Overview of Reliability Engineering

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Abstract The evolution of reliability since the late 1940 till 2000s is described. This evolution mainly came from United States, and the evolution is from system level reliability and maintenance to components reliability through statistical methods. Exponential distribution was used initially, and it was found not realistic in the 60s. Physics of failure began in the 90s, and reliability evaluation was then shifted from statistical methods to physics of failure. Since 2000, the hybrid physics–statistical approach evolve due to the need to combine both of them in order to evaluate component and system reliability realistically. While reliability is evolving and maturing in USA, the concept of reliability was introduced to Asia only in the late 70s in the form of qualification as US manufacturers were shifting their production to Asia, and they needed to qualify the factories in Asia. Unfortunately, the growth of reliability methodology is very slow in Asia, and still many are using exponential distribution to evaluate reliability. On the other hand, physics of failure approach is growing fast in Asia, due probably to the need to troubleshoot failures manufactured in Asia. This chapter helps the readers to have a border view of reliability and the necessity for its evolution.

Keywords Historical evolution · Statistical approach · Physics of Failure approach · Hybrid approach · Monte Carlo modeling · System reliability · Eponential distribution

Before World War II (WWII), reliability as a word came to mean dependability or repeatability. Such meaning still exists to many in Asia today. The modern use was redefined by the U.S. military in the 1940s and evolved to the present. By the 1940s, reliability and reliability engineering still did not exist.

The current meaning connotes a number of additional attributes that span products, service applications, software packages or human activity. These attributes now

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pervade every aspect of our present day technologically intensive world. Let us follow the journey of reliability engineering from the early days to present, where most of the information described up to year 2000s are from References (McLinn 2010; Denson 1998; Azarkhail and Modarres 2012) unless otherwise referenced.

1 The Late 1940s

The demands of WWII introduced many new electronics products into US military. At the onset of the war, it was discovered that over 50% of the airborne electronics equipment in storage was unable to meet the requirements of the Air Core and Navy. This was because the main electronic devices were still the vacuum tubes, whether it was in radar systems or other electronics. These systems had proved problematic and costly during the war. For shipboard equipment after the war, it was estimated that half of the electronic equipment was down at any given time. Vacuum tubes in sockets were a natural cause of system intermittent problems. They could not afford to have half of their essential equipment non-functional all of the time. The operational and logistics costs would become astronomical if this situation was not soon rectified.

On the other hand, much of the reliability work during this period had to do with testing new materials and fatigue of materials. M.A. Miner published the seminal paper titled "Cumulative Damage in Fatigue" in 1945 in an ASME Journal. B. Epstein published "Statistical Aspects of Fracture Problems" in the Journal of Applied Physics in February 1948. These were obviously insufficient to meet the reliability need on electronics, and IEEE formed the Reliability Society in 1948 with Richard Rollman as the first president. Z.W. Birnbaum founded the Laboratory of Statistical Research at the University of Washington in the same year, and through his long association with the Office of Naval Research, the lab served to strengthen and expand the use of statistics in reliability.

2 The 1950s

A study group was initiated in 1950. This group was called the Advisory Group on the Reliability of Electronic Equipment, AGREE for short. By 1952, an initial report by this group recommended the following three items for the creation of reliable systems:

1. There was a need to develop better components and more consistency from suppliers.
2. The military should establish quality and reliability requirements for component suppliers.

3. Actual field data should be collected on components in order to establish the root causes of problems.

In 1957, a final report was generated by the AGREE committee and it suggested the following:

1. Most vacuum tube radio systems followed a bathtub-type curve.
2. It was easier to develop replaceable electronic modules to quickly restore a failed system, and thus they emphasized modularity of design.
3. Recommend to run formal demonstration tests with statistical confidence for products.
4. Recommend to run longer and harsher environmental tests that included temperature extremes and vibration

The recommendations came to be known as AGREE testing and eventually turned into Military Standard 781. Another item provided by the AGREE report was the classic definition of reliability. The report stated that the definition is "the probability of a product performing a specified function without failure under given conditions for a specified period of time".

In parallel, Rome Air Development Center (RADC) was established in Rome, New York in 1951 to study reliability issues with the Air Force. In 1955, RADC issued "Reliability Factors for Ground Electronic Equipment". This was authored by Joseph Naresky. This decade ended with RCA publishing information in TR1100 on the failure rates of some military components. RADC picked this up and it became the basis for Mil-Std Handbook 217 (MH-217) in 1962.

The applications of the probabilistic notions of reliability around this time were widely represented by the exponential distribution. One of the main driving forces for this popularity was the simplicity of the corresponding reliability functions. Having limited computational resources, the early reliability practitioners were evidently seeking a simple reliability model with a straightforward mathematical representation. A combination of these factors made the exponential distribution the dominant model in early reliability assessments. This simplicity accelerated many improvements in traditional statistical and probabilistic approaches to measuring, predicting and testing of item reliability in the 1950s. On the other hand, Wallodi Weibull published his first paper for the ASME Journal of Applied Mechanics in English. It was titled "A Statistical Distribution Function of Wide Applicability" in 1951 in view of the limitations of the exponential distribution that he understood.

Later on, Weibull produced "Statistical Evaluation of Data from Fatigue and Creep Rupture Tests: Fundamental Concepts and General Methods" as a Wright Air Development Center Report 59-400 for the US military in 1959. Birnbaum also made significant contributions to probabilistic inequalities (i.e. Chebychev), non-parametric statistics, reliability of complex systems, cumulative damage models, competing risk, survival distributions and mortality rates during this decade. By 1956, ASQC was offering papers on reliability as part of their American Quality Congress. The radio engineers, ASME, ASTM and the Journal of Applied Statistics were contributing research papers. The IRE was already holding a conference and publishing proceedings titled "Transaction on Reliability and Quality Control in Electronics". This began in 1954 and continued until this conference merged with an IEEE Reliability conference and became the Reliability and Maintainability Symposium.

Another major report on "Predicting Reliability" in 1957 was that by Robert Lusser of Redstone Arsenal, where he pointed out that 60% of the failures of one Army missile system were due to components. He showed that current methods for obtaining quality and reliability for electronic components were inadequate and that something more was needed.

In 1955, a conference on electrical contacts and connectors was started, emphasizing reliability physics and understanding failure mechanisms. Other conferences began in the 1950s to focus on some of these important reliability topics.

This decade ended with a lot of promise and activities. It was the advent of the reliability engineering discipline, and several different methods were introduced to achieve the goal of higher reliability. Two branches of reliability began to emerge. One branch existed for investigation of failures and the other for predictions.

3 The 1960s

The demands of the military ranging from missiles to airplanes, helicopters and submarine applications drove a variety of technologies. The study of the effects of EMC on systems was initiated at RADC and this produced many developments in the 1960s.

By now, the reliability discipline was working under the tenet that reliability was a quantitative discipline that needed quantitative data sources to support its many statistically based techniques, such as allocation and redundancy modelling. Another branch of the reliability discipline focused on the physical processes by which components were failing. The first symposium devoted to this topic was the "Physics of Failure in Electronics" symposium sponsored by the RADC and IIT Research Institute (IITRI) in 1962. Richard Nelson of RADC produced the document "Quality and Reliability Assurance Procedures for Monolithic Microcircuits," which eventually became Mil-Std 883 and Mil-M 38510. This symposium later became the "International Reliability Physics Symposium (IRPS)". Unfortunately, the electronic industry continued using the lot tolerance percentage defective (LTPD) statistic to address failures of electronics. It was not until late 1980s that PoF was revisited as a serious alternative.

In 1962, G.A. Dodson and B.T. Howard of Bell Labs published "High Stress Aging to Failure of Semiconductor Devices" in the Proceedings of the 7th National Symposium of Reliability and Quality Control. This paper justified the Arrhenius model for semiconductors. Lots of other papers at this conference looked at other components for improvement.

1962 was a key year with the first issue of MH-217 by the Navy. Once issued, MH-217 quickly became the standard by which reliability predictions were performed, and other sources of failure rates gradually disappeared. Part of the reason for the demise of other sources was the fact that MH-217 was often a contractually cited document and defence contractors did not have the option of using other sources of data.

By the 1960s, the exponential distribution turned out to be not so practical for many applications and sensitive to departure from the initial assumptions. The application of this model for components with high reliability targets could result in unrealistic mean-time-to-failure (MTTF). Further, this model basically ignored any aging and degradation in the component and had no memory to keep track of the damage being accumulated in the item.

After such disappointments, reliability practitioners made an attempt to capture some of the physical characteristics of failure into their modelling by using other available traditional distributions, such as the Weibull and lognormal distributions. During this decade, a number of people began to use, and contribute to the growth and development of, the Weibull function, the common use of the Weibull graph, and the propagation of Weibull analysis methods and applications.

In 1969, Birnbaum and Saunders described a life distribution model that could be derived from a physical fatigue process where crack growth causes failure.

Human reliability had now been recognized and studied, which resulted in a paper by Swain on the techniques for human error rate prediction (THERP).

During the decade, a strong commitment of US Government to space exploration resulted in the establishment of NASA, and this provided a driving force for improved reliability of components and systems. The decade ended with a landing on the moon showing how far reliability had progressed in only 10 years.

However, the two branches of reliability engineering seemed to be diverging by the end of the decade, with the *system* engineers devoted to the tasks of specifying, allocating, predicting, and demonstrating reliability, while the physics-of-failure engineers and scientists were devoting their efforts to identifying and modelling the physical causes of failure. Both branches were integral parts of the reliability discipline.

4 The 1970s

In the early 1970s, the responsibility for preparing MH-217 was transferred to RADC, who published revision B in 1974. However, other than the transition to RADC, the 1970s maintained the status quo in reliability prediction. MH-217 was updated to reflect the technology at that time, and there was a shift in the complexity of the models being developed for MH-217.

In fact, there were several efforts to develop new innovative models for reliability prediction. The results of these efforts were extremely complex models that might have been technically sound, but were criticized by the user community as being too complex, too costly, and unrealistic. These models were never incorporated into MH-217.

The 1970s marked the birth of fault tree analysis, which was motivated by the need for safety assessment in the aerospace industry and later for nuclear power plants. Up to this point, most reliability engineering efforts were focused on reliability of components and devices. Nevertheless, there was intense interest in system-level safety, risk and reliability in different applications such as the gas, oil, and chemical industries, and above all, in nuclear power applications. These challenges were immensely appealing to reliability community in the 1970s.

The Navy Material Command brought in Willis Willoughby from NASA to help improve military reliability across a variety of platforms. During the Apollo space program, Willoughby had been responsible for making sure that the spacecraft worked reliably all the way to the moon and back. In coming to the Navy, he was determined to prevent unreliability. He insisted that all contracts contain specifications for reliability and maintainability instead of just performance requirements. Willoughby's efforts were successful because he attacked the basics and worked upon a broad front.

5 The 1980s

The 1980s demonstrated progress in reliability across a number of fronts from military to automotive and telecommunications to biomedical. This was because televisions had become all semiconductor. Automobiles rapidly increased their use of semiconductors with a variety of microcomputers under the hood and in the dash. Large air conditioning systems developed electronic controllers, as had microwave ovens and a variety of other appliances. Communications systems began to adopt electronics to replace older mechanical switching systems. RADC published their first Reliability Tool Kit.

While MH-217 was updated several times, other agencies were developing reliability prediction models unique to their industries. As an example, the automotive industry, under the auspices of the Society of Automotive Engineers (SAE) Reliability Standards Committee, developed a set of models specific to automotive electronics, SAE870050. The SAE committee believed that there were no existing prediction methodologies that applied to the specific quality levels and environments of automotive applications.

The Bellcore reliability prediction standard is another example of a specific industry developing methodologies for their unique conditions and equipment. It originally was developed by modifying MH-217 to reflect better the conditions of interest to the telecommunication industry. It has since taken on its own identity with models derived from telecommunication equipment and is now used widely within that industry.

During this decade, the failure rate of many components dropped by a factor of 10. Software became important to the reliability of systems; this discipline rapidly advanced with work at RADC. Complex software-controlled repairable systems began to use availability as a measure of success. Repairs on the fly or quick repairs to keep a system operating would be acceptable.

The Very High Speed Integrated Circuit (VHSIC) program was the US Government's attempt to leverage from the technological advancements of the commercial industry and at the same time produce circuits capable of meeting the unique requirements of military applications. From the VHSIC program came the Qualified Manufacturers List (QML)—a qualification methodology that qualifies an IC manufacturing line, unlike the traditional qualification of specific parts. The US Government realized that it needed a QML-like process if it were to leverage from the advancements in commercial technologies, and at the same time have a timely and effective qualification scheme for military parts. At this point, reliability concept was introduced to Asia as a form of qualification as some US electronics manufacturers were moving some of their manufacturing sites to some Asia countries such as Singapore and Taiwan since the 1970s.

As technology has advanced, the gate or transistor count became so high that it could no longer effectively be used as the measure of complexity in a reliability model. Furthermore, transistor or gate count data were often difficult or impossible to obtain. Therefore, the model developed for VHSIC microcircuits needed another measure of complexity on which to base the model. The best measures, and the ones most highly statistically correlated to reliability are defect density and the die area applicable to specific IC features, e.g., metalization and oxide. The failure rate (for small cumulative fraction failure) is directly proportional to the product of the area and defect density. Another factor that is also highly statistically correlated with defect density and area is the yield of the die, or the fraction of die that is functional upon manufacture.

However, the problem in using these factors in a model is that they are highly sensitive parameters from a market competition viewpoint and therefore are rarely released by the manufacturers, rendered inaccuracy of the models. The conflict between the usability of a model and its accuracy has always been a difficult compromise to address for model developers.

The traditional approach in developing a life model for such components was to collect as much field failure data as possible to build a statistical model for the component life. Because of the decreasing budget and resources, and also due to faster trends in mass production, great emphasis was placed on capturing the needed information with much less effort. As a result, design and assessment methodologies that addressed the root causes of failure and other operating conditions emerged as powerful cost saving techniques. The accelerated life modelling approach was a direct outcome of this movement.

Accelerated life models took into account some of the operational conditions and were a primary attempt by reliability practitioners to make the life models more flexible. In the first step of this approach a stress agent, which could be an aggregate effect of many physical and operational conditions, was introduced. In the next step this agent was added to the statistical distribution of TTF to form a robust and general life model. Such models had more flexibility, yet needed much less reliability (failure) data.

However, it is usually very complicated (if possible at all) to introduce one or two stress agents to replace the aggregate effect of all influential factors in accelerated life testing approach. Many assumptions and simplifications need to be made, which could unacceptably limit the relevance of the outcomes. Yet, this was not the only challenge, since the accelerated life models, like all other statistical-based approaches, needed data for validation, and data collection meant time and resources that were decisively tight for most start-ups and fast-growing businesses. In addition, there were no data available for a product in the design stage or for a highly reliable product that was hard to break. In such cases, if the modeller was lucky, reliability models could be constructed based on some generic data from the history of similar products. This data could be updated later with expert judgments or other soft data with statistical inference techniques. The uncertainty bounds of such predictions depended upon direct failure data, if available. Therefore, more dependable reliability techniques needed to be developed to address reliability challenges imposed by emerging mass manufacturing technologies.

This latter challenge led to the growing application of Bayesian method in probabilistic data analysis in the 1980s. Using this approach, engineers utilized data available in generic handbooks and from expert opinions and any previous experience with similar products to make a probability density referred to as a prior distribution. The Bayesian framework made it possible to update this prior knowledge later and with just a few available data, an upgraded posterior state of knowledge can be made. The applications of this approach, however, were originally limited to simple reliability models due to the mathematical complexity of involved algorithms. The integrals necessary for normalization at Bayesian conditional probability calculations can be very complex when dealing with multi-parameter reliability models. This remained one of the two most important constraining elements of this approach (the other was developing a proper likelihood function representing reliability data) until recently, when advanced computational tools and techniques became available after revolutionary improvement in the computational power of personal computers.

The 1980s also marked the development of initiatives for modelling dependencies at the system level. Most of these efforts tackled the common cause failures as frequent dependency problems in systems. The common cause failure (CCF), which is the failure of more than one component due to a shared root cause, is classified as a dependent failure. In the 1980s many implicit and explicit methods were developed to incorporate common cause into the system failure analysis (McLinn 2010). In early attempts to model CCF at the system level, a new independent failure event with a specific probability was usually added to the system model. The probability of this event was estimated using field data available on the dependent failures of components.

Contributions by William Meeker, Gerald Hahn, Richard Barlow and Frank Proschan in developing their statistical models for wear, degradation and system reliability made an impact on reliability in this decade and subsequent.

6 The 1990s

By the 1990s, the pace of IC development was picking up. New companies built more specialized circuits. Wider use of stand-alone microcomputers was common and the PC market helped keep IC densities following Moore's Law and doubling about every 18 months. It quickly became clear that high volume commercial components often exceeded the quality and reliability of the small batch specially screened military versions, and the move towards Commercial off the Shelf (COTS) components gained momentum. Many of the military specifications became obsolete and best commercial practices were often adopted. RADC updated their Reliability Tool Kit for COTS applications in this decade.

With the end of the cold war, the military reliability changed quickly. MH-217 ended in 1991 at revision F2. New research developed failure rate models based upon intrinsic defects that replaced some of the complexity-driven failure rates that dominated from the 1960s through the 1980s.

RAC issued a six set Blueprint for Establishing Effective Reliability Programs in 1996. The internet showed that one single software model would not work across the wide range of worldwide applications, which now includes wireless. Also, network availability goals became "five 9 s or 5 min annually" to describe the expected performance in telecommunication, raising the standard of reliability. New approaches were required such as software mirroring, rolling upgrades, hot swapping, self-healing and architecture changes.

With the spread of reliability requirements to commercial world, new reliability training opportunities and books became available to the practitioners. ASQ made a major update to its professional certification exam (i.e. certified reliability engineers certification) to keep pace with the changes evident. ISO 9000 added reliability measures as part of the design and development portion of the certification.

New technologies such as microelectromechanical systems (MEMS), hand-held GPS, and hand-held devices that combined cell phones and computers all represent challenges to maintain reliability. Product development time continued to shorten through this decade and what had been done in three years was now done in 18 months. This meant reliability tools and tasks must be more closely tied to the development process itself. Consumers have become more aware of reliability failures and the cost to them.

In this decade, several vocal critics of MH-217 have complained about its utility as an effective method for assessing reliability. While the faultfinders claim that it is inaccurate and costly, there was no viable replacement in the public domain then.

Table 1 Failure-cause distribution and definition for electronic systems

• **Parts (22%)**: Failure resulting from a part (e.g., microcircuit, transistor, resistor, connector) failing to perform its intended function
• **No defect (20%)**: Perceived failures that cannot be reproduced upon further testing. These may or may not be an actual failure; however, they are removals and therefore count towards the logistic replacement rate (which is often incorrectly referred to as failure rate)
• **Manufacturing (15%)**: Failures resulting from anomalies in the manufacturing process, (e.g., faculty solder joints, inadequate wire routing resulting in chafing, bent connector pins)
• **Induced (12%)**: Failures resulting from an externally applied stress such as electrical overstress and maintenance induced failures (e.g., dropping, bending pins)
• **Design (9%)**: Failures resulting from an inadequate design (e.g., tolerance stack-up, unanticipated logic conditions, a non-robust design for given environmental stresses)
• **Wearout (9%)**: Failures resulting from wearout-related failure mechanisms (e.g., electrolytic capacitors, solder joints, tubes (TWT), and switch and relay contacts)
• **Software (9%)**: Failure of system to perform its intended function due to the manifestation of a software fault
• **System management (4%)**: Failures to interpret system requirements, or failure to provide the resources required to design and build a reliable system

The fraction for each failure cause is given in ( ), and listed from most to least
Data are as of 2012

The premise of traditional methods, such as MH-217, is that the failure rate is primarily determined by components comprising the system. This was a not-unreasonable premise in the 1960s and 1970s when components had higher failure rates, and when systems were less complex than they are today. Also, MH-217 was originally created to support the weapon system acquisition process. As such, it was required that a reliability estimate be available to system program offices (SPO) at certain milestones in the DoD acquisition cycle.

In many cases, an estimate of reliability was required before the parts list was even complete. Model developers have long known that many of the factors which had a major influence on the reliability of the end product were not included in MH-217, but under the constraints of handbook users, no better solution was available.

Increased system complexity and component quality in the 1990s have resulted in a shift of system failure causes away from components to more system-level factors, including manufacturing, design, system requirements, interface, and software. Table 1 shows the failure cause distribution of electronic systems as

Table 2 Digital circuit board failure rates (failures per 10^6 part-hours)

	Ground benign				Ground fixed			
Temperature (°C)	10		70		10		70	
Stress (%)	10	50	10	50	10	50	10	50
ALCATEL	6.59	10.18	13.30	19.89	22.08	29.79	32.51	47.27
Bellcore Issue 4	5.72	7.09	31.64	35.43	8.56	10.63	47.46	53.14
Bellcore Issue 5	8.47	9.25	134.45	137.85	16.94	18.49	268.90	275.70
BrTelecom HDR4	6.72	6.72	6.72	6.72	9.84	9.84	9.84	9.84
BrTelecom HDR5	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59
MH-217E Notice 1	10.92	20.20	94.37	111.36	36.38	56.04	128.98	165.91
MH-217F Notice 1	9.32	18.38	20.15	35.40	28.31	48.78	45.44	79.46
MH-217F Notice 2	6.41	9.83	18.31	26.76	24.74	40.15	73.63	119.21
RAC data		3.3						

Br ⇒ British

collected by RAC. Historically, these factors have not been explicitly addressed in prediction methods.

Therefore, a good model should reflects state-of-the-art technology, and it should includes the assessment of processes used in the design and manufacture of the system, including factors contributing to failure causes as follows:

- Parts
- Design
- Manufacturing
- System management
- Induced
- Wearout
- No defect found
- Software

The probability of failure is a complex interaction between the defect density, defect severity, and stresses incurred in operation. Failure rates predicted using empirical models are therefore typical failure rates and represent typical defect rates, design, and use conditions.

Table 2 contains the predicted failure rate of the various empirical methodologies for a digital circuit board. The failure rates in this table were calculated for each combination of environment, temperature and stress. These data show that there can be important differences between the predicted failure rate values, depending on the method used.

Differences are anticipated because each methodology is based on unique assumptions and data. The RAC data in the last row of the table is based on observed component failure rates in a ground benign application.

Furthermore, the empirical models are usually developed from the analysis of field data, which take time to collect. The faster the growth, the more difficult it is to derive an accurate model.

As a result, the 1990s marked the rebirth and widespread development of the PoF approach. While the roots of PoF methods can be found in fracture mechanics, which by itself started through the work of Alan A. Griffith just after World War I and was developed by George R. Irwin in the 1950s, and the PoF approach started through a series of four symposia from 1962 to 1966, but the concept lost its drive until the late 1980s. Enormous advancements in computational tools and faster personal computers on one side and emerging, advanced testing technologies in material science, on the other side, accelerated this trend. In this approach, facts from root cause physical/chemical failure processes are used to prevent the failure of the products by robust design and better manufacturing practices. Because of the competitive environment in production of consumer products and limited budget and resources, great emphasis was placed on capturing the needed information more quickly and with less effort. As a result, design and assessment methodologies that address the root causes of failure have emerged as powerful cost saving techniques.

In the early 1990s, the US Army and Air Force initiated two reliability physics related programs. In 1992, the Army authorized the Electronic Equipment PoF projects to promote a more scientific approach to reliability assessment of electronic equipment.

The PoF approach to reliability utilized scientific knowledge of degradation processes and the load profile applied to an item, its architecture, material properties and environmental conditions to identify potential failure mechanisms that individually or in combination lead to the item's failure. The PoF models, once developed and validated, would be used to estimate life expended and expected. Use of PoF reduced the need for a substantial amount of life data to arrive at a reliability model, since PoF employs the available well-developed knowledge about the process of failure. Such knowledge models how and why the item fails and reduces the need for large quantities of life data.

By the middle of the 1990s, criticism against the application of generic data in general and MH-217, in particular, became increasingly intense, and the basic idea of using failure rate data gathered in such databases was seriously questioned. However, the critics who wanted to abandon the data provided in handbooks for being irrelevant and useless in many applications had difficulties proving that the PoF approach could do any better in reliability predictions. In fact, most of the PoF models strongly depended on life or test data in one way or another. The question was, if there is enough data available to evaluate a PoF-based model, why not use the same data for statistical inference and take the traditional failure rate modelling path again?

To help identify the manner in which reliability predictions are used by reliability practitioners, a survey was issued at the end of the decade, and approximately 60 non-DoD companies responded. From these data, the 3 predominant purposes for performing reliability assessments, in order of importance were reported as:

1. Determining feasibility in achieving a reliability goal or requirement.
2. Aiding in achieving a reliable design, derating, component selection, environmental precautions, input to FMEA and Fault Trees.
3. Predicting warranty costs and maintenance support requirements.

Survey respondents were also asked to identify the methodologies they use when predictions are performed. MH-217 was reported to be by far the most universally applied failure rate prediction methodology, although its updated ceased in 1991.

7 The 2000s

In view of the critics against MH-217 and the need to prove the usefulness of the PoF approaches as mentioned earlier, the reliability community moved towards an integrated use of both approaches. Where the PoF-based approach could save time and money by addressing the root causes of failure and reduce the burden of gathering a substantial amount of data, the traditional statistical failure rates could be useful in probabilistic reliability predictions considering uncertainties involved. However, the uncertainty bounds were often so wide as to make the result almost worthless in decision-making processes. In order to better manage uncertainty and make practical engineering decisions, two factors needed to be considered. The first important element was indeed reliance on more data, for which accelerated life testing, step-stress testing, expert judgment and many different resources were exhausted. The second element, which was considered as important as the first, was an appropriate computational framework that allows new data to be easily added to the analysis. The classical maximum likelihood estimation (MLE) method introduced by Fisher was one of the possible choices.

The MLE method used the likelihood function of the available data for the model parameter estimation. This method provided no means to incorporate prior knowledge available for the model parameters. This method would mathematically collapse when no complete failure data was available. This was almost always the case with new, highly reliable components and systems. The uncertainty bounds provided by the local Fisher information matrix are not useful when dealing with small sample sizes.

In contrast with MLE methods, the Bayesian approach provided many useful features, including a powerful means to incorporate prior knowledge, dealing with the whole distribution of the likelihood function, fair coverage of uncertainties, and finally the possibility of using many different forms of data (exact, censored, fuzzy, partially relevant and expert judgments). Nevertheless, one of the limiting factors of the Bayesian inference methods in practical reliability analysis was the mathematical complexity of the problem.

Multidimensional joint distributions are generally hard to deal with. Later in the 2000s, the numerical and computational advancements in Bayesian statistical methods, such as Markov Chain Monte Carlo (MCMC) simulations and other sampling-based methodologies, combined with advancements in computational tools and development of powerful programming platforms, made the Bayesian inference techniques a common reliable practice.

Employing Bayesian analysis, reliability practitioners combined different types of data, including simple failure rates from traditional handbooks, engineering expert judgments, simulated results of sophisticated PoF models and direct test results, in a hybrid platform. With availability of fast computing, hybrid methodology became widely available and practical. These techniques could rely on the physical and, to a lesser extent, chemical phenomena that drive degradation and failures. Along with small (accelerated) tests and field or expert judgment data, such hybrid models became the source of industry-specific reliability data and analytical models needed to assess the life and safety of highly reliable consumer products and other complex engineering systems in the 2000s.

From the above description of the historical paths of reliability engineering, we can see that the advancement of reliability engineering is driven from US military and the weak reliability of electronics components. Over the decade, reliability engineering has expanded to commercial world outside US and reliability of electronic components are also getting much higher. Today the two primary purposes for performing a quantitative reliability assessment of systems are two folds, namely to

1. assess the capability of the parts and design to operate reliably in a given application;
2. estimate the 'number of field failures' or the 'probability of mission success'.

1945	1945-1950	1952	1953	1960s	1970s	1980s	1990s	2000s
V-1 missile is developed Quantitative measure for reliability is established "Weakest Link" reliability design concept is developed	U.S. Armed Forces Only 30% of the electronic devices are successful in missions Cost of maintenance and repair is 10 times the original cost Dec. 7, 1950 Ad hoc groups are established Reliability engineering for electronics begins	U.S. DOD AGREE (Advisory Group of the Reliability of Electronic Equipment) is formed System RMA is established to meet the government procurement needs RMA requirement specification is standardized	Exponential distribution is popular approach Infant mortalities are screened out to get almost constant failure rate Degradation was not an issue for electronic systems Analyses are simple	Exponential distribution declines in popularity because: It is not practical in many applications It is sensitive to departure from the initial assumptions It leads to high chance of accepting systems with poor mean time to failure Other statistical distributions are used to get more realistic hazard rate	Birth of fault tree analysis is motivated by nuclear safety considerations Monte Carlo methods for finding minimum cut sets are avoided Combinatorial algorithms are developed for analyzing very large fault trees Bayesian approach allows development of new state of knowledge form prior experience	Common cause failure analysis and modeling dependencies are implemented System-level reliability assessment is needed Bayesian statistics become more advanced Accelerated life testing is implemented and facts from real cause of failure is used in statistical models	Physics of failure approach is widespread Facts from root-cause failure processes are used to prevent the failure of the products Robust design approaches are implemented Better manufacturing practices are implemented	The age of hybrid physics-statistics approaches begins Simulations are performed instead or in addition to testing

Fig. 1 History of methods developing in reliability engineering

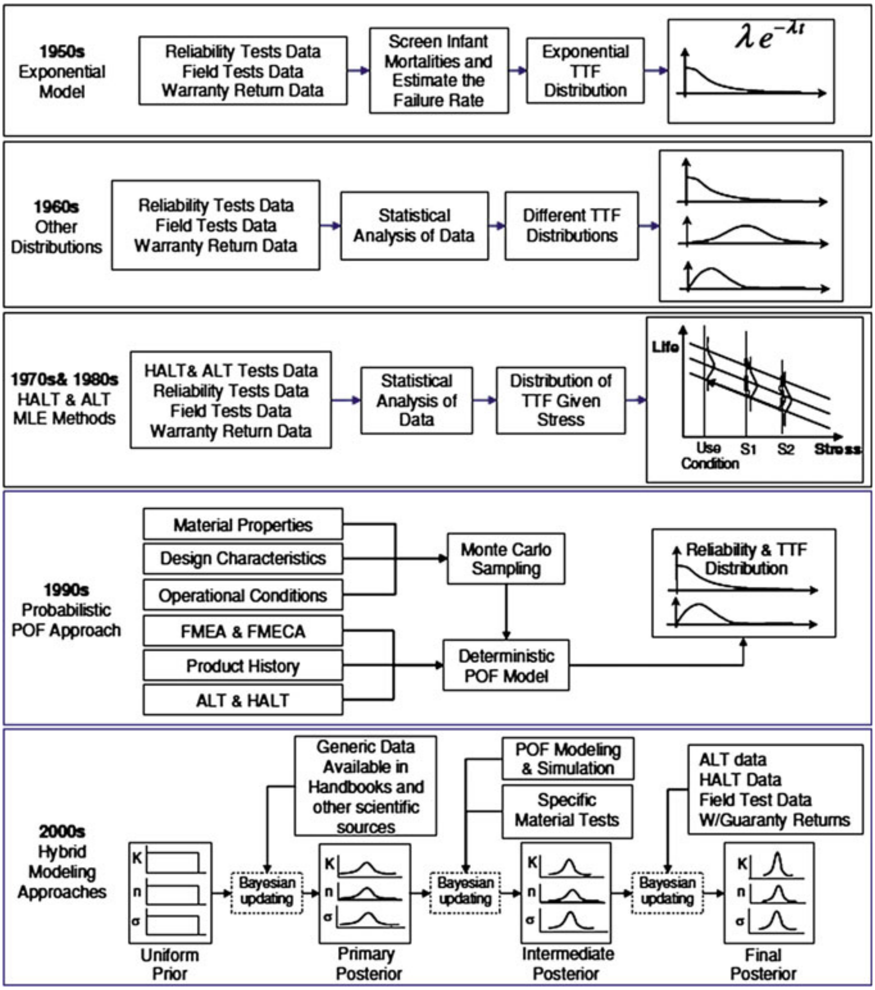

Fig. 2 Emerging PoF modelling approaches in reliability assesments

Purpose #1 does not require statistically based data or models, and physics-of-failure approaches have merit.

Purpose #2, requires empirical data and models derived from those data; this is because field component failures are predominantly caused by component and manufacturing defects which can only be quantified through the statistical analysis of empirical data.

For system acquisition, there is clearly a timeliness element. The prediction must be available early enough to influence the design and/or selection of the design for the system. Yet, the earlier the prediction is needed, the less detailed technical information is available to support the prediction itself. Also, there is a cost/benefit tradeoff that must be considered. Usually, no one is willing to spend more money to define accurately the system reliability than the system itself is worth, and few people are interested in identifying the system reliability after they own it and it is too late to influence its reliability. On the other hand, the emerging of the predictive maintenance in the 2000s used the components' reliability data to predict and schedule future maintenance time is gaining acceptance. Examples of the predictive maintenance can be found in (Tan and Raghavan 2007, 2008; Le and Tan 2013).

Figure 1 summarizes the history of methods in reliability engineering and Fig. 2 illustrates the gradual paradigm shift to applications of PoF modelling methods in reliability assessment of components and systems in the last 50 years.

As shown in Fig. 2, the early reliability models, which were originally developed to address the probability of the occurrence of a failure event, gradually became more complicated to address the real cause of failure. This important change was first realized through statistical representation of the TTF. Applications of other distributions were made by reliability engineers to at least consider some of the real-life characteristics by introducing variable hazard rate models.

The next step was the accelerated life modelling approach, in which the aggregate effect of operational conditions (or stress) was added to the life model to be used as a link between the failure data available in different operational conditions. To introduce a stress agent for an accelerated life model, a complete understanding of the progressing failure mechanisms was needed. The acquisition of this type of knowledge, alongside advancements in materials testing, helped the development of an inclusive library of deterministic PoF models that was later used as a basis for the Monte Carlo-based simulations in probabilistic PoF modelling approaches in the 1990s. A comprehensive description of the progression and status of PoF modelling for integrated circuit interconnections can be found in (Tan 2010).

Those with the view that the deterministic PoF would be sufficient to address reliability and could be used to assure that no failure would occur during the expected life of the item soon realized that there were many uncertainties associated with the PoF models. This forced further testing and data collection and accounting of the associated uncertainties. Generally speaking, the uncertainty of TTF in real data is wider than that predicted by the PoF model. To address this issue, reliability engineers are currently utilizing hybrid approaches within a Bayesian data assessment framework, meaning that a prior TTF distribution is first developed utilizing the PoF model/s; this prior is updated later, using appropriate field or test data to make the final posterior TTF distribution.

The PoF models are deterministic by nature, since they are usually predicting the basic behaviour of the materials in a controlled condition. These models therefore need a separate stochastic process, such as Monte Carlo simulation, to generate the statistical-based probability measures of reliability. Limited computational resources were the other restrictive factor for the further development of PoF modelling approach into the system-level in early stages. However, this constraint was overcome by the overwhelming advancements in personal computers and their truly inexpensive computational power, related operating systems and computational tools. Today, the hybrid physics–statistics approach is the most popular approach for assessing the reliability of components and subsystems. This is mainly because the Bayesian inference data analysis platform allows integration of many different independent sources of knowledge into the reliability assessment. The restrictions in the available system level reliability methods, however, still remain as the main barrier limiting the versatility of the PoF models.

8 Present Status

Since the middle of 2000s, the consumer culture has been dramatically altered from the past few decades. Today, most consumers anticipate shorter product lives, but expect higher dependability of their products. The product is discarded not because it is no longer functional, but rather because it is simply obsolete or because more affordable, newer versions with extra features are available. Consumer tolerance of defective products has also dramatically decreased. Only two decades ago it could take years before consumer reviews could sufficiently damage a product's reputation in the market. Today, however, it can be a matter of only a few days before customer reviews in Internet forums that can isolate a brand name and may lead to financial misfortune for the company. A combination of these factors, plus ever-increasing demand for better after-sale services, has created a very competitive environment and has left a tiny allowable margin for error and negligence.

Today, reliability engineers are asked to develop reliability assessment platforms that are capable of integrating diverse sources of knowledge, from simple field returns to the results of the most sophisticated physics-of-failure and finite-element stress analyses of the component.

From the safety regulation perspective, the diversity of design and alternative safety features, the cost saving requisite of the projects, and environmental concerns have all forced experts to abandon traditional conservative views and adopt new, promising, risk-informed, risk-based and/or performance-based decision-making approaches. This was mostly because even the conservative approaches to design, manufacturing, and operation could not eliminate the possibility of accidents. The risk assessment techniques that were originally developed to support conservatism in design, construction, manufacturing, and operation were increasingly used to develop comprehensive probabilistic risk assessment models to support critical decisions about the alternatives.

Traditional reliability methods and concepts should be revised in order to address the fast-growing demand for highly reliable and quickly evolving engineering systems, structures, and components. Traditional reliability assessment techniques have long been criticized for their shortfalls. The popular constant hazard rate failure model is not practical in many applications and is sensitive to departure from the initial assumptions and has also been obsoleted.

Technologies are evolving at a pace much faster than the time needed to generate enough field data or to perform a large amount of reliability tests economically. This poses challenges to reliability prediction and assessment.

While reliability engineering has been advancing significantly in the US over the decades, its progress in Asia is unfortunately lagging behind. In this last part of the Chapter, let me share my personal experiences in my industrial involvement in reliability activities, as reliability engineer in the 1980s and later as industrial consultant and trainer on reliability engineering in Singapore and Taiwan. Although it is not exhaustive, it is typical in Asia.

9 Reliability Engineering in Asia

Many US electronics companies set up their manufacturing plants in Taiwan and Singapore in the late 1970s. Following their practices to ensure reliability, all these manufacturing plants in Asia had to go through qualification before they were allowed to mass produced. However, design and development were not transferred over to Asia, and thus the reliability activities that these manufacturers seen were Reliability qualification and periodic reliability monitoring.

With the introduction of the concept of QML in the 1980s as mentioned earlier, the suppliers in Singapore and Taiwan were also needed to be qualified, and hence reliability qualification concept was extended to other manufacturers in Asia. As qualification tests are designed with no failure, and the computation of the product reliability was based on exponential distribution in the 1980s, the reliability knowledge for the engineers then were limited to zero failure represents good reliability and the formulae for reliability computation were those derived based on exponential distribution.

As reliability training is seriously lacking in Asia, and the trainers are mostly from industrial where they were involved in reliability in the early days, the reliability knowledge that passed down to the new engineers are again limited to the case of zero failure and exponential distribution, even up to 2000s. This is also partly due to the fact that present days reliability engineering has been evolved to become mathematically intensive, and engineers in industrial tend to avoid mathematics in Asia. Hence, many are still stick to MH-217 for reliability evaluation/prediction, without knowing that MH-217 has no longer been updated after 1990s. In fact, in some cases, companies are using the quality concept such as LTPD and Mil-Std 105 to evaluate product reliability. In a book chapter written by me, I listed 10 misconceptions in reliability that are found to be common in Asia, they are (Tan 2009):

1. High MTTF represents good reliability
2. Zero failure is better than having failures in reliability test.
3. Exponential distribution is all that I need for the analysis of test data
4. All test data are valid

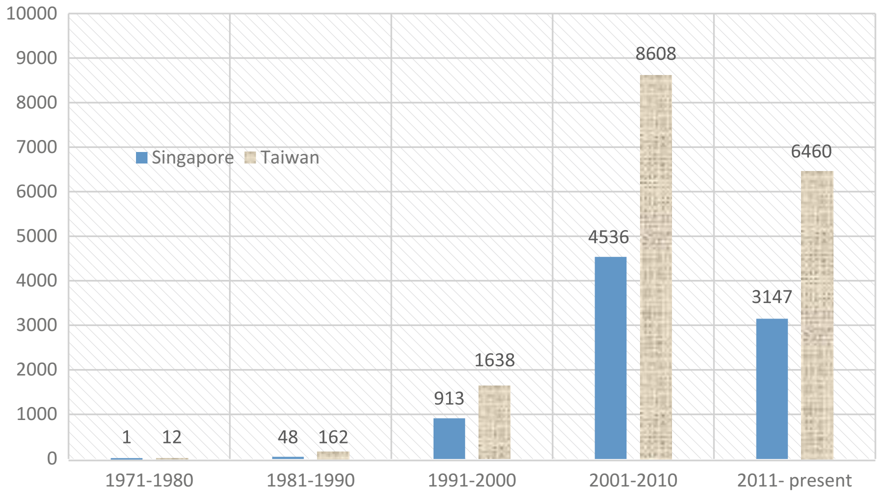

Fig. 3 Number of reliability related papers contributed from Singapore and Taiwan over the various decades. The *y*-axis represents the number of papers, and the actual number of papers are on *top of the bars*. The *x*-axis represents the various decades

5. There is only one failure mechanism in the failure data
6. Select the right suppliers through accelerated stress test.
7. To save time in reliability, simply increase the stress level.
8. Mil-Std handbook provides the basis for calculation

On the other hand, with the advancement in technology in Asia in the late 1990s, and the fact that manufacturers in Asia need to troubleshoot their low yield and customer field returns as part of their responsibilities, the knowledge of physics of failure is improving, and thus the reliability branch on PoF is progressing well in Asia.

With the evidence of good technical competency in Asia countries, such as Singapore and Taiwan, US companies are also shifting their R&D activities to these countries for cost reduction as well as to have their development activities close to their manufacturing sites and markets in Asia. This shift of R&D to Asia surface out the inadequate reliability knowledge needed for R&D activities.

On the other hand, universities in Asia are performing research in reliability engineering, both in the PoF as well as statistical approaches. Figure 3 shows the trend of Journal and conference papers on reliability engineering from Singapore and Taiwan since 1990. The research works done in universities are generally so much more advanced that engineers from industrials are either not able to understand the works or to apply the works in their workplaces. The gap in the reliability engineering knowledge between academic and industrial is large in Asia, and at the same time, reliability engineering training is scare even till now. There is no specialization on reliability engineering in almost all the universities in Asia.

To meet the need on reliability engineering evaluations for industry as more R&D activities are moving to Asia, various non-academic institutions in Asia are offering basic reliability training, where again the use of MH-217 and exponential distribution for reliability computation are taught. Some national institutes are offering certified reliability engineers program in order to meet the need. However, from the feedback of the trained engineers, they are not able to put what they have learnt into practice as their managements still holding the early concept of zero failure imply good reliability and the use of closed form formulae derived based on exponential distribution of time to failure for estimation of their product reliability. Management in Asia also tends to be put cost far above product reliability. On the other hand, as reliability is not being designed in the product and process during the R&D activities, products designed and manufactured in Asia tends to have poorer reliability as people feel generally. Of course, many exceptions are present in Asia also.

Due to the increasing need for reliability, reliability testing activities are getting popular. However, most of the testing laboratories simply perform the reliability tests according to the instruction from the clients or international standards, and no analysis of the failure and data are being done due to the complexity natures of the needed analyses.

While the industrial is still struggle with the basic reliability engineering in Asia, the complexities of current products and technologies present need new challenges in reliability engineering that require more research in it.

In summary, there is a need for the senior management in Asia to have a paradigm shift in their understanding of reliability, and I am seeing a promising change as I delivered several talks for industrial in several countries in Asia. Specialization in reliability engineering should also be provided in universities, and if not, by private institutions. But this is possible only if there are good markets for the trainees, and this again depends on the senior management. Unlike in US where an engineer can be a reliability engineer provided he or she has passed his or her certified reliability engineer program, this is not practice in Asia. Industrial should work with Universities to address the need for reliability knowledge for their engineers and to address the challenges in their product and process reliability.

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