation 3.33 involves calculating the point estimation of system reliability $R(t)$ and then subsequently calculating the LCB of level q for reliability functions of each component of N systems and choosing the minimal value for them. As a corollary of result *B* it is not difficult to get the following expression for the LCB $R_q(t)$ if all components of the system have identical (or almost identical) rate of censoring, that is

$$\delta_I = r/n_i = \text{const.}, i = 1, \ldots N:$$

$$R_q(t) = L^*_0[q, -\ln \ln(1/\check{R}'(t) \qquad (3.41)$$

where $L^*_0[q, -\ln \ln(1/\check{R}'(t)]$ is that function from $L^*_I[q, -\ln \ln(1/\check{R}(t)]$ which corresponds to the minimum sample size (that is, sample size $n_0 = \min(n_i)$).

18.4 PRACTICAL EXAMPLES

Example 1. In order to find the value of the LCB of level $q = 0.9$ for the reliability function of the electronic device which consists of $N = 3$ components, the life time of each has a Weibull distribution with unknown parameters. The components were tested according to this plans (n_i, U, r_i), $i = 1,2,3$, that is, n_I specimens of type i are tested until r_i failures appear and the failure specimens are permanent.

For this example, given the following values of the operating times until failure (in hours), the following results were obtained:

$t_1 = 1820, t_2 = 1960, t_3 = 2172$ (for specimens type 1);

$t_1 = 2441, t_2 = 2841, t_3 = 3432, t_4 = 3824$ (for specimens type 2);

$t_1 = 5329, t_2 = 5682, t_3 = 7016, t_4 = 7919, t_5 = 9566, t_6 = 11760$ (for specimens type 3).

On the basis of this data the estimates of the unknown parameters found by the method proposed in[9] (that is, maximum likelihood estimates) are:

$\bar{u}_1 = 7.62,\ \ \bar{b}_1 = 0.13,\ \ \bar{u}_2 = 8.13,\ \ \bar{b}_2 = 0.21,\ \ \bar{u}_3 = 8.46,\ \ \bar{b}_3 = 0.38.$

Using equation (3. 36) we can calculate the point estimate for reliability function $R(t)$ as the product of the corresponding point estimates of the components reliability function (for $t = T_0 = 1000$):

$$\bar{R} = \bar{R}_1 * \bar{R}_2 * \bar{R}_3 = 0.996 * 0.997 * 0.983 = 0.976$$

To calculate the LCB of level q for device reliability $R(t)$ it is necessary (in the general case) to calculate the LCB at the same level q for each devices component assuming that the point estimate of the reliability function of this component is identical to the point estimate reliability function device, that is, to $\bar{R}'(t)$. But in this particular case ($\delta_1 = \delta_2 = \delta_3 = 0.5$) we can use equation (3. 34), according to which it is sufficient to calculate LCB only for the component with smallest sample size, that is, for the 1st component, because $n_i = 6 = min\ \{6, 8, 12\}$.

First of all we have to determine the value of function $L(q, \nu)$, where $\nu = -\ln\ln\ \bar{R}' = 3.72$. Since we used the maximum likelihood estimates for parameters u_i and b_i, now we need to use the tables from[5]. But for more visualization we will use the normal approximation of functions $L(q, \nu)$ by equation (3. 29), although it gives the same uncontrollable error.

From Table 3. 7 we can find out the values σ_b^2, σ_{ub}, and σ_u^2, corresponding to $\delta = 0.5$ and then calculate $\sigma = (\sigma_u^2 - 2\nu\sigma_{ub} + \nu^2\sigma_b^2)^{1/2} = 4.39$ using equation (3. 29) which gives the following results (since $z_q = 1.28$ when $q = 9$):

$$L(q, \nu) = 3.72 - 1.28 * 4.39/\sqrt{6} = 1.424$$

and equation (3. 28) gives

$$L^*(q, \nu) = \exp\{-\exp(-L(q, \nu))\} = 0.786$$

that is, the final answer according to equation (3. 39) is $R_q = 0.786$.

For comparison we can calculate the LCB of level $q = 0.9$ for each component mentioned above.

We obtain the following results:

$$R_{1q} = 0.873,\ R_{2q} = 0.93,\ \ R_{3q} = 0.904$$

Note, that if we multiply these LCBs then we will get only the value 0.73 that is essentially lower.

Remember that the calculation of LCB for the system reliability function requires calculating the conditional LCB R_{iq}* for each components reliability function assuming that the point estimate of this component's reliability function is identical to the point estimation of system *R'*.

Corresponding calculations give the following result:

$$R_{iq} = 0.786,\ R_{2q}^* = 0.838,\ R_{3q} = 0.884.$$

As we can see, the smallest of these values determines the LCB for the device (system) reliability function which we have obtained above:

$$R_q = R_{1q}^* = 0.786$$

Example 2. Note that min (R_{iq}*) does not always fall on the component that has the smallest sample size as obtained in example 1.

Let us change the initial data in example 1 slightly. For example, we will exchange only the values n_1 = 12 and n_3 = 6, but the test results of all the components allowed have the same estimate parameters u_i and $b_{i,}$ i = 1, 2, 3.

It is not difficult to ensure that the calculation mentioned above will give the following results.

The values of conditional LCBs for all components (of the same level q = 0.9) are:

$$R_{1q}^* = 0.855,\quad R_{2q}^* = 0.838,\quad R_{3q}^* = 0.868.$$

that is, the smallest value of the conditional LCB falls onto the component number 2, that has sample size n_2 = 8 (not smallest!) and therefore the LCB of the device reliability function

$$R_q = R_{2q}^* = 0.838$$

The values of LCB's for all components (of level q = 0.9) are:

$$R_{1q} = 0.914,\quad R_{2q} = 0.93,\quad R_{3q} = 0.89.$$

And the product of these values (sometimes used for calculating the LCB for the device reliability function) gives us the value 0.75. This is much less than 0.838 which we obtained by the method suggested in this book.

Conclusions from the above methodology (3. 3):

The methodology developed allows the prediction of system reliability in which components are subjected to different types of the physics-of-degradation process during the service life, because for every type of degradation there is a separate Weibull model.

The value of this methodology is that it allows the prediction of the LCB of a system reliability function after testing several samples of each component of this system during a relatively short period of time. In addition it allows us to predict the system reliability at the beginning of development when the testing of the system as a whole either has high cost or may be impossible in a short period of time.

Moreover, we may use this methodology even when the Accelerated Life Testing results of each systems components are known. In this case we have to transform the testing results found during ALT to the equivalent testing results corresponding to ordinary conditions. For this transformation one can use the standard methods.

The time of the testing period is determined by ALT longevity for the system components and can be made sufficiently small in principle. For instance, if we could provide by ALT each component in our example 1 with a acceleration coefficient K equal to about 10 (a realistic possibility), then we could have obtained the confidence estimate of system reliability function during the required operating time of our system only on the basis of the test results its components.

Therefore, we have the possibility of decreasing the time (and consequently, the cost) of new system development.

In this book only series systems are considered, but the proposed methodology can be extended also to the systems with arbitrarily series-parallel structures.

The proposed methodology also allows combining in-service life data with results of ALT.

This methodology is especially important for reducing cost and time, and improving the quality of new product development.

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19 DURABILITY PREDICTION WITH CONSIDERATION OF EXPENSES AND LOSSES

19. 1 INTRODUCTION

If one provides accelerated reliability testing in correspondence with Chapter 2, one can obtain accurate initial information for durability prediction. During the testing period the degradation of the test subject and the expenses used for this subject during the time are approximately identical (with consideration of the correlation of ART results to field results) to the degradation and expenses incurred during the time of use in the field. One group of expenses is evaluated by ART, and another by special field testing as a result of comparison of test subjects which have executed different volumes of work during ART.

Usually methods of durability prediction relate to test subject reliability only. But test subjects in many areas of industry are connected with the product with which they are working. The results of working the above test subjects are related directly or indirectly to losses of the product. For example, the machinery (including electronic systems of control) for food technology, farm machinery, refrigerators, many special trucks, etc. is directly related to product losses (the degradation or failures of these test subjects lead to product losses).

More degradation and failures leads to more losses of the product and this is influenced by the optimal durability of the test subject. Therefore, the methodology below also takes into account the product losses. If any test subject is not affected by product loss, the results obtained will be measured more easily, because components of equations which are related to the product losses will be zero.

So, specifics for the methodology of the following solution of durability prediction are a combination of reliability and usage cost including product losses.

19. 2 PRINCIPAL SCHEME OF OPTIMAL DURABILITY PREDICTION

The total expenses in the use of the test subjects consist of three basic components:

1) expenses related directly to the work of the test subject;

2) expenses that depend on loss of the product during normal work of the test subject;

3) expenses that depend on stopping the test subject's work if there are failures or increased degradation of test subject (increased degradation and stopping of work means there is increased product loss which also costs money).

The total expenses which influence the cost of unity of work can be expressed as:

$$\sum_{i=1}^{n} C_c\,(i)$$

where i is original numeral of work volume; n is volume of work which is executed by the test subject; C_c is components of costs of unity of work.

The increase in expenses which relate to the losses of the product through normal work can be evaluated as:

$$\sum_{i=1}^{n} C_p\text{quant}(i) = [\sum_{i=1}^{n} Lp(i)] \cdot Cu$$

where

$\sum_{i=1}^{n} Lp$ is loss of product during work of the test subject

Cu is the cost of a product unit.

The degree of deterioration of the test subject is often influenced by the product quality, therefore resulting in increased cost. The losses of product cost in this case can be calculated by the formula:

$$\sum_{i=1}^{n} \text{Cpqual}(i) = [\sum_{i=1}^{n} \text{Vt.s.} (\text{Cu.n.} - \text{Cc.d.})$$

where *Cu.n.* is the cost of the unit of product which is obtained during the work of a new test subject; *Cu.d.* is the cost of the unit of product which is obtained during the work of a deteriorated test subject.

The losses of the product during its idle time depend on reliability and are a random process.

Let us find a mathematical expression for these losses, where time of test subject work is b; the time to failures ξ of the test subject is distributed by law $F(x)$; the renewal time ζ is distributed by law $H(x)$; and the idle time as a result of failures and subsequent renewals is found through interval b.

The dependence between losses of the product (in $) and total length of idle time for different products varies. In general, let us take this dependence as linear, hence the losses increase as the idle time increases. This dependence can be expressed as $C(t) = ax$, where t is total idle time. It is necessary to predict the average product losses from idle time in the interval b.

The time t has the function of distribution $G(t)$. Then mean losses are:

$$\int_0^{\infty} ax \cdot dG(t) = a \cdot \mu t$$

It is necessary to find the average time of faulty conductions of the test subject in the interval *b*. Let us take into account that at the beginning of interval *b* the test subject is in good order and begins to work.

Let us input the random process:

$$A(t) = \{V(t), \xi(t)]$$

where $V(t) = 0$ if at moment t the test subject is in good condition, and $V(t) = 1$ if at moment t the test subject is not in good condition.

If $V(t) = 0$, the $\xi(t)$ is the time from the moment t to the moment of failure of the test subject, if $V(t) = 1$ the $\zeta(t)$ is the time from the moment t to the moment of renewal of the test subject. The $A(t)$ is Markov's linear random process.

Let us show that as:

$$\varphi_I(x, t) = P\{V(t) = I; \qquad \varphi(t) < x\}; \qquad P_i(t) = \varphi_I(\infty, t)$$

If we input Laplace's transformation for demonstrated probabilities[1,2]:

$$\varphi_I(S, U) = \int_0^\infty \int_0^\infty e^{-Sx - ux} \varphi_I(x, \infty)$$

$$P_i(u) = \int_0^\infty e^{-ut} P_i(t)\, dt; \qquad \frac{d\varphi_I(o, u)}{dx} = \int_0^\infty e^{-ut} \frac{d\varphi_I(0, t)}{dx} dt$$

$$\bar{\varphi}_I^{(0)}(S) = \int_0^\infty e^{-Sx} d\varphi_I^{(0)}(x); \qquad \varphi_I(x,0) = \varphi_I^{(0)}(x); \tag{3.42}$$

$$\varphi_I^{(0)}(\infty) = P_i^{(0)}; \quad i = 0.1; \quad \bar{\varphi}(s) = \int_0^\infty e^{-Sx} dF(x); \quad \bar{h}(s) = \int e^{-Sx} dH(x) \tag{3.43}$$

$\varphi_0(x,t)$ and $\varphi_1(x,t)$ are satisfied by the following system of differential equations in certain particular derivatives

$$\frac{\partial\varphi_0(x, t)}{\partial t} - \frac{\partial\varphi_0(x,t)}{\partial x} = \frac{\partial\varphi_0(0,t)}{\partial x} + \frac{\partial\varphi_I(0,t)}{\partial x} F(x) \tag{3.44}$$

$$\frac{\partial \varphi_1(x,t)}{\partial t} - \frac{\partial \varphi_1(x,t)}{\partial x} = -\frac{\partial \varphi_1(0,t)}{\partial x} + \frac{\partial \varphi_0(0,t)}{\partial x} H(t)$$

under initial condition $\varphi_0(x, 0) = \varphi_0^{(0)}(x)$; $\varphi_1(x, 0) = \varphi_1^{(0)}(x)$.

Let us substitute in (3.38) a double Laplace's transformation. As a result, we obtain:

$$(U - S)\ \bar{\varphi}_0(s, u) = -\frac{\partial \bar{\varphi}_0(o, u)}{\partial x} + \frac{\partial \bar{\varphi}_I(0, u)}{\partial x} \cdot \frac{\bar{\varphi}(s)}{s} + \frac{\bar{\varphi}_0^{(0)}(s)}{s}$$

(3.45)

$$(U - S)\ \bar{\varphi}_1(s, u) = -\frac{\partial \varphi_1(0, u)}{\partial x} + \frac{\partial \bar{\varphi}_0(0, u)}{\partial x} \cdot \frac{h(s)}{s} - \frac{\varphi_1^{(0)}(s)}{s}$$

As $Re\{s\} \geq 0$ and $Re\{u\} \geq 0$, the right sides of (3.45) are equal to zero. Therefore,

$$\frac{\partial \bar{\varphi}_0(0, u)}{\partial x} = \frac{\partial \bar{\varphi}_1(0, u)}{\partial x} \varphi(u) + \varphi_0^{(0)}(u)$$

$$\frac{\partial \bar{\varphi}_1(o, u)}{\partial x} = \frac{\partial \bar{\varphi}_0(0. u)}{\partial x} h(u) + \bar{\varphi}_1^{(0)}(u)$$

By solving of the above system of equations, we find the expression for $\frac{\partial \bar{\varphi}_0(0, u)}{\partial x}$ and $\frac{\partial \bar{\varphi}_1(0, u)}{\partial x}$:

$$\frac{\partial \bar{\varphi}_0(0, u)}{\partial x} = \frac{\varphi_0^{(0)}(u) + \varphi_1^{(0)} \cdot \bar{S}(u)}{1 - \varphi(u)\, h(u)}$$

(3.46)

$$\frac{\partial\ \bar{\varphi}_1(0, u)}{\partial x} = \frac{\varphi_1^{(0)}(u) + \varphi_0^{(0)}(u) \cdot h(u)}{1 - \bar{\varphi}(u) \cdot \bar{h}(u)}$$

After substitution of (3.45) into (3.46), we obtain the formulas for $\bar{\varphi}_0\ (s,\ u)$ and $\bar{\varphi}_1\ (s,u)$.

For $\bar{\varphi}_0(s,\ u)$ and $\bar{\varphi}_1(s,\ u)$ there are the following equations:

$$\bar{\varphi}_0\ (s, u) = \frac{1}{s(u-s)\ (1 - \varphi(u)\ \ \bar{h}(u)}\ [\varphi_0^{(0)}(s) - \varphi_0^{(0)}(u) + \varphi_1^{(0)}(u) \cdot\ \bar{\varphi}(s) - \bar{\varphi}(u) +$$

$$+ h(u)(\varphi(s) \cdot \varphi_0^{(0)}(u) - \varphi(u)\ \ \bar{\varphi}_0^{(0)}(s)];$$

$$\bar{\varphi}_1\ (s, u) = \frac{1}{\varphi\ (u-s)\ (1 - \varphi(u)\ \ \bar{h}(u)}\ [\ \bar{\varphi}_1^{(0)}(s) - \varphi_1^{(0)}(u) + \varphi_0^{(0)}(\ \bar{h}(s) - \bar{h}(u) +$$

$$+\ \bar{\varphi}(u)(\ \bar{h}\ (s)\ \bar{\varphi}_1^{(0)}(u) - \bar{\varphi}_1^{(0)}(s)\ \bar{h}(u)].$$

<u>Consequence</u>: For Laplace's substitution of non-stationary probability that the test subject is in working condition $\bar{P}_0(u)$, the following equation exists :

$$\bar{P}_0(u) = \frac{-\ \bar{\varphi}_0^{(0)}(u) - \varphi_1^{(0)}(u)(1 - \bar{\varphi}(u) + \bar{h}(u)(\varphi_0^{(0)}(u) - P_0^{(0)}\ \bar{\varphi}(u)}{u[(1 - \bar{\varphi}(u)\ \bar{h}(u)]}$$

Therefore, for our initial conditions:

$$\varphi_0^{(0)}(x) = F(x); \qquad \bar{\varphi}_0^{(0)}(u) = \bar{\varphi}(u); \qquad P_0^{(0)} = 1; \qquad \varphi_1^{(0)}(u) = 0$$

the equation for Laplace's substitution is obtained as follows:

$$P_0(u) = \frac{-\ \bar{\varphi}(u)}{u(1 - \bar{\varphi}(u)\ \bar{h}(u)} \qquad (3.47)$$

Now it is necessary to convert this equation to evaluate the probability of the test subject being in working condition.

To obtain the equation for $P_0(t)$ we need to convert (3.41). Obviously $\mu x = \int_0^b P_0(t) \cdot \partial t.$

Therefore, the average loss of product in the interval *b* in general looks like:

$$a \int_0^b P_0(t)\, \partial t$$

Finally, to obtain the equation of product losses in each specific situation, it is necessary to carry out the following operations:

1. To evaluate F(x) and H(x).
2. To find substitution of Laplace-Steeljeca for F(x) and H(x), e.g. to calculate $\bar{\varphi}(u)$ and $h(u)$ [see equations (14.1) and (3.37)] or use tables in handbooks of operational measurement.
3. To evaluate $\bar{P}_0(u)$ using equation (3.41).
4. Substitute $\bar{P}_0(u)$, e.g. to find $P_0(t)$ with help of the mentioned handbook.
5. To integrate the obtained expression from *0* to *b* and to multiply the obtained equation by *a*.

It is necessary to multiply the earlier result by coefficient *C* (which shows the cost of the product unit), to convert the above product losses into equivalent monetary losses.

The total expenses and loss of money during the use of test subject are represented by:

$$\sum_{i=1}^{n} C_T(i) = \sum_{i=1}^{n} C_C(i) \cdot V_{t.s.} + [\sum_{i=1}^{n} Lp(i)] \cdot Cu + \sum_{i=1}^{n} V_{t.s.}(Cu.n. - Cc.d.) + ac \int_0^b P_0(t)\, \partial t$$

Correspondingly the unit of work is measured by the following equation:

$$\sum_{i=1}^{n} C_T(i) = \frac{\overset{n}{C_{u.w.}}(i)}{n}$$

Optimum durability of the test subject can be evaluated by the amount of time at minimal expense which is evaluated by the formula:

$$\frac{\sum_{i=1}^{n} C_T(i)}{n} \qquad (3.48)$$

After substitution of the components in (3.48), the final durability of test subject will be:

$$\frac{\sum_{i=1}^{n} Cc(i) + [\sum_{i=1}^{n} Lp(i)Cu + \sum_{i=1}^{n} V_{t.s.}\,(Cu.n. - Cc.d.) + ac \int_{0}^{b} P_0(t)\,\partial t}{n}$$

Specifics demonstrated in an earlier principal scheme enable us to take into account:

- the dynamics of changing all basic types of expenses during the product's life time on the basis of initial factual information obtained as a result demonstrated in Chapter 2 of this book;
- losses in quality and quantity of the product with which the test subject is working (depending on whether test subject is working or not working at all);
- the random character of the losses during the life cycle, depending on test subject reliability.

The above calculation can be done without taking into account the aging of the test subject.

This aging depends on the length of time it is on the market before a new more effective test subject appears.

In this case the optimal durability must be corrected by use of current methodologies.

19. 3 PRACTICAL EXAMPLE

The optimal durability of a harvester has been predicted by two methods:

- the current method, which does not take into account the product losses;
- a proposed new method which does take into account the product losses.

The result is shown in Figure 3.4. By the current method the optimal durability of harvesters is equal to14 years, but by the proposed method it is equal to only 7 years. This example illustrates how large the difference is.

Sometimes, instead of losses one can take into account a decrease of quality during usage.

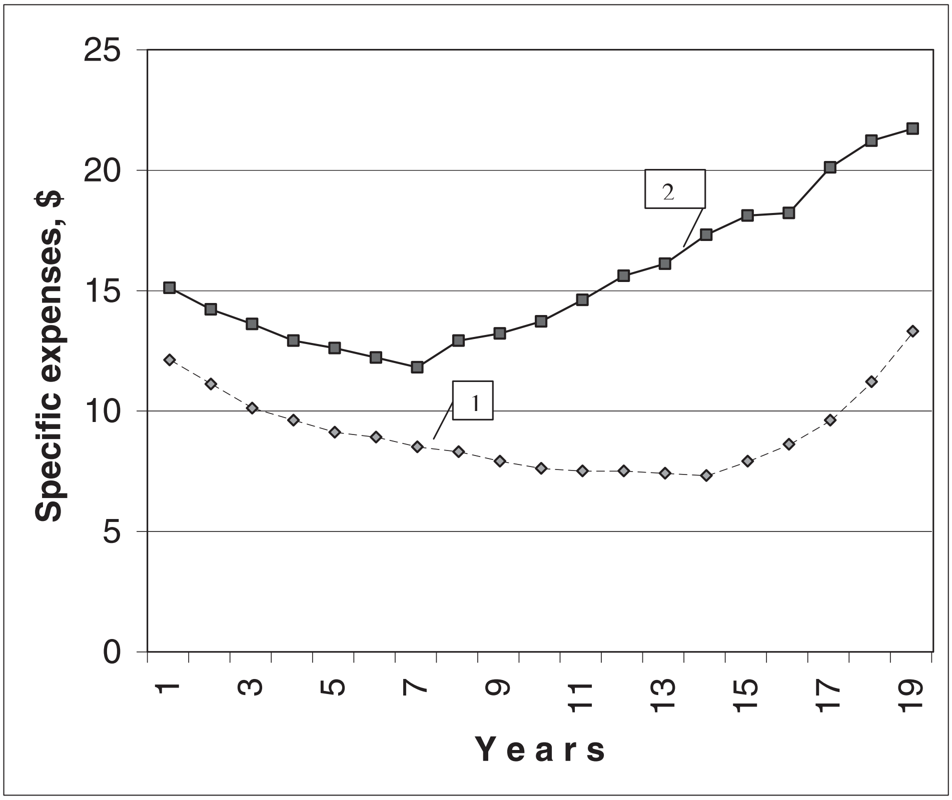

Figure 3.4 Results of counting optimal durability of the harvester (1 - proposed method, 2 – current method).

19.4 REFERENCES

[1] G. Deutch, Guide to practical implementation of Laplace's transformation, Science, Moscow, 1965.

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20 BASIC PRINCIPLES OF MAINTENANCE PREDICTION

20. 1 INTRODUCTION

Maintenance is a combination of all technical and administrative actions, including supervision actions, intended to maintain an item in, or restore it to, a state in which it can perform a required function.

Maintenance prediction is the process of assessing by analytical means the maintenance features of an item. This includes calculating its quantitative characteristics, including maintenance support.

One of the basic problems is prediction of the best system, from a reliability standpoint, of the strategy of intervals between maintenance operations, as well as the volume of maintenance work, spare parts that are needed, etc. We have to take into account that usually the time to maintenance, time between maintenance operations, etc. have random character, because the degradation process and time to failures have a random character.

The above problems and, as a result, the practical strategy for developing an accurate prediction for maintenance system, could not previously be solved accurately because it was not possible to obtain sufficient initial information about the regularity of rise and accumulation of degradation during the service life of the product.

The strategy of useful accelerated reliability testing, described earlier and in Chapter 2, offers the possibility for obtaining this information and, therefore, provides an opportunity for practical creation of system for optimal maintenance with minimal cost and time resulting in maximum effectiveness of machinery use.

Earlier there were theoretical solutions[1,2,3] for solving similar problem for systems which needed maintenance on line and cyclically, and for many systems provision of maintenance should be random. However, for many systems the maintenance must be at regular intervals, so, for example, it must be not only after each failure. This requires a precise schedule of performance.

Therefore, the character of the problem has changed, and instead of a typical stationary problem which was solved in the above publications, there is a non-stationary problem which in view of the arbitrariness of the function of distribution of the time to failure of the machinery and the time of their restoration is a difficult problem to solve

20.2 BASIC PRINCIPLES OF PREDICTION OF OPTIMAL INTERVALS BETWEEN MAINTENANCES

Presentation of preventive maintenance data requires that the duration of the tasks be identified along with their frequencies. The durations are usually expressed in terms of active preventive maintenance time. Observed non-active preventive maintenance downtime may be added when necessary. To aid maintenance planning, it is desirable to estimate maintenance man-hours for each task. In addition to the detailed task information, an overall summary of preventive maintenance times should be presented. In the following text we will use the term "maintenance" instead of "preventive maintenance".

We have solved the above problem for two situations:

1) as a criterion for evaluation of intervals between maintenances one uses the probability of prevention for a given time *T*;

2) as a criterion one uses the maximum availability.

For the first situation the problem is formulated and solved as follows.

There is the system with time to failures ξ which is distributed by arbitrary law *F(x)* and time of restoration ζ which is distributed by arbitrary law *H(x)*. The time between maintenances α = const. Maintenance after each restoration is not essential. The distribution of summary time X_a must be found when the system is in good working order on the time length interval α under the condition that began to work in moment 0.

The interval between maintenances α can be evaluated from the equation:

$$P\{X_T > T_0\} \geq P_0$$

Let us consider the situation with one and "*n*" failures in the interval (*o, a*) and finding the system at the end of the interval in either good condition or bad condition. It has been ascertained[4] that the distribution of time X_T, where the system is in good condition in the interval of length (*0, T*), can be shown by the formula:

$$X_T = X_a^{\,1} + \ldots + X_a^{\,k} - X_T\left[\frac{T}{A + T_M}\right] \cdot (a + T_M)$$

or

$$X_T + T - \left[\frac{T}{a + T_M}\right] \cdot T_M$$

with probability

$$(1 - F(a)^{\left[\frac{T}{a + Tm}\right]}(1 - F(T - \left[\frac{T}{a + Tm}\right] \cdot (a + T_M)$$

and

$$P\{X_T < X\} = \sum_{i=0}^{\left[\frac{x}{a+T_m}\right]} C_k^i (1 - F(a))^I \cdot \int \ldots \int_{x1+\ldots+xk\text{-}1+y<x-\left[\frac{x}{a+T_M}\right]\cdot i} dF(a,x) \ldots dF_{k\text{-}I}(a_I X_{k\text{-}I})\, dF(T\text{-}k(a+T_M), y) +$$

$$+ \sum_{i=0}^{\left[\frac{x}{a+T_M}\right]} C_k^i (1 - F(a))^I (1\text{-}F(T - k(a+T_M))) \int_{x_1+\ldots+x_{k\text{-}I}<x-\left[\frac{x}{a+T_M}\right] i} dF_1(a_1, x_1) \ldots dF_{k\text{-}1}(a_1, X_{k\text{-}1}) \qquad (3.49)$$

where *[x]* means whole part of number *x*; *F(a, x)* can be evaluated from the equation:

$$P\{X_a < X\} = \sum_{i=1}^{\infty} \left(\int_0^x H^{(i\text{-}1)} (a\text{-}x_1)\, dF^{(i)}(X) - \int_0^x H^i (a\text{-}X_1)\, dF^i (X_1) + \sum_{i=1} \left[\int_0^x H^i (a - X_1)) dF^i(X_1) - \right.\right.$$

$$\left.\left. - \int_0^x H^i (a - X_1) dF^{(i-1)} (X_1) - H^{(i)} (a\, X) \cdot (F^i(X) - F^{(i-1)}(X))\right] = F(X) - \sum_{i=1}^{\infty} H^{(i)}(a - X)\, (F^i(X) - \right.$$

$$F^{i+1}(X)) = F\,(a,X)$$

where T_M is the duration of maintenance; *i* is the number of failures in the area (*o, a*);

$k = \left[\frac{T}{a + T_M}\right]$ is the number of maintenances for the time of use of the system;

[a] is average of whole parts of number *a*;

1– F(a) is the probability that in the interval (*o, a*) the system will be in good working order and the necessary time is equal to *a*.

The obtained equation is an equation of *k + 1* multiple coagulations taking into account that multiple values with positive probability can have a fixed value.

From equation $P\{X_T > T_0\} \geq P_0$ the unknown interval between maintenances α is evaluated if $\max_{\alpha} P\{X_T > T_0\} \geq P_0$, otherwise this requirement cannot be executed. Therefore is necessary to determine $\max_{\alpha} P\{X_T > T_0) \geq P_0$.

The above function is too cumbersome, therefore an overt analytical solution is very difficult. For extremum finding it is recommended to use quantitative methods of optimization by the computer, for example, one of the modifications of the gradient method.

Let us consider the solution of the problem by using a second condition, e.g. the method of finding the optimal interval between maintenances α by maximization of availability.

One has to take into account that in most systems there is an aging process of the characteristics which is usually progressive. The above process can be partially eliminated during the maintenance.

In our research the processes with one-, two-, three- and multi-step aging were considered consequently. First, let us briefly describe a solution of the problem for the simplest variant – one-step aging. In this case, the distribution functions of the time to failures and the time to renewal for the considered period have only one, unchanged form.

To solve this problem, let us show the availability $A(t)$ as

$$A(t) = \frac{\frac{\tau_0(a)}{\mu_\varphi}}{\mu_\varphi + \mu_\xi} \cdot \frac{\alpha \cdot \varphi_0(a) \cdot \mu\xi + \varphi_1(a) \cdot \tau_1(a) - \varphi_0(a)\mu_\xi \cdot \mu_\xi}{\alpha + T_M \cdot \varphi_0(a) + \varphi_1(a) \cdot \tau_1(a)} \tag{3.50}$$

where μ_φ is mathematical expectation of the time to failures; μ_ξ is mathematical expectation of the time to renewal; a is interval between maintenances; $\varphi_0(a)$ is the probability of time when the system is in a good working order at the end of interval α;

$\varphi_1(a)$ is the probability of time when the system is in not in good working order at the end of interval α;

$\tau_0(a)$ is the mathematical expectation of the interval of time to failure from α to failure of the system, with the requirement that it was in good working order at the end of interval α;

$\tau_1(a)$ is the mathematical expectation of the renewal interval from α to renewal, under condition that in moment α the system was in bad working order;

0 and 1 are correspondence markers of good order (conditions) and bad order at the moment t.

In (3.50) the first factor is availability if there is no maintenance, the second is the level of availability increase if there are maintenances during interval time α.

To find the optimal interval $\alpha_{opt.}$ by maximization of $A(t)$ by α, we can find overt expressions for $\varphi_0(\alpha)$, $\varphi_1(\alpha)$, $\tau_0(\alpha)$, and $\tau_1(\alpha)$ by using the Markov theory of random processes.

In each particular situation for solving this problem it is necessary to know the expression for mathematical expectation and desired distribution of the time to failure and the time to renewal.

Then by differentiation of (3.50) by α and equating the derivative to zero, one can obtain the following equation for evaluation $\alpha_{opt.}$.

$$(1 - \varphi_0(\alpha)\cdot\mu_\xi + (\varphi_1(\alpha)\,\tau_1(\alpha))' - (\varphi_0(\alpha)\,\tau_0(\alpha))' \frac{\mu_\varphi}{\mu_\xi} (\alpha + T_M \cdot \varphi_0(\alpha) + \varphi_1(\alpha)\tau_1(\alpha)) -$$

$$(1 - T_M \cdot \varphi_0{}^1(\alpha) + (\varphi_1(\alpha)\,\tau_1(\alpha))' (\alpha + \varphi_0(\alpha)\,\mu_\varphi + \varphi_1(\alpha)\,\tau_1(\alpha) -$$

$$- \varphi_0(\alpha)\tau_0(\alpha)\frac{\mu_\varphi}{\mu_\xi}) = 0 \qquad (3.51)$$

Let us consider the second factor of equation (3.43)

$$\frac{\alpha + \varphi_1(\alpha)\,\tau_1(\alpha) + \varphi_0(\alpha)\,\mu_\xi\left(1 - \frac{\tau_0(\alpha)}{\mu_\varphi}\right)}{\alpha + \varphi_1(a)\tau_1(\alpha) + T_M \cdot \varphi_0(\alpha)} \qquad (3.52)$$

If the time to failure is distributed according to exponential law, so $\tau_0(\alpha) = \mu_\xi$, and the system does not needs maintenance; as one can see from (3.52), the maximum value will be obtained if $\alpha = \infty$. Also obviously, maintenance through period α <u>will increase</u> the reliability if

$\mu_\xi\left(1 - \frac{\tau_0(\alpha)}{\mu_\varphi}\right) > T_M$ (the numerator is greater than the denominator, and the all expressions >1) will be useless, if

$$\mu_\xi \left(1 - \frac{\tau_0(\alpha)}{\mu_\varphi}\right) = T_M;$$

or will decrease the reliability, if

$$\mu_\xi \left(1 - \frac{\tau_0(\alpha)}{\mu_\varphi}\right) < T_M$$

Therefore, if $T_M > \mu_\xi$ the maintenance is non-expedient, because $\left(1 - \frac{\tau_0(\alpha)}{\mu_\varphi}\right) < 1$.

The maintenance is also non-expedient if $\mu_\xi \to \infty$.

So, the condition of expediency for maintenance has been obtained: the maintenance is expedient if we can find so α that

$$\left(1 - \frac{\tau_0(\alpha)}{\mu_\xi}\right) > \frac{T_M}{\mu_\xi}$$

In this case, the root α_0 of the equation

$$\left(1 - \frac{\tau_0(\alpha)}{\mu_\varphi}\right) = \frac{T_M}{\mu_\xi}$$

can be called a critical point of maintenance expediency. If $\alpha_0 < \infty$, one can look for $\alpha_{opt.}$ which maximizes $A(t)$ from equation (3.51).

By two-phase aging until the K-th failure, the system has the same function of distribution of the time to failure and the time of renewal, and after the K-th failure these functions of distribution will have a different form which will not change during the following time of use.

In this case

$$A(t) = \frac{\mu_{\xi 2}}{\mu_{\xi 2}+\mu_{\varphi 2}} \cdot \frac{\alpha+\varphi_1(\alpha)\cdot\tau_1(\alpha)+\varphi_0(\alpha)\mu_{\varphi 2}\left(1-\frac{\tau_0(\alpha)}{\mu_{\xi 2}}\right) + \left(\mu_{\xi 2}\frac{\mu_{\xi 1}}{\mu_{\xi 2}} - \mu_{\varphi 1}\right)}{\alpha + T_M \cdot \varphi_0(\alpha) + \varphi_1(\alpha)\cdot\tau_1(\alpha)} \cdot \qquad (3.53)$$

$$\cdot \frac{A - \sum_{e=1}^{A-1} (A-e)\left(\varphi_0^{(e)}(\alpha) + \varphi_1^{(e)}(\alpha)\right)}{}$$

where ξ_1 is distribution of the time to failures of the system until the *K*-th failure; ξ_2 is the same after the *K*-th failure, by $F_2(x)$; φ_1 is the distribution of renewal time $H_1(x)$ of the system until the *K*-th failure; φ_2 is the same after the *K*-th failure by $H_2(x)$.

As a result of research for this situation, the equation was obtained from which it was possible to evaluate $\alpha_{opt.}$

$$(1 - \varphi_1(\alpha)\tau_1(\alpha))' + \varphi_0^1(\alpha)\mu\zeta_2 - \frac{\mu\zeta_2}{\mu\zeta_2}(\varphi_0(\alpha)\tau_0(\alpha))' + \left(\mu\zeta_2 \frac{\mu\xi_1}{\mu\xi_2} - \mu\zeta\right)\left(A(t) - \sum_{e=1}^{A(t)-1} (A(t)-e)\varphi_0^{(e)}(\alpha)\right.$$

$$\left. + \varphi_1^{(e)}(\alpha)\right)' (\alpha + T_M\cdot\varphi_0(a) + \varphi_1(\alpha)\tau_1(\alpha)) - (1 - T_M\cdot\varphi_0^1(\alpha) + (\varphi_1(\alpha)\tau_1(\alpha))')(\alpha+\varphi_1(\alpha)\tau_1(\alpha) +$$

$$+ \varphi_0(\alpha)\mu\zeta_2\left(1 - \frac{\tau_0(\alpha)}{\mu\xi_2}\right) + \left(\mu\zeta_2\frac{\mu\xi_1}{\mu\xi_2} - \mu\zeta_1\right)\left(A(t) - \sum_{e=1}^{A}(A-e)(\varphi_0^{(e)}(\alpha) + \varphi_1^{(e)}(\alpha))\right) = 0$$

From the second factor of equation (3.53) it follows that maintenance is required only when

$$T_M \cdot \varphi_0(\alpha) < \varphi_0(\alpha)\mu\zeta_2\left(1 - \frac{\tau_0(\alpha)}{\mu\xi_2}\right) + \left(\mu\zeta_2\frac{\mu\xi_1}{\mu\xi_2} - \mu\zeta\right) \cdot \left(A - \sum_{e=1}^{A-1} [A(t)-e]\right)(\varphi_0^{(e)}(\alpha) + \varphi_1^{(e)}(\alpha)) \qquad (3.48)$$

The value of α_0 by which the inequality is circulated to equality is a critical point of expedient maintenance.

Let us now generalize the obtained solutions for the most common variant – multi-phase aging.

We will take [3.51] to be a system which until the K_1th failure has a distribution of time ξ_1 to failure $F_1(x)$, from K_1-th to K_1+K_2 th failure has a distribution of time ξ_2 to failure $F_2(x)$, from $K_1 + K_2$ –th failure to $K_1 + K_2 + K_3$ –th failure has a distribution of time ξ_3 to failure $F_3(x)$, etc.

After $K_1 + \ldots + K_{i-1}$ failures the system has not changed more the distribution of time ξ_n to failure $F_n(x)$.

Analogous is a change in the distribution of renewal time, e.g. until the K_1 th failure the renewal time ζ_1 has a distribution function $H_1(x)$ etc., from K_1+K th failure until $K_1 + \ldots K_i$ th failure the renewal time ζ_1 has a distribution function H_i. After the $K_1 + K \ldots + K_i$ th failure the renewal time ζ_n has a distribution function $H_n(x)$. After the time interval α one provides the maintenance with duration T_M which renews the system in its initial phase. If the moment of the beginning of maintenance clashes with the beginning of system repair, the maintenance is moved to the end of the repair. It is necessary to evaluate the optimal interval between the moments of beginning of maintenance to maximize the system reliability.

We will call the time to failure plus following after that the time of renewal a work cycle.

For research purposes the input is a random process

$$\zeta(t) = \{V(t), \mu(t), \gamma(t), \xi(t), \zeta(t)\}$$

where $V(t)$ is equal to 0 if the system is in working order at moment t, and equal to 1 if the system is not in working order; $\mu(t)$ means the number of the current phase in moment t; $\gamma(t)$ means the number of current work cycles at moment t, the count begins from the moment of beginning the current phase; $\xi(t)$ is the time from moment t to failure moment if $V(t) = 0$; $\zeta(t)$ is the time from moment t to renewal moment if $V(t) = 1$.

Let us input the following markings:

$$\varphi_{ijk}(x,t) = P\{V(t) = I, \mu(t) = j; \gamma(t) = k; \xi(t) < x\}$$

$$I = 0.1; j = 1, \ldots, n; k = 1, \ldots, k_j$$

It is taken for granted that $\varphi_{ijk}(x,t)$ is satisfied by a system of differential equations (not shown because this is a long mathematical process).

The $A(t)$ can be shown as:

$$A(t) = \frac{\mu\varphi_n}{\mu_{\zeta n} + \mu_{\xi n}} \cdot L_1 \qquad (3.55)$$

where $\mu_{\xi n}$ is the mathematical expectation of the time to failure; $\mu_{\zeta n}$ is the mathematical expectation of renewal time.

During the Laplace mathematical transformation (a lengthy transformation, the authors have the full transformation) , $\alpha_{opt.}$ can be found by maximization of $A(t)$ to α.

The authors showed[4] that maintenance is expedient only when:

$$T_M\varphi_0(\alpha) \leq \frac{\mu\xi n}{\mu\zeta_n}\left[\sum_{e=1}^{n-1} K_e\mu\xi_e - \varphi_0(\alpha)\,\tau_0(\alpha)\right] - \sum_{d=1}^{n-1} Kd\mu\varphi_d - \frac{\mu\xi_n}{\mu\zeta_n}\sum_{e=1}^{n-1}\mu\xi_e \sum_{d=1}^{k_{i-1}}(K_e - d)(\varphi_{oed}(\alpha) + \quad (3.56)$$

$$+\,\mu\varphi_n\sum_{d=1}^{\infty}\varphi_{ond}(\alpha) + \sum_{m=1}^{n-1}\mu\varphi_m\sum_{d=1}^{k_m}\varphi_{omd}(\alpha) - \left(1 + \frac{\mu\xi}{\mu\zeta_n}\cdot\sum_{e=2}^{n-1}k_e\mu\varphi_e\sum_{m=1}^{e-1}\sum_{d=1}^{k_m}(\varphi_{omd}(\alpha)+\varphi_{imd}(\alpha)\right)\sum_{m=1}^{n-1}\sum_{e=1}^{n-1-m}k_e\,\cdot$$

$$.\,(\mu\xi_e + \mu\zeta_e)\sum_{d=1}^{k_m}(\varphi_{omd}(\alpha)+\varphi_{imd}(\alpha)).$$

The value of α_0 when the inequality (3.55) is converted to the equality, is the critical point of expedient maintenance. If $\alpha_0 < \infty$, one can look for $\alpha_{opt.}$ which is maximized $A(t)$ from the equation (3.55). Introducing $A(t)$ as in (3.55) has some advantages in comparison with others. For example, from the above it directly follows that the condition of expediently providing maintenance by a fixed α, for counting $A(t)$ one does not need to know the values of $\varphi_0(t)$ in the interval $0 \leq t \leq \alpha$; one needs only $\varphi_0(\alpha)$, $\tau_0(\alpha)$, $\tau_1(\alpha)$, which when α is large permits the use of asymptotical formulas; the integration operations that are very important for a complicated structure of $\varphi_0(t)$, etc are not necessary.

Let us show an example of use of the obtained formulas for third phase aging. As a result of accelerated reliability testing, the following was obtained:

1) the function of distribution of the time to failures on the first phase, which has the form

$$F_1(t) = 1 - e^{-\lambda 1t}$$

where $\lambda 1$ is the intensity of failures in the first phase;

2) the function of distribution of the time to failures on the second phase which has the form

$$F_2(t) = 1 - e^{-\lambda 2t}$$

where $\lambda 2$ is intensity of failures on the second phase;

3) the function of distribution of the time to failures on the third phase which has the form

$$F_3(t) = 1 - e^{-\lambda 3t}$$

4) the function of distribution of time to renewal is the same for all phases and has the form

$$H(t) = 1 - e^{-\mu t}$$

where μ is the intensity of renewal.

After testing it is established that the first and second phases of the system functionality consist of one cycle, e.g. $k_1 = 1$, $k_2 = 1$. After two cycles that are connected with the first two failures after renewal, the third phase of functionality begins, where the intensity of failures has the value λ_3. The Laplace transformations of the above distributions are:

$$\bar{\varphi}_1(u) = \frac{\lambda_1}{\lambda_1+u}; \quad \bar{\varphi}_2(u) = \frac{\lambda_2}{\lambda_2+u}; \quad \bar{\varphi}_3(u) = \frac{\lambda_3}{\lambda_3+u}; \quad \varphi_1(\alpha) = 1 - \varphi_0(\alpha);$$

$$\bar{h}_1(u) = \bar{h}_2(u) = \bar{h}_3(u) = \frac{1}{\mu+u}; \quad \tau_1(\alpha) = \frac{1}{\mu};$$

$$\bar{\varphi}_0(u) = \frac{1}{u}\left[1 - \bar{\varphi}_1(u) + \bar{\varphi}_1(u)\,\bar{h}(u)(1 - \bar{\varphi}_2(u)) + \bar{\varphi}_1(u)\cdot\bar{\varphi}_2(u)\,\bar{h}_2(u)\frac{(1-\bar{\varphi}_3(u))}{(1-\bar{\varphi}_3(u)\,\bar{h}_3(u))}\right] =$$

$$= \frac{1}{u}\left[\frac{u}{\lambda_1+u} + \frac{\lambda_1\,\mu}{(\lambda_1+u)(\mu+u)}\cdot\frac{u}{(\lambda_2+u)} + \frac{\lambda_1\lambda_2\mu^2}{(\lambda_1+u)(\lambda_2+u)(\mu+u)(u+\lambda_3+\mu)}\right] =$$

$$= \frac{u(\lambda_2+u)(\mu+u)(u+\lambda_3+\mu) + \lambda_1 u\mu(u+\lambda_3+\mu) + \lambda_1\lambda_2\mu^2}{u(\lambda_1+u)(\lambda_2+u)(\mu+u)(u+\lambda_3+\mu)}$$

In our example $n = 3$. Let us use the following designations:

$$b_0 = \frac{1}{\mu} \cdot \frac{\lambda_3}{\mu - \lambda_3} - \frac{1}{\lambda_3 + \mu} + \frac{\lambda_3}{\mu}\left(\frac{1}{\lambda_1} + \frac{1}{\lambda_2}\right) - \frac{2}{\mu};$$

$$b_1 = \frac{1}{\mu} \frac{(\lambda_3 + \mu - \lambda_1)(\lambda_2\mu - \lambda_1\lambda_2 - \lambda_1^2) - \lambda_2\mu^2}{(\lambda_3 + \mu - \lambda_1)(\lambda_2 - \lambda_1)(\mu - \lambda_1)} +$$

$$+ \frac{\lambda_2\lambda_3(\lambda_2 - \lambda_3)(\mu - \lambda_1)(\lambda_3 - \mu - \lambda_1)(\lambda_1^2\mu(\lambda_3 + \mu - \lambda_1) - \lambda_1^2\lambda_2^2\mu^2}{\lambda_1\lambda_2\mu(\lambda_2 - \lambda_1)(\mu - \lambda_1)(\lambda_3 + \mu - \lambda_1)} +$$

$$+ \frac{1}{\mu} + \frac{\lambda_1}{(\mu - \lambda_1)(\lambda_2 - \lambda_1)} + \frac{1}{\lambda_2}\left(1 - \frac{\lambda_3}{\mu}\right)\left(1 + \frac{\lambda_1}{\mu - \lambda_1}\right) + \left(\frac{1}{\lambda_1} + \frac{1}{\mu}\right)\left(1 + \frac{\lambda_1}{\mu - \lambda_1}\right);$$

$$b_2 = \frac{\lambda_1\lambda_2(\lambda_3 - \mu - \lambda_2) - \lambda_1\lambda_2\mu}{\lambda_2(\lambda_1 - \lambda_2)(\lambda_3 + \mu - \lambda_2)(\mu - \lambda_2)} - \frac{\lambda_1(\lambda_3 - \lambda_2)}{(\lambda_1 - \lambda_2)(\mu - \lambda_2)(\lambda_3 + \mu - \lambda_2)} + \frac{\lambda_1}{(\mu - \lambda_1)(\lambda_2 - \lambda_1)} \qquad (3.57)$$

$$C_0 = T_M \cdot \frac{1}{\mu + \lambda_3} + \frac{\lambda_3}{\mu(\lambda_3 + \mu)};$$

$$C_1 = \left(T_M - \frac{1}{\mu}\right) \frac{(\lambda_3 + \mu - \lambda_1)(\lambda_2\mu - \lambda_1\lambda_2 + \lambda_1^2) - \lambda_2\mu^2}{(\lambda_3 + \mu - \lambda_1)(\lambda_2 - \lambda_1)(\mu - \lambda_1)};$$

$$C_2 = \left(T_M - \frac{1}{\mu}\right) \frac{\lambda_1\mu(\lambda_3 - \lambda_2)}{(\lambda_1 - \lambda_2)(\mu - \lambda_2)(\lambda_3 + \mu - \lambda_2)}$$

We can write L as:

$$L = \frac{\alpha + b_0 + b_1 e^{-\lambda 1a} + b_2 e^{-\lambda 2a}}{\alpha + C_0 + C_1 e^{-\lambda 1a} + C_2 e^{-\lambda 2a}}$$

Then we have to solve the equation:

$$C_0 + C_1e^{-\lambda 1a} + C_2e^{-\lambda 2a} - (\alpha + C_0)b_1\lambda_1e^{-\lambda 1a} - (\alpha + C_0)\, b_2\lambda_2e^{-\lambda 2a} - b_0 + b_1e^{-\lambda 1a} - b_2e^{-\lambda 2a} +$$

$$+ (a+ b_0)\, C_1\lambda_1e^{-\lambda 1a} + (\alpha + b_0)\, C_2\lambda_2e^{-\lambda 2a} = 0$$

(3.58)

$$C_0 - b_0 + e^{-\lambda 1a}\,(C_1 - b_1 - b_1\lambda_1\,(\alpha + C_0) + C_1\lambda_1\,(\alpha + b_0)) + e^{-\lambda 2a}\,(C_2 - b_2 - b_2\lambda_2\,(\alpha + C_0) +$$

$$+ C_2\lambda_2\,(\alpha + b_0)) = 0$$

To evaluate $\alpha_{opt.}$ we must solve the equation (3.58). Let us show a numerical example. As a result of accelerated reliability testing, the following numerical values were obtained: the intensity of failures $\lambda_1 = 0.05$ 1/hour; intensity of failures $\lambda_2 = 0.001$ 1/hour; the intensity of failures $\lambda_3 = 0.02$ 1/hour; mean time of renewal after each failure is equal to 1 hour; and the duration of each maintenance is equal to 2.5 hours. From (3.57) we can calculate the coefficients:

$$b_0 = 3.3;\ b_1 = 5;\ b_2 = -1.2;\ C_0 = 0.375;\ C_1 = -0.165;\ C_2 = 0.075.$$

From (3.58) we find that $\alpha_{opt.} = 145.5$ hours.

The same methodology can be used to predict optimal intervals between maintenances for multi-phase aging.

20. 3 BASIC PRINCIPLES OF SPARE PARTS NUMBER PREDICTION

The techniques and equipment proposed earlier (Chapter 2) for useful accelerated reliability testing offer, for a short time and with high accuracy, evaluation of the dynamics of failures of components during the service life of the system. This is the initial information for predicting with high accuracy the prediction for spare parts during the service life of systems

The solution of spare parts prediction is included in[5]. But this solution has many complicated mathematical equations. Therefore, the basic solutions which one can use practically are included below briefly[6].

Let us solve the following problem: one has n basic components and time ξ of their maintainability distributed by unspecified law $F(x)$. It is necessary to find a number m of spare parts. The probability P of the system providing the spare parts in intervals of time t will be not less than P_0.

The probability of the provision of spare parts P means the probability that by the end of a given time interval the system will be in working order. In other words the number of failures of components must be no more than the number of spare parts. Let us assume that the number of spare parts is infinite.

In this case the process of system functionality will be a substitution of failures during the time of usage.

The interval $\Sigma ij = tj;\ I + 1 - tij$ is distributed by the arbitrary law $F(t)$ with mathematical expectation τ. $N_j(t)$ is number of substitution for the j-th basic component until time moment t. Obviously, the substitution of failures during the time $N_j(t)$ will be the process of renewal. Let us mark $H_j(t)$ the mathematical expectation of $N_j(t)$. For fixed time t we will find the distribution of $N_j(t)$. The probability $a_0(t)$ that for time t there will not be any substitution is $- F(t)$.

The probability of one substitution is $a_1(t) = F_1(t) - F_2(t)$, of the two substitutions – $a_2(t) = F_2(t) - F_3(t)$, . . . , probability of I substitutions $a_i(t) = F_i(t) - F_{i-1}(t)$. The $F_i(t)$ represents I-multiple substitutions of the distribution function $F_1(t)$, i.e. $F_i(t) = P[\xi_1 + \xi_2 + \xi_3 + \ldots + \xi_I < t]$, where ξ_I is the time of maintainability of ξ-th component $(\xi = 1, 2, 3, \ldots, I)$.

The distribution $N(t)$ is n-multiple convolution of distribution $N_j(t)$. Therefore,

$$P_i(t) = P\{N(t) = I\} = P\{N_1(t) + \ldots + N_n(t) = I\} = P\{N_1(t) = k_1 \ldots, N_n(t) = \sum_{k1+\ldots kn=I} P\{N_1(t) = k_1\} \ldots$$

$$\ldots P\{N_n(t) = K_n\} = \sum_{k1+\ldots+kn=I} a_{k1}(t), a_{k2}(t) \ldots a_{kn(t)} \tag{3.59}$$

where

$$a_0(t) = 1 - F(t); \quad a_i(t) = F_i(t) - F_{i+1}(t)$$

From conditions of the problem:

$$P\{N(t) \le m\} \ge P_0$$

for a given P_0 and t from which one can evaluate the necessary number of spare parts with a probability of no less than P_0.

From another side, $P\{N(t) \le m\} \sum_{i=0}^{m} P_i(t)$. Therefore, the minimal number m when the inequality is carried out

$$\sum_{i=0}^{m} \sum_{k1+\ldots+kn=i} a_{k1}(t), a_{k2}(t) \ldots a_{kn}(t) \ge P_0 \tag{3.60}$$

will be the unknown quantity of necessary spare parts. For calculation of the spare parts from this formula one needs to know at moment t the values of $F_i(t)$ – i-th convolution $F(t)$. This is a general solution of the problem.

Let us consider the implementation of solutions obtained for specific laws of distribution.

For exponential distribution, $F_i(t) = 1 - e^{-\lambda t}$, $t \geq 0$. For probability of i-substitutions [$a_i(t)$] there is the formula:

$$a_i(t) = \frac{(\lambda t)^i}{i!} e^{-\lambda t}$$

and (3.60) one can introduce as:

$$\sum_{i=0}^{m} \frac{(\lambda n t)^i}{i!} \geq P_0$$

For normal distribution:

$$F(t) = \int_0^t \frac{1}{\sqrt{2\pi}\sigma} e^{-1/2\frac{(x-a)^2}{\sigma^2}} dx \qquad (\sigma \leq a;\ a = \tau)$$

One often uses the normal law in the practical calculation of reliability. In this case, $F(t)$ one can be introduced as $F_i(t) = \Phi(\frac{t-a}{\sigma})$, where $\Phi(t)$ is the Laplace function (tables o function can be found in many handbooks on the theory of probability). For distribution law $F_i(t)$ the mathematical expectation is equal to ia and the deviation is equal $\sigma\sqrt{i}$.

Therefore, $F_i(t)$ can be introduced as:

$$a_i(t) = \Phi(\frac{t - ia}{\sigma\sqrt{i}}) - \Phi[\frac{t-(I+1)a}{\sigma\sqrt{i+1}}]$$

And the inequality (3.60) will be:

$$\sum_{i=1}^{m} \sum_{k_1+\ldots+k_n=1} [\Phi(\frac{t-k_1 a}{\sigma\sqrt{k_1}}) - \Phi(\frac{t-(i+1)a}{\sigma\sqrt{i+1}})] \ldots \{\Phi(\frac{t-k_n a}{\sigma\sqrt{k_n}}) - \Phi[\frac{t-(k_n+1)a}{\sqrt{k_n+1}\,\sigma}]\} \geq P_0 \qquad (3.55)$$

For fixed a, σ, t, and P_0 the calculation of m from equation (3.55) for a small m it is not a large problem.

For χ^2 distribution with k degrees of freedom there is the following:

$$f\chi^2(t) = \frac{t^{k/2-1}e^{-t/2}}{2^{k/2}G^{k/2}}$$

The property of χ^2: the sum of two random values that are distributed by law χ^2 with n_1 and n_2 degrees of freedom, has distribution χ^2 with n_1 and n_2 degrees of freedom. Therefore, $F_i(t)$ is χ^2- distribution with k_1 degrees of freedom. The χ^2 –distribution is tabulated, and with many degrees of freedom it is well approximated by normal law. Therefore, the problem of evaluation of minimal m from inequality (3.61) is not as hard as using a low m. If m is greater, one can use the computer.

However, some spare parts which are kept under storage may also have diminished in reliability.

In this case the formulation of the problem is changed: the first interval of consistency of substitution has the function $F_1{}^1(x)$, and those following have the function $F(x)$. Therefore, $N_j(t)$ will be a common process of renewal $F_2(t) = F^1(t) - F(t)$, and $F_i(t) = F^{(1)*}\cdot F_{i-1}(t)$ or $F_i(t) = P\{\xi_1 + \xi_2 + \ldots + \xi_I < t\}$, and the equation (3.61) does not change.

If the expected quantities of m are great the previously described way is not optimal, therefore one has to use asymptotic regularity.

The asymptotic quality indicates when some values can be taken into account as small or, on the contrary, as great. For our problem solution we will describe what is mean by small and what is mean by great. The asymptotic can be described in two possible cases: 1) with large t; with large n. In second case there can be two possibilities: when t is small and when it is not small.

Let us consider the first case. The succession of substitutions the jth basic component is a renewal process, therefore one can use the results of renewal theory. It is known[7,8] the limit of ratios by $t \to \infty$. Therefore the mathematical expectation and variance of substitution quantity are

$$H_j(t) \to \frac{t}{\mu_1} + \left(\frac{\mu^2}{2\mu_1{}^2} - 1\right) \tag{3.62}$$

$$DN_j(t) \to \frac{\mu_2 - \mu_1{}^2}{\mu_1{}^3}t + \left(\frac{5\mu_2{}^2}{4\mu_1{}^4} - \frac{2\mu_3}{3\mu_1{}^3} - \frac{\mu_2}{2\mu_1{}^2}\right) \tag{3.63}$$

where μ_i is i-th (i = 1, 2, 3, …) initial moment of distribution $F(x)$.

Here:

$$\mu_I = \int x^i \cdot dF_i(t)$$

Feller[5] proved the following limit theorem:". . . if $N_j(t)$ is a continued process of renewal, by $t \to \infty$ the following ratio is correct:

$$P\{N_j(t) \geq \frac{t}{\mu_1} - \frac{\alpha\sigma}{\mu_1}\sqrt{t/\mu_1}\} \to \Phi_{(\alpha)} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\alpha} e^{-y^2/2} dy$$

where:

$\sigma = \sqrt{\mu_2 - \mu_1^2}$; and α is quantile of normal law for probability $\Phi(\alpha)$.

Therefore, if t is big [t > (from 20 to 30)τ] one can use the normal law with mathematical expectation $N_j(t)$ and variance $DN_j(t)$ instead of accurate distribution $N_j(t)$".

Leadbetter[9] corrected the error which is obtained by using the formulas (3.62) and (3.63) with finite t. Let us show the results obtained, because it can be useful for practical implementation of (3.61) and (3.63) for calculation of the necessary number of spare parts.

Let us assume $f(x) = F^1(x)$ and we will write the Laplace transformation for $f^0(x)$ as:

$$f^*(s) = \int e^{S\lambda} \cdot f(x)dx$$

Let $f(x) \leq A \cdot e^{-\beta t}$ and select c^0 so, that $0 < c < \beta$ and all copies of equation $f^*(s) = 1$ will be left from $R_e\{S\} = -c$. Then the renewal function $H_j(t)$ will be:

$$H_j(t) = \frac{nt}{\mu_1} + n\left(\frac{\mu_2}{2\mu_1^2} - 1\right)$$

where

$$|R_1(t)| \leq \frac{e^{-ct}}{\eta(2c)^{1/2}} \left\{ \int_0^{\infty} f^2(n) \cdot e^{2cu} dy \right\} \leq ½ A \cdot \frac{e^{-ct}}{\eta[c - (\beta - c)]^2} \quad (3.64)$$

where μ_1 and μ_2 are first and second moments of *f(t)*. For variation there is a formula:

$$DN_j(t) = \frac{\mu_2 - \mu_1^2}{\mu_1^3} tn + n\left(\frac{5\mu_2^2}{4\mu_1^4} - \frac{2\mu_3}{3\mu^3} - \frac{\mu_2}{2\mu_1^2}\right) - \left| R_2(t) \right| \leq \frac{A \cdot e^{-ct}}{\eta \cdot \sqrt{c(\beta - c)}} + \frac{A \cdot e^{-ct}}{\eta \sqrt{c(\beta - c)}} \left(\frac{t}{\mu_1} + \frac{\mu_2}{2\mu_1^2}\right) \tag{3.65}$$

With large *t* one can ignore these corrections, because *R(t)* is low. Therefore, the conclusion is that where *t* is large *N(t)* is distributed by normal law with the mathematical expectation:

$$\frac{nt}{\mu_1} + n\left(\frac{\mu_2}{2\mu_1^2} - 1\right)$$

with variance:

$$\frac{\mu_2 - \mu_1^2}{\mu_1^3} nt + n\left(\frac{5\mu_2^2}{4\mu_4} - \frac{2\mu_2}{3\mu_1^3} - \frac{\mu_2}{2\mu_1^2}\right)$$

In common aspect:

$$P\left\{\frac{m - M}{\sqrt{D}} < D\right\} = \Phi(u) = P_0$$

$$\text{or} \quad \frac{m - M}{\sqrt{D}} < Up_0 \ \text{ with probability } P_0$$

$$m < M + Up_0$$

This means: $m = M + Up_0\sqrt{D}$

If we substitute *M* and *D*, we obtain:

$$R\{N(t) \geq m\} \int_m^{\infty} \frac{1}{\sqrt{2\pi \cdot DN(t)}} e^{-1/2 \frac{[(x - H(x)]^2}{DN(t)}} dx \geq P_0$$

Then from inequality $P\{N(t) \geq m\} = \int_{m}^{\infty} \frac{1}{\sqrt{2\pi \cdot DN(t)}} e^{-1/2 \frac{[x - H(t)]^2}{DN(t)}} dx \geq P_0$

we will find:

$$m = \left[\frac{nt}{\mu_1} + n\left(\frac{\mu_2}{2\mu_1^2} - 1\right) + Up_0 \sqrt{\frac{\mu_2 - \mu_1^2}{\mu_1^3} nt + n\left(\frac{5\mu_2^2}{4\mu_1^4} - \frac{2\mu_3}{3\mu_1^3} - \frac{\mu_2}{2\mu_1^3}\right)}\right] + 1 \qquad (3.66)$$

where:

Up_0 is the quantile (how many root-mean-square deviations one needs to add on the left and right of the center) of normal law (0;1).

Thus the derivation of the approximate formula for evaluation of the necessary number of spare parts for a given probability supplying with spare parts P_0 for large number of t has been shown.

This formula gives the possibility of taking into account the progressive character of product quality decrease in an aged system, because depending on the decrease in component durability the values μ_1, μ_2, μ_3 (first, second, and third initial moments) will be changed.

One needs the equations (3.64) and (3.65) in the second variant, when n is large, but t is neither a large nor a small number. In this case, the asymptotic is created by n on the basis of theory of summarizing equally distributed random magnitudes, for example, using the known Liapunov theorem which sufficient for practical accuracy one can accept when $n > (20 \div 50)$. Therefore, $N(t)$ will have approximately normal distribution with mathematical expectation $H(t)$ and variance $DN(t)$. If t is such that the estimations $|R_1(t)|$ *and* $|R_2(t)|$ using equations (3.64) and (3.65) are located within the limit of accuracy by evaluation of m, therefore:

$$H(t) = \frac{nt}{\mu_1} + n\left(\frac{\mu_2}{2\mu_1^2} - 1\right) \pm \Delta_1$$

$$DN(t) = \frac{\mu_2 - \mu_1^2}{\mu_1^3} nt + n\left(\frac{5\mu_2^2}{4\mu_1^4} - \frac{2\mu_3}{3\mu_1^2}\right) \pm \Delta_2$$

Therefore, as earlier:

$$m \pm \Delta m = \left[\frac{nt}{\mu_1} + n\left(\frac{\mu_2}{\mu_1^2} - 1\right) \pm \Delta_1 + \sqrt{\frac{\mu_2 - \mu_1^2}{\mu_1^3}\, nt + n\left(\frac{5\mu_2^2}{4\mu_1^4} - \frac{2\mu_3}{3\mu_1^2} - \frac{\mu_2}{2\mu_1^2}\right)} \pm \Delta_2\right] + 1$$

Proceeding from Δm, the tolerance for Δ_1 and Δ_2 can be obtained.

Let us consider the situation when t is small and n is large. If t is small, we can ignore the probability of two substitutions for the time interval t for one basic component. As a result, we obtain a binomial scheme with $p = 1 - F(t)$ and $q = F(t)$. It is known from the literature in mathematical statistics, that the quantity of substitutions on n basic components with $np > 9$ (or, in extreme situations, $np > 4$) can be approximated by a random value which is distributed by normal law with mathematical expectation np and variance npq.

We have:

$$P\{n < m\} = P\left\{\frac{n - np}{\sqrt{npq}} < \frac{m - np}{\sqrt{npq}}\right\}$$

From Laplace theorem:

$$P\{n < m\} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{m-np}{\sqrt{npq}}} e^{-\frac{z^2}{2}}\, dz$$

The Laplace integral is equal to P_0 when the value of the argument is equal to Up_0. Therefore:

$$Up_0 = \frac{m - np}{\sqrt{npq}}$$

Therefore:

$$m = [np + Up_0 \sqrt{npq}] + 1 \qquad (3.67)$$

As we can see, if one uses asymptotic regularity, the equation for the evaluation of m is very simple and convenient for practical implementation.

If one cannot use the asymptotic regularity, the formula (3.61) can be used on the computer.

When m is large, it is approximately distributed by normal law.

So, the minimal number of spare parts for a given probability of supplying them for a necessary interval of time t, could be evaluated by solution of equation (3.61). If one assumes that the quantity of m:

- is small, the solution can be found without the use of the computer;
- *is* medium, one needs to use a computer;
- is large, one needs to use the limiting regularities.

Let me illustrate how the solution was obtained as a practical example. The actual company produces 3,000 trailers a year. As a result of accelerated reliability testing of these trailers there are failures of 34 bushings (Table 3.8). How many spare bushings are needed for supplying 3,000 trailers during one year if each works 154 hours of pure work and gives probability of 0.9?

So, $n = 3{,}000$; $t = 154$; $P_0 = 0.9$; $m = ?$

Table 3.8 Time to bushing failure during accelerated reliability testing of trailers.

Number	Time to failures (hours)	Number	Time to failure (hours)	Number	Time to failures (hours)	Number	Time to failures (hours)
1	2	3	4	5	6	7	8
1	15.0	10	46.0	19	27.0	28	14.1
2	24.2	11	12.3	20	10.5	29	15.6
3	12.3	12	36.6	21	40.5	30	14.1
4	11.5	13	5.1	22	26.8	31	14.6
5	17.4	14	24.0	23	12.7	32	17.2
6	30.2	15	6.3	24	8.3	33	20.4
7	18.5	16	14.8	25	16.4	34	19.8
8	29.5	17	9.0	26	12.2		
9	13.7	18	7.7	27	15.5		

If we calculate by formula (3.66), we obtain:

the first initial moment is: $\mu_1 = 18.229$;

the second initial moment is: $\mu_2 = 422.388$;

the third initial moment is: $\mu_3 = 11637.627$;

the second term of formula (3.66) is: $\frac{nt}{\mu_1} = 25344.231$

and $n\left(\frac{\mu_2}{2\mu_1^2} - 1\right) = 1092.00$;

the third term of formula (3.66) is: $U p_0 \sqrt{\frac{\mu_2 - \mu_1^2}{\mu_1^3} nt + n\left(\frac{5\mu_2^2}{4\mu_1^4} - \frac{2\mu_3}{3\mu_1^3} - \frac{\mu_2}{2\mu_1^2}\right)} = 108.58.$

The required quantity of spare bushings is:

$$m = 24.361.$$

The obtained results were used to plan the number of spare parts required to produce the bushings for the above trailers.

20.3.1 Evaluation of Spare Parts Composition for a Given Common Cost for the Systems which Consist of Heterogeneous Components

In a real life situation one needs spare parts for a system which consist of heterogeneous components. One of the basic criteria of optimal acceptance often is the cost factor. One needs to known the quantity of spare parts required to supply maximum reliability. One can see the common solution of this problem later.

Let us consider a system which consists of *n* groups of different basic components, and the i-th group has *n* basic components, allowing for the sliding unloaded reservation which consists of *k* components. The cost of the components of the *i*-th group is equal to C_i. The time to failure of the components of the *i*-th group is distributed by law $F_1(t)$;

$M_j^{(i)} = \int_0^\infty x^j \cdot dF_1(x)$ which is the probability failures of the system for interval time *t,* is given and equals $P_0(t)$. The quantity of spare parts k_i must be adjusted so that their common cost will be minimal.

In this situation the time to failure of the system is equal to the probabilities of time to failure of each group of products:

$$P_0(t) = P_{01}(t) \cdot P_{02}(t) \ldots P_{0n}(t)$$

where $P_0(t)$ is the probability of the time to failure for the interval time t of the *i-th* group.

If $P_0(t)$ is given, one can find the necessary quantity of spare parts using formula (3.60). We intend in the future that we could use the asymptotic formulas and that $P_0(t)$ is normal law with mathematical expectation m_i and variance D_i. In this case, the formula (3.67) is

$$k_i = m_i + Up_0(t)\sqrt{D_i} \tag{3.68}$$

where Up_0 is the quantile of normal law $N(0, 1)$.

But if P_{0i} is not given, and only their product is given, there is an extreme problem, i.e. to find the variance of $P_{0i}(t)$

$$\min\sum_{i=1}^{n} C_iK_i = \min\left(\sum_{i=1}^{n} C_i m_i + \sum_{i=1}^{n} Up_0(t)\sqrt{D_i}C_i\right)$$

The first sum does not depend on $P_{oi}(t)$. Therefore, one needs to find $\min \sum_{i=1}^{n} Up_{oi}(t)\sqrt{D_i}C_i$ for a condition that $\prod_{i=1}^{n} P_{oi}(t) = P_0(t)$ is a quantile of normal law $N(0, 1)$ for probability $P_{oi}(t)$.

This problem can be solved using the method of indeterminate multipliers of J. Lagrange

$$\prod_{i=1}^{n} F(X_i) = P_0$$

$$d_1 + CF^1(X_1)F_2(X_2) \ldots F(X_n) = 0 \tag{3.69}$$

The authors deduced:

$$X_1 = \frac{\dfrac{d_1}{\beta_1}\left(C_0 - \sum_{i=2}^{n} d_1 \cdot \dfrac{d_i\alpha_i - d_i\alpha_i}{\beta_i \cdot d_1}\right)}{\sum_{i=1}^{n} \dfrac{di^2}{\beta_i}} \tag{3.70}$$

where

$$d_i = Ci\sqrt{D_i}\,; \quad X_i = X_1 \cdot \frac{d_i\,\beta_i}{d_1\,\beta_1} + \frac{d_i\,\alpha_i - d_1\,\alpha_1}{\beta_i\,d_1}; \quad d_1 > d_2 \ldots d_i$$

$$C_0 = \sum_{i=1}^{n} x_i \cdot d_i \tag{3.71}$$

Example: The system needs the mathematical expectation of one type of components μ_1 = 1000 and mathematical expectation of another type of components μ_2 = 1500 for a given time. The correspondence variances are D_1 = 6400 and D_2 = 8100. The cost of the first component is $95.00 and the second is $20.00. The cost of both types of spare parts with warranty probability P_0 = 0.9 must be found.

From (3.69) we have: d_1 = 1,600 and d_2 = 1350. After solution of the equation (3.68) we obtain the quantiles of the normal law of distributions for both types of spare parts:

$$X_1 = 1.6$$

$$X_2 = 1.69$$

Then, from equation (3.68) we obtain the necessary quantities of spare parts with given warranty probability:

$$K_1 = 1000 + 1.6 \cdot 80 = 1128$$

$$K_2 = 1500 + 1.69 \cdot 90 = 1655.$$

As a result, the cost of reservation is: C = $47,355.

Another problem can be solved: the total cost of spare parts is C . We need to accept that the probability of failure for time t was minimal for this composition of spare parts.

Example: The common cost of reservation is C = $4,700. For a given time the system needs the mathematical expectation of one type of details μ_1 = 1000, and mathematical expectation of a second type of details μ_2 = 1,500. The correspondence variances are D_1 = 6,400 and D_2 = 8,100. The cost of the first detail is $20.00 and second detail $15.00. One needs to find the composition of spare parts such that probability of failure will be minimal for a given common cost of spare parts:

$$d_1 = 1600;$$

$$d_2 = 1350.$$

If we use equation (3.70), we find C_0 = $4,500.

For X_1 in the interval [1.4; 1.5] :

$$\psi(x) = 0.1629 - 0.241\ (x - 1.4) = 0.5003 - 0.249x.$$

For X_2 in the interval [[1.5; 1.6]:

$$\Psi(x) = 0.1388 - 0.214\,(x - 2.5) = 0.4598 - 0.214x.$$

Using formula (3.70):

$$X_2 = X_1 \frac{1350}{1600} \cdot \frac{0.241}{0.214} - \frac{1350 \cdot 0.5003 - 1600 \cdot 0.4598}{1600 \cdot 0.214} = X_1 \cdot 0.949 + 0.175$$

Using equation (3.70) we find:

$$X_1 = 1.48 \quad X_2 = 1.58.$$

From the tables of normal distribution we find the probability for the above X_1 and X_2, and after multiplying them, we obtain:

$$P_0 = 0.9306 \cdot 0.9429 = 0.877$$

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CHAPTER 4. PRACTICAL ACCELERATED QUALITY DEVELOPMENT AND INPROVEMENT IN MANUFACTURING AND DESIGN

21 INTRODUCTION

High product quality and reliability can be obtained during the design process with the use of accelerated reliability testing, but these results might decrease during the manufacturing process. Therefore, for producing a high quality product, one usually needs accelerated improvement of quality and reliability to minimize complaints.

Also, during the design process one cannot take into account all the technological and other manufacturing aspects for providing a high quality of product. These aspects depend on the procurers of materials, components, and of the whole product as well as combinations and interactions of all the above. One can take into account the above only during the manufacturing phase. Therefore, the processes of quality (reliability, maintainability, etc.) development and improvement begin from the design phase and continue during the manufacturing phases. In general, this is one complex of quality and reliability (maintainability, durability, etc.) solutions.

Often it is a problem for automotive and other industrial companies to find the reasons for complaints and then to rapidly improve the quality, reliability, and durability, and, as a result, to eliminate complaints during the manufacturing process. This means it often takes years before these companies can increase the product's quality and reliability, and as a result, it is not adequately competitive in the market.

Currently Japanese cars and trucks are superior to those of the West. The above approach to ART and the Complex Analysis of factors that influence product quality can play a vital part dramatically improving this situation. Unfortunately, the CEOs often cannot understand and appreciate the benefit of this approach and therefore do not invest enough money in using it.

How effective this method can be, will be shown below.

Practice demonstrates that if the production company reduces testing, especially accelerated testing, of the product as a cost saving measure it loses:

- greater expenses for corrections of the rejected products;

- potential customers for future products, because the producer can not find customers who will buy small quantities of products through other selling agencies and, therefore, receives no help in correcting the damaged product during the warranty period;

- its reputation on the market as a company of high quality.

The basic way for finding the reasons for complaints is by using the complex which consists of:

- engineering technology (design, manufacture technology, quality control, etc.) analysis;
- physical analysis;
- chemical analysis;
- statistical analysis.

There is one generalized wrong direction in the quality control systems of the manufacturing companies.

In modern manufacturing, even hi-tech managers, especially top managers who develop the quality control system for their companies, think that availability of high level computerized equipment for quality control, robotizing equipment for producing the product, etc. offer the possibility for high quality product provision. But often this does not give the possibility for rapid elimination of the reasons for inferior product quality. This is especially true if the reason for insufficient quality is a group of factors that relate to specifics of manufacture.

22 BASIC CONCEPTS OF QUALITY

22.1 DEVELOPMENT OF THE QUALITY SYSTEM

In the earliest forms of industrial activity the craftsman not only performed the manufacturing of the products, but also checked them for quality as well. From the early 1900s most production departments were supervised by a foreman who was also responsible for any inspection if required. Although this arrangement provided some quality protection, there was a great emphasis on productivity. Quality was a difficult situation because the inspectors followed the direction of the foreman who was interested in getting the product out of the door.

During World War II, many non-conforming products were delivered to the military. Many companies responded by taking inspectors out of the control of the production department and having them report to an inspection department.

These inspection departments took on such related responsibilities as metrology, calibration of test equipment and disposition of non-conformities. In some companies a laboratory department was established for performing critical tests. Usually these companies assigned both the laboratory and inspections groups to a technical quality manager.

After World War II, there were difficulties and delays in making products fit for use. There was also a tremendous decrease in quality standards immediately following World War II because of the press of production to meet shortages that had built up during the war. Managers became aware that quality demanded more extensive forms of planning and control.

Inside the companies, the new technical specialists who emerged to apply sampling and SPC techniques, were called quality control engineers and along with the inspection and laboratory areas reported to the quality manager.

From the beginning of the 1960s and 1970s the need for an assurance of quality in many organizations created separate quality assurance engineering and auditing specialties.

Thus the major quality organizational components, as we know them today, were created. Today, the top management staff usually develops the company's strategic business plan. The business plan contains the vision, mission, goals and responsibilities for the implementation of the plan. A good plan will focus the company's management and employees on the same set of directions. The plans, when implemented, will help enhance the health of the company.

However, times are changing and quality is getting its fair share of favorable press. The customer satisfaction imperative is the new driving force for quality in today's organization.

The customer's expectations of quality are becoming more demanding. A company must compete for the customer not only through product quality, but also through service. The customer's requirements are changing, and so must the basic quality function in the organization. Customer needs necessitate corporate strategic planning, which, in turn, impacts on the requirements of the quality function.

22.2 QUALITY BASICS: QUALITY FUNCTION, THREE MANAGERIAL PROCESSES OF MANUFACTURING QUALITY

Most production and distribution is carried out by specialized departments, such as product development, process development, production, marketing and other departments.

The responsibility for carrying out the assigned special functions of each specialized department must be carried out by certain company wide function such as human relations, finance or quality.

In addition, each specialized department is also assigned a share of the responsibility for carrying out certain company wide function such as human relations, finance and quality.

Product quality is the result of the work of all departments together around a spiral (Figure 4.1). The responsibility of each of those specialized departments is not only to carry out its own special function, but it must also have the responsibility to do its work correctly. In this way, each department has a quality oriented activity to carry out along with its main function. These department quality - oriented activities are supplemented by other activities carried out by staff departments and by upper management.

It is essential to think through and define the universal concepts of any important function which underlies the activity's existence. Additionally the language used needs to be standardized so that the key concepts can be understood.

In the case of the quality function, identification of the universal concepts has followed an erratic course. Inspection and testing procedures and measurement concepts are thousands of years old. It was during the twentieth century that statistical methods were applied to quality functions.

There are many other ways for organizing how to think about quality. The important factor in selecting these alternatives is the ease of explanation to nonexperts, and especially to upper managers.

Quality improvement is obtained by using the same processes of planning, control, and improvement[8,10,14,15]. The concepts are the same as those used to manage for finance. However, the procedural steps are special, and the tools used are also special.

Quality Planning: The Development of processes and products required to meet a customer's needs involve a series of universal steps:

1. Determination of the desired customers.
2. Determination of their needs.
3. Development of features responding to customers' needs.
4. Development of processes for producing those product features.

5. Transfer of the resulting plans to the operations department.

Quality management depends on accurate planning.

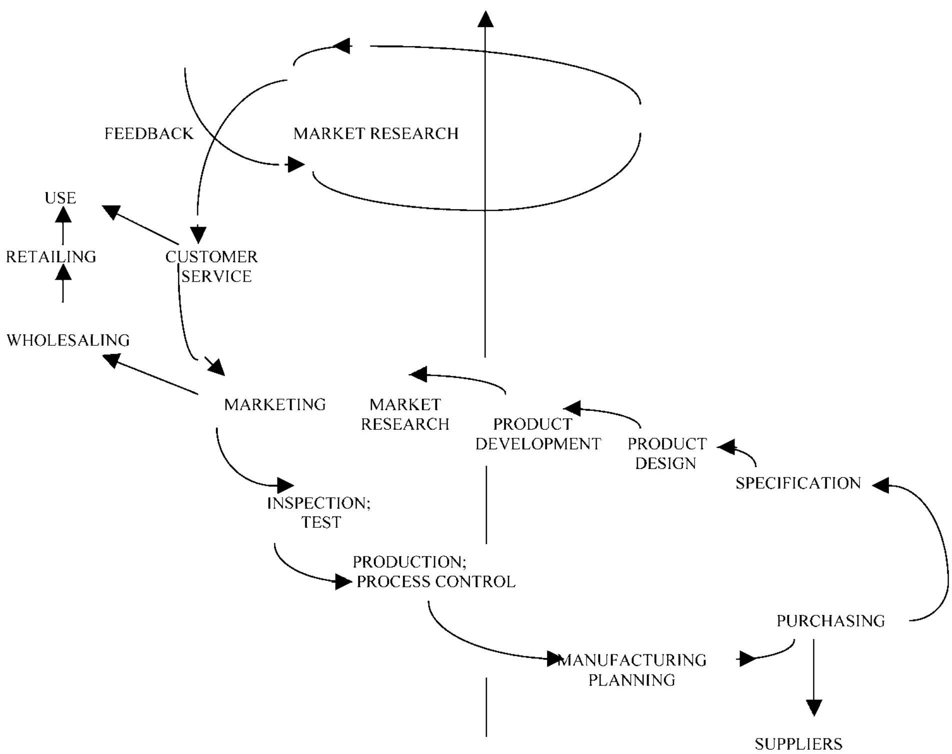


Figure 4. 1 The spiral of progress in quality (from Juran[1])

To achieve this it is necessary to establish quality objectives and develop the plans for meeting those objectives.

Standardization of terminology is essential for consumer understanding.

Objectives are all aimed-at targets, but they may be called "goals", "requirements", "missions", "visions" and so on. Nomenclature includes "systems", "procedures", "processes", "programs', and so forth. In various applications the terminology may also become specific. For instance, in the manufacture of goods, the objective may be called the "specification" or "tolerance". The plan may be called a "production process".

Within any organizations the quality plans are closely interrelated. At the top of the organization, the broad quality objectives require broad-based plans. Such broad-based plans then require establishment of subobjectives, each of which requires a subplan. In large organizations this subdivision can involve many layers of objectives and plans.

An important aspect of quality planning involves addressing the multiple quality needs. A plan should be devised for necessary actions including a quality planning road map which will be described in detail in the training manual[1].

Quality Control: The process of quality control serves as an aid to meeting the product and process goals. It is based on the feedback loop, and consists of the following steps:

1. Evaluation of actual operating performance.

2. Comparison of actual performance to goals.

3. Modification of procedures necessary to achieve these goals.

Quality control is the regulatory process through which we measure actual quality performance, compare it with quality goals, and act on the difference.

Other definitions of quality control may include:

1. Product inspection as a regulatory process.

2. Formation of a department devoted full-time to quality assessment.

3. Obtaining equipment, techniques, and procedures through which most of the quality function is carried out.

The term "quality control" has had a short but lively history. Early in the twentieth century, it began to be used as a synonym for "defect prevention" (in contrast to the widely prevailing after-the-fact inspection). However, during the 1940s and 1950s there was a wave of enthusiasm (and overenthusiasm) for the use of statistical methods in quality control. The proponents of this movement coined the phase "statistical process control" (SPC) and publicized it so widely that many managers gained the impression that quality control consisted of the use of statistical methods in industry. As a consequence, the SPC movement weakened the use of "quality control" as an accepted term for the regulatory process.

As time progressed, the term "quality control" has been replaced by various other terms.

The term "total quality control" implied that anything else was only partial quality control. Reliability engineers contended that quality control as practiced had been limited to internal quality matters.

Since them new terminology has been invented (zero defects) for use as a slogan to represent performance of the entire quality function and new terms such as quality assurance, product assurance, etc. During the mid-1980s statistical methodology become most important under the title "statistical process control".

It would be beneficial to agree on a single term for the regulatory process. However, it is difficult to find such an agreement. Most people tend to structure their terms in a way that confirms their beliefs in organizational structure, priority of techniques, and the like. There have been sufficient circumstances in which a choice of terminology was decisive in settling jurisdictional disputes which caused people to use terminology as weapons of defense. This isn't just a matter of judgment; many human beings feel sincerely that broadly standardized terminology is a hindrance to their company's needs (or personal aspirations) and that, as a result, new, more immediate terminology must be coined to reflect these needs.

Quality improvement: This third managerial process seeks to attain levels of performance that are are unprecedented – levels that are vastly better than any past levels of achievement. The methodology consists of a process, a uniform series of steps.

" Improvement " is achieving a new level of performance that is superior to any prior level.

To obtain this superiority it is necessary to apply the breakthrough concept to all problems of quality.

Quality improvement includes both the improvement of fitness for use and reduction in the level of defects or errors. Improving fitness for use does have some definite important benefits:

- Better quality for the users;
- Higher market share for the manufacturer;
- Premium price for the manufacturer;
- Status in the marketplace for the manufacturer;
- Lower cost and few annoyances for users;
- Reduction of the level of defects and errors also provides numerous benefits;
- Dramatically lowers the cost for the manufacturer;
- Improved productivity. A more useable product is produced using the same resources;
- Reduction in inventories to boost the emergency concept;

Benefits are further implemented by improved teamwork which is the result of the project team concept as well as opportunities for workers to participate in the improvement of projects.

In spite of these obvious benefits, most organizations have traditionally conducted their affairs with a limited priority on improvement. During a period of economic growth, products are saleable if they are generally competitive as to quality. The costs resulting from poor quality are passed on to customers in the form of higher prices.

A major requirement for a quality improvement program is that it be well accepted by those most involved – the managers, supervisors, work force. How acceptable a program is depends to a large degree on the success of former programs of improvement.

As always, higher management would like to avoid getting too involved in yet another problem.

Therefore, the temptation is to delegate quality improvement to their subordinates. However, subordinate managers are more impressed by the actions rather than the words of their superiors.

If their superior managers do not actively participate, the subordinates arrive at the conclusion that the higher management doesn't give top priority to quality improvement.

Most companies are unaware that to attain annual quality improvement it is necessary to have a thoroughly comprehensive and organized approach. Without that information, they conclude that one or another of those parts results in a total solution.

System managers have long had the ultimate responsibility for meeting operational goals, which includes quality goals but omits the very important goal of quality improvement. As a result, operational goals have a prime claim on the time of the operating managers. Therefore, there are minimal if any rewards for effort spent on annual quality improvement.

22.3 GENERAL CONCEPTS OF QUALITY ASSURANCE

With quality assurance there is protection against quality problems by means of early warnings of difficulties ahead. These early warnings are vital in the prevention of both internal and external problems. Quality assurance is derived from objective evidence, but the type of evidence may differ widely based on the persons requiring the assurance and the nature of the product itself.

Natural products' quality assurance is received directly through a sensory examination of the product – for example, dairy products or fruits in the village marketplace. For a manufactured product which is of a simple, short lived nature, sensory evidence needs to be supplemented by laboratory testing. Where test facilities are lacking, those in charge must rely on the world of the manufacturer or on feedback from previous test results.

To prolong a product's service life requires more laboratory (accelerated) testing, but most producers and users lack the appropriate test facilities. Therefore, they must establish additional assurance based on such things as the manufacturer's reputation for quality from independent laboratories, or warranties. But often these "independent" laboratories are not so independent.

For complex products, even the data obtained from complicated accelerated testing does not provide complete quality assurance of the product. One can read in Chapter 2 why this is and how one can improve the situation.

Quality assurance is the activity of providing the evidence needed to establish confidence that the quality function is being effectively performed.

The list of Departmental Assurance Activities includes:

- Marketing

- Product
- Supplier relations.
- Production
- Inspection and Test
- Customer service.

22.4 QUALITY SYSTEM

22.4.1 Objectives of the Quality Function

Present day advanced understanding is aware that increased quality and productivity are interdependent. The undertaking is more integrated (when this progressive view is adopted). Each and every worker is responsible for work quality. However, the necessary tools, powers, and motivation must be present to perform work correctly. The modern production cycle is beginning to resemble the days when each worker was complete master in the shop, as well as dealing with customers, making the products, and checking their quality. In order to manage both the total process or the subprocess requires many skills, including level of education in their craft.

Usually a well endowed Quality System consists of the quality departments necessary functions as well as a guideline for the deployment of quality policies.

In most cases, the quality department in an organization plans, measures, analyzes and reports on quality. This is a staff function to support other departments in the day-to-day improvement of products and services.

Generally, multiple plan, multi-division and multi-national organizations include a corporate quality group. There are instances in which laboratories report to a divisional quality manager. In large companies there are often autonomous divisions based on a particular product line. It is customary for each of these autonomous divisions to have its own quality department (at the corporate staff level).

The common functions of quality department include:

- Quality Control;
- Quality Assurance;
- Inspections;
- Reliability/Durability/Maintainability;
- Quality Engineering;
- Quality Audit;

- Procurement Quality;
- Metrology Measurement;
- Administration.

Dimensions of quality are concerned, quality may be viewed in several ways:

- various meanings of "quality";
- various characteristics of quality, for example, reliability, availability, maintainability, durability, serviceability, etc.;
- quality of design versus quality of conformance;
- drivers of quality;
- quality planning, control, and improvement;
- quality strategic.

The meaning of "quality" changes depending on the circumstances and perceptions of the situation.

Quality assumes a different assumes meaning when tangible products are the focus rather than the perception of a quality service. The meaning of quality is also time-based, or situational.

The new car receives roués the day before and is cursed the next day when it fails to start and an important appointment is missed.

Some common meanings for quality are that quality is conformance to requirements:

- Quality keeps the promises made when an order is taken or a commitment is made.
- The product or service is free from deficiencies.
- Quality means that all specifications have been met.

Quality is fitness for use:

- Quality means that the product or service carries out the intended function.
- Quality is the amount that the product or service costs a user if it doesn't function properly according to the contact undertaken.

Quality is meeting the customers' expectations:

- Quality is satisfying the customer.

- The quality of a product or service is meeting a customer's expectations.

The goal of a quality function statement should be clear and completely pave the way for strategies with quantitative objects and definite plans which can be developed. The quality function goal's statement must be part of the organization's goal statement. If the organization's goal statement underscores timeliness, the quality function mission goal statement should emphasize that particular element instead of saying, cost.

The quality function goal is based on as well as being an input into the organization's chief aims.

Both upward and downward organizational collaboration is essential in quality planning. A quality function goal can be accomplished in several successive steps:

- Find out which customers are the recipients of a service or product.
- Identify a particular service or product which will be provided by the quality function.
- Discuss with customers whether they have a need for this service or product.
- If a need exits, agree on the standards and measures which apply.
- Calculate the gap between current practice and customers' needs.
- Define what is necessary to improve that particular service or product based on the results, and relative priorities.
- Make improvements and evaluate the results.
- Review what lessons have been learned.
- Keep what has proved to be valuable.
- Repeat.

The importance given to the quality function doesn't depend on the size of the actual quality department (budget, head count, location in the organization chart, floor space), but takes into account a number of other factors, which include:

- The degree of importance placed on quality goals and objectives.
- The total costs of quality, which must be divided among quality prevention, appraisal, and failure.
- The total quality management must be involved in acquiring resources and spending the necessary time on solving problems, particularly the higher levels of management.
- Active and individual involvement in quality efforts by senior leadership.

Quality is of utmost importance in an organization, but there are other important functions as well. The quality function must be sensetitive toward its dealing with other activities within the organization (company). Quality is not the only means of bringing about success to the company and it is not free from making blunders, mistakes, poor judgment, or even lapses of human error. There are both good and bad ways of achieving quality. Thus the quality function should receive careful scrutiny in the same way as any other function is evaluated and subsequently improved.

22.4.2 Developing a Quality Plan in the Company (Organization).

Quality must be made an integral part of an organization's plans. In smaller organizations, the majority of personnel are familiar with the entire organization's knowledge, goals, policies, and procedures, many of which may be undocumented. When organizations increase in size and complexity, new personnel are brought in many of whom are in a position to make important decisions. For overall consistency and quality, it is almost importance that business principles, policies, objectives, and procedures are well defined, documented, and communicated.

Business principles are the basic beliefs or values which aid in the guidance of behavior.

It is possible to integrate and document these principles in the process of strategic planning.

In their application to the quality function, quality management principles are the basic beliefs that come into play in an organization's decision making, and which will ensure long-term success from the perspective of customers, employees, and other stakeholders. Quality management principles are basic to all levels of an organization's objectives and are proof of the depth of the organization's commitment to quality.

The following are examples of specific quality principles:

- Problems have special and common causes.
- Management must be responsible for common causes.
- It is better to prevent defects from occurring than have to root them out.

A quality plan is a document which describes particular quality practices, resources, and sequences of activities relating to a particular product, service, project, etc.

Quality plans should be defined, including:

- Steps in the process that constitute the operating practice of the organization;
- Quality objectives to be achieved (e.g. characteristics or specifications, effectiveness, cycle time, cost, natural resources, utilization, uniformity);
- The particular way in which responsibilities, authority, and resources are allocated during the various phases of the project;

- What specific documents procedures and instructions must be applied;
- Required testing, inspection, examination, and audit programs at appropriate stages of the project;
- A documented procedure for making changes and modifications in a quality plan as the projects proceed;
- A method for measuring the achievements of the quality objectives.

It is at the highest level that quality goals and plans should be made a part of the total strategic plans of the organization. As organizational goals, objectives, and plans are spread throughout the organization each aspect of function finds its own best way of contributing to the top-level goals.

At lower levels, the quality plan assumes the role of an action plan. Such plans may assume many different forms relative to the desired outcome they are intended to produce.

The operating-level quality plan must translate the customer's requirements into actions needed to produce the desired outcome and, along with this, applicable procedures, standards, practices, and protocols to specify precisely what is needed, who will carry it out, and in what way it will be concluded.

Quality plans result from the deployment of strategic quality policies together with specific necessary directions for meeting a customer's requirements within the organization's goals.

22.4.3 Review the Effectiveness of the Quality Systems.

A quality audit is a systematic and independent examination to determine whether quality activities and related results comply with a company's planned arrangements and whether these arrangements have been carried out effectively and are appropriate for achieving these objectives.

Three principal parties are involved in a quality audit. By function, they are:

- First, the auditor, or the particular company member who plans and conducts an audit in accordance with an established standard;
- Second, the client, or the person/organization who has requested that an audit be conducted;
- Third, the audit, or the organization to be audited;

An audit can be considered either as internal or external, based on the interrelationship that exists among the participants. Internal audits are first-party audits, whereas external audits may be either second - or third-party audits.

A first-party audit is an internal audit carried out by auditors who are employees of the organization being audited but who do not have a vested interest in the results of the area being audited.

A second–party audit is an external audit made on a supplier by a customer or contracted/consulting organization on a customer's behalf.

A third-party audit is performed on a supplier or regulated entity by an external participant other than a customer.

Quality audits can be made on a product/service, process, or system. A product quality audit is an in-depth examination of a particular product/service to evaluate whether it conforms to product specifications, performance standard, and customer requirements.

Internal audits of a quality system are conducted to discover whether:

- A particular system is appropriate for the organization;
- The system design follows an established standard or accepted practices;
- The system is documented;
- It can be demonstrated objectively, according to records, that the work performed has followed the subscribed documented system;

Auditing involves checking stages of the proposed cycle and consists of the following stages: audit preparation; audit performance; and audit reporting, corrective action, follow-up, and closure.

The following activities are performed during audit preparation:

- Prepare activities.
- Schedule the audit plan.
- Close and determine the ranges of the audit team.
- Select the audit team.
- Establish the scope of the audit.
- Identify essential resources for the audit.
- Review the technology.
- Select essential standards.
- Review essential documentation.

- Develop checklists and other working papers.

The data collection phase includes the following items:

- Calling an opening meeting.
- Auditing data collection strategies.
- Verifying documentation.
- Analysis of results.
- Presentation of results.

At the completion of the audit performance stage the results must formally be presented to the client. Any possible problem areas must be identified and corrected:

- Distribute the audit report and request comments.
- Evaluate the comments and perform necessary corrections.
- When this has been completed the corrective action has been verified.

The carrying out of a quality audit can provide management with facts that are unbiased and can be used to achieve the following:

- Allow management to become aware of actual or potential risks.
- Offer management vital material on which to make appropriate decisions, for example, which quality problems and costs can be prevented or improved.
- Identify areas of opportunity.
- Make assessment of personnel training as to whether or not it is effective as well as whether the equipment used is entirely suitable.
- Offer visible evidence of management's support of the quality program.
- To verify that regulations have been complied with.

Other ways of conducting internal evaluations

Management reviews such as specified by the ISO 9001 standard often happen as a result of top management's review of the following either on a quarterly or an annual basis:

- Customer satisfaction and complaints.
- Supplier performance.

- Cost of quality.
- Internal process/product quality indicators.
- Audit results.

Skip-level meetings take place when a member of senior management meets with persons two or more organizational levels below, and without the presence of any management from the in between level being present. The purpose is to get a better perspective of how effective the quality system actually is. It is important not to give the impression that the in-between management levels have been circumvented. The intention is to give lower level employees the chance of making higher management aware of the needs and problems of the system.

Skip-level meetings are important for allowing discussions of issues and concerns rather than for the management of the operation.

The availability of internal electronic communication and greater public awareness means there tends to be more contact between various organizational levels and less tendency to follow the chain of command.

It is important to collect and analyze data so as to have the necessary information for evaluating and improving customer service and satisfaction. This course of action is implied in all quality management systems and is required for meeting certain standards, for example, ISO 9001:2000.

The same is true for employee feedback in which the information can be used to evaluate and improve employee response to the quality mission, policies, and the quality system, as well as employee well-being and satisfaction, and is implied in any effective quality system.

22.4.4 Continuous Improvement

In order to improve a product or service for future customers the best improvement philosophy is to repeat the following:

- I am able to do the following for you.
- In return, what can you do for me.

Regardless of the current level of organizational performance, room for improvement always exists. The management of any organization requires project solving and process improvement.

To ensure the most effective improvements a systematic approach must be used to identify, understand, and address the available opportunities.

It is necessary to identify factors requiring changes involving the use of data and ideas. The information should be presented in a way that permits accurate interpretation.

This can be accomplished by the use of tools such as flowcharts. The usage of Pareto charts has therefore become widespread. A systematic approach to process improvement efforts is essential and can be carried out on a project-by-project basis. There are several reasons to confirm this approach:

- Chances of success may be increased, preventing the spreading of these resources too thinly.
- Problem solving is made more efficient and effective by ensuring that improvement efforts focus on the proper causes.
- Benefits to the organizations are obtained by testing solutions before implementing them.

It is necessary for any improvements to be conducted out in a systematic manner.

Organizations must be able to recognize and utilize all opportunities for improvement as well as keep records of the rate of progress. Savings made by quality improvements are a means by which an organization's financial information can evaluate the benefits of quality improvement.

The seven QC tools are diagnostic tools that are used to analyze a particular process and its data. These include: Pareto chart, flowchart, cause-and-effect diagram, check sheet, control chart, histogram, and scatter diagram. These tools are considered to be part of the basic continuous improvement toolkit. (One can find this in more detail in the literature on preparation for exams and CQE courses, for example, "CQE QUALITY COUNCIL OF INDIANA").

However, a great part of continual improvement consists of taking a process that may be performed as expected, but in which a higher level of performance is desired. In order to take the necessary steps to improve such a process it is important to understand how it functions from a managerial point of view.

22.4.5 Process Improvement Models

As not all improvement projects involve root cause analysis, a more general structure for continual process improvement may also be useful. Let's see one example:

1. Select the process to improve – To accomplish this it is necessary to analyze information from customers both within and outside the organization (internal or external), as well as to identify those processes which are vital for improvement.

2. Review current performance – Current performance measures are reviewed to take certain that they are adequate and appropriate, and include all expectations or needs.

3. Identify improvement needs or opportunities – Select areas of the processes in which improvement would be most beneficial, and analyze the process in order to decide where improvement or changes can be made.

4. Implement process changes – A plan is projected and its details communicated regarding necessary changes in the steps of the process, and these may be conducted on a small scale before embarking on a full-scale implementation.

5. Evaluate process – Process performance is given another review to see whether the desired goal was achieved. If the results are positive, the change is standardized and a new process or opportunity for improvement is selected. Many companies have celebrations and also share what has been learned from any successful new improvement endeavor with the organization as a whole.

Even after taking the appropriate steps for problem process improvement, it would still be beneficial to employ a set of guiding principles as a way of implementing all such efforts in the future.

These principles can be utilized by the steering committee, a process improvement group, or a group facilitator as a means for helping to identify any obstructions to progress improvement:

- Leadership – Senior executives should be the ones responsible for the process of continual improvement.

- Strategic – Improvement should be focused primarily on those processes that will bring about a strategic gain or advantage that is basic to the problem.

- Customer – Process changes should also take into consideration customers' feedback, needs, and the potential impact these changes will have on them.

- Involvement – Because of their knowledge and responsibility the people actually included in the process of improvement should be the ones to carry out and implement any decisions for change.

- Process – Approach all projects from the point of view that whatever improvement made is a process that transforms inputs (from suppliers) into outputs (for customers).

- Data – Decisions, for example, regarding which processes to improve and what changes are necessary for the improvement should be based on data when ever possible.

- Prevention – Since an important idea is to create processes that can meet or exceed requirements, actions taken should keep these process problems from happening or recurring.

23 BASIC CONCEPTS AND PRACTICAL STRATEGY OF ACCELERATED QUALITY IMPROVEMENT IN MANUFACTURING AND DESIGN

23.1 WHY ACCELERATED QUALITY IMPROVEMENT?

The followed text demonstrates the practical system which can help to rapidly find the reasons for low product quality, rapidly eliminate these reasons, and correct the manufacturing and design processes for quality improvement. This system was checked by the authors' experience of quality improvement during manufacturing for a short time[5].

In this chapter the authors pay attention to the quality problem, the factors which may cause a decrease in quality, and lastly, process the problem by constructing a high quality system in manufacturing, with an evaluation of the responsibility in each step, especially the role of management.

23.2 THE BASIC COMPONENTS OF CURRENT PRACTICAL QUALITY SYSTEMS

Modern manufacturing is very complicated and multi-sided.

There are many departments working together and all of them must finally reach one main purpose – to supply the client in the allotted time the desired product in quantity as well as quality.

In the current market the competition among producers is particularly keen.

Considering this, there are three main factors that are very important: arrival of their supply on time, its quality, and its quantity (Figure 4.2).

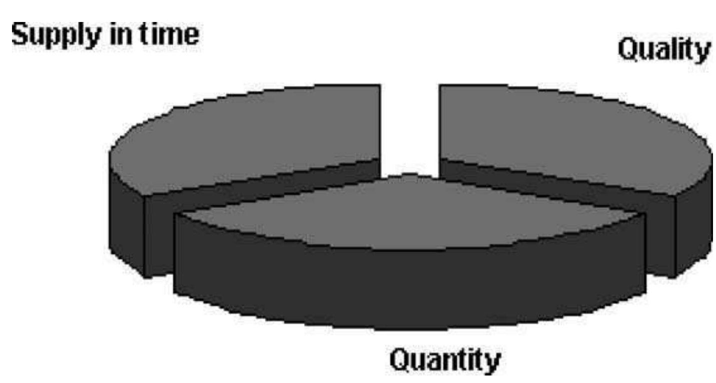


Figure 4.2 Three main equally important factors for Quality Systems of manufacturing companies.

For most of the production companies of analogous products the delivery of these on time has the greatest importance. There are always some alternative suppliers. The main problem is how to assure the earliest order date for supplying the prospective consumer with the needed product.

The problem of quality is of utmost importance. These days, early delivery isn't enough, it's also necessary that the product should be of high quality. Reliability as well as many other elements of quality have to be at a high level. There is also the shipment factor: the consumer wants to have a high quality product on time, and a complete, not a partial shipment.

In Figure 4. 3 one can see a graph of the distribution of the results of checking the product by the determinate characteristic. The horizontal red lines show the limit of maximal permissible divergences. The horizontal blue lines show the limit of desirable divergences of the obtained results.

We can also see in Figure 4.3 that some of the obtained results go beyond the limit of maximal permissible divergences. This shows that the control of quality is not being done in the desired time, and that subsequently the necessary correction of the parameters is not provided.

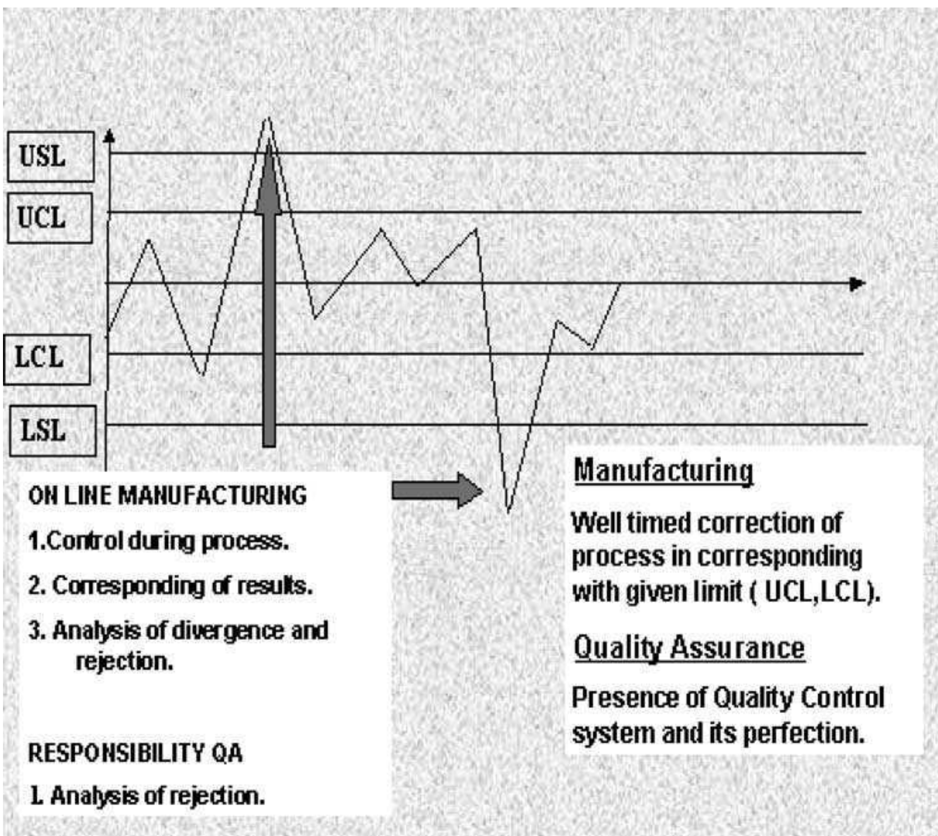


Figure 4.3 Graph of the distribution of the results of product checking:

Where:

UCL is Upper Control Limit;

LCL is Lower Control Limit;

USL is Upper Specification Limit;

LSL is Lower Specification Limit.

QA is Quality Assurance.

The responsibility for the provision of control checking, the checking of corresponding obtained results, and other necessary corrections and rejections are usually lies with the Production Department.

The responsibility for the development of an effective system of quality control and an analysis of its productive activities is usually lies in the Quality Assurance or similar Department. The analysis of divergences and rejects is provided by the interconnections between these (Quality Assurance and Production) departments.

In practice companies do not discriminate between the bellows to the Quality Assurance and the Quality Control departments. Moreover, the Quality Assurance Department is often involved with the problems pictured in Figure 4.2 exceeding the frames of maximum permissible divergences (USL and LSL). This is wrong. In the manufacturing process both the Quality Control Department and the workers who measure divergences must be responsible for the results.

A proper analysis of the reasons for divergences must be done by the Quality Assurance department together with Quality Control department, as well as engineering and technological management. The goal of analysis makes possible the transfer of manufacturing processes within the limits of UCL and LCL. A very important link in this process is the use of experience of companies advanced in this area.

Using a complex of the analysis of divergences, reasons for complaints, and the experience of advanced companies can aid in the improved results which are shown in Figure 4.4. One can see from this figure that it is essential to stay within narrow limits of maximal divergences.

This is possible if there is a developed system of quality control.

This usually happens in the large manufacturing companies, but not in small companies. For the middle companies the situation is between that of small and large companies.

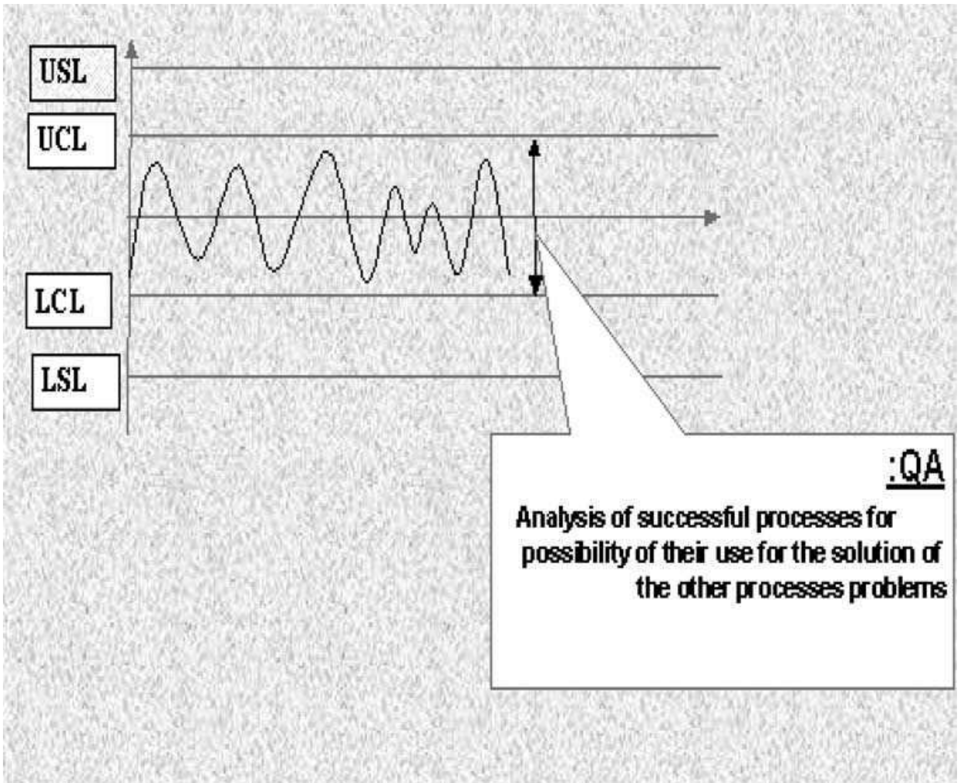


Figure 4. 4. Corrected responsibilities for product quality during manufacturing.

Therefore, the following recommendations for quality systems development are more helpful for middle and small companies which in a short time could be quite competitive in the market with the large companies (and need to obtain more consumers).

It does not mean that these recommendations might not be useful for large companies too.

23.3 ANALYZING THE CURRENT QUALITY SYSTEM

First, it is necessary to analyze the current quality, system which is shown in Figure 4.5. The process begins with obtaining orders from consumers and noting their specific requirements.

The order then proceeds to the designers (R&D Department).

After this step it is important to quickly finish the design process and to begin the manufacturing of the product (Figure 4.5 shows the designer's emphasis).

The manufacturing process begins after the design process is finished. After that the product goes to the quality control zone. In Figure 4.5 the quality control representative is like a baseball player who is about to catch the ball: usually only a small sample of the

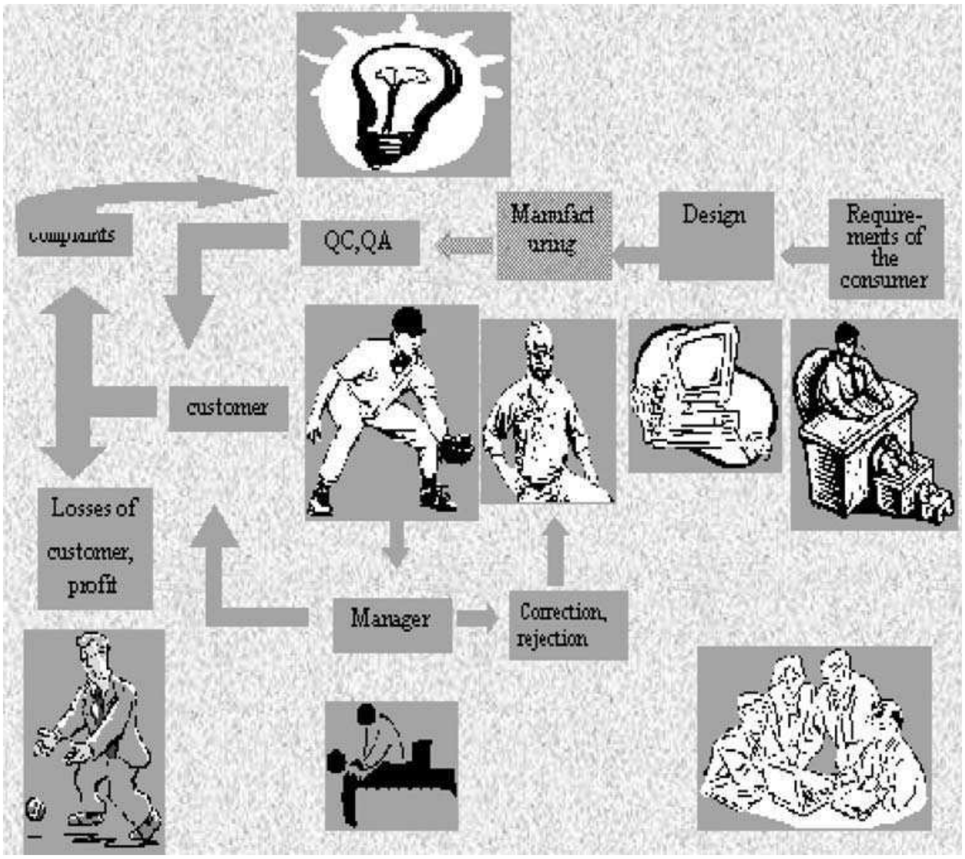


Figure 4.5 Often used current quality system in manufacturing companies

finished product goes to quality control. The results for all products that are ready to send to the customer are determined by using a small sample of the total as the checking control. This means it is possible to send a product as ordered directly to the consumers that includes parts of inferior quality.

As a result, there arises the problem of complaints from consumers and, therefore, losing the customers.

If during the quality control of a manufactured product one discovers a problem, this is passed on to the quality manager so he or she can either look for a solution to possible correct or reject these products. A responsible manager is shown in Figure 4.5 as an emergency helper: the process of problem solving is a highly critical one (the sheer numbers of problems, pressure stemming from the manufacturing management, responsibility to the consumer, etc.).

Therefore, problem solving is not always accurate.

There is only one advantage of the above quality system for manufacturing companies: the speed of going through all the steps. This "advantage" often has bad results: the use of the quality control service is very limited, which in the end makes it practically impossible to interrupt this service in order to find and eliminate quality problems early in the manufacturing process.

23. 4 THE BASIC CONCEPTS OF PRACTICAL QUALITY SYSTEM IMPROVEMENT

The above situation can be improved if the quality system is changed as shown in Figure 4. 6.

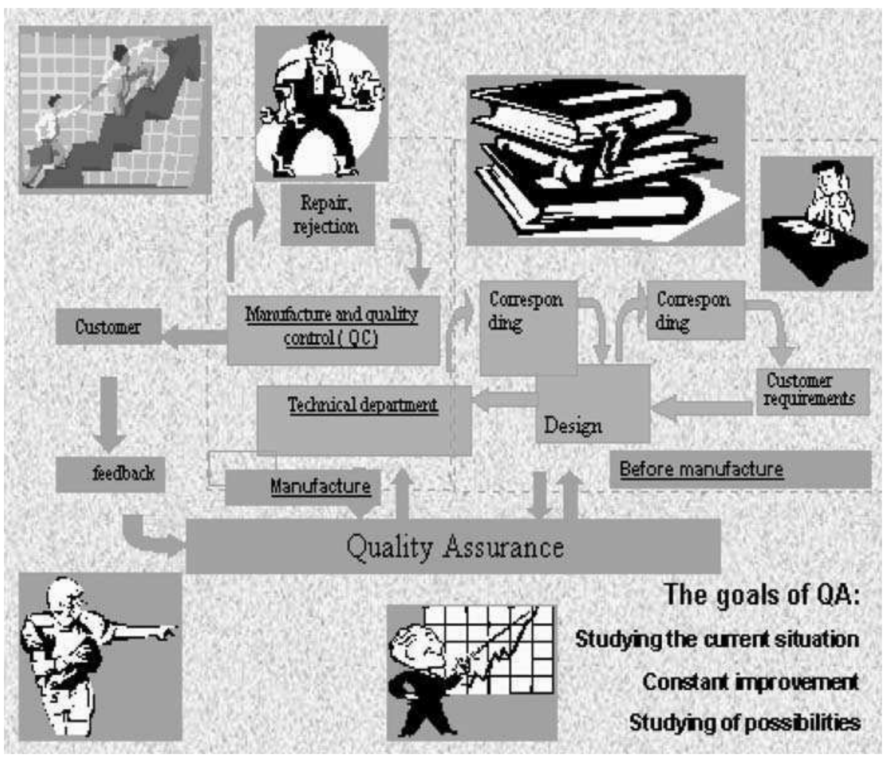


Figure 4. 6. The developed quality system in the manufacturing company.

What is the advantage of the new system over the current one?

First, there is the feedback of the customer's requirements to the Design department which can eliminate the possibility of misunderstanding during the design process.

Second, is the feedback between the Design department and the Technical department which makes possible a technical situation for comparison between what the company can do and the customer's requirements during the early stages of manufacturing, and also to estimate any necessary changes needed in the manufacturing technology (new technological solutions, equipment, changing the technological process, etc.).

In the developed system is important there is feedback between Technical department, the Manufacturing department, and the Quality Control department as well as direct contact with the client.

The above feedbacks from the beginning to the end of a complete process can help maximally eliminate a client's problems.

Whoever participates in the quality assurance service must pay particular attention to all the steps in design and manufacturing as well as obtaining information from the client after he or she has received and used the product.

The basic requirements for quality assurance service appear in Figure 4.6:

- Studying the current situation;

- Constant improvement;

- Studying the possibilities.

As was mentioned earlier, it is very important to establish and distribute responsibility for product quality at each step of the production process.

Figure 4. 7 shows two models of the quality system: current and recommended. One can easily evaluate the difference between them. The red dotted line shows the additional responsibilities of the Production department.

It is easy to see the above differences in all the steps, beginning with the checking of technology, standards, etc. to participation in the material review board (MRB) process, which form the solution responsible for the process of disclosure of divergences in requirement, and, finally, are involved in the research and analysis of complaints.

As practice shows, transfer from one system to another quickly influences on the increase selling volume and, as a result, adds to the competitiveness of the company in the market.

The formal multidisciplinary panel of peers established to perform the material review.

That is to review, evaluate and either fix, or else dispose of, specific noncomforming suppliers of services.

The recommended			Current situation		
QA	QC	manufacture	QA	Manufacture, QC	manufacture
Technology			**Technology**		
Determination of standards Checking of technology System of control	Checking of execution Standards execution	Checking of technology Standard execution	Determination of standards Checking of technology	Checking of technology Standards	Execution
Divergence from the requirements			**Divergence from requirements**		
Analysis the reasons of divergencies The necessary solutions and conclusions	MRB Taking the decision Documentation	Disclosure MRB Permissions Taken a decision	Disclosure Permissions Taken a decision	Disclosure MRB??? Permissions Taken a decision	Corrections
Complaints			**Complaints**		
Investigations Conclusion Prediction of the future actions	Participation in all processes Investigations Conclusion	Measurements Checking Actions for future	Measurements Investigations Conclusions	Measurements Checking	Actions for the future

Figure 4. 7. The difference between the current and the proposed situation in quality systems of the manufacturing companies.

23. 5 THE BASIC FUNCTIONS OF THE QUALITY ASSURANCE DEPARTMENT IN DEVELOPING THE QUALITY SYSTEM

What is the basic function of the QA department in the New Quality System?

There are nine general functions:

1. Study and analysis of manufacturing rejects for their decreasing frequency complaints analysis, divergences from given parameters (sizes) during the manufacturing process, analysis and development of the manufacturing process for quality improvement.

2. Development of the quality system, standardization system, and system of quality control during manufacture of the final product.

3. Analysis of the level of certification of quality control staff.

4. Participation in all technological changes of manufacturing processes, certification of these changes, complex testing on different steps of manufacturing process.

5. Initiative in constant updating of the manufacturing process: increasing quality plus input of the necessary documentation.

6. Use of statistical programs of quality analysis and new statistical methods.

7. Development of the system to input the new high quality product.

8. Studying statistical data using the system R & R.

9. Constant use in the company of the corresponding international standards ISO, IEC, and QS.

Successful use of the above functions is the beginning of the development of a modern quality system in the company.

Finally, the well being of each company can be evaluated by the presence of profit and its amount.

The best way to evaluate losses is to understand how much has been won return than lost the company wins because it uses modern technology, has successful experience of well being processes, corrects the product where there are divergences from given sizes and decreases the number of rejects that are impossible to correct.

An important obstacle to overcome is the mental attitude of workers who think that because things had been working over a long period of time, it wasn't necessary to make any corrections.

It is necessary to know that the important goal of quality control is the profit problem.

The support and understanding of top management are needed to emphasize the importance of the effects of poor quality which result from deviating from given standards as well as to provide appropriate technical cooperation from the manager of quality control, and thus to each worker.

And finally to know how this results in decreasing expenses during the manufacturing process. This can only succeed if top management is involved in the quality control process and has a through understanding of the above procedures.

Japanese practice demonstrates the importance of this factor in obtaining a high quality product.

23. 6 THE BASIC STEPS FOR SUFFICIENT PRACTICAL QUALITY SYSTEMS

Let's take as an example a given situation and follow the process from a disclosure of disparity from the standards required to the end result, which includes an analysis of the complete process. The model of the system includes six basic steps of quality control.

First step: evaluation of disparity/problem describes what has happened and the evaluation for not taking into consideration the consumer's requirement.

In this step, the basic data for a particular product are established: item, number of product produced, time and place when the problem occurred.

Second step: description of the first actions.

Usually when there is a disparity during the beginning steps one can provide the necessary actions to give the possibility that the manufacturing process can continue.

As soon as a problem appears, it is critical that the manufacturing process is stopped.

Then it is necessary to obtain emergency help and to find rapidly the correct solution for this problem. Obtaining this solution usually requires a short time, however the solution may be the wrong one, therefore it is recommended that the emergency situation be disregarded.

Third step: correction of disparity.

The typical reaction is to briefly evaluate what has happened and to make a correction. Practical experience shows that it isn't possible to make a sound evaluation of every divergence. For example, if during the checking of the manufacturing process one finds a paint defect on the product, the first reaction will be to correct this defect. Another response would be to simply reject this product for this particular defect. Ultimately, a high level of responsible professionals must solve this problem.

What is the difference between a rework defect and corrective actions?

For example, you buy a new car and after one week find that the engine is leaking oil.

Your initial action will be to go to the guarantee maintenance station to eliminate the problem. In most cases, this problem will be eliminated at the maintenance station. This is rework defect. However, what would happened if 10,000 drivers had the same problem with the same model of car and everybody run to the maintenance station? In this case, the distributor would immediately send these complaints to the car's producer with a detailed description of the problem. As a result, we can be sure with high probability that the car's producer will work on corrective action.

Fourth step: analysis of disparity.

This means a definition of the basis of the problem. At this point, it is necessary to understand the basic reasons leading to this disparity and on the basic of this analysis to propose a solution for eliminating this problem in the future. This analysis is expensive, because more time is spent on this in comparison with all the previous steps. There is still no guarantee that after this analysis the basic cause has been eliminated. In this case the problem is called a "black hole" and remains as such awaiting a final solution .

Usually the causes of definition are very complicated and require in depth knowledge of the manufacturing process, engineering design, quality control, etc. Therefore, the solution to the above problem must be made by only the best professionals. Sometime, consultants are employed for this purpose. The above analysis is for custom products and for most important customers.

Fifth step: corrective action/preventive action.

There are definite preventive actions to be taken as a result of the disparity analysis by the manufacturer in general as well as for specific problems. For this purpose, we recommend is using statistical techniques (for example, Paretto method) for better analysis of the reasons, which leads to a quality problem solution.

Effective corrective actions and preventive actions are a critical link to the whole process for controlling problems of disparity and divergences for each particular company.

Sixth step: the final disparity of the problems.

Can be analyzed at the conclusion of determining the effectiveness of the corrective actions and preventive actions which are the positive results of actual usage by the customer.

It is important to provide a periodical analysis to compare a concluded disparity accidents open disparity accidents for the purpose of improving the level of the analysis system as well as the control of disparity and whatever problems arise during actual use. The result is constant improvement.

24 IMPLEMENTATION OF ACCELERATED QUALITY IMPROVEMENT

24. 1 THE MAIN DIRECTION OF PRACTICAL QUALITY IMPROVEMENT DURING MANUFACTURE

The following strategy of problem solving is acceptable for automotive, aerospace, aircraft, off-highway, farm machinery, and other areas of industry, including complete machines as well as their components.

In addition to the above specifics of modern manufacturing, the main way to solve the problem is by a complex analysis of factors that influence product quality[5].

In other words, the "brain factor" of personnel is the most important factor in the each type of manufacturing. But many industrial companies do not take into account how important this factor is and as a result, they lose product quality and finally money.

24.2 COMPLEX ANALYSIS OF THE FACTORS THAT INFLUENCE PRODUCT QUALITY

When the company has a quality problem and cannot easy find a way for solve it, a complex analysis[5] of the reasons for insufficient quality of the product is very important.

"Complex" includes all areas of design, technology, equipment used for producing the product, the raw materials, the system of quality control, etc. (Figures 4. 8 and 4.9).

The specific point of this chapter is to show the analysis process, using the "brain factor"; for different types of product the content of factors of this scheme may be different, but the basic concepts are similar.

Use of this schemes (Figures 4.8 and 4.9) can help to find the reasons for complaints and to eliminate them rapidly with subsequent improvement of product quality.

Moreover, this factor is important for rapidly developing and improving product quality. This directly relates to successful accelerated testing.

For aids one can use specific software.

The basic advantage of this chapter is the use of engineering technology, and physical and chemical analyses to find the reasons for complaints send to the producer of the final product.

This includes products of components and raw material for rapid finding and eliminating of these causes.

How can this be done?

First, it is necessary to obtain the information about any changes by the producer of the final

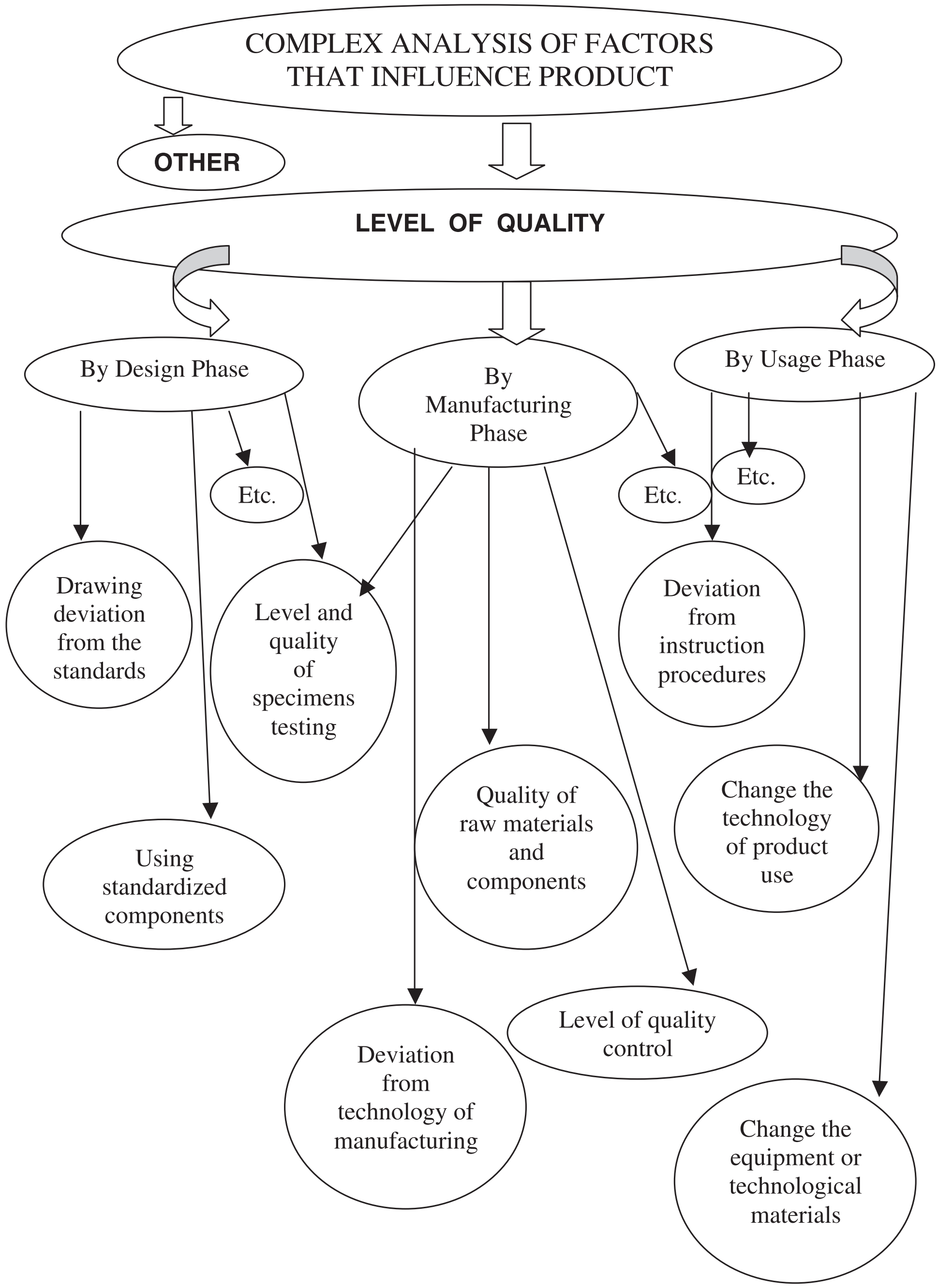


Figure 4.8 The scheme of complex analysis of factors that influence product quality during design, manufacturing, and usage.

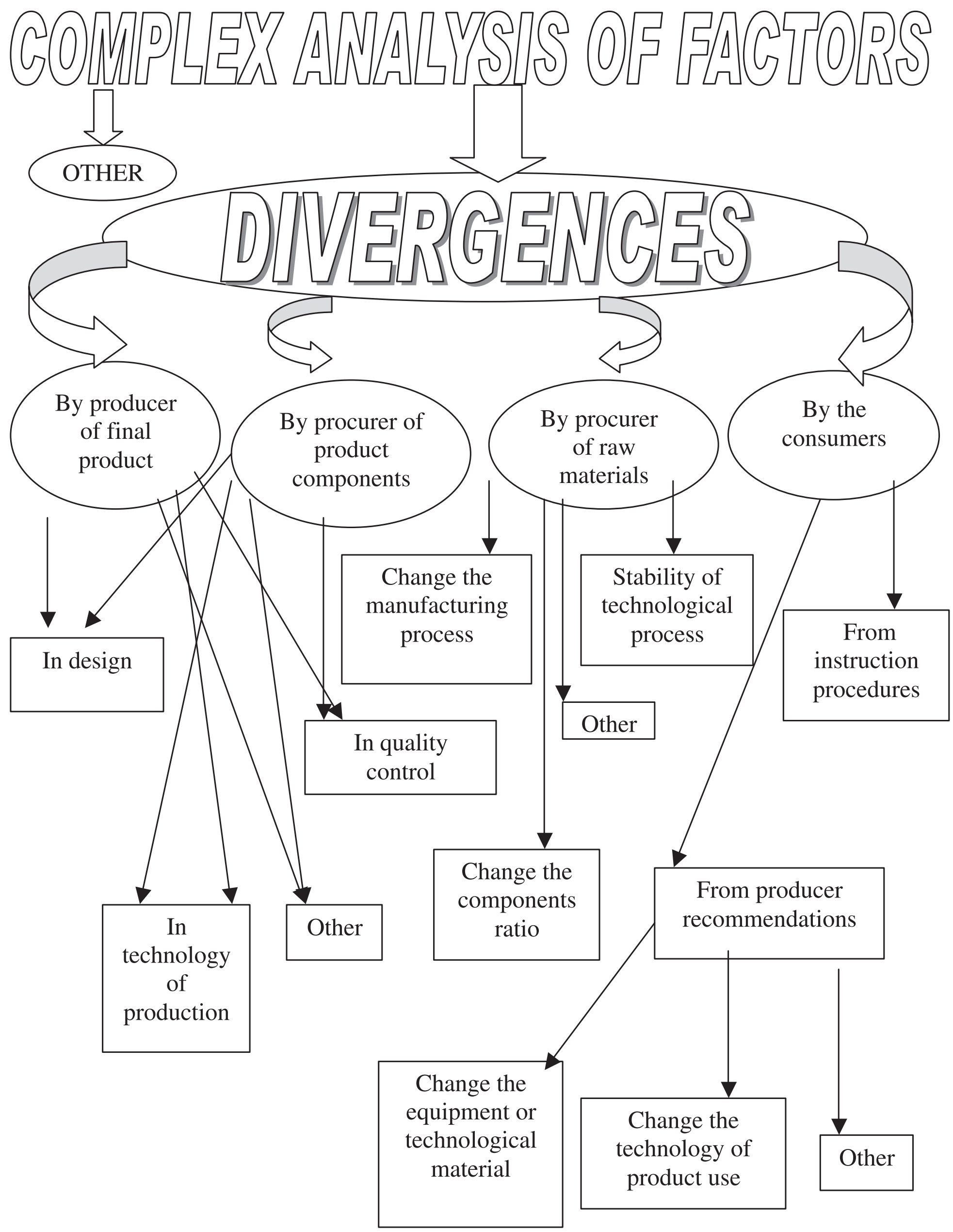


Figure 4. 9 The scheme of complex analysis of factors that influence product quality.

product, by the components producer, by the procurer of raw materials, and by the customer (regimen of work) where products have failed within the warranty period[1,2,3,4].

Let us analyze the reasons for complaints about the tools. The manufacturing company received notices from the customers that in second year the number of claims for replacement increased by a factor of 3 in comparison with the same months in first (previous) year (Table 4. 1 and Table 4. 2).

Table 4. 1 Comparison number of complaints.

July - December, first year	July - December, second year
14	39

Table 4. 2 Data on claims for replacement.

July - December, first year		July - December, second year	
Not justified	Justified	Not justified	Justified
4	14	12	39
Total	18	Total	51

We searched, studied and analyzed the reasons for this situation. As a result, seven possible reasons were found (Figures 4.10 and 4.11).

As we can see from Figure 4.10 and Figure 4.11, the main reason for many justified complaints (16, second year) was a design problem. A new product was manufactured after a brief time, ignoring testing of product quality during the design. After receiving many complaints the following reasons the product low quality were found:

1. The product, which was made from very firm but fragile material, ended with a threaded joint, which was twisted in a steel holder and centered in this holder with a very accurate cone. This was executed without a chamfer at the beginning of the threaded joint.

As a result, the frequent closing and opening of the joint, wear on the cone of steel holder occurred more rapidly than on the detail cone in one at the same place.

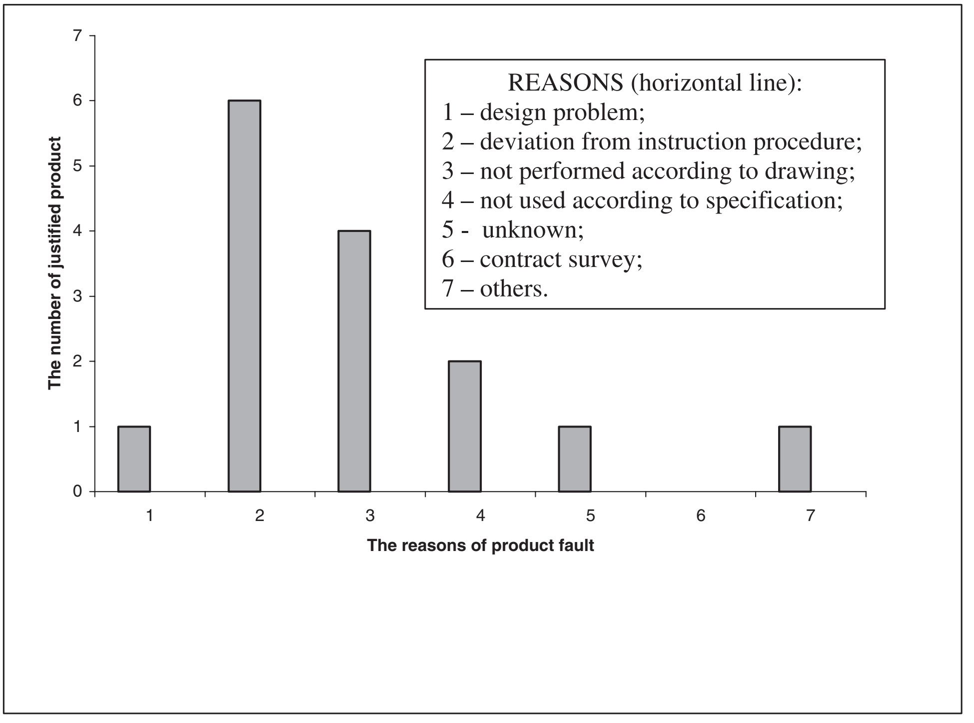


Figure 4.10 The number of reasons for production faults in justified complaints (first year).

The divergence from the center after 20 - 30 closings reached 0.03 mm which is greater than required allowance for this product.

1. The divergence from the center of the cone led to a divergence in the length of almost 10 mm at the beginning of the thread inside the holder. As a result, there was a direct power contact between two materials resulting in the breaking of the product thread. In addition, extraction of that part of thread which was left in the holder would be a very complicated process, eliminating the possibility for reuse of the holder. Therefore, it was doubly detrimental: for the whole product and the holder.

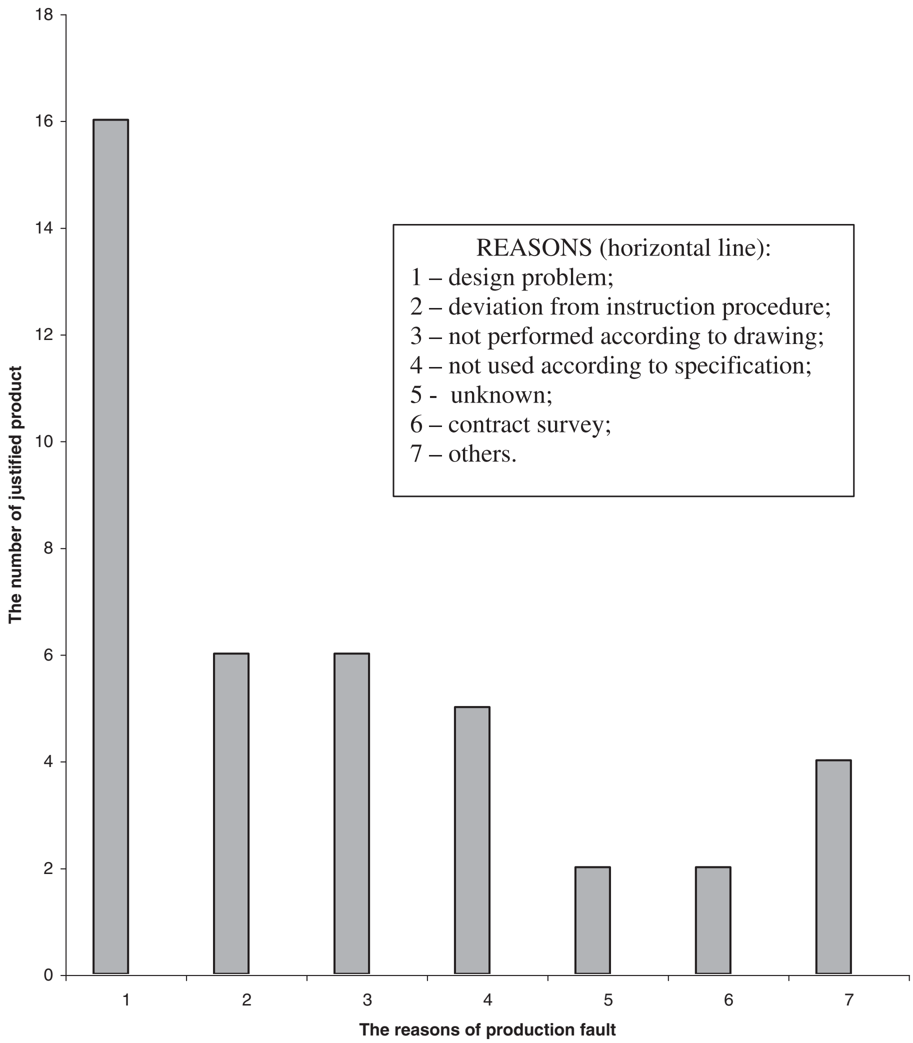


Figure 4. 11 The reasons for production faults in justified complaints (second year).

Can one find reasons for these problems? First, the above situation concerning design problems continued for a long time without finding the reasons, because an analysis of the situation was not provided. Each time a complaint of failure was received another sample(s) was sent to the customer to replace the faulty specimen, indicating each time the reason as "unknown". This situation continued until the company found a high level professional who could analyze the reasons for rapid degradation or failures. This professional investigated and in a short time established the causes for the above failures and solved the problem.

How was this done? First, he established that failure occurred at the same location each time (independent groups of the material or when it was produced).

Second, the material was analyzed to determine the quality characteristics.

This test also showed there was no problem with the quality of the material. The next test was to check the technological process to see if any step of the manufacturing process had been changed. In this case, any change (small or large) must be checked and substantiated. It was established that no problems existed in this area. Obviously the cause of the failure could be faulty design. Some experiments and measurements were taken. As a result, it was determined that there were two basic reasons, that led to failure of the product.

The second important reason for justified complaints (6, second year) was deviation from the instruction procedure (see Figures 4. 10 and 4. 11). There are many examples in this area. Often the same problems are repeated. Let us take an example from a particular product. An often repeated problem for example is inferior quality of the material from which the manufacturing companies produce the product.

24.3 PROCEDURE OF THE PRACTICAL COMPLEX ANALYSIS OF THESE FACTORS IN AN ACTUAL EXAMPLE

Often the producer of the material is also part of the same manufacturing company. The following example falls into this category. The procurer of the material for the pre-mentioned tool specializes in producing different products from any material.

The procurer of the raw material produces the material in different forms, corresponding with technical requirements.

One of the most important characteristics of the material is that its magnetic attribute causes it to be fragile. Even the least deviation from its lowest limit induces heightened fragility of the product. The process for obtaining the above material is very complicated. First, one must obtain a powdered mixture of a complicated consistency, after which the above mixture is pressed into a special mold. Then the mold is placed in a special form, then in a special furnace to bake. There is a gauge to regulate temperature and pressure.

The furnace is very expensive and the baking process is long (in addition the expenses for the electricity and rapid wear of equipment must be considered). Therefore, it is very important to make maximum use of the furnace space. But if the furnace is filled up with hundreds or thousands of products, there are some zones which diverge from others in certain characteristic ways (speed of heating, temperature, etc.). As a result, instead of uniformity there is a difference in the characteristics of various samples which is dependent on their location in the furnace.

Even if there are few quality problems with the product over several years, these problems may arise when the manufacturer begins to produce new products. For example, in the third year in one actual manufacturing company a sharp decrease of short tool life was observed.

The number of complaints from customers for the above reason was increased. It must be emphasized, that this situation relates to different types of product. The specifics of the situation were that the above complaints related to products that earlier did not have this problem.

The reasons for this situation were analyzed. It was determined that the failures could be separated into three groups of product:

- products which failed after a very short working period (0.1 - 5 % of the warranty period);

- products which failed after a short working period (5 - 50 % of the warranty period);

- products with failures after 50% of the warranty period.

A separate analysis was provided for each of the above groups.

How to analyze the basic factors?

They can be analyzed in a parallel or sequential mode. Depending on the companies' possibilities; the parallel method can be done in a shorter time, but it can only be done as part of the work, requires backup, and needs more people for checking.

With sequential analysis it is better to begin by obtaining information from the final product producer, because this doesn't require trips to other companies and can be accomplished in a short time. To achieve this goal, product divergences have to be analyzed (divergences from required sizes, mechanical damages of the product, changes of equipment, etc.) including design, technology of manufacturing, quality control, etc.

The same type of analysis has to be provided by the procurer of product components.

It is necessary to obtain information about the regimen of work undertaken by the customers (divergences from the producer recommendations), for example:

- did the customer deviate from the given directions for usage?

- does the technology of the product allow for changes (including the type of subproduct that was used)?

- has the equipment or technological material which comes in contact with the product changed during use?

- others problems that may arise during the use of this equipment.

After obtaining the above information, a percentage (for example 10%) of the complaints must be dismissed for this particular reason, because the product was used according to the producer's recommendations.

In some of these cases, most of the products used in these regimens were heavier (for example, from 15 - 20% to 100% or more) than was recommended.

The reasons for remaining 90% (in the above example) of complaints depended on the regimen of work by the customers. A complex analysis has to be made of these reasons.

Also a complex analysis has to be made by the raw material procurer. For example, it may be ascertained that the procurer of part of the raw material changed several months ago.

The initial material must then be tested (by structural and chemical analysis) which usually makes possible 92 - 95% probability in determining the material's quality. In one company the results of the above testing showed that the percentage of chemical components in the external layer of material was 1.5 times more than the maximum permissible value. This parameter is very important. The percentage of the above chemical component inside the material is very important because this component is a connecting element of material. The even distribution of this component in the initial material also very important.

The component content is determined by accurate mathematical calculations and confirmed with subsequent precise weighing. Then the mixture is mixed thoroughly, obtaining a homogeneous mass which then is pressed in special press forms, and then baked in special stoves at a specific temperature.

As long as the above component content on the surface is greater than the norm, it has a tendency during baking to move from the inside to the outside of the layer, so the component's content was tested inside the layer. The results were determined and confirmed with the help of the next test. The low component level inside makes the initial material too hard and fragile, while at the same time the material on the surface stays soft and flexible.

This problem cannot be solved by the plant which produces the material, because the loadings at this time are only 10 - 15% of the loadings that are required during the work-up of the final product. The input test is provided usually with 5% of received raw material, and is determined at random.

Therefore, the level of quality control at the plant which provides the raw material can seriously influence the quality of the final product.

The above example demonstrates how complex analysis of the reasons for low quality of the product offers the possibility for rapidly determining and then rapidly improving and controlling the manufacturing process, not only by the final product producer, but also by the procurers of raw material and components for the final product.

The next example which relates to rapid failures of the product is the problem involving the specifics of production of the initial material with a diameter of more than 20 mm.

The problem occurs even with the use of modern equipment in which serious problems develop when trying to obtain high quality products where special pressure is required.

Therefore, even today the method of extrusion is used to prepare half-finished products from the above material.

Two typical problems of this method are as follows: heating of procurement (the length of procurement takes several times longer for the pressed measure which then has to be cut to the necessary length), and inside cracks which arise in the extrusion process. The inside cracks cause problems with large diameter tools, and there are many customer complaints about this.

It is much easier and cheaper to determine surface cracks than interior ones. Very expensive equipment is required for non-destructive testing to determine whether there are interior cracks.

Therefore, not only small manufacturing, but also middle companies find that this equipment is too expensive.

However, the authors' experience shows the solution of this problem during a single experiment. Suddenly one of the half-finished products fell down and cracked. The crack was observed under a microscope which revealed two additional cracks of lengths 3mm and 7 mm from the original crack. The testing results showed interior cracks. Testing was done on 10 more half-finished products from the same group using the same method. One of the half-finished products was broken and inside microcracks were found. Then nine half-finished products were retested by standard ordinary methods.

Three of these were tested under conditions corresponding to the client's requirements, and as a result, all three passed the warranty period without failures. The last six were sent to other clients. The result of their work was also positive. The above is one more practical example of how a complex approach to a system of determining and improving a product's quality can help often rapidly to find and accept a non-standard solution as a non-standard conception for solving quality problems.

As was mentioned, the third group consists of the product with failures after 50% of the warranty period.

The specific characteristics for the failures of the product from described material in approximately of 50 % of cases is chipping, i.e. the possibility of forming small dents along the surface of tools which arise in the polishing process. The size of these dents may vary from 0.002 to 0.006 mm along the surface.

The essence of the problem is that where the dents occur there are microcracks which during the work period increase very rapidly. As a result, crumbling of the material takes place.

The surface stays toothed (the size of the crumbling parts may be approximately 0.5 mm or more) which influences the processing quality and decreases time to failure of the product.

This problem occurred most often in the particular part of the processed tools of the procuring company which is used for processing the small diameter.

So, the essence of the problem was determined. The solution of the above problem could help to improve the product quality.

First, it was necessary to determine the divergence in the processing program (these programs are accompanied by equipment from the manufacturing company, so each manufacturing company has its own program).

It was established during the process analysis that when there was no shipping process, additional processing was provided for only the last 0.2 mm of the product length. The speed of this process means it takes 3 - 3.5 times longer than usual for this process. In this way it overcomes the problems of dents and microcracks.

After follow-up checking of the products by the user, which revealed as a result the true determination and removal of the problem, the service life of the product was doubled.

But during the above research which was provided by the engineering system of quality control, the following idea was created. This was to make some specimens of the product using improved technology (double passage and honing of the surface with a radius 0.005 mm).

Comparative testing was provided on both the regular and improved product. The results of testing showed:

a) the product without honing worked a standard time of 85 minutes without divergence;

b) the product with honing worked for the same 85 minutes, but wear on the cutting edge was 5 times less than in a).

The testing of variant b) was continued. During the next 60 minutes the product worked normally, with practically no wear. During the next 15 minutes the wear was within the limits. Then wear increased and the test was stopped.

The final result was that the product with honing worked almost twice as long as the regular product.

The basic results of the above approach: the creative work of quality control as well as accelerated testing of the product[5] offer the possibility of not only eliminating the problem of quality decrease, but also find a way to increase the product's service life compared to the standard.

The process of quality improvement is very complicated. It is connected with manufacturing analysis, determination of accurate reasons for failures and divergences from certain parameters.

The reasons are involved with the quality and characteristics of the raw materials used, and are specific for each manufacturer regardless specific type of the final product.

Let us analyze, using the example of obtaining a product from the described material; the system of quality improvement begins from the moment a specific quality problem arises to the determination of the reasons for this problem, followed by elimination of these reasons, or minimizing the influence on the product's quality.

24. 4 GENERALIZED EXAMPLE OF THE CLASSIFICATION OF THE CHARACTERISCTICS WHICH MAY LEAD TO A DEFECTIVE PRODUCT

Below is shown a generalized example of the classification of the characteristics which may lead to a defective product. One can see from the tables and graphs that there are three basic reasons for a defective product:

1. The basic causes of waste are divergences from the required sizes.

2. Mechanical damages of the product.

3. Equipment used by the manufacturer.

Let us consider the first reason – deviation from the standard sizes. The number of controlled sizes varies from 30 to 60, therefore the reasons for deviations are both varied and numerous. For example, the reasons for outer diameter deviations are different from the reasons for tolerance in the heating or run-out, etc. For each specific process of analysis there are specific methods for problem solving. Let us demonstrate using Table 4.3, analyzing the generalized characteristics of the following example.

We can see from the figures that are several months there is a constant tendency for decreasing the percentage of waste by reason of the deviation from the given parameters.

These results are taken from daily and painstaking work which is related to the true connection of the characteristics to the reasons for this characteristic deviation.

Let us consider the second reason - mechanical damage to the product. The damage can be caused by robots and mechanisms (probably 30% of common damage), and 70% by staff during different steps of the production where presently they cannot be replaced by robots and other mechanisms.

At first sight, it appears from Table 4.3 that there is no essential change or improvement in the situation over the last several months, but this is not true because at the beginning of the third year there were more rigid requirements for possible damage in most of the production steps. If the above event did not occur, the waste percentage could have increased approximately by 30%. This event was used for more competitive product production, and as a result, the productivity of the company was increased by 20%, because new orders were obtained for the product.

If total defects (2 – 4% of whole product) consist of 100%, the distribution of these two types of defects can be seen from Table 4. 3.

Table 4.3 Percentage of defects during the time.

Period	Mechanical damage (%)	Divergence from required size (%)
Average for first year	63	37
December, second year	70	30
January, third year	50	50

Table 4.3 (continuation) Percentage of defects during the time.

February, third year	66	34
March, third year	61	39
April, third year	65	35
May, third year	68	32

The improvement in quality was provided without increasing the required number of people and without new apparatus for quality control. These increases were made possible because of the new system of quality control during the manufacturing process.

The essence of the new system is that the results of tests were entered into the computer with the name of the person who was responsible for the particular operation. This information allowed each level of manager or engineer to familiarize him or herself with the test results during any period of time whatsoever.

It is very easy for any person in the quality control service (quality manager, quality engineer, or quality technician, etc.) to be familiar with the last step of production (usually they check from 3% to 5% of the product) and to understand how the quality of the product corresponds to the requirements. The personal responsibility of workers involved in the manufacturing process, ensures a practical possibility of obtaining a high quality product in a short time without additional expenses.

Special attention was given to the matter through careful study of the technological process as well as consideration of the professional level of the employees during the investigation of the connection between different product characteristics and the problems of quality control.

Of particular importance is how well prepared and informed the workers are. The goal is to increase the professional skill of the employees.

One can see from Table 4.4 the causes that have an influence on the quality of the product, also that special attention was needed to improve equipment for the tooling in the production of a new group of the product (SET – UP). For this reason, the average index in the second year was 25% and in addition to this in February and April of the third year there were considerable increases in the new product production that led to an increase waste. The reason for the decrease in the percentage of waste in the SET – UP step was the increase in the professional level of the workers as well as of the wider use of waste products in providing the SET - UP for others groups of the products whenever possible.

Table 4. 4 Reasons which influence product quality.

Period of time	Faulty handing (%)	Pieces for SET – UP (%)	Amortization in manner (%)
Average for the first year	60	16	14
December, second year	57	14	13
January, third year	55	13	10
February, third year	55	13	10
March, third year	51	12	9
April, third year	50	11	8
May, third year	47	9	7

We also have to take into account that the mechanical damages decrease. The average index for the second year was 3% higher (2.9% instead 5.7%) than the average index of damage for the first 5 months of the third year.

Let us consider the third basic reason, which is the wear of the manufacturing equipment.

As a result, there is a deviation of the product from the required size. Time is required to re-tool during a critical moment before the tool wears out, so this decision depends on the operator's professional skill.

Table 4.5 shows the trend toward decreasing the waste. This trend also shows that the research for finding the reasons for waste and the accelerated elimination of them is valid.

The complex approach in this example also shows how effective it is for the accelerated improvement of quality at a minimum of expense.

Table 4. 5 The waste produced from wear.

Period	Average, second year	December second year	January third year	February third year	March third year	April third year	May third year
Waste, %	5.7	3.9	3.6	2.6	2.5	2.5	2.3

It is important to consider the costs of rejected products. Figure 4.12 shows an example of the costs of rejected actual products during the fourth year.

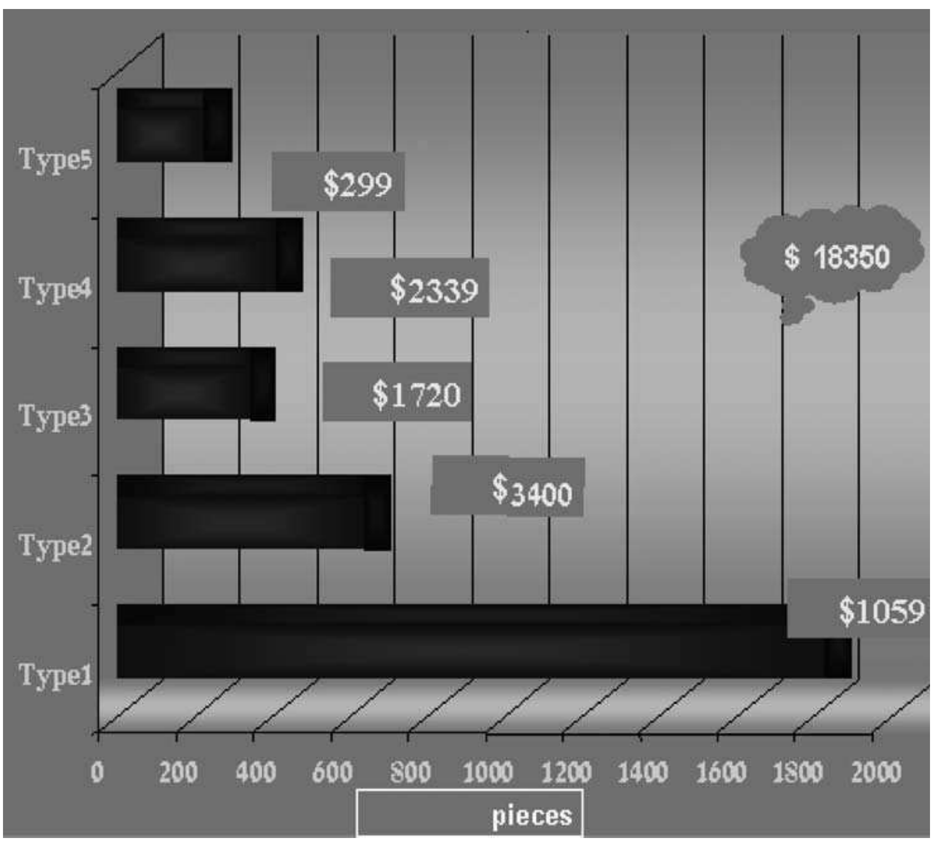


Figure 4.12 The costs of six types of rejected products during quality control (horizontal line shows the number of rejected products).

24. 5 TOTAL RESULT OF USE OF THE COMPLEX ANALYSIS

Figures 4.13 and 4.14 show the total result of using the above complex analysis of the reasons for decreasing product quality and work on elimination of these reasons.

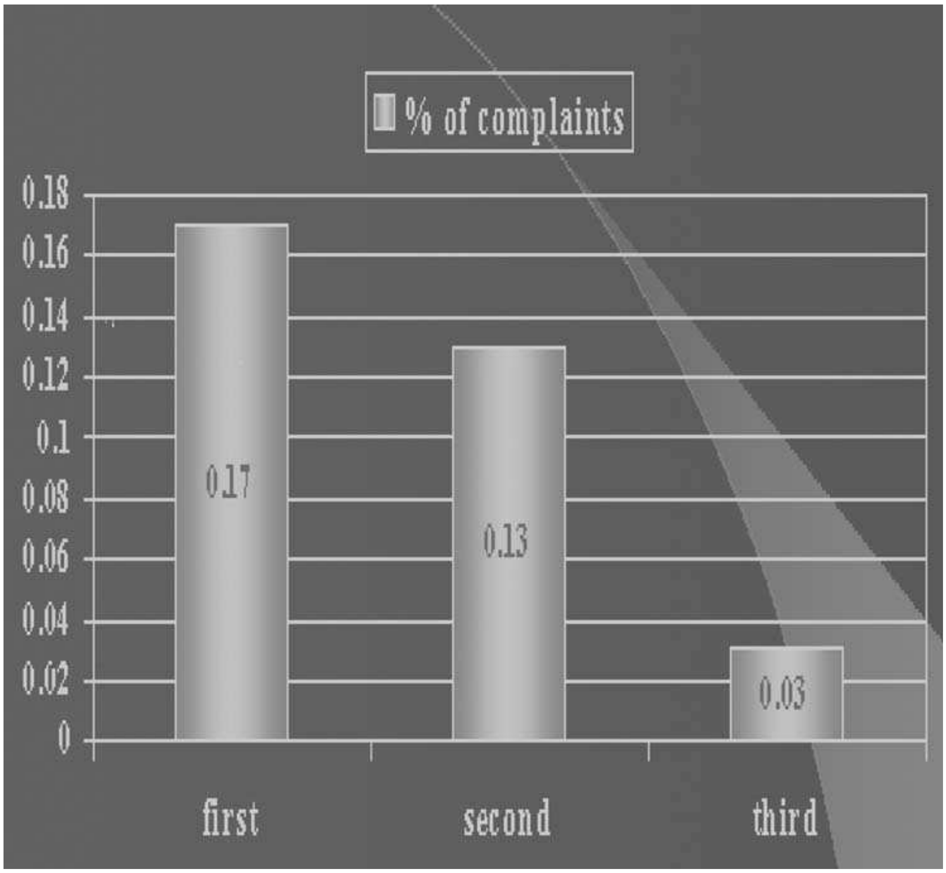
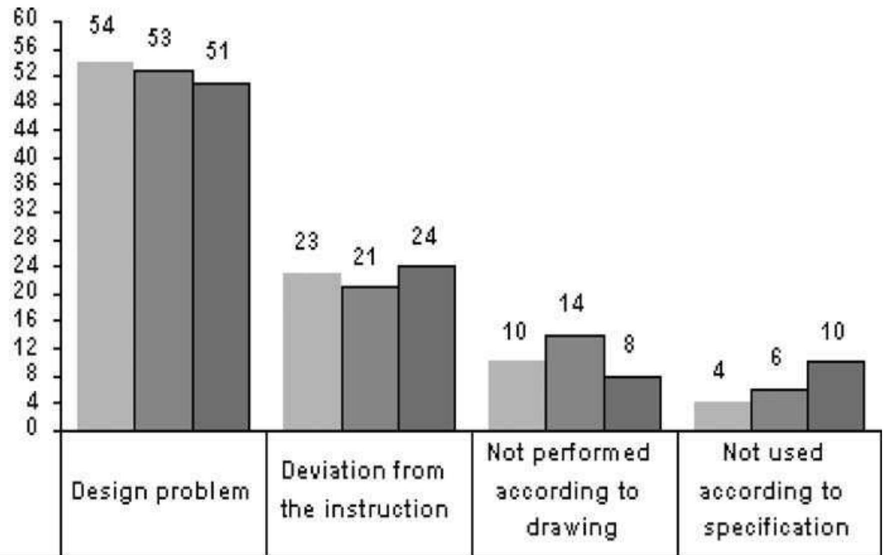


Figure 4.13 Dynamic of complaints for 3 years.

Comparison of the complaints to find a reason over these three years (Figure 4.14 and Table 4.6) shows that the basic reason was design problems, the second reason was deviation from the instruction procedure, and the third basic reason was "not performed according to drawing". Most of design problems in the third year (51%) of the complaints are related to the product that was produced earlier, but sold during the third year also.

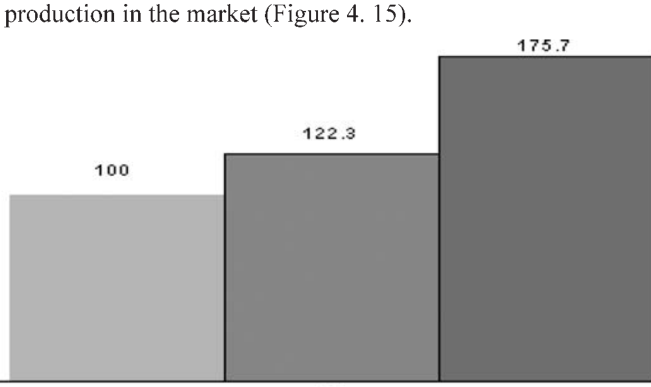


	Design problem	Deviation from the instruction	Not performed according to drawing	Not used according to specification
first	54	23	10	4
second	53	21	14	6
third	51	24	8	10

Figure 4.14 Comparison of the complaints to find a reason over three years.

24. 6 PRACTICAL ACCELERATED QUALITY IMPROVEMENT AND ESTABLISHMENT OF THE COMPANY'S SITUATION IN THE MARKET

As a result of the above, there was an increase in product sales through improving the reputation of the production in the market (Figure 4. 15).



first	100
second	122.3
third	175.7

Figure 4.15 Increase in sales for three years.

These figures show how effective the complex analysis and establishment the reasons for complaints were for accelerated improvement of product quality during manufacturing.

So, the process for final quality improvement (Figure 4. 15) by the producer is connected to the quality and the characteristics of the raw materials used, improvement in the components' quality, improvement in products used by the customers and those which are specific for each manufacturer, independent of the special type of the final product.

Table 4.6 Comparison of complaints by reason.

REASONS	Number of complaints first	 second	 third
1. Design problems	1	16	1
2. Deviation from the instruction procedure	6	6	2
3. Not performing according to drawing	4	6	2
4. Not used according to specification	2	5	3
5. Contact survey	-	2	1
6. Others	1	4	-
TOTAL	14	39	9

Table 4.7 shows the increase in actual product sales from the third year to the fourth year for two types of actual product, as a result of using the above complex approach to quality improvement.

Table 4.7 Increasing the actual product (two types) sales as a result of the above described complex system of quality improvement.

Year	Product (pcs), second quarter	
	First type of product	Second type of product
Third	23,030	77,201
Fourth	55,680	108,829

This complex approach is shown in Figure 4.16.

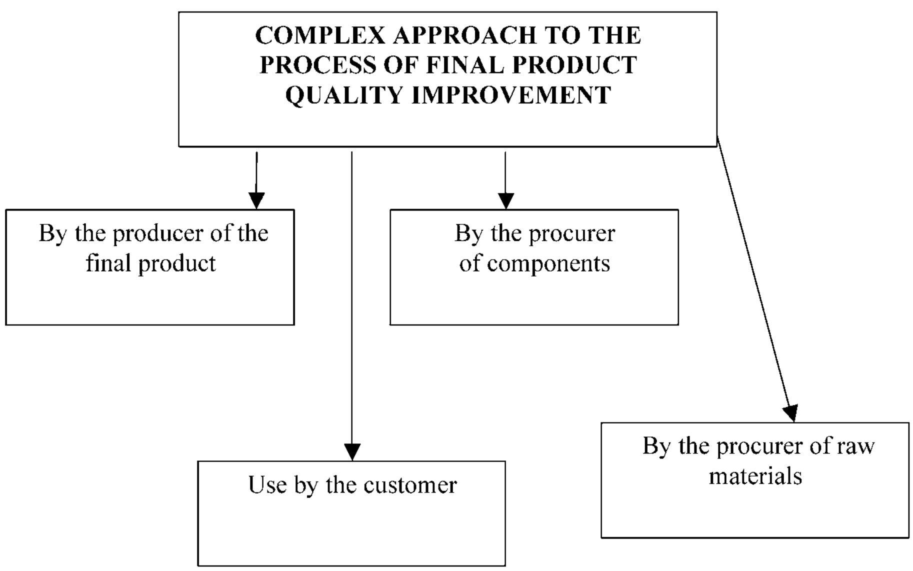


Figure 4. 16 Process of the final product quality improvement.

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CHAPTER 5. BASIC CONCEPTS OF SAFETY RISK ASSESSMENT

26 GLOSSARY AND TERMS

The following Glossary and Terms relates to all chapters of the book. In ECSS "Glossary of Terms", the International Electrotechnical Dictionary, and the Oxford English Dictionary as well as ISO/IEC Standard for Software Life Cycle Processes-Risk Management, and other[26, 27, 28, 30, 31] these terms are defined as follows:

Acceptance: The act of an authorized representative of the customer by which the customer for itself, or as an agent of another party, accepts ownership of existing and specified products tendered, or confirms satisfactory performance of specific services, as partial or complete performance of the contract on the part of the supplier.

Accident: An undesired event arising from operation of any project-specific items which result in:

a. human death or injury;

b. loss of, or damage to, project hardware, software or facilities which could then affect the accomplishment of the mission;

c. loss of, or damage to, public or private property; or detrimental effects on the environment.

Acceptance of risk: Decision to cope with consequences, should a risk scenario materialize.

Alert: The formal notification to users, informing them of failures or nonconformance's of items, already released for use or not, which could also be present on other items already delivered (e.g. items with identical design concept, materials, components or processes).

Availability: The ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided.

NOTE This ability depends on the combined aspects of the reliability performance, the maintainability performance and the maintenance support performance.

Causes: That which produces an effect; that which gives rise to any action, phenomenon or condition. Cause and effect are correlative terms.

Caution Conditions: A condition which has the potential to degrade into a Warning Conditions, and which might require specific action, including the implementation of special procedures or restrictions on the operation of the system.

Certification: Procedure by which a third-party gives written assurance that a product, process or service conforms to specified requirements.

Common Cause Failure: Failures of multiple items occurring from a single cause which is common to all of them.

Common Mode Failure: Failures of multiple similar items that fail in the same mode.

Common Mode Fault: Faults of multiple items which exhibit the same fault mode.

Configuration baseline: Configuration of a product, formally established at a specific point in time, which serves as reference for other activities.

Configuration Control: Activities comprising the control of changes to a configuration item after formal establishment of its configuration documents.

NOTE Control includes evaluation, coordination, approval or disapproval, and implementation of the changes.

Configuration Documents: Documents that define the requirements, design, build/ /production and verification for a configuration item.

NOTE 1 Documents can be in the form of any media.

NOTE 2 Configuration documents can include documents relating to operation and disposal of the configuration item.

Configuration Identification: Activities comprising determination of the product structure, selection of configuration items, documenting the configuration item's physical and functional characteristics including interfaces and subsequent changes, and allocating identification characters or numbers to the configuration item and their documents.

Configuration Item: Aggregation of hardware, software, processed materials, services of any of its discrete portions, that is designated for configuration management and treated as a single entity in the configuration management process.

NOTE A configuration item may contain other configuration item(s).

Configuration Management: Technical and organizational activities comprising:

a. configuration identification;

b. configuration control;

c. configuration status accounting;

d. configuration audit.

Configuration Status Accounting: Formalized recording and reporting on the established configuration documents, the status of proposed changes and the status of implementation of approved changes.

Configuration Verification: Examination to determine whether a configuration item conforms to its configuration documents.

Consequence: An outcome of an event.

NOTE 1 There can be more than one consequence from one event

NOTE 2 Consequences can range from positive to negative. However, consequences are always negative for safety aspects.

NOTE 3 Consequences can be expressed qualitatively or quantitatively.

Contingency Procedure: A pre-planned procedure to be executed in response to a departure from specified behavior.

Corrective Action: Action taken to eliminate the causes of an existing nonconformity, defect or other undesirable situation in order to prevent recurrence.

NOTE 1 The corrective actions may involve changes such as in procedures and systems, to achieve quality improvement at any stage of the quality loop.

NOTE 2 There is a distinction between "correction" and "corrective action". – "Correction" refers to repair, rework or adjustment and relates to the disposition of an existing nonconformity. "Corrective action" relates to the elimination of the causes of the nonconformity.

NOTE 3 The above term "nonconformance" is equivalent to the term "nonconformity" as used in ISO 8402.

Cost (Price): That which must be given or surrendered to acquire, produce, accomplish or maintain something.

Cost Breakdown Structure: A systematic decomposition and presentation of the total system cost according to Work Packages, the nature of the cost element and the organizational elements responsible for the Work Packages.

Critical Item: Any item that introduces risk which could be unacceptable to the project and requires specific attention or control in addition to that given to items not so categorized.

Customer: Recipient of a product provided by the supplier.

NOTE 1 In a contractual situation, the customer is called the "purchaser".

NOTE 2 The customer may be, for example, the ultimate consumer, user, beneficiary or purchaser.

Data: Information represented in a manner suitable for automatic processing.

Demonstration: A process whereby evidence is produced to provide confidence that the specified requirements are fulfilled.

Dependability: The collective term used to describe the availability performance and its influencing factors: reliability performance, maintainability performance, and maintenance support performance.

NOTE Dependability is used only for general descriptions in non-quantitative terms.

Deration: Process of designing a product such that its components operate at a significantly reduced level of stress to increase reliability.

Design to Minimum Risk: Design of a product to an acceptable residual risk solely by compliance to specific safety requirements, other than failure tolerance.

Development: The process by which the capability to adequately implement a technology or design is established before manufacture.

NOTE The process may include the building of various partial or complete models of the products and assessment of their performance

Durability: The ability of an item to perform a required function under given conditions of use and maintenance, until a limiting state is reached.

Emergency: Condition when potentially catastrophic or critical hazardous events have occurred, and immediate and preplanned saving action is required

Environment: Conditions in which an item exists or is operated.

Estimate at Competition: The sum of the cumulative costs incurred up to the cut-off date and the Estimate to Competition from the cut-off date.

Estimate to Competition: Based on the work completed, approved contract changes and the incurred commitments, the estimate of all costs from the cut-off date required to deliver the product as specified.

Event: The occurrence of a particular set of circumstances.

NOTE 1 The event can be certain or uncertain.

NOTE 2 The event can be a single occurrence or a series of occurrences.

NOTE 3 The probability associated with the event can be estimated for a given period of time.

Failure: The termination of the ability of an item to perform a required function.

NOTE 1 After failure, the item has a fault.

NOTE 2 "Failure" is an event, as distinguished from "fault", which is a state.

NOTE 3 The concept as defined does not apply to items consisting of software only.

Failure Mechanism: The physical, chemical, or other processes which have led to a failure.

Failure Mode: The observable effect of the mechanism through which the failure occurs, e.g. short-circuit, open-circuit, fracture, excessive wear.

NOTE This term is equivalent to the term "Fault Mode".

Fault: 1. The state of an item characterized by inability to perform as required, excluding the inability during preventative maintenance or other planed actions, or due to lack of external resources.

2. An unplanned occurrence or defect in an item which may result in one or more failures of the item itself or of other associated equipment.

NOTE 1

A fault is often the result of a failure of the item itself, but may exist without prior failure.

NOTE 2

An item may contain a sub-element fault, which is a defect that can manifest itself only under certain circumstances (definition No. 2 above). When those circumstances occur, the defect in the sub-element will cause the item to fail, resulting in an error. This error can propagate to other items causing them, in turn, to fail. After the failure occurs, the item as a whole is said to have a fault or to be in a faulty state (definition No.1 above).

Fault Tolerance:

The attribute of an item that makes it able to perform a required function in the presence of certain given sub-item faults.

Harm:

Physical injury or damage to health of people, or damage to property or the environment.

Harmful Event:

Occurrence in which a hazardous situation results in harm.

Hazard:

Potential source of harm. In other words, a condition, associated with the design, operation or environment of a system, that has the potential for harmful consequences.

Hazard Acceptance:

Decision to tolerate the consequences of the hazard scenarios when they occur.

Hazard Analysis:

Systematic and iterative process of identification, classification and reduction of hazards.

Hazard Control:

Preventive or mitigation measure, associated to a hazard scenario, which is introduced into the system design and operation to avoid the events.

Hazard Elimination:

Removal of a hazard from a particular hazard manifestation.

Hazard Manifestation:

Presents of specific hazards in the technical design, operation, and environment of a system.

Hazard Reduction: Process of elimination or minimization and control of hazards.

Hazard Scenario: Sequence of events leading from the initial cause to the unwanted safety consequence.

Hazard Free: Set a hazard scenarios originating from the same set of hazard manifestations.

Hazardous: Property of an item and its environment which provides the potential for mishaps.

Hazardous Events: An occurrence arising from the triggering of one (or more) initiator events in the presence of one (or more) hazards, which may lead to undesired consequences.

Hazardous Situation: Circumstance in which people, property or the environment are exposed to one or more hazards.

Human Error: The failure of a person to perform an action as required.

Incident: An unplanned event that could have been an accident, but was not.

Information: Intelligence or knowledge capable of being represented in forms suitable for communication, storage or processing.

NOTE Information may be represented, for example, by signs, symbols, pictures, or sounds.

Inhibit:

1. To stop or prevent the occurrence of an event.
2. A design feature that provides a physical interpretation between an energy source and the function actuator.

Inspection: An activity such as measuring, examining, testing to gauging one or more char-activities of an entity and comparing the results with specified requirements in order to establish whether conformity is achieved for each characteristic.

Instantaneous Availability: The probability that an item is in a state to perform a required function under given conditions at a given instant of time, assuming that the required external resources are available.

Item: Anything which can be individually described and considered.

NOTE An item may be, for example:

a) an activity or process a product; an organization, system or person, or

b) any combination thereof.

Life cycle cost: The total cost of a system, from "need identification" until disposal.

Maintainability: The ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources.

NOTE The term "maintainability" is also used as a measure of maintainability performance. In this sense, maintainability is "the probability that a given active maintenance action, for an item under given conditions of use can be carried out within a stated time interval, when maintenance is performed under stated conditions and using stated procedures and resources".

Maintainability Prediction: An activity performed with the intention of forecasting the numerical values of a maintainability performance measure of an item, taking into account the maintainability performance and reliability performance measures of its subsystems, under given operational and maintenance conditions.

Maintenance: The combination of all technical and administrative actions, including servicing actions, intended to retain an item in, or restore it to, a state in which it can perform a required function.

Mean time between failures: The expectation time between failures.

Model: A physical or abstract representation of relevant aspects of an item or process that is put forward as a basis for calculations, prediction, or further assessment; to create or use such a model.

Nonconformance: Non-fulfillment of a specified requirement.

NOTE The definition covers the departure or absence of one or more quality characteristics (including dependability characteristics), or quality system elements from specified requirements.

Normative Reference: A reference which incorporates requirements from a cited publication into a normative document.

Probability: The extent to which an event is likely to occur.

NOTE 1 ISO 3534-1:1993: mathematical definition of probability is "a number in the scale 0 to 1 attached to a random event. It can be related to a long-run relative frequency of occurrence or to a degree of belief that the event will occur. For a high degree of belief, the probability is near 1."

NOTE 2 Frequency rather than probability may be used in describing risk.

NOTE 3 Degrees of belief about probability can be chosen as classes or ranks, such as rare/unlikely/ moderate/likely/almost certain or incredible/ improbable/remote/occasional/probable/frequent

Procedure: Specified way to perform an activity.

NOTE 1 In many cases, procedure are documented (e.g. quality system procedures)

NOTE 2 When a procedure is documented, the term "written procedure" or "documented procedure" is frequently used.

NOTE 3 A written or documented procedure usually contains the purposes and scope of an activity; what shall be done; what materials, equipment and documents shall be used; and how it shall be controlled and recorded.

Process: Set of inter-related resources and activities which transform inputs into outputs.

Product: The result of activities of processes.

NOTE 1 A product may include service, hardware, processed materials, software or a combination thereof.

NOTE 2 A product can be tangible (e.g. assemblies or processed materials) or intangible (e.g. knowledge or concepts), or a combination thereof.

NOTE 3 A product can be either intended (e.g. an offering to customers) or unintended (e.g. pollutant or unwanted effects).

Product Assurance: A discipline devoted to the study, planning and implementation of activities intended to assure that the design, controls, methods and techniques in a project result in a satisfactory level of quality in a product.

Product State: A particular configuration of the product related to the current configuration baseline.

Product Tree: Hierarchical representation of the system resulting from an orderly or exhaustive identification of its successive levels of decomposition.

Quality: The totality of characteristics of an entity that bear on its ability to satisfy stated and implied needs.

NOTE 1 In many instances, needs can change with time; this implies a periodic review of requirements for quality.

NOTE 2 Needs are usually translated into characteristics with specified criteria. Needs may include, for example, aspects of performance, usability, dependability (reliability, availability, maintainability), safety, environment, economics and aesthetics.

NOTE 3 The term “quality” should not be used as a single term to express a degree of excellence in a comparative sense, nor should it be used in a quantitative sense for technical evaluations. To express these meanings, a qualifying adjective should be used. For example, use can be made of the following terms:

a. "Relative Quality" where entities are ranked on a relative basis in the degree of excellence or comparative sense (not was confused with "grade").

b. "Quality Level" in a quantitative sense (as used in acceptance sampling) and "Quality Measure" where precise technical evaluations are carried out.

NOTE 4

In some references, quality is referred to as "fitness for use" or "fitness for purpose" or "customer satisfaction" or "conformance to the requirements".
These represent only certain facets of quality, as defined above.

Quality Assurance:

All the planned and systematic activities implemented within the quality system and demonstrated as needed, to provide adequate confidence that an entity will fulfill requirements for quality.

Quality Control:

Operational techniques and activities that are used to fulfill requirements for quality.

NOTE 1

Quality control involves operational techniques and activities aimed both at monitoring a process and at eliminating causes of unsatisfactory performance at all stages of the quality loop in order to achieve economic effectiveness.

NOTE 2

Some of the purposes of quality records are demonstration, traceability and preventive and corrective actions.

Reliability:

The probability that an item can perform a required function under given conditions for a given time interval.

NOTE 1

It is generally assumed that the item is in a state to perform this required function at the beginning of the time interval.

NOTE 2

The term "reliability" is also used to denote the non-qualified ability of an item to perform a required function under conditions for a specified period of time.

Reliability Critical Item:	An item which contains a single point failure with a failure consequence severity classified as catastrophic, critical or major.
Reliability growth:	A condition characterized by a progressive improvement of a reliability performance measure of an item with time.
Requirement:	That which is called for or is demanded: a condition which must be complied with.
Residual Risk:	The risk remaining in a system after completion of the hazard reduction and control process.
Residual Hazard:	Hazard remaining after implementation of hazard reduction.
Review:	Systematic examination of item for the purpose of assessing the results obtained at a given time in the project, by persons not themselves responsible for the project.
Risk:	The combination of the probability of an event and its consequence or a quantitative measure of the magnitude of a potential loss and the probability of incurring that loss.
NOTE 1	The term "risk" is generally used only when there is a least the possibility of negative consequences.
NOTE 2	In some situations, risk arises from the possibility of deviation from the expected outcome or event.
Risk Acceptance:	The decision to accept a risk.
NOTE 1	The verb "to accept" is chosen to convey the idea that acceptance has its basic dictionary meaning.
NOTE 2	Risk acceptance depends on risk criteria.
Risk Category:	A class or type of risk (e.g. technical, legal, organizational, safety, economic, engineering, cost, schedule).
NOTE	A risk category is a characterization of a source of risk.

Risk Criteria: The terms of reference by which the significance of risk is assessed.

NOTE Risk criteria can include associated cost and benefits, legal and statutory requirements, socio-economic and environmental aspects, the concerns of stakeholders, priorities and other inputs to the assessment.

Risk Communication: All information and data necessary for risk management addressed to a decision-maker.

Risk evaluation: Procedure based on the risk analysis to determine whether the tolerable risk has been achieved.

Risk assessment: Overall process comprising a risk analysis and a risk evaluation.

Risk index: A score used to measure the magnitude of the risk; it is the product of the likelihood of occurrence and the severity of consequence, where scores are used to measure likelihood and severity.

Risk Management: The systematic and iterative optimization of the project, resources, performed according to the established project risk management policy.

Risk reduction: Implementation of measures that leads to reduction of the likehood or severity of risk.

Risk Scenario: The sequence or combination of events leading from the initial cause to the unwanted consequence.

Risk Trend: The evolution of risks throughout the life cycle of a project.

Risk Treatment: The process of selection and implementation of measures to modify risk.

Safety: The freedom from unacceptable risk. Safety is one of the aspects of quality.

Safety Critical Function: A function which, if lost or degraded, or which through incorrect or inadvertent operation, could result in a catastrophic or critical hazardous event.

Safety Measure: Means that eliminates a hazard or reduces a risk.

Set: Group of physically or functionally related items which are considered together for technical or administrative reason, but whose association does not increase functionally over that of the individual items.

Severity of Safety: A classification of a failure or undesired event according to the magnitude of its possible consequences.

Software: Programs, procedures, rules and any associated documentation pertaining to the operation of a computer system.

Stakeholder: Any individual, group, or organization that can affect, be affected by, or perceive itself to be affected by, a risk.

Supplier: An organization that provides a product to the customer.

NOTE 1 In a contractual situation, the supplier may be called the "contractor"

NOTE 2 The supplier may be, for example, the producer, distributor, importer, assembler or service organization.

NOTE 3 The supplier can be either internal or external to the organization.

System: Set of interdependent elements constituted to achieve a given objective by performing a specified function.

NOTE The system is considered to be separated from the environment and other external systems by an imaginary surface which cuts the links between between them and the considered system. Through these links, the system is affected by the environment, is acted upon the external systems, or acts itself on the environment or the external systems.

Task: A specific piece of work to be done.

Test: A formal process of exercising or putting to trial a system or item by manual or automatic means to identify differences between specified, expected and actual results.

Compliance Test: A test used to show whether or not a characteristic or a property of an item complies with the stated requirements.

Laboratory Test: A compliance test or a determination test made under prescribed and controlled conditions which may or may not simulate field conditions.

Endurance Test: A test carried out over a time interval to investigate how the properties of an item are affected by the application of stated stresses and by their time duration or repeated application.

Unresolved Risk: A risk for which risk reduction attempts are not feasible, or which cannot be verified, or have proven unsuccessful: a risk remaining unacceptable.

Validation: Confirmation by examination and provision of objective evidence that the particular requirements for a specific intended use are fulfilled.

NOTE 1 In design and development, validation concerns the process of examining a product to determine conformity with user needs.

NOTE 2 Validation is normally performed on the final product under normal operating conditions. It may be necessary at earlier stages.

Verification: Confirmation by examination and provision of objective evidence that specified requirements have been fulfilled.

NOTE

In design and development, verification concerns the process of examining the result of a given activity to determine conformity with the stated requirements for that activity.

Warning Conditions:

Conditions in which potentially catastrophic or critical hazardous events have been detected as being imminent and preplanned saving action is required within a limited time.

Whole-life Costs (WLC):

Total recourse required to assemble, equipment, sustain, operate and dispose of a specified asset as detailed in the plan at defined levels of readiness, reliability, performance, and safety.

NOTE

WLC also includes the costs to recruit, train and retain personnel as well as the costs of higher organizations.

Work Breakdown Structure:

Hierarchical representation of the activities and resources necessary to complete a project.

Work Package:

A group of related tasks that are defined at the lowest level within a Work Breakdown Structure.

Workmanship:

The physical characteristics relating to the level of quality introduced by the manufacturing and assembly activities".

27 SAFETY ASPECTS OF RISK CONTROL AND ASSESSMENT, RELATIONS TO TRANSPORTATION PROBLEMS. CURRENT SITUATION

Many approaches to safety risk control are possible. However, only through careful reading, evaluation, and study can one make the best choice of a practical philosophy for a safety risk assessment program. The goal is to apply the best scientific and engineering principles in the best way, resulting in the soundest and safest possible system.

System safety for the future provides in-depth coverage of this specialized discipline within the safety profession.

One needs basic and essential information about the identification, evaluation, analysis, and control of hazards in components, systems, subsystems, processes, and facilities.

One of the most dangerous situations in safety risk problems is the automotive area. One can see this from the following examples[1,20,]:

- More than a million people are killed on the world's roads each year, and this is expected to increase to 2 million by the year 2020;
- In the USA more than 40,000 people are killed on the roads each year, 43,320 people[1] died in traffic accidents in 2003;
- The World Health Organization estimates that of 1,194,115 people killed in 2001 in traffic worldwide, 848,234 were male compared to 345,881 female, giving a male-to-female ratio of 2.34 to 1;
- Traffic was responsible for: in the USA 0.190 fatalities per thousand vehicles; in Australia 0.143, in Egypt 1.875. So, the Australian rate is 92% lower than the Egyptian rate;
- A review estimates that about 50% of traffic accidents in Europe could have been prevented if road users were completely forbidden to commit traffic violations. More than 50% of fatalities would be eliminated, because fatal accidents involve more egregious law violations than typical accidents;
- In a typical month, more Americans die in traffic than were killed by the September 11 2001 terrorist attacks on New York and Washington;
- Since the coming of the automobile, more than 3 million Americans have been killed in traffic crashes, vastly more than the 650,000 American battle deaths in all wars, from the start of the revolutionary war in 1775 through the 2003 war in Iraq;
- Injuries due to traffic accidents vastly outnumber fatalities, with over 5 million occurring per year in the USA, most of them minor;
- By covering all losses of monetary values, it is estimated that US traffic accidents in 2000

cost $231 billion;

- By 2002, in terms of deaths per registered vehicle, the USA has dropped from first place into sixteen-th place behind Australia, Austria, Canada, Denmark, Finland, Germany, Great Britain, Iceland, Japan, Luxembourg, the Netherlands, New Zealand, Norway, Sweden, and Switzerland;

- In 2003 airbags reduced the fatality risk by 10% for 47% of road users, thus reducing the USA total fatalities by almost 5%;

- The US National Highway Traffic Administration estimates that adding side air bags would save 700 to 1,000 lives a year and cost the auto industry (of course, consumers) $1.6 billion to $3.6 billion.

In the automotive area almost one-quarter of the passengers killed in automobile accidents are in vehicles that are struck from the side. The danger for the driver of a car is much higher if the vehicle that hits the car is a pickup or other light truck. As a result of the above situation, the automotive industry companies, especially the US Department of Transportation pay more attention to safety risk assessment and protection.

The USA government's research (including National Highway Traffic Safety Administration, VOLPE Center, etc.) raises doubts as to whether the current designs for side air bags with head protection (some only protect the chest and midsection) are sufficiently advanced. This includes using crash- test dummies that, for the first time in government tests, would be equipped to measure injuries to the head, the most vulnerable part of the body in side-impact collisions. In another first, they also include using dummies to represent women and children of small size, who are at disproportionate risk in side-impact accidents.

The automotive industry companies in the USA designed many other approaches for the protection of people in the above situation. However, current approaches cost a lot of money and are not so effective (see the above example).

In the test now used, a 3,000-pound barrier is meant to simulate a crash between passenger cars and trucks weighing up to 6,000 pounds. The traffic safety agency (USA) proposed adding a test that would ram vehicles sideways into a fixed position at 18 to 20 miles an hour; it would reflect the effect of crashes with taller vehicles, trees or utility roles, and be conducted on vehicles up to 10,000 pounds. The US Traffic Safety Agency proposes Tough Crash Tests for studying the accident situation and improving the protective systems. This system will be used beginning from 2005 - 2006. Unfortunately, the above system, as well as other current systems of accident modeling, cannot accurately simulate real life situations. It is similar to current techniques and equipment for accelerated testing which was shown in Chapter 2 (subsection 6.2). Therefore, the results of testing are minimally useful or useless, sometimes even harmful. As a result, customary tough crash tests cannot be as beneficial as desired. This situation will continue until the traditional approach to physical simulation of real life (see Introduction to Chapter 1) improves.

There are other methods for decreasing safety risk. For example, let us consider the development of safety belts. The earliest safety harness patent in the USA dates back to 1878[2] with later design improvements. A number of innovative designs were introduced in 1930, and by the mid-1950s, elements of modern lapshoulder seat belts were taking shape.

State laws started to require lap belts in 1964 and lapshoulder belts in 1968, and countries throughout the world began to pass mandatory use laws in the 1970s. This direction of development continued until the present and will continue in the future Now one uses a new generation of yielding seats with high retention capabilities. Development of the Self-Aligning Head Restraining (SAHR) active head restraint is now available on many vehicles and has proven a field effectiveness of 43% - 75% in preventing whiplash[3].

The Volpe Center of the Department of Transportation (USA) has been assisting the Federal Highway Administration in their activities in the development of methods to estimate the safety benefits of intelligent transportation systems and provided support for a request for applications (RFA) to assess Intelligent Vehicle Initiative (IVI)[4] generation in field operational tests (1998 - 1999). Its primary goal is to accelerate the development, introduction, and commercialization of driver assistance products and services in order to improve the safety of the nation's ground transportation system by reducing the number and severity of motor vehicle collisions. This was based[4] on driver/vehicle performance data in safety-critical driving engagements encountered during the conduct of field operational tests. The Volpe Center currently is updating the crash problem definition of several IVI platforms, assessing possible IVI systems deployment schedules, developing a novel methodology to improve the estimation of IVI system safety effectiveness, assessing the safety benefits and cost of systems that provide the safety services, etc.

The Volpe Center also provides supporting research on the Effects of Human Factors on Flight (and other) Safety[5]. The aviation community has been a leader in recognizing the effect of human performance on safety. The Volpe Center supports this effort in a number of areas including flight deck consideration, air traffic control systems and operations, and air-ground integration. Among the current flight deck research projects are Advanced Low-Cost Simulator Criteria, Head Up Display (HUD) Certification Job Aid, Electronic Flight Bag, Certification Job Aid, and Realistic Communications for Training Simulators.

The demonstrated situation in current safety risk assessment is similar to other areas of mobile technologies such as aircraft, aerospace, shipping hazardous (nuclear, etc.) materials, as well as other areas of human activity: mycology, pharmaceutical, underground work, electrical, and many other activities.

Effectiveness of safety risk protection and safety risk assessment often depends on techniques and equipment used for their simulation, especially physical simulation in artificial conditions, accuracy of protected systems of accelerated reliability testing, system optimization, comparison, assessment, and prediction. Unfortunately, current inputs of physical simulation of the above systems, as well as real life input influences cannot reflect the actual real life situation. This situation is described in the earlier chapters of this book, especially the Preface, Chapter 1 and chapter 2. Therefore, testing results also do not reflect real life results. Testing results give initial information for actual safety risk assessment and prediction, and as a result, this assessment and prediction is less beneficial than might be expected (see the included earlier examples in the automotive area).

In conclusion, assessment of current publications and standards in this area shows that one needs new, more beneficial approaches to safety risk assessment, which means that future needs must be identified accurately. Consequently, a strategy must be dedicated to fulfill these needs to the benefit of both standardization and research in the improvement of safety risk protection.

This book can be used for the above goals, especially Chapter 1 and Chapter 2.

28 BASIC PRINCIPLES

28.1 ANALYSIS OF CURRENT SITUATION IN INTERNATIONAL STANDARDIZATION OF THE AREA.

There are three international standards organizations which publish standards in the area: the International Standards Organization (ISO), the International Electrotechnical Commission (IEC), and the European Cooperation for Space Standardization (ECSS).

There is one common ISO/IEC standard – "Guide 51: Safety Aspects – Guidelines for their inclusion in standards[6]. The second edition includes 10 pages and was published in 1999.

The basic content of this standard is:

"...• Use of the words "safety" and "safe";

• The concept of safety;

• Achieving tolerate risk;

• Safety aspects in standards;

Types of safety standards:

a. analysis of proposed new standards,

b. preparatory work,

c. drafting".

In correspondence with this standard:

A. "Safety is dealt in standards work in many different forms across a wide range of technologies and for most products, processes, and services".

B. "Safety is achieved by reducing risk to a tolerable level – defined in this Guide as tolerable risk. Tolerable risk is determined by the search for an optimal balance between the ideal of absolute safety and the demands to be met by a product, process, or service, and factors such as benefit to the user, suitability for purpose, cost effectiveness, and conventions of the society concerned. If follows that there is a need to review continually the tolerable level, in particular when developments, both in technology and in knowledge, can lead to economically feasible improvements to attain the minimum risk compatible with the use of a product, process or service".

There is one ISO standard in this area – ISO 14121 "Safety of Machinery. Principles of Risk Assessment"[7]. This consists of 18 pages including title page, foreword, introduction, contents, scope, normative references, terms & definitions, bibliography. So, the contents of this standard cover 13 pages, including six pages of Annex 1 (informative) and Annex B (informative).

This standard:

- Is for machinery only, which is just one of many aspects of safety risk. Biological, chemical, food, and other aspects are not considered;
- Includes a small (but not main) fraction of methods for analyzing hazards and estimating risk;
- Similarly the title directions sometimes do not correspond to IEC and ECSS standards. For example, in the Simulation area in this standard only "; B5. Fault simulation for control system" is covered, which is not essential for safety risk assessment. No less important is the "simulation of dynamic of input influences during service life", "simulation of stress conditions (vibration, environmental conditions, operator's reliability"), and others that are in the IEC standards. In the ECSS standards there are "dependability analysis", etc.
- No traffic-crash aspects of risk safety are included.
- There is no coordination with standards of other international standardization organizations.
- Other possibilities may occur.

There are several ECSS standards in this area:

1. Glossary and Terms[8].
2. Space Project Management (Risk management)[9];
3. Group of Space Product Assurance standards:
   a. Safety[10],
   b. Hazard Analysis[11],
   c. Quality Assurance for Test Centers[12],
   d. Dependability[13],
   e. Software Product Assurance[14].
4. Others.

The above standards:

- Do not take into account current 75 IEC standards in Basic Safety and 57 IEC standards in Dependability;

- The standard in Dependability (in comparison with 57 IEC standards in Dependability) consists of nothing about techniques of dependability and no examples;

- In standard Quality Assurance for Test Centers there are no examples;

- Similarly the titles of directions do not correspond with the contents of IEC and ISO standards (see above example);

- Standards are not coordinated with standards of other standardization organizations.

The IEC standards in this area assessed about 100 standards (including 57 standards in Dependability). Many of them relate to safety aspects of risk for electronics, electrotechnical, and other product assessments, especially in details of the problem.

The results of this assessment showed:

1. There are no modern generalized standards for safety aspects of risk assessment.

2. Current standards do not correspond to standards for this area of two other standardization organizations.

3. Terms often have different definitions than terms in standards of the two other organizations.

4. Standards are not coordinated with other standardization organizations.

Result of the above analysis suggest:

- The above three organizations in standardization must coordinate their efforts in safety aspects of risk assessment.

- In the future they need, as minimum, one common generic standard guideline in safety aspects of risk assessment (but in more detail than earlier described Guide 51) to the benefit of the people who use these 3 organizations standards.

- The national standards have to follow this direction.

As a result, the authors propose strategy to fulfill the above needs:

A. To create a new generic IEC/ISO/ECSS standard set of guidelines in safety aspects of risk assessment which consists of common approaches and the basic requirements for these three organizations relating to the more detailed standards in the above area.

B. For this goal the above three international organizations must organize one common working group of experts.

C. This standard set of guidelines must include the main directions for updating the standards in this area.

D. The basic requirements for the above generic (cover) standard must include:

- machinery (including traffic-crash aspects and software), biological, medical, fungus, food, pharmaceutical, and other aspects;
- techniques of their development prediction;
- reduction of number of deaths;
- protection from possibility of deaths;
- priority problem in safety area.

One of the authors of this book, as expert of IEC/ISO Joint Study Group in improving standardization in safety aspects of risk assessment and the USA representative, officially proposed the above for consideration.

As a result, the national standards in this area have to be correct in order to improve the current dangerous situation in safety area.

28.2 NECESSITY FOR RISK ASSESSMENT

Let us show the necessity for risk assessment using an example of electrotechnical and electronic machinery. Based on correspondence with the requirements of the European Machinery Directive 98/37/EC (Annex 1. Preliminary Observations):

"... The manufacturer is under an obligation to assess the hazards in order to identify all of those which apply to his particular machine; he must then design and construct it taking into account his assessment".

This philosophy is based on the machinery and complies with the principle that the manufacturer has to provide the risk assessment himself or use harmonized product standards listed in the official Journal of the International Electrotechnical Commission (IEC). In this case, the risk assessment has been provided by the Technical Committee responsible for the standard.

In the present draft of the European Low Voltage Directive (Annex 1) it is written: "The manufacturer of electrical equipment is under the obligation to perform a risk assessment according to the essential health and safety requirements. Applying Harmonized Standards covering all relevant essential health and safety requirements fulfills the obligation to perform a risk assessment".

Basically, this is also required in the areas of, for example:

- Explosive atmospheres;
- Medical devices;
- Future revision of European Low Voltage Directive;
- Functional safety."

From Guide 51[6] the understanding of tolerate risk is that when reducing risks the order of priority should be as follows:

1. Inherently safe design;

2. Protective devices;

3. Information for users.

This procedure is based on the assumption that the user has a role to play in the risk reduction procedure by complying with the information provided by the designer/supplier (Figure 5.1):

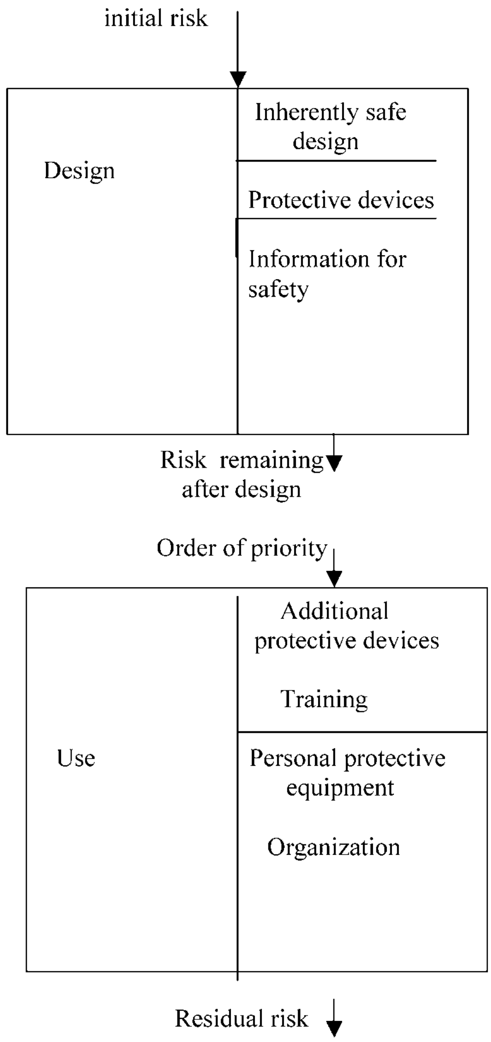

Figure 5.1. Risk reduction.

28.3 BASIC CONCEPTS

ISO 14121 states that "Risk assessment is a series of logical steps to enable, in a systematic way, the examination of the hazards associated with machinery. Risk assessment is followed, whenever necessary, by risk reduction. When this process is repeated it gives the iterative process for eliminating hazards as far as possible and for implementation safety measures".

Risk assessment includes risk analysis and risk evaluation (Figure 5.2):

As we can see from the below (Figure 5.2) risk analysis consists of:

- methods for setting limits on machinery;
- hazard identification;
- risk estimation.

Corresponding to ISO 14121 risk assessment depends on well judged decisions. These decisions must be based on qualitative techniques complemementated, to a great extent, by quantitative techniques.

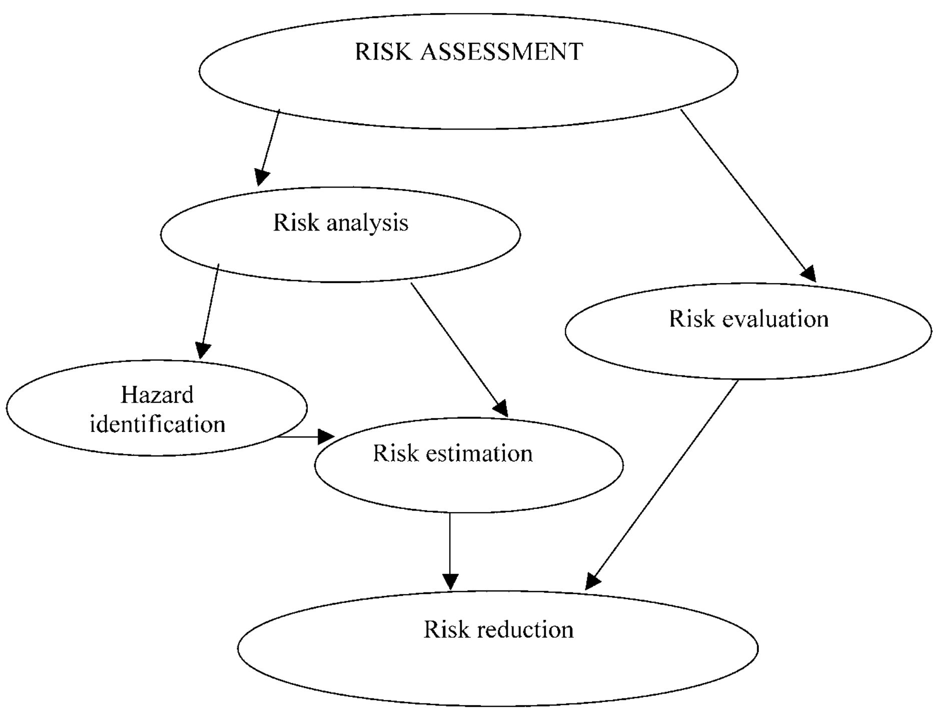

Figure 5.2 Contents of risk assessment.

Quantitative techniques are particularly useful when the possibilities for severity and disaster are high. Quantitative techniques can be employed to access alternative safety measures and to decide on whatever offers better protection.

One could improve the safety risk situation related to reliability if [15]:

1. As systems become more complex, the opportunities for failure increase.

2. A relevant cliche is "It's not acceptable to have to reboot a computer at 60 mph." In other words, it's not acceptable for a computer that is controlling the motion of a vehicle to malfunction.

3. Crash avoidance systems are especially susceptible to failures that could have disastrous consequences if components of the system fail.

4. Fail-safe is a "second-best" strategy for reliability. The best strategy is to design these advanced technology systems with unprecedented levels of reliability.

5. How to do this is the challenge that I leave with this group, and others in your industry who are responsible for developing reliable safety systems.

28.4 INFORMATION FOR RISK ASSESSMENT

This information as well as information for any qualitative and quantitative analysis should include the following[7]:

- limits of the machinery;
- requirements for the life phases of the machinery;
- basic design drawings or whatever else demonstrates the nature of the machinery;
- accident and incident history;
- statements about damages to health which can be used as information for risk assessment covers the following:
  - Often, similar comparisons can be made between hazardous situations associated with different types of machinery, as long a enough information about the hazards and accidents, and the circumstances of these situations is available;
  - If there is no accident history, a few accidents, or minor accidents can serve as an automatic low risk presumption;
  - For quantitative analysis one can use data from databases, handbooks, laboratories and specifications made by manufacturers if there is sufficient confidence that the data are suitable;
  - Doubts concerning this data must be stated in the documentation;
  - To supplement qualitative data, it is possible to employ a consensus of expert opinion based on practical experience.

29 ASSESSMENT OF A MACHINE'S LIMITS

ISO 14121 states that risk assessment shall take into account:

- the phases of machinery life;
- the limits of a machinery imply that it be used as intended, which would include correct usage and operation of the machinery as well as the possible reasonably foreseen misuse or malfunction;
- a complete inventory of how this machinery might be utilized (e.g. industrial, non-industrial and domestic) by persons identified by sex, age, dominant-hand usage, or limiting physical abilities (e.g. visual or hearing impairment, size, strength);
- an evaluation the degree of training, experience as well as an assessment of the necessary skills required by potential users:

  a. operators (including maintenance personnel or technicians);

  b. trainees and juniors;

  c. general public;
- exposure of other persons to the hazards associated with the machinery, where it can be reasonable foreseen.

30 RISK ESTIMATION

30.1 COMPONENTS OF RISK

Corresponding to ISO 14121, risk estimation shall be shall be made to determine each hazard based on risk components given in 29.2. Decisions based on these components must include the aspects given in 29.3.

30.1.1 Combination of components of risk

According to ISO 14121, the risk involved in a particular situation or technical process is based on combinations of the following components:

- the severity of harm;

  and

- the probability of occurrence of that harm which is a function of:

  1) the number as well as the length of time persons are exposed to the hazard;

  2) the probability of occurrence of a hazardous event;

  3) the technical and human possibilities to avoid or limit the harm (e.g. reduced speed, emergency stop equipment, enabling device, awareness of risks).

The basic components are shown in Figure 5. 3, other details are given in 29.2. 2 and 29.2.3.

Presently, various techniques exist to systematically analyze these components. These include simulation of input influences as well as the machines (test subject or/and test equipment), FMEA, Fault Tree Analysis, etc.

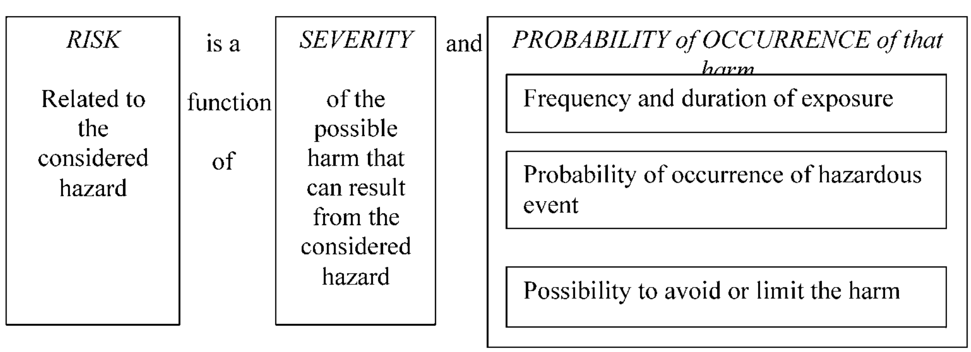

Figure 5. 3 Components of risk[7].

30.1.2 Severity (degree of possible harm).

Severity can be determined by consideration of:

• the nature of what is to be protected:

1) persons;

2) property;

3) environment.

• how serious is the damage to health:

1) slight (normally reversible);

2) serious (normally irreversible);

3) death.

• the range of harm:

1) one person;

2) more than one persons.

30.1.3 Probability of Incident of Harm

ISO 14121 indicates that an evaluation can be made by consideration of 30.2.3.1 to 30.2.3.3. the following factors:

A. Frequency and duration of being subjected to:

• need for access to the danger zone (e.g. for normal operation, maintenance or repair);

• method of access (e.g. manually feeding of materials);

• time spent in the danger zone;

• number of persons occupying this access;

• frequency of access.

B. Probability of occurrence of hazardous event:

• reliability, maintainability, availability and other statistical data;

• accident history;

- history of damage to health;
- risk comparison.

The cause of a hazardous event can be a technical or a human action.

C. Possibilities of limiting harm:

a) by whom the machinery is operated:

1) by skilled persons;

2) by unskilled persons;

3) unmanned;

b) the frequency with which this hazardous event occurs:

1) suddenly;

2) fast;

3) slowly;

c) any awareness of risk:

1) by general information;

2) by direct observation;

3) through warning signs and indicating devices;

d) the human possibility of limiting harm (e.g. reflex, agility, possibility of escape):

1) possible;

2) allowable under certain conditions;

3) not allowed;

e) by practical experience and knowledge:

1) of the machinery;

2) of similar machinery;

3) no skills;

4) no experience.

30.2 REQUIREMENTS FOR TAKING DECISIONS INVOLVING COMPONENTS OF RISK

Risk estimation must include everyone exposed to hazardous conditions (operators and other persons involved with the machinery) including type, frequency, length of time, human factors.

An appropriate estimation of the exposure to the particular hazard being considered includes analysis of long-term health damage; it also has to consider every model for how the various types operate as well as techniques for use of the machinery. All of this has an effect on the need for cleaning, teaching, problem discovery, maintenance, and repair. Whenever it is necessary to suspend safety functions (including during maintenance and repair), the risk estimation must be considered. Factors to be studied include the relationship between exposure to a hazard and its effects including the effects of accumulated exposure. In this instance, risk estimation is based on appropriate recognized data.

It is necessary also to take into account human factors in risk estimation. These may include interaction of persons with the machinery and between persons, psychological, physiological and ergonomic aspects, training, experience, and ability, components and systems reliability, types of safety measures involving persons other than the operator, consideration of the safety measure, ease of maintenance, etc.

31 RISK EVALUATION

31.1 ACHIEVEMENT OF RISK REDUCTION OBJECTIVES

Risk evaluation should be employed to determine the requirements of risk reduction. Next comes the selection of appropriate safety measures for application, and the procedure is then repeated (see Figure 5.2). This process requires checking by the designers for any additional hazards which may have occurred when new safety measures were applied.

Confidence in the safety of the machinery is established by the utilization of the risk reduction process which results in a favorable risk comparison.

By following ISO 14121 achievement of the following conditions will indicate that the risk reduction can be achieved:

a). The hazard has been eliminated or the risk reduced by:

1) design or by the substitution for less hazardous materials;

2) safeguarding.

b). The chosen safeguard is one which provides a risk free condition for its intended use.

c). Information for the use of the machinery is sufficiently clear.

d). Operating procedures for the machine's usage are on a level with the ability of the personnel who will use the machinery.

e). Recommendations for safe usage of the machinery and all necessary training requirements have been fully described.

f). The user is made aware of any remaining risks in the various phases of operation during the life of the machinery.

g). If there has been a recommendation for personal protective equipment, the training requirements for its usage must be described.

31.2 COMPARISON OF RISKS

Risks associated with particular machinery can be compared with those of similar machinery long as the following criteria apply:

- the safety factor is similar;

- the intended use, the hazard and the components of risk, the technical specifications, and the conditions for use are comparable.

When using the above comparison technique one must still follow the risk assessment process for the particular conditions of usage. For instance, when comparing the use of a band saw for cutting meat as against one for cutting wood, the risks involved with the different materials should be taken into account.

32 HAZARD ANALYSIS

32.1 INTRODUCTION

In the ECSS standard "Space Product Assurance. Hazard Analysis"[11] hazard analysis is described in detail. Safety analysis comprises hazard analysis, safety risk assessment, and necessary supporting analysis.

The goal of safety analysis is to identify, assess, reduce, accept, and control safety hazards, and the associated safety risks in a systematic, proactive, complete, and cost effective manner.

This should be done by also taking into account the project's technical and programmatic constraints. Safety analysis can be implemented with iterations being determined by the project's progress through its various phases.

Hazard analysis comprises the identification, classification, and reduction of risk factors and can be implemented at each level of the customer-supplied manual of directions. Hazard analysis interfaces with dependability analysis. Safety risk assessment interfaces with quantitative dependability (reliability, maintainability, availability) analysis.

Safety risk assessment contributes to project risk management. Ranking of safety risk according to their critically for project success, allows management to direct its attention to the essential safety issues which are a major part of risk management.

32.2 HAZARD ANALYSIS CONCEPT

Hazard analysis is based on the following concepts (Figure 5.4., Figure 5.5, Figure 5.6, and Figure 5.7). All hazards that persist throughout hazard manifestations in the system will be activated if initiating events occur. Hazardous occurrences renewal how the system will be have as a result of following the prescribed safety factors as depicted in Figure 5.4. The occurrence of events is shown alongside the observable symptoms in the system.

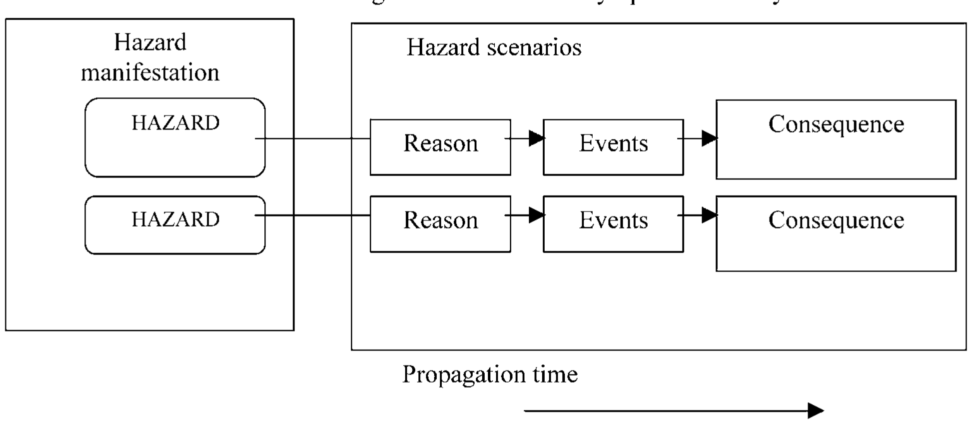

Figure 5.4 Hazards and hazards scenarios[11].

The safety results are accurately described by their severity.

Different hazardous conditions can arise from the same hazard. Furthermore, different hazardous results can lead to the same safety conclusions. For example, see Table 5. 1.

Table 5.1 Example of a hazard scenario[11]: hazard scenario list for in-orbit phase

Hazard Manifestation	**Reason – events consequence**	**Consequence Severity**	**Observable symptoms**	**Propagation and reaction time**
In-orbit pressurized manned module: meteorite debris environment	Meteorire debris impact – shell rupture exposure loss of spacecraft and astronauts	Catastrophic	None	Ptime: 1s Ptime: N/A
	Meeorite debris impact shell damage – leakade – loss of spacecraft and astronauts	Catastrophic	Module pressure drop	Ptime: 3 min Ptime: < 3 min

The collection of hazard scenarios originating from the same hazard manifestation is collated into a hazard tree (Figure 5.5).

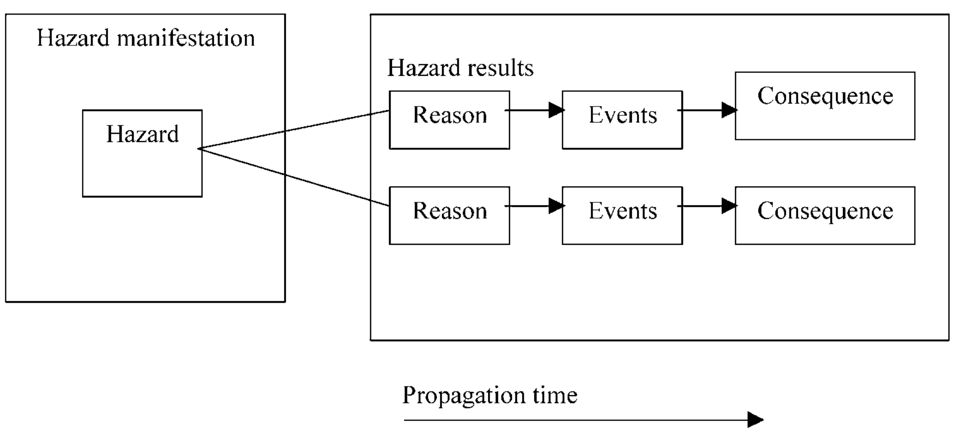

Figure 5.5 Example of hazard tree[11].

The collection of hazard scenarios leading to the same safety consequence is collated into a consequence tree as shown in Figure 5.6.

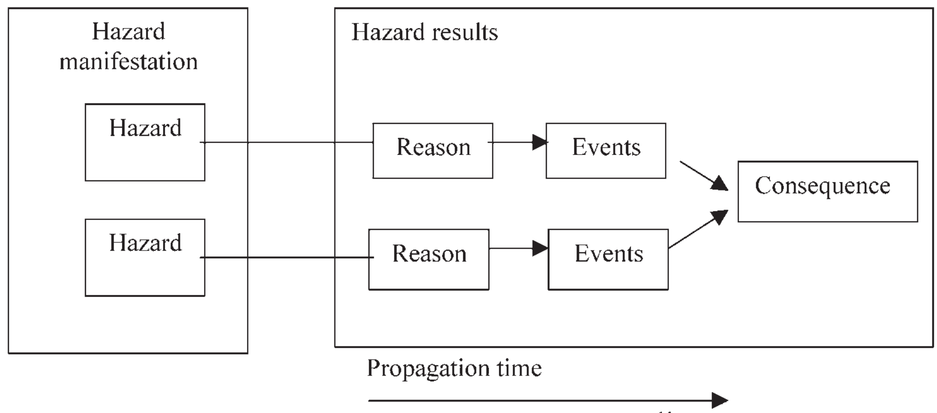

Figure 5.6 Example of a consequence tree[11].

Hazards can be reduced either by elimination or by minimizing and controlling them, as shown in Figure 5.7. Hazards can also be eliminated by removing any potential safety-threatening factors which exist in the system. Hazards are minimized through a reduction of either the level or number of specific potential safety-threatening system characteristics.

Hazards can be controlled by not allowing them to occur or by reducing the possibility of them happening, or by reducing of the effects of the events. When an event does occur, it can be detected through an observation of the symptoms.

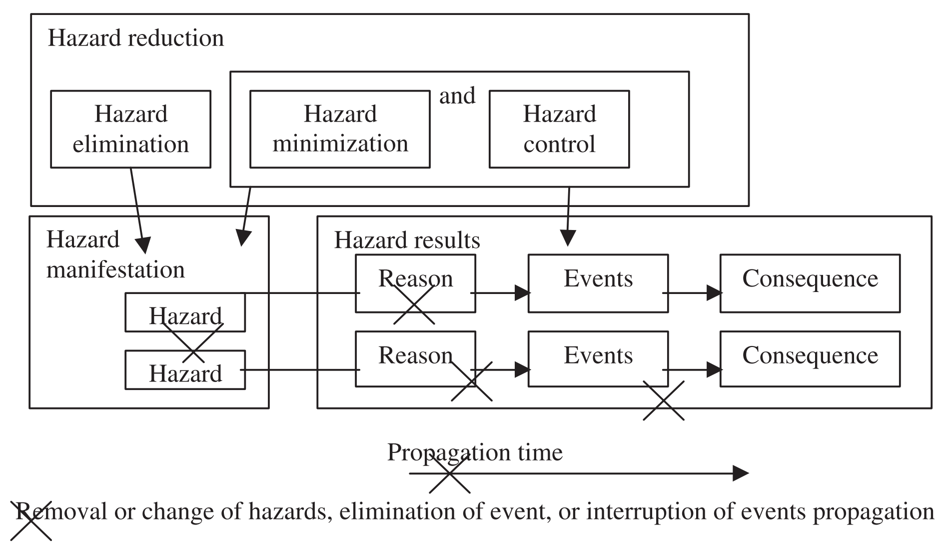

Figure 5.7 Reduction of hazards[11].

32.3 HAZARD ANALYSIS PROCESS

Hazard analysis is the principal deterministic safety analysis which helps engineers and managers to include safety aspects in their engineering practices as well as in their decision-making process throughout the project's life cycle in design, construction, testing, operation, maintenance, repair, and disposal, together with their interfaces. Hazard analysis also offers essential input to the system's safety risk assessment.

This consists of the steps and tasks necessary to identify and classify hazards, and thus to achieve hazard reduction:

- Step 1: define the hazard analysis implementation requirements;
- Step 2: identify and classify the hazards;
- Step 3: decide and act on the hazards;
- Step 4: track, communicate, and accept the hazards.

Figure 5.8 shows a summarized process of hazard analysis.

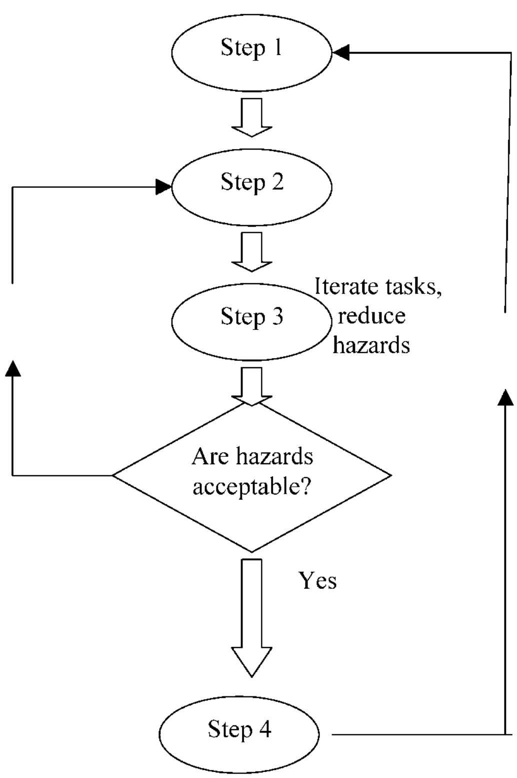

Figure 5.8 The process of hazard analysis[11].

32.4 HAZARD ANALYSIS IMPLEMENTATION

In accordance with ECSS-Q-40-02A the implementation of hazard analysis in a project is based on a single or multiple applications of the hazard analysis process. The tasks required in the individual steps of this process may vary according to the goals and objectives specified for hazard analysis. These goals and objectives are based on the particular type and phase of the project.

Hazard analysis requires commitment in each actor's organization, and the establishment of clear lines of responsibility and accountability. Project management has overall responsibility for the implementation of hazard analysis.

32.5 HAZARD ANALYSIS STEPS AND TASKS

The hazard analysis steps and tasks are presented in detail in standard ESSS-Q-40-02A. The list below gives a brief description.

STEP 1: Define hazard analysis implementation requirements:

Task 1: Define the scope, the objectives of hazard analysis and the hazard analysis planning.

Task 2: Define the system baseline to be analyzed.

STEP 2: Identify and assess the hazards:

Task 3: Identify hazard manifestations.

Task 4: Identify and classify the hazard scenarios.

STEP 3: Decide and act:

Task 5: Decide if the hazards can be accepted.

Task 6: Reduce the hazards.

Task 7: Recommend acceptance.

STEP 4: Track, communicate, and accept the hazards:

Task 8: Track and communicate the hazards.

Task 9: Accept the hazards.

32.6 TECHNIQUES FOR HAZARD ANALYSIS AND ESTIMATING RISK

32.6.1 Preliminary hazard analysis (PHA)

There are numerous techniques for this analysis, each of which usually requires a particular application. In some instances it may be necessary to modify certain details for application to specific machinery.

There are two basic methods of risk analysis: deductive and inductive. In the deductive method the final conclusion is assumed and the events which could cause this final conclusion are then sought. In the inductive method a component's failure is assumed. The analysis which follows can help identify the causes or cause of failure.

PHA is an inductive method whose goal is to make an identification of all phases in the life of a specific system/subsystem/subsubsystem, the hazards, hazardous conditions and hazardous situations which could lead to an accident (IS).The method identifies the possibility of accident and quantitatively evaluates the degree of the possible injuries or damage to health. After that, it is possible to offer proposals for safety measures and to evaluate the results of their application. The goal of PHA is to identify areas which are critical to safety and to identify and evaluate hazards, as well as to identify design and operations requirements which are necessary for inclusion in the program concept phase.

The PHA provides consideration of the following for the identification and evaluation of hazards (EC) :

- Hazard sources (propellants, lasers, explosive, corrosives, pressure systems, and other energy sources);

- Safety-related interface considerations among various parts of elements of the analyzed item, facilities and material capability, electromagnetic interference, fire or explosion initiation and propagation, etc.;

- Environmental constraints, including drop, shock, vibration, noise, extreme temperature, electrostatic discharge, radiation, etc.;

- Maintenance, test, and emergency procedures;

- Safety-related equipment, safeguards and possible alternative approaches (interlocks, monitoring, redundancies, fair protection, personal protective equipment, ventilation, etc.);

- Facilities, support equipment and training.

32.6.2 Physical Simulation of Field Input Influences for Accurate Testing and Prediction

In this inductive method the test procedures give accurate information for analyzing hazards, estimating, and predicting risk as well as effectively solving the risk reduction and protection problems. The problem is that most experiments for traffic crash simulation and testing are based on inaccurate simulation of the traffic and crash situation. This is one of the basic reasons of their low effectiveness (as described in section 25). To increase the above effectiveness one has to use physical simulation of field input influences. This approach is described in detail in Chapter 2.

32.7 HAZARD IDENTIFICATION

All hazards, hazardous situations and hazardous events associated with the machinery need to be identified. Table 5.2 gives examples to assist in this process[7]:

Table 5.2 Examples of hazards, hazardous situations and hazardous events.

No.	Hazards
	Hazard, hazardous situations, and hazardous events
1.	*Mechanical hazards* due to: • machine parts or workpieces, e.g.: 1) shape; 2) relative location; 3) mass and stability (potential energy of elements which may move under the effect of gravity); 4) mass and velocity (kinetic energy of elements in controlled or uncontrolled motion); 5) inadequacy of mechanical strength. • accumulation of energy inside the machinery, e.g.: 6) elastic elements (springs); 7) liquids and gases under pressure; 8) the effect of vacuum.
	1.1 Crushing hazard 1.2 Shearing hazard 1.3 Cutting or severing hazard 1.4 Entanglement hazard 1.5 Draving-in or trapping hazard 1.6 Impact hazard 1.7 Stabbing or puncture hazard 1.8 Friction or abrasion hazard 1.9 High pressure fluid injection or ejection hazard

2 *Electrical hazards* due to:

2.1 Direct contact of persons with live parts

2.2 Indirect contact of persons with parts which have become live under faulty conditions

2.3 Approach to live parts under high voltage

2.4 Electrostatic phenomena

2.5 Thermal radiation or other phenomena such as the projection of molten particles and chemical effects from short circuits, overloads, etc.

3 *Thermal hazards:*

3.1 Burns, scalds and other injuries caused by possible contact of persons with objects or materials with an extremely high or low temperature, by flames or explosions and also by the radiation of heat sources;

3.2 Damage to health caused by hot or cold working environment;

4 *Hazard generated by noise*, resulting in:

4.1 Hearing loss (deafness), other physiological disorders such as loss of balance, loss of awareness);

4.2 Interference with speech communication, acoustic signals, etc.

5 *Hazard generated by vibration:*

5.1 Use of hand-held machines resulting in a variety of neurological and vascular disorders

5.2 Whole-body vibration, particularly when combined with poor posture

6 *Hazard generated by radiation:*

6.1 Low-frequency radiation; microwaves

6.2 Infrared, ultraviolet, and visible radiation

6.3 X-rays and gamma rays

6.4 Alpha rays, beta rays, electron or ion beams, neutrons

6.5 Lasers

---

7 *Hazards generated by materials and substances* processed or used by the machinery:

7.1 Hazards from contact with or inhalation of harmful fluids, gases, mists, fumes, and dusts

7.2 Fire or explosion hazard

7.3 Biological or microbiological (viral or bacterial) hazards

---

8 *Hazards generated by ergonomic principles in machinery design* such as hazards from:

8.1 Unhealthy postures or excessive effort

8.2 Inadequate consideration of hand-arm or foot-leg anatomy

8.3 Neglected use of personal protection equipment

8.4 Inadequate local lighting

8.5 Mental overload and underload, stress

8.6 Human error, human behavior

8.7 Inadequate design, location or identification of manual controls

8.8 Inadequate design or location of visual display units

---

9 *Combination of hazards*

---

10 *Unexpected start-up, unexpected overrun/overspeed* from:

10.1 Failure/disorder of the control system

10.2 Restoration of energy supply after an interruption

10.3 External influences on electrical equipment

10.4 Gravity, wind, etc.

10.5 Errors in the software

10.6 Errors made by the operator (due to attributing to machinery human characteristics and abilities

---

11 *Inability to stop the machine at the most favorable moment*

---

12 *Variations in the rotational speed of tools*

13 *Failure of the power supply*

14 *Failure of the control circuit*

15 *Errors in fitting*

16 *Break-up during operation.* .

.

.

And others

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33 RISK MANAGEMENT

33.1 CONCEPTS OF RISK MANAGEMENT

According to standard ECSS-M-00-03A[9] risk management is a systematic and interactive process which makes the best use of its resources while adhering to the rules of the risk management policy. It adheres to defined roles and responsibilities throughout all the day-to-day activities which the project requires. Risk management helps managers and engineers by including risk aspects in management as well as in engineering practices and judgments throughout the project's life cycle. Everything is performed in an integrated, holistic way, which maximizes the overall benefits, in areas such as:

a) design, construction, testing, operation, maintenance, and disposal, along with their interfaces;

b) control over risk consequences;

c) management, cost, schedule.

This process brings value to the data that are routinely developed, maintained, and reported.

Risk management requires corporate commitment from every company and organization involved, and most importantly the establishment of clear lines of responsibility and accountability from the corporate level downwards. Project management has top responsibility for the implementation of risk management, which includes an integrated, coherent approach for all aspects of the project.

Risk management is a continuous iterative process. It utilizes all the existing components of the project management processes to the utmost extent.

33.2 THE RISK MANAGEMENT PROCESS

The entire spectrum of risks is taken into consideration. Trade-offs are made among different and often competing goals. There is a consideration of ways to mitigate risks which are iterated and accordingly the resulting measurements of performance and risk trends are used to achieve the best possible tradable resources.

ACSS-M-00-03A presents the four-step risk management process of a project (Figure 5.9).

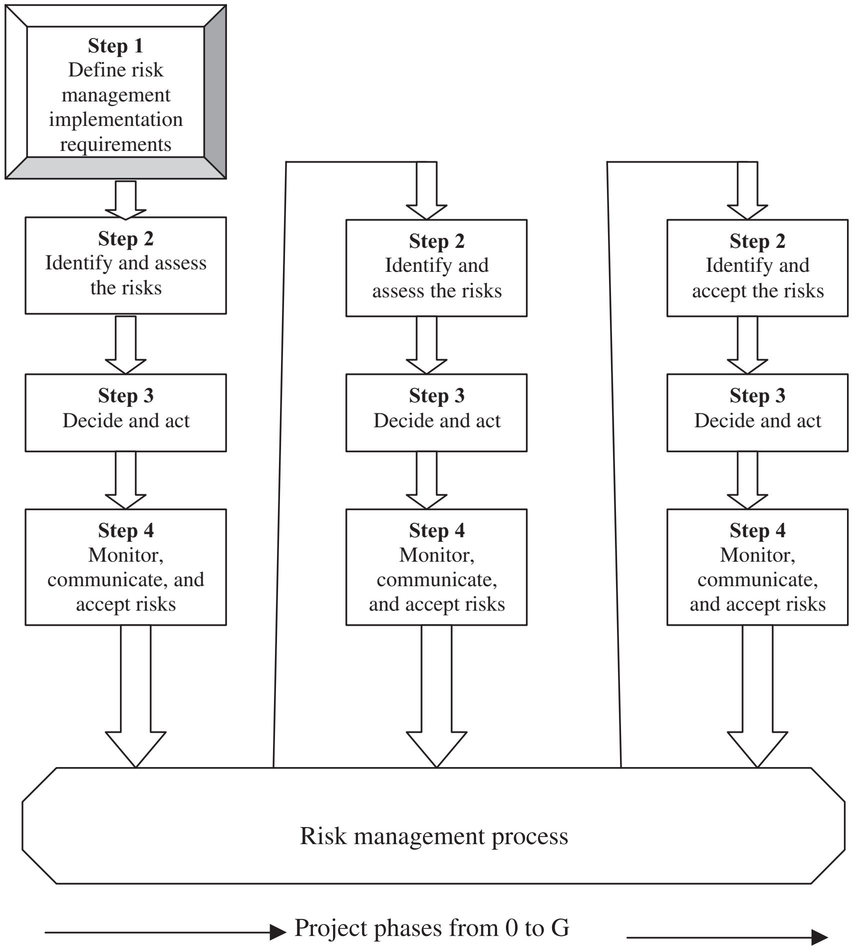

Figure 5.9 The steps and cycles in the risk management process[9].

The tasks to be performed within each of these steps are shown in Figure 5.10. Step 1 comprises the establishment of the risk management policy (Task 1) and risk management plan (Task 2), and is performed at the beginning of a project. The implementation of the risk management process consists of a number of "risk management cycles" over the project duration comprising the steps 2 to 4, subdivided into the seven Tasks 3 to 9.

The period designated in the illustration as the "Risk management cycle" includes the entire project phase of whichever project may be involved. The frequency and project events within the cycles in a project depend on its specifics: these needs are defined in step 1.

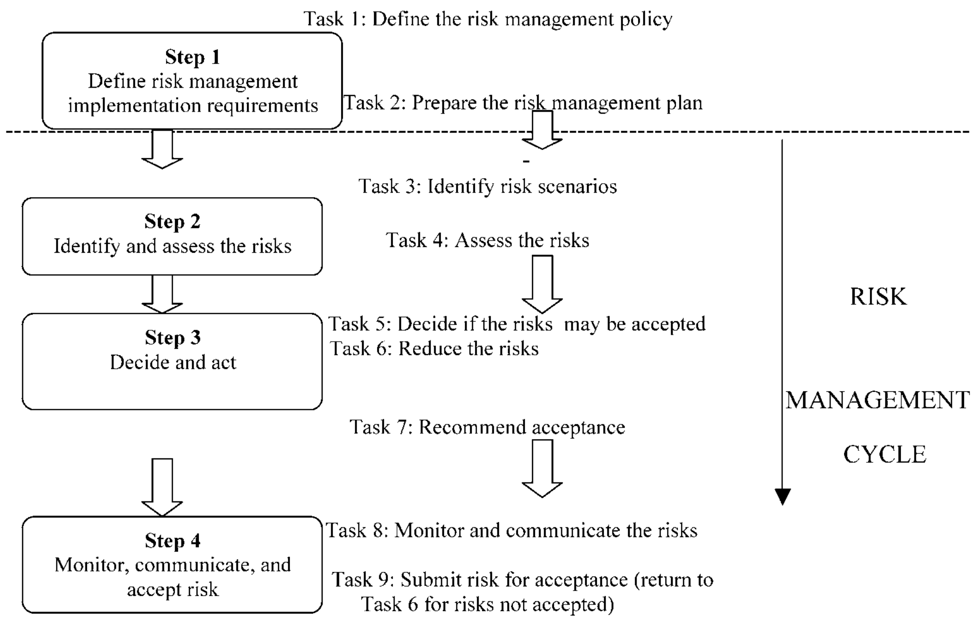

Figure 5.10 The tasks associated with the steps of the risk management process within the risk management cycle[9].

33.3 RISK MANAGEMENT IMPLEMENTATION

As required by the standard[9]:

- Risk management takes place within the normal project management structure thereby

  ensuring systematic risk identification, assessment and follow-up.

- Risk management is implemented as a team effort, with its various tasks and responsibilities assigned according to the functions of individuals within the project's organization who have the most relevant expertise in the areas concerned with a particular risk.

- The results of risk management are part of the routine project management process and include all decisions which are relevant.

The various responsibilities for risk management matters are described in the risk management plan, in which the following method applies[9]:

- The project manager is in charge of all risk management function across the board where projects are concerned. The project manager has complete responsibility for the integrated risk management within a project and must report the results of the risk management task to the next higher level in the project hierarchy. The project manager decides who in the project is responsible for controlling the risk factors in their particular division, as well as having responsibility for all communication, information and reports involving risk management matters;

- Each project division such as engineering, software, verification, schedule control, etc., manages the risks originating in their division, or those designed for attention by their division are then supervised by project management.

The following project activities are involved in risk management:

- Project feasibility studies, trades and analyses (such as design, production, safety, dependability, operations);
- Tasks, manpower and resource allocation according to the ranking of the risk factors;
- The evolution of the technical concept through iterative risk assessment;
- Evaluation of changes for risk impact;
- The development, qualification, acceptance and operation of the particular project using risk assessment as a diagnostic tool as well as for finding necessary corrective actions.

Basic for risk management are the four-step process and nine tasks illustrated in Figures 5.9 and 5.10. The starting point for risk management is the formulation of the risk management policy at the commencement of the project.

Risk management requirements are identified in a structural way for all divisions (such as management, engineering, software, test, operations) using available information such as:

- prior analysis, lessons derived from the testing data, and historical data;
- expert interviews and experience data;
- simulations, test data, and models;
- analysis of all work breakdowns, their structures and levels;
- comparison of goals and plans;
- analysis of resources;
- analysis of proposed changes;
- test results.

Also:

- the risk scenarios shall be assessed;
- the above scenarios shall be analyzed;

- risk shall be reduced in accordance with the risk management policy;
- the overall risk after consideration of the risk reduction shall be determined;
- risk shall be monitored, communicated, and the results displayed;
- risk management shall be implemented at each level of the customer - supplier network.

34 ABOUT SAFETY, CRASH SIMULATORS, AND COMPLIANCE TECHNIQUES

Earlier described current vibration equipment that is the basis for crash simulators. For example, the MTS Crash Simulator[16] is engineered to reproduce the complex crash barrier test profiles required to test the vehicles. This state-of-the-art system features velocity generator propulsion system, a sophisticated digital controller, and simulation program. The result is unparalleled capability for propelling the crash sled and test specimen to the required horizontal accelerations and velocities.

Pendulum Headform Test Systems perform critical interior component tests to facilitate the development of instrument panels, seat backs, and other components corresponding to current safety standards.

Seat Belt Anchorage Test Systems employ computer-controlled hydraulic actuation to test seats and seat belt anchorages for compliance with current safety standards.

Automated Head Restraint Test Systems provide computer-controlled testing of seat backs and head restraints to determine their compliance with required standards.

Analogous test systems are produced by other companies which produce vibration and similar test equipment, etc.

The IST servohydraulic catapult consists of the following main groups[19]:

- Hydraulic actuator with four stage servo valve and piston accumulator unit;
- Hydraulic power supply;
- Carrier sled of lightweight design with 2 – circuit braking equipment and automatic motor-driven positioning system;
- Rail system;
- Computer system with CUNSIM Simulation Software;
- Control cabinet with digital control electronics and programmable logical controller (PLC) for system control and monitoring;
- Peripheral devices.

Many companies offer a range of catapults for this goal. For example, IST[17] proposes below 3 types of catapults (table 5.2). Catapults Type 1 and 2 are commonly used for crash tests with complete car bodies, catapult Type 3 is used for testing car seats. During a side impact the struck car is accelerated by the striking car. Due to the special kinematics occurring during such a side impact (partly elastic deformation of the struck car and tire stick slip effects), the struck car is not only accelerated, but also during some phases of the crash, decelerated.

Table 5.3 Technical specifications of catapults[19].

	Catapult Type 1	Catapult Type 2	Catapult Type 3
Nominal force	2500 kN (562000 lbf)	1600 kN (360,000 lbf)	172 kN (38600 lbf)
Nominal stroke	1700 mm (67 in)	1500 mm (59 in)	500 mm (20 in)
Maximum velocity	75 km/h (46mph)	90 km/h (55 mph)	72 km/h (45 mph)
Maximum acceleration	75 g to 100 g	50 g to 75 g	30 g
Maximum payload	2,000 kg (4400 lb)	2000 kg (4400 lb)	350 kg (770 lb)
Nominal flow servo valve	140000 1/min (37000 gpm)	90000 1/min (24000 gpm)	6000 1/min (1600 gpm)

Unfortunately, often the specific standards in this area, as well as used techniques and equipment cannot accurate simulate of field crash situation, and not accurate reflect the field situation. Therefore, the results of these testing are not correspond to results of field crash situation. As a result, minimal effectiveness of these testing.

For improvement of this situation, one must accurate simulate the real field crash. For this goal one needs to use the methodology described in the Chapter 1 of this book.

35 Trends in the development of some safety problems solutions

1. Introduction

The following relates mostly to safety traffic. But in the example of safety traffic we will show how many potential improvements are involved in the safety problems As Leonard Evans[20] wrote, the traditional approach has fostered attitudes that limits expectations. In specific countries injuries and deaths. The issue of safety risk isn't thought of as an important factor of public health. Huge numbers of casualties are accepted, for the most part as inevitable, and not of great interest to the public in general or to the press. According to how the public perceives the situation, accidents are caused mainly by ongoing bad luck. This view supports the idea that nothing much can be done to improve the picture. The over –used word accident", in itself, substantiated these beliefs. Notions that changes in the design of the vehicles, etc. will be of benefit in lowering accident statistics are unrealistic.

There are well-established norms regarding the determination of success and failure. It is generally accepted that slow and steady progress is about all that can be achieved. Small reduction in risk percentages are considered as major events which in a sense they are. If it is possible to lower the deaths of more than 10,000 people in the world per year that in itself is a step forward.

Even small changes to a number of components of the safety risk system which are now in use could, along with other combined factors greatly lower the inherent dangers. It does not require major expenditures, although development of new technology is of prime importance, but progress itself requires a new relationship between those who are at risk and the established institution which exist to protect them.

2. There are the following trends in the improvement of the safety traffic area[20]:

- The two outstanding factors that above all else determine an individual's risk in traffic area:

- The individual's behavior;

- The behavior of other users.

The individual's behavior is 100% under his or her control, whereas the behavior chosen is greatly influenced by social norms and public policy: most particularly the traffic and risk laws. The role of these factors are weakened, because they attract insufficient public support, and indeed are often the target of public hostility.

The harm caused by second-hand smoke played an important role in reducing smoking. As smokers themselves suffer the harm full effects of smoking to a far greater degree than the reckless drivers themselves are harmed by reckless driving.

Air travelers allow having their luggage searched even though they know it does not contain a bomb. They realize that the only way to stop someone with a bomb is to have all luggage searched, and they willingly submit to intrusive and at times embarrassing searches.

• The extraordinary safety of commercial aviation even though flying is inherently much riskier than road travel. Many people are still afraid of flying. Few people in a motorized society are frightened of driving or being a passenger in a road vehicle. The unusually greater safety of the riskier flying mode occurs for two reasons. First, the primary goal focus is to avoid crashes, and second, pilots strictly follow established driving rules;

• The primary goal is to avoid crashes rather than surviving them;

• Pilots drive by obeying rules, not by experience;

• Enforcement.

There are two major problems which cause traditional traffic law enforcement to be relatively ineffective. First, the probability of detection is low and haphazard. Second, the public has a justifiable suspicion of motivations behind traffic law and their enforcement.

• Enforcement using current technology.

Current technology offers a solution to the traditional enforcement. The technology can bring about dramatic reductions in harm, but only if it is offered in a manner that the public accepts.

A number of automatic enforcement technologies have been developed, and are functioning to some degree in many countries, including the USA, UK, Canada, Australia, New Zealand, and a number of countries in Europe. Some of these technologies are completely automatic, while others make it easier for police to perform their enforcement work more productively than if manual enforcement were involved. Technology to measure following headways and issue tickets for illegal tailgating has been developed and field-tested in Israel. However, the chief application of new technology has been in detecting speeding violations and traffic light laws. If these new technologies are followed, one must consider that reliability of these new, automatic technologies, must be very high.

- Photo radar. This is a system designed to automatically detect vehicles violating the speed limits. It includes a camera and attached radar speed measuring device.

- Ped-light cameras. These are systems designed to automatically detect vehicles entering intersections after the traffic light has turned red. They have four advantages over photo radar. First, manual detection of red-light violations is less efficient because they occur less frequently than speeding. Second, police officers are put at greater risk in manual enforcement than they are in the detection of speeding. Third, this already has greater public support. Fourth, its technical implementation is made easier because the output from the traffic-light signal controllers are available for input to the red-light camera system.

• Advantages of automatic monitoring of driving.

These new technologies are still in the early stages. They have an enormous advantage over manual monitoring. Assigning skilled police officers to monitor traffic is not the best use of valuable public resources. What the human factors perform poorly, technology can perform well at a minimum cost. Automatic monitoring provides the following advantages:

- High probability of detection. It is the probability of detection, not the severity of punishment, which is far more effective at changing motorist's behavior.
- Objectivity and completeness. Inanimate devices are immune from changes based on a caprice or bias. At a given site, all vehicles are monitored. Anyone receiving a legal traffic ticket will not have reason to think that others committing the same act will not also receive one.
- Drunk driving. Traditional enforcement detects about one drunk driver for every 2,000 trips driven by drunk drivers. Apart from sobriety checkpoints, a police officer must observe improper driving before testing for alcohol. Automatic detection is likely to record large numbers of speeding and traffic lights violations by a drunk driver well before there is any real opportunity for a direct manual-enforcement ticket given for drunk driving. The next most effective countermeasure is the sobriety check lane which is expensive and an inconveniences for all drivers.

36. INTRODUCTION TO THE HUMAN FACTORS

Human factors are important components which directly influence the product's quality and reliability, especially safety. Human factors mean how the quality of the product depends on the quality of the people involved in the design, manufacturing, and usage processes.

A well structured and well performed by the human factor can result in an improved safety and efficiency in the operation and maintenance of the product as well as the effectiveness of the design and manufacturing processes to bring about significant cost savings. As an example, one can see 7.5 of this book.

Engineers and managers have to know the role, value, scope, and unique contributions of the field of the human factors. Aimed at the engineer and manager who lack formal training in the life and social sciences, it is not intended to train them in the methods of human factors, but rather to provide knowledge that will enable professionals to determine if including the human factors in the planning and execution of product design and manufacturing is important. One can find the frame of the value and practical applications in a perspective that specifically addresses the human factors[18,25].

In the human factors area, one of the most cost effective means of improving the ergonomic aspect of future vehicle or workplace design is to utilize the rapidly emerging technology referred to as digital human modeling. There is description[18] of seven case studies in which digital human models were used to solve different types of physical problems associated with proposed human-machine interaction tasks.

The value and fidelity of human models depend greatly on the accuracy with which natural human properties and behaviors are measured and reproduced. As a result, new methods must be developed whereby the individual properties can be measured and transformed using mathematical formulations or entered into tables for further analysis. Advances in human measurement techniques have allowed for the measurement of static as well as dynamic and kinematic motions and trajectories of humans.

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