# LIFETIME PREDICTION OF TRANSISTORS: EFFECTS OF TEMPERATURE AND WATER

by

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*To my parents*

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# ABSTRACT

Accelerated life testing (ALT) is commonly used to obtain the reliability (lifetime) of a system in a short period by applying severe stress factors (i.e. temperature, humidity, chemical etc.,) to the system. Accelerated life testing was done on 2N3904 N-P-N bipolar junction transistor. After accelerated life testing, the acceleration factor is calculated through statistical analysis to predict the lifetime of a system at a certain operating condition. Multiple temperature and water-immersed experiments were conducted on transistors at various temperatures. With the obtained results, analysis was done on the data to predict lifetime of transistors at different environmental conditions. Effects of the environmental conditions on the transistors were also discussed. Corrosion effects on transistors were studied. ALTA software is used to analyze the experimental data and to calculate the lifetime of the transistors. From the obtained failure data prediction of mean time to failure at various temperatures was done.

# 1. INTRODUCTION

## 1.1 Literature Review

The ability to predict the aging effects in an electronic component can prevent serious problems in operation that can often lead to lost productivity, process failure, economic hardship, and even loss of life. Determining the aging of an electronic device is still not thoroughly understood. A combination of experimental procedures and simulations would result in a better understanding of the performance of the electronic components and help predict their output variables at different conditions and ultimately their lifetimes [1].

Scientists have been conducting experiments to determine the life span/reliability of materials, components, and devices for years. Accelerated life testing (ALT) is a commonly used method to perform the life-stress analysis [2]. Test components are run under severe conditions and fail sooner than under normal conditions. This process is faster and more cost-efficient than testing under regular conditions, which can lead to longer periods of time to generate the stress data [3]. As an example, accelerated life testing was conducted on transistors by operating them at the voltage, current, and frequencies expected in their transmitter application, but at elevated junction temperatures [4]. This allowed the experimental time to be reduced. Also, temperature stress was used for reliability testing on double heterojunction bipolar transistor (DHBT) [5]. Furthermore, cyclic thermal stress is subjected to insulated-gate bipolar transistor (IGBT) module for reliability testing [6]. Accelerated aging to induce device degradation using bias and temperature stress was done on InP-collector DHBT's and using the increase in the B-C leakage current as failure criteria (derived from circuit requirements) to make lifetime projections [5].

Different accelerated life test analyses take different dc criteria to analyze the failure mechanism in the device, current gain (Hfe) was taken as base criteria in this study to analyze the failure data. In the accelerated life testing of GaAs/AlGaAs heterojunction bipolar transistor where the devices were under forward bias stress at higher temperatures and DC device characteristics were monitored. The primary degradation observed in some devices is a reduction in the current gain which appears to be due to an electric field-aided diffusion of interstitial Be from the base into the base-emitter graded region [7]. In reliability of InP-based HBT's and HEMT's Gm was taken as base criteria to analyze the failure of the devices, the obtained Gm versus stress time data was used to calculate the mean time to failure (MTTF) [8].

Temperature and humidity can also greatly impact the lifetime of a device. The study of how these variables influence device lifetime and reliability encourages further investigation. Previous scientific research has shown that the most important parameters for degradation of transistors are environmental factors (Temperature and humidity), mechanical and chemical stresses [9].

Common components, such as bipolar junction transistors, may benefit from further understanding of degradation and improved lifetime prediction methodologies.

The Arrhenius-Weibull model is the most commonly used approach to characterize the failure process with impacts of temperatures.

In this research, we have experimented on NPN transistors. We used accelerated life testing on transistors using temperature, water and humidity as mediums. With the obtained experimental data we predicted the lifetime of transistors using statistics.

## 1.2 Organization of Study

In Chapter 1, literature review of how accelerated life testing are done is reviewed and the environmental effects on transistors is reviewed. How the experiments are done is researched.

In Chapter 2, we learn about what a transistor is and how it works its properties and types of transistors.

In Chapter 3, experimentation part of the thesis is explained. This chapter has detained explanation of how the experiments were done step by step and equipment required to run the experiment.

In Chapter 4, we learn about accelerated life testing and how it is calculated. ALTA software is introduced and how it works is explained. simulation of the experimented data is explained. Detailed explanation of how the simulation works is done.

In Chapter 5, Effects of temperature, water and humidity on transistor is explained, how environmentally induced failure can affect. Results that were obtained was discussed and analyzed.

In Chapter 6, the conclusion and future work of the thesis were explained.

# 2. FUNDAMENTALS OF TRANSISTORS

## 2.1 How Transistors Works

The semiconductor device that is used to switch electronic signals or amplify the signals and electrical power is the transistor. A Semiconductor material is used to make transistors and they are generally with 3 terminals for external circuit connections. One pair of the transistor's terminals passes the current or voltage to another pair of terminals to control the current. A transistor can amplify a signal because the output current/voltage is greater than the input current/voltage. Nowadays, many transistors are found embedded in integrated circuits, but some are individually packed.

P-Type Semiconductor: In order to make a P-type semiconductor, the intrinsic semiconductor is doped with an electron acceptor. The electron acceptor is accountable for the formation of a hole by receiving an electron from the lattice. As a result, holes are the majority carriers in the p-type semiconductor. Whereas the minority carriers are the electrons.

N-Type Semiconductor: An extrinsic semiconductor, that is doped with pentavalent impurity elements like phosphorus or arsenic, which has five electrons in its outermost shell, is known as an N-type semiconductor. Dopant elements or impurities are added in the semiconductor for better conduction as there will be an increase in the number of electrons. The majority of carriers are electrons whereas; the minority carriers are the holes.

Majority Carriers: In a semiconductor, carriers that are primarily responsible for the current transport and which are in present in abundant quantity are called majority charge carriers. Most of the electric current and electric charge in a semiconductor is carried by majority carriers. The main responsibility for electric current flow in a semiconductor is majority charge carriers.

Minority Carriers: In a semiconductor, carriers that are present in little quantity are called minority charge carriers. In a semiconductor, charge carriers that are less abundant and carry a very small amount of electric current or electric charge are minority charge carriers.

PN junction: When a P-type material is fused with an N-type material to form a PN-junction and creating a semiconductor diode. Inside a single crystal of semiconductor, a P-N junction is an interface or a boundary between two types of semiconductor materials, n-type and p-type. Generally, a PN- junction comprises two regions with opposite doping types as shown in figure 2.1.

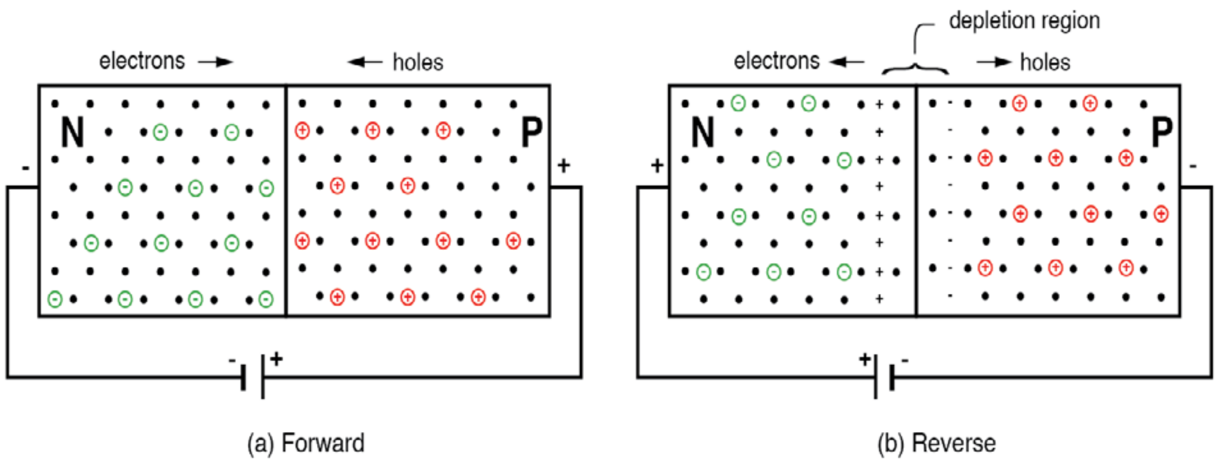



Figure 2.1. PN junction [10].

Transistor (NPN):

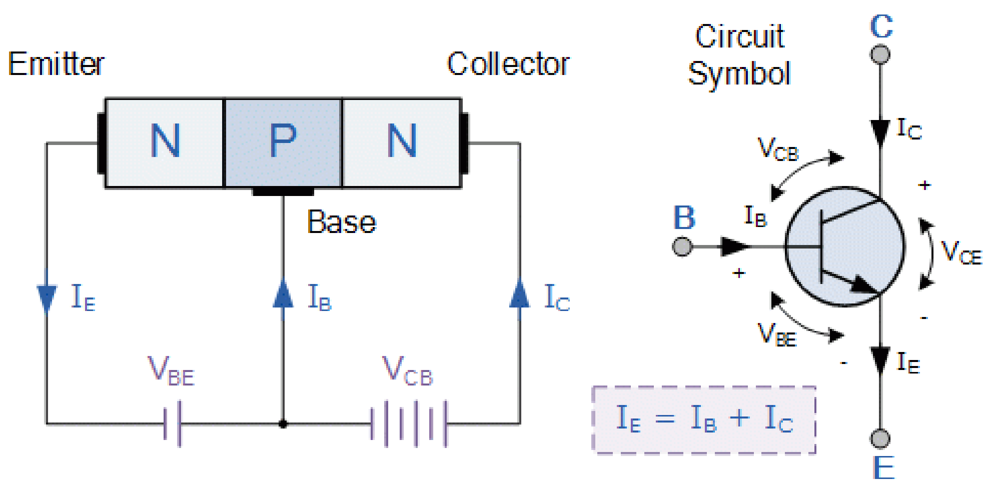



Figure 2.2. NPN transistor (Arrow defines the emitter and conventional current flow, “out” for a Bipolar NPN Transistor) [11].

NPN Transistors are 3-layer, 3-terminal devices that can operate as either electronic switches or amplifiers. The most generally used transistor configuration is the NPN Transistor. The junctions of the bipolar transistor can be biased in one of 3 different ways – Common Emitter, Common collector and Common Base.

Base, Emitter, Collector: Transistors are comprised of 3 parts: a emitter, a base, and an collector. The base is the gate controller device for the larger electrical supply. The collector is the larger electrical supply, and the current enters from the emitter. The voltage of the base must be further positive than that of the emitter. The voltage of the collector, in turn, must be further positive than that of the base [12]. A battery or some other source of direct current provides the voltages. The emitter supplies electrons. The base draws these electrons from the emitter because it has a further positive voltage than does the emitter. This transfer of electrons creates a flow of electricity through the transistor. The current moves from the emitter to the collector through the base. Variations in the voltage connected to the base modify the flow of the current by changing the number of electrons in the base. In this way, minute changes in the base voltage can cause large changes in the current flowing out of the collector [12].

Current Gain: The current gain for the common-base configuration is defined as the transformation in collector current divided by the change in emitter current when the base-to-collector voltage is constant or it can be defined as the ratio of these two currents ($I_c/I_b$).

Leakage Current: Leak current is the current generated due to the minority charge carriers, flowing in the transistor. It flows in the similar direction as the current due to the majority charge carriers.

## 2.2 Bipolar Junction Transistor (BJT)

Transistors in which both minority charge carriers and majority charge carriers conduct electric current or electric charge are called bipolar transistors. The bipolar junction transistor, the first type of transistor to be manufactured in large quantity, is an arrangement of 2 junction diodes and is formed of either a thin layer of n-type semiconductor inserted between two p-type semiconductors (a p-n-p transistor), or a thin layer of p-type semiconductor inserted between two n-type semiconductors (an n-p-n transistor). This assembly produces 2 p-n junctions: a base-collector junction and a base-emitter junction, divided by a thin region of semiconductor known as the base region (two junction diodes wired together without sharing an intervening semiconducting region will not make a transistor). In 1948, William Shockley, John Bardeen, and Walter Brattain at AT&T's Bell Labs invented the first bipolar junction transistors.


Figure 2.3. Transistor

BJTs have 3 terminals, equivalent to the 3 layers of semiconductor—an emitter, a collector, and a base [12]. They are important in amplifiers because the currents at the emitter and collector are controllable by a relatively minor base current. In an n–p–n transistor functioning in the active region, the emitter–base junction is forward biased (electrons and holes recombine at the junction), and the base-collector junction is reverse biased (electrons and holes are formed at, and move away from the junction), and electrons are injected into the base region. Because the base is constricted, most of these electrons will diffuse into the reverse-biased base–collector junction and be carried into the collector; perhaps one-hundredth of the electrons will recombine in the base, which is the governing mechanism in the base current. Likewise, as the base is lightly doped (in comparison to the emitter and collector regions), recombination rates are minimal, allowing more carriers to diffuse across the base region. By regulating the number of electrons that can leave the base, the number of electrons entering the collector can be controlled. The collector current is approximately β (common-emitter current gain) times the base current. It is usually greater than 100 for small-signal transistors but can be lesser in transistors designed for high-power applications [12].

**ELECTRICAL CHARACTERISTICS** ($T_A$ = 25°C unless otherwise noted)

| Characteristic | | Symbol | Min | Max | Unit |
|---|---|---|---|---|---|
| **OFF CHARACTERISTICS** | | | | | |
| Collector–Emitter Breakdown Voltage (Note 2) ($I_C$ = 1.0 mAdc, $I_B$ = 0) | | $V_{(BR)CEO}$ | 40 | – | Vdc |
| Collector–Base Breakdown Voltage ($I_C$ = 10 μAdc, $I_E$ = 0) | | $V_{(BR)CBO}$ | 60 | – | Vdc |
| Emitter–Base Breakdown Voltage ($I_E$ = 10 μAdc, $I_C$ = 0) | | $V_{(BR)EBO}$ | 6.0 | – | Vdc |
| Base Cutoff Current ($V_{CE}$ = 30 Vdc, $V_{EB}$ = 3.0 Vdc) | | $I_{BL}$ | – | 50 | nAdc |
| Collector Cutoff Current ($V_{CE}$ = 30 Vdc, $V_{EB}$ = 3.0 Vdc) | | $I_{CEX}$ | – | 50 | nAdc |
| **ON CHARACTERISTICS** | | | | | |
| DC Current Gain (Note 2) | | $h_{FE}$ | | | – |
| ($I_C$ = 0.1 mAdc, $V_{CE}$ = 1.0 Vdc) | 2N3903 | | 20 | – | |
| | 2N3904 | | 40 | – | |
| ($I_C$ = 1.0 mAdc, $V_{CE}$ = 1.0 Vdc) | 2N3903 | | 35 | – | |
| | 2N3904 | | 70 | – | |
| ($I_C$ = 10 mAdc, $V_{CE}$ = 1.0 Vdc) | 2N3903 | | 50 | 150 | |
| | 2N3904 | | 100 | 300 | |
| ($I_C$ = 50 mAdc, $V_{CE}$ = 1.0 Vdc) | 2N3903 | | 30 | – | |
| | 2N3904 | | 60 | – | |
| ($I_C$ = 100 mAdc, $V_{CE}$ = 1.0 Vdc) | 2N3903 | | 15 | – | |
| | 2N3904 | | 30 | – | |
| Collector–Emitter Saturation Voltage (Note 2) | | $V_{CE(sat)}$ | | | Vdc |
| ($I_C$ = 10 mAdc, $I_B$ = 1.0 mAdc) | | | – | 0.2 | |
| ($I_C$ = 50 mAdc, $I_B$ = 5.0 mAdc | | | – | 0.3 | |
| Base–Emitter Saturation Voltage (Note 2) | | $V_{BE(sat)}$ | | | Vdc |
| ($I_C$ = 10 mAdc, $I_B$ = 1.0 mAdc) | | | 0.65 | 0.85 | |
| ($I_C$ = 50 mAdc, $I_B$ = 5.0 mAdc) | | | – | 0.95 | |
| **SMALL–SIGNAL CHARACTERISTICS** | | | | | |
| Current–Gain – Bandwidth Product | | $f_T$ | | | MHz |
| ($I_C$ = 10 mAdc, $V_{CE}$ = 20 Vdc, f = 100 MHz) | 2N3903 | | 250 | – | |
| | 2N3904 | | 300 | – | |
| Output Capacitance ($V_{CB}$ = 5.0 Vdc, $I_E$ = 0, f = 1.0 MHz) | | $C_{obo}$ | – | 4.0 | pF |
| Input Capacitance ($V_{EB}$ = 0.5 Vdc, $I_C$ = 0, f = 1.0 MHz) | | $C_{ibo}$ | – | 8.0 | pF |
| Input Impedance | | $h_{ie}$ | | | k Ω |
| ($I_C$ = 1.0 mAdc, $V_{CE}$ = 10 Vdc, f = 1.0 kHz) | 2N3903 | | 1.0 | 8.0 | |
| | 2N3904 | | 1.0 | 10 | |
| Voltage Feedback Ratio | | $h_{re}$ | | | X $10^{-4}$ |
| ($I_C$ = 1.0 mAdc, $V_{CE}$ = 10 Vdc, f = 1.0 kHz) | 2N3903 | | 0.1 | 5.0 | |
| | 2N3904 | | 0.5 | 8.0 | |
| Small–Signal Current Gain | | $h_{fe}$ | | | – |
| ($I_C$ = 1.0 mAdc, $V_{CE}$ = 10 Vdc, f = 1.0 kHz) | 2N3903 | | 50 | 200 | |
| | 2N3904 | | 100 | 400 | |
| Output Admittance ($I_C$ = 1.0 mAdc, $V_{CE}$ = 10 Vdc, f = 1.0 kHz) | | $h_{oe}$ | 1.0 | 40 | μmhos |
| Noise Figure | | NF | | | dB |
| ($I_C$ = 100 μAdc, $V_{CE}$ = 5.0 Vdc, $R_S$ = 1.0 k Ω, f = 1.0 kHz) | 2N3903 | | – | 6.0 | |
| | 2N3904 | | – | 5.0 | |
| **SWITCHING CHARACTERISTICS** | | | | | |
| Delay Time | ($V_{CC}$ = 3.0 Vdc, $V_{BE}$ = 0.5 Vdc, $I_C$ = 10 mAdc, $I_{B1}$ = 1.0 mAdc) | $t_d$ | – | 35 | ns |
| Rise Time | | $t_r$ | – | 35 | ns |
| Storage Time | ($V_{CC}$ = 3.0 Vdc, $I_C$ = 10 mAdc, $I_{B1}$ = $I_{B2}$ = 1.0 mAdc) 2N3903 | $t_s$ | – | 175 | ns |
| | 2N3904 | | – | 200 | |
| Fall Time | | $t_f$ | – | 50 | ns |

Figure 2.4. 2N3904 Transistor properties [13].

# 3. EXPERIMENT

We conducted accelerated life testing of transistors using two methods. The first method was using temperature as a medium, and the second was using humidity. We also used the water-immersed method.

## 3.1 Temperature Accelerated Lifetime Testing

### 3.1.1 Experimental Setup

The common 2N3904 NPN BJT transistor has been used to predict the accelerated life and the mean time to failure using temperature. The testing was done at 200$^{o}$C and 250$^{o}$C. An industrial oven with temperature specifications of 50 °C- 275 °C was used as shown in figure 3.1.a to perform the experiments at 250°C and 200°C. Peak atlas semiconductor analyzer DCA75 is used to measure the readings of the transistors. It is a test instrument that integrates multiple measurement and analysis capabilities to perform the current-voltage (IV) and many other measurements accurately.

Initially, a set of 30 transistors was taken and placed in the oven plate as shown in figure 3.1 and were marked and arranged in order. Initial readings like CURRENT GAIN (Hfe), BASE-EMITTER VOLTAGE DROP (Vbe) were measured with the peak atlas semiconductor analyzer. After initial measurement, the transistors were placed in the heating chamber which is set at 250$^{o}$C. The current gain (hfe) and base-emitter voltage drop (Vbe) values were obtained every 4 hours for 250 °C using the semiconductor analyzer until all transistors failed factor.

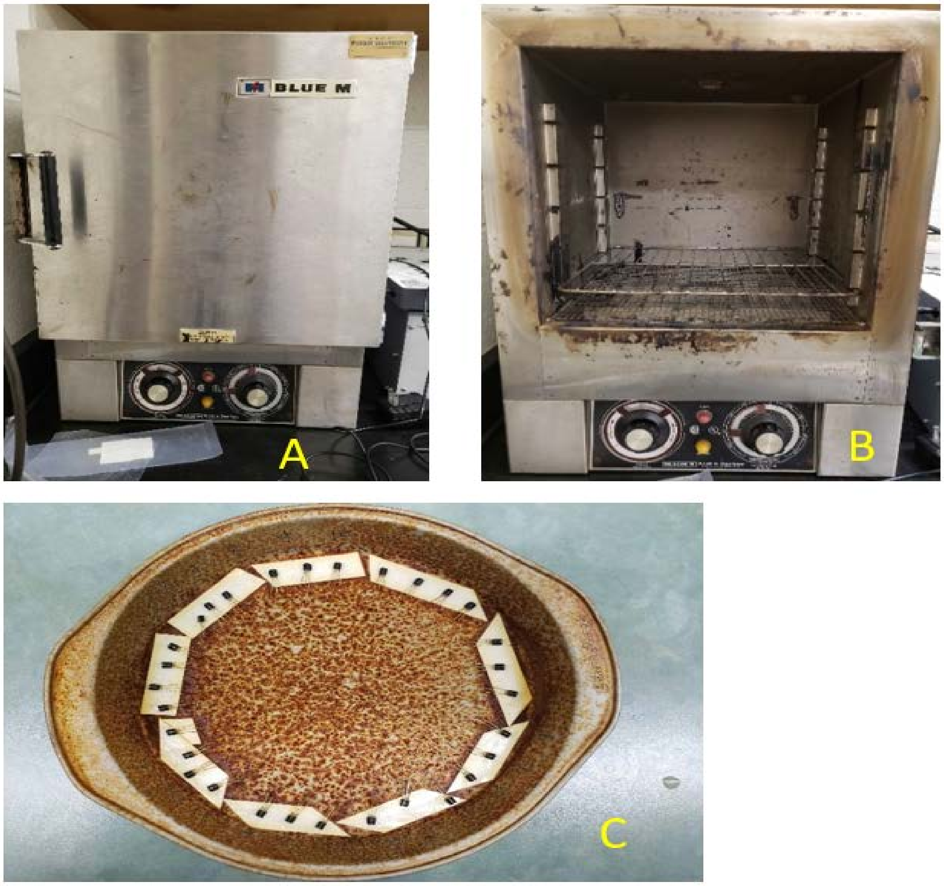



Figure 3.1. (a) Oven used to do temperature effects (b) inside of the oven (c) 30 transistors placed in oven plate.

The obtained data was used to plot graphs using Microsoft excel sheets. Multiple sets of data were obtained by conducting the experiment repeatedly and using the data obtained from all the sets of data and was used to form trend.

The experiment was repeated at 200$^{o}$C and the current gain (hfe) and base-emitter voltage drop (Vbe) values are collected every 12 hours for 200 °C using the semiconductor analyzer until all transistors failed. Similar to the 250$^{o}$C data, 200$^{o}$C data was also analyzed.

Using both sets of data that were obtained at 250$^{o}$C and 200$^{o}$C temperatures, the data was analyzed using Matlab code of maximum likelihood estimation (MLE) and also using the Reliasoft ALTA software for further verification to estimate the mean time to failure (MTTF), and acceleration factor.

From the obtained mean time to failure (MTTF), and acceleration factor data we can predict the failure of transistors at any temperature. With this data we can predict the lifetime of the transistor and even the lifetime at any temperature.

## 3.2 Water Accelerated Lifetime Testing

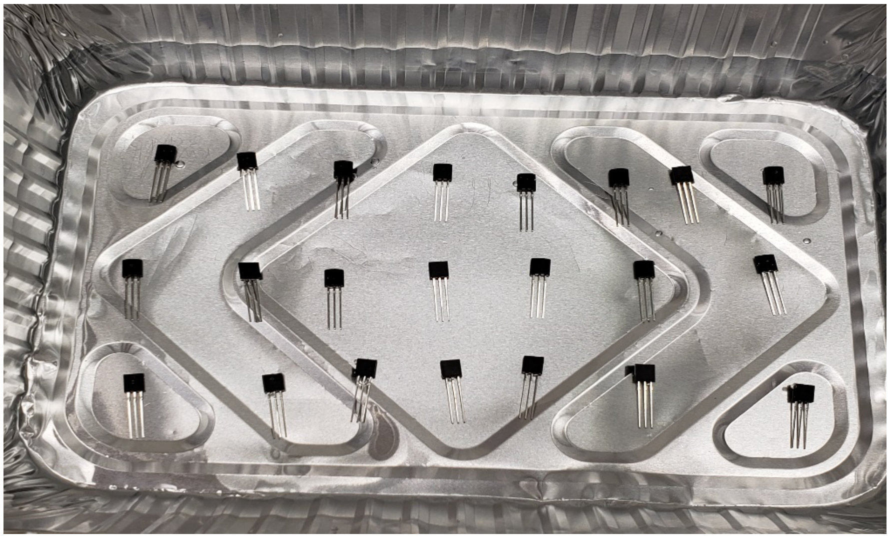


Figure 3.2. Transistors immersed in distilled water experiment.

Water that has high concentration of dissolved salts is saline water. Parts per million (PPM) is used to express the concentration in saline water. Salinity is the measure of the number of grams of salts per kilogram of seawater.

Saline water is prepared according to the salinity levels of standard sea water which is 3.5%. 1 liter of Distilled water is taken in a jar and 35g of salt is added and mixed properly until salts are dissolved completely.

Distilled water is produced using a distiller machine which produces about 4 to 5 liters of distilled water in 5 to 6 hours.

The water-immersed experiment is conducted on similar transistors. Three sets of 30 transistors are taken and immersed in two different concentrations of saline water (tap water with~ 0.9% and sea water with ~3.5%). First, the transistors are immersed in distilled water which has almost nonexistent saline in water and minerals also not present. Readings of the transistors are taken every 48 hours. This experiment is conducted at various temperatures 20ºC, 40ºC, and 80ºC.

Readings like CURRENT GAIN (Hfe), BASE-EMITTER VOLTAGE DROP (Vbe) were measured with the peak atlas semiconductor analyzer were taken for all temperatures.

Figure 3.3. Picture of water distiller with water container

Second, the transistors are immersed in normal tap water which has 0.9 % of salinity in the water. The readings of the transistors are taken every 15 minutes (readings time is significantly shorter as the reaction of salts and water takes place faster and causes failure) as salts in the water cause failure of transistors.

Lastly, the transistors are immersed in sea water which has 3.5% salinity. This is a very high percentage which causes rapid failure in transistors so the readings were taken every 5 minutes (readings time is significantly shorter as the reaction of salts and water takes place faster and causes failure).

The data is recorded from all three types of salinity and at all three different temperatures.

### 3.3 Humidity Accelerated Lifetime Testing

Humidity: It is the concentration of water vapor present in the air.

Relative Humidity: At any specified temperature, it is the ratio of the partial pressure of water vapor to the equilibrium vapor pressure of water. The pressure and the temperature of the system of interest influence relative humidity. A similar amount of water vapor results in higher relative humidity in cool air than warm air. It can also be described as the ratio of the current absolute humidity to the highest possible absolute humidity (which rest on the current air temperature). The mass of water vapor divided by the mass of dry air in a volume of air at a given temperature. It is expressed as grams of moisture per cubic meter of air (g/m3).

$$Relative\ Humidity = \frac{actual\ vapor\ density}{saturation\ vapor\ density} * 100\% \qquad (1)$$

#### 3.3.1 Humidity Chamber

Equipment used in the process of making a humidity controlled chamber are a humidifier, Arduino with temp and humidity control, sensors, fans , and acrylic opaque fiber material.
An Arduino chip is used to control the required humidity.

Initially, the design of the chamber was made and with by using fiber material, the outer chamber is made according to the design. The chamber contains an inlet hole and a vent. Probe of the sensor is inserted inside the chamber which measures the temperature and humidity. The sensor is made with Arduino chip and controller as shown below.

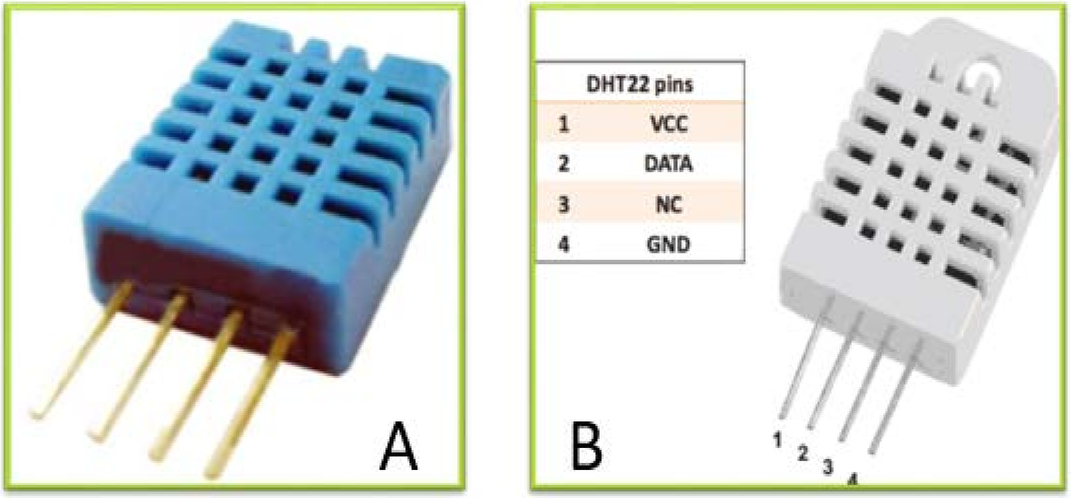



Figure 3.4. Temperature sensor (b) humidity sensor.

For humidity generation we used LV600HH Hybrid Ultrasonic Humidifier that generates humidity at required levels.

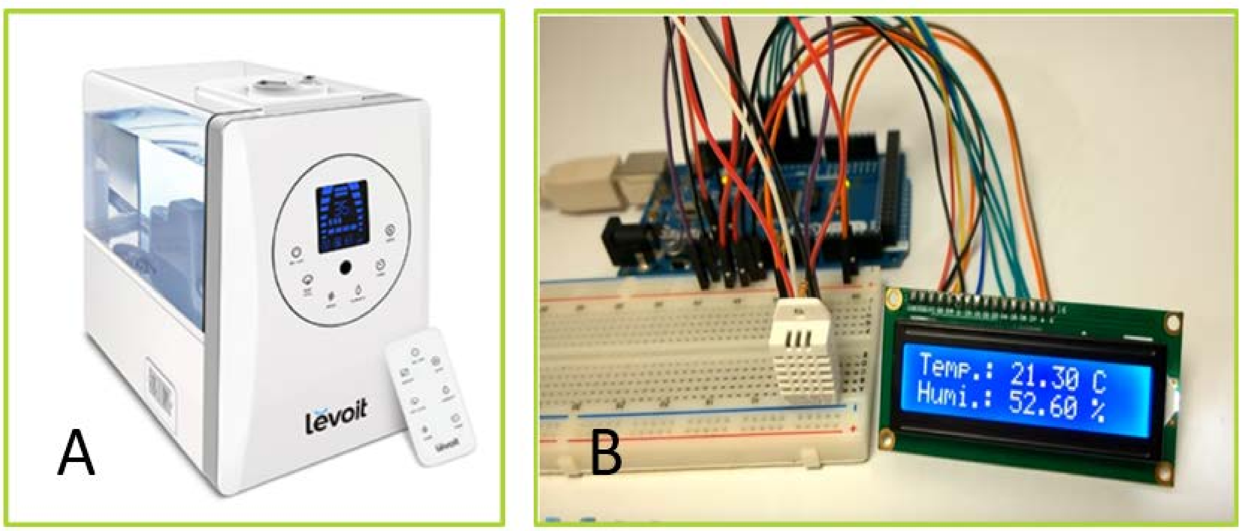



Figure 3.5. (a) Humidifier (b) Arduino chip with controller.

Using Arduino coding, we set required temperature and humidity and control the levels of humidity and temperature.

The same 2N3904 NPN BJT transistor has been used to predict the accelerated life and the mean time to failure using humidity. The testing was done at 95% and 90% (future work) relative humidity. An environmental chamber is used to perform the experiments.

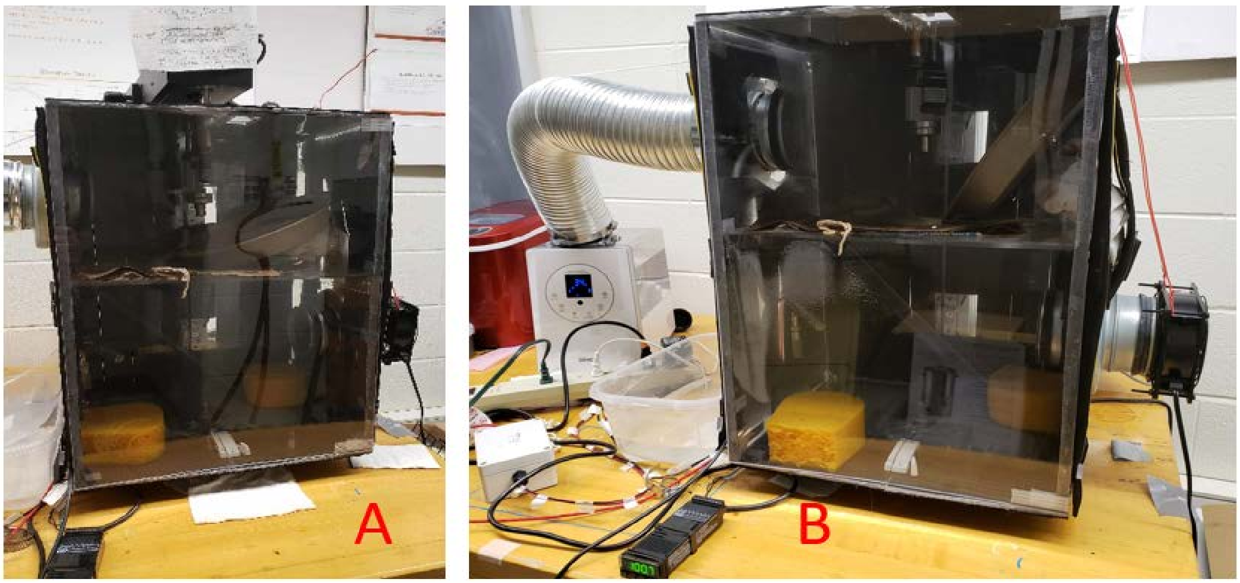



Figure 3.6. (a) Transistors inside Environmental chamber (b) Chamber with humidifier, controller, and exhaust fan.

Similar to the temperature experiment, the transistors are used and tested. The readings are taken every 24 hours. With the data obtained, we can predict the lifetime of transistors.

# 4. SIMULATION AND METHODOLOGY

## 4.1 Terminology

Accelerated Life Testing: It is a process of testing a component or a product by exposing it to environments (strain, stress, voltage, temperatures, pressure, vibration rate, etc.) in surplus of its normal service limitations, to expose liabilities and potential modes of failure in a short amount of time. By analyzing the product's reaction to such experiments, engineers can make predictions about the maintenance intervals of a product and the service life of the product.

Probability Density Function (PDF): A statistical expression that defines a probability distribution (the likelihood of an outcome) for a discrete random variable as opposed to a continuous random variable [14]. In other words, while the absolute likelihood for a continuous random variable to take on any particular value is 0 (since there are an infinite set of possible values to begin with), the value of the PDF at two different samples can be used to infer, in any particular draw of the random variable, how much more likely the random variable would equal one sample compared to the other sample [15].

Cumulative Distribution Function (CDF): CDF of a real-valued random variable X, or just distribution function of X, evaluated at x, is the probability that X will take a value less than or equal to x [16].

$$F(x) = P(X \leq x) \tag{2}$$

Mean Time to Failure (MTTF): Average amount of time taken for a non-repairable object or component to fail during experimentation or in operation. It can also be considered as average lifespan of a component. Relevant to only products or components that cannot be repaired. It can be attained from the mean of the probability density of the time to failure f(t):

$$MTTF = \int_0^\infty t.f(t)dt \tag{3}$$

Acceleration Factor (AF): Acceleration factor could be given when a kind of stress similar to use stress applied to the device in a very short period of time results in device failure. Failure may occur because of mechanical or electrical mechanisms. The device lifetime would change with the change of the operating parameters. "This change is quantified as the acceleration factor and is defined as the ratio of the measured failure rate of the device at one stress condition to the measured failure rate of identical devices stressed at another condition".

$$A_f = \frac{MTTF_{use}}{MTTF_{stress}} \tag{4}$$

Arrhenius Equation: The Arrhenius equation is a formula intended for the temperature dependence of reaction rate for many chemical and physical reactions. The most commonly used life-stress relationship in accelerated life testing is possibly Arrhenius life-stress. Arrhenius equation is extensively used when thermal (i.e., temperature) is the incentive or acceleration variable (or stress).

$$R(T) = A.e^{-\frac{E_a}{k.T}} \tag{5}$$

Where,

R is the rate constant (speed of reaction) like lifetime etc.,

T is the absolute temperature (in Kelvin),

A is a constant

$E_a$ is the activation energy for the reaction (in the same units as RT),

K is Boltzmann's constant ($8.6173X10^{-5}eVK^{-1}$)

Weibull Distribution: The continuous mathematical function that delivers the probabilities of occurrence of different possible outcomes in an experiment. In reliability engineering, the Weibull distribution is broadly used for lifetime distributions.

The probability density function of a Weibull random variable is:

$$f(x;\lambda,k) = \begin{cases} 0, & x < 0 \\ \frac{k}{\lambda}(\frac{x}{\lambda})^{k-1}.e^{-\left(\frac{x}{\lambda}\right)^k}, & x \geq 0 \end{cases} \quad (6)$$

Where,

K > 0 is the shape parameter

- Weibull distributions with k < 1 have a failure rate that decreases with time, also known as infantile or early-life failures. Weibull distributions with k close to or equal to 1 have a fairly constant failure rate, indicative of useful life or random failures. Weibull distributions with k > 1 have a failure rate that increases with time, also known as wear-out failures.

λ > 0 is the scale factor [17]

- If η is increased, while k and γ are kept the same, the distribution gets stretched out to the right and its height decreases, while maintaining its shape and location.
- If η is decreased, while k and γ are kept the same, the distribution gets pushed in towards the left (i.e., towards its beginning or towards 0 or γ), and its height increases.
- η has the same unit as T, such as hours, miles, cycles, actuations, etc.

A value of k > 1 shows that the failure rate increases with time.

A value of k<1 shows that the failure rate decreases over time.

A value of k = 1 shows that the failure rate is constant over time.

Censored/Non-Censored: In statistics, censoring is a stipulation in which the value of a measurement or observation is only partially known.

Uncensored values are those we are used to dealing with. The value is reported and used as given. Censored values are those reported as greater than some value (e.g., > 12 weeks), less than some value (e.g., < 10 gallons), or as an interval (e.g., a value in the middle of 298K and 375K).

## 4.2 Accelerated Life Testing (ALT)

To make predictions statistical models depend significantly on data. In life data analysis, the data is the times to failure data or life data of our product and the models are the statistical distributions. In the case of accelerated life data analysis, the data is the times to failure data at a specific stress level and the models are the life-stress relationships. The precision of any prediction is directly proportional to the accuracy, completeness, and quality of the complete data. For excellent predictions, valuable data along with a suitable model choice is required. Imperfect or inadequate data will usually result in Inferior predictions.

In the analysis of life data, we want to use all available data sets, which are sometimes incomplete or include vagueness as to when a failure occurred. Life data can hence be divided into two types: censored data (some of the data is missing) or complete data (all data is available).

## 4.3 Statistics

We use maximum likelihood estimation (MLE) method to analyze the failure data from the accelerated life testing experiment. In statistics, maximum likelihood estimation (MLE) is a method of estimating the parameters of a probability distribution by maximizing a likelihood function, so that under the assumed statistical model the observed data is most probable [18]. The point in the parameter space that maximizes the likelihood function is called the maximum likelihood estimate. The logic of maximum likelihood is both instinctive and variable, and as such, the method has become a main means of statistical inference [18].

Maximum likelihood estimation begins with writing a mathematical expression known as the Likelihood Function of the sample data [19]. Roughly speaking, the likelihood of a set of data is the probability of obtaining that particular set of data, given the chosen probability distribution model. This expression contains the unknown model parameters. The values of these parameters that maximize the sample likelihood are known as the Maximum Likelihood Estimates or MLEs.

Maximum likelihood estimation is a totally analytic maximization procedure. It applies to every form of censored or multi-censored data, and it is even possible to use the technique across several stress cells and estimate acceleration model parameters at the same time as life distribution parameters (life distributions is described as the set of statistical probability distributions that we use in reliability engineering and life data analysis). Moreover, MLEs and Likelihood Functions generally have very desirable large sample properties. They become unbiased (an estimator or decision rule with zero bias is called unbiased. In statistics, "bias" is an objective property of an estimator) minimum variance estimators as the sample size increases they have approximate normal distributions and approximate sample variances that can be calculated and used to generate confidence bounds likelihood functions can be used to test hypotheses about models and parameters.

There are only two drawbacks to MLEs, but they are important ones [19]:

- With a small numbers of failures (less than 5, and sometimes less than 10 is small), MLEs can be heavily biased and the large sample optimality properties do not apply
- Calculating MLEs often requires specialized software for solving complex non-linear equations. However, this is less of a problem as time goes by, as more statistical packages are upgrading to contain MLE analysis capability every year.

Likelihood Function Examples for Reliability Data [19]:
Let f(t) be the Probability Density Function (PDF) and F(t) the Cumulative Density Function (CDF) for the chosen life distribution model. Note that these are functions of t and the unknown parameters of the model. The likelihood function for Type I (Time Censoring: Study ends at a specified time before all failures have occurred.) Censored data is:

$$L = c\left(\prod_{i=1}^{r} f(t_i)\right)[1 - F(T)]^{n-r} \qquad (7)$$

With C denoting a constant that plays no role when solving for the MLEs. Note that with no censoring, the likelihood reduces to just the product of the densities, each evaluated at a failure time. For Type II (Failure Censoring (aka Type II) Study ends after specified number of failures have occurred) Censored Data, just replace T above by the random end of test time $t_r$.

The likelihood function for Type 2 data is [19]:

$$L = c(\prod_{i=1}^{k}[F(T_i) - F(T_{i-1})]^{r_i}[1 - F(T)]^{n-\sum_{i=1}^{k} r_i} \qquad (8)$$

With $F(T_0)$ defined to be 0.

In general, any multi-censored data set likelihood will be a constant times a product of terms, one for each unit in the sample, that look like either f(ti), [F(Ti)−F(Ti−1)], or [1−F(ti)], depending on whether the unit was an exact time failure at time ti, failed between two readouts Ti−1 and Ti, or survived to time ti and was not observed any longer [19].

The general mathematical technique for solving for MLEs involves setting partial derivatives of ln L (the derivatives are taken with respect to the unknown parameters) equal to zero and solving the resulting (usually non-linear) equations. However, the equation for the exponential model can straightforwardly solved [19].

## 4.4 ALTA Statistical Models

### 4.4.1 ALTA Software

We use ReliaSoft software applications which provide a powerful range of solutions to facilitate a comprehensive set of reliability engineering modeling and analysis techniques to analyze our data. ReliaSoft ALTA provides an intuitive and user-friendly way to employ complex and powerful mathematical models for quantitative accelerated life testing data analysis. ALTA provides a widespread toolset for accelerated test planning and quantitative accelerated life testing data analysis, plots and reporting. The software provides a complete array of utilities for designing accelerated life tests, evaluating the fit of the model, calculating reliability metrics, generating plots and performing related statistical analyses [20].

ALTA provides all the tools and options you will need for accelerated life testing data analysis.

The software supports all the following data types testing conditions would yield:

- Right-censored (suspended) data is a widely used case of censoring. In the case of life data, right-censored data sets are comprised of components that did not fail. For example, if we experimented on 100 components and 70 had broken down when the experiment is concluded, we would have the right-censored data for the 30 components that did not break down. The word right-censored infers that the event of interest (the time to failure) is to the right of our data point. In another words, if the components were to keep on operating, the break down would occur at some time after our data point (or to the right on the time scale). Figure 4.1 shows the right censoring data with example of 5 units.

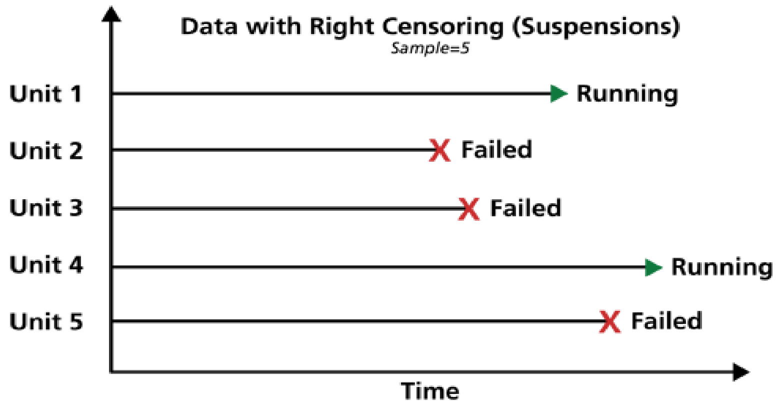



Figure 4.1. Types of censoring of data.

- Left censored
- Complete (time-to-failure)
- Interval

To have capacity for larger datasets data can be written in groups or individually. Based on the analysis the software delivers a complete array of results and plots. For accelerated life testing data analysis, this includes:

- Failure rate
- Acceleration factor
- BX% life (i.e., time for a given unreliability)
- Reliable life (i.e., time for a given reliability, also called "warranty time")
- Conditional reliability or conditional probability of failure
- Mean life
- Reliability or probability of failure
- Probability plots and pdf plots
- Life vs. stress, acceleration factor vs. stress, and standard deviation vs. stress plots
- Three-dimensional surface plots such as reliability vs. time vs. stress
- Residuals plots

### 4.4.2 Models

I. Model describing the failure due to temperature:

Arrhenius-Weibull: The most commonly used life-stress relationship in accelerated life testing is possibly Arrhenius life-stress. It has been extensively used when the incentive or acceleration variable (or stress) is thermal (i.e., temperature).

This model is used mainly because when the failure is due to temperature.

Model 1:

The pdf for the 2-parameter Weibull distribution is given by:

$$f(t,V) = \frac{\beta}{C.e^{\frac{B}{V}}} . \left(\frac{t}{C.e^{\frac{B}{V}}}\right)^{\beta-1} . e^{-\left(\frac{t}{C.e^{\frac{B}{V}}}\right)^{\beta}} \tag{9}$$

- V denotes the stress level (formulated for temperature and temperature values in absolute units, degrees Rankine or degrees Kelvin).
- C is one of the model parameters.
- B is another model parameter.

$$B = \frac{E_a}{K} \tag{10}$$

- K is Boltzmann constant.
- $E_a$ is activation energy.
- β is shape parameter.

II. Model describing the failure due to humidity:

Eyring Relation: From quantum mechanics principles, the Eyring relationship was formulated. It is mostly used when the acceleration variable is thermal stress (temperature). Nevertheless, the Eyring relationship is also often used for another stress variables other than temperature, such as humidity. The relationship is given by:

$$L(V) = \frac{1}{V}.e^{-(A-\frac{B}{V})} \tag{11}$$

L denotes a quantifiable life measure, such as median life, life, mean life, characteristic life, etc.

V denotes the stress level (temperature values are in absolute units: degrees Rankine or kelvin).

B is another model parameter to be determined.

A is one of the model parameters to be determined.

III. Model describing the failure due to temperature and humidity

A variant of the Eyring relationship, the Temperature-Humidity (T-H) relationship has been proposed for calculating the life at use conditions when humidity and temperature are the accelerated stresses in a analysis. This combination model is given by:

$$L(V,U) = A.e^{\frac{\phi}{V}+\frac{b}{U}} \tag{12}$$

V is temperature (in absolute units).

U is the relative humidity (percentage or decimal).

Φ is one of the three parameters to be determined.

B is another model parameter to be determined.

$$B = \frac{E_a}{K} \tag{13}$$

K is Boltzmann constant.

$E_a$ is activation energy.

A is another constant to be determined.

### 4.5 Temperature Effect Simulation (ALTA)

Using the obtained data from the experimentation to run the simulations in ALTA/ Weibull++ software. Using ALTA acceleration model enter the data into the sheet.

| | Time Failed (hr) | Temperature K |
|---|---|---|
| 1 | 24 | 523 |
| 2 | 40 | 523 |
| 3 | 44 | 523 |
| 4 | 44 | 523 |
| 5 | 44 | 523 |
| 6 | 44 | 523 |
| 7 | 48 | 523 |
| 8 | 48 | 523 |
| 9 | 48 | 523 |
| 10 | 48 | 523 |
| 11 | 48 | 523 |
| 12 | 52 | 523 |
| 13 | 52 | 523 |
| 14 | 52 | 523 |
| 15 | 56 | 523 |
| 16 | 56 | 523 |
| 17 | 60 | 523 |
| 18 | 60 | 523 |
| 19 | 60 | 523 |
| 20 | 60 | 523 |
| 21 | 60 | 523 |
| 22 | 64 | 523 |
| 23 | 64 | 523 |
| 24 | 68 | 523 |
| 25 | 72 | 523 |
| 26 | 72 | 523 |
| 27 | 76 | 523 |
| 28 | 80 | 523 |
| 29 | 81 | 523 |
| 30 | 82 | 523 |
| 31 | 108 | 473 |
| 32 | 120 | 473 |
| 33 | 120 | 473 |
| 34 | 132 | 473 |
| 35 | 156 | 473 |
| 36 | 168 | 473 |
| 37 | 180 | 473 |
| 38 | 192 | 473 |
| 39 | 192 | 473 |
| 40 | 192 | 473 |
| 41 | 192 | 473 |
| 42 | 286 | 473 |
| 43 | 310 | 473 |
| 44 | 310 | 473 |

Figure 4.2. Obtained data inserted in ALTA software.

Selecting the type of model that is required. We use Arrhenius-Weibull. We calculate the parameters of the equation, which are etha, beta, B and C.

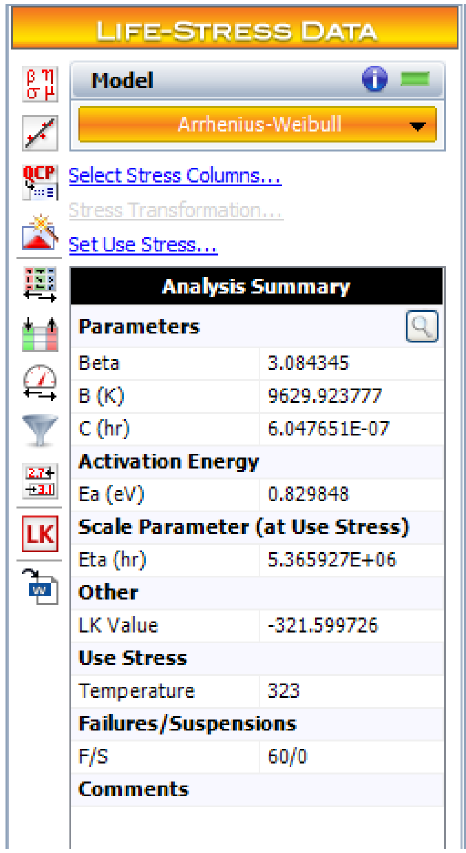



Figure 4.3. Calculation of parameters.

Using the obtained parameter values we can calculate acceleration factor, mean life, etc.,

The following possible results can be calculated:

- Reliability: We can calculate the reliability of the component at any particular time.
- Probability of Failure: This gives us the probability of failure at any specified time.
- Conditional Reliability: Using the conditional option we can calculate the reliability of the component with conditions like assuming it worked for a period of time. (e.g., the probability that an item that has survived for 100 hours will survive for an additional 100 hours)
- Conditional probability of failure: Similarly with conditional option we can calculate the failure of the device.
- Reliable life: It can also be called as warranty time. As it calculates time for a specified probability.

- BX% life: We can calculate the time for a specified unreliability. For example, if a component has a B10 life of 1000 hours, then 10% of the total components will have failed by 1000 hours of operation.
- Mean life: This is the average time to failure and is denoted as the MTTF (Mean Time to Failure).
- Mean remaining life: Calculates the mean remaining life after certain period of time.
- Failure rate: Calculates the instantaneous failure rate.

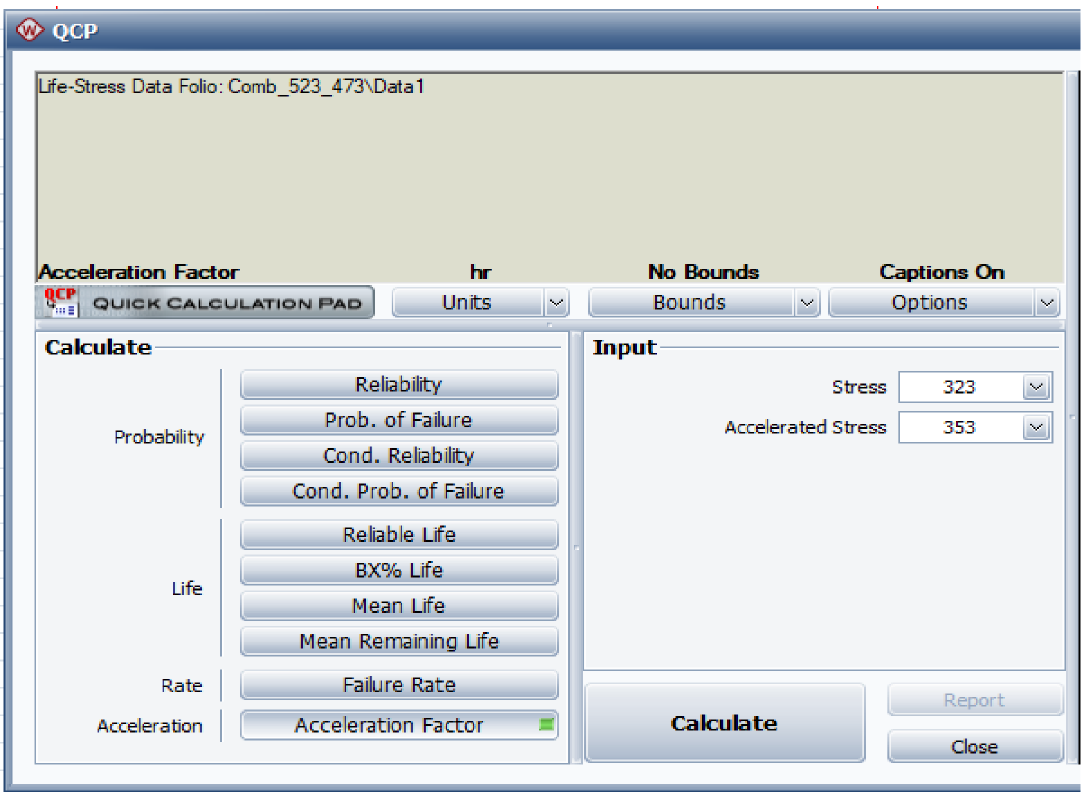



Figure 4.4. Calculation of acceleration factor.

Using the software, we can calculate the required parameters and with those parameters, we can estimate the life expectancy.

We set the stress levels to calculate the acceleration factor and the required parameters.

### 4.6 Water Effect Simulation (ALTA)

Acceleration can be done by using ALTA to simulate the accelerated like of semiconductors in water.

The data is inserted in life-stress data analysis sheet then the required model is selected which is Arrhenius- Weibull.

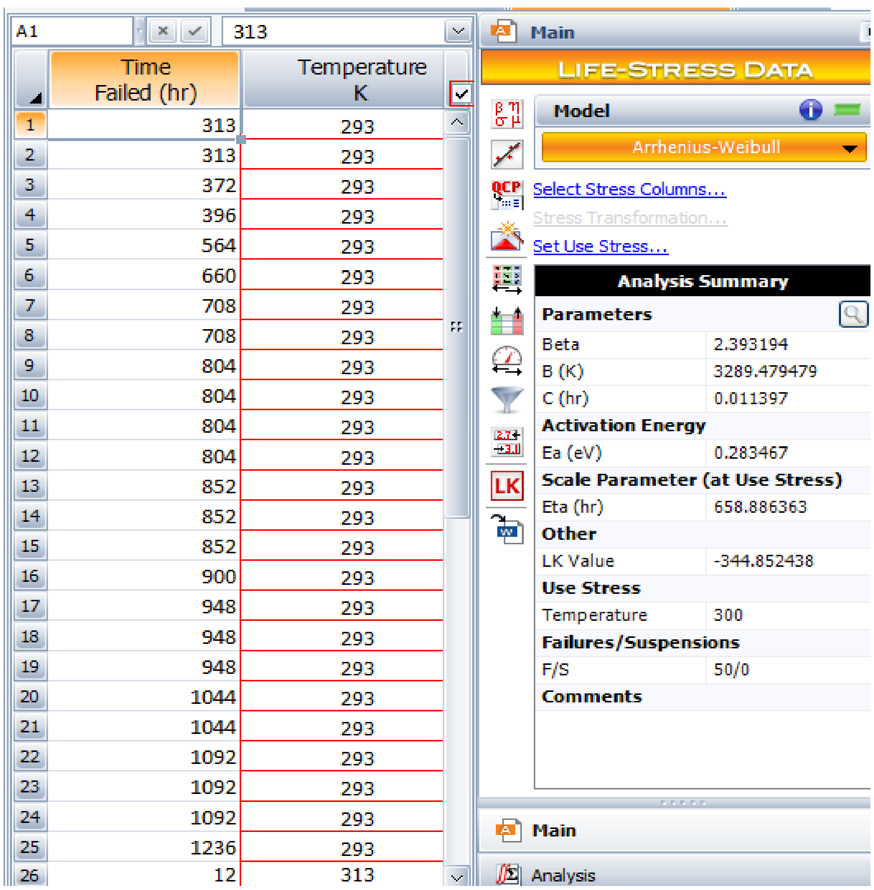



Figure 4.5. Data sheet

Calculation of the parameters is done. With the obtained parameters we can calculate mean life (MTTF) and acceleration factor, as well as many other factors.

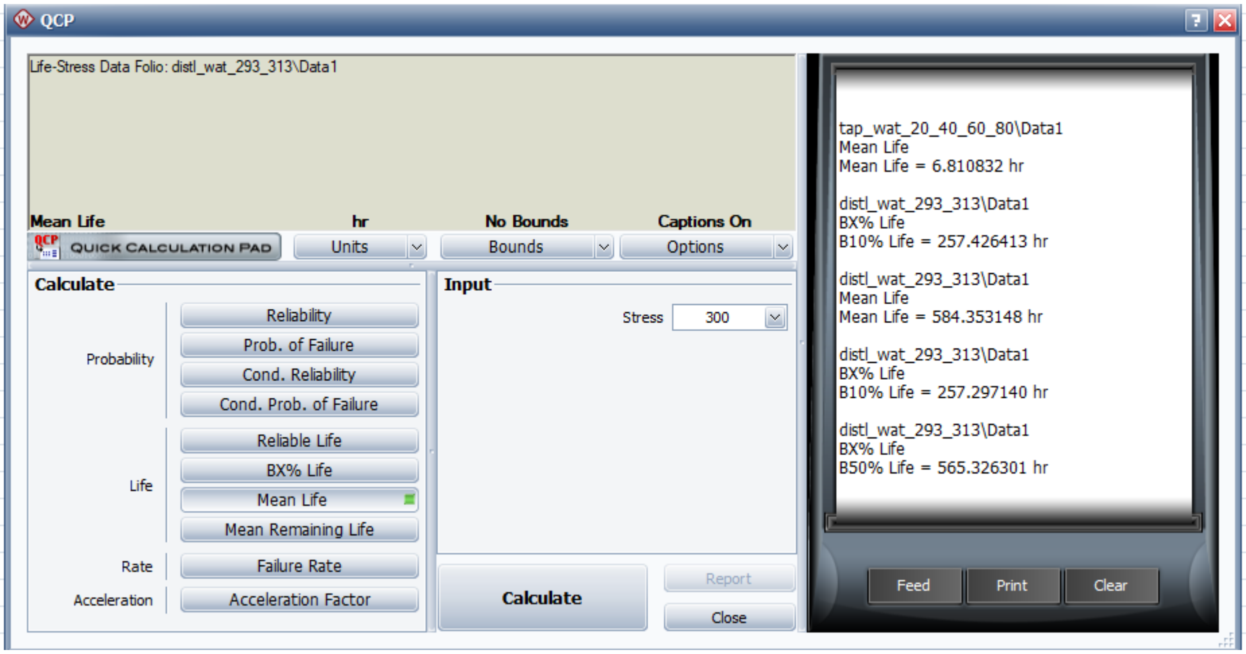



Figure 4.6. Calculation of various parameters.

We use a set level of stress as a basis for calculating the required parameters. This set value can be any value. In this experiment, we used 300k as the stress set value. Results vary depending on the set stress value. As the stress value acts the stress factor to calculate the acceleration factor. With this we can analyze the effects of water at any given temperature for a set saline level of water.

### 4.7 Temperature Simulation Analysis MATLAB

We generated Matlab code to analyze the data as further verification. First, we combined the failure time of all the transistors at $200^0$C and $250^0$C temperatures as a column vector. We generated a column vector of temperature corresponding to the failure time of each transistor. Using probability density function (PDF) of Arrhenius- Weibull equation along with failure time vector and temperature vector we find the parameters of the Arrhenius-Weibull PDF matching the experimental data using MLE method: activation energy ($E_a$), shape parameter ($\beta$), and constant C. Using these parameters we are able to calculate the acceleration factor. Acceleration factor at a specific temperature can be calculated with respect to $250^0$C.

We also generated Cumulative density function (CDF) and compared that with experimental data. The results of the Matlab simulation are almost identical to the result of ALTA software. Detailed results will be discussed in the results section. Complete Matlab code is attached in the appendix.

# 5. RESULTS AND DISCUSSIONS

## 5.1 Degradation factors

Environmental conditions, such as temperature and humidity, have many effects on semiconductors. These stress factors cause different types of failure mechanisms in semiconductors. The possible failure mechanisms are mentioned below.

Table 5.1. Failure mechanism examples of semiconductors by environmental conditions.

| Environmental Conditions (Stress) | Failure Mechanism Examples |
| --- | --- |
| Temperature | • Thermal break down<br>• Material aging<br>• Thermal degradation<br>• Thermal/stress migration<br>• Electro migration |
| Humidity (Moisture Concentration) | • Moisture induced swelling, delamination<br>• Corrosion<br>• Conductive anodic filaments (CAF)<br>• Electro-chemical migration<br>• Electrostatic discharge |

### 5.1.1 Effects of Water

Electronic devices like semiconductors etc., are used in many fields and areas where they come in contact with water. Our aim was to see the effects of the water on semiconductor level before analyzing the water effects on electronics. As semiconductors are small components that might come in contact with water we have taken the transistor as our initial testing sample. We have investigated how different types of saline water and distilled water effect when the transistors are in the water environment. Different saline water that were taken are 0.9% saline water which is tap water, 3.5% saline water also commonly known as sea water with average salinity. Investigation of salt water on semiconductors is done. In majority of the sea based equipment's like submarines etc. come in contact with water when exposed so we would like to estimate the time to failure of the devices.

1. Distilled Water:

   Pure water is a very poor conductor, so it won’t affect electronic devices like semiconductors or transistors very much if at all. Since there won’t be much of the ions transfer there will be no corrosion in ideal case.

2. Tap Water:

   Tap water blends with polarized minerals as it makes its way through a pipe hence it is not pure water. These polarized minerals in water is the cause for conduct electricity. This is how water, affects most electronics like transistors and other semiconductors to short (fail).

3. Salt Water:

   Salt water, on the other hand, can be hazardous to transistors and other semiconductors and electronics. This is due to the NaCI (Sodium chloride) forming a chemical bond with metal surfaces [21]. On addition to water the Na+ section of NaCl is attracted to the oxygen side of the water molecules, while the Cl- side is attracted to the hydrogens' side of the water molecule. This causes the sodium chloride to split in water, and the NaCl dissolves into separate $Na^+$ and $Cl^-$ atoms. This $Na^+$ and $Cl^-$ reacts with metals through bond formation. These bonds happen instantaneously upon wetting — resulting in a salt residue lasting long after the water is gone. Salt water has the same effect on the transistors if they are immersed in salt water for any given amount of time. Over a period of weeks, months or even years, the salt left behind continues to corrode any susceptible, influenced surface. The corrosion process continues until the salt residue is exhausted or the corroded surface is destroyed [21].

Electronic components are a complex assembly of metallic and non-metallic materials [22]. Corrosion of the metallic components can promptly occur in the presence of moisture with the process being aided or accelerated by corrosive contaminants often present at micro-contamination levels. Sources of contamination that play an significant role in the corrosion

of electronic materials are often derived from a wide variety of atmospheric pollutants, low levels of contaminants that exist in packaging materials, and as a result of human handling. Given their complexity, corrosion of electronic components can occur by many mechanisms. These include pore and creep corrosion of base metals plated with a noble metal, corrosion instigated by deposited pollutants in combination with moisture, fretting corrosion, localized and stress corrosion in the existence of corrosive contaminants (i.e. chlorides), galvanic corrosion ensuing from contact of dissimilar metals, and electrolytic corrosion subsequent from applied potentials normally found in electronic devices. [22]
Aluminum alloy can support resistance to corrosion in marine because of its oxide film barrier [23]. An oxide layer bonds strongly to the surface and once it is damaged or weathered, it can amend quickly in the majority environmental conditions. The rust is hydrated iron oxide developed by redox reaction in presence of water and air. The first reaction occurring in corrosion is the anodic reaction. The reactive metal surface is oxidized to form rust, which does not afford any protection to the iron underlying. During this process, electrons are released from the iron surface. Thus, it contributes to next reaction called cathodic reaction. In the reduction reaction, electrons released in the oxidation process chemically react with the water molecules to form hydroxide ions [23].

### 5.1.2 Effects of Humidity

It is reputed that the effect of humidity on semiconductor devices is very high and there will be a huge effect on the device's mean time to failure if there are minuscule changes in Relative humidity (RH). Corrosion reliability of electronic products is a vital factor for the electronics industry, and today there is a huge demand for performance reliability in great spans of temperature and humidity during the day and night shifts [24]. Corrosion failures are still seen due to the effects of temperature, humidity, and corrosion accelerating species in the atmosphere, and the surface region of printed circuit board assemblies are frequently contaminated by various contaminating species. The reliability of electronic components, devices, and assemblies is strongly influenced by their use environment and, in particular, by the contaminants (i.e. salt, mineral, metals like zinc, iron, copper etc…) that are present. Ionic particles are ubiquitous in the environment. The absorption of moisture by the particles creates an electrolyte solution that leads to corrosion and, on electronic devices in the presence of an applied voltage, it results in leakage currents and electrolytic corrosion. Few studies have been reported on the effect of ionic dust particles on the corrosion of electronic metals and devices.

Products are exposed to all sorts of climatic conditions [24]. Therefore, the protection of these devices is a significant factor in system designs. Moisture and local condensation inside electronic enclosures can considerably alter the enclosed electronic device's performance. The observed outcomes of this phenomenon are decreased life span of the products and profound economic loss due to failures. Today, remarkably little is known among design engineers about design for robustness and prediction of lifetime for electronics in moist environments and in condensing applications [24].

There are 2 types of corrosions. The first type corrosion is moisture ($H_2O$) and high electrical fields within the transistor package responds and yield to discharge of ionic species ($H^+$ and $OH^-$ ). The salts in moisture can hurry up the process of corrosion.

The second type of corrosion is cranny corrosion due to hydrolysis, which is due to Crevice corrosion. This is a localized form of corrosion usually correlated with a stagnant solution on the micro-environmental level. Nevertheless, there is a variety of different deterioration mechanisms. One class of mechanisms is crevice corrosion, which is a localized form of corrosion usually correlated with a stagnant solution on the micro-environmental level. For both cases, steady high temperature stress tests without humidity do not show any irregularity. There are corrosion mechanisms taking place outside of transistor such as legs of the transistors. The most common corrosion mechanism, occurring on the legs of electronic devices under high humid conditions, is the electrochemical corrosion (e.g. metal corrosion).

One of the common corrosion failure modes observed in semiconductors is the electrolytic migration [25]. The electrolytic migration is an electrochemical phenomenon involving metal dissolution at the anode and deposition at the cathode, which is controlled by the chemistry of the solution layer over the components and electric potential. An adsorbed surface layer of water on the PCB surface often establishes the electrolyte contact needed for the process to take place. Charged dust particles, which are drawn to the surface, to improve the possibility of formation of water layer as they absorb moisture. Therefore, migration involves dissolution and deposition reactions and metal ion transfer induced by such factors as metal dissolution, diffusion and migration [25]

$M \rightarrow M^+ + e^-$ (Anode or positive electrode)

$M^+ + e^- \rightarrow M$ (Cathode or negative electrode)

At the cathode, a part of the current will also be used for other cathodic reactions such as oxygen reduction or hydrogen evolution depending on the solution chemistry and potential. Creation of metal complexes salts or oxides are other possible anode reactions. In spite of this, the important factor is the deposition of the metal at the cathode [26]. Due to large resistance within the thin solution layer, significant current localization occurs at the electrode surface directing to preferential deposition and growth in the form of dendrites from cathode towards anode eventually packing the electrode gap and short circuiting two parts of the components temporarily or permanently [25].

### 5.1.3 Effects of Temperature

The doping ions give the semiconductor crystal its properties, but they are somewhat intruders in the regular intrinsic semiconductor lattice, since every thermodynamic system at a temperature above 0K tends, if left developing, to a state of uniform concentration of chemical species [27]. In other words, the ions tend to transfer from their position in order to make their concentration in the crystal uniform. This phenomenon is called diffusion, and it is diverged by the forces of the chemical bonds that keep together the crystal. Note that the larger the amount of ionic diffusion, the more different regions of the chip lose their "identity," i.e. their characteristics as electronic devices. This effect is accelerated by high temperature because the thermal agitation have a tendency to disrupt chemical bonds: ions with greater thermal energy diffuse more effortlessly. This phenomenon is always present, even at room temperature, but it is usually insignificant. Nevertheless, ionic migration is not a linear effect, but an exponential one: so it increases radically with temperature. Over that temperature, ionic migration and other temperature-related effects can actually harm the device in a relatively short time, i.e. the part could have its potential operating life shortened [27].

The collector current is increased by the leakage current due to high junction temperature; this effect creates a positive feedback (more dissipation) that can damage the transistor due to “thermal runaway.” It can also be explained as redundant transfer of charge carriers from one region to another region through an insulating region.

Due to high temperature, there are many failures in semiconductors. Due to an existing defects in the crystal, when the transistors are under stress it causes Nucleation and growth of dislocations. Due to nucleation the structure is changed and it self assembles or self-organize its new structure due to heat. Nucleation is generally a random process so even two identical system nucleation will occur at different times.

If there is dislocation in the crystal structure due to high temperature there will be movement of crystals further and cause failure in the semiconductor.

At time of formation of crystal (nucleation) in semiconductors, there will be different grain boundaries that are defects in crystal structure they tend to decrease the electrical and thermal conductivity of the material. Which leads to failure of transistor. As high temperature affects the nucleation process which leads to failure of the semiconductors. Similarly the dislocation in the crystal also created defects in the crystal structure which leads to failure of transmitting electrical signals in the semiconductors.

## 5.2 Temperature Experiment Results

The data obtained from experiment (Experimental data was attached in the appendix) is used to calculate the parameters. Provided below are the parameters which are calculated. Using both MATLAB and ALTA software we calculated the parameters.

The pdf for the 2-parameter Weibull distribution is given by:

$$f(t,V) = \frac{\beta}{C.e^{\frac{B}{V}}} \cdot \left(\frac{t}{C.e^{\frac{B}{V}}}\right)^{\beta-1} . e^{-\left(\frac{t}{C.e^{\frac{B}{V}}}\right)^{\beta}} \tag{14}$$

- V denotes the stress level (formulated for temperature and temperature values in absolute units, degrees Rankine or degrees Kelvin).
- C is one of the model parameters.
- B is another model parameter.

$$B = \frac{E_a}{K} \tag{15}$$

- K is Boltzmann constant.
- $E_a$ is activation energy.
- β is shape parameter.

The results obtained from both MATLAB and ALTA software are compared in the following table. As we can observe that both results are similar which gives confirmation to our MATLAB code.

Table 5.2. Parameters obtained from the MATLAB and ALTA.

| | MATLAB | ALTA | %Error |
|---|---|---|---|
| $E_a$ (Activation energy) | 0.829329 | 0.829334 | 0.000602893 |
| C | 6.122600e-07 | 6.122668e-07 | 0.001110627 |
| β | 3.079765 | 3.079735 | 0.00097411 |

Excel is used to organize the obtained experimental data which is shown in below figure 5.1. It shows how the transistors fail over a period of time. We can observe that average current gain decreases over time. The data shows how 30 working transistors over a period of time degraded with all transistors failing. At 250°C temperature the failure time is very fast as we can see that all 30 transistors fail at nearly ~80 to 90 hours.

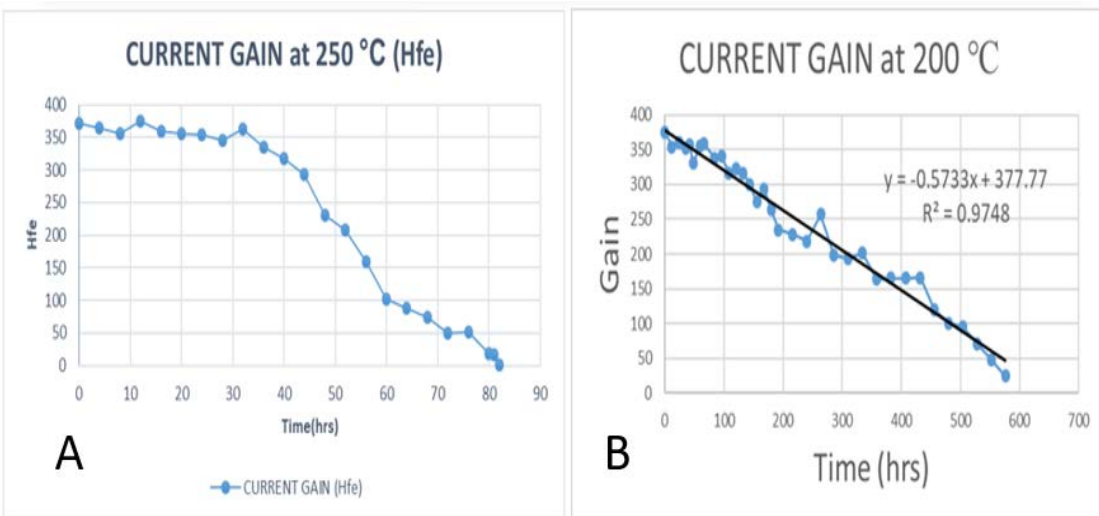



Figure 5.1. (a) Current gain vs time plot of 250$^0$C (b) Current gain vs time plot of 200$^0$C.

The combined plot of current gain, as well as the time of two different temperatures, is shown in below figure 5.2.

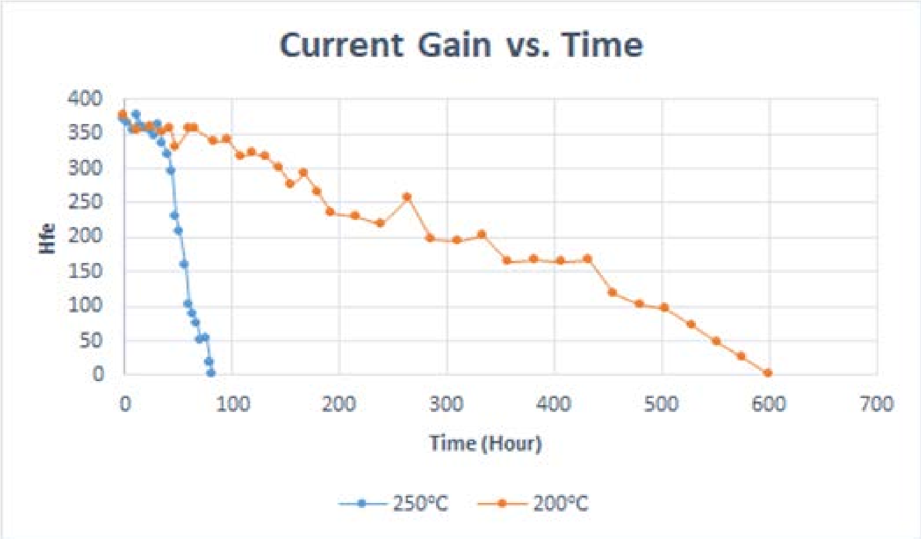



Figure 5.2. Combined plot of current gain vs time.

ALTA software is used to calculate the required parameters. Here are few results which can be calculated using ALTA shown in table 5.3.

- MTTF (Mean Time to Failure): This is the average time to failure
- B10 life: Life of the transistor with 10% failure
- AF: Acceleration Factor (with respect to 250 °C)
- Example: MTTF of 225 °C = 2.5 * 54 = (AF of 225 °C)* (MTTF at 250 °C)
- Failure rate: probability of failure in the next hour after a specific hour

Table 5.3. Parameter results using ALTA.

| | 250 °C | 225 °C | 200 °C | 150 °C | 100 °C |
|---|---|---|---|---|---|
| MTTF using ALTA (hours)<br>MTTF using Matlab (hours) | 54<br>55 | 135<br>138 | 376<br>385 | 4161<br>4262 | 87852<br>89985 |
| B10 Life (hours) | 29 | 72 | 202 | 2241 | 47322 |
| AF | 1 | 2.5 | 7 | 77.5 | 1636 |
| Reliability at 50hrs (%) | 56.63 | 96.74 | 99.86 | 99.999 | 100 |
| Failure rate at 50 hours (%) | 3.5 | 0.2 | 0.0088 | 5.3E-6 | 4.43E-10 |

Using the plot features, we plotted the unreliability versus time plot for 200$^{o}$C and 250$^{o}$C as shown in figure 5.3. We predicted for 225$^{o}$C temperature. Similarly, we can predict lifetime at any temperature and estimate the life time of the component.

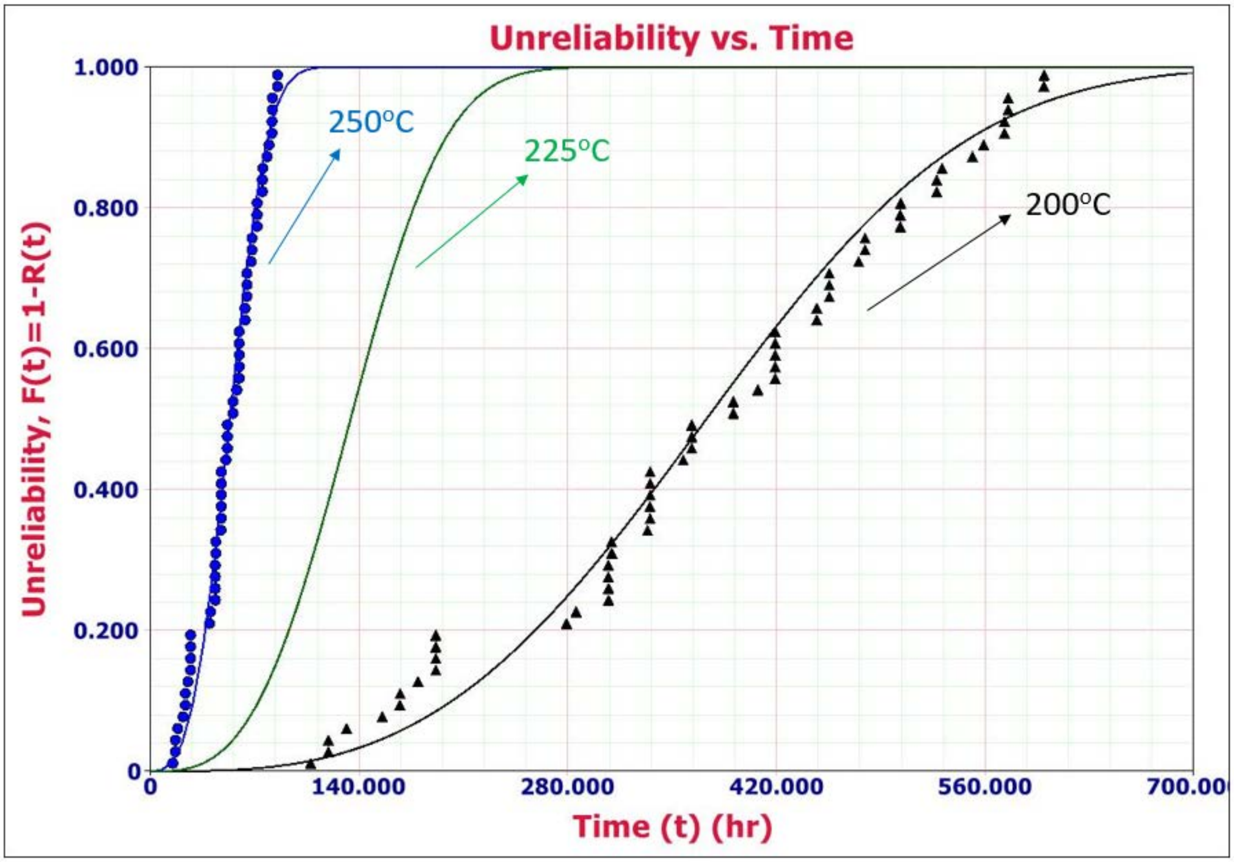



Figure 5.3. Unreliability verse time plot for 200ºC and 250ºC with prediction of 225ºC.

3D plots were plotted for further analysis. 3D plots help us analyze how the component is affected by temperature over a period of time, it shows us what the failure rate of the component is. In figure 5.4 we can see the unreliability of transistors over a period of time as the temperature is from 300K to 523K. We can see that unreliability is high at higher temperatures.

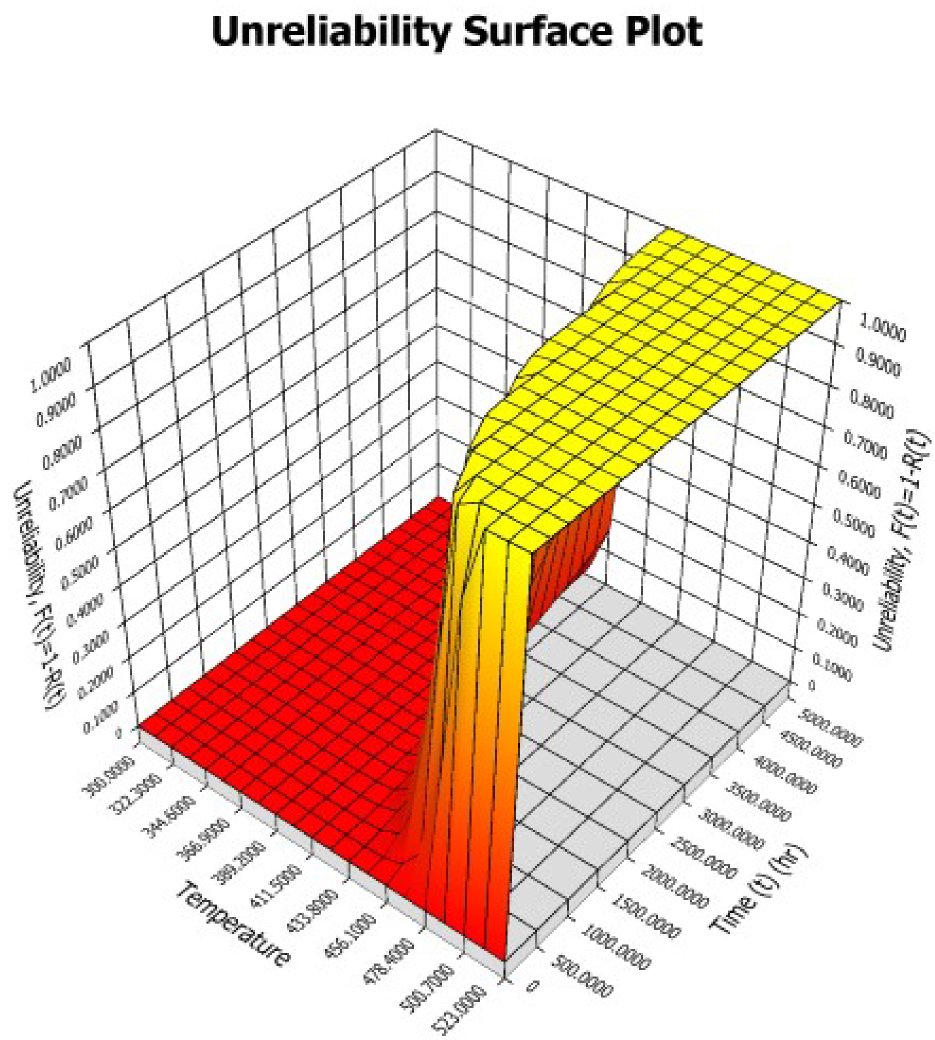



Figure 5.4. 3D plot unreliability surface plot.

In figure 5.5 we can see the probability density function plot over period of time at temperatures from 300K to 523K.

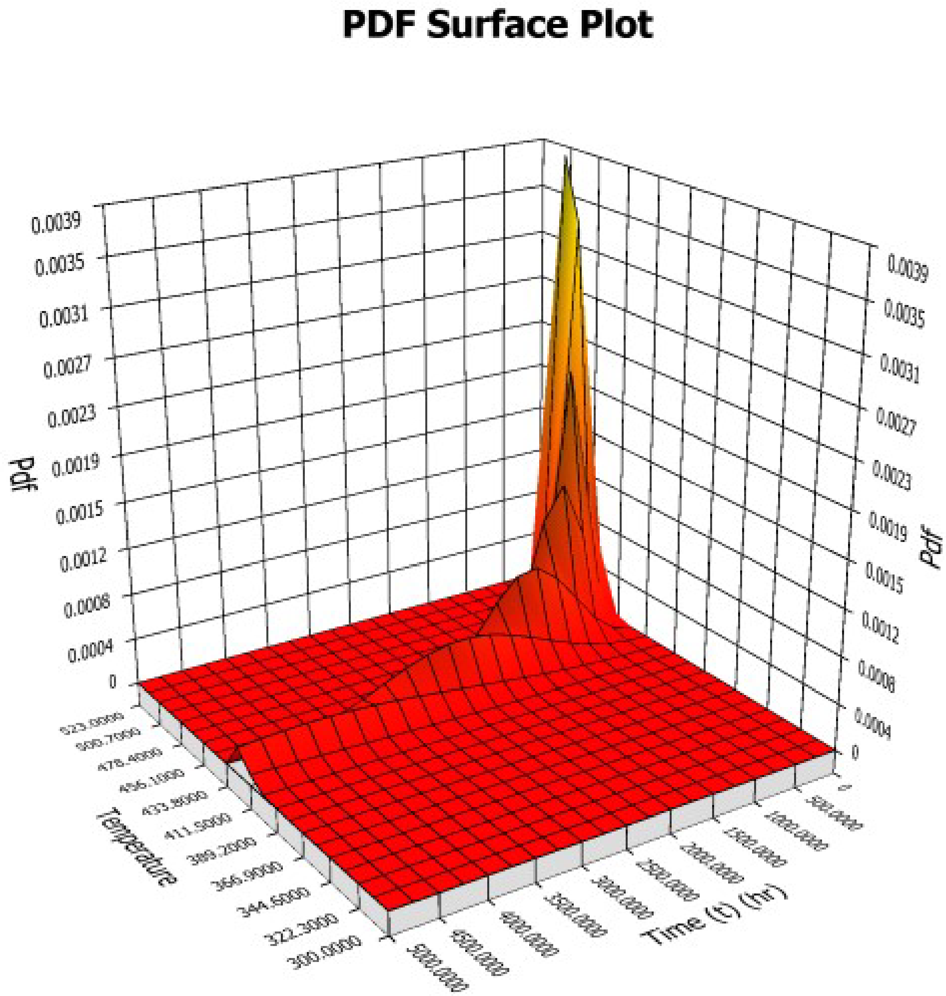



Figure 5.5. Plot of PDF surface plot

The data was analyzed in Matlab after calculating the optimized parameters of Arrhenius-Weibull. Using Matlab we can calculate only acceleration factor and mean time to failure (MTTF). Figure 5.6 shows the CDF comparison between experimental data and statistical model at 200$^o$C and 250$^o$C. Final percentage error between the experimental and statistical model at 250$^o$C is about 12% and at 200$^o$C it is about 25%. Percentage error was calculated at each failure time and then the final percentage error is the average value of all the failure time.

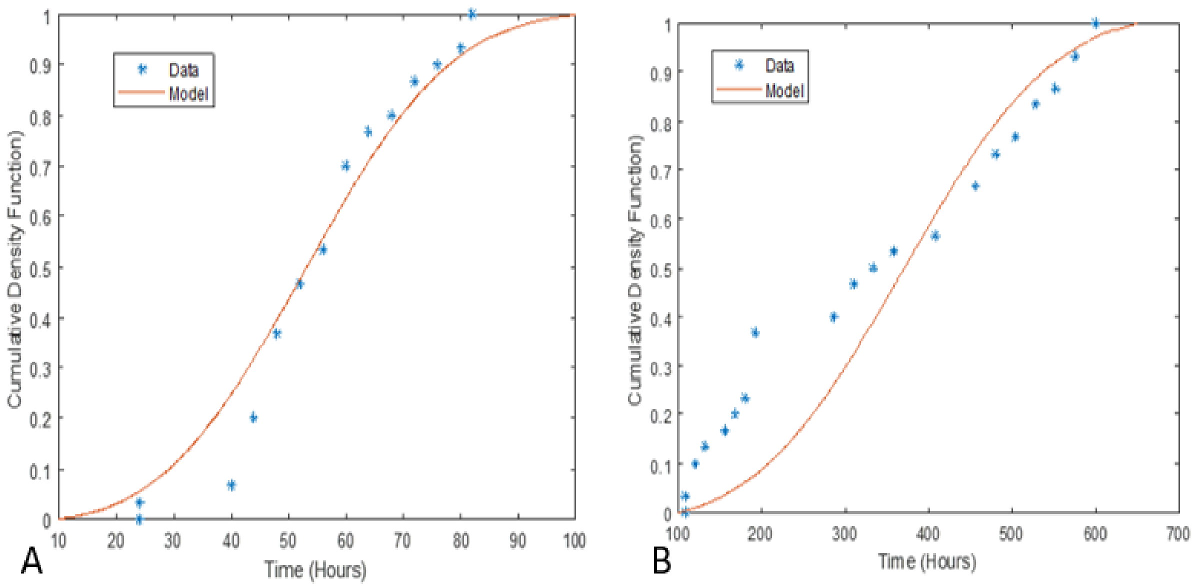



Figure 5.6. (a) MATLAB results at 250ºC (b) MATLAB results at 200ºC.

Based on the analysis results, the acceleration factors (AF) and MTTF of transistors at different temperatures were predicted. Table 5.4 shows the lifetime prediction results at 100°C, 150°C, and 225°C. The commercial software ALTA was used to verify the MATLAB prediction results, which is a commercial software used for lifetime prediction based on accelerated life testing data.

Table 5.4. Predicted Results at various temperatures.

| **Temperature [°C]** | **MATLAB $A_F$** | **MATLAB MTTF** | **ALTA $A_F$** | **ALTA MTTF** |
|---|---|---|---|---|
| 100 | 1636 | 10 years | 1643 | 10 years |
| 150 | 77.5 | 175 days | 77.7 | 174 days |
| 225 | 2.5 | 6 days | 2.52 | 6 days |

### 5.3 Distilled and Tap Water Experiment Results

Experimental data obtained from the distilled water experiment and tap water experiment were analyzed to obtain the parameters. Using Arrhenius-Weibull distribution we calculated the parameters.

$$f(t,V) = \frac{\beta}{C.e^{\frac{B}{V}}} . \left(\frac{t}{C.e^{\frac{B}{V}}}\right)^{\beta-1} . e^{-\left(\frac{t}{C.e^{\frac{B}{V}}}\right)^{\beta}} \quad (16)$$

- V denotes the stress level (formulated for temperature and temperature values in absolute units, degrees Rankine or degrees Kelvin).
- C is one of the model parameters.
- B is another model parameter.

$$B = \frac{E_a}{K} \quad (17)$$

- K is Boltzmann constant.
- $E_a$ is activation energy.
- β is shape parameter.

Parameters are obtained for distilled and tap water based on the failure data at 20, 40, 60, and 80 °C shown in table 5.5.

Table 5.5. Parameter results of distilled water and salt water.

| | **Distilled water** | **Tap water** |
|---|---|---|
| **$E_a$ (Activation energy)** | 0.191 | 0.2591 |
| **C** | 0.425 | 0.001429 |
| **β** | 2.755 | 2.087 |
| **Time unit** | Hour | Minute |

Using excel, we analyzed the current gain of distilled water environment at various temperatures. Figure 5.7 shows the plot of current gain at different temperatures, and we can see that at higher temperatures the failure rate is faster.

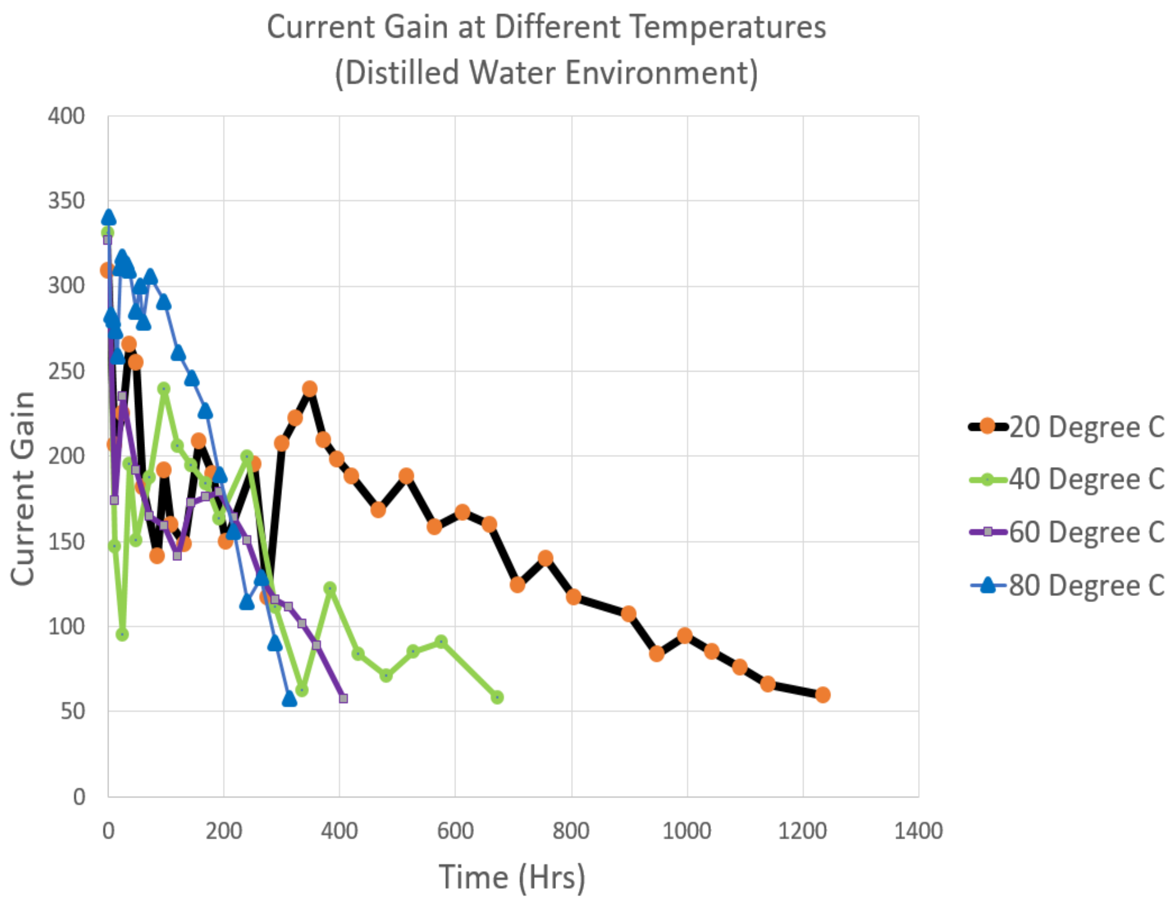



Figure 5.7. Plot of Current gain vs time of distilled water at different temperatures.

Using excel to analyze tap water experimental data at various temperatures was analyzed. Figure 5.8 shows the plot of tap water at various temperatures. We can see that at higher temperatures the failure rate is higher in tap water.

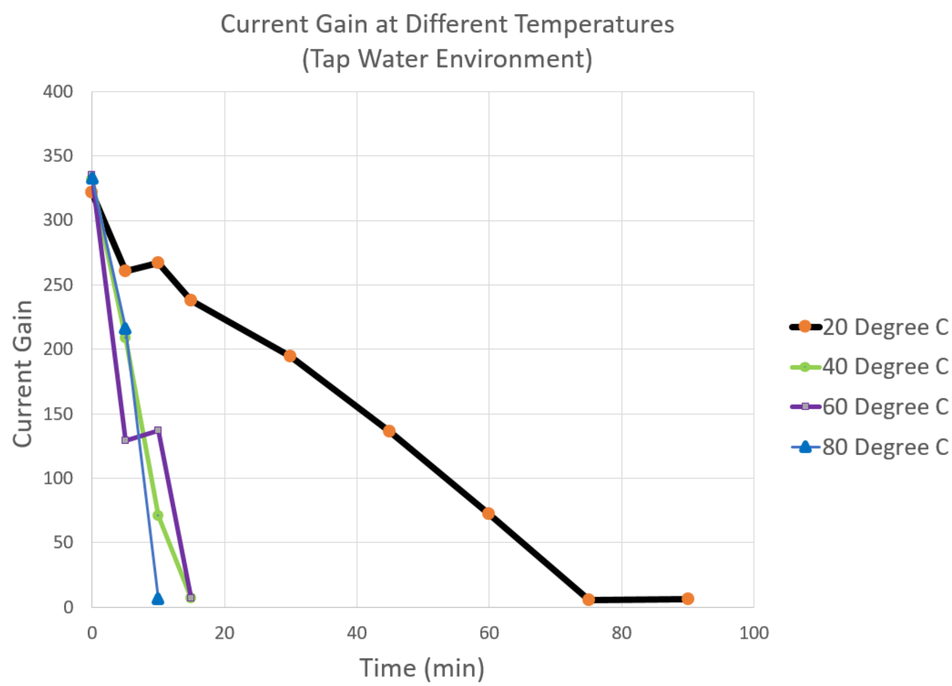



Figure 5.8. Plot of current gain vs time at various temperatures of tap water experiment.

Using ALTA software analysis of distilled water and tap water at 20$^{o}$C temperature was analyzed as shown in figure 5.9.

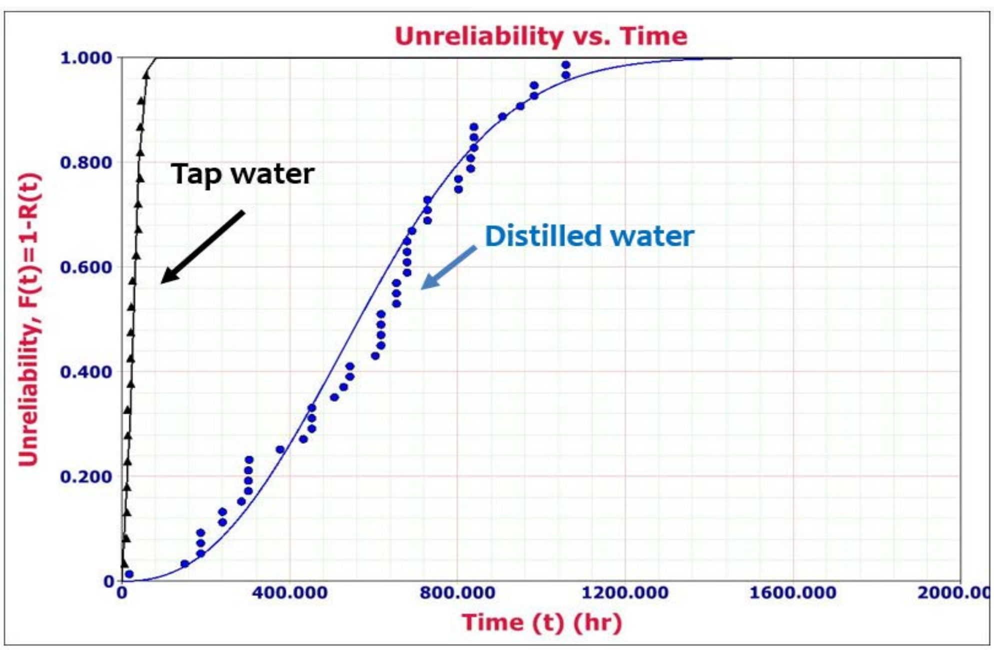



Figure 5.9. Unreliability vs time of both distilled water and tap water.

Using ALTA software, we predicted the unreliability of distilled water at different temperatures. Using the experimental data, we were able to predict at higher temperatures like 50°C and 100°C as shown in figure 5.10.

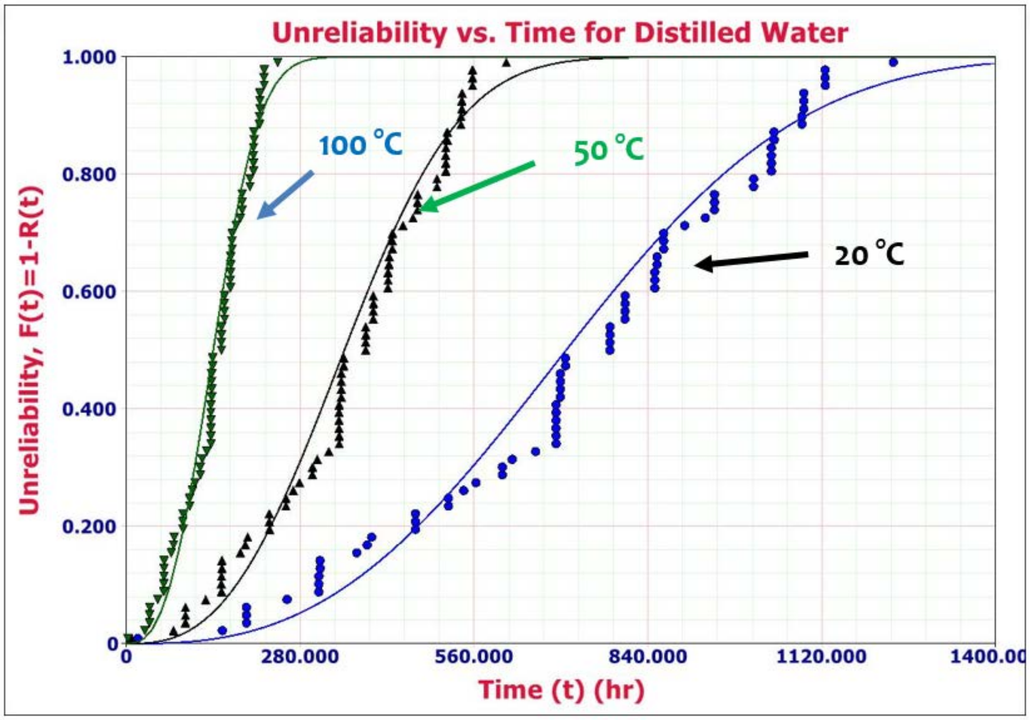



Figure 5.10. Predicted unreliability vs. time for distilled water at higher temperatures.

Similarly, the tap water experiment data was analyzed to predict the unreliability at various temperatures. In figure 5.11 we can see the unreliability at various temperatures.

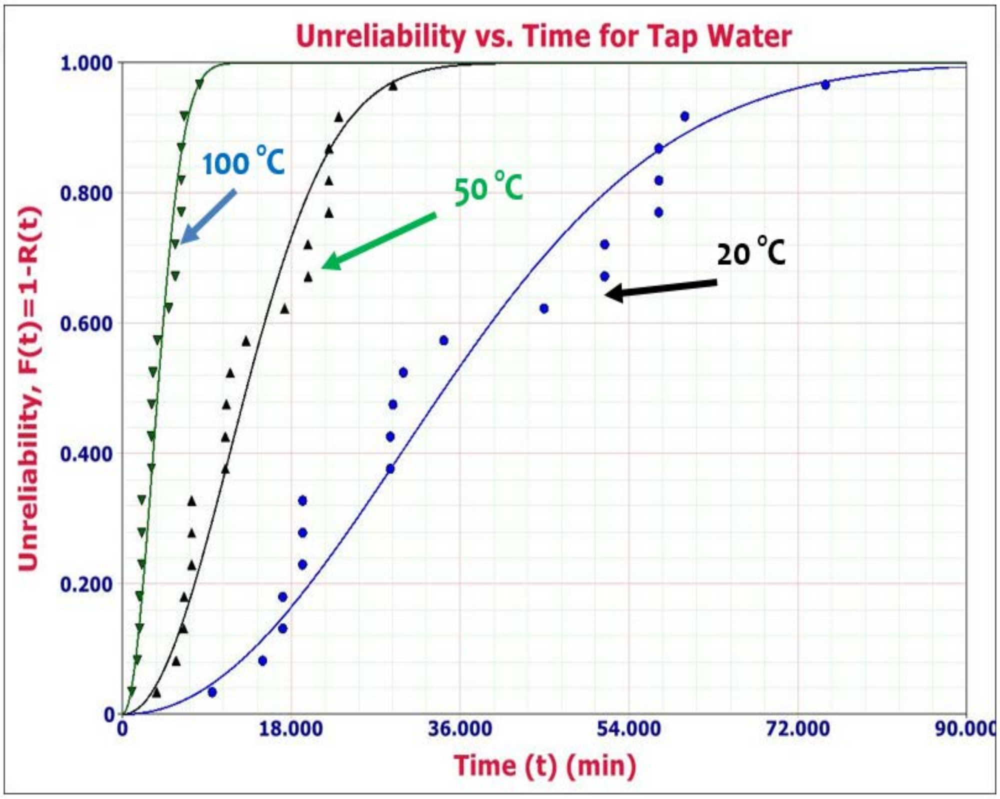



Figure 5.11. Predicted data of unreliability at various temperatures.

Figure 5.12 and figure 5.13 shows how 3D plot analysis was done for water experiment. We plotted the unreliability of both distilled water and tap water over a period of time at certain temperatures.

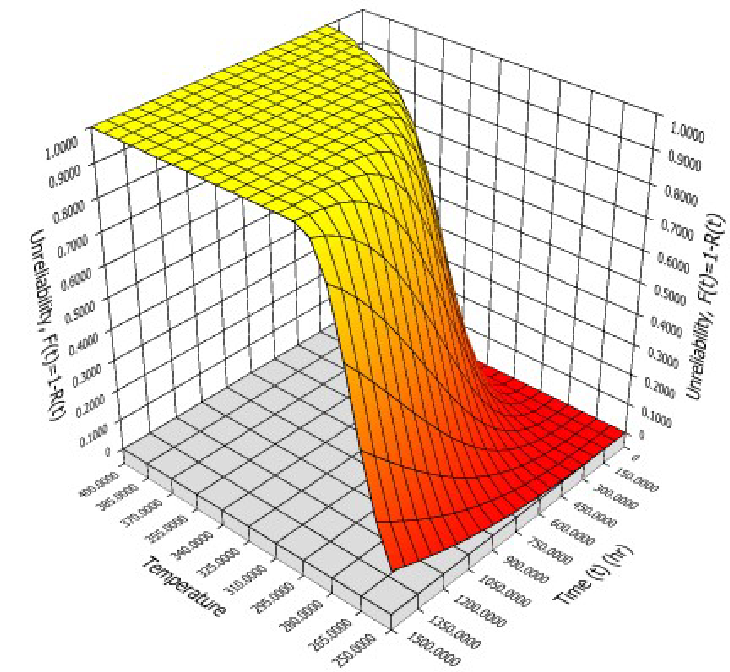



Figure 5.12. 3D plot of distilled water Unreliability.

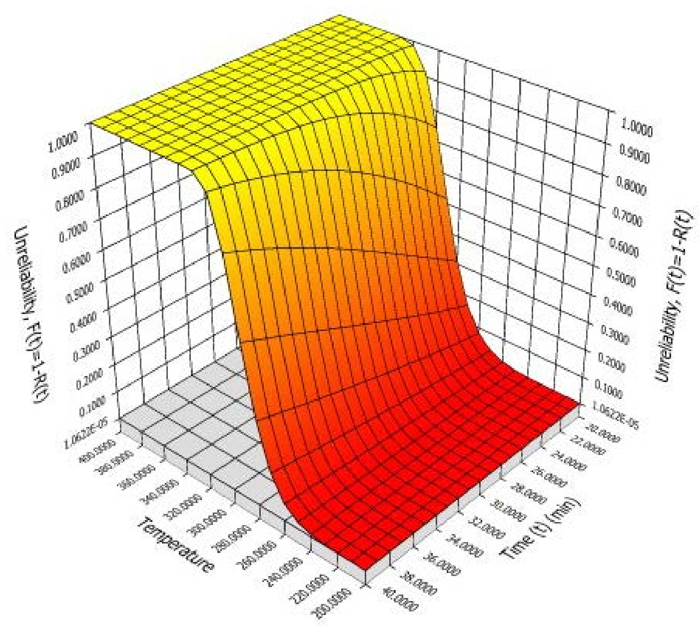



Figure 5.13. 3D plot of tap water unreliability.

Further results were calculated using ALTA software. The obtained results were mentioned in table 5.6

Table 5.6. Results obtained from ALTA.

| | Distilled water | | Tap water | |
|---|---|---|---|---|
| | 20°C | 40°C | 20°C | 40°C |
| MTTF using ALTA (hrs) | 720 | 444 | 0.6 | 0.31 |
| B10 Life (hrs) | 357 | 221 | 0.232 | 0.12 |
| AF | 3.61 | 2.2 | 5.7 | 2.97 |
| Reliability at 50hrs (%) | 99.9 | 99.8 | 1E^-99 | 1E^-99 |
| Failure rate at 50hrs (%) | 0.003 | 0.009 | 32520 | 127762 |

## 5.4 Salt Water Experiment Results

Transistors failed very fast in salt water. Figure 5.14 shows how salt crystals are formed after water is evaporated over a period.

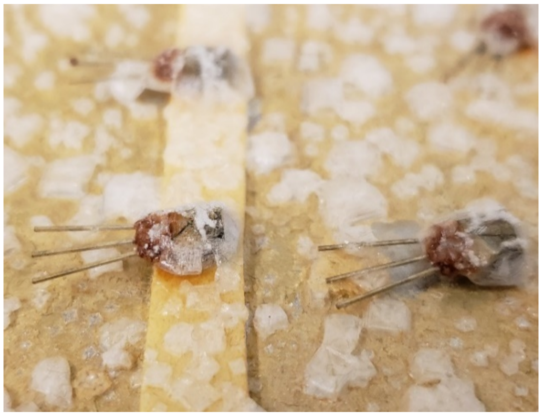


Figure 5.14. Salt crystal formed after a water evaporated in salt water experiment.

# 6. CONCLUSION AND FUTURE WORK

## 6.1 Conclusion

This thesis is based on the experimental data obtained by conducting accelerated life testing on transistors. We analyzed the data obtained from the experiment and investigated the environmental effects like temperature, humidity and water on semiconductors like transistors. The objective of this thesis was to analyze the accelerated life testing of the semiconductors and study how temperature and water effect the transistors. From the study we created a MATLAB code to analyze the experimental data and calculate Acceleration Factor (AF), Mean Time to Failure (MTTF). For further verification we used Reliasoft ALTA software to verify our results. By using ALTA software we were able analyze the data and calculate many results.

Experimental results that were obtained are all transistors failed within 82 hours at 250°C and within 600 hours at 200°C. With this data, prediction of the life time of a transistor can be done at any given temperature. By analyzing the data we can calculate the results like mean time to failure (MTTF), acceleration factor (AF) etc.

The distilled water experiment results and salt water results were obtained and analyzed to predict the life time. Effects of water corrosion on the transistors is primary cause of failure in transistors. Salts affect the transistor legs and corrode the metals.
At higher temperatures the failure of the transistors are faster.

## 6.2 Future Work

Further environmental related experiments can be conducted and analyzed to predict the life time of semiconductors. Further experiments can be conducted using chemicals and humidity as factors. With all the environmental factors, an accurate prediction of lifetime of semiconductor can be calculated.

# APPENDIX A. MATLAB CODE

**CODE:**

```
%2020 07/07


clear all
close all


x=[108
120
120
132
156
168
180
192
192
192
192
286
310
310
334
358
408
456
456
456
480
480
504
528
528
552
576
576
```

```
600
600
24
40
44
44
44
44
48
48
48
48
48
52
52
52
56
56
60
60
60
60
60
64
64
68
72
72
76
80
82
82];


%Find Parameters of Likelihood using mle
k = (8.617330350*(10^(-5)));
%In Electron volts/Kelvin

% T = 323.15*ones(42,1);
```

```
T = [473*ones(30,1);523*ones(30,1)];

% T is Temperature in Deg. Kelvin
% T = 50 Deg. Celcius
% a = (C*exp(E/(k*T)));
options = statset('MaxIter',30000,'MaxFunEvals',6000);

custpdf = @(x,b,C,E) (b./(C*exp(E./(k.*T)))).*((x./(C.*exp(E./(k*T)))).^(b-1)).*(exp(-
(x./(C.*exp(E./(k.*T)))).^b));

est_para1 = mle(x,'pdf',custpdf,'start',[1E-5 9E-10 1E-5],'options',options);

%%%%%%%%  Compare CDF data of 473 K with optimized parameter
equation  %%%%%%%%%%%
x1=[108
120
120
132
156
168
180
192
192
192
192
286
310
310
334
358
408
456
456
456
480
480
504
528
528
552
```

```
576
576
600
600];


b=est_para1(1);
C=est_para1(2);
E=est_para1(3);
k = (8.617330350*(10^(-5)));
T = 473;

z=[100:1:650];
pdf1=(b./(C*exp(E./(k.*T)))).*((z./(C.*exp(E./(k*T)))).^(b-1)).*(exp(-
(z./(C.*exp(E./(k.*T)))).^b));
cdf1=cumsum(pdf1);
cdf_est=cdf1/cdf1(end);


figure;
[f,d1] = ecdf(x1); plot(d1,f,'*'); %CDF
hold on
plot(z,cdf_est)
legend('Data','Model')
xlabel('Time (Hours)')
ylabel('Cumulative Density Function)')

%%%%%%%%  Compare CDF data of 523K with optimized parameter
equation  %%%%%%%%%%%%
x2=[24
40
44
44
44
44
48
48
48
48
48
```

```
52
52
52
56
56
60
60
60
60
60
64
64
68
72
72
76
80
82
82];

b=est_para1(1);
C=est_para1(2);
E=est_para1(3);
k = (8.617330350*(10^(-5)));
T = 523;

z=[10:0.1:100];
pdf1=(b./(C*exp(E./(k.*T)))).*((z./(C.*exp(E./(k*T)))).^(b-1)).*(exp(-
(z./(C.*exp(E./(k.*T)))).^b));
cdf1=cumsum(pdf1);
cdf_est=cdf1/cdf1(end);


figure;
[f,d1] = ecdf(x2); plot(d1,f,'*'); %CDF
hold on
plot(z,cdf_est)
legend('Data','Model')
xlabel('Time (Hours)')
ylabel('Cumulative Density Function)')
```

```
%%%%%%%%  Predic CDF data of 423K with optimized parameter
equation  %%%%%%%%%%%

b=est_para1(1);
C=est_para1(2);
E=est_para1(3);
k = (8.617330350*(10^(-5)));
T = 313;

z=[10000:1:28000000];
pdf1=(b./(C*exp(E./(k.*T)))).*((z./(C.*exp(E./(k*T)))).^(b-1)).*(exp(-
(z./(C.*exp(E./(k.*T)))).^b));
cdf1=cumsum(pdf1);
cdf_est=cdf1/cdf1(end);

figure;
plot(z,cdf_est)

%%% Calculation of acceleration factor for 200 assuming we do not have experimental values of
200 %%%

T_use=200+273; %Unit= K
T_stress=250+273; %Unit= K
AF=exp(E/k*(1/T_use-1/T_stress))

% Lifetime of transistor at 200 C
MTTF_250=55; %hrs
MTTF_200=AF*MTTF_250
MTTF_200_day=MTTF_200/24
MTTF_200_year=MTTF_200_day/365


% Lifetime of transistor at 150 C basd on 250C experiment

T_use=150+273; %Unit= K
T_stress=250+273; %Unit= K
AF=exp(E/k*(1/T_use-1/T_stress))

% Lifetime of transistor at 150 C
MTTF_250=55; %hrs
```

```
MTTF_150=AF*MTTF_250
MTTF_150_day=MTTF_150/24
MTTF_150_year=MTTF_150_day/365


% Lifetime of transistor at 100 C basd on 250C experiment

T_use=100+273; %Unit= K
T_stress=250+273; %Unit= K
AF=exp(E/k*(1/T_use-1/T_stress))

% Lifetime of transistor at 100 C
MTTF_250=55; %hrs
MTTF_100=AF*MTTF_250
MTTF_100_day=MTTF_100/24
MTTF_100_year=MTTF_100_day/365


% Lifetime of transistor at 50 C basd on 250C experiment

T_use=50+273; %Unit= K
T_stress=250+273; %Unit= K
AF=exp(E/k*(1/T_use-1/T_stress))

% Lifetime of transistor at 100 C
MTTF_250=55; %hrs
MTTF_50=AF*MTTF_250
MTTF_50_day=MTTF_50/24
MTTF_50_year=MTTF_50_day/365


% Lifetime of transistor at 225 C basd on 250C experiment

T_use=225+273; %Unit= K
T_stress=250+273; %Unit= K
AF=exp(E/k*(1/T_use-1/T_stress))

% Lifetime of transistor at 225 C
MTTF_250=55; %hrs
MTTF_225=AF*MTTF_250
```

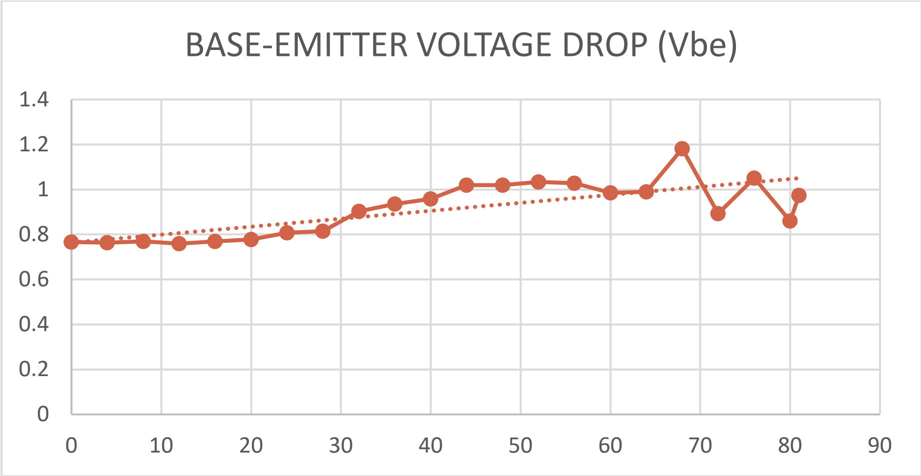
```
MTTF_225_day=MTTF_225/24
MTTF_225_year=MTTF_225_day/365

% Lifetime of transistor at 60 C basd on 250C experiment

T_use=60+273; %Unit= K
T_stress=250+273; %Unit= K
AF=exp(E/k*(1/T_use-1/T_stress))

% Lifetime of transistor at 225 C
MTTF_250=55; %hrs
MTTF_60=AF*MTTF_250
MTTF_60_day=MTTF_60/24
MTTF_60_year=MTTF_60_day/365


% Lifetime of transistor at 40 C basd on 250C experiment

T_use=40+273; %Unit= K
T_stress=250+273; %Unit= K
AF=exp(E/k*(1/T_use-1/T_stress))

% Lifetime of transistor at 225 C
MTTF_250=55; %hrs
MTTF_40=AF*MTTF_250
MTTF_40_day=MTTF_40/24
MTTF_40_year=MTTF_40_day/365
```

# APPENDIX B. EXTRA PLOTS

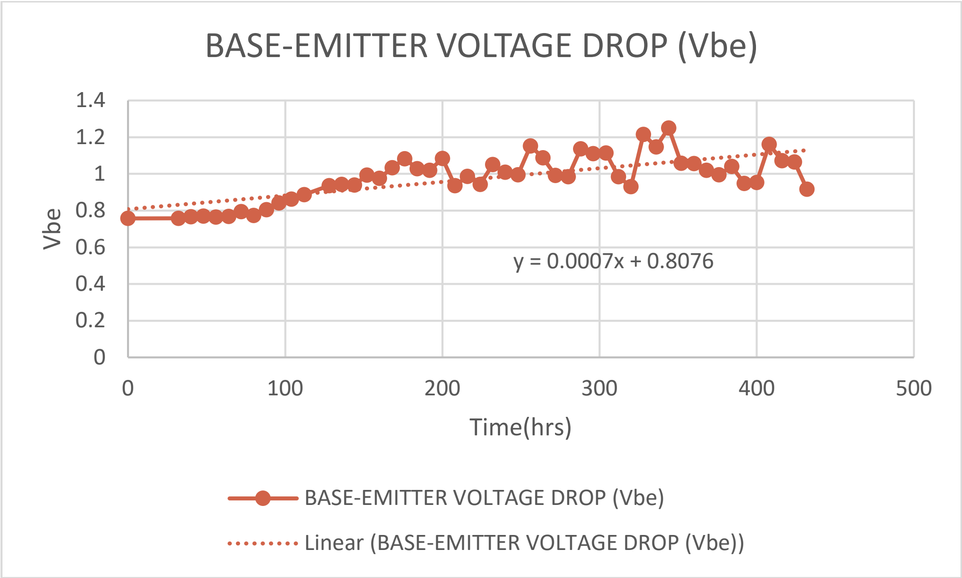
Base emitter voltage drop (Vbe) Verse Time plots

Temperature:

Plot of base-emitter voltage drop (Vbe) at 250°C was plotted and we can see that over a period of time the Vbe increases which explains the drop in current gain.

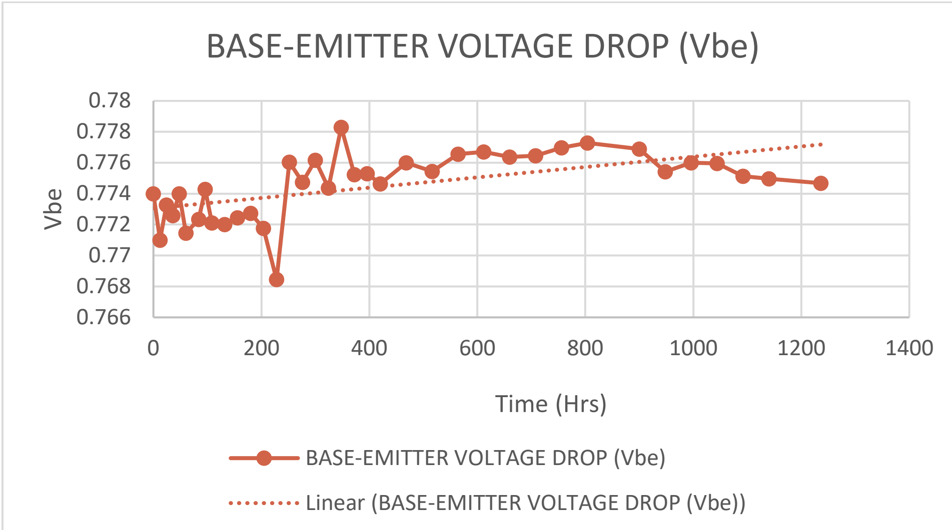



Plot of base-emitter voltage drop (Vbe) at 225°C was plotted and we can see that over a period of time the Vbe increases which explains the drop in current gain.

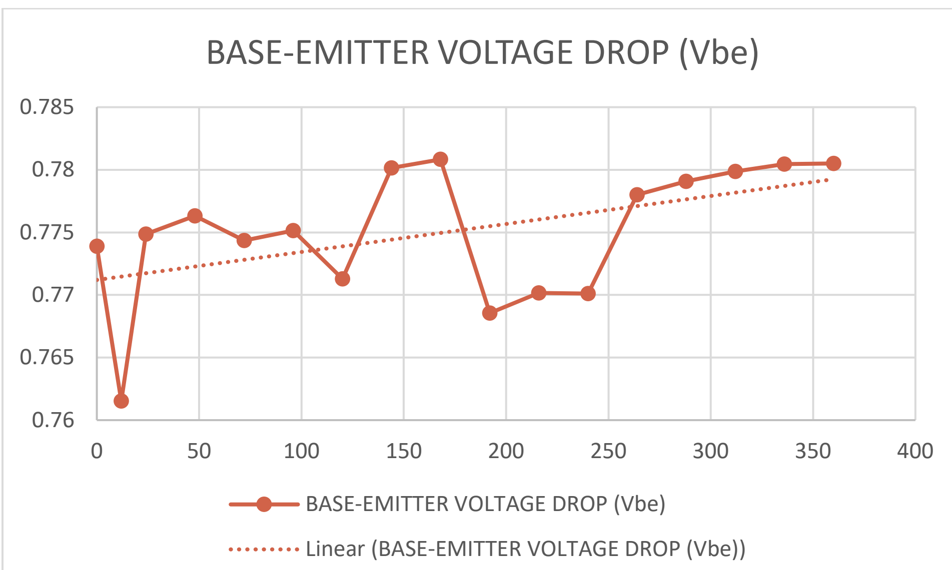


Distilled Water:

For distilled water, plot of base-emitter voltage drop (Vbe) at 20$^{o}$C was plotted and we can see that over a period of time the Vbe increases which explains the drop in current gain.




For distilled water, plot of base-emitter voltage drop (Vbe) at 20$^{o}$C was plotted and we can see that over a period of time the Vbe increases which explains the drop in current gain.



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