

Introduction

1.1 THE PURPOSE OF ACCELERATED TESTING (AT)

In an AT, one accelerates the deterioration of the test subject beyond what is expected in an actual normal service environment. AT began many years ago with the development of the necessary methodology and equipment. Development continues into the future. As the knowledge about life and the laws of nature evolves, the requirements for products and technologies have also increased in complexity. Thus, the requirements for AT have and continue to increase in scope. Often, AT methods and equipment that were satisfactory in the past are no longer satisfactory today. Those that are good today will not satisfy the requirements of producers and users in the future. This encourages research and development for AT. This process, reflected in the literature, encourages and directs the research and advancement of test disciplines.

Unfortunately, in real life, people who perform AT for industry and other organizations usually do not have the time, incentive, or the opportunity to write books. Authors of AT books unfortunately often know their subject primarily in theory rather than from an actual application of AT. The situation is not better if an author includes such terms as “practical,” “practice,” or “practitioner’s guide” in the title of the publication. As a result, most books on AT do not demonstrate *how* to conduct testing or identify what type of testing facility and equipment is appropriate, and they also neglect to identify the benefits of one method over another. Publications usually fail to show the long-term advantages and savings accruing from an investment in more

expensive and advanced testing equipment to increase product quality, reliability, durability, and maintainability while reducing the development time and decreasing a product's time to market. How can one accomplish this? One must provide a combination of practical and theoretical aspects for guidance and use.

The basic purpose of AT is to obtain initial information for issues of quality, reliability, maintainability, supportability, and availability. It is not the final goal. It is accomplished through prediction using the information provided by AT under laboratory (artificial) conditions. The most effective AT of a product design needs to occur under natural (field) conditions. AT design and the selection of appropriate testing parameters, equipment, and facilities for each method or type of equipment to be tested must be coordinated to provide the test inputs and results that are most beneficial for the quality, reliability, or maintainability problems that the test identifies. An AT design is very important in determining how accurate the decision process is in selecting the method and type of equipment to use.

Quality, reliability, durability, and maintainability are factors that are not separable. They are interconnected, have complex interactions, and mutually influence each other. This complex represents the parameters and processes needed to conduct AT and includes simulation, testing, quality, reliability development, maintainability, accurate prediction, life cycle costs, field reliability, quality in use, and other project-relevant parameters and processes. AT is a component of a complex supporting the design, manufacturing, and usage processes, and its benefits depend on how one configures the complex for optimization.

If industrial companies would properly apply this optimization process, then they would choose more carefully among the many popular current test methods and types of equipment such as highly accelerated life testing (HALT), highly accelerated stress screening (HASS), accelerated aging (AA), and others to use them for the accurate prediction of reliability, durability, maintainability, supportability, and availability. It is verifiable that buying simple and inexpensive methods and equipment for testing becomes more expensive over a product's life. It is also true for a simulation as a component of an AT, evaluation, and prediction. A basic premise of this book is that the whole complex needs to be well-thought-out and approached with a globally integrated optimization process.

1.2 THE CURRENT SITUATION IN AT

The following presents three basic approaches for the practical use of AT as shown in Figure 1.1.

1.2.1 The First Approach

The first approach is special field testing with more intensive usage than under a normal use. For example, a car is usually in use for no more than 5–6 h/day.

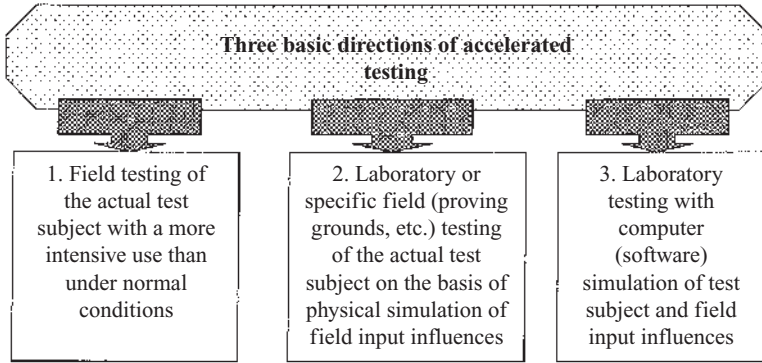


Figure 1.1. The basic directions of accelerated testing.

If one uses this car 18–20 or more hours per day, this represents true AT and provides enhanced durability research of this car’s parameters of interest. This is a shorter nonoperating interval than normal (4–6 hours instead of the normal 18–20 hours). The results of this type of test are more accelerated than they would be under normal field conditions.

This type of AT is popular with such world-class known companies as Toyota and Honda; they call it “accelerated reliability testing” (ART). For example, in the report of the U.S. Department of Energy (DOE), INL/EXT 06-01262 [5], it was stated that

A total of four Honda Civic hybrid electric vehicles (HEVs) have entered fleet and accelerated reliability testing since May 2002 in two fleets in Arizona. Two of the vehicles were driven 25,000 miles each (fleet testing), and the other two were driven approximately 160,000 miles each (accelerated reliability testing). One HEV reached 161,000 miles in February 2005, and the other 164,000 miles in April 2005. These two vehicles will have their fuel efficiencies retested on dynamometers (with and without air conditioning), and their batteries will be capacity tested. Fact sheets and maintenance logs for these vehicles give detailed information, such as miles driven, fuel economy, operations and maintenance requirements, operating costs, life-cycle costs, and any unique driving issues

Another example is cited by Frankfort et al. [6] in the *Final Report of the Field Operations Program Toyota RAV4 (NiMH) Accelerated Reliability Testing*. This field testing took place from June 1998 to June 30, 1999 corresponding to the Field Operation Program established by the U.S. DOE to implement electric vehicle activities dictated by the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976. The program’s goals included evaluating electric vehicles in real-world applications and environments, advancing electric vehicle technologies, developing the infrastructure elements necessary to support significant electric vehicle use, and increasing the

awareness and acceptance of electric vehicles. The program procedures included specific requirements for the operation, maintenance, and ownership of electric vehicles in addition to a guide to conduct an accelerated reliability test. Personnel of the Idaho National Engineering and Environmental Laboratory (INEEL) managed the Field Operation Program. The following appeared in the final report:

One of the field evaluation tasks of the Program is the accelerated reliability testing of commercially available electric vehicles. These vehicles are operated with the goal of driving each test vehicle 25,000 miles within 1 year. Since the normal fleet vehicle is only driven approximately 6,000 miles per year, accelerated reliability testing allows an accelerated life-cycle analysis of vehicles. Driving is done on public roads in a random manner that simulates normal operation.

This report summarizes the ART of three nickel metal hydride (NiMH) equipped Toyota RAV4 electric vehicles by the Field Operation Program and its testing partner, Southern California Edison (SCE). The three vehicles were assigned to SCE's Electric Vehicle Technical Center located in Pomona, California. The report adds "... To accumulate 25,000 miles within 1 year of testing, SCE assigned the vehicle to employees with long commutes that lived within the vehicles' maximum range. Occasionally, the normal drivers did not use their vehicles because of vacation or business travel. In that case, SCE attempted to find other personnel to continue the test."

A profile of the vehicle's users from Frankfort et al. is presented in Table 1.1. This is a useful work in many areas, but practice shows that this type of field testing is not applicable for an accurate reliability, durability, and maintainability prediction, by this book's definition and methodology, for several reasons:

1. Many years of field testing for several specimens are necessary to gather initial information for an accurate quality, reliability, and maintainability prediction during a given period. This book proposes a methodology and equipment that can accomplish this at a much faster pace and at a lower cost.

TABLE 1.1 Profile of Vehicle Users [2]

Vehicle Number	1	2	3
Normal round-trip commute (miles)	60	120	82
Other daily mileage—lunch, business, and so on (miles)	50 (one to two times per week)	20–30	10–40
Average weekly mileage	410	501	524

2. An industrial company usually changes the design and manufacturing process of its product every few years, not always on a regular basis. In this situation, test results of a previous model's testing have only relative usefulness, but they are not directly applicable.
3. Field testing can only provide incomplete initial information for solving problems related to an integrated system of quality, reliability, and maintainability as will be shown in this book.
4. A combination of laboratory and field testing is more useful for finding a solution to these and many other problems.

These problems show that after describing its field testing, and the tests of the above-mentioned models, Toyota still had many problems in reliability and safety that led to recalls, complaints, degradation, and failures. Consider one more example from Toyota's practice. The report *Hybrid Electric Vehicle End-of-Life Testing on Honda Insight* [7] stated that "Two model year 2004 Toyota Prius hybrid electric vehicles (HEVs) entered ART in one fleet in Arizona during November 2003. Each vehicle will be driven 160,000 miles. After reaching 160,000 miles each, the two Prius HEVs will have their fuel efficiencies retested on dynamometers (with and without air conditioning), and their batteries will be capacity tested. All sheets and maintenance logs for these vehicles give detailed information such as miles driven, fuel economy, operations and maintenance requirements, operating costs, life-cycle costs, and any unique driving issues . . ."

In fact, this was an accelerated field test performed by professional drivers for short periods of time (maximum of 2–3 years). This testing cannot provide the necessary information for an accurate prediction of reliability, life cycle costs, and maintenance requirements during a real service life since it does not take into account the following interactions during the service life of the car:

- The corrosion process and other output parameters, as well as input influences that act during a vehicle's service life
- The effects of the operators' (customers') influences on the vehicle's reliability because it was used by professional drivers during the above testing
- The effects of other real-life problems

Mercedes-Benz calls similar testing "durability testing." For example, the test program for the new Mercedes-Benz C-Class stated in Reference 8 "... For the real-life test that involved 280 vehicles they were exposed to a wide range of climatic and topographical conditions. Particularly significant testing was carried out in Finland, Germany, Dubai, and Namibia. The program included tough 'Heide' endurance testing for newly developed cars, equivalent to 300,000 km (186,000 mi) of everyday driving by a typical Mercedes customer. Every kilometer of this endurance test is around 150 times more

intensive than normal driving on the road, according to Mercedes. Data gathered are used to control test rigs for chassis durability testing . . .”

A similar situation existed with a Ford Otosan durability testing in 2007. It was stated in the article “LMS Supports Ford Otosan in Developing Accelerated Durability Testing” [9] that “Ford Otosan and LMS engineers developed a compressed durability testing cycle for Ford Otosan’s new Cargo truck. LMS engineers performed dedicated data collection, applied extensive load data processing techniques, and developed a 6-to-8-week test track sequence and 4-week accelerated rig test scenario that matched the fatigue damage generated by 1.2 million km of road driving.”

Companies specializing in testing areas often find similar situations. For example, in the note about MIRA’s (MIRA Ltd.) durability testing [10], it was stated in the Proving Ground Durability Circuits & Features that MIRA’s proving ground is used extensively for accelerated durability testing (ADT) on the whole vehicle in addition to these traditional durability surfaces:

- Belgian pave
- Corrugations
- Resonance road
- Stone road

Many other proving ground surfaces and features serve to build up a track base equivalent to real-world road conditions.

Referring to different sources about proving ground testing published 30–40 years ago, in The Nevada Automotive Test Center (NATS) [11], in Kyle and Harrison [12], and in others, one will see that similar proving ground stress testing was used for obtaining initial information for machinery strength and fatigue. Professionals understand that this type of testing cannot offer the information for an accurate prediction of a test subject’s durability and reliability because it does not take into account the

- Environmental factors (temperature, humidity, pollution, and sun exposure) and their effect on a product’s durability and reliability during its warranty period or service life
- Random character of real input influences that affect a product’s performance in the field
- The type of data simulation required for system control is not capable of being simulated during a proving ground test
- Many other real-life tests cannot be simulated on the proving ground

Many authors often ignore the above-mentioned points, especially in publications of companies that design, produce, and use the equipment or methodology for AT. Therefore, this flawed reasoning occurs in many publications that relate to reliability or durability testing.

1.2.2 The Second Approach

The second approach is to use accelerated stress testing (AST). For example, if one conducts research upon or tests the actual car using a simulation of the field input influences with special equipment (vibration test equipment, test chambers, and proving grounds), then the level of the car (or other product) loading is higher than it is in normal usage. In this case, there is a physical simulation of the field inputs on the actual test subject. In most instances, there is a separate simulation of each of the field input influences such as temperature, humidity, sun exposure, pollution, or several of the many field inputs. Therefore, this type of testing does not offer the possibility of obtaining an accurate quality and reliability prediction and of conducting accelerated development.

The level of inaccuracy of this prediction depends upon the level of inaccuracy of the simulation of field input influences, safety problems, and human factors. More details for this situation are provided later in this book.

1.2.3 The Third Approach

This approach relies on using a computer (software) simulation or analytical/statistical methods. A computer simulation is a “computer program that attempts to simulate an abstract model of a particular system” (Wikipedia).

Computer simulations have become a useful part of the mathematical modeling of many natural systems in physics, chemistry, and engineering. They help to gain insight into the operation of those systems. Wikipedia classifies computer models according to several criteria:

- Stochastic or deterministic (and as a special case of deterministic, chaotic)
- Steady-state dynamic
- Continuous or discrete (and as an important special case of discrete, discrete events, or discrete event models)
- Local or distributed

Simulation results are different from actual results.

A simulated test subject is different from the actual test subject, and simulated field input influences are different from the actual field input influences. The results of a reliability and quality prediction and evaluation using computer (software) simulation show a greater difference from the appropriate field results than results from using methods 1 and 2 mentioned earlier. This is attributable to a greater difference from a real field environment. Two examples show the economics of software simulation: “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 the American’s National Institute of Standards (NIST), a government

research body, found that software errors cost the American economy \$59.5 billion annually” [13]. Currently, this approach is in the early stages of development and is more popular with professionals in the software development field.

It is often popular with customers because it is less expensive and less complicated than methods 1 and 2. The following tests are included in computer simulation methods: fixed duration, sequential, test to failure, success test, reliability demonstration, reliability growth/improvement, or others. This book does not address these types of testing. They include qualitative accelerated tests, quantitative accelerated tests, or quantitative time and event compressed testing.

1.2.4 The Second Approach: A More Detailed Review

One common example applies to the following discussion. When Boeing wanted to produce a sensor system for satellites with minimum expenditures, the company specialists decided not to conduct the subsystem testing until they mounted the subsystems with more complicated components to provide testing for the entire block. This approach required more funding than planned. The subsystems that had not been tested had failures that led to the failures of completed blocks, which then had to be dismantled and reassembled [14]. This approach complicates the problem of finding the root cause of failures. Therefore, costs were higher and more time was required to complete testing and reassembly.

There are several approaches to AT, and it is important to differentiate among them because each approach needs its specific techniques and equipment. The effectiveness of these approaches sometimes depends upon the complexity of the product. It sometimes depends on the complexity of the operating conditions for the product, including the need for one or several climatic zones of usage and indoor/outdoor usage. For example, electrode testing requires simpler techniques and equipment than engine testing. Devices or vehicles having indoor applications do not need solar radiation testing. The testing approach for devices that operate for a short period of time needs to be different from the testing approach for devices that operate for a long period of time for greater testing effectiveness. In general, there are three basic methodological concepts to the second approach of AT. Let us briefly describe them:

1. Accelerate the test by reducing the time between work cycles. Many products experience brief usage during a year. Therefore, one can test them by ignoring the time between work cycles and the time with minimal loading that has no influence on the product degradation or failure process. For example, most farm machinery, such as harvesters and fertilizer applicators, have seasonable work schedule. Harvesters work only several weeks during a year. If this work occurs 24 hours a day with an average field loading, one accumulates the equivalent of 8–10 years of

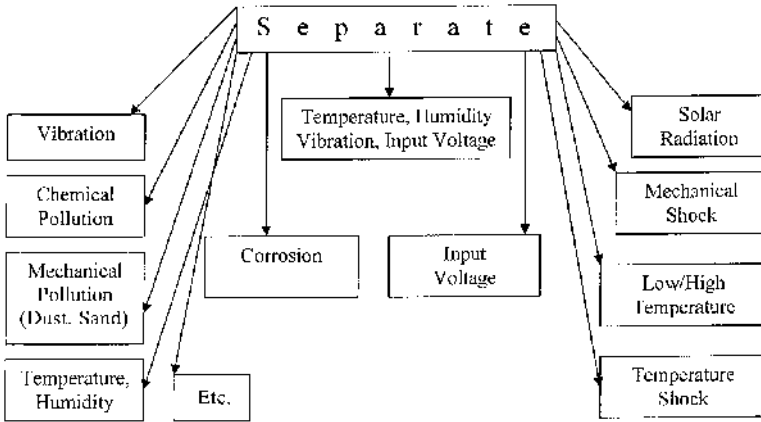


Figure 1.2. Example of separate types of simulation and accelerated stress testing during design and manufacturing.

field operation in several months. The same principle relates to aircraft testing. However, this approach ignores the degradation process during storage time (corrosion and other environmental influences, as well as its contact with mechanical and other factors). Therefore, for reliability/durability testing, one has to take into account stress from the above-mentioned factors.

2. Accelerate the test using stresses. Most industrial companies use this approach to testing (Fig. 1.2).
3. Acceleration through high-level stresses. This method involves increasing the intensity of stress factors. Stress factors accelerate a product's degradation process in comparison with its normal usage. There are many types of higher-level stresses that occur under normal usage: higher loading (tension), higher frequencies and amplitudes of vibration, and a higher rate of change in input influences (temperature, humidity, higher concentration of chemical pollutions and gases, higher air pressure, higher voltage, higher fog, and dew). This approach is often used and is beneficial if the stress does not exceed the given limit. This approach is relatively simple and effective for raw materials and simple components. But often, it applies stresses that are higher than the field stresses and for complicated components or for the entire equipment. The above-mentioned testing approach relates to most types of current AT, including HALT [15], AA [16], and [17], and HASS [18]. Often, these tests are incorrectly called "ADT" or durability testing.

HALT is a process that uses a high-stress approach in order to discover design limitations of products. HALT usually includes two parameters:

vibration and temperature [19]. The following example demonstrates HALT and HASS testing.

System Performance

- HALT/HASS temperature range: -100 to 200°C
- HALT/HASS temperature change rate: 60° per minute
- HALT/HASS temperature stability: $\pm 1^{\circ}\text{C}$ after stabilization
- HALT/HASS vibration type: repetitive shock and triaxial noncoherent testing: The product experiences 6 degrees of freedom during broadband random vibration
- HALT/HASS working area ranges: $30\text{--}48'' \times 40\text{--}48'' \times 36\text{--}48''$ high
- HALT/HASS maximum vibration power: 60 g
- HALT/HASS frequency ranges: $5\text{--}5000$ Hz and $5\text{--}20,000$ Hz

HASS: Apply high stress levels to reduce the reliability stress screening (RSS) time as much as possible. However, do not exceed the specifications of the operational limits of components unless it is a management decision. RSS is a reliability screening process using environmental and/or operational stresses as means of detecting flaws by inducing them as detectable failures.

Combined stresses, combined temperature change, and vibration or bumps are especially efficient for stimulating flaws as failures. Before starting the RSS with its high stress levels, the operational limits for the assemblies must be determined. Furthermore, by repeating the RSS cycle a large number of times, it must be proven that the planned RSS cycles reduce the lifetime of the assemblies to an insignificant degree, even during repeated RSS due to the repairs of induced failures.

Perform the screening process under consideration at the subsystem level of the manufacturing system. The planning includes a number of steps:

Step 1. Specify the maximum allowable fraction of weak assemblies.

Perform this step by examining the requirements for the end product including the printed board assembly (PBA) as a subsystem. In this case, no other parts of the end product contribute to early failures. Therefore, the acceptable fraction of weak assemblies that remained after reliability screening is the same for the end product and the PBA.

Step 2. Evaluate the actual fraction of weak assemblies. Calculations in Steps 1 and 2 are required. In this case, there are two rogue component classes: integrated circuits (ICs) and power transistors. It is necessary to reduce the fraction of early failures by an order of magnitude before including the PBA in the end product.

Step 3. Consider the stress conditions. First, identify the flaws that one expects to induce during the assembly process.

For ICs, the following may appear:

- Partial damage of the internal dielectric barriers due to electrostatic discharge (ESD) in the production handling
- Formation of cracks in the plastic encapsulation due to a difficult manual production process

Transistors may appear to have the formation of cracks in the plastic encapsulation due to a difficult manual production process.

Users of the above-mentioned approaches, especially AA, claim that after several days of testing, they can obtain results equivalent to several years of field results. They call these approaches reliability and durability testing. To achieve an accurate field simulation, one has to carefully use and truly understand a high level of acceleration.

Practically, if one wants to obtain accurate initial information for an accurate prediction of product reliability or durability, then one has to take into account that the most current test equipment may only be able to simulate one or a few of the field inputs. But many actual environmental influences such as temperature, humidity, chemical and dust pollution, and sun radiation act simultaneously with many mechanical, electrical, and other influences. Most of the current test equipment simulate these actions (or only a part of the real input complex) separately. Therefore, users tend to implement these parts of the environmental influences separately. As a result, this equipment is not appropriate for accelerated durability, reliability, or environmental testing.

This circumstance applies to the methodology and equipment that simulates not only one type of input influence (e.g., temperature) but also two (temperature and vibration), and three types (temperature, vibration, and humidity) of input influences. The same is true for mechanical and other types of testing. The companies that design and manufacture equipment for AT and especially the users of this equipment should ask themselves, “What can we evaluate or predict after testing? How extensively can we simulate the field environment?” If one wants to cause the product to fail more quickly than in the field, then it is necessary to ask a second question: “How is the product degradation process in the field similar to the degradation process during AT?”

Those who have a high level of professional experience in practical AT for product development and reliability/durability prediction will agree that one cannot accurately predict product durability and reliability if only a part of the field environment is simulated. To solve this problem, some who work in the area of accelerated product development use HALT, AA, and other types of AST with a high level of stress to quickly obtain test results. So, in a few days, one can obtain test results that compare adequately to a few years of use in the field. For example, “When a 10-year life test can be reduced to 4 days, you have time to improve reliability while lowering cost” [16]. This method is simple because the intense stress applied for a short time period is sufficient to determine the results quickly. Also, the equipment is less expensive.

However, what is the quality of these results? The quality of these results is poor. The basic reason for poor results is that by using this approach, one cannot obtain the physics-of-degradation (or the chemistry degradation) mechanism that would be similar to the one obtained in the field physics-of-degradation (or the chemistry degradation) mechanism. Therefore, this approach cannot provide a sufficient correlation between ART/ADT results and field results. If one takes measurements of the time of failure during an AT, it is still impossible to know how accurately these measurements represent the time of failure taken in the field. Moreover, testing may destroy the product during ART/ADT or may show failures in the laboratory that do not occur in the field, because the level of temperature and vibration is higher than in real life.

Today the automotive, aerospace, aircraft, electronic, farm machinery, and many other industries often utilize this approach with minimal success. The accelerated test results (reliability and maintainability) are different from the field results. Consequently, product development, reducing complaints, and recall facilitation need more time, incurring an associated delay in product availability, a decrease in sales numbers, higher production costs, and a decrease in customer satisfaction. Most highly educated professionals in these areas monitor the stress level very carefully and use the physics-of-degradation mechanism as a criterion of simulation. To conduct AT for a unit of electronic equipment, they often combine a minimum of three parameters in the test chambers simultaneously with a minimum level of stress. These parameters include temperature (humidity), multiaxis vibration, and input voltage.

More negative aspects of this approach follow. Those who have practical experience in AT know that one cannot estimate the acceleration coefficient of the whole product (car or computer) or the unit during a test of the whole product or its units (which consist of different assemblies, and each assembly has a different acceleration coefficient). Therefore, if we know the time to failure for different components of the whole product during an AST, we still cannot accurately estimate the time to failure and other reliability parameters of the whole product or unit during real life. This is true because the ratio of the acceleration coefficients (the ratio between the AT time and the field time) for the failures of the test subject elements varies too widely.

This relates to the situation shown in this book when different subunits interact with each other and cause possible failures to disappear. However, additional new subunit failures also appear. Thus, we have nonlinear combinations. For example, for different parts of caterpillar units, the ratio of failure acceleration varied from 17 to 94 [20]. In this case, it is impossible to find the reliability parameters for the whole caterpillar device. One of the research conclusions was that “This confirms the practical impossibility of selecting the regime of AST that will give the ratio of loading of all parts and units of the complete device that will correspond to field” [20].

J.T. Kyle and H.P. Harrison [12] wrote more than 40 years ago that “. . . 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.” Therefore, this approach to AT is one of the basic reasons why one cannot obtain a sufficient correlation between the AT results and the field results.

Test equipment (chambers) for the automotive industry usually includes a volume from 0.5 to 500 or more cubic meters. Accelerated environmental testing (AET) results of electronics, automobiles, aerospace, aircraft, and other types of products all experience similar negative results.

Specific areas of industry have specific types of AT. For example, AT of farm machinery can be

- In the field
- On special experimental proving grounds
- On special test equipment in the laboratory
- Any combination of the above tests

It can be a complex testing of entire machines or testing of components or combinations of components.

Usually, complex testing of an entire machine occurs in the field and at proving grounds. Components and their combinations are tested at proving grounds and on laboratory equipment. At proving grounds, it moves the whole machine but usually tests only the components of the machine, mostly the body. In the field, one can also test new or modern components that are components of entire machines. Methodological aspects of current AT in the laboratory vary depending on the specifics of test subjects and operating conditions. In general, laboratory AT uses various methods of loading such as

- Periodic and constant amplitude loading
- Block-program stepwise loading
- Maximum stress loading
- Maximum simulation of basic field loads in simultaneous combinations

It is important to consider a load process while analyzing field environments and testing performances, especially when stress testing (AST) is used. One has to identify and evaluate different levels of real-life input influences (loads) and how to account for them when performing an accelerated test. In this case, we classify accelerated tests as constant stress, step stress, cycling stress, or random stress. The highest level is random stress, because it is closer to the real world. In the real world, all loads for mobile equipment, as well as many loads for stationary equipment, have a random character. A field simulation using other types of stress is not accurate, but it has a lower cost. Often people prefer lower cost simulations and tests, but they ignore the consequent increase in costs for the subsequent work during design and manufacturing. If they would take this into account, they would understand that a less expensive test

in actuality becomes more expensive and produces more problems and delays during design and manufacturing phases. During testing, one cannot find the real-world degradation and failures and accurately predict field reliability, durability, recalls, time to market, and the cost of maintenance. The least expensive test is the one that uses constant stress, and the constant stress test causes more problems for the subsequent processes.

There are two possible stress loading scenarios: loads in which the stress is time independent and loads in which the stress is time dependent. For a mathematical analysis, models and assumptions vary depending on the relationship between stress and time. Similar to the discussion in the previous paragraph, time-independent stress and loading is the cheapest and simplest to conduct but becomes more expensive and needs more time for subsequent design, research, and manufacturing processes.

In Figure 1.3, one can see the basic reasons that AST often cannot help to accurately predict reliability and durability.

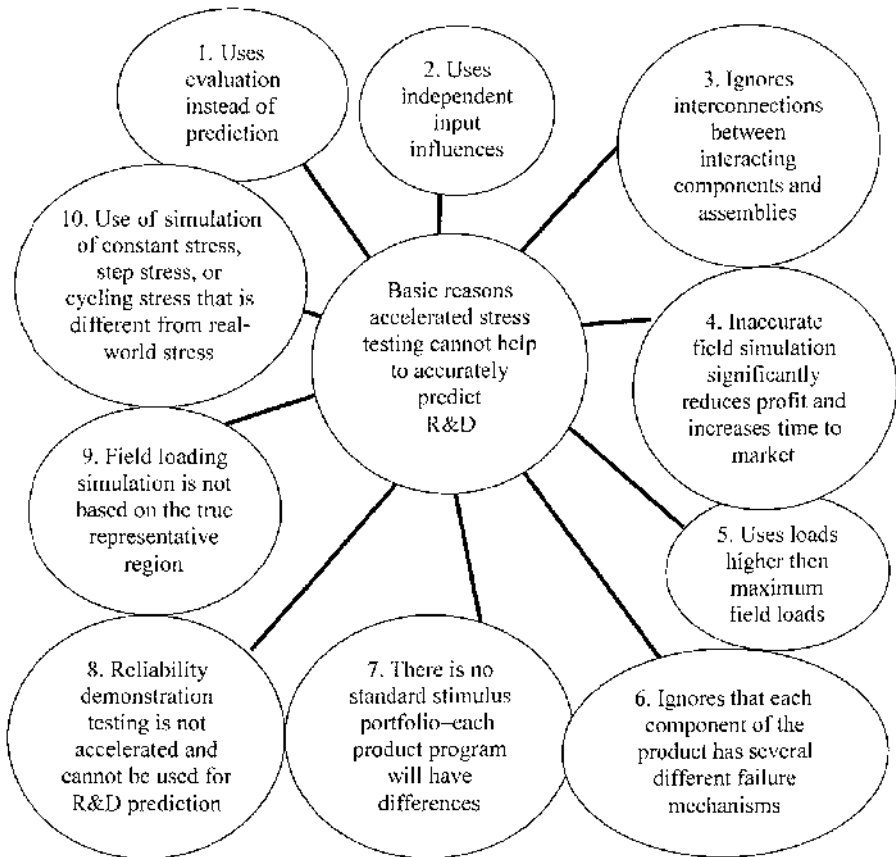


Figure 1.3. Reasons one-dimensional accelerated stress testing makes often incorrect predictions.

AST requires the extensive use of universal and specific test equipment and proving grounds for automobiles, tractors, tanks, farm machinery, and off-highway machinery on concrete and other surfaces. Usually, a number of tracks/surfaces exist in one particular section of the proving ground that is equipped with a drainage system. The procedure for testing under these conditions follows from the principle of a substantial increase in the frequency of application of the maximum working loads. For an accelerated environmental stress test, the increase in temperature, humidity, and/or air pressure makes sense.

The AT of vehicles, tractors, tanks, farm machinery, off-highway vehicles, and other mobile products occurs on specially equipped proving grounds designated for

- Wheeled machine frames by running them under various conditions along a racetrack set with obstacles
- Investigation of the coupling properties of wheeled machines, tool carriers, and wheeled tractors on a concrete track
- Testing of tanks, tractors, agricultural machines, and other mobile vehicles in abrasive media (in bath)

To improve working conditions, in addition to more rationally using the testing time and creating a higher level of testing conditions, one can use an automatic system of control. Usually, this control system includes the following basic components:

- A system to automatically drive a machine along the proving ground track and operate its attachments
- A remote control system for the unit's operating schedule
- A system for the prevention of damage

AST is also applicable to laboratory equipment (universal and specific) found in proving ground test centers. These are different types of vibration equipment, dynamometers, and test chambers. When this equipment is used for an accelerated test for engines of mobile products, the permissible limits of wear on components such as cylinders, pistons, connecting rods, and crank assemblies can be determined quickly. Artificially increasing the dust content of the intake air and introducing solid particles into the crankcase oils accelerates engine component wear. These current methods and equipment for AT simulate primarily separate components or subcomponents of field input influences for the real field situation. Chapter 5 describes the testing equipment in more detail.

Some authors have believed accelerated durability testing or durability testing are related to this category of AT. In Reference 21, P. Briskman considered a cycling stress test to be a durability test. This fails to take into account

the real-life input influences on the test subject. For example, the Bodycote Testing Group [22] considered environmental testing to be durability testing. Another example, taken from the article “Full Vehicle Durability” from the RGA Research Corporation, shows that “. . . There are six test tracks with over 30 different types of surfaces available for full vehicle durability tests.” But proving ground testing is not accurate durability testing as previously described. In one more example, C.E. Tracy et al. [23] considered ADT of electrochromic windows. They wrote: “. . . The samples inside the chamber were tested under a matrix of different conditions. These conditions include cycling at different temperatures (65, 85, and 107°C) under irradiance, cycling versus no-cycling under the same irradiance and temperature, testing with different voltage waveforms and duty cycles with the same irradiance and temperature, cycling under various filtered irradiance intensities, and simple thermal exposure with no irradiance or cycling.” The above-mentioned citation equating a proving ground test to a durability test is another example of a misconception of what “durability test” or “reliability test” actually means. As one can see from the above, the cycling test is not an “accelerated durability test” because in a field environment, a change of input and output parameters has a random character, but not in cycling.

The use of reliability and durability testing terms in the scientific literature often misleads practical engineers. The term “reliability testing” (“ART,” durability testing, ADT) is often blocked out by other words or phrases that change its meaning. This happens most of the time in theoretical discussions, and sometimes it occurs in standards. For example, “accelerated reliability demonstration,” “acceleration of quantitative reliability tests,” “acceleration reliability compliance or evaluation tests,” “acceleration reliability growth tests,” and other terms are inappropriate to represent ART.

1.2.5 Durability Testing of Medical Devices

The application of ART/ADT in this book relates not only to mobile equipment but also to stationary equipment. A current situation in AT, especially durability testing, for one group of stationary equipment, medical devices, will be examined. There are many publications [24, 25, 31] that address building state-of-the-art durability and fatigue testing devices for biomaterials, engineered tissues, and medical devices such as stents, grafts, orthopedic joints, and others. Real-time computer control, electrodynamic mover technology, and laser measurement and control options are just some of the features of these test systems. Mechanical testing is a critical step in the development of medical devices. Medical Device Testing (MDT) Services provides a wide variety of mechanical tests from the U.S. Food and Drug Administration (FDA), American Society for Testing and Materials (ASTM) International, and International Organization for Standardization (ISO) medical testing requirements. Some of these tests are

- Stent testing
- Graft testing
- Intravascular medical device testing
- Orthopedic medical device testing
- Dental implant and materials testing
- Biomaterials evaluation testing

However, medical device durability testing has similar negative features as described earlier for the AT of mobile products. Let us begin with durability testing formulation. For example, as the Orthopedic and Rehabilitation Devices Panel of the Medical Devices Advisory Committee [28] described: “The durability testing of medical devices should involve cyclic loading testing several loading models (e.g., flexion/extension, lateral bending, and axial rotation) and involve a maximum of six samples of the worst-case construct out to ten million cycles. This test can incorporate all testing directions into one test or conduct separate tests for each loading mode. Durability testing establishes loading direction, stability of the device, and the potential to cause wear. Clinical justification for the loads and angles chosen should be provided.”

As we can see, the above-mentioned test requirements have the same negative features as the description of mobile product tests for farm machinery or the automotive industry product tests that were created 50 or more years ago. In industrial areas, professionals came to the conclusion many years ago that this test could not offer satisfactory initial information for an accurate prediction of durability, reliability, and maintainability in a real-world situation. This is true since this type of testing does not take into account real factors such as

- The speed of change for the real stress processes
- A random character of loading in a real situation
- A simultaneous combination of many factors that influence durability in a real environment

Additionally, this type of testing does not provide an accurate simulation of the whole complex of factors in a real field situation. For example, a heart attack is often the result of a sudden high stress, not step-by-step stresses.

“The 10 million cycles” approach is one used for metals (or other materials). However, it should not be used for devices constructed from these metals because this approach does not take into account local concentrations of tension within these devices.

Consider in more detail some examples of durability testing of vascular stents. The 2005 FDA Guidance document [29] outlines durability testing requirements for vascular stents for use in the United States. According to this document, the primary purpose of testing the materials and structure of a device is to provide accurate initial information to accurately predict the

performance of the device during its intended use. Apply finite element analysis (FEA) models to determine regions of high stress or strain in a design under specific boundary conditions. A major variable in properly preparing the finite element model is the accurate measurement of properties of the representative materials, including all processes and treatments on appropriately sized material. Reliable test data on relevant samples of material for the device are critical for a successful FEA model. To properly test the device, it is important to identify potential failure modes for the device during normal use. Typically, an early step in the creation of a new device design is to identify potential failure modes that could occur with the device to determine the effects of these modes. This is the failure modes and effects analysis (FMEA).

For example, a typical FMEA for a balloon-expandable metallic stent may include the following [30]:

- The stent slips off of the delivery catheter prior to inflation.
- The stent snags the vessel during transition to the deployment site.
- The stent exhibits structural failure, that is, breakage of a strut
 - Due to crimping on the balloon
 - Due to expansion of the balloon
 - Due to cyclic distension of the vessel resulting from the pressure change caused by each heartbeat.
- The vessel may close due to insufficient radial strength of the stent.

Additional concerns arise when using the stent in the peripheral vascular system, such as in the femoral artery. This adds additional loading conditions that may seriously affect the performance of the device and may include stent structural failure due to

- Cyclic flexion of the vessel due to regular motion
- Cyclic extension/compression of the vessel due to regular motion
- Compression of the vessel due to regular motion
- Cyclic rotation of the vessel due to regular motion

Once one identifies the failure modes, the next step is to identify the physical tests that are necessary to access the device.

We can see that this is similar to a misconception of a cycling loading test for a durability prediction in engineering. Any surface modification may influence or change corrosion resistance and fatigue life characteristics. Polymeric coatings may crack, tear, slip off, and flake off the stent due to compression of the deployment balloon, deployment expansion, or pulsation distension fatigue. As a result, an embolism and/or thrombosis may occur and the sus-

ceptibility to corrosion may also increase. Complete device tests are used to determine the acute failure for durability evaluation of the coated stent during deployment and the chronic failure modes for the pulsating fatigue of the device for the duration of 10 years of equivalent cyclic loading. Most of these tests used stent fatigue testing equipment such as those shown in Figures 1.4 and 1.5.

Accelerated durability testing of a coated stent has to take into account the material limitations of the coating. For example, care is necessary when increasing test frequencies to ensure that the physical properties of the polymer

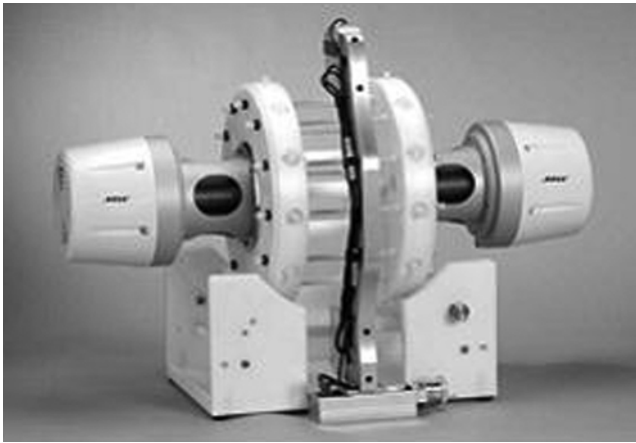


Figure 1.4. Bose® 9100 series accelerated stent durability test instrument [30].

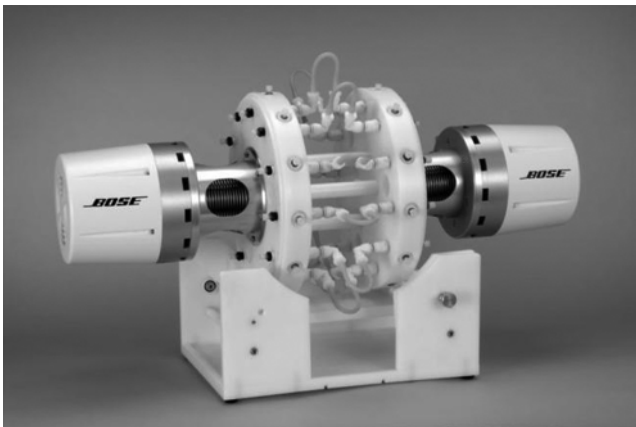


Figure 1.5. ElectroForce 9110-12 stent/graft test instrument (Bose).



Figure 1.6. ElectroForce® multiple-specimen stent durability testing system [30].

coating do not exceed their glass transition zone. But the basic problem is that this “durability” testing cannot provide sufficient information for an accurate prediction of durability or reliability because the test conditions do not accurately simulate field conditions (random character and simultaneous combination) as shown earlier. The following chapters will demonstrate how to achieve better results by improving test setups. One improvement is the use of multi-axis durability testing equipment, which is shown in Figure 1.6.

Multiaxis fatigue (durability) test systems (such as the Bose 9100 series stent/graft test instruments) have become key components in a design process to bring these devices to market more quickly. There is a growing trend to treat other vascular diseases such as peripheral artery disease (PAD) and carotid artery disease (CAD) [31] with stent and stent-graft testing. The rapid growth of the stent (and its components; Fig. 1.7) and graft markets has created a variety of medical manufacturers needing both stent and graft fatigue testing. MDT Services routinely conduct these mechanical tests using testing methods per FDA 1545, ISO 25539-1, Endovascular Devices, and CE requirements:

- *Strength:* Burst, crush, flex, tensile, migration, radial force, and bond strength

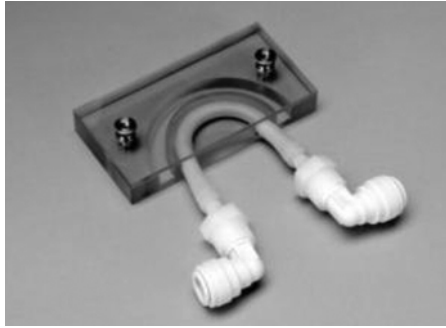


Figure 1.7. Bose fixed bend fixture for stent fatigue testing [25].

- *Stability:* Device pulsating fatigue (durability) testing and material fatigue testing for FEA analysis
- *Fatigue:* Radial, bending, torsion, and compression

Pulse-on-a-Bend Test, Coronary Artery Device [31] Regulatory bodies, including the FDA, have recently requested the performance of pulsating durability tests in a physiologically relevant geometry. For this purpose, MDT Services use Bose ElectroForce Systems (Fig. 1.8) Pulse-on-a-Bend testing equipment. This test can accommodate the following wide range of device sizes and test configurations:

- *Geometry:* Bend radius from 7 to 40 mm
- *Configuration:* 12 tubes, which are able to accommodate either single or overlapped devices
- *Tubes:* Custom dipped to accommodate small bend radii
- *Custom Laser:* Perpendicular measurements along the curve
- *Frequency:* 40–60 Hz, depending on the size of the device
- *Environment:* 37°C saline

Medical device tests provide testing for a wide variety of intravascular devices. Medical device submissions require many tests, including “durability testing to 10-year equivalent cycles.” For intravascular devices such as stents or stent-grafts, this translates into 380–400 million fatigue (durability) cycles. Medical devices tests provide testing in the following areas:

- Mechanical test methods per ISO 25539-1
- Heart valve fatigue testing
- Pacemaker lead testing
- Wire fatigue testing
- New device testing



Model 9110-12 with Pulse on a Bend Fixture for Coronary Stents



Model 9130-8 SGT for Vascular Grafts



Model 9120 SGT for Abdominal Devices



Model 9140-20 SGT

Figure 1.8. ElectroForce stent/graft test instruments [26].

Many years ago, practical results of the cycle test method for farm machinery, the automotive industry, and others demonstrated that it alone is not sufficient to obtain the necessary initial information to predict durability accurately because this type of cycle test does not accurately simulate real environments. Dynatek Delta Scientific Instruments [27] demonstrated that the development of a coating durability tester (CDT) responds to a belief within the industry that developers of drug-eluting and coated devices will soon be required to test the shedding of drug particles as a part of their product's durability evaluation. Dynatek's CDT adds the benefit of real-time evaluation of the device coating for the proven ADT of the small vascular stents prosthesis tester (SVP) and the large vascular stents prosthesis tester (LVP). "Stents have improved the treatment of coronary artery disease, with close to

100 percent penetration in the US, and 50–60 percent in the UK. The market for drug-eluting stents is expected to reach \$5.5 billion by the end of 2005 and \$6.3 billion by 2007” [27]. But accurate durability prediction for these stents is still not obtainable because their durability testing is an unsolved problem.

Finally, the choice of testing methods and equipment for medical devices has the same principal negative properties as were described for other types of tested equipment. Volunteer standards organizations such as ASTM, International Electrotechnical Commission (IEC), and others have sometimes reflected this issue in their standards. The FDA also based its requirements on these standards. Therefore, we can conclude that different types of AT offer different degrees of accuracy for the results in comparison with field results for the actual product. These tests cannot produce sufficient initial information for the accurate prediction of quality, reliability, durability, and maintainability in the field because test results do not correspond to actual field results.

1.3 FINANCIAL ASSESSMENT OF THE RISKS INVOLVED IN CREATING A TESTING PROGRAM

To optimize the investment in a testing program, a company must consider all financial cost benefits for the program. This is a very complicated process because ART interconnects with quality, reliability and maintainability, accuracy, costs, and many other factors. Therefore, the simplified approach shown here is similar to that described by Dodson and Johnson [32]. Failure costs and significant degradation followed by an abrupt decrease in quality, reliability, and maintainability consist in the following aspects shown in Figure 1.9. Additional costs attributable to early failure include warranty costs, stop shipping costs, recall costs, costs associated with additional complaints, loss of business, loss of good will and reputation, and retrofits. One method to quantify these costs would be to give a score to each element in the testing program

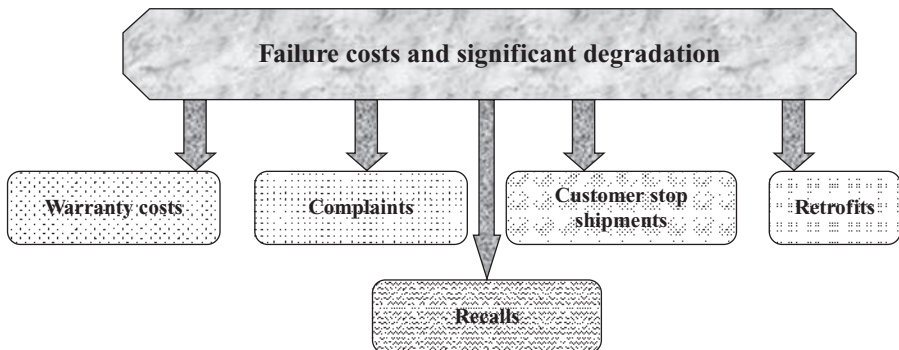


Figure 1.9. Failure cost components.

TABLE 1.2 Example of Test Program Scores [25]

Test Program Item	Score (GPA)
Understanding of customer requirements	B-3
Failure and significant degradation	A-4
FRACAS	C-2
Verification	C-2
Validation	D-1
Manufacturing	B-3
Overall program score	2.33

FRACAS, failure rate analysis and corrective action system.

TABLE 1.3 Example of Field Testing Performance [25]

Testing Performance Item	Cost (\$)
Customer returns	8245
Customer stop shipments	0
Retrofits	761,000
Recalls	2420
Overall program costs	1,011,581

then to examine the product's comparative performance in the field. Auditors can perform this task utilizing a grade scale of A through F for each component of the program. Combine the grades for each component into a grade point average (GPA) for the program using four points for an A, three points for a B, and so on. Table 1.2 shows how to score a reliability testing program using this system. Table 1.3 shows how field performance is noted. All laboratory travel costs, paperwork, and research expenses incurred should also be included in the total cost. This can easily be in thousands of dollars. The company's monetary loss from recalls must also be added. It is evident how AT, particularly ART, offers financial benefits. For example, Toyota Motor Corporation, which had a reputation as a high-quality manufacturer, had 1.27 million recalls in 2005 and 986,000 recalls in 2006. (As noted in the Preface, recalls by this company jumped in 2009–2010 to 9 million cars and trucks.)

Figure 1.10 is a scatter chart of results of several programs. The slope of the trend line totals the loss when the testing program is not entirely completed. In this example, increasing the GPA of the overall program by a single point projects a savings of \$755,000 in failure cost avoidance. These savings alone can financially justify the investment in the considered project. These failure costs are similar to the expense of water pipes bursting in a house. The homeowner has knowledge of the risks and makes the decision of whether to act on the risk or to tolerate the risk based on the costs involved to rectify the situation.

Another method for bringing management's attention to reliability is presenting the effects on corporate profits using the data shown in Table 1.4. The

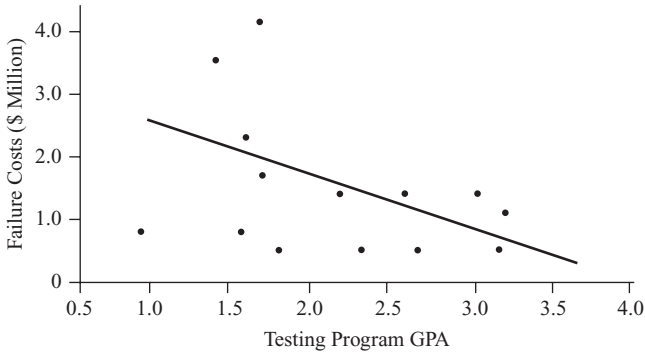


Figure 1.10. Testing program execution score versus failure costs [32].

TABLE 1.4 Vehicle Resale Value [45]

Vehicle (1998 Model Year)	Retail Value as of July 2001 (\$)	Consumer Reports Reliability Rating*
A	8430	-45
B	9500	20
C	9725	18
D	11,150	25
E	11,150	30
F	13,315	-5
G	14,365	55
H	15,215	50

*The Consumer Reports scale is from -80 to 80, with -80 being the worst and 80 being the best.

data in Figure 1.11 show an example of the negative impact of an inadequate testing program. Some years ago, money was saved in the short term by taking a chance on a substandard testing program; however, Figure 1.11 reveals that it was not a profitable long-term investment decision. Just as termites can damage a house without the owner’s knowledge, hidden low-reliability and low-quality producing programs result in poor decisions that increase losses or damage profits. Losses created by these hidden costs can be much greater than warranty costs. As an example of this concept, consider the automotive industry.

For an average vehicle manufactured by General Motors, Ford, or Chrysler in the 1998 model year, the company had to pay an average of \$462 in repairs [33]. These automakers sell approximately 3 million vehicles in North America annually, which results in a total warranty bill of \$1.386 billion. This amount may sound like a lot of money, but it is only a very minimal lower bound on the total cost of substandard reliability and quality. Table 1.4 illustrates the retail value of several 1998 model year vehicles sold at prices within a \$500 range. As for lease vehicles, the manufacturer absorbs the \$5715 difference in resale value between vehicles B and H. For purchased vehicles, the owner of

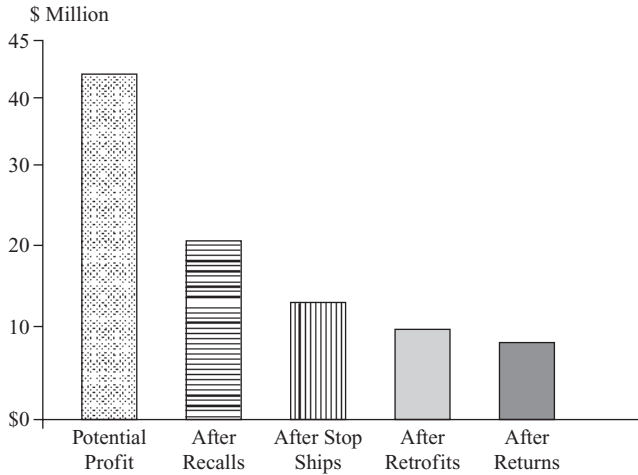


Figure 1.11. Effect of poor reliability and quality on company profits [32].

vehicle B absorbs the cost. But this does not mean that the manufacturer benefits. Reduced retail value becomes evident in the ability of the manufacturer to set prices for new vehicles and sell them. The manufacturer of vehicle H can charge more for new vehicles because its depreciation is slower. The sales for many of these midsize sedans topped 200,000 units, and the \$5715 difference in resale value was valued at more than \$1 billion annually.

1.4 COMMON PRINCIPLES OF ART AND ADT

Accelerated reliability and durability testing technology is the key factor for the accelerated development and improvement of quality, reliability, durability, maintainability, supportability, and availability for a product/process. This technology offers the possibility for accurate prediction of the above factors as well as a quick method for identifying the reasons for failure and degradation during a given time period (service life and warranty period). One can use this technology to quickly solve many other problems.

1.4.1 The Current Situation

Many engineers and managers use the term reliability testing or durability testing. Few people think that they actually conduct reliability *or* durability testing. Often, in fact, neither of them provides such testing. The basic reason is they do not clearly understand what this type of testing means and how it is different from other types of testing. The literature and practice show that professionals who use vibration testing, thermal shock testing, environmental testing, HALT, HASS [15], or other types of testing [35, 39, 40] often think that they provide reliability or durability testing. Companies from a wide range of industry specialization and size make this error.

TABLE 1.5 Stages, Purposes, and Contents of Reliability Test (from Table 3.1.1 in TOSHIBA, *Testing for Reliability*)

	Stage	Purpose	Content	Test
Semiconductor device development	Verify material, process, and basic design	Determine whether the material, process, and design rules allow the desired quality/reliability objectives and user specifications to be met	A metal electromigration, gate oxide film breakdown voltage, TDDB, MOS transistor hot carrier injection effect, failure rate for medium-and large-scale integrated circuits or products, new package environmental test, and so on.	Process test element groups (TEGs), function block TEGs, and so on.
		Determine whether the product satisfies design quality/reliability objectives and user specifications	Development verification tests (life test, environment test, etc.)	
TEG	Verify product reliability	Determine whether the product quality and reliability are at the prescribed levels	Structural analysis Screening and the reliability monitoring (by product family)	Products Products Reliability TEGs

The following examples demonstrate this:

1. In the book *Testing for Reliability*, TOSHIBA asked [34], “1. What is reliability testing?” And the answer was “Toshiba testing follows the stages shown in Table 3.1.1.” Table 1.5 shows no definition of reliability testing, no clear description of their contents, nor how one can provide this (separately or partially simultaneously or all simultaneously). In fact, this is an example of AST, but it is not ART.
2. IBM published the book *Reliability Testing and Product Qualification* [35].

The contents of this book include the following:

- IBM Microelectronics Quality System
- Development Process
 - Technology Feasibility
 - Technology Qualification
 - Product Qualification
- Quality and Customer Satisfaction
- Summary

Reliability testing is only in the title of the book. The “Table of Contents” does not even include reliability testing, what it is, or how to conduct it.

3. Surridge et al. in their paper “Accelerated Reliability Testing of InGaP/GaAs HBTs” wrote [36] “Our standard method of reliability testing is to perform a three temperatures (3T) accelerated test and predict the failure time at maximum junction temperature using an Arrhenius expression.” Real-life factors include

- More environmental factors than temperature only
- More groups of input influences than environmental

Therefore, this type of testing will yield a low correlation of test results to field results. The basic reason is that the simulation of the field situation is not accurate. As a result, this test will yield an inaccurate prediction of failures in the field.

4. The paper “What You Should Know about Reliability Testing” [37] consists of only one note on reliability testing: “A final stretch of testing cycles checks for reliability with four different tests: Bare board, flying probe, ICT (in-circuit tests), and functional.” In this paper, there is nothing about the definition of reliability testing or how one conducts it.
5. In the book *Reliability of MEMS: Testing of Materials and Devices* [38], the authors compared the mechanical and other properties of thin films to the properties of micro-electro-mechanical systems (MEMS) devices, especially in terms of reliability. In the preface, the authors wrote: “At the present day, industrial products are distributed all over the world and used in a broad range of environments, making reliability evaluation of the products more important than ever.” This is true. However, they describe strength and fatigue, as well as the evaluation of elastic properties. So in fact, the authors ignored that fatigue and strength testing is vastly different from reliability testing and cannot provide sufficient initial information for a reliability evaluation or prediction. They mention the standard IEC 62047-3 that specified a standard test piece for thin-film tensile testing for the accuracy and repeatability of a tensile testing machine. But this standard does not consider reliability testing and reliability evaluation.
6. In the paper “Product Reliability Testing and Data” [39], reliability testing is mentioned only in the title.

7. In *LMS Supports Ford Otosan in Developing Accelerated Durability Testing Cycles* [9], in the chapter entitled “Meeting 1.2 Million km Durability Requirements,” it states that “. . . Ford Otosan decided to involve an external engineering partner to establish an accelerated proving ground test scenario that matches the fatigue damage that the truck experiences throughout its lifetime.” “They displayed the results in a rain flow matrix format that showed how often events of particular amplitudes occur and extrapolated the data to estimate the damage generated by road testing over the full 1.2 million kilometers. This extrapolation was based on Ford Otosan’s targeted weighting mix of 60% highway, 30% local roads, and 10% city driving. The goal was to achieve the full 1.2 million kilometers without any cracks in the major components of the vehicle.” Referring to the research on proving ground testing that was published 40–50 years ago [12, 20] and others, one can see that similar techniques were published in those years. But professionals did not call this testing method durability testing, which would be wrong. They called this strength testing or fatigue testing, which is right. Professionals understood that proving ground testing does not take into account the random character of field input influences and environmental influences, such as temperature, humidity, pollution, and light exposure that act on the test subject over the years. A result of their action is corrosion and damage from other sources that the proving ground tests did not address.
8. The brochure *Solar Simulation Systems* reported: “Durability testing, also known as fatigue testing, is used to validate the aircraft’s design structural service life (8334 hours) based on a demanding flight spectrum representing expected flight usage. The first such testing was conducted between July 2002 and April 2003. After an inspection through tear-down inspection, the test vehicle was subjected to a second service life testing (an additional 8334 hours) between August 2003 and October 2004” [40].

There are many other examples. Many companies write that they conduct ART or ADT (reliability testing or durability testing) but in fact reveal that they provide the following separately: vibration testing, air-to-air thermal shock testing, temperature cycling, temperature/humidity testing, highly accelerated stress testing (HAST), and high- and low-temperature storage tests (Fig. 1.2).

1.4.2 Improving the Situation

To understand the difference between ART and ADT or AT or reliability testing, one must examine their definitions. AT is a test that quickens the deterioration of the test subject. Reliability testing is testing performed during actual normal service that offers initial information for evaluating the measurement of reliability indicators during the test time.

ART or ADT is testing in which

- The physics (or chemistry)-of-degradation mechanism (or failure mechanism) is similar to this mechanism in the real world using a given criteria
- The measurement of reliability and durability indicators (time to failure, degradation, and service life) have a high correlation with these respective measurements in the real world using a given criteria.

Accelerated reliability and durability testing is connected to the stress process. Higher stress means a higher acceleration coefficient (ratio of time to failures in the field to time to failures during ART) and a lower correlation between field results and ART results. The common layout for accelerated reliability and ADT is in Figure 1.12.

The basic principles of accelerated testing reliability and ADT are

- A complex of laboratory testing and special field testing as shown in Figure 1.12

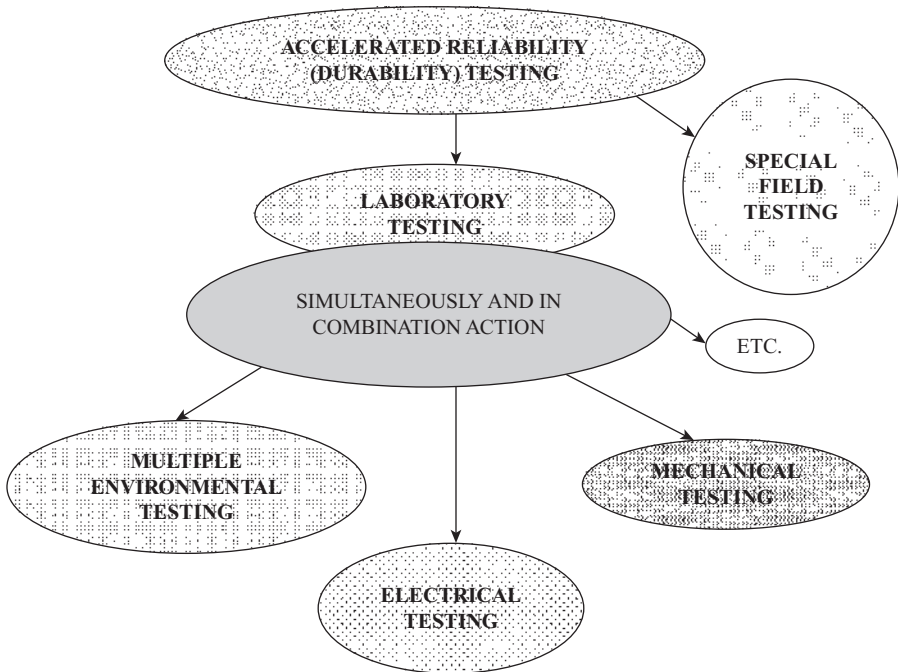


Figure 1.12. Scheme of accelerated reliability (durability) testing.

- That laboratory testing provides a simultaneous combination of a whole complex of multi-environmental tests, mechanical tests, and electrical tests
- That special field testing takes into account the factors that cannot be accurately simulated in the laboratory such as stability of the product's technological process and how the operator's reliability influences the test subject's reliability and durability
- It requires an accurate simulation of the whole complex of field input influences on the product as well as safety and human factors.

Durability is the ability of an object (material, subcomponent, component, or whole machine) to perform a given function under given conditions of use and maintenance until reaching a limiting state. The measurement of durability is its length of time (hours, months, or years) or its volume of work.

ART and ADT have the same basis—an accurate simulation of the field environment. Therefore, if there is no accurate simulation of the field situation, then there is no ART or ADT. The only difference is in the indices of these types of tests and the length of testing. For reliability, it is usually the mean time to failure, time between failures, and other parameters of interest. For durability, it is length of time or volume out of service. ART can be set for different lengths of time, that is, warranty period, 1 year, 2 years, or service life. Accelerated durability testing continues until the test subject is out of service.

A basic goal of the ART/ADT technology is to describe what and how one can rapidly obtain objective and accurate initial information for accurate prediction of quality, reliability, maintainability, availability, and other measurements during the product's design and manufacturing. The basic desirable results of ART are reduction of time and cost for product development and the ability to rapidly find causes for product degradation and failures. The main goal is quick elimination of failure and degradation root causes resulting in a rapid increase in the product's quality, reliability, maintainability, and durability. Currently, the basic causes for seldom conducting ART are the following:

- The knowledge of reliability testing, obtained from the literature, is often poor.
- Many professionals do not understand the specifics of ART or the need to conduct ART.
- The CEOs delegate their responsibilities in quality/reliability to a lower level without delegating the authority and providing the funding to implement ART/ADT.
- CEOs do not understand that it requires an initial investment over a period of time to obtain greater continuing benefits over a longer period of time.

- Lower-level managers involved in quality/reliability are not responsible for expenses and therefore do not have the funding authority to lead the process of reliability testing implementation.
- Not enough accredited professionals in industrial companies can describe to CEOs how to use reliability testing to save money, dramatically decrease recalls, and make the companies more successful in the market.
- The governmental research, development, and engineering centers in the Department of Defense and other federal government departments do not often require reliability and durability testing during acceptance tests. Therefore, they cannot accurately predict the reliability and durability of the tested product and they do not require ART of industrial companies. As a result, U.S. Army personnel in Iraq and Afghanistan often face dangerous situations due to early failures or defective equipment.

1.5 THE LEVEL OF USEFULNESS OF ART AND ADT

Professionals did not begin to understand one of the basic principles of ART until the late 1950s, namely, they did not understand that the interactions of different inputs on the product/process can result in overlooking significant failure (degradation) mechanisms. This new approach to testing, simultaneously subjecting the product to different inputs, was called Combined Environmental Reliability Testing (CERT) (DOD 3235.1H) [3]. MIL-STD-810F made use of this approach at about the same time. In 1981, the DOD CERT workshop confirmed that CERT was ready for implementation.

Then, this approach was undertaken in Japan [41], according to the description of CERT, as a concept and practice of combining effects of environmental factors (especially temperature + humidity, temperature + humidity + vibration + low pressure, and temperature + humidity + isolation).

However, they did not apply this approach for the development of ART using a whole complex of field inputs that interacted with and influenced each other on the test subject. Moreover, this is linked to the development of a more complicated program now known as “system of systems.” The simulation of this concerted program in a laboratory will lead to a more accurate simulation of field input influences. It will provide a basis for obtaining, after ART, the initial information for the accurate prediction of quality, reliability, durability, and maintainability. The author’s book [42] describes this development. Then, beginning in the 1990s, several other books by the author including *Accelerated Quality and Reliability Solutions* [18] and *Successful Accelerated Testing* [43], several patents, and dozens of articles, papers, and presentations describe this new direction of ART.

Dzekevich [44] from Raytheon wrote that there are some critical questions to answer when planning for reliability testing:

- What is the length of time to market?
- Is this a safety critical product where people's safety or life may be at stake upon a failure?
- What is the life expectancy of the product?
- Does the manufacturing process use accelerated test techniques to find process failures?
- How costly are field failures?
- Are there reliability problems with an existing product?

But if the type of testing is called ART, then it does not necessarily mean that this testing will automatically provide sufficient information for the initial estimation of the quality, reliability, durability, and maintainability parameters as a solution to problems.

ART has different approaches, and many professionals mean different things when they write or talk about reliability testing. The effectiveness of ART depends on the approach taken. With respect to these different approaches, accelerated reliability (durability) tests can be

- Helpful
- Minimally useful or useless
- Harmful

ART is helpful when methods and equipment provide a practical possibility for an accelerated evaluation and prediction of the product reliability and quality with a high degree of accuracy. Accuracy implies the conditions or quality are correct and exact. The level of accuracy of testing results depends on the accuracy of the simulation of the real-life full influences, including temperature, humidity, pollution, fluctuation, pressure, radiation, road conditions, and input voltage, while also including safety and human factors.

One achieves accuracy for field inputs to simulation when the output variables like loading, tensions, output voltage, amplitude and frequency of vibration, and corrosion in the laboratory differ from those under field conditions by no more than a given amount of divergence. The same is true for simulation of safety problems and human factors. If the resulting degradation and failures during ART correlate to those in the field, then accelerated prediction, development, and improvement of reliability and quality occur with minimum expenditure of time and cost. The basic concepts that account for an accurate simulation of field conditions are

- Maximum simulation of field conditions (including all and not only some stresses)
- Simulation of the whole 24-hour day, every day (except the weekend), but not including

- Idle time (breaks, etc.)
- Time with such low loading that it does not cause failures
- Accurate simulation and integration of each group of field conditions (full input influences, safety problems, and human factors)
- Accurate simulation of each group of input influences (multi-environmental, mechanical, electrical, etc.)
- Use of the degradation mechanism as a basic criterion for an accurate simulation of field conditions
- Consideration of a system of interacting components as those found in the field while taking into account their cumulative reaction (Fig. 1.13)
- Reproduction of a complete range of field schedules and maintenance (repair)
- Maintaining a proper balance between field and laboratory testing
- Simultaneous simulation of each input influence necessary to accurately replicate field conditions. For example, pollution consisting of chemical air pollution and mechanical (dust and sand) air pollution must be simulated simultaneously.

Current testing methods and equipment are seldom helpful in conducting ART because they do not produce the desired accuracy. Basic problems with implementing the “classical” accelerated life testing (ALT) relate to the second and sometimes to the third group. In Figure 1.14, one can see that ART is minimally useful or useless if

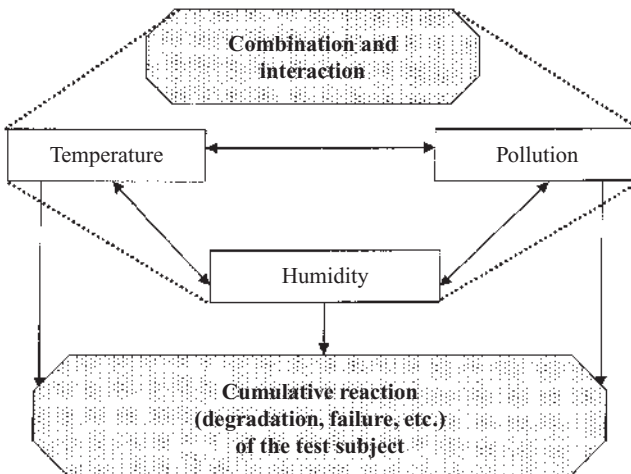


Figure 1.13. Example of the principle of cumulative reaction of a test subject on several input influences.

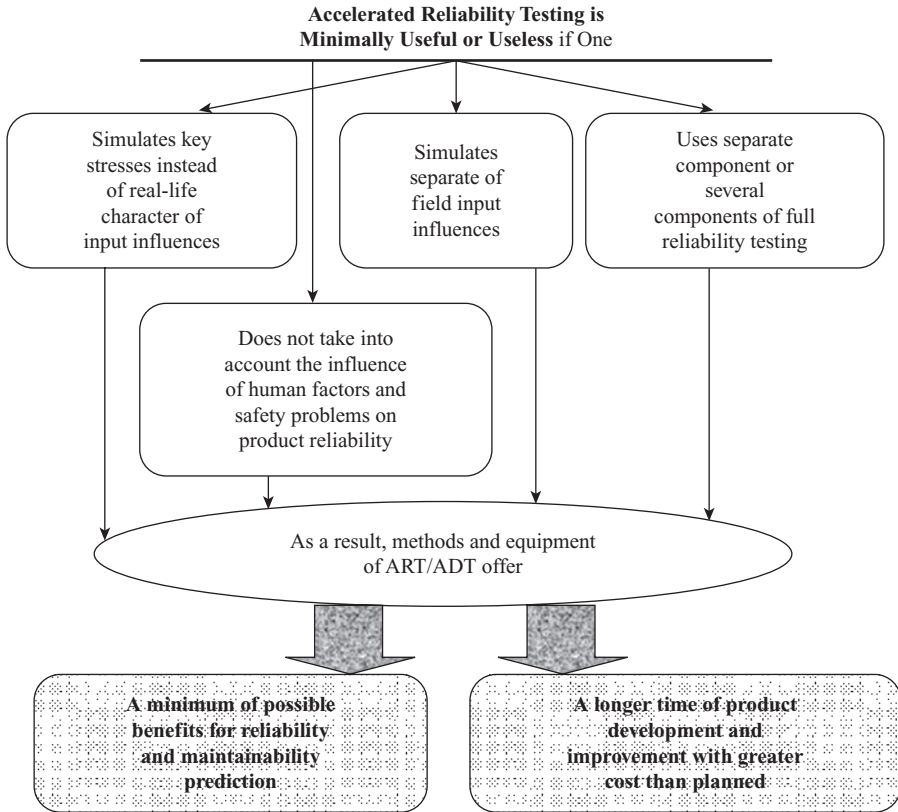


Figure 1.14. Scheme of basic situations when accelerated reliability testing is minimally useful or useless.

- One simulates high stresses instead of real-life input influences. For example, establishing temperatures between -100 and $+150^{\circ}\text{C}$ in the test chamber can change the physics-of-degradation process for many types of test subjects in comparison with the physics-of-degradation process in the field. This does not provide an accurate simulation of real-world and realistic data.
- The test independently simulates one or only a part of full field input influences. Therefore, separate accelerated laboratory testing occurs with either individual input influences or a combination of only a portion of the necessary input influences (temperature/humidity, vibration, corrosion, braking, and electrical) that affect reliability, without a connection and interaction with each other. This contradicts real-life situations where full (or most) of the input influences simultaneously interact with each other.

- One only uses separate components or several components of full ART technology.
- One does not take into account the influence of human factors, including the operator's actions and safety problems affecting the test subject reliability.
- The test results will most likely be incorrect due to low or no correlation between accelerated test results and field results. Failure to adequately address the combined field conditions during testing results in low correlation.
- As a result, current methods and equipment for ART often offer few benefits for reliability evaluation and prediction. Consequently, product development and improvement requires more time with greater expenditures than previously planned because the reasons for degradation and failures in the field are not exactly known. This is one of the reasons for the constant rapid modernization of design and manufacturing technologies for new and updated products and slow modernization of reliability testing techniques and equipment. More often, there is a practical combination of a high-level modern design and manufacturing technology with old testing similar to that used many years ago. As a result, the use of high-level reliability evaluation, analysis, and prediction techniques does not deliver the expected results because the initial information (practical testing results) does not support predictions and evaluation at this high level. Thus, the product continues to have problems with reliability, maintainability, and availability (RAM) performance.

Reliability testing is harmful (Fig. 1.15) when

- It identifies incorrect reasons for field degradation and failures.
- The work for improving the design and manufacturing processes does not lead to an increase in product reliability and quality.
- The work requires excessive time and funds.

Additional basic reasons for the above-mentioned situation include the following:

- Poorly qualified professionals are sometimes involved in ART.
- Following incorrect directions in establishing conditions for ART
- Not enough literature and courses are available for increasing professional knowledge for implementing successful approaches to develop effective ART technology.

These basic negative ART results follow from users selecting or isolating parameters that are different from reality to predict quality, reliability, cost, and time of maintenance. But manufacturing companies also incur losses

In addition to the scheme of situation shown in figure 1.14, accelerated reliability testing is harmful if

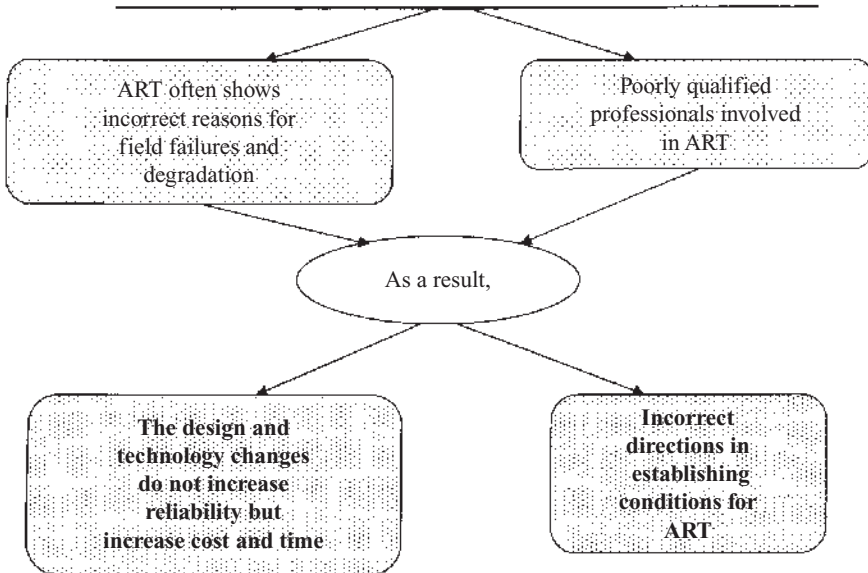


Figure 1.15. Scheme of basic situations when accelerated reliability testing is harmful.

because they do not make effective use of this situation to achieve better market competitiveness. Without implementing true ART, cost increases probably will not have beneficial results.

How can one eliminate the above-mentioned situation? The basic goal of this book is to introduce principles and descriptions of useful theoretical and experimental technological approaches and practical tools for solving this problem. From the definition of ART, it can be determined that ART enables measurement of reliability indices (time to failures and time between failures) that correlate with the field reliability parameters within the duration of a field test. This makes a direct evaluation and prediction of field reliability and maintainability possible for the service life. ART makes it possible to rapidly increase reliability and improve the robustness of a product. True ART requires an accurate physical simulation of the whole complex of field input influences leading to degradation and failure of the product. As a result, successful identification and resolution of the problems occurring during accelerated development and improvement of the product's reliability and maintainability improved the product. Implementation of this type of ART is rare because management does not choose to simulate the whole complex of real-life input influences with great accuracy in combination with safety and human factors.

One of the basic problems is the cost of AT, especially ART/ADT. Often we read and hear that ART is very expensive. This occurs when professionals consider ART as a goal but not as a resource for obtaining initial information for accurate evaluation, prediction, improvement, and development of product reliability. Therefore, one usually only takes into account the one-time cost of the testing process. But if one also takes into account the design, manufacturing, and usage processes, especially the cost of maintenance, then the cost of ART is not as high. This is especially important to the military.

Many publications and standards

- Include AT as a part of a reliability assurance program
- Describe the strategy for analyzing AT data and other problems based on the information obtained
- Use a single-parameter testing equipment, especially in applied statistics

Of course, these results are also different from an actual real-world results. The standards reflect only past achievement. Therefore, they cannot point the way to improve the current situation of ART. As a result of the poor strategies for testing and predicting the reliability and maintainability of the equipment, many results are several times lower than that predicted due the use of faulty AT during the design and manufacturing phases. This is especially true for military programs and applications. The situation in durability testing is similar.

One can see in Figures 1.16 and 1.17 the way to ART/ADT technology from testing with simulation several or separate field inputs.

The above analysis of reliability/durability testing leads to the following conclusions:

1. There are practical situations involving different testing approaches to ART/ADT that are not intended for accelerated improvement of product quality, reliability, durability, and maintainability.
2. The proposed approach can help to increase the quality of testing, reliability, availability, and maintainability, especially for the military that is interested in increasing equipment RAM and decreasing the total ownership cost. This applies to the design, manufacturing, and utilization phases.
3. It helps to increase the warranty period and especially to predict the RAM and durability performance of systems more accurately. As a result, it helps to dramatically decrease recalls, failures, and complaints.
4. A team of knowledgeable professionals is required to use the above-mentioned approach. These professionals must have knowledge not only of testing and prediction technology but also of advanced technology,

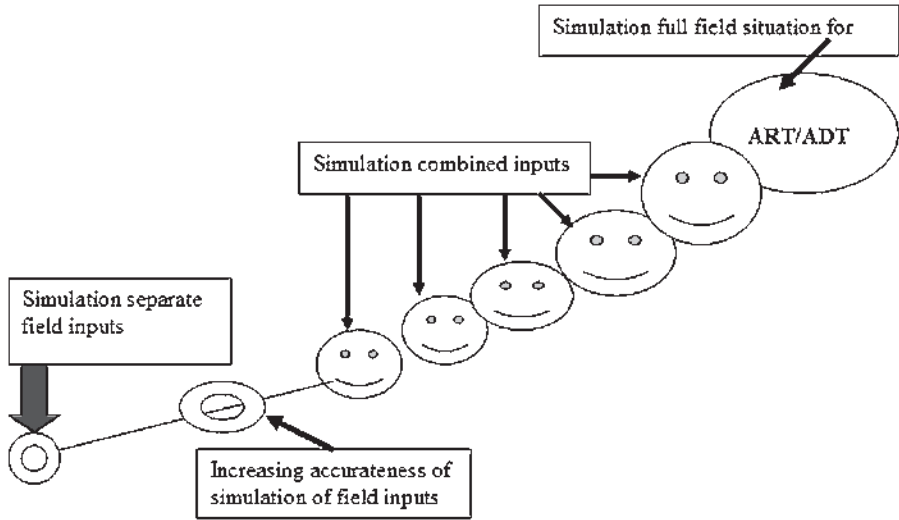


Figure 1.16. The way to accelerated reliability and accelerated durability testing technology.

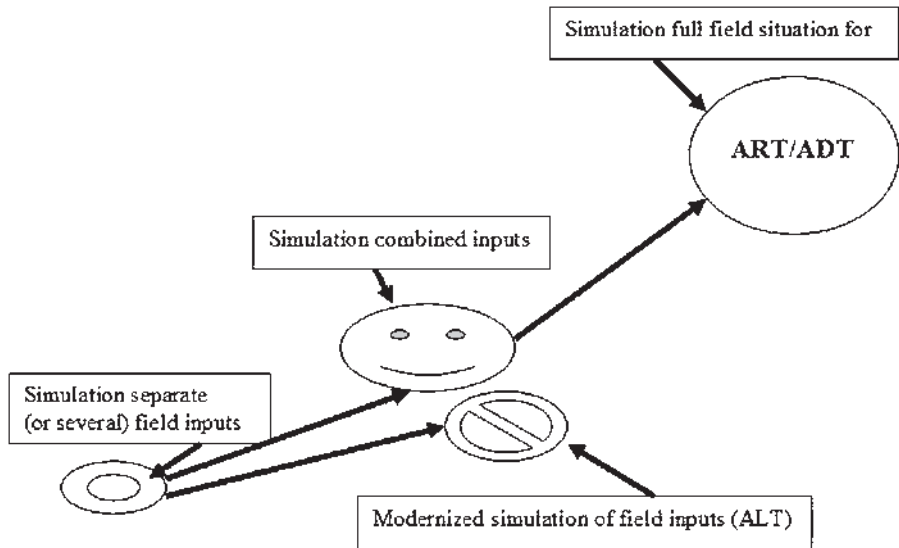


Figure 1.17. The way to accelerated reliability/durability testing technology from traditional accelerated stress testing.

product use, economics, applied statistics, and other areas of mathematics, reliability, fatigue, physics, and chemistry. Requirements for durability testing are similar to those for reliability testing due to interconnection and interdependence of the real world full input influences with safety and human factors.

EXERCISES

- 1.1 Why are Mercedes-Benz, Honda, and Toyota incorrectly calling the testing that they conduct in the field ART?
- 1.2 Ford Otosan and LMS said that they conducted durability testing in 2007. How did they incorrectly use the term durability testing?
- 1.3 Industrial companies often use computer simulations to provide ART. What are the basic reasons they do not simulate field environments accurately?
- 1.4 Industrial companies are using HALT, HASS, and AA for reliability and durability evaluations. These reliability and durability results are different from those obtained in the field. What are the reasons for this difference?
- 1.5 Durability testing is not useful for providing accurate predictions of medical device durability. What are the basic reasons for this deficiency?
- 1.6 An industrial company's profits decrease due to poor reliability and quality. What are the basic causes for this decrease? How can you illustrate this process?
- 1.7 In many books that mention reliability testing or durability testing, one cannot find information about the basic essence of these types of testing. How can you illustrate this situation?
- 1.8 Proving ground testing does not offer the same possibility for conducting ART/ADT as laboratory testing. What are the basic reasons?
- 1.9 Why is the development of proving ground testing slower than the development of laboratory testing? What are the basic reasons and how can you overcome this obstacle?
- 1.10 Name the types of AT that you know.
- 1.11 What is the basic difference between ART and ADT?
- 1.12 What is the difference between AT and ADT?
- 1.13 What are the components of ART/ADT?
- 1.14 What are the basic reasons that ART and ADT are seldom used in practice?

- 1.15 ART can be more or less useful. Determine the basic reasons for this situation and formulate how they differ.
- 1.16 Why does the reaction of the test subject have a cumulative character?
- 1.17 What is the difference among basic approaches to current AT methods?

