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RELIABILITY ESTIMATES IN ELECTRONICS INDUSTRY

– Reliability study in the HFC network

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- Reliability study in the HFC network

Consumers have come to expect a certain level of reliability from the products put on the market. Nowhere is this more under scrutiny than in the electronics industry. Designers and manufacturers need to have an efficient, reliable, and cost managed methods in place to make sure their products are keeping up with the standards and demands of the industry.

The aim of this study was to clarify what reliability actually stands for, what it means to the designers, manufacturers, and end users alike, how reliability calculations are carried out, what the reliability percentages really mean, and how the validity of those claims is verified. The thesis also aims to shed light on the possible criticism these old methods have received as of late.

There are many methods of calculating reliability, but for the scope, this thesis, focuses on the Weibayes zero failure test method, and presents a case study where this method is implemented in testing a new HFC network product. This thesis presents the test methods used and the following results and how these results verify reliability requirements set for this product.

The study concludes that the Weibayes method is sufficiently accurate, and as all reliability estimates, it does not apply on a single unit level but as a calculated average of the products life cycle as a whole and the possible risk of failure it contains. It still leaves room for possible improvement of many of the engineers estimate based parameters as manufacturing methods and materials used have gone through significant improvement over time whereas the statistical math-based estimates have remained relatively static.

KEYWORDS:

reliability; Weibull; Weibayes; HFC network; zero failure test method

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LUOTETTAVUUSARVIOINTI ELEKTRONIIKAN TUOTANNOSSA

- luotettavuustestausta HFC-verkossa

Kuluttajat osaavat odottaa tietyn tasoista luotettavuutta markkinoilla olevilta tuotteilta. Tämä on erityisen tarkasti suurennuslasin alla elektroniikan ja elektronisten tuotteiden kohdalla, joissa luotettavuudelle asetetut panokset ovat suhteellisen paljon korkeammat kuin muilla aloilla. Suunnittelijat, valmistuttajat ja tuottajat tarvitsevat tehokkaita, luotettavia ja kulutasapainotettuja tapoja tuotteidensa laatustandardien ja alan vaatimusten ylläpitoon.

Opinnäytetyön päätavoite oli tarkastella, mitä luotettavuudella tarkoitetaan. Lisäksi tarkoituksena on selvittää mitä arvoja ja odotuksia se luo suunnittelijoiden, valmistuttajien ja loppukäyttäjien mieliin ja miten se ohjaa heidän valintojaan. Miten luotettavuutta lasketaan matemaattisesti ja mitä luotettavuusprosentit tarkoittavat ja miten ne on todennettu sekä mahdollinen viimeaikainen kritiikki näitä vanhoja metodeja kohtaan.

Opinnäytetyössä tarkasteltiin pintapuolisemmin alan monia luotettavuuslaskemia, mutta aiheen laajuuden vuoksi keskityttiin tarkemmin Weibayes zero failure test -metodiin, sekä esiteltiin HFC verkon tuotteen laatutestauksen, jossa kyseistä metodia on käytetty testisuunnitelman laatimisessa, testin toimeenpanossa ja tulosten todentamisessa.

Tuloksina on todettavissa, että nämä metodit ovat riittävän tarkkoja tarkoitukseensa, on kuitenkin pidettävä mielessä, että tuotteen luotettavuutta ei lasketa yksikkötasolla, vaan se mittaa tietyn tuotteen keskimääräistä elinkaarta riskit huomioonottaen. Muutamia arviopohjaisia parametrejä jätetään testaavan insinöörin tietotaidon ja kokemuksen varaan. Koska valmistustavat ja materiaalit ovat kokeneet varsin mittavaa kehitystä sitten luotettavuuslaskennan alkupäivien, kritiikki näiden arvojen ja arvioiden uudelleen tarkastelusta on ihan oikeutettua.

ASIASANAT:

luotettavuus; Weibull; Weibayes; HFC verkko; zero failure test method

CONTENTS

LIST OF ABBREVIATIONS (OR) SYMBOLS

β	Greek alphabet letter lowercase beta, Slope or shape parameter in this context
η	Greek alphabet letter lowercase eta, Characteristic life or scale parameter in this context
γ	Greek alphabet letter lowercase gamma, Location parameter in this context
AFR	Annualized Failure Rate
ALT	Accelerated Life Test
AST	Accelerated Stress Test
CCAP	Converged Cable Access Platform
CMTS	Cable Modem Termination System
DAA	Distributed Access Architecture
DFR	Decreasing Failure Rate
DOCSIS	Data Over Cable Service Interface Spesification, an international telecommunications standard
DTV	Design Verification Test
DUT	Device Under Test
EUT	Equipment Under Test
ESD	Electrostatic Discharge
F	Fahrenheit (Unit of temperature)
FDM	Frequency-division Multiplexing
FIT	Failures In Time
HFC	Hybrid Fibre Coax
IEC	International Electrotechnical Commission
ICON	Intelligent Connected Optical Node, a Teleste product
JEDEC	Solid State Technology Association (FKA Joint Electron Device Engineering Council)

MHz	Mega Hertz (Unit of frequency, million hertz)
MLe	Maximum Likelihood
MPEG	Moving Pictures Experts Group, name for a media file format
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
OEM	Original Equipment Manufacturer
OFDM	Orthogonal Frequency-Division Multiplexing
OOB	Out-of-Band signal
pdf	Probability Density Function (in lower case)
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation
RDT	Reliability Demonstration Test
RF	Radio Frequency
RPD	Remote PHY Device, PHY standing for physical RF layer
SFP	Small Form-factor Pluggable
VoD	Video on Demand
WDM	Wavelength Division Multiplexing

1 INTRODUCTION

The concept of reliability is a matter of great importance when designing, manufacturing and purchasing electronic goods. Reliability has an affect all areas of the industry, from matters of life and death, for example the reliability of an airplane, a pacemaker or the ventilation system of a containment laboratory, to stockmarket crashing failures of large companies before large audiences, to the little everyday conveniences we purchase for our homes to make our lives easier, safer or just more convenient. Reliability is required and demanded in all these instances. If we focus now on electronics and their design and manufacturing, reliability comes into play from the very inception of a product and throughout its lifecycle. Electronic products are sold with promises of reliability in use. Where do these promises stem from? How are the percentages measured and how are they proven true? What sort of processes lie behind these claims and who performs them?

There is a myriad of studies published on performing such tests on various products and processes. However, the literature on the theory behind all the tests performed today has changed very little since the first rulebooks were written in the WWII era. The math behind it has remained unchanged and little has been added beyond these well-used equations [1][2][3][4][5]. Lately there has been a growing voice of concern over the validity of some of these old ideas, especially with the rapid development of manufacturing processes and materials and the ways to measure their properties more efficiently than was previously possible [5][6][7][8].

In this thesis, the author examines the theory behind the reliability statements provided by the manufacturers with the electronics used in the vast network of HFC connections that stretch across countries and continents. The objective is to shed light on what these statements are based on and what has been done to prove them true. The author will also look at the possible alternatives and improvements that this old methodology could use.

This thesis provides a look into the history of reliability testing, the theory of it, and its implementation. In regard of the scope, the thesis mainly focuses on HFC network related electronics and the Weibayes method of reliability prediction [2][4][1]. The Weibayes method will be examined in detail and a case study of a particular product is presented in the end to showcase the testing method in use. Chapter two focuses on the topology and hardware of a HFC network. Chapter three contemplates on the benefits of reliability testing from various angles and introduces some of the mathematics used to calculate reliability. Chapter four introduces Weibull and Weibayes methods, the history, the theory, and the math. And the final chapter showcases a testing process that implemented these methods to provide a manufacturer a reliability estimate for a new product [9].

The author of this thesis provides her insights into the contemplative parts of the writing. Mainly, the thesis is written in the form of compilement of data from various sources, as well as the author’s process of learning about these methods and mastering the mathematics and theories behind them. The author has been provided with the opportunity to observe the testing process of the case study by the manufacturer company that has commissioned this thesis. Some of the details of the case study are subjected to a non-disclosure agreement (NDA) and are, therefore, left out of the scope of this thesis.

Many of the sources and reference materials used for this thesis are somewhat aged. As mentioned previously, the theory is old and the author could not find more recent publications on, for example, the Weibull and Weibayes core principles [5]. Most of the sources cited are publications that implement these methods and build upon them. Direct works on reliability as a concept were not readily available.

2 HFC NETWORKS

It is necessary to provide a general introduction to HFC networks because that is where we are operating at the moment. The device in our case study is a node to a HFC network and the customer company operates in this field. This thesis is not only about reliability in general, but also of reliability in the HFC network more than in electronics in general. Having mentioned that, all the methods and theories introduced, do apply to a much broader field.

2.1 HFC networks

Old cable networks are rapidly being replaced with the more developed and efficient HFC networks. They are more reliable and have far superior bandwidth compared to the old cable network. HFC stands for Hybrid Fiber Coaxial and it is a broadband hybrid network that combines coaxial cable with optic fiber in the most optimal manner. The coaxial cable is subjected to more loss than optic fiber with attenuation per kilometer some 20 dB compared to optical single-mode fiber attenuation of some 0.2 to 0.4 dB per kilometer [10].

Optical fiber is therefore used for long distance cabling because it needs fewer amplifiers across long distances which increases the reliability of the network due to having fewer active components, and less noise generation. In addition, this feature makes these networks significantly more inexpensive to build.

Distribution of the network by tapping into neighborhood, block, or home is done on coaxial cabling. Fiber delivers the packages to a node that transforms light into radio frequency (RF) that is then delivered through the coaxial cable to residences. The closer the node is to the end user the more line capacity the end user receives [11].

By using frequency-division multiplexing, HFC networks are well suited for transporting analog tv, digital tv, telephony, and high-speed data and the usage of optical fiber leave room for expansion of the network’s distribution at a later point in time when demand for more data transport inevitably grows [11].

2.2 Network topology

An HFC network works in both downstream and upstream. The network starts from the cable operator/ service provider's main headend that then transfers the optical signal to the regional headends. From there, the signal goes to the neighborhood hubsites and to a node that transforms the optical signal to RF and distributes it to the end users through the coaxial cable as seen in Figure 1.

The downstream and upstream of data are separated in the optical fiber either by using two separate cables of by using two different wavelengths in the same fiber, usually 1310 nm for downstream and 1550 nm for upstream. This is called wavelength division multiplexing and it allows the different signals to pass through same optical fiber without interfering or causing distortions on other signals on the fiber. The wavelengths 1310 nm and 1550 nm are commonly used due to their lower attenuation qualities. In coaxial cable, this division is carried out by the signals using different frequencies (FDM).[12]

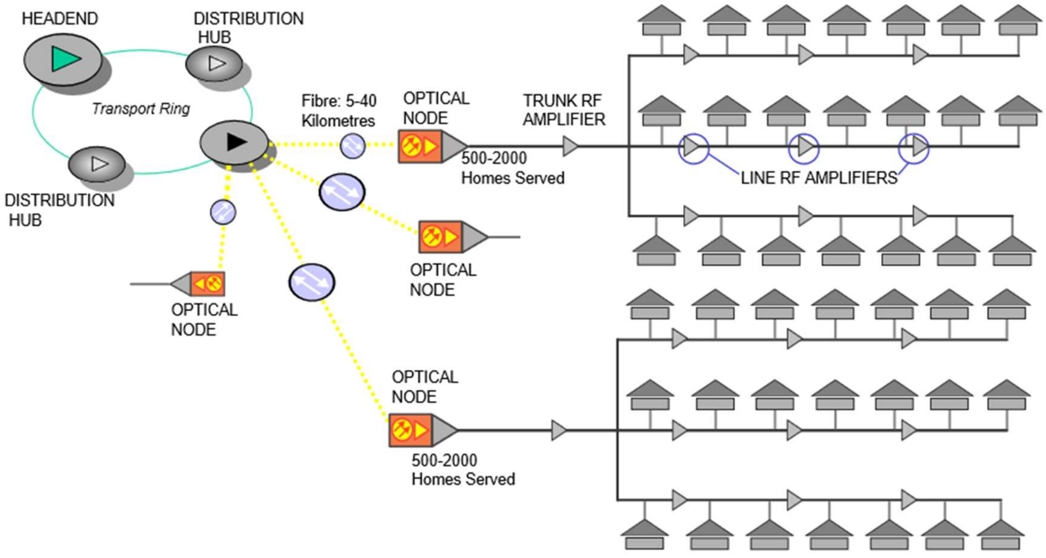


Figure 1. HFC Network topology modified by author

The master headend will also usually have satellite dishes for long-distance video signals and telephony equipment for telecommunication services. The downstream signal is amplified with RF amplifiers to ensure the signal strength and quality at the end user.

Distribution nodes/ fiber optic nodes contain a broadband optical receiver that converts the downstream optical signal into the electrical signal that is then distributed to the homes by a transmitter. The node also contains a return-path transmitter that sends communication from the home to the headend, illustrated in Figure 2. This setup can now also be replaced by the remote PHY device (RPD, PHY stands for physical layer). The RPD is a physical layer converter that converts downstream DOCSIS (Data Over Cable Service Interface Specification), video and out-of-band (OOB) signals received from digital form to analog for transmission and upstream DOCSIS and out-of-band signals from analog to digital[13][14]. This compresses the node into being just two parts, the RPD and CCAP (Converged Cable Access Platform), which combined QAM (Quadrature Amplitude Modulation) and CMTS (Converged Cable Access Platform) functions into one platform in the hub, as seen in Figure 3. Testing of the RPD will be looked at in detail in the case study section of this thesis.

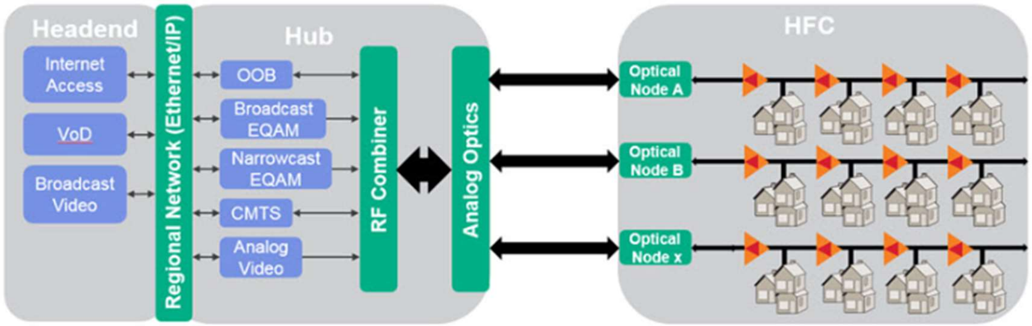


Figure 2. CCAP combining QAM, CMTS, and digital video. Modified by author.[10]

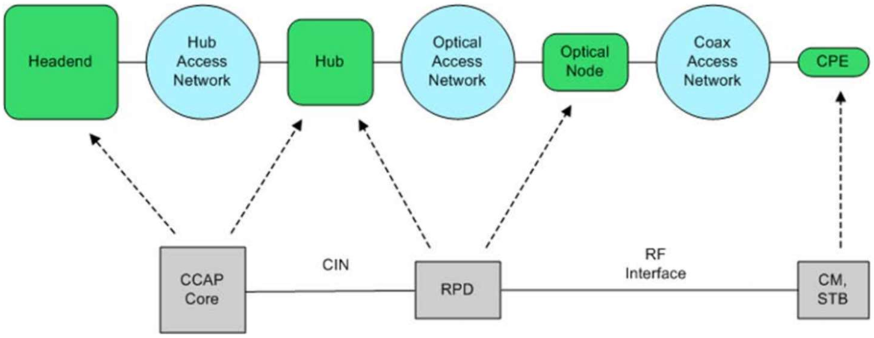


Figure 3. Abstracted view of a cable operator’s network. The items in green are physical locations.[14]

The downstream and upstream frequency range is dependent on the service provider and the country of operation. In most countries and regions that range is between 258 MHz and 1.2 GHz on DOCSIS channels. A lower frequency of 5MHz to 204 MHz is used for upstream DOCSIS channels and that limit is going up at a fast pace. Extended Spectrum DOCSIS is lifting the downstream max to 1.8 GHz and Upstream max to 684 MHz. In the follow-up of the release of DOCSIS 4.0, most manufacturers are prepared to meet growing demand towards equipment with the possible capacity up to 3 GHz.

As the lower limit of the downstream bandwidth keeps on creeping, the upper limit of the upstream bandwidth is increased to take up the freed frequencies. Considering the increased energy usage of keeping such a bandwidth for upstream data available, it is questionable if it is a waste to do so when taking the significantly lower rate of usage for upstream bandwidth into account. The gap between upper limit upstream and lower limit downstream is seen as wasted frequencies in a prime area of usage and, therefore, closing that gap would be ideal, or better yet combine both streams to use the entire spectrum with Full Duplex technology. A full-duplex (FDX) system uses two physical twisted pairs of cable inside one jacket both of which are connected to each networked device, one is used for receiving data packets (Rx for receiver) and the other sending data packets (Tx for transmitter) respectively. This way both upstream and downstream can use the entire spectrum without collisions or disturbances.

2.3 HFC network hardware

This section examines what sort of hardware goes into making an HFC network and how they are tested. Are these tests performed upon manufacturing or are some tests performed in the field?

In the category of indoor passives are such devices as multimedia outlets. The outdoor passives category contains a wide variety of power passing splitters, couplers, power inserters and taps. Also, high and low pass filters are used to filter out unwanted frequencies. Diplex filters are used to combine or separate forward and return path frequencies. Inline attenuators are used when extra attenuation is needed in the signal path. Amplifier nodes amplify the downstream signal in the coaxial cable. Distribution nodes containing optical receivers and transmitters and nodes containing RPDs (Remote PHY Devices) and CCAPs (Converged Cable Access Platforms). A headend and a main headend describe the unit that everyone's coaxial cable connects to for bundling back to the cable provider. It could be a street cabinet or a CMTS (Cable Modem Termination System).

Cabling, fiber optic, and coaxial cable are tested by the manufacturer and all nodes that contain fiber optic receivers are cleaned and tested with cameras to make sure the fiber end is clean and the fiber itself and the splices are intact and optimal. Bad soldering, dirt and acute bends in the fiber cause attenuation and optical loss. [15] On PCB level, numerous cases show a mass of burned plug connectors and relays. These parts receive excessive user expectations when it comes to current load and voltage but their specifications are often overrated.[16]

All of the hardware is tested during manufacturing by the processes set up by the individual manufacturers. Manufacturers practice quality control in all the phases of production and perform checkups to confirm that standards are being met. All new products also go through reliability testing if the product is unique and no previous reliability data is available. After being sold to, for example, a cable provider, a technician working for the cable provider company performs the installation of the product to the HFC network and carries out rigorous regulatory performance testing during and after installation.

2.4 Reliability and expected lifespan of the hardware

What can be derived from the field experience?

Cheap passive RF components are the single most unreliable components in the whole HFC chain. Coaxial connectors cause 80% of all failures in the field [17]. This is mainly attributed to human error, as these connectors are mainly put in place and tightened by hand even though they are meant to be tightened with an appropriate torque wrench. The installer, using his fingers to push the braiding back when doing the installation, has a corrosive effect that becomes amplified over time in outdoor elements, such as temperature and humidity. These components have, therefore, fared poorly in the rapid aging tests [17].

Next-generation coaxial connectors are being designed and manufactured to circumvent this issue by being pluggable without tools or manual tightening. These components have fared well in the early rapid aging tests because of the design focusing on sealing the connection and improving weatherproofing [17][18][16].

Placement and environmental factors such as weather contribute to the wear and tear of the HFC network hardware.[19] These products are designed with this in mind and manufactured to last ideally for decades as they are rarely replaced due to their cost and often their placement in the field, which is deliberately hard to access.

3 RELIABILITY TESTING: PROCESSES AND BENEFITS

What is the reasoning behind using reliability testing methods and measurements and what they really bring to the table? How is reliability defined? Reliability can be worded as to mean ‘*yielding the same*’, the word ‘*reliable*’ means that an item, product or a program is dependable and that it will give with the same inputs the same outcome every time. Engineering literature defines reliability as the probability that an item will perform a required function without failure under stated conditions for a stated timeframe [20]. Reliability testing in the electronics industry assures that the product is fault free and reliable for its intended purpose [21].

3.1 The benefits of reliability testing

The failure rate of any given product (not just electronics) follows the so called ‘bathtub curve’ pictured in figure 3. This generally means that there is a relatively high rate of initial failures soon after manufacture, as this is the period when products with flaws or defects tend to fail. The phase is known as the “infant mortality” or “wear-in” phase. After this stage passes the products with no defects enter a period with very low failure rate called the “steady-state” phase. After the lifecycle closes in on the end of the intended lifecycle of a product, the rate of failures begin to increase until a relative high rate of failure is observed, the “wear-out” phase [20][2].

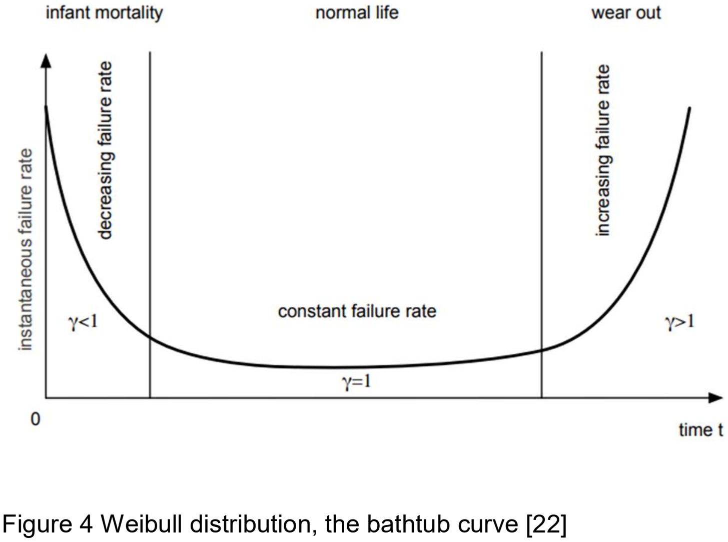


Figure 4 Weibull distribution, the bathtub curve [22]

The purpose and goal of reliability testing is not only to predict the span and effect of this bathtub curve but to prevent and minimize as much of the “infant mortality” part of the curve. With that in mind most early failures, most warranty claims and customer dissatisfaction would be eliminated, benefiting not only the companies involved in designing, manufacturing, branding, and retailing the product but also the end user, the customer who purchases and uses a product.

3.1.1 Manufacturer benefits

For manufacturers the purpose for testing their products is to locate and identify the structure of repeating failures. It’s also good to establish the number of failures occurring in a specified amount of time. This goes towards being able to determine such reliability statements and measurements that contribute to produce numbers like the AFR (Annualized Failure Rate) that the customer companies and end users can also understand and utilize. Unanticipated failures cost time to resolve and by minimizing failures manufactures can avoid wasting time.

Testing is used to discover the main cause of failure. These faults may not become apparent in a simple performance test done at the manufacturing process and therefore it is important to the manufacturer to perform more lengthy, more in depth tests such as temperature cycling and rapid aging tests, that simulate usage of the product, in the field, for a longer time. It is therefore performed on select units to determine reliability factors and revisit and reperform these from time to time, as processes, methods, and equipment tends to improve and get upgraded as time goes by.

Manufacturers are also bound by many international and regional standards which their products need to adhere by to be considered fit for retail purposes and use, such as safety standards which also wary depending on what market the product is aimed for. For example, is the end user a layman and the environment a residential unit or a technician or a machinist in an industrial environment. Meeting the requirements of some standards may be the prerequisite of being able to market your product a certain way or to a certain purpose. Standards also promote the interoperability of different manufacturers products and promote common understanding of a product.

3.1.2 Customer company benefits

The customer company of a manufacturer company orders products either of their design or design by the manufacturer, to operate on the field of services they provide or on the product retail they are involved in. Not only is it important for the customer company to be assured that they are receiving quality products that meet their standards of quality but very often they are the entity that defines and communicates to the manufacturer what those requirements are.

As many customer companies are the solicitor of contact between the end user and the manufacturer, they are usually high profile companies that need to be confident in giving their company name and assurances to the product and it's reliability. Customer satisfaction is in often case directed directly to them and any warranty claims will be theirs to handle. Products that operate as expected avoid being returned or serviced under warranty. Calls to service support, troubleshooting, product returns, failure analysis, and possible re-engineering, cost. Therefore it is imperative to make sure that the manufacturer upholds those standards and does their testing and only work with manufacturers where this can be confirmed.

Customer companies are in varying degree part of the testing process of their product. As it is in the case study of this thesis, the customer company has produced the reliability statement and calculated the test methods and test cycles required to confirm that statement.

3.1.3 End user benefits

There are some abbreviations such as AFR and MTBF that even end users look for and understand to varying degrees, when prospecting products in the field of electronics and electrical devices. Customers want the best possible product for the capital they are willing to invest in it. One of the last things a customer hopes for the manufacturer to have been skimming with is product reliability. The end user needs to be able to trust as much on the testing and reliability estimates given for the product as they should be able to trust that standards have been met with the manufacturing and the product does what it says it does and its safe to use.

As much as warranty claims burden the retailers and manufacturers it is never seen as a positive interaction on the customers part even if the warranty is being handled to the best of the companys ability. It is still a waste of time and money and operating time of the product from the customers point of view. Racking reliability issues with certain products or product lines leave negative impacts on the customer base.

Eliminating the “infant mortality” phase and elongating a product lifecycle will improve customer satisfaction. Companies providing their products with the information of expected life cycles, annual failure rates and accurate reliability estimates help the customers choose the best products for their intended usage and their finances.

3.2 Improvement of current methods

Is there already more effective prosesses in use? Are there more effective test machinery in use? There is of course an industry for manufacturing test chambers for different environmental conditions and stressors and just like any industry they are doing constant research and development on their products and services. Advances and innovation on the designs and materials prompts improvements on the new generation of testing equipment too. Maybe a more advanced nozzle for the saline spray or more integrated sensors for measuring the various changing parameters in an environmental chamber. Innovation also brings about improvements on the power consumption/loss in the processes improving in turn the cost effectiveness of testing.

What are the minimums in testing cycles that still produce usable/reliable data? The amount of testing cycles required relies solely on the the numbers the test engineer sets out to prove. If a slope parameter has been established and a minimum life expectancy has been set, the test engineer can calculate to minimum amount of testing needed. Ideally though, to get the most reliable data on a product, as many units should be stress tested to the point of failure as possible [23]. Repeatability is the corner stone for all reliability testing [20].

What is “sufficient” quality/reliability? As costs grow, where is the equilibrium of cost versus benefit? Reliability is always a question of cost and cost efficiency as seen illustrated in Figure 5. The end user and the manufacturer have different ways of looking at the possible cost through the lifecycle of a product but the same quality issues still effect on the overall cost of both parties. A manufacturer shirking on quality control and therefore gambling on the reliability of his product will save on the cost in short term and pushes the risk of extra expenses on the end user but in the long term negative user reviews and an high amount of repairs or returns under warranty will shift the overall expenses of a unit towards the manufacturer.

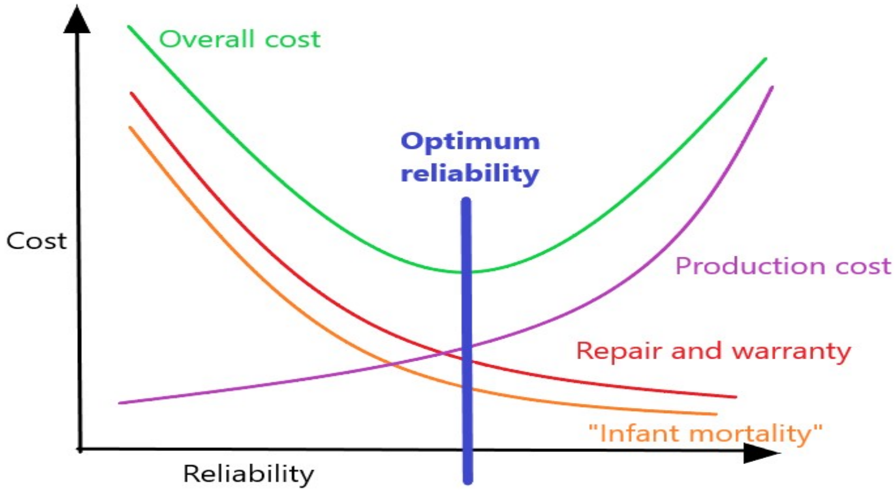


Figure 5. Cost vs reliability graph, by the author[24]

Reliability can be improved upon almost endlessly but the cost of manufacturing such product also continues to ramp up accordingly making the product unable to compete in the market with other cheaper albeit less reliable competitors. End users are mostly not willing to pay extra for a few additional years of premium functionality if a more inexpensive, “sufficient” quality option is available. This also brings in to consideration the worthwhile rate of product cycling especially in the commercial field. Products with longer life spans will still quickly become “old tech” and sales will decline [25].

When it comes to industrial use however, and especially critical industries such as nuclear power plants, where high security is not regarded as a cost balance issue, the reliability of product becomes non cost dependent and can be taken much further, raising the threshold of “sufficient reliability”. Products that go for example into infrastructure maintenance, and thus will not be expected to be replaced often, will need a higher standard of reliability at a higher budget and production cost becomes less of an issue.

3.3 Other testing methods

A big part of a products testing cycle begins already at the proto-build stage, such as salt spray, ESD and RF emissions. Some product testing methods are performed by the electronics manufacturers as a part of a so-called DTV (Design Verification Test). These tests are run as the first units have been manufactured and assembled. Some of the commonly used test methods include AST (Accelerated Stress Test), conventional life tests and mechanical abuse. [26]

AST consists of

- Humidity and temperature cycling
- High humidity, high temperature storage
- UV
- Dust ingress

Conventional life tests include testing switches and making sure materials and finish can withstand some abrasion. Mechanical abuse includes drop and vibration tests and in some cases also water splash or even submersion. Products also go through standard testing to make sure they are compliant with the regulations of the industry. Over 60% of failures in integrated cicuits are caused by oxide film defects and a large accumulation of macro defects.[27]

Accelerated Aging or rapid aging test creates the conditions that simulate aging in the product or material. This data is considered by regulatory authorities to be a decisive estimate of shelf life. This method means using heat, UV, oxygen, moisture, vibration, etc. to accelerate the normal aging process of a product. One commonly used rapid aging testing method is salt-water spray. The tests are conducted in a salt-spray corrosion oven according to standards like JEDEC standard JESD22-A107B for salt atmosphere test method.[28][29] The standard describes the requirements of the oven, the salt solution, its application, humidity, and magnifier. The procedure describes the required temperatures, application cycles as well as the criteria for failure. [30]

ESD testing is standardized by multiple standardization organizations. European companies adhere to the IEC 6100-4-2 standard that is a system level test that replicates a charged person discharging to a system in a system end user environment. The purpose of this test is to ensure the products can withstand and survive normal operation as it is assumed that the end user will not be taking any ESD precautions.

3.4 Required mathematics

Reliability over time R(t) can be expressed as with failures over time F(t) [31]:

$$R(t) = 1 - F(t)$$

In addition, with failure rate (λ), as follows [31] with the caveat that R(0)= 1 meaning that the device functions at the start:

$$R(t) = e^{-\lambda t}$$

Failure rate, in a function of failure density over time *f(t)* can be expressed as [31]:

$$f(t) = \lambda e^{-\lambda t}, when\ t \geq 0$$

Alternatively, failure density as derivative of reliability [31]:

$$f(t) = \frac{-dR(t)}{dt}$$

Failure over time can be expressed as [31] where R(0) = 1:

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

This may seem a bit counter intuitive as it would suggest that λ(t) = λ. This is called the hazard function or the hazard rate which becomes instantaneous hazard rate as ∆t approaches zero [32].

One frequently used unit of failure rate (λ) is FIT (Failure over Time). One FIT stands for one failure in one billion (10^9) device hours of operation. FIT is related to MTBF (Mean Time Between Failure sometimes denoted with θ) by θ = 1/λ. MTBF can also be said to stem from two other units of reliability, mainly Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR). For a device that is fixable MTBF=MTTF+MTTR. Failure rate is reversely proportional to both MTBF and MTTF [31].

Decreasing failure rate (DFR) describes when the probability of a failure decreases over time. As increasing failure rate is a concept that is sensible as components tend to get worse in performance over the wear and tear of time and usage, decreasing failure rate describes a unit or a system that gets better with time. DFR mainly uses units of hours but the applications are very limited as this is not a common phenomenon [33].

4 RELIABILITY TESTING: THE THEORY

The first considerations towards product reliability were aired during the Second World War, in the products of the wartime industry. The German A-4 (*Aggregat 4*), later known as V-2 (*Vergeltungswaffe 2 / Vengeance Weapon 2*) rockets, were deemed too unreliable, as they were aimed at England and at least one of them, the so-called Bäckebo Bomb, ended up in Sweden, and the one aimed at London that inspired the designer's famous quote "the rocket worked perfectly, except for landing on the wrong planet."[34] The designer and developer Wernher von Braun deduced that a product is a sum of its parts and therefore only as reliable as its weakest link [31][35].

Reliability testing had a boom period in the 50's due to the state of the world at the time. Biggest affecting individual instances being the Korean War circa 1950-1953 and the Vietnam War circa 1955-1975, and the Cold War which was fought with several proxy wars between 1947 and 1991 [36]. Nations were allotting large amounts of capital to the manufacturing of and researching of various wartime technologies. In addition, let's not forget the space race between the Soviet Union (USSR) and the United States (US) and the huge funding and demand placed on the aerospace industry. After managing to unintentionally fly the V-2 rocket to space, von Braun went to work for NASA and the technology that fueled to V-2 spawned the propeller rockets that won US the space race [35].

The increased funding fueled a lot of new areas of research in the field of engineering, including reliability and the methods of making products, such as weapons, air crafts, ballistic missiles and satellites more reliable but also developed new ways of predicting reliability of manufactured products and processes [35].

4.1 Weibull Methodology

Developed by Ernst Hjalmar Waloddi Weibull, a Swedish engineer, scientist and a mathematician, published first at 1939 on his paper on the Weibull Distribution. In 1951, his paper was presented to the American Society of Mechanical Engineers (ASME) and a handbook describing his method was released for Aerospace industry uses [37].

Weibull’s theories introduces a method for predicting long time reliability from even a relatively small sample size of failure using probability theory and statistics.[37]

Methods he introduced proved to be so accurate that they are in use today. The case study presented in this thesis will be using the Weibayes method, which is a method utilizing Bayesian method of statistical prediction to plot a successful Weibull distribution.

Weibull distributions original mathematical formula[37] is as follows:

$$F(t) = 1 - e^{-((t-t_0)/\eta)^{\beta}}$$

Where:

$\mathcal{F}(t)$ = fraction failing

t = failure time

t_0 = starting point or origin of distribution (later versions replace it with the location parameter (γ))

η = characteristic life or scale parameter

β = slope or shape parameter

e = exponential

Also known as the Weibull reliability function [37].

The use of the Weibull method and the plotting of the Weibull curve requires the engineers to have a failed unit or data of several failed units. If one or more parameters are unknown, some of the lesser parameter Weibull’s can still apply [2].

The 3-parameter Weibull [37][2]

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$$

Where:

$$f(t) \geq 0,\ t \geq \gamma$$
$$\beta > 0$$
$$\eta > 0$$
$$-\infty < \gamma < +\infty$$

$\eta =$ scale parameter, or characteristic life
$\beta =$ shape parameter (or slope)
$\gamma =$ location parameter (or failure free life)

The 2-parameter Weibull [2][37]

Is obtained by setting the location parameter to 0:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

The 1-parameter Weibull [2][37]

Is obtained by setting location parameter (γ) to 0 and assuming $\beta = C$ (=constant)

$$f(t) = \frac{C}{\eta}\left(\frac{t}{\eta}\right)^{C-1} e^{-\left(\frac{t}{\eta}\right)^{C}}$$

Weibull Failure Rate Function [2]

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1}$$

One parameter that is present is still the slope or shape parameter β. The lack of the slope parameter is covered in the next chapter with the introduction of Bayesian statistics.

One of the major uses of Weibull analysis is to predict the number of occurrences of failure as a function of time. This is important as it can provide the engineers a clear view of the potential magnitude of the problem caused by the failure. In addition, if the prediction is made of several different failures, it becomes easier from the forward predictions to estimate the most critical failure that needs priority. The risk analysis calculates the number of incidents projected to occur over some future period. The required parameters are the number of failed and non-failed units, usage rate of unit per month (or year etc.), and the introduction rate of new units. This information can help to formulate a simple risk analysis, the more complex ones requiring a Monte Carlo simulation. [37]

Advantages of the Weibull analysis is that it provides a very simple graphical solution, the process consisting only plotting a curve and its analysis. The x-axis of the graph represents some measure of life such as start/stop cycles or operating time. The y-axis shows the probability of an event (failure). The slope of the line created in the graph in Figure 6 represents the β parameter, which the Weibull equations rely on.

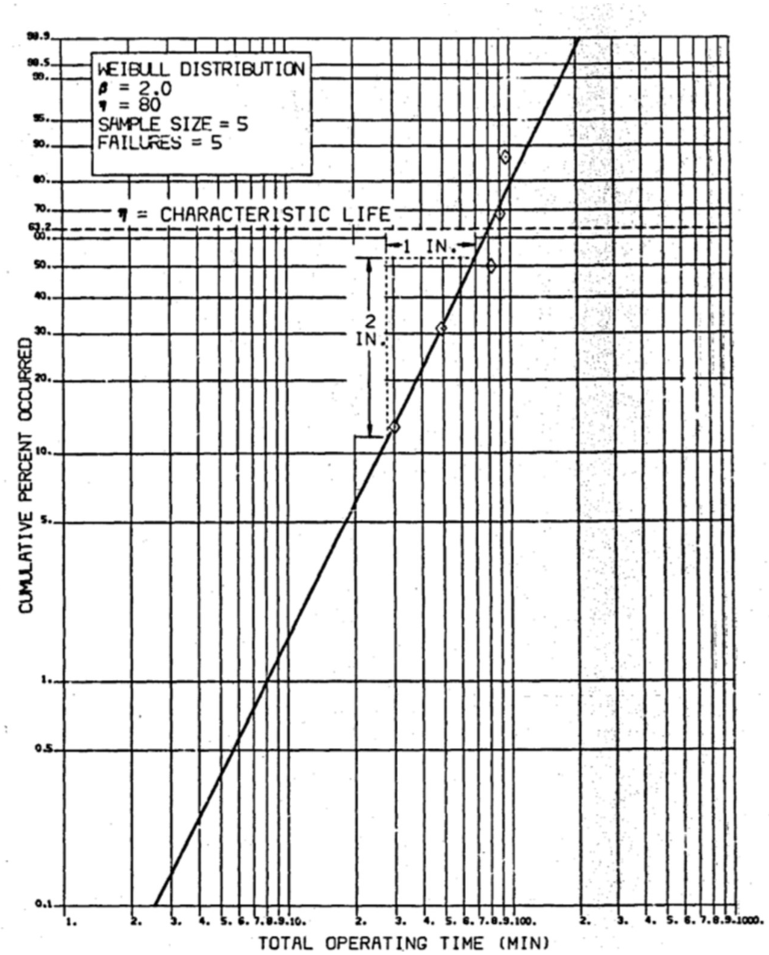


Figure 6 Plotted line of a Weibull distribution and the extracting of the β slope parameter [33].

As a downside to these methods is the possible deficiency of required data, such as nonzero time origin, extremely small sample size, or no failures, and the possible inaccuracies it introduces to the results. The lesser parameter Weibull's are in place to be used in such cases. Moreover, in the case of no failure data on a unit the missing slope parameter would need to be circumvented [4].

4.1.1 Bayesian Statistics

Bayesian statistics is a method of statistical estimation, which uses probabilities to solve statistical problems. It allows for the updating of data in the evidence of new data.

Bayesian Theorem is based in conditional probability and it comes into effect when multiple events form an exhaustive set with another event [38].

Bayes' rule:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

Where A and B are events P(B) ≠ 0. P(A|B) is a conditional probability: likelihood of A occurring given that B is true. P(B|A) therefore being likelihood of B occurring given A is true. P(A) and P(B) are marginal probabilities, meaning the probability of observing them separately.

Bayesian Confidence Bounds is one of the ways in which confidence bounds can be set to the desired test method. The other methods are confidence bound on parameters, time, or reliability. Bayesian confidence bounds are derived from Bayes' rule [38].

$$\rightarrow \qquad f(\theta|Data) = \frac{L(Data|\theta)\varphi(\theta)}{\int_{\sigma} L(Data|\theta)\varphi(\theta)d\theta}$$

Where:

f(θ|Data) is the posterior probability density function (pdf) of *θ*

θ is the parameter vector of Weibull distribution

L( ) is the likelihood function

$\varphi(\theta)$ is the prior pdf of θ

σ is the range of θ

4.2 Weibayes Method

Most commonly used in the electronics industry, this method is designed to solve problems when Weibull analysis cannot be used. Making a Weibull plot can be deemed difficult or impossible due to for example; too few or no failures, unknown elements like the age of the DUT, or when a test plan for a brand new device is needed [2][1].

Weibayes method's defining difference to Weibull method is that the β parameter is assumed. This assumption relies on the operator's judgment and is therefore regarded as an informal Bayesian procedure.

Parameter β (the slope/shape parameter) is assumed from historical failure data of similar units or from engineering knowledge of the physics of the failure under scrutiny. When β is determined, the equation can be formed using the method of maximum likelihood to determine η [37][2].

$$\eta = \left[\sum_{i=1}^{N} \frac{t_i^{\beta}}{r}\right]$$

Where t_i is the time or cycles in the unit and r is the number of failed units.

Weibull equation can now be determined from the assumed β and calculated η. The results can be plotted to a Weibull paper and is used exactly like a Weibull distribution.

$$F(t) = 1 - e^{(\frac{\gamma}{\eta})^{\beta}}$$

In many cases of Weibayes problems no failure has yet occurred. This forces the engineer to operate on the assumption that the first failure is imminent; meaning that r in the equation is 1.0. The equation would not work with a zero as a denominator. The Weibayes line derived this way is a very conservative estimation with at least 63% confidence rate. If the data never receives the true time of the first failure, the lower bound of the confidence level remains unknown. If the Weibayes analyses are consistently done long before the first failure, the confidence level is actually much higher than that. Therefore, it goes to assume that whilst the confidence level is unknown it is at least 63%.

Weibayes estimates can nowadays be found as web based programs where a test engineer can plot their data and receive estimates in the form of AFR percentage over the time frame of their choosing and the probability percentage of it being true (confidence). The two types of data required is either sample of data with failure/ failures or a sample of data with no failures. The methodology we will be further exploring in this thesis is the Zero Failure Test Methodology where the test method is derived from the unit's life expectancy when no failures have yet occurred [2][37][3].

4.3 Zero Failure Test Methodology

Designing a Zero Failure test for reliability starts with defining the reliability goal for the unit. For example an 80% reliability at 2 year period (or say 1000 cycles) under service-like conditions. Second parameter to define is the definition of success or what is deemed a failed unit and what a non-failed unit is. After these parameters are answered the calculation is used to determine how many units must be tested and for how long (or how many cycles) to demonstrate this goal with a high level of confidence [3][37].

With a known β, reliability at a time t is a function of η [2][4]:

$$R(t) = e^{(t/\eta)^{\beta}}$$

Assuming β is f.ex. 2, plotting the desired reliability rate of 0.80 in the time frame of 1000 cycles gives:

$\eta = \frac{1000}{|\ln(0.80)|^{1/2}}$ which gives η= 2116.9365

This means that the 0.80 reliability requirement requires η (characteristic life) to be at least 2116.9 cycles.

Cycle is defined as the length of the monitoring in which the DUT runs through one test period. For example in a cold start test when the unit being powered is the start of the cycle. Cycle runs through the monitoring period, being turned off and cooling off and starts anew when the device is booted again.

Once the characteristic life requirements has been calculated tables based on desired confidence level featuring the calculated parameters then gave the testing engineer the tools to design a test plan. These tools being the amount of units needed for testing and the required test cycles. As seen on Table 1 the β parameter of 2.0 and a sample size of three is picked. The corresponding table entry is used as the multiplier for the chosen η parameter of 500 hours. This gives the testing time of 438 hours per unit.[37]

Table 1 One of the multiplier tables from the 1983 handbook [37]

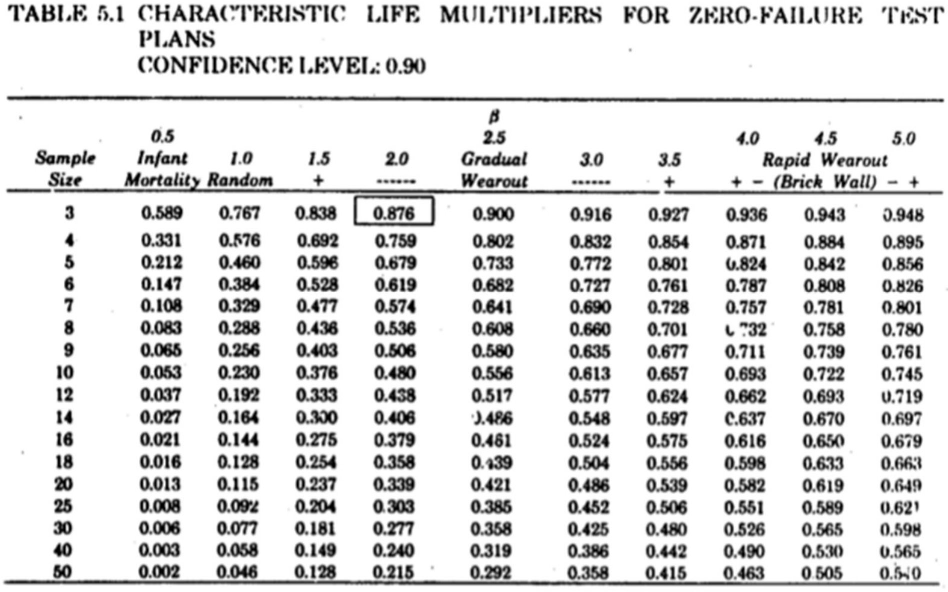


TABLE 5.1 CHARACTERISTIC LIFE MULTIPLIERS FOR ZERO-FAILURE TEST PLANS
CONFIDENCE LEVEL: 0.90

					β					
Sample Size	0.5 Infant Mortality	1.0 Random	1.5 +	2.0 ------	2.5 Gradual Wearout	3.0 ------	3.5 +	4.0 + −	4.5 Rapid Wearout (Brick Wall)	5.0 − +
3	0.589	0.767	0.838	0.876	0.900	0.916	0.927	0.936	0.943	0.948
4	0.331	0.576	0.692	0.759	0.802	0.832	0.854	0.871	0.884	0.895
5	0.212	0.460	0.596	0.679	0.733	0.772	0.801	0.824	0.842	0.856
6	0.147	0.384	0.528	0.619	0.682	0.727	0.761	0.787	0.808	0.826
7	0.108	0.329	0.477	0.574	0.641	0.690	0.728	0.757	0.781	0.801
8	0.083	0.288	0.436	0.536	0.608	0.660	0.701	0.732	0.758	0.780
9	0.065	0.256	0.403	0.506	0.580	0.635	0.677	0.711	0.739	0.761
10	0.053	0.230	0.376	0.480	0.556	0.613	0.657	0.693	0.722	0.745
12	0.037	0.192	0.333	0.438	0.517	0.577	0.624	0.662	0.693	0.719
14	0.027	0.164	0.300	0.406	0.486	0.548	0.597	0.637	0.670	0.697
16	0.021	0.144	0.275	0.379	0.461	0.524	0.575	0.616	0.650	0.679
18	0.016	0.128	0.254	0.358	0.439	0.504	0.556	0.598	0.633	0.663
20	0.013	0.115	0.237	0.339	0.421	0.486	0.539	0.582	0.619	0.649
25	0.008	0.092	0.204	0.303	0.385	0.452	0.506	0.551	0.589	0.621
30	0.006	0.077	0.181	0.277	0.358	0.425	0.480	0.526	0.565	0.598
40	0.003	0.058	0.149	0.240	0.319	0.386	0.442	0.490	0.530	0.565
50	0.002	0.046	0.128	0.215	0.292	0.358	0.415	0.463	0.505	0.540

If there is a constraint on the amount of test time allotted to a unit another table on figure 6 can be used in the following way. Each unit could be tested for the time of 300 hours with the characteristic life parameter still being the same 500 hours as in the previous example. 300 hours/500 hours gives the ratio of 0.6 and this together with the β parameter of 2.0 when plotted gives the number of units required for testing to be 7 to keep the 90% confidence.

Table 2 Ratio x slope table from the 1983 handbook [37]

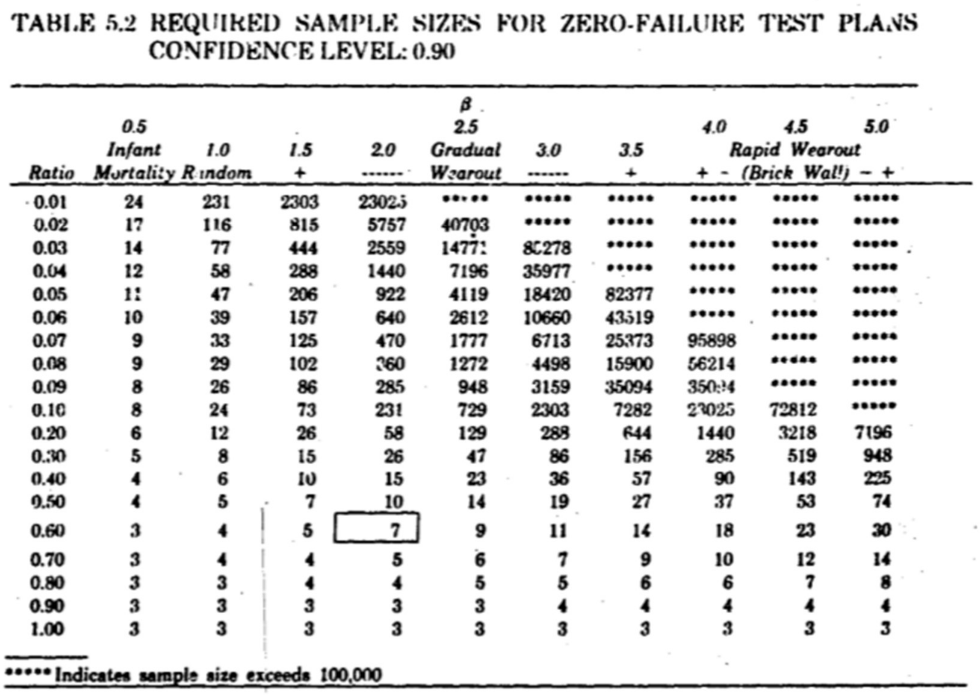
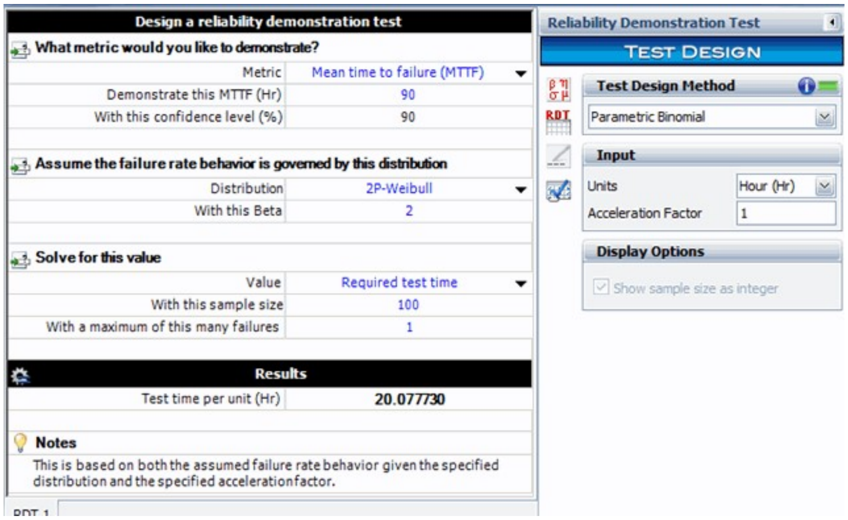


TABLE 5.2 REQUIRED SAMPLE SIZES FOR ZERO-FAILURE TEST PLANS
CONFIDENCE LEVEL: 0.90

Ratio	0.5 Infant Mortality	1.0 Random	1.5 +	2.0 ------	β 2.5 Gradual Wearout	3.0 ------	3.5 +	4.0 + -	4.5 Rapid Wearout (Brick Wall)	5.0 − +
0.01	24	231	2303	23025	*****	*****	*****	*****	*****	*****
0.02	17	116	815	5757	40703	*****	*****	*****	*****	*****
0.03	14	77	444	2559	14771	85278	*****	*****	*****	*****
0.04	12	58	288	1440	7196	35977	*****	*****	*****	*****
0.05	11	47	206	922	4119	18420	82377	*****	*****	*****
0.06	10	39	157	640	2612	10660	43519	*****	*****	*****
0.07	9	33	125	470	1777	6713	25373	95898	*****	*****
0.08	9	29	102	360	1272	4498	15900	56214	*****	*****
0.09	8	26	86	285	948	3159	35094	35094	*****	*****
0.10	8	24	73	231	729	2303	7282	23025	72812	*****
0.20	6	12	26	58	129	288	644	1440	3218	7196
0.30	5	8	15	26	47	86	156	285	519	948
0.40	4	6	10	15	23	36	57	90	143	225
0.50	4	5	7	10	14	19	27	37	53	74
0.60	3	4	5	$\boxed{7}$	9	11	14	18	23	30
0.70	3	4	4	5	6	7	9	10	12	14
0.80	3	3	4	4	5	5	6	6	7	8
0.90	3	3	3	3	3	4	4	4	4	4
1.00	3	3	3	3	3	3	3	3	3	3

*****Indicates sample size exceeds 100,000

Nowadays it is highly recommended to use some of the available software like Weibull++ (ReliaSoft) to do the estimation and data analysis. The programs require the user to insert the parameters where prompted and it will give the user required sample sizes and test times as seen in Figure 9. [3]



Design a reliability demonstration test

What metric would you like to demonstrate?

Metric	Mean time to failure (MTTF)
Demonstrate this MTTF (Hr)	90
With this confidence level (%)	90

Assume the failure rate behavior is governed by this distribution

Distribution	2P-Weibull
With this Beta	2

Solve for this value

Value	Required test time
With this sample size	100
With a maximum of this many failures	1

Results

Test time per unit (Hr)	20.077730

Notes

This is based on both the assumed failure rate behavior given the specified distribution and the specified acceleration factor.

Reliability Demonstration Test

TEST DESIGN

Test Design Method

Parametric Binomial

Input

Units	Hour (Hr)
Acceleration Factor	1

Display Options

☑ Show sample size as integer

Figure 7 Weibull++ by ReliaSoft [3]

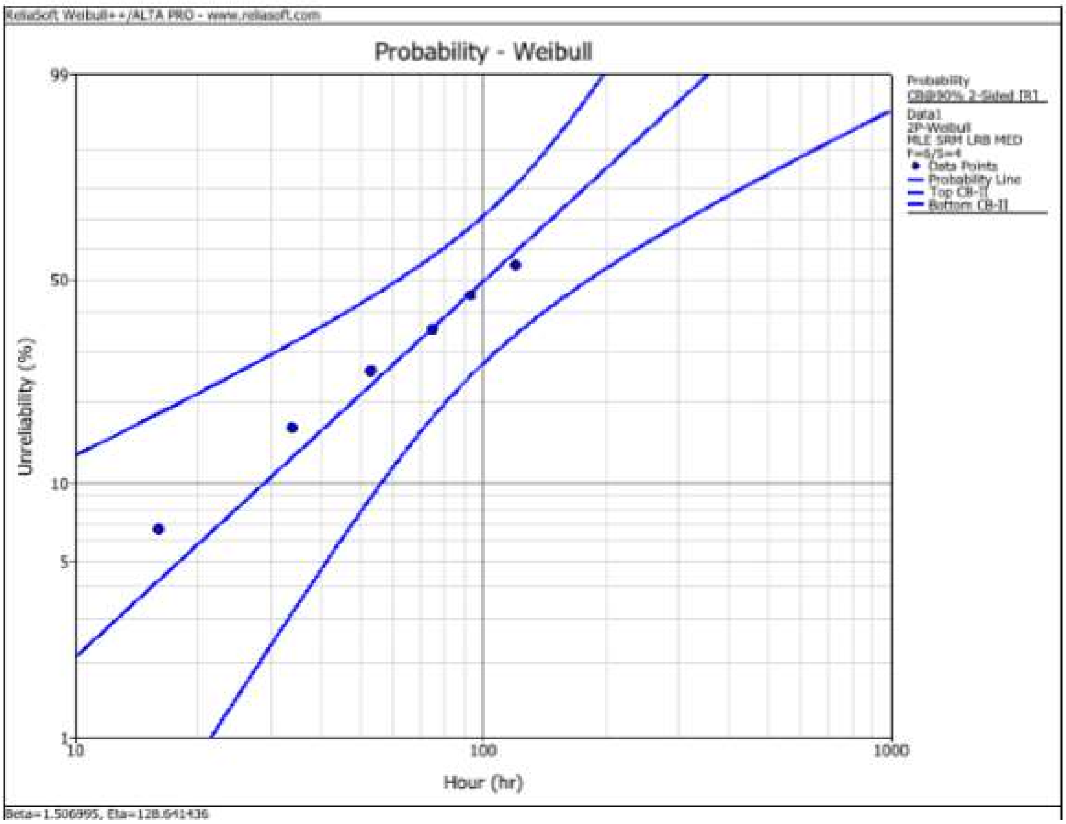


Figure 8. Plots on Weibull paper by Weibull++ by ReliaSoft [3]

These programs are very versatile and allow the calculation of several different metrics with varying degrees of data points and the programs can also be used to plot your eventual results into the Weibull distribution scale and print out reports [3].

4.4 AFR

One of the parameters often looked for in with the Weibayes zero failure test methodology is Annualized Failure Rate (AFR). It’s important to understand that AFR never refers to or indicates a single individual units lifespan as it estimates the reliability of a population of units[39].

Most cases AFR is calculated as a relation between the mean time between failure (MTBF) and the actual operating hours that the units are run per year [31][27]:

$$AFR = 1 - e^{\left(\frac{-8766}{MTBF}\right)}$$

The approximate hours in a year is 8766.

The reliability estimate states that this product should see a 6% AFR during 5 years at 80% confidence level. To achieve 6% AFR or 0.06 the MTBF would need to be in estimate of:

$$MTBF = -\frac{8766}{\ln(0.94)}$$

MTBF = 141671.8029 hours

The estimated hours of operating between failures and the needed run cycles from the previous chapter should be combined with the knowledge of the length of one operating cycle of the unit. The annual failure rate can also be determined from the existing failure data but to keep in the scope of the paper we assume no previous data exists.

4.5 Sample size

For the reliability estimation, a sample size is often also calculated if it is not simply determined by the engineer conducting the testing or by simple availability of units to be tested. The sample size can be determined based on the requirement of the confidence interval of reliability metrics, such as, reliability at a given time, B10 life (when confidence is 90%) or the mean life. It can be either determined using a simulation like the Weibull++ or analytically [40].

Analytically using the Weibull distribution, we can use the reliability function:

$$R(t) = e^{(t/\eta)^{\beta}}$$

And some parameters need to be set such as:

- μ_x = the assumed percentage of occurrences

- $k_{\alpha/2}$ = percentile of the standard normal distribution where α is 1+CL (confidence level)
- n = sample size
- B = the bound width

The bound width [40]:

$$B = 2k_{\alpha/2} * \sqrt{\frac{\mu_x(1-\mu_x)}{n}}$$

With the desired confidence level, the $k_{\alpha/2}$ can be solved and together with the bound width, the necessary sample size can be solved with [40]:

$$n = \frac{\mu_x(1-\mu_x)}{B^2} * 4k_{\alpha/2}^2$$

To simulate the required sample size to design a reliability test the input of an assumed failure distribution and the associate parameters are required. Using the reliability equation of the chosen failure distribution the chosen failure rate can be used to represent the μ_x component of the analytical method and calculate the times to failure. This can be repeated multiple times to obtain the desired sample size of times to failure. Then the sample is used to re-estimate the parameters of the chosen distribution. This way we can obtain the upper and lower bounds at a given confidence level of the parameters [40].

In short, the engineer plots the β slope parameter and the η characteristic life parameter to a Weibull++ tool. Expecting the bound ratio to be less than 1.2 in time of 400, the sample size is estimated to be at least 25 in order to meet the requirements.

When designing ALT (Accelerated Life Test) tests it is also required to determine the appropriate stress levels. These refer to the stress levels that are determined to be feasible for the unit to experience during its lifecycle and in the conditions it is meant to be used in. For this the analytical method is more widely used [40].

5 CASE STUDY: RPD

RPD stands for a remote PHY (physical layer) device and its primary function is to implement the Remote-PHY specification to provide conversion from digital Ethernet transport to analog RF transport. It converts downstream DOCSIS, MPEG video, and OOB (Out-of-Band) signals it receives from the CCAP core in digital form to analog form for transmission over RF or linear optics. Reversely it also converts analog upstream DOCSIS, and OOB signals over to digital transmission over Ethernet or PON (Passive Optical Network) to the CCAP core. [14] The RPD contains PHY related circuitry; downstream QAM modulators, upstream QAM demodulators, and pseudo-wire (an IP tunnel between two points in an IP network) logic for connecting to the CCAP core.[14] For this product, the customer company requested a test that was designed using the Weibayes zero failure test method. Whereas the RPD as a product is not new, the technology in this DUT (Device Under Test) is. From the data and eventual final report, the company will be able to make the reliability statement, which will be looked at the end of this segment.

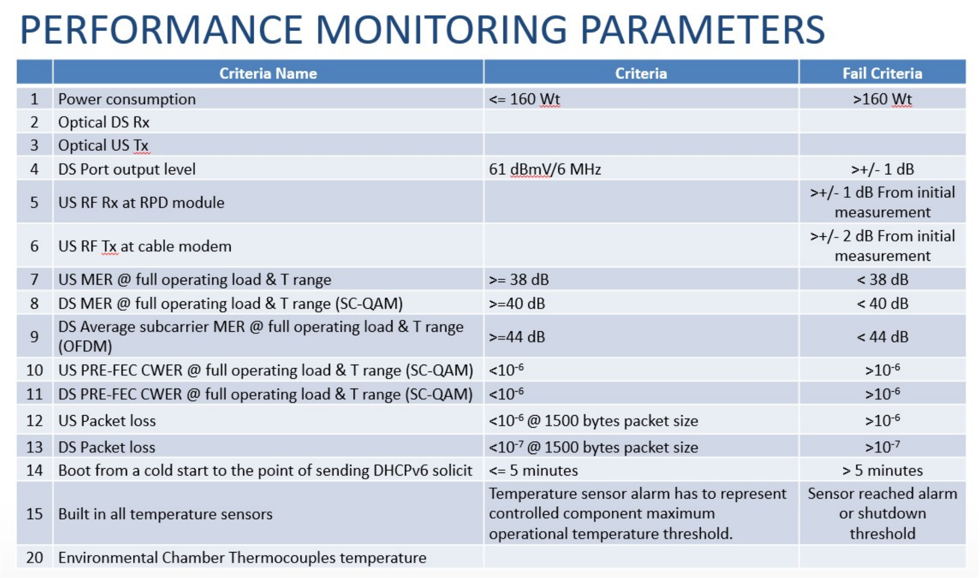
5.1 Measurements

The test was performed at the manufacturer’s location and with their equipment. The manufacturing company has a custom-built environmental chamber in it’s premises that could perform the required lower and upper temperatures. In the initial setup of the chamber, it was noted that even with the large industrial fans, the temperature change in the chamber and inside the DUT’s was not fast enough and the findings were reported to the reliability engineer who provided the manufacturer with recalculated cycles and test duration.

All parameters must be timely synchronized, measured and documented with initially 10-minute increments during the temperature-cycling test and in 5-minute increments during the cold start cycles. This was lengthened due to the environmental chamber’s capacities. Time stamps of all measurements must be synchronized. Pass and fail criteria are specified by the customer company and listed in table 1. All documented data will be submitted to the customer company.

As for the reasons why the customer company's reliability engineer chose the Weibayes zero failure test method, he mentions that one must keep in mind that the RDT (Reliability Demonstration Test) looks for failure modes that appear in the early life portion of the bathtub curve. In the late 20th century, when all industries decided to implement the RCM (Reliability Centered Maintenance), the aerospace industry has done extensive studies to define the hardware curves of life. These studies looked at the aircraft hardware failures and defined six reliability curves. The most used version of the bathtub curve was applicable in only 4% of those and 68% of hardware does not see any aging or wear out during the useful life portion of the hardware life cycle. Electronic components show the same behavior according to him.

Table 3 RPD test plan material [9].



PERFORMANCE MONITORING PARAMETERS

	Criteria Name	Criteria	Fail Criteria
1	Power consumption	<= 160 Wt	>160 Wt
2	Optical DS Rx		
3	Optical US Tx		
4	DS Port output level	61 dBmV/6 MHz	>+/- 1 dB
5	US RF Rx at RPD module		>+/- 1 dB From initial measurement
6	US RF Tx at cable modem		>+/- 2 dB From initial measurement
7	US MER @ full operating load & T range	>= 38 dB	< 38 dB
8	DS MER @ full operating load & T range (SC-QAM)	>=40 dB	< 40 dB
9	DS Average subcarrier MER @ full operating load & T range (OFDM)	>=44 dB	< 44 dB
10	US PRE-FEC CWER @ full operating load & T range (SC-QAM)	$<10^{-6}$	$>10^{-6}$
11	DS PRE-FEC CWER @ full operating load & T range (SC-QAM)	$<10^{-6}$	$>10^{-6}$
12	US Packet loss	$<10^{-6}$ @ 1500 bytes packet size	$>10^{-6}$
13	DS Packet loss	$<10^{-7}$ @ 1500 bytes packet size	$>10^{-7}$
14	Boot from a cold start to the point of sending DHCPv6 solicit	<= 5 minutes	> 5 minutes
15	Built in all temperature sensors	Temperature sensor alarm has to represent controlled component maximum operational temperature threshold.	Sensor reached alarm or shutdown threshold
20	Environmental Chamber Thermocouples temperature		

Figure 12 presents the 7 testing components including a virtual server that houses most of the testing software, Raspberry Pi (#6) which functions as a server taking temperature measurements, controls the environmental chamber and acts as a messenger between the virtual server and the Arduino taking power measurements.

Figure 9 Picture of the environmental chamber on the left and the modems outside on the right

In the figure 12 you can see the setup of the external devices and the DUTs inside the environmental chamber.

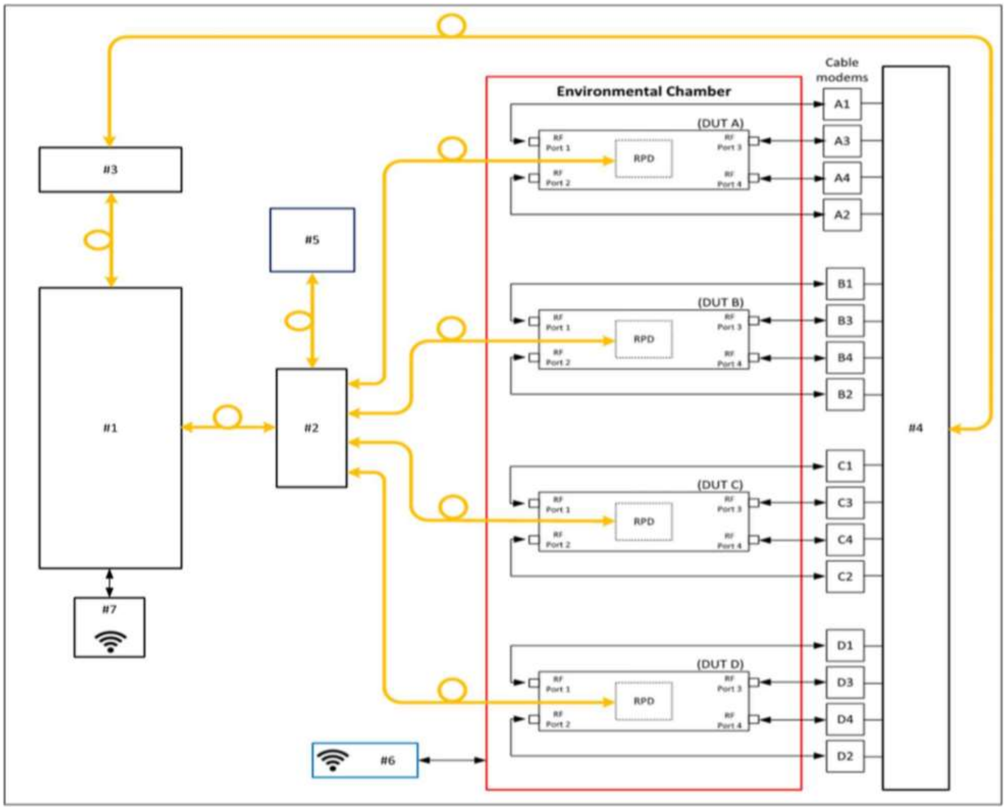


Figure 10. In this setup #1 is a switch, #2 and #4 are also switches, #3 is a traffic generator and #7 is a PC for monitoring. RPD test plan material [9].

5.2 The process

The test is performed with four ICON units with RPD units in them. Each RPD will transport 32 forward operating QAM channels in the range from 111MHz to 999MHz, one OFMD channel and 4 return operating QAM channels with a range from 8.2MHz to 38.8MHz. The customer has specified that the same company must manufacture all SFP+ transceivers. Each ICON unit has four modems connected to its ports, 16 modems in total.

This reliability demonstration test contains 178 cycles of temperature cycling test that will be further explored in chapter 4.2.1 and visualized in figure 2, followed by 50 cycles of cold start test described in chapter 4.2.2 and in figure 3.

During the 178 cycles, all four RPD units must be monitored and powered throughout the entire length of the test. The following 50 cycles of cold start test, unit parameters only need to be monitored during UAT power on condition and monitoring is to be started after 5 minutes of power activation.

The sensor location was requested to be in the so-called worst-case locations in the corner or in the middle of the load. Ambient temperature sensors must be located away from EUT heating effects. The thermocouple’s output must be monitored during the entire test and they must meet the ambient temperature test profile at all times. All test units are hermetically sealed and fasteners tightened to the OEM specified torques. All parameters must be documented prior to test startup, especially since some of the criteria are dependent on initial values.

5.2.1 Temperature cycling test

Test parameters are the demonstrated reliability of 6%, design life requirement of 5 years, operating ambient range from -40°F to 149°F and the performance monitoring measurements being taken every 10 minutes.

The test was performed with temperatures ranging from -28℃ (-18°F) to +65℃ (149°F) and was run 312 cycles with one cycle lasting 4 hours with four units. These four units had prior 30 cycles of operation prior the test. The temperature cycle spent one hour in the low temperature and 2 hours in the high temperature, excluding transition periods, as shown in Figure 13.

As the one of the main goals of this test was to test functionality and reliability in life-like environment, a specialized traffic generator was used to mimic network traffic in the test setup. The temperature cycling is performed to simulate the extremities of the outdoor environment these units would be operating on in the field.

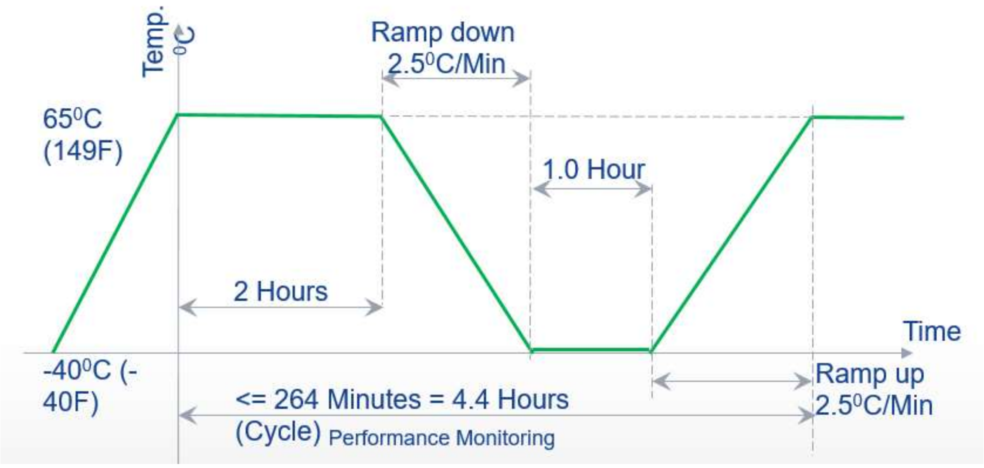


Figure 11.Visual representation of one cycle of the temperature-cycling test with parameters. [9]

As for the results: the temperature cycling test the units met their defined signal quality requirements.

Output amplifier hybrids failed during the test in four node ports. Component supplier has identified the problem and supplied new components and the test was redone Q4/2019 to confirm previous findings. During the first test, it is also noted that the cable modems used created some packet losses, disturbing the test data.

5.2.2 Cold start

Performance monitoring measurements are to be taken in 5 minute increments starting 5 minutes from the initial power up and lasting only the power-on phase.

Test was modified to run for 50 cycles, each cycle lasting 60 minutes, with four units, this can be seen in figure 14. Nodes were placed in -28℃ (-18°F) temperature with on and off phases lasting 30 minutes each. The purpose of the cold start test was to determine how the devices function in cold environments after being powered down for a significant amount of time.

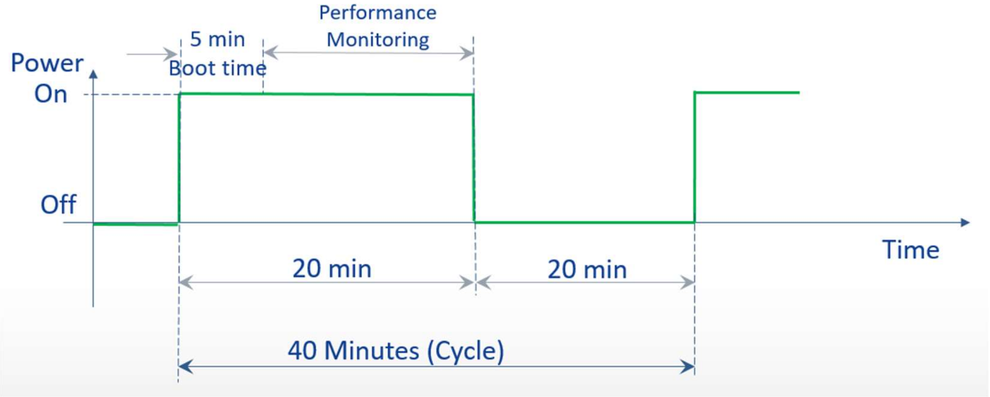


Figure 12. Initial plan of 40-minute cycle was extended. [9]

The cold boot test revealed no difficulties in operating the units.

5.3 Results

The RPD has no historical performance data available. The test parameters were calculated using the Weibayes Zero failure test methodology. The test was expected to, therefore, confirm 6% AFR during 5 years at an 80% confidence level. This desired reliability will be considered confirmed when there are no failed performance monitoring parameters, no RPD hard failures, and successful completion cold starts.[9]

The original test length of the temperature-cycling test was extended due to the limitations of the temperature chamber. The length was increased to 56 days from the original 33 to meet the requirements of the desired statistical reliability.

Some of the cable modems had complications and some of them had to be replaced with new ones during the test. Also towards the end of the first test, a critical component broke from four outputs in three units due to the stress from the temperature changes. The third-party manufacturing this component verified the results and manufactured a more durable component for the second test. The broken components functional issues affected only the higher temperature results.

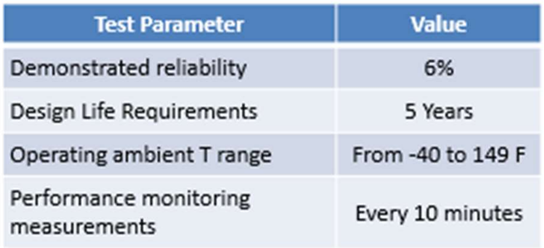
The testing company worked closely with the reliability engineers from the customer company to make sure the resulting data was as useful as possible. Anomalies in the data were resolved post-test. The test results indicated that the devices could be relied upon to withstand considerable temperature changes while continuing to perform as expected. All the fluctuations in the derived data could be explained by external factors. Therefore it could be concluded that the test was a success in the given test parameters.[9]

The final report sent to the customer company consisted of all the test setup data, the resulting data as well as descriptions of the anomalies and hardware failures and the correspondence with the third party manufacturer confirming the hardware issues origins.

5.4 Compiling the data

The reliability estimation to be shown true was 6% AFR during 5 years at an 80% confidence level. The annualized failure rate has been dissected to its math core during this thesis and its meaning and use explained in chapter 4.4. It has been used as a basis for the testing as is seen in table 4 for the test parameters for the temperature-cycling test by plotting the required info in the Reliasoft program. AFR's relation with MTBF gives a good estimation of the hours of operation before initial failure. Combined together with the units design life result, found in the test parameters for the reliability demonstration test, gives all the parameters needed for designing the tests.

Table 4[9]



Test Parameter	Value
Demonstrated reliability	6%
Design Life Requirements	5 Years
Operating ambient T range	From -40 to 149 F
Performance monitoring measurements	Every 10 minutes

What is meant by confidence? All the mathematical proof and tie-ins of the equations used has been shown and broken down in this thesis in chapter 4.5. Can we assume that the confidence level presented here is a two-sided confidence bound? After going through the process of calculating the parameters required for the test to be performed and the confidence to be proven, the confidence level must be a two-sided confidence bound. All the initial parameter calculation for the RPD reliability demonstration test was done with the Reliasoft program by the test engineer at the customer company.

Have we now explained expected life/cycles? Expected life cycles are cycled in every calculation throughout chapter 4 of this thesis and it is important to understand that this number is first and foremost an estimation based on the data received from similar products and compilation of data received throughout the testing process. Most of reliability calculation needs these estimates for the functions to be usable and the reliability demonstration test is set to prove these estimates accurate. None of these estimates is in any way a realistic number on any given single unit but generalization on where most of the units would fall on a bell curve.

The slope parameter of the Weibull equation has to be determined and evaluated by the testing engineer; in this case, it was determined to be 1.2. An excel spreadsheet was made where all assumptions were placed and Monte Carlo simulation was run to see the outcome distribution mode parameter. Then a characteristic life parameter was derived through experience and previous data on similar products and these gave the required test cycles to prove the desired confidence bounds. [2] The confidence bounds, in turn, contribute to the amount of units needed for the test through an equation presented in chapter 4.5. Even though the manual calculation of these equations and the subsequent application of charts and plotting of the Weibull curve has been made moot by the software created to do these things on our behalf, it is still beneficial for engineers performing reliability testing to be aware of the origins of what they are working on.

6 CONCLUSION

This thesis presented the history, theory, application, and benefits of reliability estimates in the design, manufacturing, and testing of electronics. Especially the theory behind reliability estimation is a subject somewhat poorly understood by even the engineers who still need to apply it to their work. The Weibayes zero failure method is a straightforward concept of producing these estimates and designing the testing environments and methods to prove the estimates true.

All of the measures and units required to make the estimates can be derived from the corresponding mathematical formulas but most of these have been combined to programs such as Weibull++ that make the calculations and plot the graphs and produce tools for the testing engineer by simply plotting the requested parameters. This speeds up the process and in a way makes it more reliable in its own right but has sure also contributed greatly to the gaping maw of ignorance that most electronics engineers have towards the math of reliability.

Many reliability engineers, quality engineers, test engineers, systems engineers, or design engineers could benefit from the understanding of the methodology behind reliability estimation. The scope of this thesis forces the subject to be narrowed down to focusing primarily on one branch of reliability methods and the theoretical discussion of its downsides and various opposing or surpassing methods had to be too brief. Especially a further and more in-depth look on the ways to improve the verifying testing methods should be in the interests of every manufacturer.

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