Chapter 1: Introduction

B. Stark and W. C. Tang

This chapter offers a brief description of the MEMS industry as it stands today. Assuming no familiarity with the subject matter, it explains the basic concepts behind MEMS and how they are being applied to meet current technological challenges in different markets. This chapter also describes the basic methodology that will be applied throughout this book towards qualifying a high-reliability MEMS device.

I. A Brief Description of MEMS

MEMS is an acronym that stands for microelectromechanical systems. It is a broad term that encompasses a fairly nebulous group of products. Essentially, MEMS are any product, ranging in size from a micron to a centimeter, that combines mechanical and electrical structures. Although the possible scope of MEMS is fairly limitless, for the sake of conventions and the need for brevity, this book will only address the more common MEMS technologies.

Initially MEMS developed from technologies used in the semiconductor industry for the production of electronic circuits. Less than 10 years after the invention of the integrated circuit, H. C. Nathanson used microelectronic fabrication techniques to make the world's first micromechanical device.[2] By the early 1980s, due to massive improvements in processing technologies, micromechanical devices grew in popularity. In the ensuing years, a new industry was born, where electromechanical systems could be realized on micrometer scales. The result was a whole new class of sensors and actuators that performed common tasks on smaller scales that were ideally suited for mass production.

MEMS, in its most conventional sense, refers to a class of batch-fabricated devices that utilize both mechanical and electrical components to simulate macroscopic devices on a microscopic scale. This guideline focuses upon the conventional definition of MEMS. The essence of MEMS is that they are small devices that perform mechanical tasks in ways and, more importantly, in quantities that conventional devices cannot.

II. The Potential of MEMS

In the wake of the explosion of the microprocessor in the early eighties, the semiconductor industry revealed its immutable law that smaller is better. With economies of scale turning tiny firms into industrial behemoths, it became evident that mass miniaturization, along with mass distribution, could produce huge revenues and substantively change the daily lives of average citizens. Given the unmitigated success of the microcircuit, it became only a matter of time before technologies would emerge that could bring machines to the microscopic world and produce similar results. With MEMS poised to do for machines what the transistor did for computers, there has been a vast explosion of interest, and thus funding, in MEMS research.

MEMS are used to perform the tasks of macroscopic devices at a fraction of the cost and with, occasionally, improved functionality and performance. By using simple mechanical structures and tailoring integrated circuits to suit specific tasks, designers have seen a drastic reduction in device scales and the implementations of functions that were previously unrealized. Their size alone makes them attractive for limited mass applications, with the automotive, biomedical, communications, data storage, and aerospace industries taking a keen interest in MEMS developments. Far more promising, though, is the possible reduction in costs offered by MEMS. By combining increasing throughput with fixed cost structures, manufacturers can linearly reduce prices by a comparable production increase. Offering economies unique to the semiconductor industry, MEMS have the potential to revolutionize the industrial age.

The effects of MEMS could enact sweeping reforms within the space industry. NASA hopes to eventually phase out the large satellites that it employs to reach the farthest points in the solar system. With every kilogram sent to Mars costing upwards of one million dollars, the potential of sending a fully integrated spacecraft weighing a few

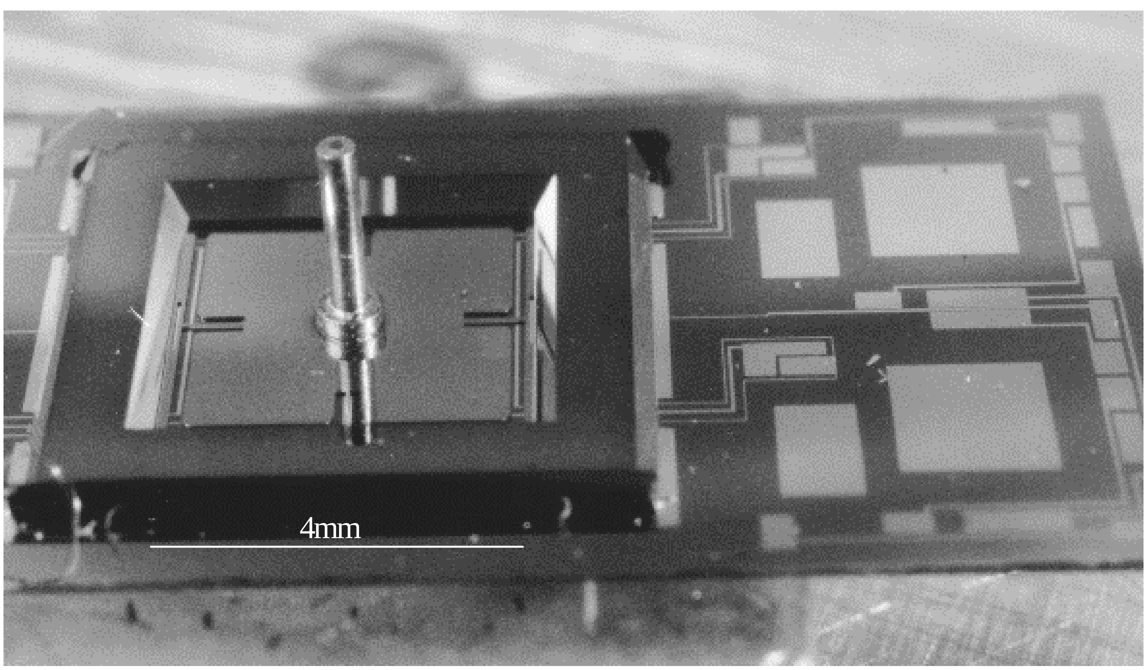

Figure 1-1: A partially packaged microgyroscope developed at JPL.

kilograms instead of the thousands of kilos offers significant monetary benefits. With MEMS capable of performing certain functions of macroscopic devices, the benefit of cutting the cost of research missions cannot be understated given this era of shrinking budgets. Space applications of MEMS are only a small part of their full potential. MEMS are also capable of revolutionizing the information age by changing the daily fabric of our terrestrial existence.

III. Current MEMS Technologies

Understanding the stated advantages of MEMS, designers have started developing a range of products to suit their needs. The first major MEMS to hit markets were pressure sensors for engine control in cars. This development was followed by the introduction of microaccelerometers, which were pioneered to provide zero-fault air bag deployment systems. Integrating a diagnostic circuit into a sensor, engineers were able to produce a device that could not only sense acceleration but that could also detect internal failures. Replacing a faulty system based on ball bearings and plastic tubing that was prone to misfire, these devices swept through the automotive industry. Building from the technological, as well as commercial, success of these initial designs, engineers have developed MEMS to act as a wide variety of motion sensors. Recently intense research has been conducted into producing microgyroscopes as part of a fully integrated inertial reference unit. Development has also commenced, seismometers, anemometers, temperature sensors, pressure sensors, and hygrometers which, when incorporated with accelerometers, could provide miniaturized weather stations.

MEMS have also shown promise for aerospace applications. Research into magnetometers shows that it may be possible to build devices that far outperform traditional solid-state sensors, which could provide cost saving reductions in the weight of spacecraft. Furthermore, the bulky propulsion systems in modern satellites will be phased out by advances in micropropulsion coming from new generations of ion drives and microthrusters. Recent developments at universities have shown that MEMS microactuators, when placed upon the leading edge of aircraft, can offer significant drag reduction and thus increase fuel efficiency.[182] Some even more interesting research has led to the design of a MEMS controlled aircraft, where control surfaces are replaced by micromachines, which could offer unprecedented control and diagnostic capabilities.

One of the more promising fields within MEMS is the concept of optical MEMS. Using micromirrors placed on top of memory arrays, researchers have developed a television projection unit on a semiconductor wafer that has all the functionality of a cathode ray tube.[3] Another promising development is in the field of optical switches. Conventional optical switching networks are costly and, with the forecasted growth in optical communications systems, cheaper alternatives are at a premium. Multiple groups have developed MEMS-based optical switches that can be produced at a fraction of the cost of conventional systems.

With the digital age largely upon the American public, MEMS are poised to offer greater improvements in computer technology. Given that power dissipation of the average microprocessor increases with every generation of microchip, microtubules research has been initiated to attempt to find better ways to conduct heat away from integrated circuits. MEMS structures have also been developed as microprobes for integrated circuits.[10] Using MEMS, it may be possible to take point contact voltage and current measurements on microprocessors. Another exciting development has been the pioneering of nanometer scale data storage. With miniaturized tunneling tips now possible, engineers have developed systems that could eventually store information at commercially competitive speeds in an area twenty nanometers on a side.

Another field that shows promise is the development of biological sensors. MEMS provides an opportunity for the development of new sensors to monitor the human environment. Researchers at JPL have begun to develop MEMS-based pills that can provide information about the digestive system. Another interesting application of MEMS has been in the development of new biological instruments. Researchers have, among other developments, produced probes to measure the strength of the human heart cell.[183]

While the potentials of MEMS are almost limitless, production of commercial parts has been heretofore limited. MEMS, as products of a young industry, remain largely prototypical. While their potential have been demonstrated their actual implementation has been relatively scarce, with commercial successes still the exception rather than the rule. In order for this rapid growth to be realized, the field of MEMS reliability will need to rapidly mature.

IV. The Need for, and Role of, MEMS Reliability

With MEMS still in their infancy, the question has been posed as to the need for reliability issues in MEMS. The goal of this book is not just to provide reliability information for the current designers but to set the standard for reliability in MEMS for the foreseeable future. Given the almost unstoppable commercialization of MEMS, reliability issues that have previously been ignored are destined to become of paramount importance. Researchers at NASA feel that these issues must be raised in unison with the development of MEMS in order to assure their rapid insertion into industrial and space applications. Understanding the future of the MEMS industry, it would be shortsighted to ignore the importance of reliability.

In confronting the issues of MEMS reliability assurance, users will certainly have different requirements and this book could not hope to address them all. Undoubtedly a Martian probe will have a different set of requirements and specifications than a communications satellite, but there will be similar methodologies for assessing qualification for both. This book is designed to utilize basic similarities in design requirements to provide a means of developing high-reliability MEMS parts. In order to produce a high reliability, or high-rel, part one must not only examine the device itself, but one must also examine the entire process surrounding the part, from conception to finish. This means that the process must be qualified, with the supplier fully investigated, the design verified, and the packaging certified. This book lays out the methods to perform this task in an efficient manner that ensures the development of a high reliability part without enforcing cumbersome specifications.

V. Additional Reading

Helvajian, H. ed. Microengineering Technology for Space Systems, The Aerospace Corporation Report Number ATR-95(8168)-2, El Segundo, CA (September 30, 1995).

O'Rourke, L. Space Applications For Micro & Nano-technologies, European Space Agency, Noordwijk, The Netherlands (April 1997).

Chapter 2: Reliability Overview

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Reliability is understood in modern times as the probability that an item will perform its required task for a set amount of time. Reliability is ultimately a measure of the rate at which things fail and can be used to make intelligent predictions about the performance of a system. If the assumption is made that a system is operating at time t = 0, and a time T is defined as the time to failure, then it is possible to define the complementary failure and reliability rates as:

$$F(t) \equiv P\{T \leq t\} \tag{2-1a}$$

$$R(T) \equiv P\{T > t\} = 1 - F(t) \tag{2-1b}$$

where

P{a} = The probability that the event 'a' will occur

F(t) = The probability that a system fails in [0,t]

R(t) = The probability that a system survives until time t

From probability theory, it is known that F(t) and R(t) are non-negative and that F(0) = 0 and F(∞) = 1, since all parts will eventually fail. A good measure of reliability in the interval (t,t+Δt] is the probability that a system does not fail in the internal (t,t+Δt], given that it has not failed by time t, which is written as:

$$P\{T \notin (\mathrm{t}, \mathrm{t} + \Delta t] \mid T > t\} \tag{2-2}$$

this quantity is known as the conditional reliability of a system of age t, represented by the expression R(Δt|t) and is related to R(t) by Equation 2-3.

$$R(\Delta t \mid t) = \frac{R(\mathrm{t} + \Delta t)}{\mathrm{R(t)}} \tag{2-3}$$

It should be apparent that R(Δt|0)=R(Δt), since R(0)≡1, as defined earlier.

I. Reliability Measures

The main challenge of reliability analysis is to quantify a system's reliability. This can be done in a number of ways by utilizing some important probability principles. When data from a reliability test is first collected, it is plotted as failure versus time. This plot is usually smoothed by fitting the reliability data to established reliability models, which are discussed later in the chapter. After this is done, the probability density function, or pdf, is determined.

A. Probability Density Function

The measure of the probability of failure around a point in time, t, is represented by the probability density function of T:

$$f(t) \equiv \frac{dF(t)}{dt} = \lim_{\Delta t \to 0} \frac{F(t+\Delta t) - F(t)}{\Delta t} \tag{2-4}$$

f(t) is, for a small Δt, approximately equal to the probability of failure in the time interval [t,t+Δt]. Once f(t) is found by whatever approximation is made for the failure function, one can determine the failure rate, which is the same as the reliability rate.

B. Failure Rate

The instantaneous failure rate is defined as:

$$l(t) \equiv \lim_{\Delta t \to 0} \frac{P\{t < T \le t + \Delta t \mid T > t\}}{\Delta t} \tag{2-5a}$$

which can be rewritten as:

$$l(t) = \lim_{\Delta t \to 0} \frac{P\{t < T \le t + \Delta t\}}{\Delta t P\{T > t\}} \Rightarrow \tag{2-5b}$$

$$l(t) = \frac{1}{R(t)} \lim_{\Delta t \to 0} \frac{F(t+\Delta t) - F(t)}{\Delta t} = \frac{f(t)}{R(t)} \tag{2-5c}$$

Since λ(t) = f(t)/R(t), it is also possible to define λ(t) by:

$$l(t) = -\frac{1}{R(t)} \frac{dR(t)}{dt} \Rightarrow \tag{2-6a}$$

$$l(t) = -\frac{d}{dt}\left(\ln R(t)\right) \tag{2-6b}$$

This can be rearranged to give:

$$\ln(R(t)) - \ln(R(0)) = -\int_0^t \lambda(T)\,dT \qquad (2\text{-}6c)$$

Thus, given that R(0) = 1, it is possible to determine R(t) as a function of λ as:

$$R(t) = e^{-\int_0^t \lambda(T)\,dT} \qquad (2\text{-}7)$$

So, if λ is constant for a period of time, the reliability function is:

$$R(t) = e^{-\lambda t} \qquad (2\text{-}8)$$

which is the exponential model of reliability. However, for most systems, the failure rate is not constant with time. In fact, the change of λ with time becomes one of the most important reliability measures. A decreasing λ indicates improvement with time, while an increasing λ indicates wear-out and a reduction in reliability over time.

C. The Bathtub Curve

By looking at a plot of failure rate over time, it is possible to derive substantive information about reliability. From experience in the semiconductor industry, it has been shown that most devices, including MEMS,[50] have a failure rate λ(t) that is shown in Figure 2-1. This model is known as the bathtub curve and was initially developed to model the failure rates of mechanical equipment, but has since been adopted by the semiconductor industry.

The bathtub curve can be reduced to three regions of reliability. The failure rate of a successful part is initially high and falls off as latent defects cause devices to fail until a time, t_{infant}, at which point the failure rate levels off. A decreasing failure rate will typically justify initial testing and burn-in. The failure rate remains constant for a period of time specified as the useful life, t_{useful}. Failures that occur during this period of time may be considered random and, for high-rel operations, λ should be exceedingly small. Finally, after $t_{operation}$, devices begin to exceed their lifetimes and wear-out causes the curve to rapidly increase. From this data it is evident that t_{useful} can be defined as:

$$t_{useful} = t_{operation} - t_{infant} \qquad (2\text{-}9)$$

As indicated by the bathtub curve, manufacturers aim for the failure rate to remain fairly constant over t_{useful}, which justifies using the exponential reliability model for each part to be used in system reliability models. The time scale is often plotted logarithmically, although the

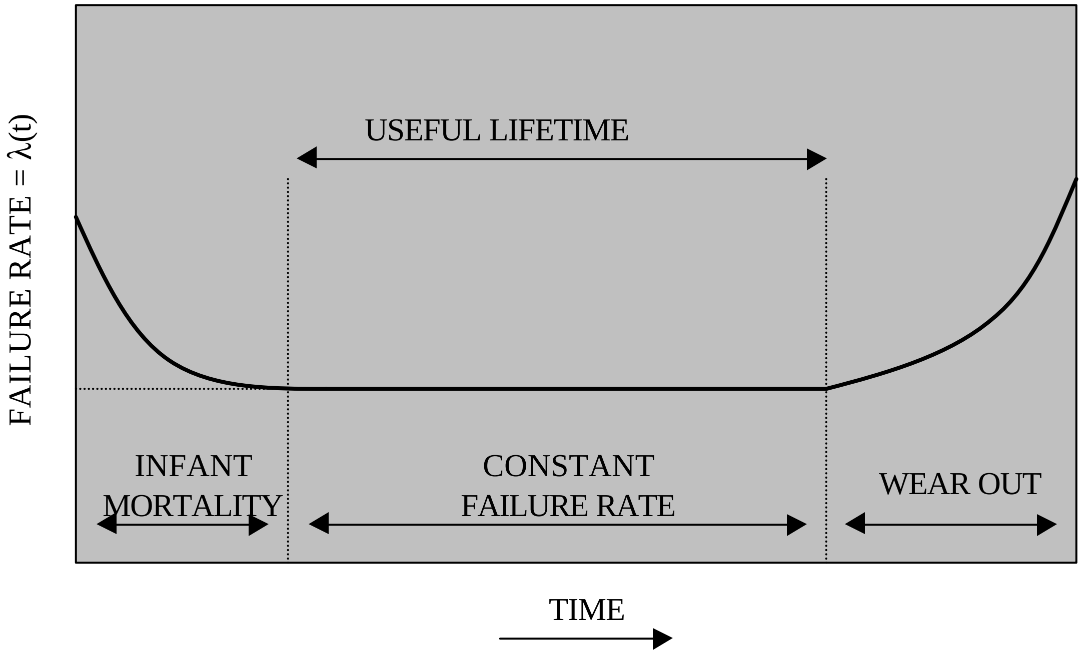

Figure 2-1: The Bathtub curve.

values of t_{useful} and t_{infant} are rarely well defined. Consequently, every manufacturer has its own specific test and burn-in procedure to maximize the reliability of each product.

D. Predicting Time to Failure

Sometimes it is desirable to discuss the average time to failure instead of the probability of failure. This value, called the mean time to failure (MTTF) is defined as:

$$MTTF \equiv \int_0^\infty t f(t) dt \tag{2-10a}$$

It is also possible to prove[108] that the MTTF equals

$$MTTF = \int_0^\infty R(t) dt \tag{2-10b}$$

Once a device is operational, a more useful value is the mean residual life, or MRL. This quantity is derivable as:

$$MRL(t) = \frac{1}{R(t)} \int_t^\infty R(T) dT \tag{2-11}$$

It should be noted that MRL(0) = MTTF.

E. Failure Rate Units

Since, for most systems, $\lambda(t)$ is a small quantity, special units are used to describe reliability. The failure rate is given as the number of units failing per unit time. In common operation, this number, when expressed as the number of devices failing per unit time, K, is a fraction of a percent. To make this function more useful, the values are scaled to a more meaningful time frame. Thus $\lambda(t)$ is expressed as tenths of a percent of devices failing per 1×10^6 hours or as the total number of devices failing in 1×10^9 hours. This latter quantity is known as the failure in time, or FIT, and is the common unit of reliability defined as:

$$1 \text{ FIT} = \frac{1 \text{ failure}}{1\times10^9 \text{ device hours}} \tag{2-12}$$

A FIT is an approximate rate measure over the useful life of a part, assuming a constant failure rate, given the bathtub curve model, the FIT rate = $\lambda/10^9$, where λ is the constant failure rate shown in Figure 2-1.

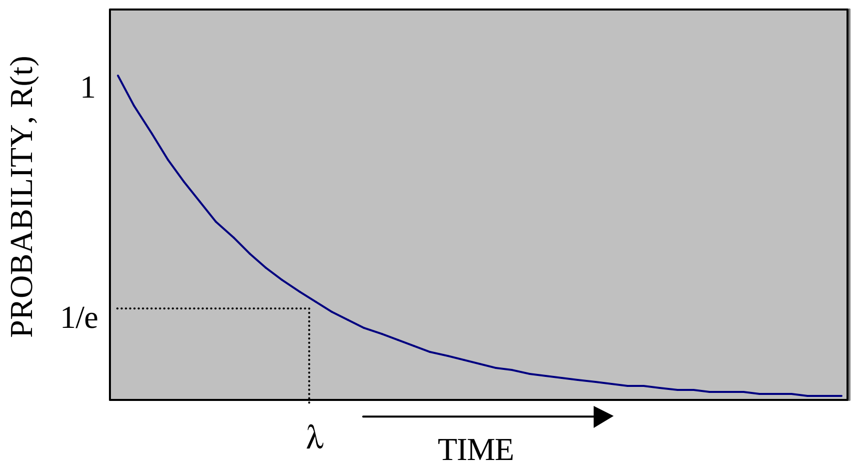

Figure 2-2: Probability of survival to time t.

II. Probability Models

Several standard probability models are often used to model failure of systems.

A. The Uniform Distribution

The uniform model is the most common probability model used to predict the lifetime of systems. For a system with multiple components with distinct MTTF and λs, it is often only possible to model the entire system as having a combined failure rate λ_c, Assuming that the failure rate of a single component will constitute a total failure, then it is possible to directly determine λ_c by:

$$R(t) = \prod_{i=1}^{n} R_i(t) = e^{-l_1 t} e^{-l_2 t} \ldots = e^{-\left(\sum_{i=1}^{n} l_i\right)t} \Rightarrow \tag{2-13a}$$

$$l_c = \sum_{i=1}^{n} l_i \tag{2-13b}$$

where λ_i = failure rate of the *i*th component of a system. A system that has any redundancy or error tolerance will be more difficult to model in detail, but generally, a series system will have a reliability determined by Equations 2-13. The pdf of this model is:

$$f(t) = l_c e^{-l_c t} \tag{2-14}$$

which is shown in Figure 2-2. This model is often the only available predictor of reliability for multi-component systems.

B. The Weibull Distribution

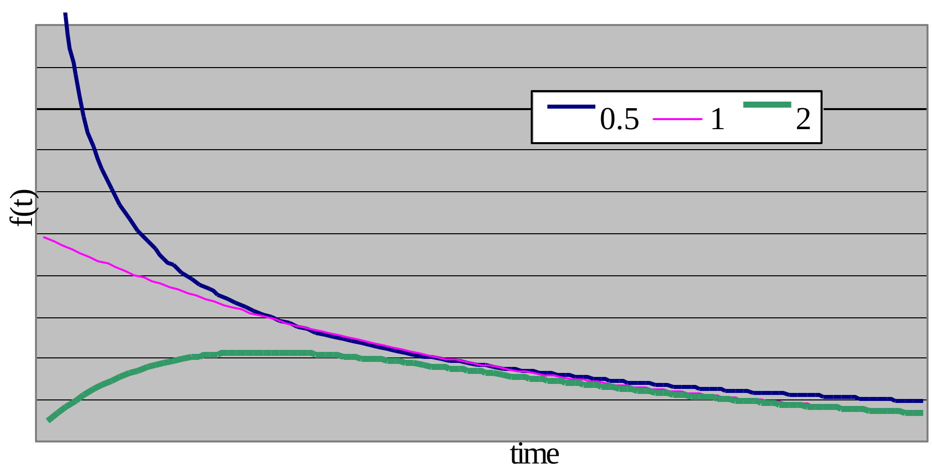

Figure 2-3: The pdf of the Weibull function with different b values.

In a system composed of n components, the probability of the first component failing is determined by:

$$F(t) = \prod_{i=1}^{n} F_i(t) \qquad (2\text{-}15a)$$

where F_i is the probability of failure of the *i*th component. For systems where all components exhibit uniform failure rates, the probability of failure of the system can be expressed as:

$$F(t) = \left(1 - e^{-\lambda t}\right)^n \qquad (2\text{-}15b)$$

This model is called the Weibull model. It is conventionally written as:

$$f(t) = \alpha^{\beta} \beta t^{\beta-1} e^{-(\alpha t)^{\beta}} \text{ and } \lambda(t) = \alpha^{\beta} \beta t^{\beta-1} \qquad (2\text{-}16)$$

where

α = the scale parameter

β = the shape parameter

The shape parameter enables the Weibull distribution to model multiple aging trends:

- If $0 < \beta < 1$, then $\lambda(t)$ is decreasing with time
- If $\beta = 1$ then $\lambda(t)$ is constant ➔ the exponential model
- If $1 < \beta < \infty$ then $\lambda(t)$ is increasing with time.

For the Weibull distribution, the MTTF is given as:

$$MTTF = \frac{1}{\alpha}\Gamma\left(1 + \frac{1}{\beta}\right) \qquad (2\text{-}17)$$

where Γ is the gamma function, which is defined as:

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt \text{ for } x>0 \qquad (2\text{-}18)$$

C. The Normal Distribution

Physical data often fits a Normal, or Gaussian, distribution. This distribution is derived from the central limit theorem, which states that the distribution of a large number of random values usually results in a normal distribution, no matter what their individual distributions were.

The normal distribution is expressed by the equation:

(2-19)

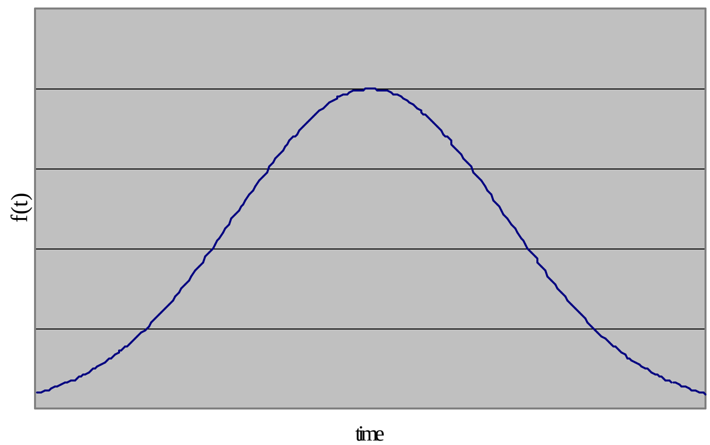

Figure 2-4: pdf of the normal distribution.

$$f(t) = \frac{1}{s\sqrt{2p}} e^{-\left(\frac{t-t_0}{2s}\right)^2}$$

where

σ = the standard deviation

t_0 = the MTTF

For this model, F(t) and R(t) are given by the respective error and complimentary error functions, Φ and 1-Φ. This function is usually approximated by

$$\Phi(z) = \frac{1}{\sqrt{2p}} e^{-\frac{z^2}{2}} \qquad (2\text{-}20)$$

D. The Lognormal Distribution

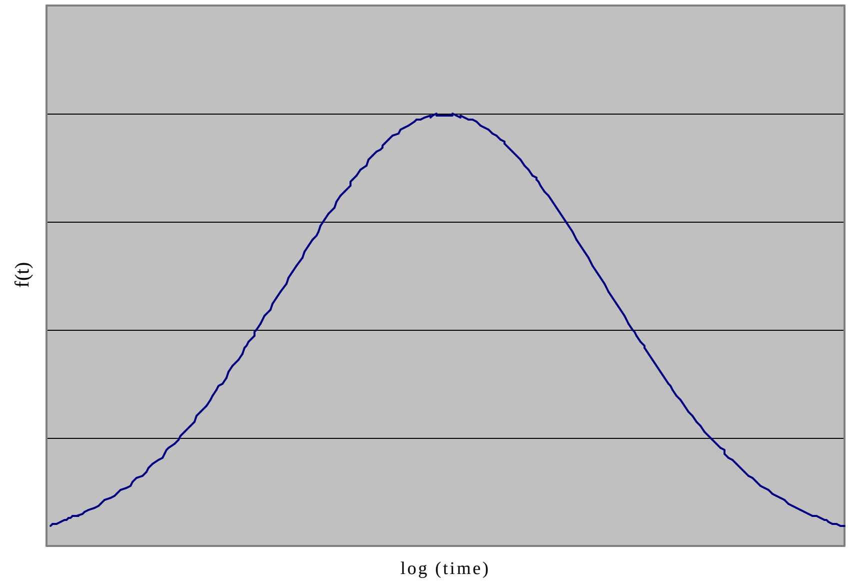

Figure 2-5: pdf of the lognormal distribution.

The logarithm of many failure times are found to be normally distributed in what has been termed a lognormal distribution. The physical justification for the lognormal model is that thermally activated systems will have a failure rate that is determined by the Arrhenius relation:

$$MTTF\ (T) = t_0 e^{-\left(\frac{E_a}{kT}\right)} \tag{2-21}$$

where:

E_a = the activation energy

k = Boltzmann constant (8.6×10^{-5} eV/K)

If the activation energy, E_a, is normally distributed in energy:

$$p(E) = \frac{1}{s\sqrt{2p}} e^{-\frac{(E-E_{a0})^2}{s^2}}, \tag{2-22}$$

then the failure rate will have the form:

$$f(t) = \frac{1}{ts\sqrt{2p}} e^{-\left(\frac{\ln(t-t_0)}{\sqrt{2}s}\right)^2} \tag{2-23}$$

For this model, F(t) is given by

$$\Phi\left(\frac{\ln\left(t-t_0\right)}{s}\right)$$

III. Application of Reliability Models

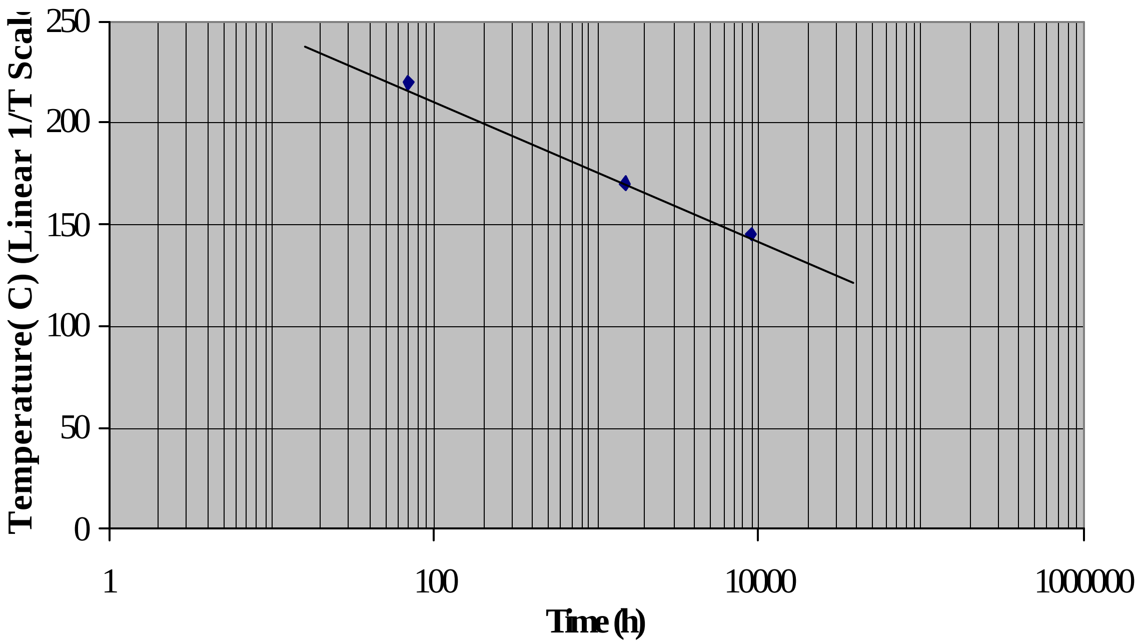

Figure 2-6: An example of using the lognormal distribution to predict lifetime in ICs. Each data point represents a life test and the line provides lifetime data at any given temperature.

While the above models offer a good basis for describing reliability, they must be accurately utilized to predict lifetime data. The simplest way to measure reliability is to submit a large number of samples to testing under normal operating conditions until failure occurs. However, since most high-rel applications utilize devices with lifetimes of several years, this approach is often too costly and time-consuming for most applications. Instead, devices are operated under accelerated conditions for a shorter period of time until failures occur and then, using probability theory, actual device lifetime is reconstructed.

While this kind of testing is relatively simple for purely electrical systems, it is significantly more difficult for MEMS, or for any mechanical system. Since failure mechanisms are not well understood, there is no simple test to accelerate lifetime. To further compound matters, the vast difference in types of MEMS devices means that each set of devices may require unique acceleration conditions. These kinds of difficulties are not encountered in purely electrical systems because lifetime is determined almost exclusively by the rate of thermally activated processes. These interactions are easy to accelerate by increasing temperature. In MEMS, on the other hand, it may be temperature, humidity, vibration, or a number of other factors that limit device lifetime, and accelerating one failure mode may decelerate another.

Once life-test data is collected, it can be modeled with one of the above probability distributions. Take, for example, data that fits a lognormal distribution. This can be determined by plotting the data on a lognormal graph. If the life-test data fits into a straight line, then the data fits into a lognormal distribution. The intersection of this straight line with 50% cumulative failure indicates the MTTF.

To accurately predict lifetime at any operating conditions, at least three distinct high stress tests must be performed. The median lifetime from each of the three tests is then transferred onto a lognormal plot and fit with a line. Median life at any operating condition can then be determined.

In a world with limitless resources and time, lifetime test would be conducted with nearly infinite sample sizes. Since this is a practical impossibility, the size of the sample must be considered in determining the confidence in lifetime predictions. Confidence is expressed in terms of a percentage, where a confidence value says that for a given percentage of the time, a test would yield a result within the two limits of the test. Thus an upper and lower confidence of 90% on respective lifetimes of two and four years means that nine out of every ten tests would predict a lifetime between two and four years. The following equations yield confidence limits:[118]

$$\text{upper limit} = \mathrm{T}_{test} \times e^{(t(df,\, alpha)\times s/N)} \tag{2-24a}$$

$$\text{lower limit} = \mathrm{T}_{test} \times e^{(-t(df,\, alpha)\times s/N)} \tag{2-24b}$$

where

σ^2 = the standard deviation in the data

T_{test} = median life at test temperature

$t(df, alpha)$ = value from the Students' *t* distribution (see ref. [118] for more detail on this subject)

df = degrees of freedom (N-1)

alpha = (1% confidence) / 2

N = sample size

Due to the variability of test data, it should be apparent that an understanding of failure mechanisms within MEMS is critical to determining device lifetime. This kind of information can only be determined from further research into MEMS reliability. As stated above, the diversity of MEMS technologies on the market almost necessitates an individualized approach to a statistical lifetime study. One of the great obstacles to space qualifying MEMS is the individuality of the devices. MEMS manufacturers do not have the luxury of ASIC and MMIC designers, who can use a great deal of prior work and knowledge in space qualifying their products. Despite these obstacles, it is inevitable that MEMS will eventually work their way into high-rel applications and this methodology will provide the means for realizing that goal.

IV. Failure

While this chapter has devoted a lot of time to quantifying reliability, it has not discussed the roots of reliability, namely failure. The time dependence of reliability, R, and failure, F, are complimentary, so the rates are both equal to the failure rate, λ. In order to accurately study MEMS reliability, the nature of failures must be quantified. Failure may be separated into two distinct categories:

(1) Degradation failure, which consists of device operation departing far enough from normal conditions that the component can no longer be trusted for reliable operation

(2) Catastrophic failures, which are, as the name implies, the complete end of device operation.

Failures occur when the stresses on a device exceed its strength. While the most prevalent failure mechanisms in MEMS are not yet fully understood, there is a great deal of knowledge about failure mechanisms within more common semiconductor devices, which should have a bearing upon failure within MEMS.

In order for a device to be classified as high-rel, it must meet some basic criteria. The most significant of these is that a device cannot exhibit a dominant failure mechanism. This ensures that there is no inherent design flaw that prohibits long-term reliable device operation. In order to make this assessment, the failure mechanisms with a device must be understood.[109]

The identification and mitigation of failure mechanisms in MEMS is both one of the most important and one of the newest issues in MEMS. The most relevant way to keep abreast of the failure mechanisms within MEMS is to search the current literature, as data contained within this manual is almost sure to be revised after publication. With this in mind, Chapter 3, “Failure

Modes and Mechanisms" provides a description of the most commonly observed failure mechanisms and associated failure modes in MEMS.

V. Additional Reading

E. A. Amerasekera and F. N. Najm, Failure Mechanisms in Semiconductor Devices: Second Edition, John Wiley & Sons, New York, 1997.

C. C. Montgomery and G. C. Runger, Applied Statistics and Probability for Engineers, John Wiley & Sons: New York, 1994.