RELIABILITY ANALYSIS

Why reliability should be everyone's business

TReliC

Contents:

Reliability analysis

Good reliability is one of the most important features of a successful product. The expenses due to poor reliability are considerable and reliability issues can cause significant delays in product development.

A systematic approach is needed to ensure that a product fulfills all its reliability requirements. There are several tools and methods which can be used in reliability analysis. The correct use of these tools requires interdisciplinary expertise of many different fields and consideration of many different factors.

In Trelic we have worked with different parts of reliability process in numerous projects. Although there are differences how reliability should be analysed for different products, there are also lots of similarities in all reliability processes.

We have written this guide to gather some of the important considerations common for all reliability analyses. We hope you will find this guide both useful and interesting.

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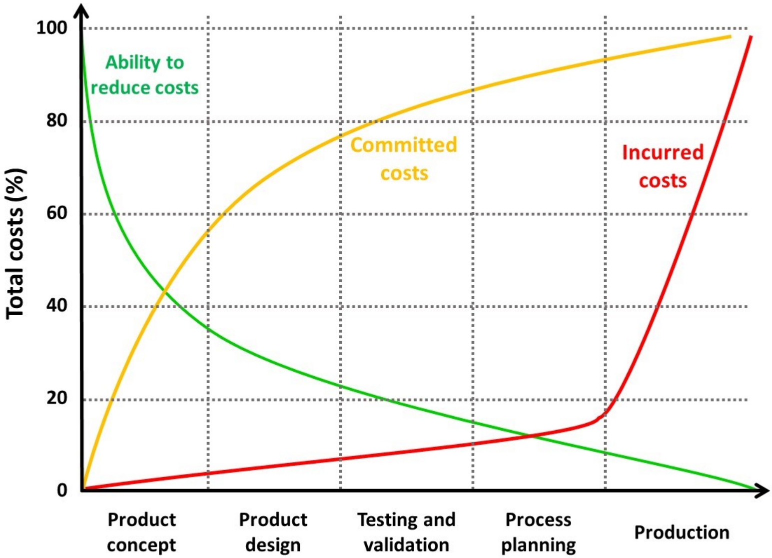
Why is reliability analysis so important?

Many factors need to be considered to meet customer expectations and to succeed in highly competitive markets. These include, for example, functionality and quality requirements, cost, manufacturability, time-to-market, and reliability.

It is well known that products with poor reliability should be avoided, since reliability problems cause high warranty costs. However, it is not often understood, that in addition to warranty costs, poor reliability will result in other expensive problems. These include failure analysis costs, retrofit costs, customer downtime, loss of customers, and eventually lawsuits. The expenses caused by some of these are difficult to define and therefore they may easily be overlooked.

Warranty costs are only the tip of the iceberg as the overall costs of poor reliability can be 10 to 100 times higher

Reliability means, that the product functions as it should not only at the end of the manufacturing line, but also after transportation and storage, and at the hands of the customers. To ensure good reliability, it is vital that reliability is considered as early in product development as possible!



The reliability of a product is affected by all the decisions that are made during product development

The decisions made during product development affect not only the incurred costs but also the committed costs. In other words, the decisions that are made during the product concept and design phases will commit the majority of the product development budget.

If reliability problems which require component, material, or design changes are observed during the testing and validation phase, this will result in significant delays and cost overruns. The ability to reduce costs is the highest during the first concept phase. The same can be said for the ability to affect the reliability of the final product.

What does reliability mean?

As a term, reliability can be defined:

"The probability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time."

A product can be considered to be reliable, when it does not fail during its service life. In order to do this, the lifetime of the product in different use conditions needs to be defined. It is important to notice, that the idea of a suitable lifetime and use conditions of the customer may differ from those of the manufacturer, which can cause reliability issues even though the product functions as planned.

Why do failures occur?

There are several reasons for failures, which all need to be considered. The typical reasons for failures include:

- ***Environmental factors***
- ***Poor design or choice of materials***
- ***Manufacturing variation and mistakes***
- ***Aging of components and materials***
- ***Misuse and random events***

It is important to notice that stresses, which cause the failures, can occur at several stages of product's manufacturing and use. Therefore, the whole lifecycle of a product needs to be considered in the reliability analysis. Typically, this means considering the stresses due to:

- ***Manufacturing***
- ***Transportation***
- ***Storage***
- ***Use conditions***

It is common that failures occur due to combination of several different factors. This can cause difficulties for both prediction and testing of failures.

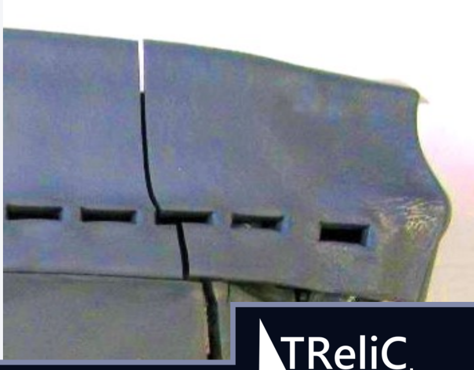
It is important to determine what is a failure!

Sometimes it can be very easy to tell when a product fails. For example, when an electrical device does not turn on at all, it is clear, that it has failed and does not work as planned. However, quite often defining, whether a failure has occurred, is not this easy and simple. A product may function partially or failures occur only at certain conditions. The manufacturer of a product and its user may also have a different idea of suitable functionality and reliability, and therefore determine a failure differently.

A failure can be defined as: "The inability of a material, component, device, or process to function properly."

In reliability analysis it is always important to carefully consider what is counted as a failure. In addition to a whole product, reliability analysis is commonly conducted to sub-parts and bulk materials. Consequently, it is important to determine the failure limits also for these parts. When this is done, failures can be clearly recorded, and the data used for reliability prediction and further analysis. This facilitates also the comparison of the reliability for different structures and products.

Several different failure types can be defined and their occurrences collected. This enables collection of high-quality reliability data and improves the quality of the reliability analysis and reliability prediction.



How should reliability be tested?

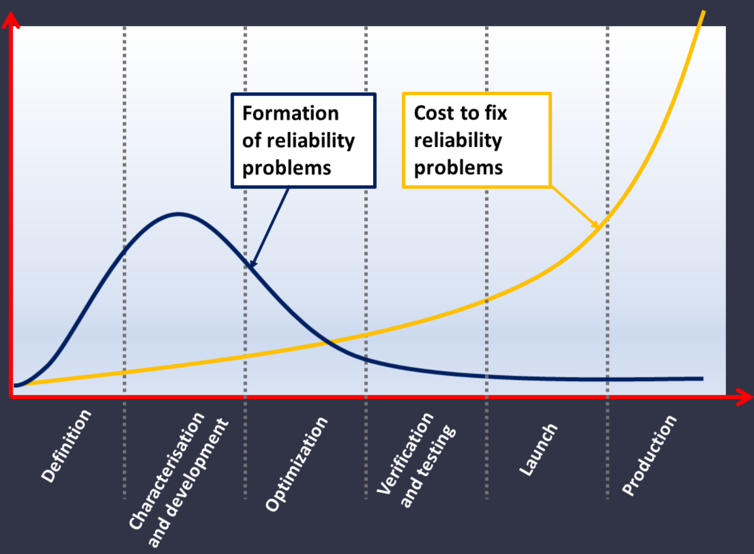
Before experimental reliability testing, analysis of the most critical stresses, failure mechanisms, and structures should be conducted. This information should be used to make a test design which takes these into consideration and ensures that none of the critical factors is ignored.

Numerous experimental test methods are available for reliability analysis. These include for example mechanical, environmental, and functionality tests.

Laboratory testing using specific test methods and equipment is beneficial, as it allows controlled analysis of both test conditions and tested products. Additionally, in laboratory testing real-time or repeated measurements of the product are often possible to improve the quality of the test data.

It may be beneficial and necessary to use different test methods to study the reliability and failure mechanisms of materials, components, sub-parts, and whole products. Additionally, different methods may be beneficial at different stages of product development.

Reliability should be taken into consideration as early as possible, hopefully from the start of the product development process



Reliability goals and mission profiles

The first step of reliability analysis is to create a reliability goal, which is then discussed by the development team and modified, if necessary. The reliability goal varies from a product to product, but it should clearly state ***how the product should operate, in what kind of conditions, for how long, and how many products are expected to fail***.

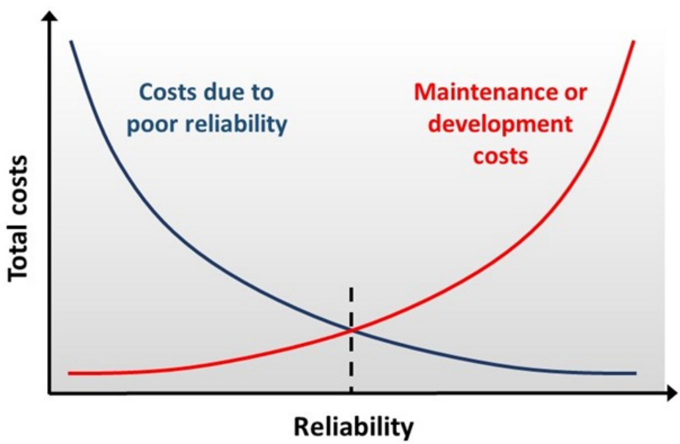
For example, the reliability goal might state that the product is required to function as planned for three years in industrial conditions with expected survival probability of 95 %. That is, after the three-year period only 5 % of all the devices are expected to have failed.

By using reliability goals, it is possible to evaluate if the product is reliable enough to meet the specified requirements. Similarly the reliability goals can be used to avoid over-engineering, or in other words, making the product too robust.

In the reliability goal setting, probably the most important and challenging aspects are the specifications of the use and environmental stresses. This mission profile should include all the stress factors that will affect the lifetime of the product. These factors include the stresses caused by assembly, transportation, storage and actual use as well as their estimated severities and durations. This requires in-depth knowledge of how, when and where the product will be used.

Information of the mission profile can then be used in the development of the product itself but also its reliability test plan.

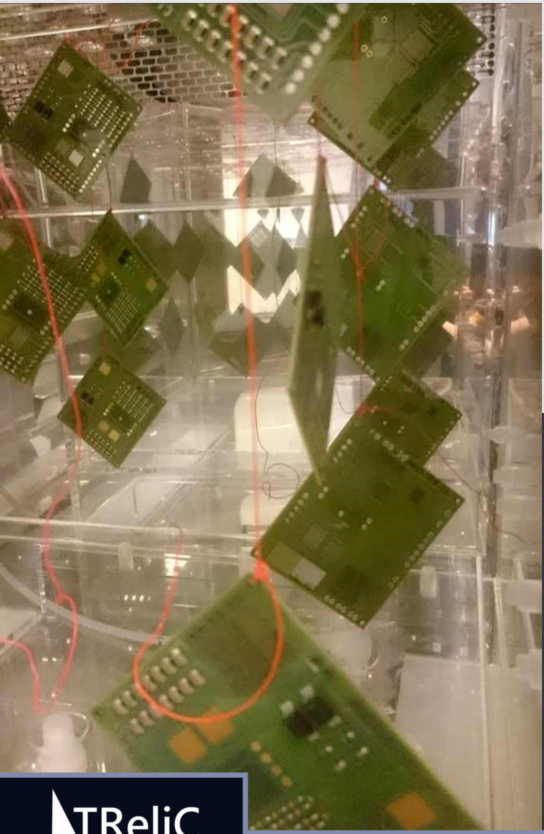
Without a mission profile or similar information, reliability-critical stress factors may be excluded. This will most likely not only cause significant errors in the reliability analysis but also reliability problems in the field.



Accelerated Life Testing (ALT)

Reliability testing can be very expensive and time-consuming and therefore, ***accelerated life tests (ALT) are commonly used to achieve results as quickly as possible.*** The acceleration is achieved by using greater stresses than a product experiences in its real use conditions. For example, higher temperature or faster cycling may be used to accelerate aging and failures.

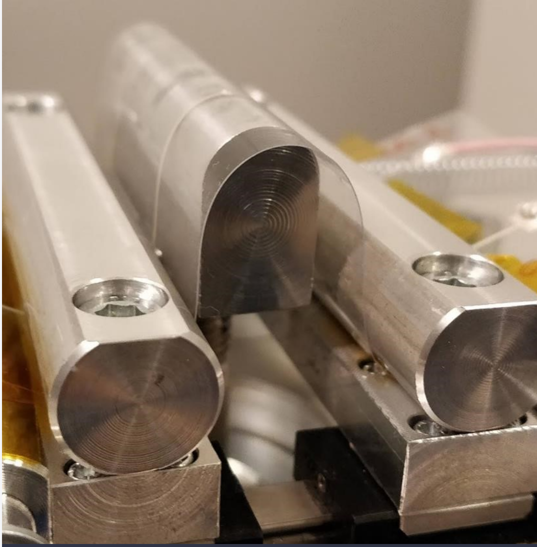
Before testing a careful consideration should be conducted to design the most suitable test procedure. There are several standards which can be used in the process. However, many standards only give indication of the suitable test conditions and they should always be determined on basis of the stresses the product is exposed to.



It is important to notice that ***a standard may have been originally developed for different structures and materials than those studied*** and therefore they may accelerate incorrect failure mechanisms. Additionally, it is possible that the tests do not take all important stresses into consideration which can lead to unexpected failures.

If unsuitable test methods are used, wrong conclusions may be drawn from the test results leading to overly optimistic failure prediction or overdesign due to too pessimistic prediction.

Test methods



Test methods need to be chosen according to the mission profile or other information related to the stresses a product is exposed to. The aim of testing is to simulate the stress factors observed in the real-life conditions, and therefore suitable test methods need to be carefully considered.

When stresses are tested separately, it is easier to analyse the effect of each stress. However, stresses often have combinatory effects which may be critical. In such situation combinatory testing should be used. A typical example of combinatory testing is a high humidity high temperature test, in which high temperature is used to accelerate the negative effects of humidity.

Typical test methods include:

- *Thermal testing, both high and low temperature*
- *Thermal cycling and shock*
- *Humidity testing*
- *Corrosion testing*
- *Other impurities such as dust, sand and biological factors*
- *Mechanical shocks and vibration*
- *Other mechanical stresses*
- *Radiation testing, such as UV and solar tests*
- *Electrical stresses, power cycling*

Highly Accelerated Tests

When the use life of a product is long, or severe time constrictions apply to the reliability analysis, highly accelerated life testing (HALT) or highly accelerated stress testing (HAST) may be used. In highly accelerated tests very harsh conditions are used to cause failures in a very short time. For example, a combination of temperature cycling, vibration and power cycling may be conducted simultaneously. In HAST acceleration is achieved by using extremely high temperature and humidity under elevated pressure.

Highly accelerated tests may be used to determine the weakest parts of a design and this information may be used to improve the robustness of a product. However, overstress conditions are typically used in HALT. Therefore, it is extremely important to confirm that the failures are meaningful to prevent incorrect improvements and over-design of a product. It is also important to notice, that due to its high acceleration HALT testing is typically not suitable for reliability prediction.

Tailored testing

For many products the use environment has become more complex and demanding. For example, the service conditions of sensors and electronics has widened to cover many challenging environments, for example mines and water treatment plants. At the same time, new materials and structures are used to bring totally new functionalities to products.

When a product is used in new environment or new materials and structures are utilized, the standard test methods may not give accurate results. In such situation it is very important to carefully consider the test methods and to tailor them to suit the product and its use conditions. Tailoring of tests is, however, demanding and should be based on detailed knowledge of both most likely failure mechanisms and stresses causing them.

Tailored testing can provide both accurate results and high acceleration. However, often reliability prediction for such tests can be difficult, since no suitable models exist.

Reliability vs. validation testing

Reliability testing should be conducted as early as possible during the product development. However, testing of a final product is also needed to confirm that it fulfills all requirements. Such testing is called validation testing. Both reliability and validation testing are important and useful in their own way.

RELIABILITY TESTING

Based on mission profile which takes into account the combination of use, storage and transportation conditions

Done at various stages of R&D to make sure that reliability requirements are fulfilled

Done with accelerated tests and acceleration models to find failures in short time

Purpose is to test until failure (if possible)

VALIDATION TESTING

Based on test requirements set for the product internally or by customers or by a third-party

Done at the end of R&D to verify functionality and reliability

Done with standardized tests

Purpose is to use short pass/fail tests

Failure and root cause analyses

The aim of failure and root cause analyses is to find out how and why a failure has occurred. Such analysis makes it possible to determine whether a failure is meaningful and if corrective actions are needed.

Without analysis of failures, the corrective actions cannot be conducted systematically. In worst case the corrective actions conducted are both expensive and harmful!

Both failure and root cause analysis aim to study the reasons for a failure

- **The root cause analysis** typically refers to a **more general process** which can refer to any problem. The emphasis is in **eliminating or correcting** the cause to prevent a problem from happening.
- Failure analysis typically concentrates on the actual failure mechanism and on the reasons why they occurred. Failure analysis provides critical input for root cause analysis, but cannot always answer why the failure occurred!
- **Physics of failure** is a term commonly used to describe a science-based approach to understand failure mechanisms, their reasons, and their scientific models.

Several different stresses can cause failures:

- **Electrical stresses**
- **Thermal stresses**
- **Humidity stresses**
- **Chemical and electrochemical stresses**
- **Mechanical stresses**
- **Radiation stresses**
- **Stresses induced by impurities such as dust and sand**
- **Biological stresses**

Different stresses can cause different failure mechanisms. Additionally, it is common that several stresses have affected the formation of a failure. Stresses may also have a combinatory effect which greatly accelerate the formation of failures.

Failure analysis process

Failure analysis is a vitally important part of reliability analysis. Systematic approach is needed in the process to ensure, that all critical factors are considered. Several different analysis techniques and methods are often required to perform the analysis. These include non-destructive techniques, such as electrical measurements and microscopy, and destructive techniques, such as cross-sectioning and material characterisation.

The failure analysis process starts with data collection. The object is to gather data related to the failure and of the causal factors related to it. For example, the aim is to determine what failed and where, how it happened, and when the failure occurred i.e. how long did the product perform before the failure.

Next a hypothesis for the cause of the failure is made. The aim is to use the gathered data and the knowledge of the typical failures to predict what the failure mechanism could be.

Then **the samples are analysed using suitable methods.** The analysis is **started with the least destructive methods and** after these **destructive techniques** are utilised, if needed. Sometimes it is very difficult to find the reason for the failure and **elimination of potential causes** needs to be conducted.

Finally, conclusions are drawn and the results reported. Clear and systematic reporting of the techniques and results is vital. After conclusions the corrective actions may be conducted.

Reliability prediction

One important aim of reliability analysis is to predict the failures of components, materials and products. These predictions are used to evaluate the feasibility of a design, to compare different alternatives, to identify potential risk factors, and to compare different product generations.

Different methods and tools can be used in the prediction of reliability depending of the data and reliability analysis methods available. Prediction tools include relatively simple analytical models, for example Arrhenius equation, and complex models, for example models utilising dynamic finite element models (FEM). It is common that the models are based on material properties, failure mechanism and conditions affecting them.

For some structures and materials several models with supporting literature data are available. For example, in electronics several reliability models have been developed for fatigue based failures of solder joints. In addition, numerous studies analysing the suitability of the models have been published. However, often such models are not available, or their reliability has not been confirmed through research.

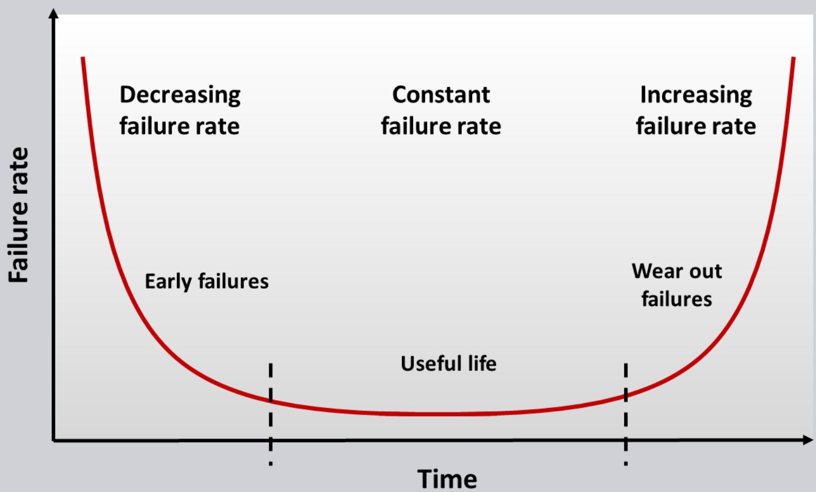
It is important to notice that reliability predictions may have lots of uncertainty in their results. It is vitally important to consider this uncertainty, when major changes or corrective actions are considered.

Bathtub curve

The aim of reliability prediction is to determine when and how often failures will occur. When failures are analysed, it is important to know when failures occur during the lifetime of the product.

The occurrence of failures is often described by using a bathtub curve. The curve has three areas which describe the life cycle of the product.

- The first area describes the failure rate for early failures. These are commonly caused due to mistakes and variation in manufacturing. A decreasing failure rate is typical for this area.
- The second area is the main useful life of a product. Commonly, constant failure rate is expected to occur in this area and failures are caused by random failures.
- The third area is in the end of the life cycle of a product. In this part a product fails due to wear and aging. An increasing failure rate is expected for this area.



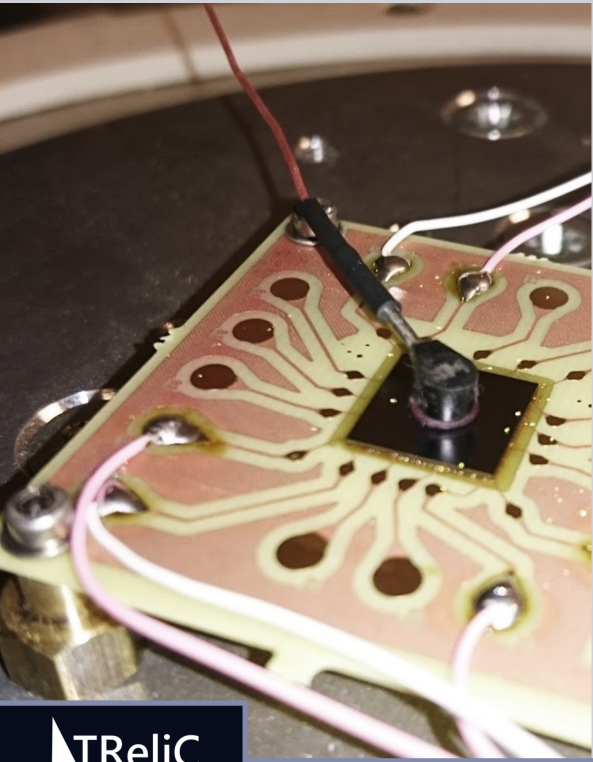
The bathtub curve gives an easy and simple way to describe the failure rates of a product during its lifetime. However, it is a simplification and the failure rates of a product may considerably vary from it.

Reliability data

Availability of good quality data is vital for good quality reliability analysis and especially for reliability prediction.

Field data is very beneficial for reliability analysis. It can be used, for example, to verify the results of laboratory testing. Additionally, it can be used to improve the accuracy of reliability prediction. However, collection of good quality field data can be very difficult or even impossible. It is common that the field data is censored and incomplete. Additionally, the source of the data and the conditions leading to failures may be unknown. This needs to be carefully considered when the data is analysed, since such data may lead to wrong conclusions and corrective actions.

To collect good quality data careful planning is required to ensure, that the test conditions and samples are meaningful and that the results are valid.



There are several sources for reliability data:

- ***Reliability and validation testing during the product development***
- ***Warranty data***
- ***Maintenance data***
- ***Data of field failures after the warranty period***
- ***Additional reliability testing during products life-cycle***
- ***History data from earlier products***
- ***Literature data***
- ***Simulation***

Another common source for reliability data is laboratory testing. The benefit of this data is, that it can be collected in controlled conditions for controlled test samples. However, the amount of this data may be limited due to financial and time constraints. For example, the number of tested samples is commonly limited by practical and financial factors. It is also common that testing is not conducted long enough to cause failures, which significantly limits the possibilities for failure analysis and reliability prediction.

Reliability data can be analysed using different statistical methods. These can be used to analyse for example failure rates, the probability of failures after different time periods, and to compare data for different products or tests. It is common, for example, to use different statistical distributions such as Weibull and lognormal distributions to analyse data. Several software options allowing also the analysis of incomplete data are also available for data analysis.

There are several models to analyse accelerated life testing data. For example common ones are:

- Models based on the **Arrhenius equation**. These are often used to calculate test time acceleration when the stress factor is constant temperature. The Arrhenius equation describes temperature dependent reaction rates of chemical processes but can also be used in other applications.
- **Peck and Lawson models** can be used in situations where accelerating stresses include both temperature and humidity.
- The **Coffin-Manson model** and its derivatives can be used to estimate temperature cycling induced fatigue failures of solder joints.