

MECHANICAL ENGINEERING AND SOLID MECHANICS SERIES



Fracture Mechanics 3

Applied Quality Control

Ammar Grous

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First published 2013 in Great Britain and the United States by ISTE Ltd and John Wiley & Sons, Inc.

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27-37 St George's Road
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Hoboken, NJ 07030
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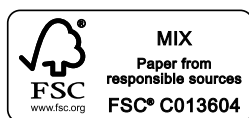
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Library of Congress Control Number: 2012950201

British Library Cataloguing-in-Publication Data
A CIP record for this book is available from the British Library
ISBN: 978-1-84821-442-2



Printed and bound in Great Britain by CPI Group (UK) Ltd., Croydon, Surrey CR0 4YY

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Preface

This book is intended for technicians, engineers, designers, students and teachers working in engineering and vocational education. Our main goal is to give a succinct evaluation of quality indicators and reliability as decision-making tools. To this end, we recommend an *intuitive* and practical approach, based on mathematical rigor.

The first part of this series presents the fundamental basis of data analysis in both quality control and in studying the mechanical reliability of materials and structures. Results from laboratory and workshop are discussed, keeping the technological procedures inherent to the subject matter in mind. We also discuss and interpret the standardization of manufacturing processes as a causal link with geometrical and dimensional specifications (geometrical product specification, GPS). This is, in fact, the educational innovation offered in these books compared to the praiseworthy publications quoted here.

We examine many laboratory examples, thereby covering a new industrial organization of work. We also use mechanical components from our own real mechanisms, which we built and designed at our production labs. Finite element modification is thus relevant to real machined pieces, controlled and soldered in a dimensional metrology laboratory.

We also examine mechanical component reliability. Since statistics are common to both this field and quality control, we will simply mention reliability indices in the context of using the structure for which we are performing the calculations.

Scientists in specialized schools and corporations often take interest in measurement quality, and thus in measurement uncertainties. So-called cutting-edge

endeavors such as the aeronautics, automotive and nuclear industries, to mention but a few, put an increasing emphasis on *just measurement*. The educational content of this series stands out due to the following:

- 1) the rigor of the probabilistic methods that support statistical-mathematical treatments of experimental or simulated data;
- 2) the presentation of varied lab models that come at the end of each chapter: this should help the student to better understand how to:
 - i) define and justify a quality and reliability control target,
 - ii) identify the appropriate tools to quantify reliability with respect to capabilities,
 - iii) interpret quality (capability) and reliability (reliability indices) indicators,
 - iv) choose the adequation test for the distribution (whether justified or used *a priori*),
 - v) identify how trials can be accelerated and their limits,
 - vi) analyze the quality and reliability of materials and structures,
 - vii) size and *tolerance* (GPS) design structures and materials.

What about uncertainty calculations in applied reliability and quality control?

Structure behavior at breaking point is often characterized (in linear mechanics) as a local variation of the material's elastic properties. This inevitably leads to sizing calculations that seek to secure the structures from which the materials have come. Much work has been, and still is, put into a large range of fields that go from civil engineering to the various flavors of mechanics. Here, we do not consider continuum mechanics, but rather probabilistic laws for cracking. We are aware that some laws are systematically repeated here and there in order to better approach reliability.

Less severe adequation tests would confirm the fissure propagation hypothesis. wherever safety is a priority, such as medicine (surgery and biomechanics), aviation and nuclear power plants, where theorizing unverifiable concepts would be unacceptable. The relevant reliability calculations must therefore be as rigorous as possible.

Defining safety coefficients would be an important (or even major) element of structure sizing. This definition does not really offer any real guarantees on safety provisions (unlike security provisions). Today, the interpretation and very

philosophy behind these coefficients are reinforced by increasingly precise probabilistic calculations. Well-developed computer tools largely contribute to the calculation time and effort. Thus, we will use software commonly found in various schools (Auto Desk Inventor Pro and ANSYS in modeling and design; MathCAD, GUM and COSMOS in quality control, metrology and uncertainty calculations).

Much work has been done toward rationalizing the concept of applied reliability, but no “united method” between the mechanical and statistical interpretations of rupture has appeared yet. Some of the many factors for this non-*consensus* are unpredictable events that randomly create the fault, its propagation and the ensuing damage. Many researchers have worked on various random probabilistic and deterministic methods. This resulted in many simulation methods, the most common of which was the Monte Carlo simulation.

In these books, we will present some documented applied cases so as to help teachers present probabilistic problems (reliability and/or degradation) succinctly. The intuitive approach is a large part of our problem-solving methods, and one of the main goals of this book is to offer up this humble contribution. Many praiseworthy works and books have described reliability, quality control and uncertainty perfectly well, but as separate entities. However, our task here is to verify measurements and ensure that the measurand is well-taught. As Lord Kelvin said, “if you cannot measure it, you cannot improve it”. Indeed, measuring identified quantities is an unavoidable part of laboratory life. Theoretical confirmation of physical phenomena must go through *measurement reliability* and its effects on the function attributed to the material and/or structure, among other things.

Mechanical models (rupture criteria) of continuum mechanics discussed (Chapter 1, volume 2) make up a reference pool of work used here and there in our case studies, such as the Paris–Erdogan law, the Manson–Coffin law, SN curves (Wöhler curves), Weibull’s law (solid mechanics), etc. We could probably (and justly) wonder how this chapter is appropriate in works dedicated to reliability. The reason is that these criteria are targeted deliberately. We used mechanical modeling here to avoid the reader having to “digress” into specialized books.

Establishing *confidence* in our results is critical. Measuring a characteristic does not simply mean finding the characteristic’s value. We must also give it an *uncertainty* so as to show the measurement’s *quality*. In this book, we will show educational laboratory examples of uncertainty (GUM: Guide to the Expression of Uncertainty in Measurement).

Why then publish another book dedicated to quality control, uncertainties and reliability?

This book covers quality control including uncertainties and some case studies upon reliability. In quality control, the process is often already known or appears to be under control beforehand, hence the intervention of capability indices (statistical process control – SPC). Furthermore, the goal is sometimes the competitiveness between manufactured products. Security is shown in secondary terms. Indeed, it is in terms of maintainability and durability that quality control joins reliability as a means to guarantee the functions attributed to a mechanism, component or even an entire system.

When considering the mechanical reliability of materials and structures, the reliability index is inherently a *safety* indicator. It is often very costly computationally and has very serious consequences. The common aspect of both fields is still the probabilistic approach. Probabilities and statistical-mathematical tools are necessary to supply theoretical justifications for the computational methods. Again, this book intends to be pragmatic and leaves reasonable room for the intuitive approach of the hypotheses stated here and there.

Finally, we will give a succinct glossary in order to soften the understanding of dimensional analysis terms (VIM – International Metrology Vocabulary) and those in structural mechanical reliability. This educational method allows us to “agree” on the international language used to define the measurand, reliability index or a succinct definition of the capability indicators largely used in quality control.

Component reliability (for both materials and structures) is absolutely unavoidable in the field of safety and performance.

The field of reliability is used in many fields of engineering, from civil engineering to mechanical and electrical engineering: it is thus manifold. It often aims to estimate the functions for the various component lifespans, depending on the study. Reliability users increasingly rely on reproducible software, though they struggle to determine whether the component is active or passive, the size of the experience return and its imperative validation, the phenomena that tend to decrease the likelihood of failure or the reliability index, etc.

These three volumes use some methods used here and there to estimate operational or target reliabilities. The apparent controversy between frequentist and Bayesian probabilistic approaches will be irrelevant in our humble opinion if we know how to set the problem *a priori*. Setting boundaries for the likelihood of

rupture (failure or even degradation) is worth doing. As for us, we prefer calculating rupture through the damage indicator integral, made explicit by Madsen's work.

Just as estimating reliability can allow us to understand the history of something to better anticipate the future, we must show pragmatism in measuring the factors responsible for the likely rupture. Since the measurement is always inherently flawed and uncertain, we must include uncertainty calculations in our reliability methods. Without such calculations, our result would lead to doubt.

Reliability has its own, specific terminology (see Glossary) that, like for metrology, affects the decision's terms. Thus, we will abide by the EN 13306 standard (see Appendix, Table A1.45). In Appendix and the glossary, definitions for reliability, durability, failure and degradation can be found.

Reliability data are necessary to:

- prioritize between components → occurrence rate of each mode (system failure mode and effects analysis – SFMEA);
- identify the degradation mechanism for a clear experience feedback;
- optimize preventative and corrective maintenance;
- gather data efficient for and necessary to the correct calculation of reliability parameters and especially their uncertainties.

Analysis and *validation* are done by analyzing the experience feedback with respect to critical failure criteria, such as failure modes, mean time between failures (MTBF), probability of failure on demand (P_s) and its reliability index according to a “selected criterion”, the repair and/or material unavailability time, the confidence intervals or even the sample size.

We note that reliability is usually taken into account from the design aspect, based on the specifications. It is calculated and compared to the allocated reliability (reliability demand). It includes all phases of life (design, manufacture, development trials).

During exploitation, the expected reliability is calculated and compared to a threshold (e.g. rate of failure) such as physical calculations, with the intent of extending it beyond the lifespan anticipated during design.

Reliability is mostly measured, therefore making its *metrology* a serious business: hence, the calculation of its uncertainties including instrument and measurement equipment calibration.

Among the various difficulties that rise against the reliability function, we note the component type (repairable or not, redundant or passive) and even some controversial methods and models (frequential/Bayesian), among others.

To calculate reliability indicators for components that present active redundancy, we use:

- various degradation mechanisms with different modes of failure;
- unknown or even complex physical modeling;
- sometimes we use appropriate classical and Bayesian reliability;
- incomplete or even truncated data;
- modeling using a Gaussian distribution, an exponential law, a two or three parameter Weibull law or especially a Birnbaum–Saunders law (as is often the case in cracking rupture: wear and tear in zone II of the Ritchie curve – see Figures 1.2 and 1.17 in Chapter 1 volume 2).

The component reliability can be with active and passive redundancy using:

- few degradation mechanisms;
- degradation type: slow or progressive;
- few failures (if any);
- physical modeling of degradation: fissure initiation and propagation;
- numerical methods (energetic methods, integral calculations, finite elements);
- Bayesian approach for available failure data.

Whether a physicist, statistical mathematician or mere engineer, “controversies” sometimes appear in many schools of thought on the method or model (frequential/Bayesian). In these three books, we will try to remain pragmatic and synthesize opinions.

From a *physicist’s* perspective, the experimental conditions of data gathering are known, and their uncertainties well-bound. Its so-called frequential analysis is based only on objective data, because they were measured *correctly*. We know that measurements are costly and time-consuming. If the data from “our physicist’s” experiments are insufficient and if the process turns out to be non-repetitive or the number of parameters to estimate is high, the frequential approach falsely introduces a confirmation bias in the analysis. The paradox is that the calculations are correct, but they only answer to a logically mathematical demand. In other words, the mathematics are correct but are superficially stuck on an inappropriate case, hence a rejection of the solution and the birth of controversy...

The *engineering* approach is *attractive* due to its “applied arts and crafts” aspect (i.e. learning). Its analysis includes the knowledge that we must apply an *a priori* law, which must by definition be biased. Without rejecting the Bayesian approach, this is where we favor the *engineering* approach because it uses *decision-making tools* for which preferences are clearly expressed. At the end of this approach, the uncertainty function greatly helps make the decision...

Finally, it is important to specify and frame the problem well: its context, hypotheses, available data, etc. Simulations (using software) are a helpful educational tool, but they should not be treated as *replacements* for real experiments. Relying on *real data* from the *experiment feedback* of the collection conditions is more suitable. Indeed, experiments and “real” data are a strategic necessity in the case of preemptive validation.

In this book, we present (see Chapters 1 and 2) the qualitative analysis elements preceding quantitative, deterministic and probabilistic analysis. The laws and tests discussed in the first two chapters (volume 1 of this series) are required reading for any probabilistic study of physical phenomena, and it falls to us to be pragmatic.

Regardless of the approach used, we must analyze the sensibility of factors and always use common sense. Among many other methods of analysis, reliability is a tool for understanding the past. For example, many failures, degradations and ruptures or ruin (damage) cannot be explained by deterministic models such as aging, degradation mechanisms, models and laws (see Chapter 1, volume 2: Fracture Mechanics by Fatigue). Studying reliability allows us to find the components and subcomponents to critique, the important variables (initial faults, factor of intensity of constraint (*f.i.c.*), etc.) for which uncertainties should be reduced, and so on through a sound knowledge of physical phenomena.

Reliability anticipates and prepares for the future in order to improve performance and safety by optimizing exploitation strategies.

However, reliability alone cannot replace an experimental understanding of physical phenomena.

We present in the Appendix, not less than fifty reference tables to appreciate the acceptance quality level (AQL) and typical Dodge-Romig tables for a sampling plan AOQL and LQL (Average Outgoing Quality Limit) and (Limiting quality Level) corresponding to a consumer’s risk.

A. GROUS
November 2012

Glossary

5S

A Japanese method for application in manufacturing, office, etc. acronym for Seiri (to sort), Seiton (to set in order), Seiso (to shine), Seiketsu (to standardize), Shitsuke (to sustain).

Abbreviations

CITAC	Cooperation on International Traceability in Analytical Chemistry
CSA	Canadian Standards Association
EA	European Cooperation for Accreditation
Eurachem	Focus for Analytical Chemistry in Europe
EUROLAB	European Federation of National Associations of Measurements, Testing and Analytical Laboratories
GUM	Guide to the expression of Uncertainty in Measurement (reference document recognized by the CSA, EUROLAB, Eurachem and EA)
IEC	International Electrotechnical Commission
ILAC	International Laboratory Accreditation Co-operation
ISO	International Organization for Standardization
S (or σ)	Standard deviation
SAS	<i>Service d'accréditation suisse</i> (Swiss Accreditation Service)
U	Uncertainty
VIM	International Vocabulary of basic and general terms in Metrology

Abrasion resistance

Hard materials also show good abrasion resistance: in other words, they are not easily worn down by friction. In practice, they are harder to grind down.

Acceptable risk

Acceptable risk describes the structural and non-structural measures to be put in place to reduce probable damage to a reference level. A risk scale is often associated with dangers in order to classify them in order of seriousness.

Availability

Availability is a (dimensionless) attribute of *dependability*. It is the capacity of a system to properly deliver the service (quality) when the user has need of it. Availability is a unitless measurement; it corresponds to the ratio of uptime to total execution time of the system.

Chance

Imaginary cause of something that occurs for no apparent or explicable reason (dictionary definition).

Conditional probability

(Bayesian) probability of a consequence when the causal event will definitely occur. If we suppose that a fracture has reached the limit suggested by a pre-established hypothesis, the probability of cracking is a conditional probability.

Corrosion resistance

This denotes the ability of a material to withstand damage from the effects of the chemical reaction of oxygen with the metal. A ferrous metal that is resistant to corrosion does not rust.

Degradation

Irreversible evolution of one or more characteristics of a product related to time, to the duration of use or to an *external cause – alteration of function, constant phenomenon, physical ageing*.

Dependability

This is the property that enables users to justifiably place their faith in the service provided to them: *reliability, availability, safety, maintainability, security*.

Dilation and contraction

When a material is heated, it expands slightly: this is called dilation. Conversely, if it shrinks (cold), this is a contraction. The level of dilation and contraction of a metal affects its weldability. The more the metal is expanded or contracted, the greater the risk of *cracks* or deformations appearing.

Distribution function

This is an integral function of the probability density (or cumulative probability function), calculated in order of ascending values of the random variable. It expresses the probability of the random variable assuming a value less than or equal to a given value.

Ductility

Ductility represents the ability of a metal to be deformed without breaking. It can be stretched, elongated or subjected to torsion forces. Ductile materials are difficult to break because the cracks or defects created by a deformation do not easily propagate.

Durability

This is the ability of a product to perform its required function, in given conditions of use and maintenance, until a critical state is reached.

Elasticity

The ability of a material to return to its original form after a deformation.

Failure

Alteration or suspension of the ability of a system to perform its required function(s) to the levels of performance defined in the technical specifications.

Fault (error) resistance

Fault resistance is implemented to detect and handle errors.

Fault tree

This is a *logical* diagram using a tree structure to represent the causes of failures and their combinations leading to a *feared state* (Bayes). Fault trees enable us to calculate the *unavailability* or the *reliability* of the system model.

FMECA – risk analysis

Failure mode, effects and criticality analysis is a method for systematic risk analysis of the causes and effects of failures that might affect the components of a system. FMECA analyses the seriousness of each type of failure. It enables us to evaluate the impact of such failures on the reliability and safety of the system.

Frailty

Frailty describes the characteristic of a metal that breaks easily on impact or from a deformation.

Hardness

The ability of a body to resist penetration from another body harder than it. It is also characterized by its scratch resistance.

HAZ Heat-affected zone

The HAZ represents the heat affected region of the base metal that was not melted during welding process. Metallurgists usually define the HAZ as the area of a base material which has had its microstructure and properties altered by welding or heat.

Hazard

Describes any event, unpredictable phenomenon or human activity that would result in the loss of human lives, or damage to materials or the environment.

Maintainability

Maintainability is one of the aspects of *dependability*. The maintainability of a system expresses its capacity for repair and evolution, with maintenance supposedly completed under certain conditions with prescribed procedures and means.

Corrective maintenance or restoration to a state of proper function: The maintenance performed when a breakdown is detected, aimed at *restoring* a product to a state where it can fulfill its required function.

Preventive maintenance: *To avoid loss of function; thus, it is a probabilistic notion, one of anticipation and prediction.* Such maintenance is performed at predetermined intervals, in accordance with prescribed criteria, intended to reduce the probability of failure or degradation of the function of a product.

Malleability

This is a characteristic that allows the metal to be molded. It is the relative resistance of a metal subjected to compression forces. The malleability of a material increases with increasing temperature.

Markov chains

Used to evaluate the *dependability* of systems in a quantitative manner, this technique is based on the hypothesis that failure and repair rates are constant and that the stochastic process modeling its behavior is Markovian (a memoryless process). When the space of potential states of the system is a discrete set, the Markovian process is called a Markov chain.

Materialized measure

A measuring instrument that replicates or permanently provides different kinds of values during use, each with an assigned value.

Measurand

A value to be measured.

Measuring accuracy

Proximity between a measured value and the true value of a measurand.

NOTE.—

– Measuring accuracy is not a value and is not expressed numerically. A measurement is sometimes considered *accurate* if it offers a *smaller uncertainty*.

– Although linked to the concepts of *correctness* and *fidelity*, it is better not to use the term *measuring accuracy* for measuring *correctness* or the term *measuring fidelity* for *measuring accuracy*.

– Measuring accuracy is occasionally associated with the proximity between the measured values attributed to the measurand.

Measuring instrument, measuring apparatus

Usually a device used for making *measurements*, on its own or possibly in conjunction with other devices.

Measuring repeatability

This is the measuring fidelity according to a set of repeatability conditions.

Measuring reproducibility¹

This is the measuring fidelity according to a set of *reproducibility* conditions.

Measuring uncertainty

The non-negative parameter that characterizes the dispersion of values attributed to a measurand, arising from information used according to the method (e.g. A or B of the GUM).

N.B.—

Measuring uncertainty includes elements caused by systematic effects (associated with the corrections and the assigned benchmark values) as well as definitional uncertainty. Estimated systematic effects are not always corrected. Elements associated with uncertainty would be added. The parameter is often the standard uncertainty (from the standard deviation, σ) or the half range ($U/2$) of an interval with a determined coverage probability (e.g. $k = 2$ for 95% confidence). Certain elements are evaluated with the type-A GUM from the statistical distribution of measured values characterized by standard deviations. The evaluation using the

¹ For statistical terminology refer to ISO 5725-1:1994 and ISO 5725-2:1994.

type-B GUM is characterized by standard deviations of probability density functions based on experience, among other things.

Metrology

The science of measurements and its different applications, which encompasses all theoretical and practical aspects of measuring, regardless of the uncertainty of the measurement or the domain to which it relates.

PHA

This is a method for identifying and evaluating hazards, their causes, their consequences and the seriousness of these consequences. The aim of this analysis is to determine the appropriate methods and corrective actions to eliminate or control dangerous situations or potential accidents.

Probability

Statistical concept that can either express a degree of confidence or a measurement of uncertainty (subjective probability) or be taken as the limit of a relative frequency in an infinite series (statistical probability).

Probability density (or distribution function)

Function describing the *relative likelihood* of a random variable assuming a particular value. It assigns a probability to each value of a random variable.

Q9000 series

Standards that refer to ANSI/ISO/ASQ Q9000 series of standards.

QS-9000

It is a harmonized quality management system requirements “ISO/TS 16949.”

Quality

This is a subjective term for which each person or sector has its own definition.

- The characteristics of a product or service that bear on its ability to satisfy stated or implied needs;
- A product or service free of deficiencies. According to Joseph Juran, quality means “fitness for use”.

Quality assurance/quality control (QA/QC): ANSI/ISO/ASQ A3534-2, Statistics

“Assurance” can mean the act of *giving confidence*, the state of *being* certain or the act of *making* certain; “control” can mean an evaluation to indicate needed corrective responses.

Quality audit

This is a systematic independent examination and review to determine whether quality activities and related results comply with plans and whether these plans are implemented effectively to suits the achievement of objectives.

Quality loss function

This is a parabolic approximation of the quality loss that occurs when a quality characteristic deviates from its target value. The quality loss function was first introduced in this form by Doctor G. Taguchi.

Quality management (QM)

This is the application of a quality management system in managing a process to achieve maximum customer satisfaction at the lowest overall cost to the organization.

Quality plan

This is a set of documents that describe the standards, quality practices, resources and processes pertinent to a specific product, service and project.

Quality score chart

This is a control chart for evaluating the stability of a process.

Quality tool

This is a technique to support and improve the activities of process quality management and improvement.

Random

Process in which the result varies even if the input data set remains identical (a protocol leads to different results).

Reliability

The reliability of a system (work) is its aptitude to meet its design objectives over a specified period of time, in the environmental conditions to which it is subjected. Reliability is based on the probabilities used to evaluate it.

Reliability is one of the aspects of *dependability*. It corresponds to the continuity of service that the system must provide to its users, with the system being considered as irreparable. Any accidental failure is taken into account, regardless of its severity. Reliability measures the rate of failure, and is the inverse of the MTTF (mean time to failure).

Risk

Risk is “a more or less predictable potential danger”, or in other words a drawback that is more or less probable to which we are exposed. The scientific definition of risk involves an aspect of hazard and an aspect of loss, both expressed as probabilities.

Risk analysis

A system inevitably contains design errors, regardless of the amount of validation work done. The “zero error” criterion is not a realistic goal, in view of the development costs this would entail. Thus, it is important for so-called critical systems to evaluate the risks for users:

- FMECA: failure mode, effects and criticality analysis;
- SEEA: software error effects analysis;
- PHA: preliminary hazard analysis.

Risk assessment

Procedure to determine the probability of a hazard *occurring* and its possible consequences.

s.i.f. (ΔK) Stress intensity factor

s.i.f (ΔK) is a function of the stress, crack size and crack shape. Stress intensity factors do not have variability. They have uncertainty and modeling errors. The crack shape may be unknown and be approximated by a semicircle.

In Mode 1 (during a fatigue cycle, in mechanic of rupture) (s.i.f = ΔK) is a measure of the stress-field intensity near the tip of an ideal crack in a linear-elastic solid when the crack surfaces are displaced in the opening mode. The *stress intensity factor range* (ΔK) in fatigue crack growth rate is the variation in a cycle, that is, $K_{\max} - K_{\min}$.

Safety case

The *safety case* approach is mainly used in the oil, nuclear and rail transport sectors. In practice, this procedure facilitates the monitoring of studies.

Sample

One or more observations from a larger collection (population) – samples need to be random, independent and unbiased.

Sampling Plan

This is a scheme used for determining sample sizes and actions in order to make clear decisions.

“The decision, based on counting the number of defectives in a sample, can be to *accept the lot*, *reject the lot*, or even, for multiple (sequential) sampling schemes in order to take another sample and then repeat the decision process”.

Security

We distinguish between safety and security. Thus:

- Safety guards against catastrophic failures, for which the consequences are unacceptable in relation to the *risk*;
- Security relates to the prevention of unauthorized access to information.

SFMEA

Maintenance method, acronym for system failure mode and effects analysis.

Significant Characteristics

Product and process characteristics designated by the customer, including governmental regulatory and safety, and/or selected by the supplier through knowledge of the product and process.

Software reliability

Software inevitably contains *design errors*, no matter how strict the rules of design and validation. The ability of a software suite to provide acceptable service in spite of its residual errors defines its *reliability*.

Specifications (term which is largely used in quality control)

Specifications are engineering requirements for judging the acceptability of a component characteristic. For the production part approval process, every feature of the product as identified by engineering specifications must be measured. Actual measurement and test results are required.

Stability (known as drift)

This is the total variation in the measurements obtained with a measurement system (e.g. gage) on the same master or part when measuring a single characteristic over an extended time period.

Stable Process (in quality control)

This is a quantitative condition for the process which describes a process that is free of assignable/special causes of variation).