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A Methodology for Testing Life-Cycle Performance of Consumer Products

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Preface

This treatise is intended primarily for engineers without background in reliability engineering who have an interest in life-cycle performance testing of consumer products. Much of the material should be of use also to others interested in performance testing in general.

Life-cycle performance testing attempts to predict a probable useful life and to assess the performance during that time interval. This is a new endeavor in which NBS is pioneering and requires some significant changes in approach and execution compared to usual product testing.

Although the published literature in reliability engineering is extensive, most deal with data handling and statistical concepts, and tacitly assume the data are trustworthy. Relatively little appears on experimental approach or underlying engineering concepts, and what does appear is fragmented and scattered.

The present work is a systematic and coherent body, and an attempt is made to make it didactic. The emphasis first is on understanding the basic engineering concepts, then systematically applying them.

The aim of the methodology -- a body of working concepts, terminology, rules, and procedures -- is to guide in the formulation of objective tests (tests which exclude as far as possible the subjective element), to standardize testing, and to make testing easier and better. Predictive testing is inherently risky. Nevertheless, it is believed that by following a scientifically-based methodology, the risk will be minimized.

Contents

Chapter 1

Introductory Remarks

Although extensive and sometimes elaborate testing of consumer products is made in industry (e.g., for design concepts and objectives, in-warranty costing, etc.), it is not directed to determining life-cycle performance. That is, there is no effort generally to assess product performance during a determined actual useful life. The objective of this work is to formulate a methodology for measuring life-cycle performance of consumer products; the resultant data are to be used for life-cycle costing.

Test methodology is a generalized coherent body of operational concepts, terminology, rules, methods, and procedures to be used in the solution of performance testing problems on any consumer product. Test method, on the other hand, is the particular approach for a specific product only, made in accordance with methodology. Thus, for example, the tests for clothes dryers, dishwashers, and water heaters will all be different, but all will conform to the same methodology.

Apparently, no prior standard test methodology, as such, exists even for initial performance testing. Instead, testing is laissez-faire: approaches vary widely according to philosphy, funding, staff and equipment capabilities, product and urgencies.

The present formulation makes much use of reliability engineering concepts and methods, but reliability engineering has been concerned mainly with the military and aerospace where operating life is sometimes very short and reliability means close to 100%. For example, maintenance is geared to stave off any wear-out failure, as the consequences of failure could be dire, and parts are replaced before they can wear out. Clearly, for consumer products such a philosophy would not be sensible. Some existing concepts needed to be modified and new concepts needed to be created.

Too, there is no standardized terminology for communication. Many existing terms are imprecisely defined or are understood differently by different persons, and a suitable terminology needed to be devised; for example: What are the meanings of useful life and durability of consumer products? A glossary of the terms developed in the present work is given at the back of this treatise.

Life cycle of a consumer product begins with acquisition and ends with the end of useful life, a concept defined subsequently in this work. Performance-related factors which determine life-cycle cost are:

energy consumption
maintenance (frequency and action)

repair (frequency and action)
time duration of useful life

Costs can be derived from the above, and together with acquisition cost (purchase price, delivery, installation), and disposal costs or salvage value form the main bases for calculation of life-cycle cost.

Chapter 2

Performance

A highly significant characteristic of an utilitarian consumer product is performance: to perform a needed function is the reason the product exists in the first place. Moreover, the consumer is concerned with reliability, durability, failure, maintenance and repair. These concepts will be developed in this study, and all will be derived or constructed from performance. The test engineer will measure performance per se, and from those observations will identify failures, will distinguish between maintenance and repair actions, and will calculate reliabilities. Clearly, performance is the plinth of the test methodology, and it is important to understand and to define the concept.

Performance in its elemental form is the accomplishments of a component or product. Each consumer product of interest has a main utilitarian function: a refrigerator to produce and maintain coldness; a vacuum cleaner to clean or remove dirt from a substrate; a clothes dryer to dry or remove moisture from damp laundry; etc. To perform satisfactorily, however, the refrigerator cannot merely produce and maintain coldness; the degree of coldness in the chamber must be proper: if too cold, foods will freeze; if not cold enough foods will spoil prematurely. Similarly, the vacuum cleaner must remove a sufficient amount or percentage of the dirt; the clothes dryer must remove a sufficient amount of moisture in a reasonable time, and at suitable temperature; etc. [Incidentally, some components, like a relay and a switch, need only operate to perform satisfactorily.] How well each function is accomplished can be expressed qualitatively or quantitatively in terms of performance.

So far primary performance criteria have been addressed; there are also secondary performance criteria associated with each product which have to be considered in determining whether the overall performance of the product is or is not satisfactory. The vacuum cleaner will be used as an illustration. In cleaning or removing dirt from a rug, the vacuum cleaner must not cause undue wear or damage to the rug. It must also be portable enough to be used easily. These requirements may conflict with the primary performance characteristic, the cleaning ability.

Cleaning ability generally improves with increased suction; the latter can be produced by incorporating a larger, heavier motor. Using a larger, heavier motor increases the size and weight of the vacuum cleaner, which decreases portability and may also cause more wear or damage to the rug. These requirements are considered by the design engineer who tries to strike the best compromise, within the restraint of cost. Such mutually dependent requirements must be considered by the test designer too.

Continuing with the example of the vacuum cleaner, assume that the cleaning ability is determined by the percentage of dirt removed from the

rug. The composition of the dirt is a factor in the cleaning; does it contain hair, sand, caked mud, dry soil, dust? Some ingredients are easier to remove than others. What type of rug will be vacuumed? A shag, for example, is much more difficult to clean than an oriental type, with its tight weave. How is the cleaner used? A haphazard, speedy vacuuming will not be as effective as a systematic, repeated, or prolonged vacuuming.

Obviously, the performance of a product is not a characteristic of the product per se, but depends also on the use conditions and environmental factors.

Use conditions is defined as the method or manner in which a product is employed by an operator, including the load.

Everything surrounding an object, exclusive of the load, is its environment, but only a limited number of things in the environment can be expected to influence performance. These are designated environmental factors, and examples are vibration, temperature, humidity, dust, etc. Line voltage also will be considered as an environmental factor. The environmental factors may vary from product to product.

Environmental factors is defined as factors exclusive of the load, external to and immediately surrounding the object, which influence its performance.

An elemental, but inadequate definition of the term performance was given at the beginning of this chapter; now a more accurate and useful working definition can be stated:

Performance is defined as the accomplishments of a component or product under specified use conditions and environmental factors.

In the vacuum cleaner example, given above, the use conditions are the method of vacuuming (haphazard or systematic; repetitiveness); time duration of cleaning; type of rug (shag or tight-woven); nature and composition of the dirt*. Environmental factors are the line voltage and (possibly) ambient temperature and humidity.

*The dirt and rug are the load, defined as whatever is acted on or processed by a product to accomplish its main utilitarian purpose. For simplicity, the load (if any) will be regarded a use condition, rather than a separate entity.

Chapter 3

Failures

General Description

If satisfactory performance is one side of the coin, unsatisfactory performance is the other: There can be no in-between; no standing on edge. Unsatisfactory performance constitutes a failure.

Failure is defined as the state of inability to perform a function or action to test specifications.

This points up the importance of the performance criteria, prescribed in advance of testing. Under one set of criteria performance might be judged satisfactory; under another, a failure. Further, the clarity and the preciseness with which the criteria are described are of importance: if specifications are not clearly and rigorously set down, the technician or test engineer will be given much room in which to make subjective decisions or misinterpretations--an altogether deplorable situation. Thus, failure is dependent not only on the product and the prevailing use conditions and environmental factors, but also on the performance criteria chosen, and on their expository form.

In most cases involving consumer products, failure will be the inability of the system to meet a minimum performance level; in some cases involving components such as switches and relays failure will be merely inability to operate; in others such as motors, performance which does not fall into the specified bounds.

Classification

Failures are classified into one of four broad categories--early, random, wear-out, and aging -- which, in practice may not be easy to identify.

Early failure

Sometimes, owing to design errors, substandard components, poor assembly, or damage incurred in transportation, a product will fail relatively early in life. The time duration over which these so-called early failures (also called burn-in or break-in failures) occur depends partly on the test conditions and varies from product to product according to the nature of the constituent defects.

Early failure is defined as the failure which results early in life when substandard or weak specimens are tested.

Early failures are characterized by a rapidly decreasing failure rate (percentage of failures per unit time), as well as its occurrence early in life.

Random failure

Some failures arise because of latent defects in design or quality, or undetectable material weaknesses. In the event that too large a stress is applied suddenly or the cumulative effects of stress are excessive, then the component will fail. In other cases, misuse, improper maintenance, or accidents will result in failure. Breakdown is sudden, and is not preceeded by symptoms of deterioration. The failures discussed immediately above are all independent of time; i.e., when such a failure will occur is not predictable for any individual unit, and is just as likely to occur when a product is relatively young as when old. Aptly, such failures are designated random (or chance) failures.* As will be shown subsequently (Chapter 4), random failure is characterized by a constant failure rate.

Random failure is defined as a time-independent failure caused by (1) sudden stresses or their cumulative effects beyond the design strength of the component; or (2) latent quality or material defects.

Wear-out failure

Perhaps the most important type of failure to be considered in the present undertaking is that due to wear.

Wear is defined as the impairment of an object or part by use; the utility, strength, or quality is diminished.

Wear is a naturally occurring phenomenon expected to begin once the object is put into service. The more severe the use, the greater the wear; generally, the more frequent and longer the use, also the greater the wear. Products which are well designed and well fabricated will wear gradually, and signs of wear may not be perceptible or obvious for a long time.

Wear is frequently associated with gross or macroscopic motion (sometimes called dynamic wear), a surface of one part or object sliding, rolling, or otherwise contacting and rubbing against another. The mechanisms of dynamic wear are (1) friction which generates heat, causing thermal expansion and increased internal disorder; (2) material transfer, usually in the form of particles, from one part to another; and (3) mechanical breaking off of rough surface elevations, the debris often acting as an abrasive which causes rapid wear; e.g., scored surfaces. Thus, dynamic wear is often characterized by removal or loss of constituent matter, usually starting at a surface and proceeding inwards. Other examples of dynamic wear phenomena are cracking due to fatigue and brittle fracture due to impact.

*Random, or chance, failure is sometimes referred to in the literature as catastrophic failure, but use of this term is not advised. It is a misnomer because failures other than random can occur suddenly, or catastrophically.

Because wear has been defined here as resulting from use, it is not necessarily conditional on motion. Examples of wear which occur even in the absence of gross or macroscopic motion of the object are electronic components such as capacitors and TV picture tubes, and incandescent light bulbs. The mechanism of static wear may involve motion, but it would be on a microscopic rather than macroscopic scale.

After prolonged or severe use, the amount of wear will become intolerable: the affected part will become useless and manifested by failure. This is the condition of wear out.

Wear out is defined as becoming useless from long or excessive wear or use. The term implies failure and therefore is equivalent to the term wear-out failure.

Wear-out failure is defined as a time-dependent failure caused by use.

Aging failure

Aging failure is allied to wear-out failure, except that deterioration is caused by environmental factors, not use. Just as for wear-out failure, aging failure is time dependent and is usually gradual. Similarly, aging failure will occur after long exposure to environmental factors or exposure to excessive environmental factors. An example is corrosion. Additionally, objects with so-called shelf life such as electrolytic capacitors, photographic film and dry cell batteries may experience aging failures.

Aging failure is defined as a time-dependent failure caused by environmental factors.

Chapter 4

Reliability

Introductory Remarks

Reliability is an important and desirable attribute of a consumer product. If a product is perfectly reliable it will be available always to perform satisfactorily on demand, and it will not break down during operation.

Nothing, however, is perfectly reliable. Reliability refers to a future event or action, and predictions cannot be made with certainty. Ultimately all things fail.

Reliability, then, involves probability. In simple terms it is the probability that a product will perform satisfactorily on demand. The probability may depend on the age or the accumulated operating hours; for example, wear-out failures are more likely to occur, the older the product is; random failures on the other hand are independent of age or accumulated operating hours. The probability depends also on a specified interval of time during which the product is expected to perform; the longer this interval, the more likely the occurrence of failure.

A precise, working definition of reliability should involve probability; an arbitrarily chosen future or present point in time; and an arbitrarily specified time interval beginning at this future or present point in time. Two other factors should be incorporated for explicitness: (1) That the product will have survived to this future or present point in time; (2) that reliability, like performance on which it is dependent is not a characteristic of the product per se, but depends also on the use conditions and environmental factors.

An adequate definition of reliability can now be given:

Reliability is defined as the probability that an object which has survived to some particular time will continue to perform satisfactorily for an additional specified period of time under prescribed conditions of use and environmental factors.

Mathematical Formulation

General equations

Reliability, or probability of survival, R, can be written

$$R = \frac{N_s}{N_o} \qquad (1)$$

where N_s is the number of survivors of the test at the end of an arbitrarily chosen operating period, and N_o is the total number of units present at the start of this same operating period.

The number of units which fail to survive the operating period, N_f, must be the difference between the number at the start and the number of survivors, because units must either survive or fail. Therefore,

$$N_o = N_s + N_f \tag{2}$$

N_o is an arbitrary constant, or parameter.*

$$R = \frac{N_o - N_f}{N_o} = 1 - \frac{N_f}{N_o} \tag{3}$$

By differentiation,

$$\frac{dR}{dt} = -\frac{1}{N_o} \frac{dN_f}{dt} \tag{4}$$

$$\frac{dN_f}{dt} = -N_o \frac{dR}{dt} \tag{5}$$

$$\frac{1}{N_s} \frac{dN_f}{dt} = -\frac{N_o}{N_s} \frac{dR}{dt} \tag{6}$$

The term on the left in (6) is defined as the failure rate (per unit number of survivors), λ, or the instantaneous probability of failure per unit.

N_s is the number of units at any time t bounded by the time interval dt. If at the start, $N_s = N_o$, and (6) reduces to (4).

Substituting (1) into the right side of (6) gives

$$\lambda = -\frac{1}{R} \frac{dR}{dt} \tag{7}$$

*The term parameter is a possible source of misunderstanding, especially between statisticians and engineers. To the former it means an arbitrary constant whose values characterize a member of a system, as a family of curves. To the latter it means one of a group of related actions contributing to a larger action; i.e., a factor. Historically and strictly, parameter is a mathematical term and it is advisable to use it as such.

Rearranging terms and integrating both sides of the equation,

$$\int \lambda \, dt = - \ln R \qquad (8)$$

At $t = t_1$, $R = 1$, and

$$R = \exp \left[- \int \lambda \, dt \right] \qquad (9)$$

<u>Random failure</u>

Where failures occur only by pure chance, every unit in an assembly of like units has exactly the same probability of failing. This probability does not depend on time, per se (age or accumulated operating time).

The number of failures dN_f in an arbitrary time interval dt will be proportional to the number of workable units (survivors) at the start of the time interval; i.e.,

$$dN_f = - kN_s \, dt, \qquad (10)$$

where k is a constant of proportionality, and the minus sign indicates a continuously decreasing population.

Rearranging terms

$$\frac{1}{N_s} \frac{dN_f}{dt} = -k \qquad (11)$$

The constant is recognizable as the failure rate λ, previously defined; cf (6). Thus, for the special case of random failure, the failure rate per unit number of survivors is a constant (λ in general is not a constant). As the number of survivors decreases, the number of failures per unit time will also decrease proportionately to maintain λ constant.

Substituting λ = constant in (9) gives (12)

$$R = \exp [- \lambda t]$$

Equation (12) is often written in slightly modified form:

$$R = \exp [- t/m] \qquad (13)$$

where $m = 1/\lambda$ is the mean time between failures (MTBF)* For the special case λ = constant, m is also constant.

Mean time between failures is simply the arithmetic average of the times to failure of a sampling. Many engineers use this term when referring to repairable objects, and the term mean time to failure (MTTF) when referring to non-repairable objects. On the other hand, mathematicians may use the latter term to indicate expected life of components, as distinguished from systems.

The MTBF does not indicate the time a product can be depended upon to run without failure; the probability of survival is given by eq. (13). The MTBF is primarily a figure of merit for comparing one object with another or for rapid estimation of reliabilities. Some examples to follow will make clear the significance of MTBF, as well as some implications of reliability theory.

In all three problems, below, it is assumed that the MTBF is 1000 h and that random failures only occur.

(1) What is the probability that a single unit will survive to 1000 h?

$$R = e^{-t/m} = e^{-1000/1000} = e^{-1} = 36.8\%$$

Thus, it is unlikely that the unit will survive to a time equal to the MTBF. Put another way, if 100 units were placed on test, about 63 would have failed before reaching 1000 h.

(2) What is the probability that a single unit will survive the first 1 h of operation after being put in service; that a unit viable after 1000 h will survive to 1001 h?

The chances of survival are equal for equal lengths of time throughout the entire random failure period of time. In eq. (13) t is the time duration of any arbitrarily chosen operating period, with t = 0 designating the start of this period; t is not in general a measure of age or total accumulated operating life since the product was new.

$$R = e^{-1/1000} = {}^{-0.001} = 99.9\%$$

From example (1) above, however, the unit will have only a 36.8% probability of surviving to 1000 h. Still, if it does survive, the probability it will survive the next 1 h is 99.9%.

These examples should make clear also why reliability has been defined as it has.

*In the published literature the term often is tacitly restricted to random failures. Nevertheless, it is a generalized concept, applicable to wear out as well.

(3) What is the probability that a single unit will survive to 100 h?

$$R = e^{-100/1000} = e^{-0.1} = 90.5\%$$

If 100 units (devices, components, etc.) are run for 1 h their chance of survival is still 90.5%. Similarly, this same reliability figure holds if 500 units were run for 0.2 h; 50 units for 2 h.

Equation (13) is for a single unit. In applying this equation to an assembly of N like units, t is replaced by the product Nt.

Wear-out failure

Figure 1 is an idealized schematic diagram of the instantaneous failure rate of a large assembly of virtually identical new components or systems vs accumulated operating time since first put on test, T. (The designation T is used to distinguish such accumulated time from t, any aribtrarily chosen interval of time.) Components or systems are neither replaced nor repaired on failure; simply removed.

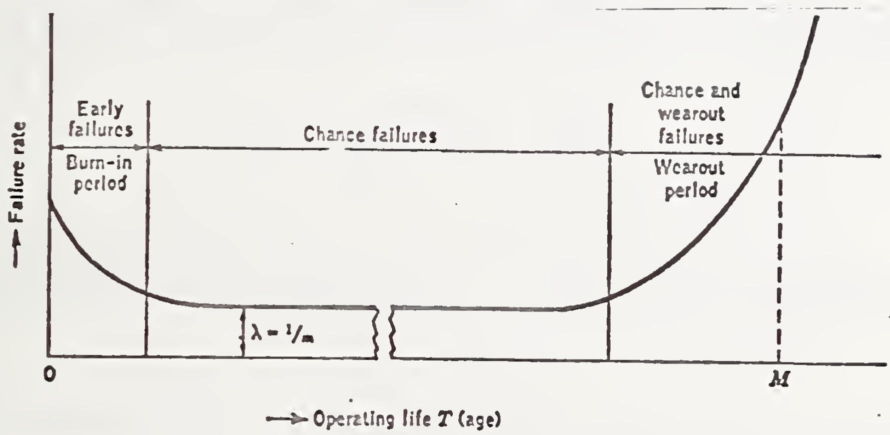


Figure 1. Component or system failure rate as a function of operating life.

Initially a few early failures assumedly appear, and as the number of these substandard units dies out, the failure rate rapidly decays. Then the random failure period of time sets in, characterized by the constant failure rate. This is the period of highest reliability. This exclusively random failure period of time eventually terminates with the onset of wear-out failures, and the failure rate then increases rapidly. Random failures can continue to occur, of course, but wear-out failures are expected to predominate.

The MTBF, in general, has already been defined. The mean time between wear-out failures (sometimes called mean wear-out-life) is designated M to distinguish it from mean time between random failures, where m was used.

The time dependence of wear-out failures is usually approximated well by a normal, or Gaussian, distribution, and the failures tend to cluster around M. Half the population, exclusive of any early or random failures, will have failed by the time T = M is reached. In contrast, for the exclusively random failure period 63% of the population will have failed by the time T = m. Generally, however, m >> M, so only a small percentage of the population fails randomly up to the onset of wear-out failures, and approximately half of the population fails subsequently in the time period bound by T = M.

Wear-out reliability is characterized mathematically by two parameters, or arbitrary constants, M and σ , the standard deviation, and it is convenient to use standard units in which σ is used as a unit of measurement of deviation. Thus, multiplication of a function by σ standardizes it.

The failure density function or (failure) distribution f(t) is defined as the failure frequency per unit (or component). Thus, from (4)

$$f(t) = \frac{1}{N_o} \frac{dN_f}{dt} = - \frac{dR}{dt} \qquad (14)$$

The standardized failure density function or standardized (failure) distribution ϕ (t) is defined as

$$\phi (t) = \sigma f (t)$$

Similarly, the standardized failure rate curve r (t) is defined as

$$r (t) = \sigma \lambda \qquad (16)$$

From (7) and (14)

$$\lambda = \frac{f (t)}{R} \qquad (17)$$

$$\sigma \lambda = \frac{\sigma f (t)}{R} \qquad (18)$$

From (15) and (16)

$$r (t) = \frac{\phi (t)}{R} \qquad (19)$$

Usually wear-out failures display a normal, or Gaussian, distribution which is given by

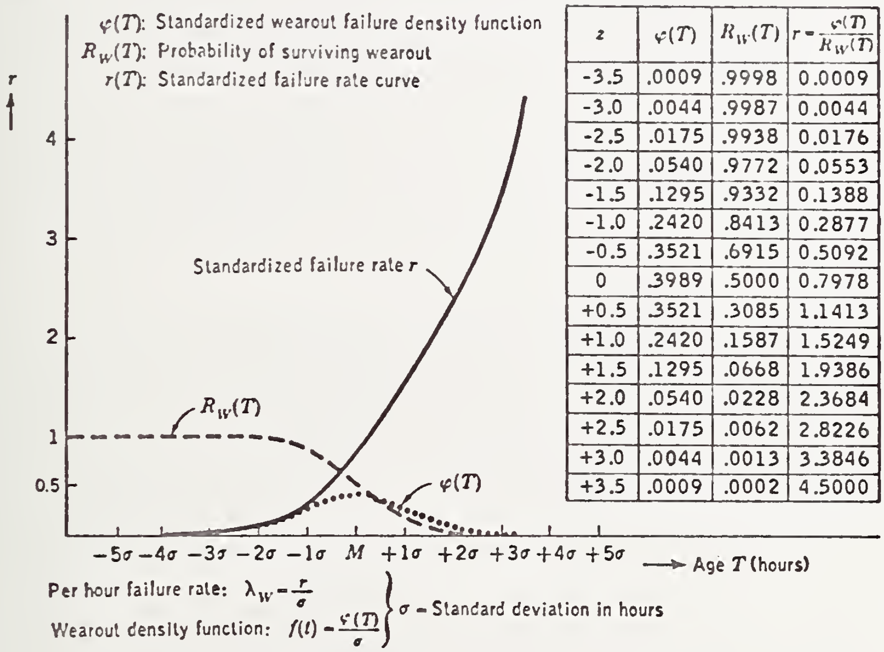
$$f(T) = \frac{1}{\sigma\sqrt{2\pi}} \exp - [(T-M)^2/2\sigma^2] \qquad (20)$$

where T is the cumulative time measured from T = 0 when the product was first put on test.

From (14) the wear-out reliability (cumulative probability of survival from T = 0), R_W, is given by

$$R_W = \frac{1}{\sigma\sqrt{2\pi}} \int_T^\infty \exp - [(T-M)^2/2\sigma^2]\, dT \qquad (21)$$

Figure 2 shows a standardized failure rate curve for the Gaussian distribution of failures, together with curves of R_W and ϕ (T).



z	$\varphi(T)$	$R_W(T)$	$r = \frac{\varphi(T)}{R_W(T)}$
-3.5	.0009	.9998	0.0009
-3.0	.0044	.9987	0.0044
-2.5	.0175	.9938	0.0176
-2.0	.0540	.9772	0.0553
-1.5	.1295	.9332	0.1388
-1.0	.2420	.8413	0.2877
-0.5	.3521	.6915	0.5092
0	.3989	.5000	0.7978
+0.5	.3521	.3085	1.1413
+1.0	.2420	.1587	1.5249
+1.5	.1295	.0668	1.9386
+2.0	.0540	.0228	2.3684
+2.5	.0175	.0062	2.8226
+3.0	.0044	.0013	3.3846
+3.5	.0009	.0002	4.5000

Figure 2. The Gaussian failure rate (after Bazovsky, loc. cit.).

Notice that the failure rate increases steeply at T > (M-1.5 σ) . The probability of survival (reliability) to time T = (M-1.5 σ) is 93%; to T = M it is 50%.

The values of ϕ (T) together with R (T) can be obtained directly from normal probability tables.*

*For example, Tables of Normal Probability Functions, NBS, Applied Mathematical Series No. 23, (U.S. Government Printing Office, Washington, D. C., 1953).

If random failures are not negligible with respect to wear-out failures, the combined cumulative probability of a product to survive both, for the life period from $T = 0$ when the product is new, to an age T is

$$R = \exp [- \lambda T] R_W \tag{22}$$

where R_W is defined by (21). The shape of the curves in figure 2 would be altered.

Chapter 5

Maintenance and Repair

Maintenance is defined as an action performed on a satisfactorily operative equipment to keep it performing satisfactorily for a longer time than would otherwise be the case; i.e., maintenance postpones wear-out failure of the equipment.

Maintenance embraces systematic inspection; prevention of incipient failures, including replacement of parts; lubricating; and cleaning. Effective maintenance results in a lower failure rate; hence, greater reliability.

Repair is defined as an action performed on an equipment which does not perform satisfactorily, to restore it to a satisfactory level of performance by fixing or replacing parts which caused the malfunction.

Replacement and repair are not contradictory. The definition of repair is to be applied to the unit in toto; i.e., the entire assembly, rather than to its individual components. Thus, a component replaced does not constitute a repair of the component, but the assembly, equipment, or machine, of which the component is a part may be repaired by such action.

Although the military have done much work in maintenance engineering and definitions of their terminology are often quoted in the published literature, they are not suitable for the present work. For example, according to English usage maintenance is upkeep, and repair is fix. Notwithstanding, the military do not distinguish between the two, and the latter is considered corrective maintenance. That time has to be spent on the equipment, thus reducing its availability, is important; not distinguishing the type of action.

The situation for consumer products is not equivalent: consumers are not indoctrinated in the jargon, and would be misled by omission of the term repair. It is advantageous, for this work, to distinguish between maintenance and repair.

Another source of possible misunderstanding is the militarily-inspired term, maintainbility. It is not interchangeable with the term maintenance. The former is a characteristic of design and installation relating to the ease of performing a maintenance action. A similar distinction applies to repairability and repair.

If maintenance has been prescribed, the design engineer has considered it necessary to meet the design objectives of the product, and assumes it will be carried out as specified. In laboratory testing (as well as controlled field testing), this is generally a valid assumption; in field or home use, however, maintenance may not be done, or done properly.

Although maintenance actions and repair actions are sometimes identical in nature (e.g., replacing a battery in an automobile before or after it has failed), the latter generally is more complex, more difficult to perform, and costlier than the former. If repairs have not been made proficiently, subsequent failures will result prematurely [see also, Chapters 3 and 10 (Correlativity)].

Chapter 6

Useful Life

Useful life, like performance, is a product characteristic required to be measurable in the laboratory. As for performance testing, engineering skills are necessary for objective determination. That consumers may dispose of still-functional products does not alter this fact.

A definition of the term useful life hinges on the concept of usefulness since the word life simply denotes a period of time.

Usefulness of a product is intimately bound up with functionality in the sense of both intended performance and service expected as due by virtue of the nature, structure, and condition of the product. Specifically, if a product generally performs satisfactorily, does not break down in use, and will perform satisfactorily on demand, the product is useful. These criteria can be summarized with a single term -- reliability*, a concept in which probability of survival depends on an arbitrarily chosen time duration (see Chapter 4, Reliability).

Reliability itself is an engineering concept, but as the ultimate aim of the present work is to assist in the obtainment of product value, a suitable reliability, or one expected as due, must include economic considerations. (Fulfillment of expectations considered due, and acceptability are related.) Although determination of a suitably high reliability may involve consideration of the type, age, and initial or replacement cost of the product, the most important factors are repair cost (relative to replacement cost) and reliability, per se. Usually reliability is perceived as the time to or between failures.

If the cost of a repair is considered prohibitively high, the useful life of an individual unit is effectively terminated at failure, regardless of reliability. On the other hand, if the failure rate becomes excessive -- i.e., the product becomes unreliable -- the useful life is terminated independently of any repair costs. In the case of non-repairable objects, useful life of an individual unit terminates when failure occurs.

Useful life is defined as the time span over which the reliability of the product is suitably high, or to a time of failure when it is considered uneconomical to repair regardless of reliability, or until an irrepairable failure occurs.

*Satisfactory performance is inherent in reliability; if a product fails, it is no longer reliable, unless repaired.

Note on the term durability

Maybe it's because the word is so old and familiar -- it can be traced back to the Middle Ages -- that durability crops up so often in both consumer - and product testing vocabularies. This is why the term is being treated here. To the consumer it means the lasting quality of a product -- the ability to endure; and although not articulated, it probably connotes something akin to the technical term, useful life. As used by engineers, however, it is perhaps the term most pluralistic in meaning and the most vague. Sometimes it is supposed to mean useful life; sometimes, resistance to wear out; sometimes it alludes to reliability; other times it refers to ability to endure an abnormally high stress, including that caused by misuse or abuse.

The following qualitative definition of the term is suggested:

Durability is the ability to endure prescribed operational and environmental conditions without failure due to wear out; i.e., durability is the lasting quality over the useful life.

In any event, it is advisable to circumvent terminological confusion where possible; for purposes of life-cycle performance the term useful life is preferable.

Chapter 7

The Concept of Stress

An engineering tool

The concept of stress affords a valuable analytical tool for test design and interpretation. Put simply, performance is regarded as reaction to stress; stress being the concomitant combination of use conditions and environmental factors. As performance permeates the methodology, however, the consequences of stress are far reaching, affecting failure, reliability, and useful life, as well.

To be of value, testing aims to relate laboratory results to normal field, or home, results. Differences between laboratory - and field stresses can lead to disproportionately large discrepancies; even to spurious results. Application of the concept should further testing effectiveness. The concept will be elaborated and applied below.

Performance in another prespective

How a product is used and factors in its environment can sensitively affect resultant performance. Analogous to the stress - strain relationship of mechanics, both use conditions and evnironmental factors are considered as stresses acting on the product, and performance as the reaction, or strain. Generally, larger the stress, and the greater the strain, the greater the toll. Thus, increased performance is usually obtained at sacrifice of useful life. Converse relations also hold.

Stresses are synergistic

Use conditions and environmental factors act concomitantly on a product; they may occur independently of one another. Nevertheless, the combined effects of each as stresses may be synergistic. Several examples follow:

a) A soldered connection will remain intact if temperature is elevated and there is little vibration; or if there is much vibration, but temperature is low. If both temperature and vibration become excessive, however, the connection will sever.

b) A part may corrode gradually, even if surrounded by high moisture, provided temperature is low; or if temperature is high, provided there is little moisture. If both moisture and temperature are high, however, corrosion will be rapid.

c) A battery whose use conditions are fixed will wear out more rapidly, the higher the ambient temperature.

Sometimes, the combined actions of use and environment result in a decrease of stress: A switch or relay not used may fail owing to dust accumulation or corrosion at the contacts. Use staves off aging failures by mechanically removing dust particles or destroying the thin oxide film.

Stress is varied

Different persons may use the same, or nearly identical, products differently according to their needs and habits; and even an individual user may not always use a product identically each time. Environmental factors may vary similarly; for example, because of temporal changes or climatic differences. Nevertheless, statistical methods can be used to construe so-called normal use conditions and environmental factors in the sense of being typical or average; in other words, normal stress. Testing for every stress would not be feasible.

In testing for performance or life, however, to propose only the normal stress for imitation generally would be unrealistic: Many products customarily are overstressed at some time during their useful lives; for example, the occasional extra-heavy load of laundry in the washer; the current surge, or transient, in a speaker which burns out the coil; a brown-out in which reduced voltage overtaxes running electric motors (an example in which low magnitude of a factor is more damaging than high). However infrequently overstress occurs, its effect on the product's deterioration can be much more severe than that of normal stress acting more frequently, or for longer duration.

Stress pattern -- the model proposed as the example to be imitated in the laboratory -- should not be based merely on a constant normal stress, however much it may simplify testing. It should include the occasional customary overstress.

Performance is non-linear with stress

Small changes or differences in stress generally make large differences in performance and useful life. The relationships usually are not linear because the laws of physics and chemistry which govern performance and life are usually exponential. For example, for incandescent light bulbs, a 10% increase over rated voltage increases light output 40%, but decreases life over 60%.

Small discrepancies in assumed normal stress and overstress, whether by engineering judgement, based on experience and intuition, or statistical analysis of human factor data, can lead to large discrepancies between results in the laboratory and those actually occurring in the home.

Further, sufficient overstress can precipitate failures in the laboratory which normally would not occur in actual home use, thus making laboratory results invalid.

Two different kinds of time need to be distinguished for product testing: clock and operating. The former refers to time of day or month; the latter to the time a product is energized or used. In both cases time generally signifies a duration. Further, time may be expressed as number of cycles (of use).

Consumers usually conceive of product life in clock time without regard for actual time operated; for example, 15 years for a vacuum cleaner, 7 years for a color television receiver, 10 years for a water heater. In the laboratory, operating time or number of cycles is recorded.

Most products are not run or used continuously, so the total operating time during its useful life is less than the corresponding clock time. For example, a vacuum cleaner with an assumed useful life of 15 years (130,000 hours), typically will have accumulated 500 hours operating time.

As a matter of practical necessity, almost all life testing "compresses" clock time in the sense of being carried out in less time than the actual useful life of the product in the home. This is accomplished by any one of the following methods: (1) increasing stress per se to accelerate failures; (2) increasing frequency of use; (3) running the product continuously.

The effects of time (duration - and frequency of use) on stress need to be considered, as products may be over - or under stressed as a result. Some examples follow:

(1) An environmental factor acts gradually and causes an aging failure to occur in the home after a long time; e.g., corrosion, insulation on motor windings, hoses in dishwashers and washing machines. "Compressing" time will understress the product, and the failure will not show up.

(2) An internal combustion engine is run nearly continuously or frequently on test instead of being cycled as in normal use. This understresses the engine and retards wear, as moving parts are always lubricated.

(3) An internal combustion engine run for very short times increases stress through corrosive actions.

(4) A light duty motor run too long will be overstressed and fail; e.g., some coffee mills and blenders.

"Compressing" time in the laboratory does not always understress or overstress. For some products, time can be "compressed", yet normal stress maintained; vacuum cleaners and hair blower-dryers, are considered examples.

In a product such as a clothes dryer run continuously, the motor may be put under stress, but the timer understressed.

"Compression" of clock time itself is not of engineering significance; how it affects product stress, is. If understressed, product useful life will be prolonged; if overstressed, useful life will be shortened, and non-typical failure modes also may result. If stress is normal, number of cycles or operating time in the laboratory may be equivalent to its home counterpart.

To refer to life testing as accelerated testing in the sense of "compressing" time would convey little useful information. Further, failures may be decelerated; not accelerated. In the next chapter, accelerated and normal testing will be defined in terms of the significant factor, stress.

Chapter 8

Accelerated Testing

Life testing in the laboratory can be done in one of two general ways: (1) normal testing, and (2) accelerated testing. In the former, the use conditions and environmental factors maintained during the testing are made to approximate those prevalent during actual normal home use of the product; in the latter, a use condition or environmental factor is made more severe than normal in order to bring on failures more rapidly, and the data are extrapolated to normal stress conditions.* The advantages of accelerated testing are (1) test results may be obtained with less testing and in shorter time and (2) lower cost.

Notwithstanding, accelerated testing, in the absence of historical data, is inherently risky -- by making a use condition or environmental factor more severe than normal, failure mechanisms different from those which would occur normally may be brought on; further, it is difficult to predict the performance at the normal stress level. There should be justification for predicting what the characteristic would be at normal use conditions and environmental factors. Otherwise, predictions are little more than guess work. Justification can take the form of historical data or a quantitatively calculable knowledge of the processes governing the predominant failure mechanisms.

Because of the risk involved in accelerated testing it is advisable to do normal testing when practical; except if historical data are available. If the product class were rapidly evolving, or the time to complete testing were excessively long, or the cost were prohibitive, the normal test would be considered impractical. A way to reduce clock time while still doing a normal stress test may be to increase the frequency of use (an example where this should work is the vacuum cleaner).

In summary, where historical data are not available, because of the risk in making accelerated tests, normal tests are advisable wherever practical. Where normal tests are not practical, and this is often the case, then accelerated tests should be considered, but accelerated tests will not always be feasible and the specific product class must be considered and evaluated. A necessary condition for making credible accelerated tests is (1) historical data or (2) a calculable knowledge of the main failure mechanisms.

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*See, for example, Rabinowicz, E., et alii, Transactions of the ASME, Series B, Journal of Engineering for Industry 92, No. 3, 706-710 (Aug. 1970).

Chapter 9

Some Statistical Considerations

This monograph deals with engineering test methodology. Additionally, there exists well-developed statistical methodology which should be used conjunctively. Treatment of that field is neither within the scope of the present work, nor is it necessary; the reader is referred to some esteemed publications on the subject.* It is the intent of this chapter only to indicate the importance of statistical methods in test planning and in analyzing results, particularly with regard to validity.

The number of units which make up the total population of a given product generally is very large, but it is feasible to test only a limited number of units. The sampling is supposed to be representative of the population, but unless properly chosen it may not be, and the results of the test may be invalid -- that is, a (mathematical) solution obtained for the sampling, may not be a solution of the population.

Suitable sampling involves two factors: (1) sampling size; (2) sampling selection. (1) The size is required to be sufficiently large to be statistically significant. How large depends on the shape of the failure distribution curve of the population. This may already be known from prior testing or might be estimated initially; (2) the sampling should be randomly selected.

Random does not mean the same as haphazard; the former is a deliberate process and there are means for random selection. Random implies that the probability of selecting one unit is the same as any other (available) unit. Lotteries, dice throwing, roulette are assumed to be random processes; tables of random numbers may also be useful.** On the other hand, if all units are bought from the same vendor, for example, these may have been consecutively manufactured within a short space of time. Lot sampling -- taking samples at spaced out intervals of time -- is a means for avoiding such a problem.

*MIL-STD-781B; Natrella, M. G., Experimental Statistics, NBS Handbook 91 (U.S. Government Printing Office, 1966)

**See, for example, Fisher, R. A. and Yates, F., Statistical Tables for Biological, Agricultural, and Medical Research, 6th ed., Table XXXIII (Hafner Publishing Co., New York, 1963).

Statistical methods are available which enable an estimate to be made of the confidence attached to a given set of statistical data.* Confidence coefficient (or confidence level) expresses the probability of truthfulness; that is, it gives the probability that an interval of values will include the parameter value. The data reported should include a statement of both level and limits.

*See, for example, Amstadter, B. L., Reliability Mathematics, cited in Bibliography.

Chapter 10

The Quality of Testing

Life-cycle performance testing seeks to assess the qualities of a product with prolonged use. That it does so satisfactorily should not be assumed; it is conditional on the quality of the testing meeting standards. Thus, the quality of testing itself needs to be assessed and the criteria are (1) validity, (2) reproducibility, and (3) correlativity.

Validity

Validity is the truthfulness of the data; it relates to whether what is claimed to be measured is in fact measured. Causes of invalidness include faulty instrumentation; human errors in measurement, judgment, and reasoning; errors or negligence in sampling selection; failure to recognize or distinguish primary and extraneous factors.

Reproducibility

Reproducibility measurements establish the consistency of a test. It is not sufficient that tests be reproducible within an individual laboratory; to have utility there must also be inter-laboratory reproducibility. Too, failure to obtain reasonable reproducibility may cast serious doubt on the test's validity. Reproducibility depends in general on (1) sampling constancy or invariance; (2) measurement apparatus, techniques, and skills; (3) following of instructions and carrying out of test procedures.

To abet attainment of reproducibility -- particularly inter-laboratory -- different samplings should be chosen judiciously to ensure they are virtually equivalent. For intra-laboratory testing to establish precision, the time between successive tests should be kept short so that constancy of the product may be reasonably assumed. Also, test procedures and descriptions should be written clearly and precisely, to minimize the possibility of misunderstanding or subjectiveness by test engineers or technicians.

Correlativity

The usefulness of life-cycle performance testing in the laboratory is contingent on the relevancy of the results to those which actually occur in the field, and the quality of the relationship is the correlativity.

Correlativity is defined as the quality or state of exhibiting correlation between results of performance testing in the laboratory and corresponding results obtained from field or home use.

Obtaining or demonstrating correlation, however, is difficult and may be full of pitfalls: (1) it is difficult to determine or predict what actual normal use conditions and environmental factors in the field are; (2) use and environment generally cover a much broader spectrum in the field than is feasible to simulate in the laboratory; (3) it is often difficult to simulate changing environmental factors accurately over a prolonged period of time; (4) product evolvement, manufacturing or material changes, and variations in conformance of manufactured parts to design specifications make a statistically significant and random sampling difficult; (5) the requirement of reproducibility in laboratory testing may impose conditions which are not representative of actual field use.

Laboratory data are obtained from controlled testing; field data may be from (partially) controlled testing or uncontrolled activities, such as surveys.

Consider first uncontrolled field data. Information is obtained from the consumer on the frequency and nature of repairs, retention life, and possibly the reason for disposal. There are several pitfalls: (1) maintenance actions, which are important factors in life, performance, and reliability, may not have been carried out as specified; (2) products may have been misused or abused; (3) the consumer may not have perceived failures accurately or in conformity with the test designer's definition; (4) repair actions may not have been made proficiently; e.g., primary failure may not have been recognized and corrected; replacement parts may have been of substandard quality; workmanship may have been poor. If repairs are not proper, failures will occur prematurely; (5) the retention life is not necessarily the same as the useful life, and indeed products are often disposed of before the end of their useful life; e.g., because of obsolescence or for aesthetic reasons. Thus, uncontrolled field data pose a serious problem in validity: Do the data represent what are supposed to be measured or represented, free of extraneous, unaccountable or unrecognized factors which cause deleterious results? Because very little performance data on consumer products over an extended life exists at the present time, the problem is perhaps academic, but it does point up the pitfalls inherent in any approach which attempts to correlate laboratory results with uncontrolled field results. It may be possible to indicate validity through use of statistical tools, but the problems are awesome.

It is desirable, perhaps even necessary, to resort to controlled field tests instead. Here, a sufficiently large number of new units, randomly chosen together with those for laboratory testing, are placed in the field and periodic inspections are made by qualified technical personnel with appropriate test equipment and parts, to ensure that prescribed maintenance is done, to confirm the accuracy of the consumer's perception of failure relative to the test specifications, and to carry out repairs proficiently, when necessary. Only the stress pattern (use conditions and environmental factors) is not controlled. On the other hand, in the laboratory, the stress pattern is controlled, and this is presumed to constitute the only difference between laboratory and field tests.

Controlled laboratory and controlled field tests together constitute an experiment in which there are presumably only two variables: laboratory stress pattern and field stress pattern. The chances of demonstrating correlation are considered good and the analysis of results is much simplified.

Chapter 11

Feasibility

Although not an engineering concept, the term feasibility is treated here because it is an important consideration in test planning.

A common meaning of feasible is: capable of being done or carried out, and this implies being given the proper conditions. Just as performance is not an attribute of an equipment or object per se, but depends also on the stress (use and environmental factors), so feasibility--the quality of being feasible--is not a sole function of the plan, test, or action being considered, but depends also on constraints and conditions. Examples are: funding, manpower, equipment and alloted time. Given the same plan or test, it may be feasible under certain specified conditions; not feasible under others.

Whether or not a plan or test is feasible thus cannot be answered with any assurance unless the conditions are specified. Because of its importance, the conditional aspect should be made explicit, rather than remain implicit. The term feasible therefore is redefined:

Feasible means capable of being carried out under specified conditions such as funding, manpower, alloted time, and equipment.

Chapter 12

Procedure

This chapter sets forth in outline form a suggested procedure for use in formulating tests. An understanding of the concepts discussed above is prerequisite to intelligent application.

1. State objectives

example: To test life-cycle performance of a widget.

2. List data to be presented

example: a) probable useful life, together with confidence level and limits;

b) number and type of maintenance actions during useful life;

c) number and causes of failures; repair actions (components, materials, time to repair) during useful life;

d) energy consumed during useful life.

3. Search & familiarization

a) sampling characterization

1) homogeneous or heterogeneous? (If heterogeneous, different tests for different units may be required.)

2) repairable or non-repairable?

3) product evolution slow or rapid? (If slow, historical data will be of great value; in its absence, tests may still be worthwhile. If rapid, historical data may be of little or no value: the product may be obsoleted by the time tests are completed.)

b) historical data, particularly as regards failure modes, mean times to - or between failures, and stresses. (For slowly evolving products, historical data, if available, will not only greatly facilitate testing, they may also permit accelerated, or overstress, testing to be made.) In-warranty data, service records, laboratory results are all useful information.

c) existent tests -- if available, review for applicability.

d) published literature -- service manuals, trade journals market research reports, etc.

e) discussions -- with design and test engineers.

f) inspection: design; construction; materials; operation. Identify major working parts and likely wear-out contenders (low MTTF).

4. Test design & development

a) human factors input

1) determine use conditions; load; use-environment, all as a population distribution -- (these may not be independent variables);

2) frequency and duration of use;

3) how was information obtained? (e.g., questionnaires, observations);

4) number in sampling;

5) is sampling random? How chosen?

6) is sampling representative of user population?

7) what is the confidence level of these data?

b) identification of stresses

which use-(including load) and use-environment conditions are known to or believed to affect performance significantly? Consider use and environment singly and in combination. Examples of possible environmental factors: ambient temperature; humidity; dust; mechanical shock; vibration; temperature and humidity; temperature and vibration.

c) selection of stress pattern

1) if historical data are available, consider accelerated testing and how this test might be integrated with the previous; if no historical data are available, avoid overstress (except for that customarily expected) and attempt to use normal stress testing where possible.

2) restrict testing to prime stresses only (side experiments may be desirable to help in determination).

3) prescribe use, load, and environmental factors; specify allowable ranges; include customarily expected over-stresses; prescribe operating time schedule.

d) <u>stress analysis</u>

1) list major components of product, especially those known to or believed to fail typically in use.

2) indicate whether these components will be over-, under- or normally-stressed by stress pattern.

3) consider desirability of altering stress pattern, above [4.c)3)].

e) <u>performance and failure specifications</u>

1) state main utilitarian function (primary performance attribute); specify (usually minimum) level of acceptable performance;

2) specify salient secondary performance criteria. Examples to consider are degradation of the load by the product; excessive noise; excessive vibration; leaking of liquid or gaseous fluids.

f) <u>specification of useful life criteria</u>

1) specify minimum acceptable reliability;

2) specify maximum acceptable repair cost;

3) for allowable repairs, specify reliabilities which will justify costs.

It is advisable to obtain human factor data to assist in determination of the preceding three criteria.

For repairable products useful life terminates with failure to meet criterion 1), 2) or 3) above. For non-repairable products useful life terminates with failure.

For products where average retention life is less than probable useful life, it may be desirable to terminate testing at a time equivalent to the former.

g) <u>sampling</u>

1) estimate number of units required for a desired confidence level and limits; or

2) estimate confidence level and limits for the number of samples obtainable. Are they satisfactory?

3) arrange to obtain random sampling, if possible.

h) repair readiness

1) are replacement parts readily available? If not, stock selected parts.

2) are qualified repairmen on site? If not, secure or have personnel trained.

i) controlled field tests

1) how many units (or households) are desirable or are accessible?

2) how are units (households) to be selected? Consider, for example, geographic location; income level; size of family.

3) how are field data to be obtained? Some possibilities are: manufacturer's in-warranty records; other service records. Can arrangements be made with consumer to provide free or discounted repairs beyond warranty period? Can monitoring instrumentation be installed on products?

j) feasibility

1) consider funding, qualified personnel, equipment, facilities, time duration of project, etc.

2) estimate what may be feasible under the above constraints.

3) modify statement of objectives or data to be presented, if indicated by 2), above.

5. Test execution

ALL PERFORMANCE CRITERIA AND USEFUL LIFE CRITERIA MUST BE SPECIFIED IN ADVANCE OF TESTING!

a) simulate prescribed use conditions and environmental factors;

b) monitor performance frequently;

c) note, inspect, and identify all failures.

1) classification? (Early; random; wear out.) Don't guess -- if unable to identify, pass up.

2) failure mechanism?

d) make qualified repair, if appropriate (see 4.f), this chapter); return unit to test.

e) maintenance

1) carry out all maintenance actions prescribed by manufacturer (exception: if maintainability is so poor as to preclude a maintenance action by consumer, this may be omitted at discretion of test designer, but the omission should be noted).

2) correction of incipient failures are to be included as maintenance actions.

f) keep complete records of data.

g) testing of a unit terminates in accordance with useful life criteria (or in special circumstances, earlier -- see Chapter 6).

Test analysis & interpretation

a) data handling: no omissions; no rationalized "laundering"; no unjustified extrapolations. Early failures are not counted in reliability and life testing.

b) is test acceptable?

1) validity?

2) reproducibility?

3) correlativity? (Do failure modes and distributions of laboratory - and field tests agree?)

c) re-appraise assumptions in light of field data.

d) repeat stress analysis in light of field data.

e) revise for future tests, as required.

Epilogue

Life-cycle performance testing, like many other kinds of testing, is not an <u>exact</u> science. It attempts to predict a probable life, judgments frequently are required, and many of the interpretations and conclusions follow from a course of action prescribed, presumably, by an authority. Nevertheless, testing properly practiced is a science, albeit a difficult one. Unfortunately, in practice the difficulties are often aggravated by pressures of time, facilities, and funding.

Testing is imperfect, but that is no reason not to test. The question is whether the testing likely will provide new or better needed information compared to what presently is available, and whether it justifies the cost.

Testing is complex problem solving. Regarded and practiced as a cumulative and continuous science, it will become increasingly upgraded, increasingly valuable.

<u>accelerated testing</u>: testing made while maintaining a supernormal or excessive stress pattern -- i.e., the laboratory use conditions or environmental factors are more severe than those prevalent during normal field or home use.

<u>aging failure</u>: a time-dependent failure caused by environmental factors.

<u>burn in</u>: the process of testing previously unused devices, objects, or products to weed out substandard or weak specimens.

<u>burn-in failure</u>: see early failure.

<u>break in</u>: see burn in.

<u>chance failure</u>: see random failure.

<u>correlativity</u>: the quality or state of exhibiting correlation between results of performance testing in the laboratory and corresponding results obtained from field or home use.

<u>durability</u>: the lasting quality of a product; the ability to endure prescribed use conditions and environmentals factors over the useful life.

<u>early failure</u>: the failure which results early in life when substandard or weak specimens are tested for the first time; break-in failure; burn-in failure; "infant" mortality.

<u>environmental factor</u>: factors exclusive of the load, external to and immediately surrounding the object, which influence its performance.

<u>failure</u>: the state of inability to perform a function or action to specifications; for finished products (systems) minimum levels of performance are usually specified.

<u>feasible</u>: capable of being carried out under specified conditions such as funding, manpower, alloted time, and equipment.

<u>feasibility</u>: the quality of being feasible.

<u>load</u>: whatever is acted on or processed by a product to accomplish its main utilitarian purpose.

<u>maintainability</u>: a characteristic of design and installation relating to the ease of performing a maintenance action.

maintenance: an action performed on a satisfactorily operative equipment to keep it performing satisfactorily for a longer time than would otherwise be the case.

mean-time-between-failures: the arithmetic average of the times to failure of a sampling of repairable objects.

mean-time-to-failure: the arithmetic average of the times to failure of a sampling of non-repairable objects.

normal testing: testing made while maintaining a normal stress pattern -- i.e., the laboratory use conditions and environmental factors are assumed to approximate those prevalent during field or home use.

parameter: statistical -- an arbitrary constant whose value characterizes a member of a system, as a family of curves. Engineering -- one of a group of related actions contributing to a larger action.

performance: the accomplishments of a device or equipment under specified use conditions and environmental factors.

primary failure: failure of a component as a direct result of some deterioration of the component itself.

random failure: a time-independent failure caused by (1) sudden stresses or their cumulative effects beyond the lower limits of the design strength of the component; (2) latent quality defects.

reliability: the probability that an object which has survived to some particular time will continue to perform satisfactorily for an additional specified period of time under prescribed conditions of use and environmental factors.

repair: an action performed on an equipment which does not perform satisfactorily, to restore it to a satisfactory level of performance by fixing or replacing parts which caused the malfunction.

repairability: a characteristic of design and installation relating to the ease of performing a repair action.

retention life: the time span from inception of operation to disposal (which may be before or after the end of useful life).

secondary failure: failure of a component as a result of some deterioration in some other component.

stress: the concomitant combination of use conditions and environmental factors.

test method: a particular approach or procedure for testing of a specific attribute(s) of a consumer product.

test methodology: a generalized, coherent body of methods, procedures, working concepts, rules, and postulates, to be used in the solution of testing problems on any class of consumer product.

use conditions: the method or manner in which an equipment is employed as determined by an operator; including the load.

useful life: the time span over which the reliability of the product is suitably high or to a time when it is considered uneconomical to repair regardless of reliability; or until an irrepairable failure occurs.

wear: the impairment of an object or part by use; the utility, strength or quality is diminished.

wear-out: to become useless from long or excessive wear or use. The term implies failure and therefore is equivalent to the term wear-out failure.

wear-out failure: a time dependent failure caused by use; see wear out.

wear-out life: the time it takes one-half the original units, exclusive of any early or random failures, to fail because of wear out.

Roberts, Norman H., Mathematical Methods in Reliability Engineering, (McGraw-Hill Book Co., New York, 1964).

This book treats those mathematical ideas and techniques which the author had found to be useful in the field of reliability engineering. Some of the statistical fundamentals of the theory, as well as mathematical ways of handling data are presented. Although statistical factors to be considered in setting up tests are discussed, no guidance to making these tests experimentally meaningful is provided. In short, the book title is appropriate, as the emphasis is on mathematics, but one wishes that the author, a physicist, had seen fit to include more discussion of the engineering aspects of the subject.

Haviland, R. P., Engineering Reliability and Long Life Design, (Van Nostrand, New York, 1964).

The intent of this volume is to provide concepts and techniques essential to attaining engineering solutions to reliability problems. The intent is noble, the execution inadequate. Nevertheless, this is a useful book, particularly for its coverage of performance and life testing.

Goldman, A. S., and Slattery, T. B., Maintainability: A Major Element of System Effectiveness, (John Wiley and Sons, Inc., New York, 1974).

This systems-oriented text deals with fundamentals that interrelate maintainability to system effectiveness and cost, and is heavily slanted to military considerations and applications.

Barovsky, I., Reliability Theory and Practice, (Prentice-Hall, Inc., Englewood Cliffs, New Hersey, 1961).

This book can be recommended to engineers who desire to learn how quantitative theory may be applied to reliability testing of components and systems. Published fifteen years ago, it is still in print and it is still timely, which -- considering that a great deal of work has since been done in this field -- is quite commendable. The level is intermediate, and knowledge of elementary calculus will suffice to follow mathematical derivations. The author is a design engineer with a good feel for the practice of reliability. A word of caution: because the author writes from experience in the aerospace industry where reliability means virtually no failures and parts are replaced well before they can wear out, some statements and remarks may appear unrealistic or even absurd, if thought of in relation to consumer products.

Amstadter, Bertram L., Reliability Mathematics, (McGraw-Hill Book Company, New York, 1971).

This readable book might well be titled Reliability Mathematics for Engineers. It emphasizes the application of statistics to reliability engineering, rather than the rigorous derivation of formulas, and it meets a need. Ample use of graphs, tables, and illustrations facilitate its application. It is highly recommended to engineers who aspire to do their own statistical planning and analysis -- which is probably desirable and certainly commendable -- and are willing to make the effort to teach themselves.

Kivenson, Gilbert, Durability and Reliability in Engineering Design, (Hayden Book Co., Inc., New York, 1971).

The author's aim is to provide the knowledge essential to designing better and more reliable functional units by examining various breakdown mechanisms causing degradation, and by providing techniques for minimizing deterioration. He does not succeed: One does not become a design engineer by reading a book; the subject is much too extensive, complex, and esoteric for that. On the other hand, the reader can expect to get some appreciation of the difficulties facing the design engineer, his limitations, and the need for testing and redesign. That "Durability" appears in the title is puzzling: the term hardly appears in the text and the subject is barely treated; this is essentially a book on reliability and engineering design for reliability. Nevertheless, this slim volume is useful, especially for its treatment of the engineering as well as the elementary methematical aspects of reliability analysis.

Gilmore, H. L. and Schwartz, H. C., Integrated Product Testing and Evaluation, (John Wiley & Sons, New York, 1969).

The authors have produced a dichotomy: a part deals with the managerial aspects of product testing; the balance with the engineering. That each should appreciate the other's problems is certainly a valid point; that each will make the effort to do so is debatable. In any event, this book should prove useful to engineers, particularly for its detailed treatment of environmental testing such as temperature, humidity, mechanical shock and vibration and for its treatment of statistical techniques.

Finney, D. J. Experimental Design and its Statistical Basis, (The Univ., of Chicago Press, Chicago, 1955).

This simple and elegant little book was written by a statistician for biologists, but it may be read by others as well with profit. Fearing that his intended reader is not only unknowledgeable in mathematics, but would be frightened off by it, the author adopts a sympathetic manner, offers encouragement and rewards for labor, and keeps the mathematics to a bare easy-to-swallow minimum. Yet, he does explain a few basic ideas on statistical analysis and shows its importance in formulating and analyzing experiments, specifically those in biology. Although its application to consumer product testing is limited, it is almost delightful reading and is a good introduction to statistical appreciation.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Life-cycle performance testing of consumer products attempts to predict a probable useful life and to assess the performance during that time duration. A methodology--working concepts, terminology, rules, and procedures--to help accomplish this aim is presented. A glossary and an annotated bibliography are included.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*
Consumer products; life-cycle performance; methodology; reliability; terminology; testing; useful life.

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