Degradation modelling of Voltage comparator using modified physics of failure approach
Adithya Thaduri³¹, A K Verma³², V Gopika³³, Rajesh Gopinath³⁴, Uday Kumar³⁵
# Department of Electrical Engineering, IIT Bombay, Powai, Mumbai, India
ladithya.thaduri@gmail.com
& Stord/Haugesund University College, Haugesund, Norway
2akvmanas@gmail.com
*RSD, BARC, Trombay, Bombay, India
3vgopika@barc.gov.in
4rajeshgopin@gmail.com
$Division of Operation and Maintenance, Lulea University of Technology, Lulea, Sweden
5Uday.Kumar@ltu.se

Abstract
There are several electronic systems running continuously to control and monitor the various activities in the nuclear industry and reliability and safety of these systems is taken care of utmost importance. The Neutron Flux Monitoring System has individual electronic components is one of the modules present in the signal processing unit. This unit consists of numerous components such as Optocoupler, Constant fraction discriminator, Voltage Comparator, Instrumentation Amplifier etc., and this paper studies the degradation aspects of the Voltage comparator. The prediction of reliability was conducted at earlier phases of electronics but in the present advances in the technology that methods were no longer obsolete. Hence, the other alternative, physics of failure approach laid emphasis on the root cause analysis and degradation of the performance parameters. Apart from that, we combined physics of failure approach with the statistical methods such as Design of Experiments, Accelerated testing and failure distribution models to quantify time to failure of this electronic component by radiation and temperature as stress parameters. The degradation of the performance parameter is modelled and compared using regression analysis, parametric analysis, several response plots and response surface method.

Keywords
Accelerated Testing, Design of Experiments, Physics of Failure, Radiation testing, Reliability Prediction, Voltage Comparator

1. Introduction

The nuclear industry consists of numerous critical components at various stages of the operation. The incorrect prediction of these critical components poses safety and quality issues which leads to the improper shutdown. Hence there is a need to concentrate on the prediction methodologies that was implemented in selection, installation and working conditions of the respective components.

Electronics division of BARC is engaged in design & fabrication of CMOS and BJT ASICs for nuclear pulse processing unit. These new microelectronic devices often exhibit infant mortality and wear-out phenomena in operation of the unit. The reliability of electronic systems, used in nuclear power plants, is traditionally estimated with empirical databases such as MIL-HDBK-217, PRISM etc. These methods assigns constant failure rate to the electronic devices, during their entire course of useful life. The constant failure rate assumption treats failures as random events. In the advancements in science and technology,
Electronic reliability prediction is moving towards applying the Physics of Failure (PoF) approach which illustrates information on materials, process, technology, fabrication techniques etc. It depicts competing degradation mechanisms such as electro migration, hot carrier injection, dielectric breakdown etc.-that makes a device’s useful life contrast to the predicted life by empirical methods [1]. The robust understanding of the dominant mechanisms that leads to device failure –Physics of Failure– is a more realistic approach to reliability prediction.

In practical considerations, it was not possible to get the sufficient device information and also has serious limitations from the manufacturers. There are even other limitations such as failure analysis using sophisticated instruments, amount of time and cost to conduct the physics of failure approach. In contrast, there were highly developed methodologies available in the statistical domain of the reliability prediction using data from design of experiments and accelerated testing which characterises various parameters leading to the failure. In order to get advantage from both the methodologies, a modified physics of failure approach was developed with inputs from failure characteristics of PoF approach and data and analysis of statistical approach.

Neutron Flux Monitoring System-NFMS- comprises of different modules (Pulse Translator, Logarithmic Count Rate, Mean-Square Value Processor etc) that process pulse and current signals from detector. Besides, there are modules that generate trip signals [2]. Trip signals are of 24V level and optically isolated.

It is worthwhile to study the failure mechanisms of the components involved in the signal processing chain of NFMS, as its reliability is being evaluated with conventional MIL-HDBK-217 method [3]. The physics of failure study of these components will generate reliability data that can be eventually compared with the MTBF figures provided by MIL-HDBK-217. A few components have been identified in this regard-They form a part of trip signal generation which has direct implication on safety. 4N-36: Optocoupler, AD-620: Instrumentation Amplifier, OP-07: A general purpose operational amplifier etc., are widely used in the trip modules of NFMS.

Another candidate chosen for study, Voltage comparator was used in the pulse processing circuits of NFMS. This component generates a pulse when the input voltage exceeds the threshold voltage. From the field studies and literature available [4, 5], the degradation of the output voltage was due to the effect of temperature and radiation excitation over the extended life time. Hence, both these parameters were selected as stress parameters. There was a constraint in the experimentation that both the stress parameters cannot be applied simultaneously and instead excited with one after another. The effect of individual parameter was quantified on voltage output and degradation of device was studied. In order to select the stress levels, design of experiments (DOE) to provide maximum degradation considering different runs. These stress levels was then fed to accelerating testing for extended period of time. Since there is no sufficient physical model present for this device, modelling was to be carried out by probabilistic methods such as linear regression, response surface regression and support vector machine. From these models, relation between design parameters and time to failure was observed and provided to designer for the reliability growth.

2. Block diagram for reliability prediction

2.1 Component Description

The first step in this methodology was to describe the component with all the necessary and essential information for analysing the failure and calculating the reliability indices. The sources required for the information on the component were: materials, processes, layout
diagrams, technology, architecture, design, criticality, cost, datasheet, manuals, field data and any similar item analysis that was analysed earlier.

2.2 Literature Survey and Failure Survey

To study the failure behaviour of the component, the literature survey was required to understand the behaviour of several factors that affecting the performance. The information essential for this study were: expert reviews, stress factors, failure criteria, failure mechanisms, failure modes, failure analysis, degradation analysis and other factors.

The advanced methodology, physics of failure lay emphasis on the root cause of failure inherently depends on the operational stress factors, environment and physical characteristics of the device [6]. From the information on component description and literature survey, appropriate failure phenomenon and failure criteria were selected.

2.3 Failure Phenomenon

There was several failure mechanisms reported in the literature characterized on operational environment, stress parameters, level of approach, technology etc [1,6]. There were several failure time to failure models associated with each mechanism and appropriate model was picked for the application. According to the selected component, the appropriate failure mechanism or degradation mechanisms were studied. From the literature, an appropriate failure analysis was selected to examine and illustrate the failure of the component and root cause of failure by electrical characterization or by using non-destructive testing by making use of sophisticated instruments like scanning electron microscope, infrared spectroscopy, thermal analysis etc [7]. For some of the components where there was no information on the failure mechanism, this step was need to be implemented beforehand to acquire information on failure characteristics.

2.4 Experimentation

From the acquired data, the next process of experimentation was planned for testing and reliability prediction. The desired circuitry was designed and fabricated using printed circuit board. This step also includes the number of samples, stress parameters and experimental setup for further testing of the component.

2.5 Design of Experiments

Design of Experiments was very advanced and efficient methodology to find the prominent factors, component selection and variability analysis of the component [8]. The prominent approach, Taguchi method was implemented here. In order to get best out of design of experiments, a modified methodology was designed as two-step DOE. In general, there was uncertainty in selecting the stress factors for design of experiments and accelerated testing. Hence, at first screening step, the test was designed to know variability of stress on
the effect of performance parameters. In the second testing step, the levels of the stress were aggressive which defines the degradation of the performance parameters.

2.6 Accelerated Testing

The input pattern obtained for degradation from modified design of experiments was applied in the accelerated testing step [9]. As from the analysis, this particular pattern leads to further degradation over the accelerated time.

2.7 Regressions and Failure Modelling

The data collected from both design of experiments and accelerated testing was used for statistical data and modelling analysis using various methods such as response surface regressions, regression methods and other tools to quantify the stress parameters and its behaviour on the performance of the device. This data was also useful for failure models obtained from failure mechanisms.

3. Voltage Comparator: Component Description

The voltage comparator consists of an operational amplifier (op-amp) which amplifies the small difference between the two input signals. The output voltage depends on the voltages between inverting input (-ve) and non-inverting input (+ve). In the general operation, one of the inputs was set to the threshold value which can be tuned by a potentiometer [10]. The Voltage comparators were not perfect devices as the operation and suffer from the intrinsic effects of Input Offset Voltage due to the fabrication constraints. This problem normally occurs when the Input voltage changes very slowly and in the order of few milli volts. The net result of the Input Offset Voltage and input base current resulted that the output transistor does not fully turn on or off when the input voltage is close to the reference voltage.

![Fig 1: Voltage Comparator](image)

4. Literature Survey and Failure phenomenon of Voltage Comparator

Failure possibly happened due to the degradation of internal transistor parameters with the applied stress parameters. By the physics of failure approach, the stress parameters affect the transistors to change their behavior of electrical h-parameters. Commonly, when an electrical or temperature stress applied on the transistor, it develop reverse current from emitter to base to increase in such a way to degrade the performance of output electrical characteristics such as collector current and output voltage. If the values of this device parameter vary, the effective voltages and currents tend to vary at the larger levels of the operational amplifier and output pulse width changes. If the value of the output voltage was not sufficient to generate signal to the next component, it was considered as failure. The failure criterion was selected when output voltage reduces to 5% of its initial value with inputs from the field.
A. Effect of Temperature

The temperature dependence of bipolar transistors depends on a multitude of parameters affecting the bipolar transistor characteristics in different ways. Important effect is the temperature dependence of the current gain. Since the current gain depends on both the emitter efficiency and base transport factor [4].

The emitter efficiency depends on the ratio of the carrier density, diffusion constant and width of the emitter and base. As a result, it is not expected to be very temperature dependent. The carrier densities are linked to the doping densities. Barring incomplete ionization, which can be very temperature dependent, the carrier densities are independent of temperature as long as the intrinsic carrier density does not exceed the doping density in either region. The width is very unlikely to be temperature dependent and therefore also the ratio of the emitter and base width. The ratio of the mobility is expected to be somewhat temperature dependent due to the different temperature dependence of the mobility in n-type and p-type material.

The base transport is more likely to be temperature dependent since it depends on the product of the diffusion constant and carrier lifetime. The diffusion constant in turn equals the product of the thermal voltage and the minority carrier mobility in the base. The recombination lifetime depends on the thermal velocity. The result is therefore moderately dependent on temperature. Typically the base transport reduces with temperature, primarily because the mobility and recombination lifetime are reduced with increasing temperature. Occasionally the transport factor initially increases with temperature, but then reduces again.

Temperature affects the AC and DC characteristics of transistors. The two aspects to this problem are environmental temperature variation and self-heating. Some applications, like military and automotive, require operation over an extended temperature range. Circuits in a benign environment are subject to self-heating, in particular high power circuits.

Leakage current ICO and β increase with temperature. The DC β hFE increases exponentially. The AC β hfe increases, but not as rapidly. It doubles over the range of -55°C to 85°C. As temperature increases, the increase in hfe will yield a larger common-emitter output, which could be clipped in extreme cases. The increase in hFE shifts the bias point, possibly clipping one peak. The shift in bias point is amplified in multi-stage direct-coupled amplifiers. The solution is some form of negative feedback to stabilize the bias point. This also stabilizes AC gain [4].

As from the studies from BJT technology, temperature and radiation is selected as stress parameters. The emitter and collector current of npn BJT is given as Equation (1) and (2).

\[ I_E = I_{ES} \left( e^{\frac{V_{CE}}{V_T}} - 1 \right) \]  

\[ I_C = \alpha_T I_{ES} \left( e^{\frac{V_{CE}}{V_T}} - 1 \right) \]  

The output voltage VCE is given as in (3)

\[ V_{CE} = V_{CC} - I_c R_{eff} \]

where \( R_{eff} \) is effective output resistance at the output, \( I_{ES} \) = reverse saturation current at base-emitter diode, \( \alpha_T \) = common base forward short circuit gain, \( V_T = \) Thermal Voltage kT/q, \( V_{BE} \) = base-emitter Voltage, \( V_{CE} \) = base-collector Voltage, \( V_{CC} \) = Source Voltage typically 5V/10V.

In Eber-Moll Model, IC grows at about 9%/°C if you hold VBE constant and VBE decreases by 2.1mV / °C if you hold IC constant with the temperature. Since both the currents depend on temperature parameter \( V_T \), the raise in the temperature leads to vary these parameters which finally lead to degrade the performance of component.
B. Effect of Radiation

Another stress parameter which degrades the BJT devices is β-radiation. Degradation of many types of bipolar transistors and circuits is known to depend strongly on dose rate. For a given total dose, degradation is more severe in low dose rate exposure than high dose rate exposure. This effect has been attributed to space charge effects from trapped holes and hydrogen related species through oxygen vacancies in base oxide. There are several hardness assurance tests and most popular has been high dose rate irradiation at elevated temperatures [5].

Although radiation exposure generally leads to grain degradation in npn and pnp devices, the mechanisms by which radiation effects their gains are quite different. Ionizing radiation degrades the current gain of npn bipolar transistors by introducing net trapped positive charge and interface traps into the oxide base. This positive oxide trapped charge spreads the emitter-base depletion region into the extrinsic base results in increase of base recombination current under forward-bias operation at the junction. Radiation-induced interface traps, especially those near mid-gap, serve as generation-recombination centers through which recombination current in the base is further increased due to enhanced surface recombination velocity. In pnp transistors [6], near-midgap interface traps in the base oxide also increase the base current by surface recombination. Compared with npn transistors, radiation-induced net positive oxide trapped charge can mitigate gain degradation by creating an imbalance in carrier concentrations at the surface of the base.

From the statistical results explained in et al. Witczak [5], Current gain degradation grows worse with decreasing dose rate regardless of dose. Excess base current, an increase in base current due to radiation exposure, increases gradually with decreasing dose rate. This effect is due to weak dependence of excess base current on radiation-induced defect densities at large total dose. Changes in collector current as compared to base current is small because it provides meaningful assessment of amount of gain degradation while relating closely to the physical mechanisms, excess base current is a convenient parameter to evaluate radiation-induced damage in these devices [5].

Although much progress has been made in understanding the effects of dose rate and temperature on radiation-induced bipolar gain degradation, still there is ambiguity in selecting the optimum values for assurance testing. From the analysis carried out by Ronald [13], the combined influence of both radiation and temperature has considerable dependence on gain degradation and excess base current enhancement. The combined effect of temperature and radiation results in degradation of pulse amplitude of Voltage Comparator.

5. Experimentation, Design of Experiments and Accelerated Testing

A printed circuit board was developed for five samples of LM311 of each with the testing circuit of voltage comparator as shown in fig 2. In the earlier section it was studied that temperature and radiation was considered as stress parameters and also noted that both the parameters cannot be applied simultaneously. Initially each lot was subjected to 4 steps of radiation 0, 3Kgray, 6Kgray and 9Kgray respectively. Then each lot was ramped from 30°C to 90°C in steps of 5°C from the source of temperature controller. Then design of experiments was conducted to achieve and select a run which poses higher degradation of the output voltage. This particular run further fed to the accelerated testing up to several hours to impact further degradation. The table 1 was the results for both the exposure of radiation and temperature at different stress levels. This result was graphically depicted in the figure 3. This information showed that increase of both radiation and temperature leads to the degradation of the output voltage.
The stress level of 9Kgray of radiation and 90\(^\circ\)C of temperature has higher degradation and this stress levels was controlled at extended period of time by conducting accelerated testing. The Table 2 and Figure shows the degradation of the output voltage with time.

**Table 2: Impact of accelerated time at each radiation step (T = 90\(^\circ\)C)**

<table>
<thead>
<tr>
<th>R/T</th>
<th>0</th>
<th>50</th>
<th>100</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.9654</td>
<td>4.9544</td>
<td>4.9434</td>
<td>4.9318</td>
</tr>
<tr>
<td>3</td>
<td>4.9452</td>
<td>4.9346</td>
<td>4.921</td>
<td>4.9086</td>
</tr>
<tr>
<td>6</td>
<td>4.9138</td>
<td>4.9016</td>
<td>4.8904</td>
<td>4.8784</td>
</tr>
<tr>
<td>9</td>
<td>4.8842</td>
<td>4.8728</td>
<td>4.8604</td>
<td>4.848</td>
</tr>
</tbody>
</table>
From the Table 2 and figure 4, the output parameter further degrades over the accelerated time. This procedure was extended until the voltage comparator lead to failure (i.e., 5% of initial value). The 3D plots in fig 5, interactions plot in fig 6 and main effects plot in fig 7 characterizes the effect of stress parameters on the output voltage. These parametric analysis illustrates that the increase in all the stress parameters leads to higher degradation and also shows the non-linear and independent behaviour of each stress parameter.

![Graph](image.png)

**Fig 4:** Impact of accelerated time at each radiation step ($T = 90^\circ C$)

![Graph](image.png)

**Fig 5:** 3D surface plots of stress parameters with output voltage
Identify the Best Factor Settings with Analyze Variability

A traditional analysis of a designed experiment helps you to determine the factor settings that produce the best average response [11]. But to identify the factor settings those not only perform well on average, but also perform the most consistently can be found out by using this variability analysis available in Minitab. The pareto chart was generated by considering the standard deviations calculated at each of different run subsequently finding out the the parameters or interaction of the parameters that defines higher variability. From the data obtained from the experimentation, it was found out that the radiation was the dominant stress parameter for variability and quality factor as shown in fig 8.
6. Regression and Data Modelling

The response surface regression procedure fits a quadratic response-surface model with the input and output parameters, which is useful in searching for factor values that optimizes the response according to the application. The following features make it preferable to other regression procedures for analysing response surfaces: automatic generation of quadratic effects, a lack-of-fit test, and solutions for critical values of the surface, eigen values of the associated quadratic form, a ridge analysis to search for the direction of optimum response [12]. The response equation (4) that was generated from the above data with the interactions and its coefficients as

\[ V = 4.98791 - 0.00650306R + 8.96032E^{-05}T - 2.07619E^{-04}t - 3.32099E^{-04}R^2 - 6.68796E^{-06}T^2 - 8.01589E^{-08}t^2 + 2.69630E^{-06}RT - 1.27303E^{-06}Rt \]  

The time to failure was calculated with the required value of failure criteria and operating parameters in the above equation.

7. Conclusion

In this paper, the need of reliability study of voltage comparator was studied. Furthermore, reliability and degradation mechanisms that affects the performance of output pulse with temperature and dose rates acts as input characteristics was properly explained and verified with the experiments. A modified physics of failure approach considering the inputs from the PoF analysis and statistical analysis was implemented on the testing of Voltage Comparator. Design of experiments and Accelerated testing was carried out and the data obtained from these methods was characterized by several parametric analyses. The failure model was obtained from the more accurate response surface regression considering the above data.
8. References


