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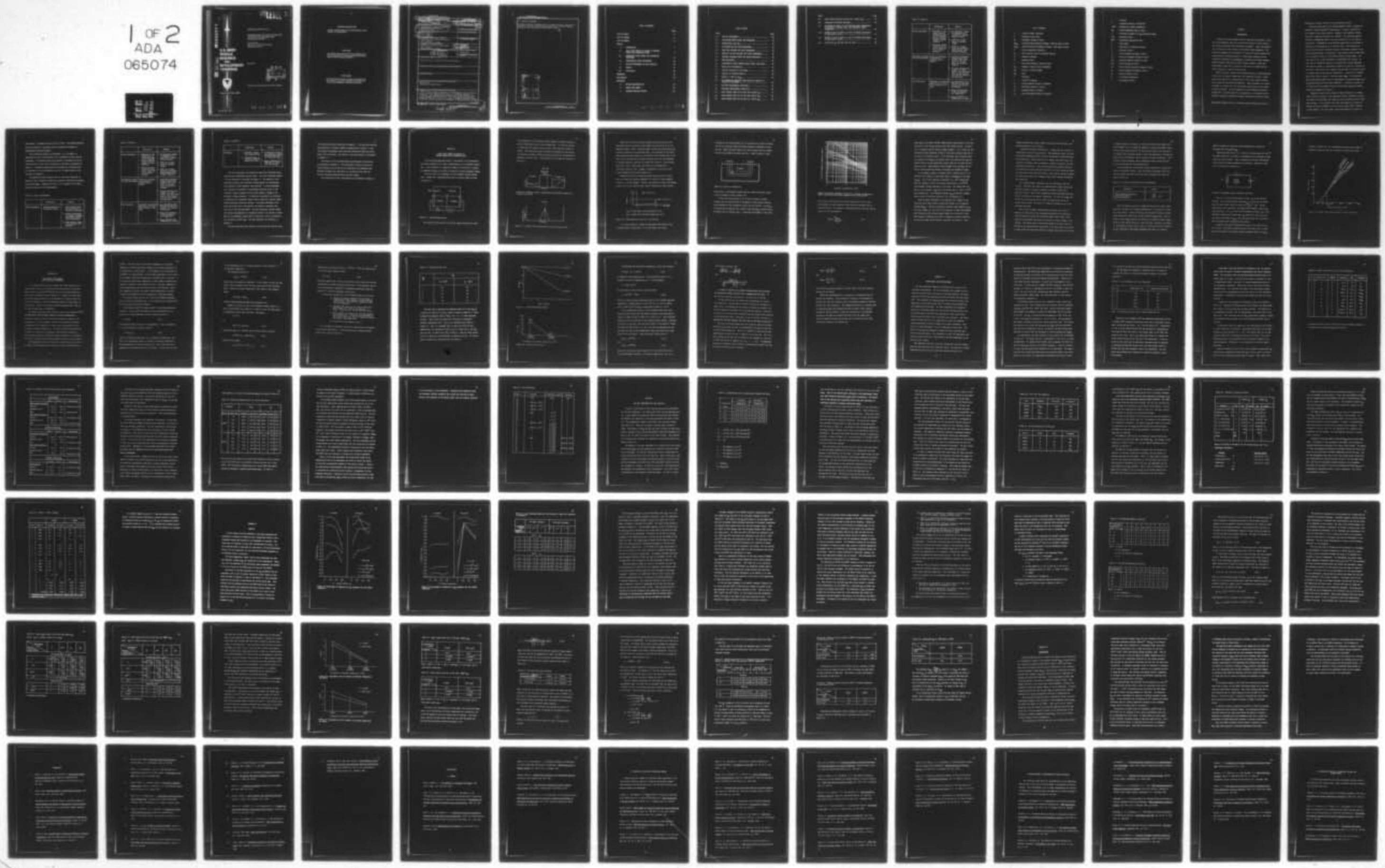

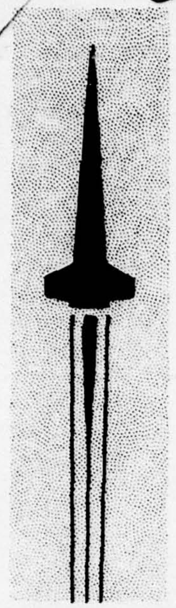

U.S. ARMY MISSILE RESEARCH AND DEVELOPMENT COMMAND

Redstone Arsenal, Alabama 35809

TECHNICAL REPORT E-78-14

COMBINED EFFECT OF AGING AND NEUTRON IRRADIATION ON SEMICONDUCTOR AVALANCHE VOLTAGE

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April 1978

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This report presents the results of an investigation into the combined effects of neutron irradiation and aging on the breakdown voltage in transistors. The combined effect was found to be a simple additive effect. It was determined from other results of the investigation that transistor parameters change as a function of the number of times the breakdown voltage is measured and that the gain of the transistor is degraded more if the device

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has been aged before irradiation than if the device has been irradiated and then aged. This last result brings into question the validity of present methods of establishing neutron susceptibility levels.

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	Objectives	Results
Second experiment	1. Determine if the lowest level of reliability testing of breakdown voltage produced change in device parameter. 2. Determine temperatures for accelerated aging that do not produce failures.	1. No detectable change in parameter as a function of testing method selected. 2. 250°C for 10 days failed to produce change. 3. 300°C for 10 days produced accelerated aging without catastrophic failures.
Experimental design for main experiment	Devise an experiment to determine if a combined effect exists.	1. Selected accelerated aging stress levels of 250°, 275°, and 300°C for 20 days based on second experiment. 2. Selected neutron flux levels of 0, 10^{12}, $5x10^{12}$, and 10^{13} n/cm^2 based on the literature and the author's previous work.
Main experiment	Determine acceleration aging rate as a function of neutron flux level.	1. H_{FE} degradation was a function of both temperature and neutron irradiation. 2. BV_{CBO} was unaffected by the irradiation and temperature. 3. BV_{CBO} parameter was unaffected by testing.

LIST OF SYMBOLS

A - Arrhenius Model Intercept

B - Arrhenius Model Slope

BV - Breakdown Voltage in Volts

BV_{CBO} - Collector-Base Breakdown Voltage - Emitter Open in Volts

BV_{CEO} - Collector-Emitter Breakdown Voltage - Base Open in Volts

D - Device Degradation Function

D_n - Test Statistic Used in Normality Testing

df - Degree of Freedom

ev - Electron Volts

E - Activation Energy in Electron Volts

E_{SB} - Energy to Produce Second Breakdown

E_{SD} - Energy to Produce Damage

H_{FE} - Gain

i - Intrinsic

I - Current in Amperes

I_A - First Breakdown Current in Amperes

I_C - Collector Current in Amperes

I_R - Leakage Current in Amperes

I_S - Second Breakdown Current in Amperes

J - Junction

K - Boltzmann Constant, 8.63×10^{-5}ev

n/cm^2 - Neutrons per Square Centimeter

P_{sb} - Second Breakdown Power in Watts

Q - Intercept Parameter for H_{FE} Prediction Model

R(T) - Degradation Rate

$\tilde{R}(T)$ - Uncorrected Degradation Rate

S - Test Number

T - Temperature in Degrees Absolute

V - Voltage in Volts

V_A - First Breakdown Voltage in Volts

V_B - Junction Breakdown Voltage in Volts

V_{CE} - Collector Emitter Voltage in Volts

V_{DR} - Driven Voltage in Volts

V_R - Diode Reverse Breakdown Voltage in Volts

V_S - Second Breakdown Voltage in Volts

V_Z - Zener Voltage in Volts

Z - Correlation Coefficient

T - Acceleration Factor

CHAPTER I

INTRODUCTION

A system is always designed with its operating environment in mind. The two environments that are of particular interest in this research are neutron irradiation and overvoltage transients. These environments are of interest to both military and civilian system designers. The neutron environment can be produced in pulses from nuclear weapons and continuously from nuclear reactors. Overvoltage transients can be produced by lightning or exoatmospheric detonation of nuclear weapons. System designers must know how their systems respond to these two environments singly and in concert so that they can predict service life or design in a specific service life.

Modern electronic systems are composed primarily of semiconducting devices such as diodes, transistors, and integrated circuits. These devices are selected for incorporation in the system design based on their electrical and physical parameters. These parameters are subject to change as a function of the environment experienced and the length of time in service. One such parameter is the breakdown (avalanche) voltage (BV). The objective of this research is to determine how the breakdown voltage is affected by neutron irradiation during the normal

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*Superscript numbers refer to references listed beginning on page 73.

operating or storage lifetime of the semiconductor device.

Transistor gain (H_{FE}) is the second parameter known to change as a function of device longevity[1*] and exposure to neutron irradiation.[2] This change in gain (H_{FE}) produces a change in the breakdown voltage across the transistor (collector to emitter). The real-time aging of devices is prohibitive because real-time testing for 7 to 10 years is impractical. Consequently, an accelerated aging method is necessary to complete this investigation in a realistic time. The literature on accelerated testing was reviewed in order to determine a method to produce accelerated aging of transistors. This review indicated that there are two different types of accelerated testing in common usage. The first and by far the most prevalent is accelerated life testing. In this type of testing the devices are stressed above normal operating level and the number of catastrophic failures are noted as a function of test time. This allows one to predict the mean time to failure but does not provide data on the aging of transistors. A second set of investigations was found on aging of transistor gain (H_{FE}). No accelerated aging investigations were found on semiconductor breakdown voltage or on any semiconductors that had been irradiated. A detailed discussion of the results of the literature search in accelerated aging and neutron damage are presented in Chapter 2.

Integrated circuits are composed of many transistors on a single wafer or chip of silicon. This complexity makes it difficult to study the effect of environments and longevity on the individual device breakdown voltage. It is essential that this investigation be limited to devices that can be studied in a one-at-a-time manner with a minimum of side effects. For this reason, this investigation is limited to three types of transistors and one type of diode. The devices selected and the rationale for selecting them are described in Chapter 4, Experimental Design Development.

Once accelerated aging is accomplished, it is necessary to determine the rate of acceleration (T) to determine how much time was compressed. The Arrhenius model was selected to determine the acceleration factor or rate, and a discussion of the model is presented in Chapter 3. Accelerated aging models and statistical techniques that are pertinent to this investigation but not in common usage are also presented in Chapter 3.

Information and data obtained from the literature described in Chapters 2 and 3 indicated a method for parameter testing and achieving accelerated aging. Presented in Table 1-1 is a summary of the objectives and results of this investigation.

Table 1-1 Flow of Experiments

	Objectives	Results
First experiment	Establish methods of accelerated aging.	1. 125°C stress level was insufficient to produce acceleration. 2. Selected techniques of breakdown voltage measurement affects device parameters. 3. Diode was not affected by elevated temperature.

Table 1-1 (Cont'd.)

	Objectives	Results
Second experiment	1. Determine if the lowest level of reliability testing of breakdown voltage produced change in device parameter. 2. Determine temperatures for accelerated aging that do not produce failures.	1. No detectable change in parameter as a function of testing method selected. 2. 250°C for 10 days failed to produce change. 3. 300°C for 10 days produced accelerated aging without catastrophic failures.
Experimental design for main experiment	Devise an experiment to determine if a combined effect exists.	1. Selected accelerated aging stress levels of 250°, 275°, and 300°C for 20 days based on second experiment. 2. Selected neutron flux levels of 0, 10^{12}, 5×10^{12}, and 10^{13} n/cm^2 based on the literature and the author's previous work.
Main experiment	Determine acceleration aging rate as a function of neutron flux level.	1. H_{FE} degradation was a function of both temperature and neutron irradiation. 2. BV_{CBO} was unaffected by the irradiation and temperature. 3. BV_{CBO} parameter was unaffected by testing.

Table 1-1 (Cont'd.)

	Objectives	Results
Findings	1. Calculate accelerated aging factors. 2. Calculate BV_{CEO} at different points in device life cycle.	1. Acceleration factors and activation energy calculated for flux of 0 and 10^{12} n/cm^2. 2. BV_{CEO} calculated for 3000 days of operation and storage.

The first experiment was constructed using four different device types and two acceleration stress levels. The first experiment (Table 1-1) was conducted as described in Chapter 4. The results of this experiment indicate that different testing methods for determining the breakdown voltage parameter were required. A second experiment was conducted to determine if the minimum achievable level of the breakdown voltage parameter testing would produce a change in the breakdown voltage parameter. An additional experiment was conducted to determine the accelerated stress levels required to produce change without producing excessive failures. The second experiment determined the stress level, test method, and length of exposures that are used in the main experiment. The main experiment combines aging and neutron environments in a sequential manner in an attempt to determine if the breakdown voltage (BV) is affected by neutron irradiation as a function of device age. The main experiment is described in Chapter 5.

The main experiment was conducted, and the data was reduced using the statistical methods described in Chapter 3. The data were analyzed using Analysis of Variance (ANOVA) techniques and a paired "t" test. The changes in parameters were noted and accelerated aging was determined to have occurred. The results of the data analysis is presented in Chapter 5.

The results of the experimentation and subsequent calculations are presented in Chapter 6. The acceleration factors and the activation energies were calculated for comparison with published data. Breakdown voltages were calculated at an arbitrary time with the neutron irradiation applied before and after aging.

The conclusions of this investigation are presented in Chapter 7.

CHAPTER II

SOLID STATE THEORY AS RELATED TO NEUTRON DAMAGE AND ACCELERATED AGING

The following paragraphs present a description of the background and theory essential for a basic understanding of the breakdown phenomenon. Also presented is a numerical example of the effect of changes in breakdown voltage of a device in relation to second breakdown damage.

The first area to be addressed is the breakdown voltage phenomenon. Assume that a semiconducting diode is reverse biased as shown in Figure 2-1.

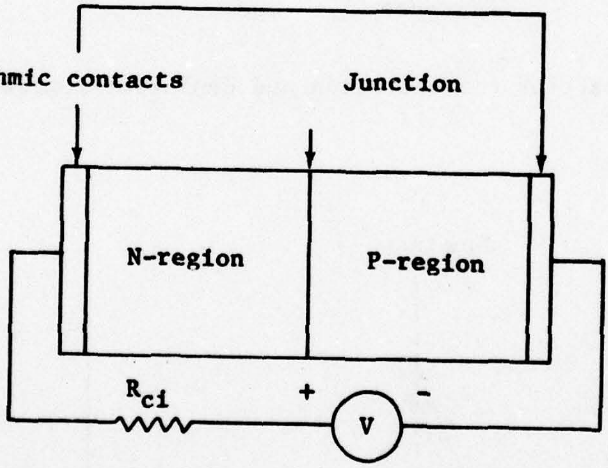


Figure 2-1 Reverse-biased diode

The electric field across the junction causes hole-electron pairs to be generated in the depletion region (Figure 2-2) which produces a current through the device called leakage (I_R). If the bias voltage is increased, the energy of the carriers in the depletion region is raised. This increased energy increases the possibility that during a scattering collision, another hole-electron pair may be generated by breaking a covalent bond. A distribution of the field can be seen in Figure 2-3.

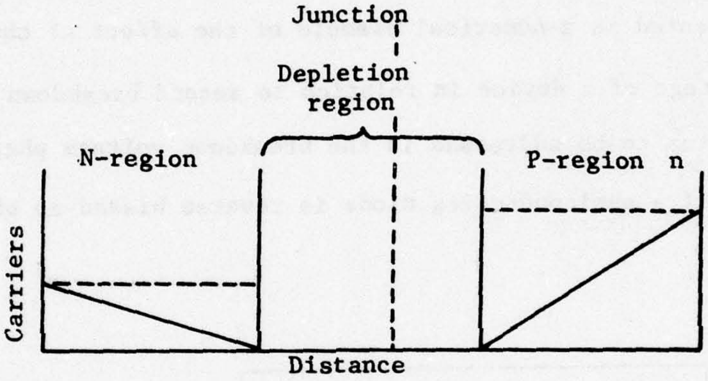


Figure 2-2 Minority carrier concentration and depletion region in a reverse-biased diode

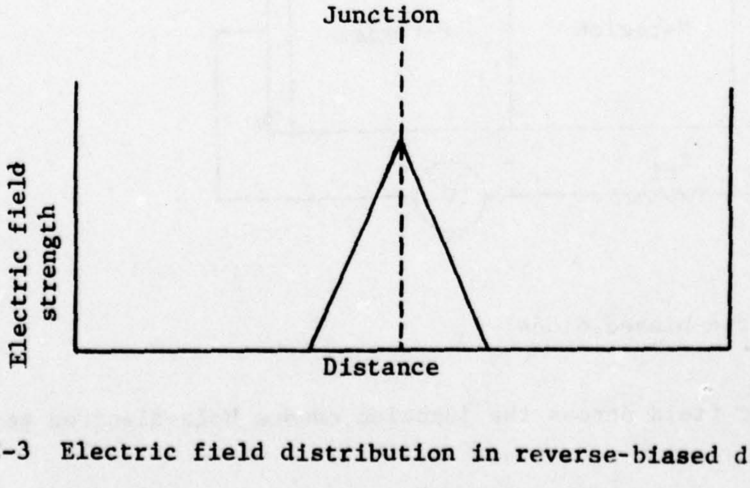
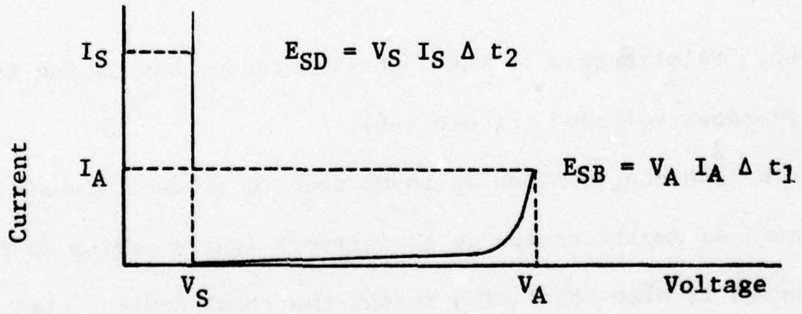


Figure 2-3 Electric field distribution in reverse-biased diode

Each hole and electron causes another hole-electron pair to be generated before the electric field sweeps the first pair out of the depletion region. Thus, a growing number of pairs are created and this process is referred to as multiplication. The threshold of the breakdown process has been found to be a function of the doping level on the side of the junction with the smaller doping level, and the breakdown is complete when the junction is flooded with carriers. Second breakdown occurs after a device has been taken into breakdown for a sufficient period of time. Damage or degradation occurs only after second breakdown has occurred (Figure 2-4).

Budenstein's[3] work in second breakdown indicates that a device must be carried into second breakdown for a period of time (normally 10 μsec) to produce damage. Further, the assertion is made that damage cannot occur to the junction until second breakdown has been reached.



E_{SB} = energy where second breakdown occurs

E_{SD} = energy where threshold damage may occur

Figure 2-4 Characteristic curve for a P-N junction

It is now necessary to expand the discussion from simple diode to actual device construction. It is well known that diodes, transistors, and other devices are not constructed as shown in Figure 2-1 but are junctions which have been diffused or implanted in pure silicon. These junctions (Figure 2-5) have corners that are rounded and can be described as having radii (R). Larin[2] presents a chart which gives a relationship between junction radius and doping levels to give breakdown voltages (Figure 2-6).

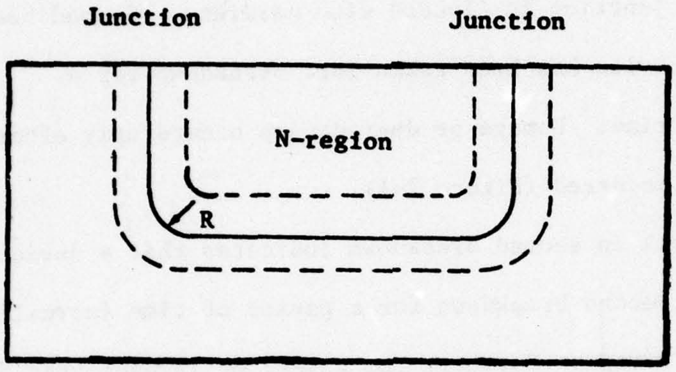


Figure 2-5 Junction construction

If more than one junction is to be used to produce a useful function such as amplification in transistors (three region devices), then breakdown is also considered across the total device. Let BV_{EBO} be emitter-base breakdown with collector open and BV_{CBO} collector-base breakdown with the emitter open. (A detailed development of the solid

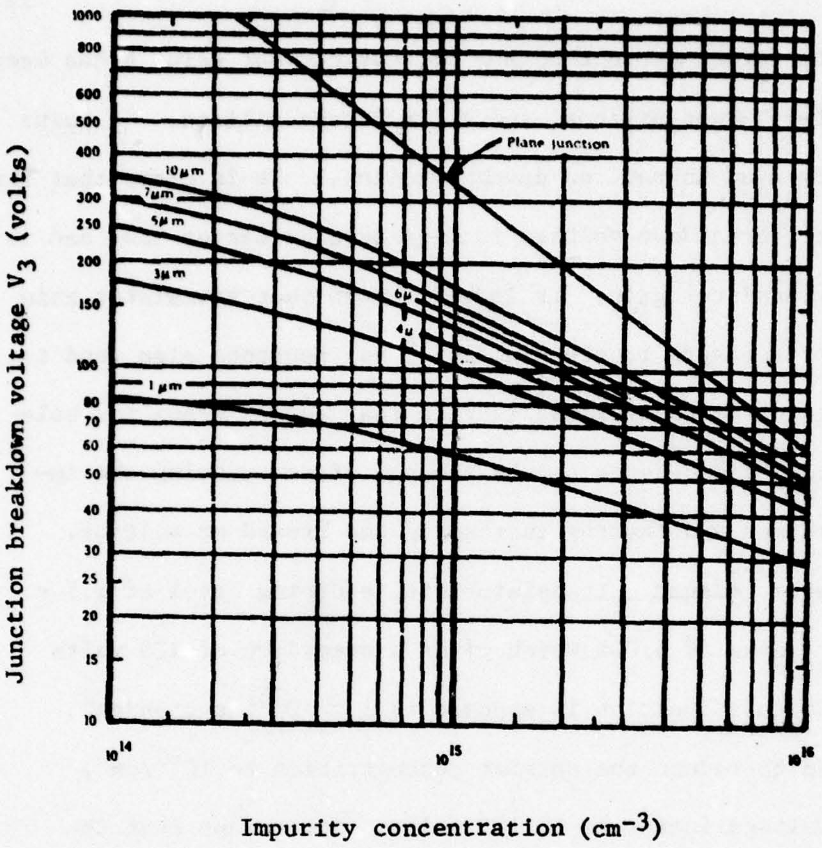


Figure 2-6 Junction breakdown voltages as a function of doping on lightly doped side and various junction radii (from Larin[2])

state theory associated with multiple junctions has not yet been accomplished, but some empirical theory has been developed and is discussed below.) If breakdown is considered across the total device, (BV_{CEO}) can be approximated by

$$BV_{CEO} = \frac{BV_{CBO}}{(H_{FE})^{1/N}}, \qquad (2\text{-}1)$$

where H_{FE} is the direct current common emitter current gain, N has been found to be 6 for N-type silicon, and 4 for P-type silicon. (A value of 5 is normally used in neutron damage studies.) It is clear that the collector-emitter breakdown voltage is less than collector-base and is a function of transistor gain. It is well known that transistor gain is a function of exposure to neutron flux,[4] but neutrons also tend to produce defects in the crystalline lattice that act as traps for hole-electron pairs. These defects can be thought of as reducing the impurity concentration and thereby increasing the breakdown voltage.

As an example, assume a transistor with a doping level of $1.5 \times 10^{15}/cm^3$ and a radius of 6.0μm which gives a breakdown of 120 volts (BV_{CBO}). Now if this junction is exposed to 1×10^{15} neutron/cm^2, which is assumed to reduce the carrier concentration to $10^{15}/cm^3$, the breakdown voltage increases to 135 volts. Now assume that the gain of the transistor (H_{FE}) was 50 initially and 4.6 after 1×10^{15} n/cm^2 irradiation. The breakdown voltage BV_{CEO} would have changed from 55 volts to 100 volts using an N of 5 in Equation 2-1.

From the above discussion it is apparent that changes in the transistor gain (H_{FE}) produce significant change in the breakdown voltage (BV_{CEO}). Neutron irradiation produces large changes in H_{FE}, but these changes can also occur from exposure to other environments. Kang[5] indicates that the gain (H_{FE}) changes as a function of time. This change is normally attributed to changes in surface properties at the point where the PN junction intersects the surface. Other common problems that produce change in devices are bond failure and metal penetration of the silicon.

Consider the surface problem first. Assume that the silicon is coated with an oxide for passivation. The passivation layer is porous and contains numerous defects caused by the method of application and basic properties. These defects act as charge traps which can be envisioned as forming a path from anode to cathode in parallel with the semiconducting material. Any potential difference between the anode and cathode will cause tunneling from defect to defect along the shortest path between the anode and cathode. This forms a separate conducting path which appears as a leakage current which reduces the gain of the transistor.

In a similar manner, the metal ions are transferred into the silicon. The metal ions reduce the mean-free path length between the anode and cathode, causing an increase in leakage current and a decrease in gain. Both of the degradation methods described above are directly affected by the ambient temperature. At 25°C the charge formation is a slow process, but at 300°C it takes several hours to several days to form. The source of charge is believed to be at the oxide-gas interface.

The process of change described above requires some level of energy to be delivered to the semiconducting devices for activation. Let this energy be called the activation energy E(ev), which is defined as the potential that must be overcome to produce change in the devices. The lowest value of activation energy is 0.69 ev, which is defined as the radiationless transition[6] or the point where the lattice in some solid state materials reaches an energy level sufficient to emit a single frequency of energy. At the other extreme, the highest activation energy is 15 ev, which is required to cause displacement effects in the bulk silicon lattice.[2] No data can be found in the literature to indicate the activation energy to start the processes of filling the defect in the crystalline lattice caused by neutron irradiation. This process, called annealing, starts immediately after irradiation and can be accelerated by elevated temperature.

The investigation of activation energy required for a particular failure is somewhat limited. Peck and Zierdit[7] published a few activation energies associated with particular mechanisms and these are shown in Table 2-1.

Table 2-1 Activation Energy Levels and Mechanisms

Mechanism	E(ev)
Surface-inversion failures	1.02
Au-Al bond failures	1.02 - 1.04
Metal penetration	1.77

With the physical reason for change defined and the energy range required to produce such change established, it is desirable to determine what effect a change in gain H_{FE} and subsequent changes in breakdown voltage will have on the second breakdown damage level. The decrease in gain (H_{FE}) produces an increase in breakdown voltage (BV_{CEO}), which at first glance should be a more desirable condition, but damage to semiconductors occurs when a device is driven into second breakdown **V_s as a function of the energy dissipated and there is a range of** applied voltages for which the energy dissipated in a device is increased with increased BV_{CEO}.

Damage has been found to be a function of pulse power and time.[8,9] The power delivered to a device is determined by the breakdown voltage times the driven current. This is consistent with early discussions on the effects of second breakdown of junctions. Consider an equivalent circuit shown in Figure 2-7.

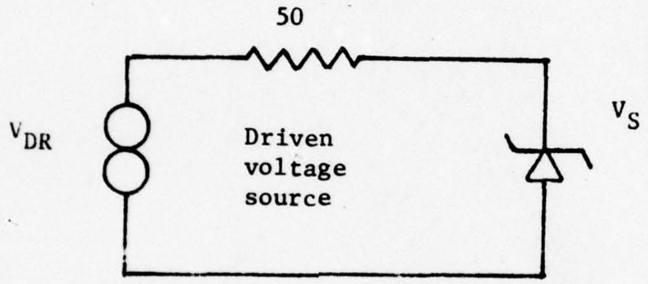


Figure 2-7 Breakdown voltage equivalent circuitry

Now if V_S is the diode breakdown voltage, V_{DR} is the driving voltage, and the characteristic impedance is 50, then one can determine the power driven into the device as $\frac{V_{DR} - V_S}{50}(V_S)$. As the neutron dose level increases, the theoretical breakdown voltage (V_S) also increases. Let V_{S1} be the initial breakdown voltage, V_{S2} be the breakdown voltage after irradiation, V_{DR} exceed the sum of V_{S1} and V_{S2}, which is defined as V_{DRO}, then the power driven into the device will be greater after irradiation than before.

Assume for the sake of discussion that V_{S1} is 55 volts and V_{S2} is 75 volts. Then after breakdown occurs, more power will be dissipated in the device for driving voltages exceeding 130 volts (V_{DRO})

as shown in Figure 2-8. It is therefore essential that changes in breakdown voltage be known as a function of neutron dose level.

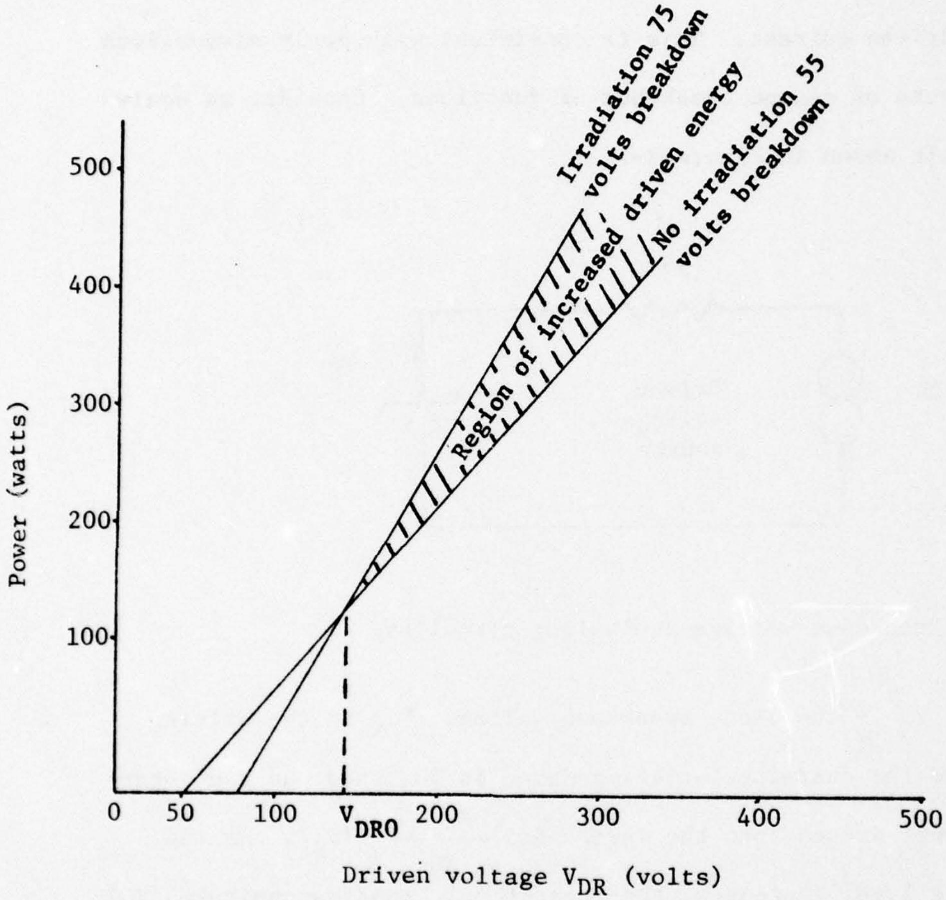


Figure 2-8 Neutron irradiation effects on power dissipation

CHAPTER III

ACCELERATED AGING MODELS AND STATISTICAL TECHNIQUES

It is apparent that the time required for normal aging is prohibitive and a method of accelerating the aging process is required. Walsh, Endicott, and Best[10] indicate that any accelerated aging process must be conducted in such a manner as to produce the same effect that normal aging would have on the parameter of interest, which requires the assumption that all mechanisms undergo the same degree of acceleration. Hence, in an ideal accelerated aging process, time is the only variable that is compressed.

The stress environment that has been found in the literature,[11-14] and described in the previous chapter is elevated temperature. Accelerated aging at elevated temperature presents a problem of interpretation of device parameter test data and from this test data, interpretion of the behavior of a device over long periods of time at normal operating temperatures. In order to gather sufficient data to develop a prediction of degradation during normal operation, a device should experience accelerated aging (stressing) at a minimum of two levels, and three levels would determine linearity of the process.

The temperatures that are selected for stress must be sufficiently high to cause parameter drift but not too high to produce device failure. The lower limit of the stress temperature is the lowest temperature at which significant changes in the device parameters can be observed over a test period. A low estimate of this temperature is preferable to a high estimate, as the stress temperature can be raised if no change in the device parameters is observed after a few days. If an excessively high stress temperature is used, device parameters may change too rapidly to yield significant data. The upper temperature limit depends mainly upon the eutectic point of the devices. Above this temperature, devices can suffer severe degradation or failure caused by the formation of Au-Al intermetallic compounds (plague).

The stress levels that are to be used are determined experimentally and will be described later. It is important now to discuss how the acceleration data will be modeled.

The Arrhenius model[15] is highly useful in analyzing accelerated test data. In this model the amount of device degradation D is a function of a device parameter (such as leakage current) M:

$$D = f(M). \qquad (3\text{-}1)$$

The Arrhenius model is based on two assumptions. First, degradation is a linear function of time S_K in days

$$D = R(T_j)\ S_K, \qquad (3\text{-}2)$$

where T is absolute temperature, j is a particular temperature, and R(T) is the degradation rate as a function of absolute temperature, which depends only on the stress level (i.e., the stress rate is independent of the stress history of the device). Second, the logarithm of the degradation rate is a linear function of the reciprocal of the absolute temperature.

The Arrhenius equation is

$$R(T_j) = e^{A-B/T_j}, \qquad (3\text{-}3)$$

where A and B are empirical constants. If the values of $R(T_j)$ are negative, only the absolute value of $R(T_j)$ can be used in the Arrhenius model. Taking the natural logarithm of both sides of this equation yields

$$\ln R(T_j) = A-B/T_j. \qquad (3\text{-}4)$$

A plot of this relation is known as an Arrhenius plot.

Suppose that tests are run at two different stress levels ($j = 1$ and 2) and different test times ($K = 1$ and 2) so that the same amount of degradation results from each test. This means

$$D_1 = D_2$$

or

$$R(T_1)\ S_1 = R(T_2)\ S_2. \qquad (3\text{-}5)$$

Noting that $R(T_j)$ is a function only of stress level, we obtain

$$(e^{A-B/T1})\ S_1 = (e^{A-B/T2})\ S_2. \qquad (3\text{-}6)$$

Solving for S_2 yields

$$S_2 = e^{-B(1/T_1 - 1/T_2)}\ S_1. \qquad (3\text{-}7)$$

Defining an acceleration factor $T = e^{-B(1/T_1 - 1/T_2)}$ and substituting it into the above equation yields

$$S_2 = TS_1. \qquad (3\text{-}8)$$

The model assumes that a linear extrapolation can be made from elevated temperatures to normal operating temperatures. This assumption may not be valid and must be evaluated by considering potentially different values of T found from different stress tests.

A step-by-step application of the Arrhenius model is as follows:

a) Measure the device parameter M and establish a transformation which produces a linear function f(M) by trial. Plot f(M) as a function of time for each temperature.

b) Determine the slopes of the lines in this plot. These slopes are values of the function $R(T_j)$. $R(T_j)$ can only take on positive values.

c) Find $\ln R(T_j)$ as a function of $1/T_j$ and construct the Arrhenius plot. From this plot determine B, the slope of the line. Test for quadratic effects and estimate their magnitude.

d) Determine the acceleration factor T.

In a hypothetical experiment two sets of transistors are stressed with elevated temperatures. Transistor gain H_{FE} is measured periodically and is given in Table 3-1.

Table 3-1 Hypothetical Data Set

Day (S)	H_{FE}	
	$T_1 = 150^{\circ}C$	$T_2 = 200^{\circ}C$
1	100	100
2	99	98
3	98	96
4	97	94
5	96	92

The next step in applying the Arrhenius model is to plot H_{FE} as a function of time for T_1 and T_2, which is shown in Figure 3-1. Next, determine the absolute value of $R(T_j)$, for $j = 1, 2$; then calculate $\ln R(T_j)$. Then $\ln R(T)$ is plotted as a function of reciprocal absolute temperature (1/T). This is the Arrhenius plot shown in Figure 3-2. Here it is assumed that if there were data for more temperatures, the resulting $\ln R(T_j)$ for all j would lie on the same line as $[1/T_1, \ln R(T_1)]$ and $[1/T_2, \ln R(T_2)]$. When all these points lie on the same line, true Arrhenius acceleration exists. The limitations of having only two data points are obvious.

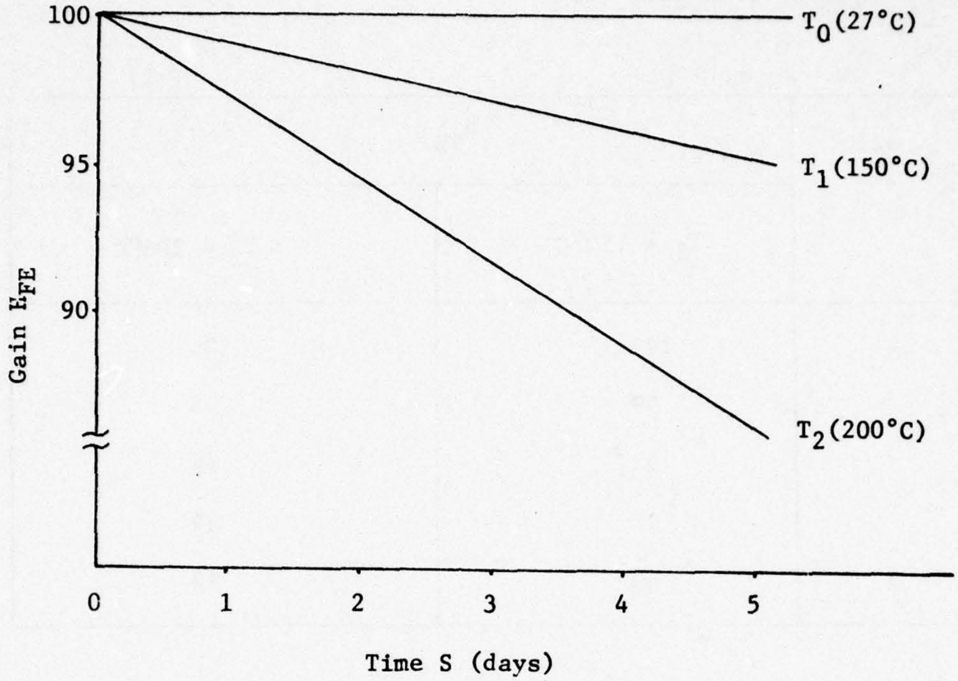


Figure 3-1 Current-gain-aging example

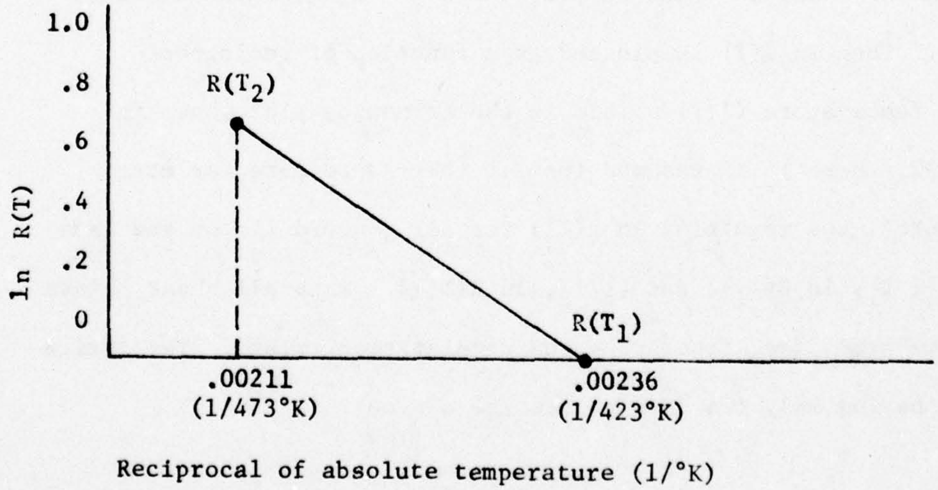


Figure 3-2 Arrhenius-plot example

To determine the acceleration parameters A and B, the relation

$$\ln R(T_j) = A - B\ (1/T_j). \qquad (3\text{-}9)$$

is applied to the Arrhenius plot. The acceleration factor T is a function of B but is independent of A. In this example,

$$B = 2.68 \times 10^3\ °K.$$

The acceleration factor can be calculated from

$$T = e^{-B(1/T_1 - 1/T_2)}, \qquad (3\text{-}10)$$

where T_1 is some elevated temperature and T_2 is the normal operating temperature. Substituting $B = 2.68 \times 10^3$ °K, $T_1 = 473$ °K (200°C), and $T_2 = 300$ °K (27°C) gives an acceleration factor $T = 24.27$.

If all assumptions implicit in the Arrhenius model are valid, the above result means that the subject-transistor gain ages approximately 24 times as fast at 200°C as it does at 27°C. The activation energy can now be calculated if the Arrhenius model applies. Assuming that E(ev) is constant, the activation energy is calculated by taking two values of $R(T_j)$ where $j = 1$ and 2 and the corresponding two temperatures (T_1 and T_2) and substituting these known values into Equation 3-13 to calculate E. Peck and Zierdit[7] define R(T) as

$$R(T_1) = Fe^{-E/KT_1}, \qquad (3\text{-}11)$$

and

$$R(T_2) = Fe^{-E/KT_2}, \qquad (3\text{-}12)$$

where R is the reaction rate constant, E is the activation energy, K is the Boltzmann constant, T is absolute temperature, and F is a proportional constant, and

$$\ln\left[\frac{R(T_2)}{R(T_1)}\right] = 2.3 \log\left[\frac{R(T_2)}{R(T_1)}\right],$$

then

$$E = \frac{2.3 \log\left[\frac{R(T_2)}{R(T_1)}\right](8.63 \times 10^{-5})}{\left[\frac{10^3}{T_1} - \frac{10^3}{T_2}\right] \times 10^{-3}}.$$

In order to develop an accurate Arrhenius model and calculate the activation energy, one must have a homogeneous data base. To achieve this data base, mavericks or outliers must be removed.

All data points will be reviewed for the presence of outliers, (see Chapter 5). Outliers may be caused by faulty test equipment, by human error in performing the test and/or recording the results or by similar reasons not pertinent to the statistical analysis. Retention of outliers in the data could introduce bias and decrease the precision of the statistical tests. Therefore, a test to identify outliers is required in the data analysis, and this test is the Dixon criterion.[16]

The Dixon criterion assumes that the population mean and standard deviation are unknown and that the experimental observation comes from a single normal population. The test is capable of rejecting extreme observations at either the low or high end of the data set. The first step in applying the test is to arrange all the readings in a data set in order from lowest to highest ($x_1 \leq x_2 \leq . . . \leq x_n$). Two equations are used to calculate a test statistic, depending upon whether the high or low end of the data set is suspect:

$$\text{Upper} = \frac{x_n - x_{n-2}}{x_n - x_2}, \qquad (3\text{-}14)$$

and

$$\text{Lower} = \frac{x_3 - x_1}{x_{n-1} - x_1}. \qquad (3\text{-}15)$$

If the value calculated exceeds a critical value, then the reading is rejected as an outlier.

Before any experimentation is initiated, all parameters must be checked for normality. The Lilliefors'[17] analog to the Kolomogorov-Smirnov test (the test normally used in determining normality) has been selected for this evaluation. The Kolmogorov-Smirnov test requires that the population mean and standard deviation be known before testing. Lilliefors' analog, however, allows the calculation of the unbiased estimate of the mean and standard deviation from the sample data. Since the population mean and variance will be unknown for our data, Lilliefors' analog is the desired test.

CHAPTER IV

EXPERIMENTAL DESIGN DEVELOPMENT

The main experiment design was developed from a series of two preliminary experiments. The first experiment was designed from information obtained from the literature (see Bibliography), the implementation of which was constrained by the facilities that were available. Test equipment for measuring H_{FE} with sufficient accuracy and BV_{CBO} with a pulse sufficiently short to comply with published work was designed and fabricated. The first experiment was intended to develop an accelerated aging rate for the four selected devices, but the actual results indicated that temperature stress levels which had been selected based on the literature were incorrect. The second result obtained from the first experiment was that the breakdown voltage measurement produced changes in the device parameter. This led to a second experiment to set the temperature stress level. The effect of testing was minimized by using the latest available automatic testing procedures. The discussion of these two experiments and the way in which they led to the design of the main experiment is presented in this chapter.

The components selected as the test vehicle for the first experiment were one diode and three transistor types. The diode was a 1N4148 (identified by the letter D), which was selected because of its extensive use by Tasca[18] in his investigation of avalanche breakdown in semiconductors. The 2N2222 NPN (identified by the letter N) transistor was selected because of its wide use in circuitry and its use as a test vehicle in breakdown and neutron damage investigations. These two devices offer the best opportunity to relate this investigation to previous work. The next device, a 2N2907 (P) PNP transistor, was selected because it is used as a complementary device to the 2N2222 in many circuits. The last device was a medium power NPN transistor that was readily available, 2N2537 (NN). The characteristics of these devices are displayed in Appendix A.

The Arrhenius model requires that a minimum of three stress temperatures be used. Three temperatures were selected based on available equipment and were 25°C, 125°C, and 155°C. Special electronic measuring equipment was designed to permit *the measurement* with an accuracy within ±2%. The H_{FE} of these devices was measured at 10V, 10 ma, and 10 μsec, and BV_{CBO} was measured at 1 ma for 10 μsec. The H_{FE} measurement levels are within the devices' normal operating limit. The current and duration of the pulse for measuring the BV_{CBO} were selected based upon the work of Budenstein, Ponins, and Smith,[3] and these values were selected to be well below the threshold of second breakdown and damage.

An experimental plan was developed for each device and is displayed in Table 4-1. The actual test lot is described by a set of two or three alphanumerics. An example would be NN3, which designates the third lot and its associated testing of the 2N2537 transistor. Each lot contains 15 units, and 300 devices were committed to the experiment. The sample size and the two elevated temperatures were selected based on the availability of two ovens. The experiment was conducted in these two ovens for a period of 60 days with device parameters measured every other day.

The experiment was designed to determine first, if aging had occurred and second, if testing had produced changes in the device parameters.

Table 4-1 Lot Definition for First Experiment

Lot	Temperature (°C)	Measured periodically
1	25°C	Yes
2	125°C	No
3	125°C	Yes
4	155°C	No
5	155°C	Yes

Note: 15 devices per device type, 4 device types per lot.

Devices in Lot 2 (Chamber 125°C not measured periodically) and Lot 3 (Chamber 125°C measured periodically) were used to determine if parameter testing had any effect. Lot 1 was the control lot. Unfortunately, Lot 3 of the 2N2222 devices (3N) was destroyed in transportation back from the test site, and all four device types in the 155°C temperature oven, Lots 4 and 5, were destroyed because of a runaway condition which occurred on the 45th day of the experiment. It was apparent at this point that an additional experiment would be required to determine acceleration stress level, but some insight could be derived from the data obtained in this first experiment. All data which were available were subjected to statistical analysis as described below.

A two-sided t-test was selected to determine at the .05 significance level the effect of repeated measurements upon device parameter means. The two-sided t-test was selected because deviation may be on either side of the mean. An F-test was selected to determine, at the .05 significance level, the effect of repeated measurements upon device parameter variability. Sample Lots 2 and 3 were used for these determinations. All tests were performed on the differences between initial and final measurements on each part and not on the individual measurements. Catastrophic failures were removed from each lot before analysis.

A summary of the calculated differences on each lot is found in Table 4-2. Significant differences were found between Lots NN2 and NN3 with respect to the H_{FE} mean and the BV_{CBO} variance. (See Table 4-3.) No measurement effects at the .05 significance level were found in the other lots. This indicates that the BV_{CBO} measurement produced a change in the 2N2537 device parameter and a new measuring technique will be required.

A two-sided t-test was conducted on the differences in the initial to final diode data to determine if aging had taken place, but no significance could be detected at $\alpha = .05$. This implies that the low temperature baking had no detrimental effect on the diodes. The stress temperatures used in this experiment did not produce changes in the diode parameters. Therefore, it was eliminated from further experimentation.

The PNP transistor in Lot 2 and 3 had a combined pre-aged mean H_{FE} of 561.8 and a combined post-aged mean H_{FE} of 143.0, which is nearly a factor of four difference between these two means. These values were

Table 4-2 Means and Variance for the First Experiment

Lot	Device type	Samples	Variance	Mean	Parameter
2	D	14	13.3	5.7	V_R
3	D	11	14.0	4.8	V_R
2	NN	14	389.3	46.1	BV_{CBO}
3	NN	14	1399.0	58.6	BV_{CBO}
2	P	15	50.2	30.8	BV_{CBO}
3	P	9	36.8	30.4	BV_{CBO}
2	NN	14	531.9	80.4	H_{FE}
3	NN	14	896.1	104.2	H_{FE}
2	P	15	11,425.0	448.7	H_{FE}
3	P	9	12,505.0	364.1	H_{FE}

so grossly different that no statistical test was deemed necessary to be assured that accelerated aging had occurred.

Table 4-3 Analysis of Data Obtained from First Experiment

H_{FE} parameters

	Lot 2	Lot 3	Test results
NPN transistors (Type NN)			
Variance	531.9	896.1	Not significant (5%)
Standard deviation	23.1	29.9	
Mean	80.4	104.2	Significant (5%)
PNP transistors (Type P)			
Variance	11,425.0	12,505.0	Not significant (5%)
Standard deviation	106.9	111.8	
Mean	448.7	364.1	Not significant (5%)

Breakdown voltage BV_{CBO}

	Lot 2	Lot 3	Test results
NPN transistors (Type NN)			
Variance	389.3	1,399.0	Significant (5%)
Standard deviation	19.7	37.4	
Mean	46.1	58.6	Not significant (5%)
PNP transistors (Type P)			
Variance	50.2	36.8	Not significant (5%)
Standard deviation	7.1	6.1	
Mean	30.8	30.4	Not significant (5%)

Breakdown voltage BV_{CBO}

	Lot 2	Lot 3	Test results
Diodes (Type D)			
Variance	13.3	14.0	Not significant (5%)
Standard deviation	3.6	3.7	
Mean	5.7	4.8	Not significant (5%)

The result of this first experiment indicates that test levels of BV_{CBO} and H_{FE} on the transistors should be changed because of the degradation caused by testing. The new test levels must be set well below those indicated in Dr. Budenstein's work for BV_{CBO}, and the H_{FE} test level should be minimized.

Because of lost data, a second experiment was performed to determine what temperature should be used to produce accelerated aging of parameters in the three types of transistors. The second experiment is described below.

The second experiment was conducted in two phases. In the first phase ten 2N2222 and 2N2907 transistors were subjected to 25 tests of their H_{FE} and BV_{CBO} parameters. The test conditions for the devices were BV_{CBO} at 1 microampere and 1 μsec, and H_{FE} at 10 μsec and 100 microamperes. These are the lowest level test conditions at which the parameter could be measured automatically and still produce consistent results. The initial and final measurements were tested to determine if they are from the same population; this was subsequently confirmed by the t-test. Therefore, it was concluded that there was no testing effect and the temperature level for accelerated aging could then be determined.

In the second phase a sample of fifty of each of two device types, 2N2907 and 2N2222, which were obtained for use in the main experiment, was tested and subsequently subjected to various temperature stress levels to determine the maximum level which would be used without generation of typical failure modes. For each device type a subgroup of ten units was exposed for 240 hours to temperatures of 25°C, 150°C, 200°C, 250°C, and 300°C. The means of the individual subgroups and their shifts as a result of accelerated aging are listed in Table 4-4.

Table 4-4 Measured Parameter Means for Second Experiment

Parameter		BV_{CBO}			H_{FE}		
Device	Temp. (C)	Initial	Post	%	Initial	Post	%
2N2907	25	106.2	106.3	+.09	216.8	218.2	+0.6
	150	106.4	106.6	+.18	205.6	205.8	+0.1
	200	107.3	107.5	+.18	222.2	222.9	+0.3
	250	110.1	110.0	-.09	191.8	191.7	-.05
	300	106.6	106.3	-.28	227.2	214.4	-5.6
2N2222	25	96.3	98.1	+1.9	80.8	80.5	-0.4
	150	95.3	94.9	-0.4	76.0	82.9	+9.0
	200	92.0	93.3	-1.4	83.7	80.4	-3.9
	250	93.2	95.0	+1.9	78.0	79.2	+1.5
	300	94.7	96.2	+1.6	83.5	62.0	-25.7

These results indicated that no significant parametric shifts occurred at or below 250°C and no catastrophic failures occurred at or below 300°C. The 240 hours at temperatures at or below 250°C were insufficient in duration to produce accelerated aging. In order to achieve accelerated aging at 250°C for these devices, a stress period in excess of 240 hours is required. A stress period of 480 hours was selected for the main experiment.

The Arrhenius model requires two or more stress levels to be valid, and for this reason three stress levels were selected for use in the main experiment. These temperatures were 250°C, 275°C, and 300°C. Next, the neutron flux level had to be selected. This was accomplished by reviewing the literature on the 2N2222 and 2N2907 devices. The data available on these devices indicated that the lowest level of neutron irradiation to produce change in device parameters occurs at 10^{12} n/cm^2 and that the device ceases to perform any useful function at the value of $2\text{x}10^{13}$ n/cm^2. For this reason a range of 10^{12} to 10^{13} n/cm^2 was selected. The neutron fluxes were selected to be 0, 10^{12}, $5\text{x}10^{12}$, and 10^{13} n/cm^2, which selection covers the four regions of transistor damage and corresponds to conditions of no damage, threshold of damage, moderate damage, and severe damage respectively. The main experiment was developed based on the above temperatures and flux levels and is outlined in Table 4-5. The experimental design is identical for the two device types which were tested. Twelve samples were included in each group. The 2N2537 was not available for inclusion in the main experiment.

Group 1 of the main experiment was electrically tested at the beginning and end of the experiment and serves to detect any effect of electrical testing when compared to the control, Group 2. Group 2 was electrically tested whenever other groups were tested and served to establish any correction factors required to compensate for test equipment deviations. Electrical tests were performed initially every five days of accelerated aging, before and after irradiation, and also at the conclusion of the experiment. Parameters were measured using the Tereadyne J259/261 automatic test system and recorded on paper printout (see Appendix 3) and punched paper tape for computer analysis.

Table 4-5 Main Experiment

Group	Pre-age	Irradiation (n/cm^2)	Post-age
1	None	None	None
2A	"	"	"
2B	"	"	"
3A	480 hrs., 250°C	"	"
3B	"	"	"
4A	480 hrs., 275°C	"	"
4B	"	"	"
5A	480 hrs., 300°C	"	"
5B	"	"	"
6A	NONE	1×10^{12}	"
6B	"	"	"
7A	"	5×10^{12}	"
7B	"	"	"
8A	"	1×10^{13}	"
8B	"	"	"
9	480 hrs., 250°C	1×10^{12}	"
10	"	5×10^{12}	"
11	"	1×10^{13}	"
12	480 hrs., 275°C	1×10^{12}	"
13	"	5×10^{12}	"
14	"	1×10^{13}	"
15	"	1×10^{12}	"
16	"	5×10^{12}	"
17	"	1×10^{13}	"
18	None	1×10^{12}	480 hrs.,250°C
19	"	5×10^{12}	"
20	"	1×10^{13}	"
21	"	1×10^{12}	480 hrs.,275°C
22	"	5×10^{12}	"
23	"	1×10^{13}	"
24	"	1×10^{12}	480 hrs.,300°C
25	"	5×10^{12}	"
26	"	1×10^{13}	"

CHAPTER V

THE MAIN EXPERIMENT AND DATA ANALYSIS

A total of 500 devices of each type was procured and serialized for the main experiment. All devices were from the same manufacturing lot. Three hundred and ninety-six (396) of each device type (2N2222 and 2N2907) were committed to this main experiment described in Table 4-5. The experimental design is described in the previous chapter (See Table 4-5). There are 33 groups, and each group contains 12 items. Measurement of BV_{CBO} and H_{FE} were made initially on each group. Groups 2 through 26 were tested periodically during the experiment, but group 1 was not tested and serves as the control group. The remainder of the groups were allocated for temperature stress and irradiation as shown in Table 5-1.

The purpose of the main experiment is to obtain data on the breakdown voltage BV_{CBO} and H_{FE} parameters as a function of neutron irradiation and aging. The neutron irradiation effects on semiconductors can be divided into short term and long term. After irradiation, semiconductors recover from neutron irradiation rapidly in the short term, and this phenomenon is called short term annealing[2] (usually in hours but a maximum of 10 days). The effect of the short term annealing was specifically not considered in this investigation. The effect under investigation is the permanent long-term damage. In order to conduct

Table 5-1 Experimental Matrix Showing Group Number from Table

Irradiation levels	Pre-aged				Post-aged			
	Temperature				Temperature			
	A	B	C	D	A	B	C	D
I.	9	12	15	6A	18	21	24	6B
II.	10	13	16	7A	19	22	25	7B
III.	11	14	17	8A	20	23	26	8B
IV.	3A	4A	5A	2A	3B	4B	5B	2B

I. - $(1.02 \pm .05) \times 10^{12}$ Neutron/cm^{2*}
II. - $(4.74 \pm .63) \times 10^{12}$ Neutron/cm^{2*}
III. - $(1.14 \pm .29) \times 10^{13}$ Neutron/cm^{2*}
IV. - (0)

A - 250 degrees C ± 2° C**
B - 275 degrees C ± 2° C**
C - 275 degrees C ± 2° C**
D - 25 degrees C ± 2° C**

* Measured
** Controlled

this investigation, the main experiment was divided into two equal segments. **Half of the devices were allocated to the experimental condition that produces accelerated aging before irradiation. The second half of the devices were irradiated before they were subjected to conditions intended to produce accelerated aging.**

The groups in the pre-aged division of Table 5-1 were subjected to a 20-day stressing period before being irradiated. These devices were tested every five days during temperature stressing. These tests along with the initial test produced five data points on these devices before they were subjected to neutron irradiation. The groups were temperature stressed by being placed in ovens that were controlled within ±2%°C as shown in Table 5-1. At the end of this pre-aging temperature stressing, groups 6 through 26 were sent to the fast-burst reactor for irradiation. The actual flux levels received by groups, as measured by dosimetry, is shown in Table 5-1. After one month of "cooling" (radiation level decay to a level that was nonhazardous), the devices were returned for electrical testing.

When the devices were received from the reactor, they were tested but the post-aging temperature stress was not immediately initiated because of unavailability of the ovens. The time lapse between the test after irradiation and the starting of post-aging temperature stressing was 29 days. The test just before entering ovens for post-aging was not accomplished because of the unpredicted availability of the ovens. The testing of these devices was accomplished every five days as before, and at the end of 20 days the experiment was removed from the oven. The final test and the 20th day test are the same in the post-aging treatment. Including the test which was made when the devices were received from the reactor, a total of five tests were made on the devices in the post-aging section of the experiment. All devices were tested at the completion of the post-aged stressing, which produced seven test measurements on the devices that were pre-aged and six on those that were post-aged. The test were assigned numbers corresponding to the days on which they were made. The test that was made upon starting the experiment is designated I for "initial" and the test after irradiation is designated AN for "after neutrons." The last test performed, the final test, is designated F.

The main experiment (Table 5-1) was derived from the results of the previous two experiments and consists of four radiation levels, four stress temperatures (including the 25°C case), and two methods of treatment. This degree of complexity required an extremely powerful statistical tool to determine significant effects and interactions. The analysis of variance technique (ANOVA) was selected for the analysis tool. This tool required that there be no missing data and that the experimental error be random and normally distributed. The most statistically sound results are obtained if the mavericks are removed.

In order to replace outlying data points using the Dixon criterion, it is necessary to assume that the population from which the sample is drawn is normally distributed. The total population is unavailable for testing but the initial measurement of the parameters was tested for normality using the Lilliefors' technique. (The computer program used in this test is presented in Appendix B.) The results are shown in Table 5-2. The observed values deviated too far from the critical value to allow the assumption that the population is normal, and subsequently the use of the Dixon criterion. A log

Table 5-2 First Test for Normality

Part	Parameter	D-critical	D-observed
2N2222	BV_{CBO}	.045	.066
2N2222	H_{FE}	.045	.104
2N2907	BV_{CBO}	.045	.150
2N2907	H_{FE}	.045	.072

Table 5-3 Outliers Replaced by Group Mean

Device	Group	Test	Parameter
2N2222	22	5	H_{FE}
2N2222	22	10	H_{FE}
2N2222	22	15	H_{FE}
2N2222	22	F	H_{FE}

transformation of the 2N2222 H_{FE} data was found to be normally distributed (D-observed of .044) permitting the use of the Dixon criterion.

The transformed 2N2222 H_{FE} data were examined for mavericks (outliers) by use of the previously described Dixon criterion. The transformed data from each test was evaluated, and only four outliers were found, always the same device (identified by serial number). The outliers that were identified are shown in Table 5-3, and these outliers were replaced by the mean of the respective groups.

The data in each group of the final test (F) were then subtracted from the data in the initial test (I). The results of this subtraction were checked for normality. All groups of H_{FE} were found to be normally distributed, but the BV_{CBO} had many groups that were non-normal. The ANOVA is valid only for the H_{FE} parameters, and another test for BV_{CBO} will be required.

The ANOVA was conducted on the difference between initial and final test data on both the 2N2222 and 2N2907 H_{FE}. The results of this analysis are shown in Table 5-4, and the computer programs used are displayed in Appendix C.

The ANOVA on the H_{FE} parameter indicates that both devices are sensitive to radiation, temperature stressing, and the sequence of exposure (pre-aged and post-aged). There is a high degree of significance in the interactions leading one to the conclusion that the process involved is nonlinear, but in any case, the experiment has produced change in the H_{FE} parameter. Now it must be determined if the aging can be modeled so as to calculate an accelerated aging factor. This model and calculation will be addressed in the next chapter.

Table 5-4 Analysis of Variance Results

		2N2222 H_{FE}		2N2907 H_{FE}	
Factors	**df**	**MS**	**F ratio**	**MS**	**F ratio**
Irradiation level (B)	3	16,125	*108	304,291	*444
Temperature (C)	3	8,763	* 59	39,975	* 58
Method of aging (D)	1	5,872	* 39	217,372	*317
B x C interaction	9	10,160	* 6.8	5,932	* 8.6
B x D interaction	3	2,144	* 14	29,426	* 43
C x D interaction	3	1,172	* 7.9	20,984	* 31
B x C x D interaction	9	430	* 2.9	4,260	* 6.2
Error	352	160		685	
Total	383				

Degree of freedom is denoted by df, MS is mean square, and * is a significant variation.

Factors		**Critical values**
Replications	12	F.05 (3, ∞) = 2.6
Irradiation levels	4	F.05 (1, ∞) = 3.84
Temperature	4	F.05 (9, ∞) = 1.88
Aging type	2	
	384	

Before leaving this data for the modeling discussion, it is essential to determine two more points: first, that the breakdown voltage has not changed during the experiment and second, the measuring of BV_{CBO} has not caused change in this parameter. The breakdown voltage BV_{CBO} data can be analyzed to determine if any significant changes occurred during the experiment.

The ANOVA technique was used on H_{FE} but was not considered valid for BV_{CBO} because the residuals were found to be non-normal. The literature survey did not provide any insight into the form of transformation required to produce normality. A number of transformations were used in order to find one that produced normal residuals. This included e^x, log, ℓn, sin, cos, tan, hyperbolic sin, hyperbolic cos, hyperbolic tan, and inverse. No transformation was found to produce normal residuals.

A paired "t" test was used to test the BV_{CBO} data on both device types. The paired "t" was performed on the means, and the means are normally distributed according to the Central Limit theorem. The paired "t" test was performed by taking the difference between the mean of the group for the fifth day of elevated temperature and the 20th day. The 5th day measurements were used in this test because device testing was not accomplished just before entering the oven in the post-aged treatment, and then for consistency between testing in both treatments. The result of the paired "t" was that the 2N2907 and 2N2222 BV_{CBO} were unaffected by temperature before or after irradiation. The results are displayed in Table 5-5.

Table 5-5 Paired "t" Test on BV_{CBO}

		2N2222		2N2907	
Level	Temp. °C	Pre-aged	Post-aged	Pre-aged	Post-aged
1	250°	0.5	0.6	0.2	0
2	250°	0.5	0.3	0.3	0
3	250°	0.5	0.2	0	-0.1
4	250°	0.7	-	0	-
1	275°	0.3	-0.1	1.0	0.5
2	275°	0.3	-1.7	-1.0	0.0
3	275°	0.4	-0.3	0	0.0
4	275°	0.3	-	0	-
1	300°	-1.5	-2.7	0	0
2	300°	-0.4	-1.0	0	0
3	300°	-0.3	-0.5	0	0
4	300°	-0.5	-	0	-
		$\alpha = .05$			
	N	12	9	12	9
	X	0.042	0.044	0.067	-0.58
	S	0.044	0.17	0.63	1.06
	t	0.33	0.77	0.019	-1.64
	t (table)	2.201	2.306	2.201	2.306
Conclusion: No significant difference between mean and no temperature effect.					

In a similar manner the paired "t" test was conducted between group 1 (untested control) and group 2 (tested control) to determine if testing had effect on either H_{FE} or BV_{CBO}; no significant difference could be found at $\alpha = .05$. It is concluded that testing has had no effect on these devices and the BV_{CBO} can be assumed to be constant.

CHAPTER VI

RESULTS

In this chapter the data developed in the main experiment are exercised to determine if aging has had a significant effect on the breakdown voltage when exposed to an environment of neutrons. The steps that are required to reach this determination are three: (1) The Arrhenius model is developed for each device, (2) the acceleration factors (T) are calculated, (3) the projected breakdown parameter at an arbitrary time is calculated.

The first significant result from the main experiment was that the breakdown voltage BV_{CBO} was unaffected by the experiments. Therefore, for the remainder of the discussion these parameters are assumed to be at 95 volts for the 2N2222 and 105 volts for the 2N2907.

The effect of the main experiment on the H_{FE} parameters was not negligible, and a plot of percent reduction in final values of each group is shown in Figures 6-1 and 6-2 and Table 6-1. The percentage reduction was obtained by subtracting the initial group mean. This differs from the technique used in the ANOVA where final values of individual devices were subtracted from their initial values. The error mean square (EMS) obtained in the ANOVA can be used to estimate deviation from the mean. This is accomplished by taking the square root of the EMS and multiplying by 2 to obtain a two-sigma estimate on H_{FE}.

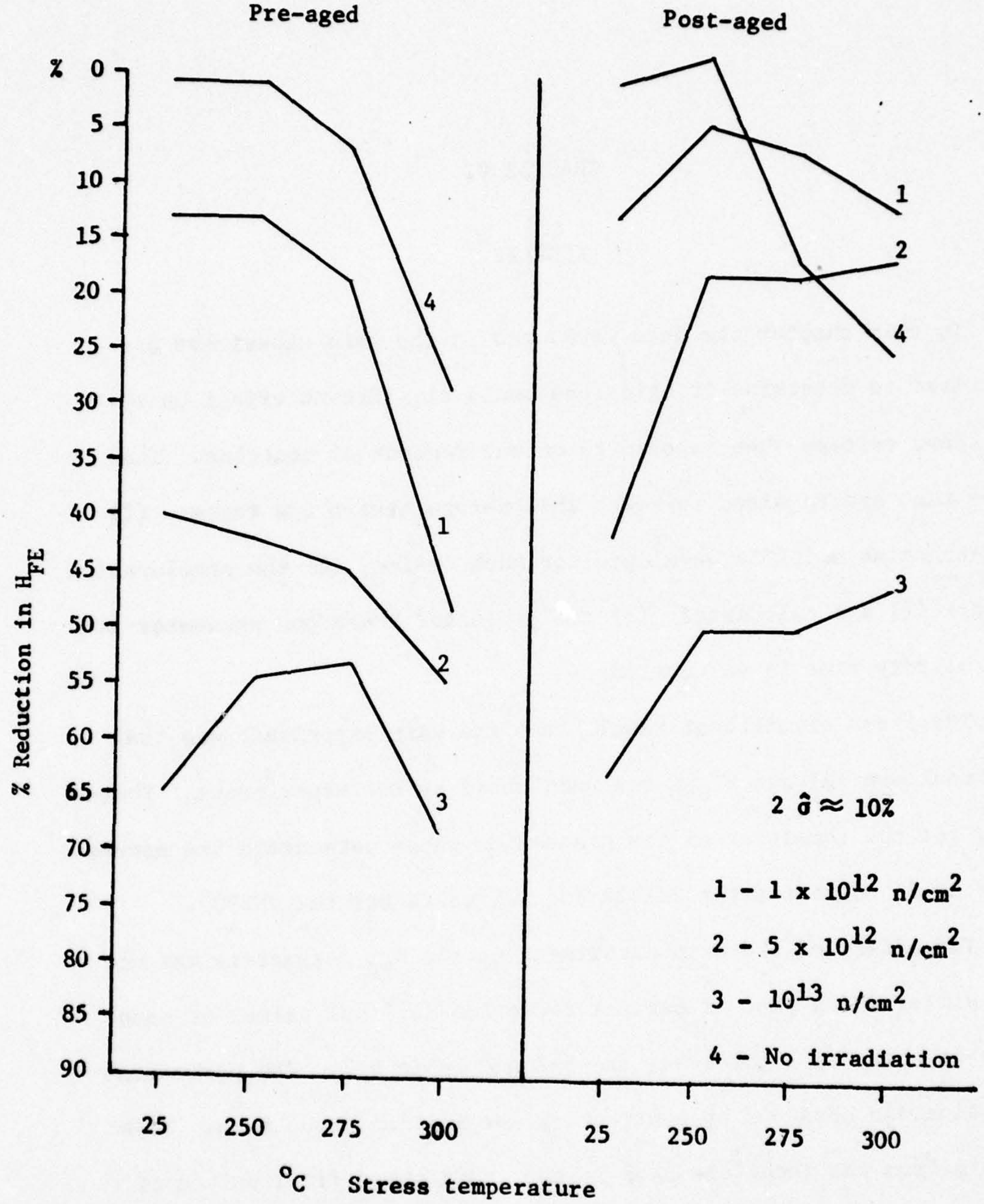


Figure 6-1 Percentage of reduction in H_{FE} parameter for the 2N2222 transistor

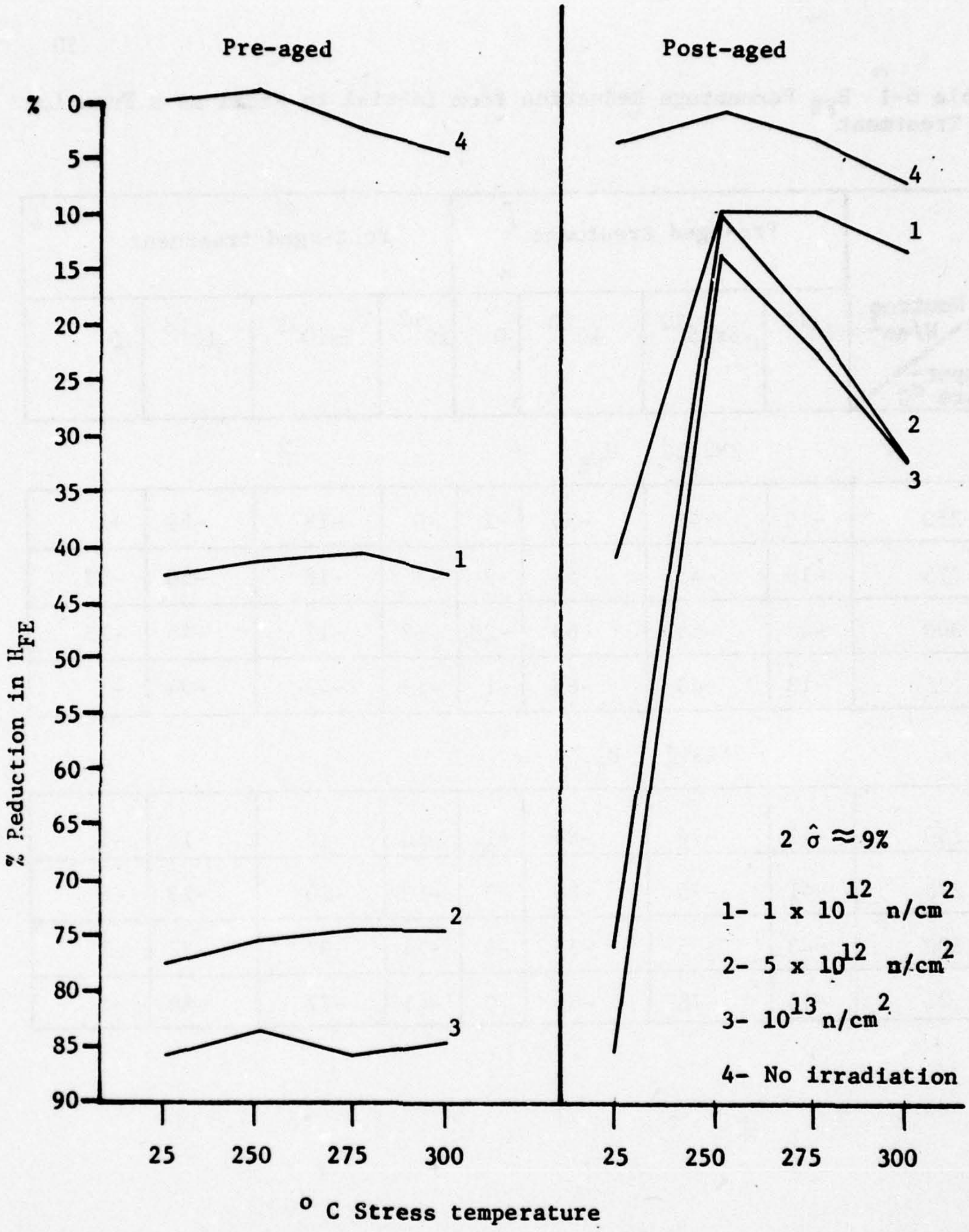


Figure 6-2 Percentage of reduction in H_{FE} parameter for the 2N2907 transistor

Table 6-1 H_{FE} Percentage Reduction from Initial to Final as a Function of Treatment

	Pre-aged treatment				Post-aged treatment			
Neutron N/cm^2 / **Temperature °C**	10^{12}	5×10^{12}	10^{13}	0	10^{12}	5×10^{12}	10^{13}	0
		2N2222	H_{FE}					
250	-13	-42	-55	-1	-5	-18	-50	+1
275	-19	-45	-54	-7	-7	-18	-50	-17
300	-47	-55	-68	-28	-12	-17	-46	-25
25	-13	-40	-65	-1	-13	-42	-64	-1
		2N2907	H_{FE}					
250	-42	-76	-84	+1	-10	-10	-14	-1
275	-41	-75	-86	-3	-10	-20	-23	-4
300	-43	-75	-85	-5	-14	-32	-32	-7
25	-43	-78	-86	0	-41	-77	-86	-4

The two-sigma estimate is on the individual device H_{FE}, and it is desired to have a two-sigma estimate on the mean. This is accomplished by dividing the two-sigma estimate of H_{FE} by the square root of the number of degrees of freedom of the group. The value of the degrees of freedom is eleven (11). The two-sigma estimate is now on the mean H_{FE}. The mean H_{FE} must be divided by the initial mean of the group in order to be converted into percentage. From Table 5-4 the EMS for the H_{FE} parameter of the 2N2222 was found to be 160, and for the 2N2907 it was found to be 685. The largest mean of 2N2222 is 83.0 with the lowest being 74.2, which produces an estimated two-sigma of 9.3% and 10.3% about the mean respectively. In the 2N2907 the largest group mean is 235, and the lowest is 171, which produces an estimated two-sigma deviation of 6.7% and 9.3% respectively. The median two-sigma deviation from the mean of 2N2222 is 9.8%, and that of the 2N2907 is 8.5%. The two-sigma limit can be applied to the data displayed in Table 6-1.

Referring again to Figure 6-1 and 6-2, one should note that the controlled groups in both devices (no irradiation case) exhibit similar values and have similar shapes for both pre-aged and post-aged treatment. Similarly, one should note that the effect on gain produced by irradiation alone is the same for the device maintained at ambient temperature. The irradiation effects on gain can be seen in Figure 6-1 and 6-2 by examining the pre-aged and post-aged means at all four neutron levels at 25°C. These initial points in the data for neutron irradiation and temperature treatment are sufficient for accepting the conclusion that the initial experimental conditions are the same for the pre-aged and post-aged.

Pre-aged treatment of the 2N2222 produced a significantly different change in H_{FE} from that in the post-aged treatment as seen in Figure 6-1. The values of the H_{FE} group means in the post-aged treatment are all higher (less percentage reduction) for elevated temperature and neutron fluxes greater than zero than the pre-aged values. They all differ in value greater than the two-sigma estimate (10%) except for three points: (1) 250°C and 10^{12} n/cm^2 where the difference is 8%, (2) 250°C and 10^{13} n/cm^2 where the difference is 5%, and (3) 275°C and 10^{13} n/cm^2 where the difference is also 5%. The conclusion that the 2N2222 devices are affected differently as a function of device age and neutron flux levels is validated, and further, one can conclude that the irradiation of an aged 2N2222 is more detrimental than irradiating a new 2N2222 and permitting it to age.

There is a significant difference in the final values of 2N2907 H_{FE} obtained at all three elevated temperature stress levels between pre-aged and post-aged treatment. This leads one to the conclusion that there is a significant difference in parameters between aged devices that have been irradiated and un-aged devices that have been irradiated. From the previous discussion on the 2N2222, it is clear that at least two devices are sensitive to the order of the application of aging and neutron irradiation.

In the post-aged treatment of the 2N2907 transistor (Figure 6-2), it can be seen that 250°C at 480 hours has caused an increase in the H_{FE} parameter over that initially obtained at 25°C. (This is true for 10^{12}, 5×10^{12}, and 10^{13} n/cm^2.) At this stress point and irradiation levels, the means of the measured data were essentially equal. This reduction in damage induced by irradiation is probably caused by defects in the crystalline lattice being refilled. A similar phenomenon was noted in the post-aged treatment of the 2N2222 transistor (Figure 6-1) but this increase in gain was not dramatic. Because of the similar characteristic in both devices of increased gain at elevated temperature, precise knowledge of the neutron flux received by each group of devices dosimetry and the fact that the data are normally distributed about the mean (points plotted in Figures 6-1 and 6-2), it is extremely unlikely that the phenomenon displayed in Figure 6-2 has not actually occurred. The difference between the two devices in the amount of increase in gain (H_{FE}) caused by elevated temperature is probably due to the difference in replacement mechanism between the two devices. There is a major difference in materials, dopants, geometry, and construction between the two devices. This phenomenon will require additional investigation to be understood.

By comparing the 2N2222 and 2N2907 results as shown in Figure 6-1 and 6-2, one should note the difference in performance of the two devices in the pre-aged treatment. The 2N2222 device is sensitive to neutron and stress temperature, but the 2N2907 device is not sensitive to the combined effects of neutron irradiation and temperature. In the post-aged treatment the performance of the 2N2907 and 2N2222 are similar. Both devices have increased H_{FE} after being exposed to elevated stress temperatures, but the 2N2907 has a declining H_{FE} as stress temperature is increased above 250°C. The difference in H_{FE} performance between the two devices leads one to the conclusion that either the mechanism of neutron damage or the aging is not the same in the 2N2222 and 2N2907. A summary of the results of the main experiment are listed as follows:

a) Neither neutron irradiation nor exposure to elevated temperature produced changes in BV_{CBO} in either device.

b) There is no significant difference between pre-aged and post-aged degradation of H_{FE} for no irradiation.

c) There is no significant difference between pre-aged and post-aged irradiated devices maintained at 25°C.

d) There is a significant difference in the percentage reduction in H_{FE} between pre-aged and post-aged at neutron irradiation levels greater than zero for both device types.

The results summarized in (d) are unexpected; the solid state and nuclear-radiation-effects literature does not provide any insight into the phenomenon. One possible conclusion that can be drawn is that the irradiation of new devices produces changes in the accelerated aging mechanism and subsequently, the accelerated aging factor (T). In order to check this possibility, it is necessary to develop the Arrhenius model for irradiated and nonirradiated devices. The next step is to develop the model and then check the assumptions necessary for the use of the model.

From the earlier discussion of the Arrhenius model, it was determined that the elevated temperature treatment must be linearly related to the normal operating temperature. The achievement of a linear extrapolation requires that the phenomenon under investigation has two characteristics:

a) Degradation in performance is a linear function of time, and the rate of degradation is dependent on time.

b) The logarithm of the degradation rate yields a linear function of the reciprocal of the absolute temperature.

The most effective and powerful means of obtaining the slope of the degradation curve (B) and subsequently the acceleration factor (T) would be to make use of all the available data. The literature on the Arrhenius model outlines a two-step process in which the first step uses the experimental data to establish point estimators upon which the slope of the degradation curve (B) is estimated. This method does not allow for estimation of error or establishment of confidence levels.

A number of methods were researched for possible application in this investigation, but the one that held the greatest promise was one described by Williams,[19] which is an iterative technique. The use of this technique requires a precise mathematical model. The model was developed as follows:

Let H_{prsti} represent the data in the experiment where

p is (1 = pre-aged, 2 = post-aged)

r is radiation level (1 = 10^{12}, 2 = 5×10^{12}, 3 = 10^{13}, 4 = 0)

s is test number (I, 5, 10, 15, 20, AN, 5, 10, 15, F)

t is temperature level (0 = 25°C, 1 = 250°C, 2 = 275°C, 3 = 300°C)

i is repetition (1 through 12).

It should be noted that all possible locations described by the model H_{prsti} are not filled as shown in Tables 6-2 and 6-3.

Table 6-2 Pre-aged Experimental Conditions

Temperature °C \ Measurements	I	5	10	15	20	AN	5	10	15	F
25	0	0	0	0	0	4	x	x	x	4
250	0	0	0	0	0	4	x	x	x	4
275	0	0	0	0	0	4	x	x	x	4
300	0	0	0	0	0	4	x	x	x	4

where x = empty,

0 = no irradiation,

4 = all four levels of irradiation

P = 1.

Table 6-3 Post-aged Experimental Conditions

Temperature °C \ Measurements	I	5	10	15	20	AN	5	10	15	F
25	0	x	x	x	x	4	4	4	4	4
250	0	x	x	x	x	4	4	4	4	4
275	0	x	x	x	x	4	4	4	4	4
300	0	x	x	x	x	4	4	4	4	4

where x = empty,

0 = no irradiation,

4 = all four levels of irradiation,

P = 2.

From Table 6-2 and 6-3 it can be seen that the Arrhenius model can only be applied to nonirradiated devices in the pre-aged condition, whereas it can be applied to devices irradiated at all levels of irradiation in the post-aged condition. The Arrhenius model that will be developed in the nonirradiated condition is based on data obtained in both the pre-aged and post-aged condition. The model for the mean degradation of H_{FE} can be written

$$\overline{H}_{2r\cdot t} = Q + \tilde{R}_r(T)S + C_r\,S^2, \qquad (6\text{-}1)$$

where Q is the intercept, $\tilde{R}_r(T)$ is the absolute value of the degradation factor, C_r is the linearity testing factor, and S is time in days.

If this model is linear, then C_r must not differ from zero significantly. This model allows $\tilde{R}_r(T)$ to be negative and further requires $\tilde{R}_r(T)$ to be increasingly negative as S becomes larger. The Arrhenius model requires that ln $\tilde{R}_r(T)$ be linearly decreasing as a function of the inverse of the absolute temperature (1/T). The model for $\tilde{R}_r(T)$ is

$$\ln R_r\,(T) = A_r + B_r\,1/T + F_r\,(1/T)^2, \qquad (6\text{-}2)$$

where A_r is the Arrhenius model intercept, B_r is the Arrhenius model slope, F_r is a linearity testing factor (that must approach zero for the Arrhenius relation to apply), and T is temperature in degrees Kelvin. Converting 6-2, one obtains 6-3 thus:

$$\tilde{R}_r\,(T) = e^{[A_r + B_r(1/T) + F_r\,(1/T)^2]}. \qquad (6\text{-}3)$$

Substituting into 6-1, equation 6-4 is obtained thus:

$$\overline{H}_{2r\cdot t} = Q + Se^{A_r} + B_r\,(1/T) + F_r(1/T)^2 + C_rS^2 \qquad (6\text{-}4)$$

The solution to equation 6-4 is not possible in a closed form and requires an iterative technique. Available automatic iterative methods were investigated to determine their applicability, and none was found to be adaptable to this problem. The size of the problem demands that an automated technique be developed. An attempt to develop such a computer program was undertaken, but its complexity was overwhelming. Because the development of such a program was outside of the research plan and would require an extremely long time for development, it was abandoned. The only option remaining was to revert to the technique described in the literature.

The first step that is outlined in the literature is to determine if the parameters of interest degraded as a linear function of time. The H_{FE} in the no-radiation treatment was found to be degraded as a function of time and temperature. The degradation was modeled using linear regression techniques (least square curve fit).[20] This satisfied the first required characteristics and yielded the intercepts, slopes, and correlation factors for both devices which are shown in Tables 6-4 and 6-5. The linear curve fit was performed on all the data obtained at each measurement, starting with the initial and ending with the 20th day for devices in the pre-aged treatment. The linear curve fit was performed on the data in post-aged treatment starting with the 5th test and ending with the final F test. Day-zero data were not taken just before placing the device into temperature treatment. The slope parameter $\tilde{R}(T)$ for the no-temperature, non-irradiation case is 0.172 for the 2N2222 and 0.08 for the 2N2907. These slope parameters $\tilde{R}(T)$ were tested using a two-tailed "t" test to determine if they were significantly different from zero. The calculated test values were significantly

Table 6-4 Least Square Curve Fit of Test Data 2N2222 H_{FE}

Model: $H_{FE} = Q + \tilde{R}(T)S$, where S is in days.

Temperature (°C) / Neutron irradiation levels (n/cm^2)	25	250	275	300
	Calculated $\tilde{R}(T)$, Q, and Z			
0	Q=78.3 $\tilde{R}(T)$= 0.172 Z= 0.77	77.5 0.04 0.61	78.1 - 0.196 - 0.63	76.3 - 1.07 - 0.98
10^{12}	Q= -- $\tilde{R}(T)$= -- Z= --	78.5 0.03 0.5	73.9 - 0.396 0.55	70.1 - 1.56 0.98
$5x10^{12}$	Q= -- $\tilde{R}(T)$= -- Z= --	72.9 0.05 0.45	77.8 - 0.76 - 0.996	76.1 - 2.34 - 0.996
10^{13}	-------- not calculated ------------------			
	Corrected R(T)			
0	0	- 0.132	- 0.368	- 1.242
10^{12}	0	- 0.142	- 0.568	- 1.736
$5x10^{12}$	0	- 0.122	- 1.03	- 2.51

Z represents correlation.

Table 6-5 Least Square Curve Fit of Test Data for 2N2907 H_{FE}

Model: $H_{FE} = Q + \tilde{R}(T)S$, where S is in days.

Temperature (^{o}C) Neutron irradiation levels (n/cm^2)	25	250	275	300
	Calculated Q, $\tilde{R}(T)$, and Z			
0	Q=191.6 $\tilde{R}(T)$= 0.08 Z= 0.66	201.5 - 0.06 - 0.46	203.6 - 0.21 0.4	194.8 - 0.42 0.44
10^{12}	Q= -- $\tilde{R}(T)$= -- Z= --	177.2 - 0.08 0.99	184.7 - 0.41 - 0.99	182.4 - 0.78 - 0.994
$5x10^{12}$	Q= -- $\tilde{R}(T)$= -- Z= --	139.6 0.11 0.99	188.2 - 0.45 - 0.62	154.0 - 0.26 - 0.999
10^{13}	-------- not calculated -------------------			
	Corrected R(T)			
0	0	- 0.14	- 0.28	- 0.5
10^{12}	0	- 0.16	- 0.49	- 0.86
$5x10^{12}$	0	0.03	- 0.53	- 0.34

Z represents correlation.

less than the critical value. A possible explanation of this phenomenon is the annealing of manufacturing defects. Because of its small value, $\tilde{R}(T)$ was accepted, and this value is deducted from all other slopes of the same device. This was done to have the slope of the no-treatment case equal to zero. Over the short time of this measurement (4 months) this slope should be zero. With this correction made to the $\tilde{R}(T)$ parameter, all linear curves are decreasing as a function of time, and each successive stress level has a higher negative value.

Linear regression was not conducted on the data obtained at 10^{13} n/cm^2 level because of the nonconformance of the $5x10^{12}$ n/cm^2 case to the first characteristic of the Arrhenius model (i.e. linearly decreasing H_{FE} with elevated temperature) and the similarity of form of the 10^{13} n/cm^2 data to the $5x10^{12}$ n/cm^2 case.

The corrected slope parameter R(T) now satisfies the requirement of the Arrhenius model. The next step is to determine if the linear characteristic of ln R(T) is satisfied.

The second characteristic was checked by plotting the ln R(T) on graph paper. This was done for both the 2N2222 and 2N2907 H_{FE} no-irradiation and 10^{12} n/cm^2 cases and is shown in Figure 6-3 and 6-4 respectively. A least-square-curve fit was conducted on each set of R(T) with the results shown in Tables 6-6 and 6-7. The absolute value of the correlation coefficient approach one, indicating a linear model produces a good fit to the data. This further substantiates the conclusion that ln R(T) is linear.

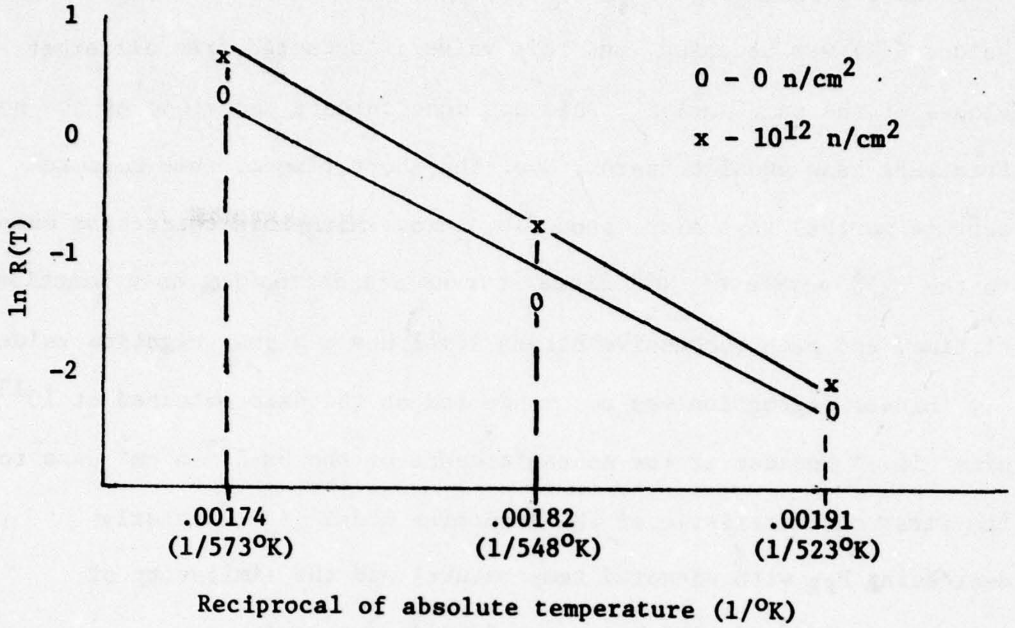


Figure 6-3 Degradation rate vs inverse of absolute temperature for 2N2222

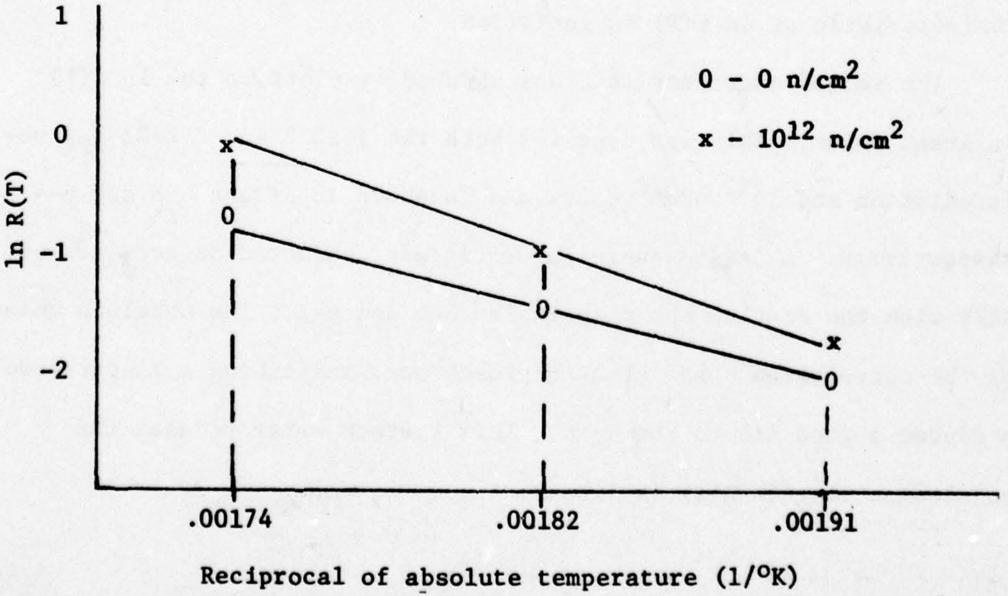


Figure 6-4 Degradation rate vs inverse of absolute temperature for 2N2907

Table 6-6 Least Square Curve Fit of the R(T), 2N2222 H_{FE}

Irradiation level / Parameter	0 n/cm^2	10^{12} n/cm^2
A	22.8	26.7
B	-13.0×10^3	-15.0×10^3
Z	- 0.995	- 0.999

Model: $\ln R(T) = A + BY$, $Y = \frac{1}{T}$, A = intercept, B = the slope, and Z = correlation coefficient.

Table 6-7 Least Square Curve Fit of the R(T), 2N2907 H_{FE}

Irradiation level / Parameter	0 n/cm^2	10^{12} n/cm^2
A	12.9	16.9
B	-7.82×10^3	-9.7×10^3
Z	- 0.999	- 0.988

Model: $\ln R(T) = A + BY$, $Y = \frac{1}{T}$, A = intercept, B = the slope, and Z = correlation coefficient.

Now that a true acceleration has been found, the accelerated aging factor can be determined, but before completing this calculation, the activation energy to start the process will be examined. The calculation involves the R(T) factor which has just been determined and the equations previously presented (Equation 3-13):

$$E = \frac{\left(2.3 \log \left[\frac{R(T_2)}{R(T_1)}\right]\right)\left(8.63 \times 10^{-5}\right)}{\left[\frac{1}{T_1} - \frac{1}{T_2}\right]}. \qquad (3\text{-}13)$$

$R(T_1)$ and $R(T_2)$ can be derived from the equation of least square curve fit, but for the temperature of 250°C and 300°C, the values of $R(T_1)$ and $R(T_2)$ can be read directly from Tables 6-4 and 6-5. The results of the activation energy calculation are shown in Table 6-8.

Table 6-8 Calculated Activation Energies

Device Irradiation level	2N2222	2N2907
No irradiation	1.17 ev	0.65 ev
10^{12} n/cm^2	1.27 ev	0.85 ev

These values for the 2N2222 devices are within the range that was predicted in the literature for aging effects, but the 2N2907 is at the level of radiationless transition. The results are consistent within device types and indicate that the neutron irradiation has not invalidated the accelerated aging technique.

The next step is to calculate the acceleration factor (T) where the acceleration factor is defined by the relation as presented in Equation 3-8.

$$S_2 = T\, S_1 \qquad (3\text{-}8)$$

where S_2 is real time in days, and S_1 is time at a stress level in days.

The calculation of the acceleration factor (T) requires that a normal stress level be established. Let the stress level of real time be at two levels. The normal stress levels usually assumed for semiconductors are 25°C, which is the normal storage temperature, and 100°C, which can be assumed to be normal operating temperature. The acceleration factor (T) can now be calculated for devices in storage and in operation. Using equation 3-10,

$$T = e^{-B(1/T_1 - 1/T_2)}, \qquad (3\text{-}10)$$

where T_j is absolute temperature from which one can calculate the acceleration factor. For example, let the real time S_2 be at 25°C, the storage case, and the time S_1 be at the stress level temperature at 250°C. The B term is shown in Tables 6-6 and 6-7.

Now for a sample calculation, let the device be the 2N2222 and the parameter H_{FE}. The value of B is obtained from the table and is $-13.0\text{x}10^3$ for the no-irradiation case and $-15.0\text{x}10^3$ for a flux level of 10^{12} n/cm^2. Now the acceleration factor can be calculated.

a) no-irradiation case

$$\begin{aligned} T &= e^{-13.0\text{x}10^3 \left[\frac{1}{523} - \frac{1}{298}\right]} \\ &= e^{-13.0\text{x}10^3 \; [1.91 - 3.35] \text{ x } 10^{-3}} \\ &= e^{[13]\;[1.44]} \\ &= 134 \text{ x } 10^6 \end{aligned}$$

b) 10^{12} n/cm^2 case

$$\begin{aligned} T &= e^{-15.0\text{x}10^3 \left[\frac{1}{523} - \frac{1}{298}\right]} \\ &= e^{-15.0\text{x}10^3 \; [1.44\text{x}10^{-3}]} \\ &= 2403 \text{ x } 10^6 \end{aligned}$$

The results of the calculation of the acceleration factor are shown in Table 6-9.

The next step is to calculate the parameter H_{FE} at an arbitrary time, based upon the above acceleration factor and the calculated breakdown voltage.

Table 6-9 Acceleration Factor (T) for Elevated Stress Temperature as Related to Storage (25°C) and Operation (100°C) Temperature

Stress temperature / Irradiation level (n/cm^2)	Stored (25°C)			Operation (100°C)		
	250°C	275°C	300°C	250°C	275°C	300°C
2N2222 H_{FE}						
No	13.4×10^7	4.34×10^8	1.81×10^9	2.2×10^4	7.1×10^4	2.03×10^5
10^{12}	2.4×10^9	9.26×10^9	4.82×10^{10}	10.3×10^4	4.0×10^5	1.33×10^6
2N2907 H_{FE}						
No	7.77×10^4	1.57×10^5	3.71×10^5	412	833	1.55×10^3
10^{12}	1.16×10^6	2.79×10^6	8.1×10^6	1.75×10^3	4.2×10^3	9.12×10^3

The H_{FE} parameter of the two devices can be predicted for any real time S. Using the calculated accelerating factor T in Table 6-9, the number of days of stressing at 250°C can be calculated to produce the same effect as being stored for a selected number of days at 25°C. Table 6-10 shows the results for S = 3000 days. The data in this table indicates that 3000 days at 25°C will not produce any significant change in the H_{FE} parameter.

Table 6-10 Number of Days of Stress at 250°C to Produce Equivalent of 3000 Days at 25°C

Device / Irradiation level	2N2222	2N2907
No-irradiation	$\simeq 0$	$\simeq 0$ Days
10^{12} n/cm^2	$\simeq 0$	$\simeq 0$ Days

Repeating the process for the devices that are operated at 100°C, one can obtain the number of days at 250°C to produce the same effect as being operated for 3000 days. The results of these calculations are displayed in Table 6-11.

Table 6-11 Number of Days of Stress at 250°C to Produce Equivalent of 3000 Days at 100°C

Device / Irradiation level	2N2222	2N2907
No-irradiation	.14	7.2
10^{12} n/cm^2	$\simeq 0$	1.7

Employing the degradation curve in Tables 6-2 and 6-3, the values of H_{FE} at the end of 3000 days can be calculated and are shown in Table 6-12.

Table 6-12 Calculated H_{FE} for 3000 Days at 100°C

Device / Irradiation level	2N2222	2N2907
No-irradiation	77.5	200.5
10^{12} n/cm^2	78.5	177.0

The relation $BV_{CEO} = \frac{BV_{CBO}}{(H_{FE})\ 1/n}$ where N = 5, BV_{CBO} for 2N2907 = 105, and BV_{CBO} for 2N2222 = 95 can be used to calculate the value of collector to emitter breakdown BV_{CBO} after aging for 3000 days with and without being irradiated. Because of the small change in H_{FE}, and the insensitivity of the BV_{CEO} parameter to change in H_{FE}, no calculation of the BV_{CEO} is required. No change in 3000 days of operation can be predicted for BV_{CEO}.

If an acceleration factor could have been found for higher neutron fluxes, then the significant change in H_{FE} at high-dose rate may have produced a significant difference in breakdown voltage.

CHAPTER VII

CONCLUSIONS

This investigation does not support the assertion that there will be a significant change in the breakdown voltage BV_{CEO} in aged devices as a function of neutron irradiation at least to 10^{12} n/cm^2 level. This result is derived from the lack of sensitivity of the collector-to-base breakdown voltage BV_{CBO} to both neutron irradiation and aging and the small changes in H_{FE} that were predicted over 3000 days of storage and operational conditions. This investigation yields some startling results in the area of breakdown voltage testing. Even though a device is not carried into second breakdown, testing of the breakdown voltage can produce changes in device parameters. A second unexpected result was that the gain (H_{FE}) of aged devices responds differently to neutron irradiation from that of unaged devices.

The accelerated aging and neutron irradiation failed to produce significant changes in the collector to base breakdown voltage BV_{CBO} for either the 2N2222 or the 2N2907. This result was not totally unexpected from the theory of accelerated aging and neutron irradiation, but it was an essential element in the determination of the collector to emitter breakdown voltage BV_{CEO}, and for this reason, it was included in this investigation.

The irradiation of devices that were not stressed with elevated temperature produced changes in H_{FE} that are consistent with the expected and previously reported results.[21] The H_{FE} of the devices that were aged after irradiation is consistently lower than those aged before irradiation; and at large flux levels (at and above $5x10^{12}$ n/cm^2), these differeneces become extremely large. This observation applies to both the 2N2222 and 2N2907 transistors and indicates there is a significant difference in the results obtained when devices are aged before irradiation and when they are aged after irradiation. An extended experiment should be conducted to determine if the observed result is a general condition or a condition peculiar to these two devices. The extended experiments should be conducted on different device types with similar and different operating characteristics and construction techniques.

The Arrhenius model was developed for both devices at 0 and 10^{12} n/cm^2 flux levels and was found to meet the constraint on the use of the model. A "true" acceleration factor was found, and this factor was used to predict the H_{FE} parameter at 3000 days. The predicted H_{FE} was used to determine the collector to emitter breakdown voltage BV_{CEO}. It was determined that irradiation at 10^{12} neutrons per square centimeter does not produce significant changes in this breakdown voltage within the normal life of the device.

Acceleration at higher levels of irradiation ($5x10^{12}$ n/cm^2 and 10^{13} n/cm^2) was not accepted as true, and an acceleration rate could not be determined for those cases. At these levels one could expect to find different breakdown voltage in aged and unaged devices. Without an acceleration factor to determine relative age, no meaningful comparison could be made. Additional experimentation and probably a different model would be required to develop a method of determining the aging factor at these levels.

The assertion made by Budenstein that damage does not occur until second breakdown is reached was not sustained by this investigation. The analysis of the data from the first experiment indicates that continual testing of BV_{CBO} within the first breakdown limit produced changes in the parameter's means and first moments about the mean. A detailed investigation of the mechanism that produced this change in the 2N2537 as a function of testing of BV_{CBO} should be undertaken to add to the information that has been developed on transistor damage. A predictive model should be developed that will permit the estimation of change that will be caused by exceeding the breakdown voltage (BV_{CBO}).

The activation energy of the 2N2222 was consistent with the previous work on aging, but the 2N2907 activation energy was in the same range as radiationless transition. This latter finding leads one to the conclusion that the aging mechanism is not the same for both devices. Additional study is required to determine why these differences occurred and what physical mechanism of aging is the prime factor.

In addition, neutron irradiation was found to affect the accelerated aging factor and activation energy. An investigation should be conducted from both the solid state theory and physics of failure viewpoints to determine why this phenomenon occurs and to model such occurrences for predicting future response to neutron irradiation.

Both the 2N2222 and 2N2907 devices showed a tendency to recover gain (H_{FE}) when subjected to elevated temperature after being irradiated. This tendency to recover is considerably more pronounced in the 2N2907 than in the 2N2222 transistor. The difference in recovery could be due to difference in construction, geometry, doping, or material. An experiment should be conducted varying parameters until an understanding of this mechanism is obtained.

The Arrhenius model that was used in this research is a two-step model that does not allow error estimation or confidence level to be established on the activation energies and acceleration factors. It would be extremely valuable in future accelerated aging studies to have a model that would use the experimental data in such a manner to permit these confidence intervals to be established.

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APPENDIX A

DEVICE CHARACTERISTICS

APPENDIX A

DEVICE CHARACTERISTICS

A. 1N4148 switching diode:

(1) $V_R = 75$ V

(2) $t_{RR} = 4$ nsec

(3) $I_F = 10$ mA at 1 V

(4) $I_R = 25$ mA at 20 V and 25°C

(5) $C = 4$ pF at 0 V

B. 2N2222:

(1) $P_{max} = 500$ mW at 25°C

(2) $f_T = 300$ MHz

(3) $BV_{CBO} = 75$ V

(4) $BV_{CEO} = 40$ V

(5) $BV_{EBO} = 6$ V

(6) I_{CBO} (max) = 800 mA

(7) $I_{CBO} = 10$ mA at 60 V and 25°C

(8) $C_{OB} = 10$ pF

C. 2N2537 medium-power NPN transistor:

(1) $P_{max} = 800$ mW at 25°C

(2) $f_T = 250$ MHz

(3) $BV_{CBO} = 60$ V

(4) $BV_{CEO} = 30$ V

(5) $BV_{EBO} = 5$ V

(6) I_C (max) = 800 mA

(7) I_{CBO} = 0.25 μA at 10 and 25°C

(8) C_{OB} = 8 pF.

D. 2N2907:

(1) P_{max} = 400 mW at 25°C

(2) f_T = 200 MHz

(3) BV_{CBO} = -60 V

(4) BV_{CEO} = -40 V

APPENDIX B

SAMPLE DATA SHEETS

APPENDIX B

SAMPLE DATA SHEETS

Presented in this appendix are the final measurements made on the 2N2907. Each sheet lists the group and the data on which the measurements were taken. The mean and standard deviation of the measurements are calculated and printed automatically.

SUBGROUP 2A TEST 20 DATE OCT 10 1977

A1150214

```
2N2907 SPECIAL TEST
           BVCBO      HFE
            1UA      100UA
                      10V

13
     13     83.8     294.1
     14    112.6     192.3
     15    112.1     188.6
     16    111.5     108.6
     17    109.0     161.2
     18     90.6     192.3
     19    105.1     153.8
     20    101.5     151.5
     21    106.5     172.4
     22    108.5     196.0
     23    109.0     181.8
     24    113.9     212.7


PARAM. NO.        1
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      85.2
15.9% PT.      90.0
   MEDIAN      108.
84.1% PT.      112.
90.0% PT.      113.
     MEAN      106.
    SIGMA      9.30

PARAM. NO.        2
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      118.
15.9% PT.      148.
   MEDIAN      182.
84.1% PT.      198.
90.0% PT.      210.
     MEAN      184.
    SIGMA      44.0
```

SUBGROUP / TEST Final DATE OCT 1 0 1977 **A1150240**

```
2N2907 SPECIAL TEST

          BVCBO     HFE
           1UA     100UA
                    10V

1
      1   109.9    163.9
      2   105.6    232.5
      3   113.0    188.6
      4   113.6    192.3
      5   114.4    204.0
      6   103.7    204.0
      7   106.9    222.2
      8   114.4    147.0
      9   115.1    208.3
     10    98.6    277.7
     11   109.5    181.8
     12   111.5    131.5

PARAM. NO.       1
CELL WIDTH       1
# OF UNITS      12

10.0% PT.    099.
15.9% PT.    103.
   MEDIAN    110.
84.1% PT.    114.
90.0% PT.    114.
     MEAN    110.
    SIGMA    5.00

PARAM. NO.       2
CELL WIDTH       1
# OF UNITS      12

10.0% PT.    135.
15.9% PT.    146.
   MEDIAN    192.
84.1% PT.    223.
90.0% PT.    231.
     MEAN    196.
    SIGMA    39.0
```

SUBGROUP 2B TEST Final DATE OCT 11 1977 A1150262

```
2N2907 SPECIAL TEST

          BVCBO     HFE
           1UA     100UA
                    10V

25
      25   113.5    181.8
      26   108.1    156.2
      27    98.9    263.1
      28   103.5    243.9
      29   102.7    98.03
      30   110.1    181.8
      31   109.6    204.0
      32   102.2    243.9
      33   113.7    204.0
      34   108.1    188.6
      35   101.8    243.9
      36    80.2    303.0

PARAM. NO.        1
CELL WIDTH        1
# OF UNITS       12

10.0% PT.     84.0
15.9% PT.     97.3
   MEDIAN     104.
84.1% PT.     110.
90.0% PT.     112.
     MEAN     105.
    SIGMA     9.10

PARAM. NO.        2
CELL WIDTH        1
# OF UNITS       12

10.0% PT.     110.
15.9% PT.     151.
   MEDIAN     197.
84.1% PT.     246.
90.0% PT.     259.
     MEAN     209.
    SIGMA     54.3
```

SUBGROUP 3A TEST F DATE OCT 10 1977 **A1150246**

```
2N2907 SPECIAL TEST

         BVCBO     HFE
          1UA     100UA
                   10V

37
     37    98.9    181.8
     38   102.3    156.2
     39   112.4    161.2
     40   100.6    263.1
     41    91.9    217.3
     42   113.7    212.7
     43   113.4    212.7
     44   107.7    217.3
     45   104.2    238.0
     46   113.8    232.5
     47 105.9 ~~7.5~~  210.4
     48   106.6    222.2

PARAM. NO.        1
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      24.8
15.9% PT.      84.8
   MEDIAN      104.
84.1% PT.      113.
90.0% PT.      113.
     MEAN      ~~97.8~~  105.9
    SIGMA      29.2

PARAM. NO.        2
CELL WIDTH        1
# OF UNITS       11

10.0% PT.      157.
15.9% PT.      160.
   MEDIAN      214.
84.1% PT.      234.
90.0% PT.      238.
     MEAN      210.4
    SIGMA      32.0
```

SUBGROUP 3B TEST F DATE OCT 10 1977 **A1150250**

```
   2N2907 SPECIAL TEST

             BVCBO    HFE
              1UA    100UA
                      10V

 49
      49     107.9    227.2
      50     108.7    232.5
      51     101.1    149.2
      52     111.4    200.0
      53      88.5    285.7
      54      88.4    270.2
      55     105.2    140.8
      56     114.2    217.3
      57     105.8    243.9
      58     106.0    204.0
      59     113.7    192.3
      60     109.8    163.9

 PARAM. NO.        1
 CELL WIDTH        1
 # OF UNITS       12

 10.0% PT.    88.4
 15.9% PT.    88.5
    MEDIAN    106.
 84.1% PT.    111.
 90.0% PT.    112.
      MEAN    105.
     SIGMA    8.60

 PARAM. NO.        2
 CELL WIDTH        1
 # OF UNITS       12

 10.0% PT.    143.
 15.9% PT.    148.
    MEDIAN    204.
 84.1% PT.    247.
 90.0% PT.    265.
      MEAN    211.
     SIGMA    45.0
```

SUBGROUP 4A TEST F DATE OCT 12 1977 A1150343

```
2N2907 SPECIAL TEST
            BVCBO     HFE
             1UA     100UA
                      10V

61
      61    109.0    169.4
      62    100.4    243.9
      63     93.7    222.2
      64    104.2    243.9
      65     96.8    192.3
      66    108.4    158.7
      67    111.5    178.5
      68     85.2    285.7
      69     95.2    185.1
      70    109.9    149.2
      71    113.5    192.3
      72    103.7    188.6

PARAM. NO.        1
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      86.9
15.9% PT.      93.0
   MEDIAN      102.
84.1% PT.      110.
90.0% PT.      112.
     MEAN      103.
    SIGMA      8.70

PARAM. NO.        2
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      151.
15.9% PT.      158.
   MEDIAN      189.
84.1% PT.      234.
90.0% PT.      242.
     MEAN      201.
    SIGMA      40.0
```

SUBGROUP 4B TEST F DATE OCT 12 1977 **A1150345**

```
2N2907 SPECIAL TEST
          BVCBO     HFE
           1UA     100UA
                    10V

73
     73   109.7    208.3
     74    99.4    256.4
     75   113.5    227.2
     76   109.7    196.0
     77   107.2    263.1
     78    98.7    263.1
     79   106.3    222.2
     80    99.2    129.6
     81    87.0    285.7
     82   105.8    161.2
     83   113.3    172.4
     84   108.5    192.3

PARAM. NO.       1
CELL WIDTH       1
# OF UNITS      12

10.0% PT.    89.4
15.9% PT.    97.7
   MEDIAN    106.
84.1% PT.    110.
90.0% PT.    112.
     MEAN    105.
    SIGMA    7.70

PARAM. NO.       2
CELL WIDTH       1
# OF UNITS      12

10.0% PT.    136.
15.9% PT.    158.
   MEDIAN    208.
84.1% PT.    260.
90.0% PT.    262.
     MEAN    215.
    SIGMA    47.0
```

SUBGROUP 5A TEST F DATE OCT 10 1977 A1150254

```
2N2907 SPECIAL TEST

           BVCBO     HFE
            1UA     100UA
                     10V

85
     85    113.2    149.2
     86    105.2    185.1
     87    105.4    238.0
     88    113.4    196.0
     89    109.8    192.3
     90    104.3    188.6
     91    100.7    131.5
     92    110.5    188.6
     93    109.2    144.9
     94    109.2    232.5
     95     98.7    192.3
     96    106.0    175.4

PARAM. NO.       1
CELL WIDTH       1
# OF UNITS      12

10.0% PT.    099.
15.9% PT.    101.
   MEDIAN    106.
84.1% PT.    111.
90.0% PT.    112.
     MEAN    107.
    SIGMA    4.60

PARAM. NO.       2
CELL WIDTH       1
# OF UNITS      12

10.0% PT.    135.
15.9% PT.    144.
   MEDIAN    187.
84.1% PT.    200.
90.0% PT.    226.
     MEAN    185.
    SIGMA    32.0
```

SUBGROUP 5B TEST F DATE OCT 10 1977 A1150258

```
 2N2907 SPECIAL TEST

           BVCBO     HFE
            1UA     100UA
                     10V

97
      97   101.7    149.2
      98   114.2    175.4
      99   110.8    208.3
     100   110.8    188.6
     101   104.6    192.3
     102   108.7    158.7
     103   113.0    153.8
     104   106.3    192.3
     105   110.8    121.9
     106   113.8    175.4
     107   112.3    212.7
     108   106.1    126.5

PARAM. NO.        1
CELL WIDTH        1
# OF UNITS       12

10.0% PT.    103.
15.9% PT.    105.
   MEDIAN    110.
84.1% PT.    113.
90.0% PT.    113.
     MEAN    110.
    SIGMA    4.00

PARAM. NO.        2
CELL WIDTH        1
# OF UNITS       12

10.0% PT.    123.
15.9% PT.    127.
   MEDIAN    167.
84.1% PT.    194.
90.0% PT.    205.
     MEAN    171.
    SIGMA    30.0
```

SUBGROUP 6A TEST F DATE OCT 1 1 1977 A1150304

```
2N2907 SPECIAL TEST

          BVCBO     HFE
           1UA     100UA
                    10V

217
    217   105.5    158.7
    218   112.0    114.9
    219    86.1    175.4
    220   107.5    114.9
    221    96.5    161.2
    222    90.4    161.2
    223   110.8    112.3
    224   111.8    101.0
    225   113.8    108.6
    226    96.3    138.8
    227    87.2    181.8
    228    95.6    120.4

PARAM. NO.       1
CELL WIDTH       1
# OF UNITS      12

10.0% PT.     86.3
15.9% PT.     87.1
   MEDIAN     96.5
84.1% PT.     112.
90.0% PT.     112.
     MEAN     101.
    SIGMA     10.4

PARAM. NO.       2
CELL WIDTH       1
# OF UNITS      12

10.0% PT.     103.
15.9% PT.     108.
   MEDIAN     120.
84.1% PT.     162.
90.0% PT.     172.
     MEAN     137.
    SIGMA     29.0
```

SUBGROUP 6B TEST F DATE OCT 1 1 1977 **A1150306**

```
2N2907 SPECIAL TEST

               BVCBO     HFE
                1UA     100UA
                         10V

  229
      229      113.8    119.0
      230      102.1    114.9
      231      112.9    121.9
      232      112.6    119.0
      233      100.6    158.7
      234      104.3    91.74
      235      113.2    88.49
      236      111.7    116.2
      237      105.8    129.8
      238      109.4    74.07
      239      110.6    120.4
      240      105.4    98.03

PARAM. NO.        1
CELL WIDTH        1
# OF UNITS       12

10.0% PT.     101.
15.9% PT.     102.
   MEDIAN     109.
84.1% PT.     113.
90.0% PT.     113.
     MEAN     109.
    SIGMA     5.00

PARAM. NO.        2
CELL WIDTH        1
# OF UNITS       12

10.0% PT.     77.0
15.9% PT.     87.3
   MEDIAN     116.
84.1% PT.     123.
90.0% PT.     128.
     MEAN     113.
    SIGMA     22.2
```

SUBGROUP 7A TEST F DATE OCT 11 1977 A1150312

```
2N2907 SPECIAL TEST

          BVCBO      HFE
           1UA      100UA
                     10V

241
    241   107.8     39.52
    242   107.8     53.47
    243   106.3     41.84
    244   113.8     53.47
    245   111.3     45.24
    246   111.8     49.75
    247   106.9     57.14
    248   110.2     51.54
    249   102.6     57.47
    250   114.2     45.45
    251   114.0     45.45
    252   113.5     53.76

PARAM. NO.        1
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      104.
15.9% PT.      106.
   MEDIAN      110.
84.1% PT.      113.
90.0% PT.      113.
     MEAN      110.
    SIGMA      4.00

PARAM. NO.        2
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      40.0
15.9% PT.      41.6
   MEDIAN      49.8
84.1% PT.      54.1
90.0% PT.      56.5
     MEAN      49.5
    SIGMA      5.90
```

SUBGROUP 7B TEST F DATE OCT 1 1 1977 **A1150314**

```
2N2907 SPECIAL TEST

           BVCBO    HFE
            1UA    100UA
                    10V

253
     253   108.0   40.65
     254    78.5   67.11
     255   111.6   48.78
     256   101.6   49.01
     257    88.8   66.22
     258   112.2   46.29
     259   113.4   45.04
     260    82.3   65.78
     261   108.7   39.84
     262    99.7   45.45
     263   104.6   44.84
     264   103.1   48.07

PARAM. NO.       1
CELL WIDTH       1
# OF UNITS      12

10.0% PT.     79.3
15.9% PT.     82.0
   MEDIAN    103.
84.1% PT.    111.
90.0% PT.    112.
     MEAN    101.
    SIGMA     11.8

PARAM. NO.       2
CELL WIDTH       1
# OF UNITS      12

10.0% PT.     40.0
15.9% PT.     40.6
   MEDIAN     46.3
84.1% PT.     65.8
90.0% PT.     66.1
     MEAN     50.6
    SIGMA     9.90
```

SUBGROUP 8A TEST F DATE OCT 1 1 1977 **A1150316**

```
2N2907 SPECIAL TEST

             BVCBO      HFE
             1UA        100UA
                        10V

265
     265    112.7      23.80
     266     87.2      42.91
     267    110.2      22.57
     268    105.3      20.83
     269    107.7      33.44
     270    101.4      33.11
     271    103.4      34.84
     272    111.4      25.18
     273    109.2      29.23
     274    113.2      24.39
     275    103.4      31.34
     276    111.6      30.12

PARAM. NO.       1
CELL WIDTH       1
# OF UNITS      12

10.0% PT.     090.
15.9% PT.     100.
   MEDIAN     108.
84.1% PT.     112.
90.0% PT.     112.
     MEAN     106.
    SIGMA     7.30

PARAM. NO.       2
CELL WIDTH       1
# OF UNITS      12

10.0% PT.     21.2
15.9% PT.     22.4
   MEDIAN     29.2
84.1% PT.     33.5
90.0% PT.     34.5
     MEAN     29.3
    SIGMA     6.30
```

SUBGROUP 8B TEST F DATE OCT 11 1977 **A1150318**

```
2N2907 SPECIAL TEST

            BVCBO     HFE
             1UA     100UA
                      10V

277
     277    110.9    24.21
     278    105.2    30.58
     279    100.8    35.58
     280    106.5    34.84
     281    112.2    27.54
     282    100.7    21.78
     283    106.8    26.17
     284    109.1    25.44
     285    112.7    30.58
     286    110.3    33.00
     287    114.3    28.98
     288    109.1    26.24

PARAM. NO.        1
CELL WIDTH        1
# OF UNITS       12

10.0% PT.    061.
15.9% PT.    097.
   MEDIAN    108.
84.1% PT.    112.
90.0% PT.    113.
     MEAN    108.
    SIGMA    4.00

PARAM. NO.        2
CELL WIDTH        1
# OF UNITS       12

10.0% PT.    22.3
15.9% PT.    24.0
   MEDIAN    27.5
84.1% PT.    33.2
90.0% PT.    34.5
     MEAN    28.7
    SIGMA    4.30
```

SUBGROUP 9 **TEST** F **DATE** OCT 11 1977 **A1150282**

```
2N2907 SPECIAL TEST

            BVCBO     HFE
             1UA     100UA
                      10V

109
    109      98.8    147.0
    110      94.7    101.0
    111     109.3    108.6
    112      94.3    161.2
    113      95.9    90.90
    114     111.4    133.3
    115      61.3    136.9
    116     106.0    114.9
    117      97.2    117.6
    118     103.8    96.15
    119      87.8    175.4
    120     112.0    75.75

PARAM. NO.        1
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      66.7
15.9% PT.      85.6
   MEDIAN      97.2
84.1% PT.      109.
90.0% PT.      111.
     MEAN      97.7
    SIGMA      13.7

PARAM. NO.        2
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      78.9
15.9% PT.      89.6
   MEDIAN      115.
84.1% PT.      148.
90.0% PT.      158.
     MEAN      122.
    SIGMA      29.8
```

A1150288

SUBGROUP 10 TEST F DATE OCT 11 1977

```
  2N2907 SPECIAL TEST

              BVCBO      HFE
               1UA      100UA
                         10V

121
      121     109.4     56.49
      122     104.4     39.68
      123      98.1     50.25
      124      89.8     72.99
      125   104.7 ~~97.5~~     51.54
      126     103.3     42.73
      127     112.3     55.55
      128     108.6     54.94
      129     114.3     52.91
      130     102.1     40.81
      131     108.3     40.16
      132     100.7     63.69

PARAM. NO.         1
CELL WIDTH         1
# OF UNITS        12

10.0% PT.       24.4
15.9% PT.       82.9
   MEDIAN       103.
84.1% PT.       109.
90.0% PT.       111.
     MEAN       ~~96.5~~ 104.7
    SIGMA       28.8

PARAM. NO.         2
CELL WIDTH         1
# OF UNITS        11

10.0% PT.       39.8
15.9% PT.       40.1
   MEDIAN       51.6
84.1% PT.       58.3
90.0% PT.       63.0
     MEAN       51.8
    SIGMA       10.6
```

SUBGROUP 11 TEST F DATE OCT 1 1 1977 A1150294

```
2N2907 SPECIAL TEST

             BVCBO    HFE
              1UA    100UA
                      10V

133
     133     109.8    23.20
     134     108.7    23.31
     135     112.2    23.69
     136     103.5    23.92
     137     101.4    25.25
     138     113.3    31.44
     139      94.3    24.50
     140     113.4    30.12
     141     108.2    32.25
     142     108.3    32.78
     143     109.8    32.46
     144     100.9    27.85


PARAM. NO.        1
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      095.
15.9% PT.      097.
   MEDIAN      108.
84.1% PT.      112.
90.0% PT.      112.
     MEAN      107.
    SIGMA      5.70

PARAM. NO.        2
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      23.2
15.9% PT.      23.3
   MEDIAN      25.3
84.1% PT.      32.3
90.0% PT.      32.5
     MEAN      27.6
    SIGMA      4.00
```

SUBGROUP /2 TEST F DATE OCT 11 1977 A1150284

```
  2N2907 SPECIAL TEST

             BVCBO     HFE
              1UA     100UA
                       10V

 145
     145     104.0    109.8
     146      92.3    104.1
     147     109.4    131.5
     148     103.2    144.9
     149     109.6    121.9
     150     110.4    119.0
     151     106.7    71.94
     152     112.8    108.6
     153     111.3    114.9
     154     112.2    98.03
     155     110.8    88.49
     156     106.5    147.0

 PARAM. NO.        1
 CELL WIDTH        1
 # OF UNITS       12

 10.0% PT.    094.
 15.9% PT.    102.
    MEDIAN    109.
 84.1% PT.    111.
 90.0% PT.    112.
      MEAN    107.
     SIGMA    5.70

 PARAM. NO.        2
 CELL WIDTH        1
 # OF UNITS       12

 10.0% PT.    75.3
 15.9% PT.    87.1
    MEDIAN    110.
 84.1% PT.    133.
 90.0% PT.    142.
      MEAN    114.
     SIGMA    21.9
```

SUBGROUP /3 TEST F DATE OCT 1 1 1977 A1150290

```
2N2907 SPECIAL TEST

            BVCBO     HFE
             1UA     100UA
                      10V

157
     157     96.0     35.97
     158    109.3     51.28
     159    106.2     60.60
     160    104.5     62.11
     161    102.8     59.52
     162    110.4     46.08
     163    103.8     38.61
     164    112.7     40.98
     165    104.1     50.50
     166     87.4     68.49
     167    108.2     45.87
     168    105.3     38.61

PARAM. NO.        1
CELL WIDTH        1
# OF UNITS       12

10.0% PT.     89.2
15.9% PT.     95.3
   MEDIAN     105.
84.1% PT.     109.
90.0% PT.     110.
     MEAN     104.
    SIGMA     6.80

PARAM. NO.        2
CELL WIDTH        1
# OF UNITS       12

10.0% PT.     36.3
15.9% PT.     37.2
   MEDIAN     46.1
84.1% PT.     60.7
90.0% PT.     61.8
     MEAN     49.9
    SIGMA     10.7
```

SUBGROUP /4 TEST F DATE OCT 1 1 1977 A1150296

```
2N2907 SPECIAL TEST

            BVCBO     HFE
             1UA     100UA
                      10V

169
    169     112.4    27.70
    170     113.5    31.74
    171     112.5    28.81
    172     111.6    25.90
    173     109.2    31.64
    174     113.1    28.73
    175     108.1    28.81
    176     107.4    34.96
    177     105.9    28.65
    178     113.8    28.49
    179     106.5    28.90
    180     112.0    28.98


PARAM. NO.         1
CELL WIDTH         1
# OF UNITS        12

10.0% PT.       106.
15.9% PT.       106.
   MEDIAN       110.
84.1% PT.       113.
90.0% PT.       113.
     MEAN       111.
    SIGMA       3.00

PARAM. NO.         2
CELL WIDTH         1
# OF UNITS        12

10.0% PT.       26.3
15.9% PT.       27.5
   MEDIAN       28.8
84.1% PT.       31.6
90.0% PT.       31.7
     MEAN       29.4
    SIGMA       2.30
```

SUBGROUP 15 TEST F DATE OCT 11 1977 A1150286

```
2N2907 SPECIAL TEST

          BVCBO     HFE
           1UA     100UA
                    10V

181
    181   113.1    120.4
    182   112.9    108.6
    183    96.6    75.18
    184   109.5    98.03
    185   109.5    79.36
    186   103.3    136.9
    187    95.3    92.59
    188   112.6    135.1
    189    91.5    81.30
    190   103.1    140.8
    191   109.8    75.75
    192   113.2    120.4

PARAM. NO.       1
CELL WIDTH       1
# OF UNITS      12

10.0% PT.     92.3
15.9% PT.     95.0
   MEDIAN    105.
84.1% PT.    112.
90.0% PT.    112.
     MEAN    106.
    SIGMA    7.80

PARAM. NO.       2
CELL WIDTH       1
# OF UNITS      12

10.0% PT.     75.3
15.9% PT.     75.7
   MEDIAN     98.0
84.1% PT.    135.
90.0% PT.    137.
     MEAN    105.
    SIGMA    24.9
```

SUBGROUP /6 TEST F DATE OCT 11 1977 A1150292

```
2N2907 SPECIAL TEST

          BVCBO     HFE
           1UA     100UA
                    10V

 193
      193   113.9    49.50
      194    93.3    63.29
      195   105.3    59.88
      196   107.6    43.10
      197   110.1    50.76
      198   109.5    42.55
      199   113.6    46.08
      200   110.2    49.01
      201   111.4    39.37
      202    97.9    58.13
      203   109.8    43.29
      204   111.1    50.50

PARAM. NO.        1
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      94.2
15.9% PT.      97.5
   MEDIAN      109.
84.1% PT.      111.
90.0% PT.      112.
     MEAN      108.
    SIGMA      6.30

PARAM. NO.        2
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      40.1
15.9% PT.      42.3
   MEDIAN      49.0
84.1% PT.      58.3
90.0% PT.      59.6
     MEAN      49.6
    SIGMA      7.50
```

SUBGROUP 17 **TEST** F **DATE** OCT 11 1977 **A1150298**

```
2N2907 SPECIAL TEST

             BVCBO     HFE
              1UA     100UA
                       10V

205
      205    109.4    22.98
      206    105.2    30.12
      207    113.6    26.45
      208    113.2    28.32
      209    111.8    31.44
      210    110.4    24.03
      211     79.1    23.86
      212    112.6    28.01
      213    111.2    30.95
      214    107.8    23.98
      215     99.2    36.23
      216    112.5    26.04

PARAM. NO.        1
CELL WIDTH        1
# OF UNITS       12

10.0% PT.     83.2
15.9% PT.     97.5
   MEDIAN     110.
84.1% PT.     113.
90.0% PT.     113.
     MEAN     107.
    SIGMA     9.80

PARAM. NO.        2
CELL WIDTH        1
# OF UNITS       12

10.0% PT.     23.2
15.9% PT.     23.8
   MEDIAN     26.5
84.1% PT.     31.0
90.0% PT.     31.3
     MEAN     27.7
    SIGMA     3.90
```

SUBGROUP 18 TEST 20 DATE OCT 10 1977 A1150222

F

```
2N2907 SPECIAL TEST

               BVCBO     HFE
                1UA     100UA
                         10V

289
      289       96.9    156.2
      290      110.9    204.0
      291      105.9    222.2
      292       88.9    270.2
      293      113.3    192.3
      294       93.3    133.3
      295      113.2    120.4
      296      113.3    178.5
      297      110.7    138.8
      298      114.2    120.4
      299      106.7    217.3
      300      107.5    185.1

PARAM. NO.        1
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      89.8
15.9% PT.      92.9
   MEDIAN      108.
84.1% PT.      112.
90.0% PT.      113.
     MEAN      106.
    SIGMA      8.50

PARAM. NO.        2
CELL WIDTH        1
# OF UNITS       12

10.0% PT.      072.
15.9% PT.      115.
   MEDIAN      179.
84.1% PT.      217.
90.0% PT.      221.
     MEAN      178.
    SIGMA      46.0
```

APPENDIX C

COMPUTER PROGRAM LISTINGS

APPENDIX C

COMPUTER PROGRAM LISTINGS

(a) Computer test of normality of the 2N2907 using the Lilliefors' analog to Kolmogorov-Smirnov.

(b) Computer automated ANOVA and subroutines.

```
FORTRAN IV G1  RELEASE 2.0              MAIN                DATE = 76026          13/14/18   PAGE 0001

                   CCCC   PROGRAM  RB021%INPUT,TAPE5#INPUT,OUTPUT,TAPE6#OUTPUT,TAPE9<                       0
                   C                                                                                       10
 0001                     IMPLICIT REAL*8(A-H,O-Z)
 0002                     REAL*4     Y, XCOR
 0003                     ALOG(ABCD) = DLOG(ABCD)
 0004                     SQRT(ABCD) = DSQRT(ABCD)
 0005                     DIMENSION X1(1000), X2(1000)
 0006                     DIMENSION  XCOR(8192), AX(2)                                                     20
 0007                     DIMENSION    ALF(12),OPTION(6),MSK(12)
 0008                     COMMON /READ/ ALFATH(17),ADALFA,FACTOR(12,12),OBSER(12),FMT(18),
                         1X(8192),JEND,M,KODE,NEST,JDUM,KTRAN,KDATA,NP,KDEV,KO(12),L(12)
 0009                     COMMON /CALC/Y(8192),CHAR(12),F(12),S(12),T(12),R(12),BST,Z,AKT,
                         1KR(12),LV(12),LVS(12),LVID(12),NSKIP(12),JR(12),MO(12),IGO(12),KT,
                         2KBT,KKKBT
                   C                                                                                       90
                   C                                                                                      100
 0010                     DATA ALF              /1HA,1HB,1HC,1HD,1HE,1HF,1HG,1HH,1HI,1HJ,1HK,             110
                         1                        1HL/                                                    120
 0011                     DATA OPTION /4HDEVI,4HATES,4H MEA,4HNS   ,4H     ,4H    /
 0012                     DATA  BLANK/1H /,  MSK          /1,2,4,8,16,32,64,128,256,512,                  150
                         1              1024,2048/,MRE/5/,MPR/6/,JW/3/,JX/4/,MEOF/0/                      160
 0013                   1 FORMAT (I1,17A4,A3)
 0014                   2 FORMAT (1H1,17A4,A3)
 0015                   3 FORMAT (20I4)                                                                   190
 0016                   4 FORMAT (1X,I3,19I4)                                                             200
 0017                   5 FORMAT (1H0,5X,20HANALYSIS OF VARIANCE/1X)                                      210
 0018                   6 FORMAT (12A6)                                                                   220
 0019                   7 FORMAT (8X,6HFACTOR,2X,A1,5H  IS ,12A6)                                         230
 0020                   8 FORMAT (1H0,7X,21HOBSERVED VARIABLE IS ,12A6)                                   240
 0021                  90FORMAT (1H1,52X,13HDATA OBSERVED,6X,18HFACTORS AND LEVELS/72X,                   250
                       9112(3X,A1))                                                                      260
 0022                  10 FORMAT (49X,43(1H-)/1X)                                                         270
 0023                  11 FORMAT (1H1,57X, 2A4,6X,18HFACTORS AND LEVELS/72X,12(3X,A1))                    280
 0024                  12 FORMAT (1X)                                                                     290
 0025                  13 FORMAT (72X,12A1)                                                               300
 0026                 140FORMAT (1H0,7X,84(1H-)/8X,11HGRAND MEAN ,F15.4,22X,10HINVOLVING ,                310
                      14114,13H OBSERVATIONS/1H0,7X,24HGRAND STANDARD DEVIATION,15X,F15.4,                320
                      14212H WITH GSS # ,E16.8/8X,84(1H-)/1H1)                                           330
 0027                  15 FORMAT (8X,84(1H-)/1X)                                                          340
 0028                  16 FORMAT (1X,91(1H#)/1X)                                                          350
 0029                 170FORMAT (1H0,6X,14HSUM OF SQUARES,7X,3HDFS,8X,11HMEAN SQUARE,8X,                  360
```

```
                 1712A4, 6X,21HSOURCE IDENTIFICATION/72X,12(3X,A1))                  370
0030             18 FORMAT (4X,F17.6,5X,I4,5X,F15.6,22X,12A1)                          380
0031             19 FORMAT (49X,F17.6,6X,12I4)                                         390
0032             200FORMAT (1H0,3X,F17.6,5X,I4,5X,F15.6,38H %POOLED REP ERROR FROM ALL 400
                 201 @AN ITEMS<)                                                       410
.0033            210FORMAT (1H0,91(1H-)/1X,3HTOT,  F17.6,5X,I4,41H EXCLUSIVE OF DEVIAT 420
                 211ION OF MEAN FROM ZERO)                                             430
0034             220FORMAT (1H0,1X,74HBARTLETT@S CHISQUARE TEST OF HOMOGENEITY OF POOL 440
                 221ED REP ERROR VARIANCE TERM/8X,8HCOMPARE ,F15.4,23H WITH CHISQUARE  450
                 222HAVING ,I4,5H DFS.)                                                460
0035             23 FORMAT (1H0,5X,7HFACTOR ,A1,21H, LINEAR    MSQ%1 DF<,F15.6)        470
0036             24 FORMAT (     6X,7HFACTOR ,A1,21H, QUADRATIC MSQ%1 DF<,F15.6)       480
0037             25 FORMAT (     6X,7HFACTOR ,A1,21H, CUBIC     MSQ%1 DF<,F15.6)       490
0038             26 FORMAT (     6X,7HFACTOR ,A1,12H,RESID. MSQ%I4,5H DFS<,F15.6)      500
0039             27 FORMAT (1H1,32HNESTED SUBSET ANALYSES IN STAGE ,I2,57(1H*))        510
0040             280FORMAT (1H1,2X,52HERROR IN INPUT DATA. ANALYSIS TERMINATED BY PROG 520
                 281RAM.)                                                              530
```

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FORTRAN IV G1  RELEASE 2.0            TRAN              DATE = 78026          13/14/18   PAGE 0001

0001                 SUBROUTINE TRAN                                                              5020
              C      @TRAN@ TRANSFORMS OBSERVED DATA IN SPECIFIED MANNER FOR @ANV@.               5030
              C                                                                                   5040
0002                 IMPLICIT REAL*8(A-H,O-Z)
0003                 REAL*4     Y
0004                 ALOG(ABCD) = DLOG(ABCD)
0005                 ATAN(ABCD) = DATAN(ABCD)
0006                 SQRT(ABCD) = DSQRT(ABCD)
0007                 DIMENSION  CARC(12), NIND(12), AETTER(12)                                     5050
0008                 COMMON /READ/ ALFATH(17),ADALFA,FACTOR(12,12),OBSER(12),FMT(18),
                    1X(8192),JEND,M,KODE,NEST,JDUM,KTRAN,KDATA,NP,KDEV,KU(12),L(12)
0009                 COMMON /CALC/Y(8192),CHAR(12),F(12),S(12),T(12),R(12),BST,Z,AKT,
                    1KR(12),LV(12),LVS(12),LVID(12),NSKIP(12),JR(12),MO(12),IGO(12),KT,
                    2KBT,KKKBT
0010                 DATA AETTER        /1HA,1HB,1HC,1HD,1HE,1HF,1HG,1HH,1HI,1HJ,1HK,              110
                    1                    1HL/
0011                 TKT=KT                                                                       5130
0012                 IF (KTRAN.EQ.1) GO TO 3210
0013                 XY=0.0
0014                 DO 3200 I = 1, KT
0015           3200 IF(X(I).LT.XY) XY=X(I)
0016                 IF (XY.GT.0.0) GO TO 3205
0017                 DO 3202 I = 1, KT
0018           3202 X(I)=X(I)-XY
0019           3205 CONTINUE
0020                 GO TO(3210,3220,3230,3240,3250,3260,3270), KTRAN                             5140
0021           3210 RETURN                                                                        5150
0022           3220 DO 3225 J=1,KT                                                                5160
0023           3225 X(J)=.434294482*ALOG(X(J))                                                    5170
0024                 RETURN                                                                       5180
0025           3230 DO 3235 J=1,KT                                                                5190
0026           3235 X(J)=.434294482*ALOG(X(J)+1.0)                                                5200
0027                 RETURN                                                                       5210
0028           3240 DO 3245 J=1,KT                                                                5220
0029           3245 X(J)=SQRT (X(J)+.5)                                                           5230
0030                 RETURN                                                                       5240
0031           3250 DO 3255 J=1,KT                                                                5250
0032                 X(J)=SQRT (X(J))                                                             5260
0033           3255 X(J)=57.2957795*ATAN (X(J)/SQRT (1.0-X(J)**2))                                5270
0034                 RETURN                                                                       5280
0035           3260 DO 3265 J=1,KT                                                                5290
```

```
 3265 X(J)=        .5*ALOG((1.0+X(J))/(1.0-X(J)))
      RETURN
 3270 CONTINUE
      READ 3271,  ATRAN, NALT, (CARC(I),NIND(I),I=1,NALT)
 3271 FORMAT(F10.0,3X,I2,12(A1,I2) )
      PRINT 3272,  ATRAN, (CARC(I), NIND(I),I=1,NALT)
 3272 FORMAT(/// 20X,15HTRANSFORMATION ,F15.6,11H APPLIED TO /
     1  42X, 12(A1,I3,2X) )
      DO 200 K = 1, NALT
      CARCHA = CARC(K)
      LEVCAR = NIND(K)
      DO 100 I = 1, 12
      IF(CARCHA.NE.AETTER(I)) GO TO 100
      ICAR = I
      GO TO 110
  100 CONTINUE
      PRINT 6
```

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FORTRAN IV G1  RELEASE 2.0              MAIN                DATE = 78026          13/14/18   PAGE 0002

0041             36 FORMAT (18A4)
0042             51 READ  (MRE, 1) JEND,ALFATH,ADALFA                                          540
0043                IF (JEND) 9000,52,9000                                                      550
0044             52 WRITE (MPR, 2)        ALFATH,ADALFA                                         560
0045                READ  (MRE, 3) M,KODE,NEST,JDUM,KTRAN,KDATA,NP,KDEV,(KO(I),I=1,12)
0046                IF(M) 53,54,54                                                              580
0047             53 M = -1*M                                                                    590
0048                DO 5333 I = 2,12
0049           5333 KO(I) = 0
0050                READ(5,3) IPLOT,IX1,IY1,ISIZE,ITYPE,IMODE,IPGS                              600
0051             54 READ(5,3) (L(I),I=1,M)                                                      610
0052                WRITE (MPR, 4) M,KODE,NEST,JDUM,KTRAN,KDATA,NP,KDEV,(KO(I),I=1,M)           620
0053                WRITE (MPR, 4) (L(I),I=1,M)                                                 630
0054                WRITE (MPR, 5)                                                              640
0055                IF (KODE .LE. 1) KODE=1                                                     650
0056                IF (KODE .GE. 2) KODE=2                                                     660
0057                IF (KTRAN .LE. 1) KTRAN=1                                                   670
0058                IF (KDEV .LE.  0) KDEV=3                                                    680
0059                IF (KDEV .GE.  3) KDEV=3                                                    690
0060             60 DO 61 J=1,M                                                                 700
0061                READ  (MRE, 6)        (FACTOR(J,I),I=1,12)                                  710
0062             61 WRITE (MPR, 7) ALF(J),(FACTOR(J,I),I=1,12)                                  720
0063                READ  (MRE, 6) OBSER                                                        730
0064                WRITE (MPR, 8) OBSER                                                        740
0065                KR(1)=1                                                                     750
0066                DO 62 I=2,M                                                                 760
0067             62 KR(I)=KR(I-1)*L(I-1)                                                        770
0068                KT=KR(M)*L(M)                                                               780
0069                KEEP=KT                                                                     790
0070                LOCAT=0                                                                     800
0071                KYCLE=0                                                                     810
0072                READ  (MRE,36) FMT
0073                READ (MRE,FMT)  (X1(I),I=1,KT)
0074                READ (MRE,FMT)  (X2(I),I=1,KT)
0075                DO 621 I=1,KT
0076                X(I) = X2(I) - X1(I)
0077            621 CONTINUE
0078                CALL TRAN                                                                   840
0079                IF (KDATA) 70,70,63                                                         850
             C  OPTIONAL PRINTOUT OF DATA STARTS                                                860
0080             63 WRITE (MPR, 9) (ALF(I),I=1,M)                                               870
```

```
      WRITE (MPR,10)
      LV(1)=0
      DO 67 J=1,KT
      N=J-1
      IF (M-1) 67,66,64
   64 DO 65 KK=2,M
      I=M-KK+2
      LV(I)=N/KR(I)
      N=MOD (N,KR(I))
   65 LV(I)=LV(I)+1
      LV(1)=N+1
      GO TO 67
   66 LV(1)=J
   67 WRITE (MPR,19) X(J),(LV(I),I=1,M)
C  CALCULATION OF GRAND MEAN AND GRAND ST DEV  STARTS
   70 GSUM=0.0
      GSS=0.0
```

```
FORTRAN IV G1  RELEASE 2.0            TRAN                 DATE = 78026          13/14/18  PAGE 0002

0052                    6 FORMAT(1H0,25(1HX)/30H UNABLE TO MAKE TRANSFORMATION /1X,25(1HX) )       5470
0053                      RETURN                                                                   5480
0054                  110 LTOTAL = 1                                                               5490
0055                      DO 120 I = 1,M                                                           5500
0056                  120 LTOTAL = LTOTAL*L(I)                                                     5510
0057                      LPAR = 1                                                                 5520
0058                      DO 130 I = 1, ICAR                                                       5530
0059                  130 LPAR = LPAR*L(I)                                                         5540
0060                      NORIG = LTOTAL/LPAR                                                      5550
0061                      LPAT = 1                                                                 5560
0062                      DO 140 I = ICAR,M                                                        5570
0063                  140 LPAT = LPAT*L(I)                                                         5580
0064                      LFREAK = LTOTAL/LPAT                                                     5590
0065                      LSTART = (LEVCAR-1)*LFREAK + 1                                           5600
0066                      LJUMP = (L(ICAR)-1)*LFREAK + 1                                           5610
0067                      INDEX = LSTART - LJUMP                                                   5620
0068                      DO 150 I = 1, NORIG                                                      5630
0069                      INIT = INDEX + LJUMP                                                     5640
0070                      DO 150 J = 1, LFREAK                                                     5650
0071                      INDEX = INIT + J - 1                                                     5660
0072                  150 X(INDEX) = X(INDEX)*(1.+ATRAN)                                           5670
0073                  200 CONTINUE                                                                 5680
0074                      RETURN                                                                   5690
0075                      END                                                                      5700
```

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FORTRAN IV G1  RELEASE 2.0              MAIN                DATE = 78026          13/14/18   PAGE 0003

 0097                SKT=KT                                                                    1050
 0098                RSKT=1.0/SKT                                                              1060
 0099                DO 71 I=1,KT                                                              1070
 0100                GSUM=GSUM+X(I)                                                            1080
 0101             71 GSS=GSS+X(I)*X(I)                                                         1090
 0102                GMEAN=GSUM*RSKT                                                           1100
 0103                GSS=GSS-GMEAN*GMEAN*SKT                                                   1110
 0104                GSD=SQRT (GSS*RSKT)                                                       1120
 0105                MSTA=NEST+1                                                               1130
               C  OPTIONAL EARLY PRINTOUT OF ALL COMPONENT MEANS OR DEVIATIONS STARTS          1140
 0106                IF (NP-1) 411,72,73                                                       1150
 0107             72 IF(IPLOT.GT.0)  GO TO 1106                                                1160
 0108                WRITE(6,11)  (OPTION(I),I=3,4),(ALF(I),I=1,M)                              1170
 0109                GO TO 74                                                                  1180
 0110             73 WRITE (MPR,11) (OPTION(I),I=1,2),(ALF(I),I=1,M)                            1190
 0111             74 WRITE (MPR,10)                                                            1200
 0112                GO TO 1106                                                                1210
 0113            411 WRITE (MPR,14) GMEAN,KT,GSD,GSS                                           1220
 0114                NP=NP-10000                                                               1230
 0115                AKT=0.0                                                                   1240
 0116                BST=0.0                                                                   1250
 0117                Z  =0.0                                                                   1260
 0118            412 IF (KODE-2) 1100,413,1100                                                 1270
               C CALCULATION OF REP-WITHIN-BLOCK ERROR SS AND TEST OF HOMOGENEITY START        1280
 0119            413 KBT=L(1)                                                                  1290
 0120                KKKBT=KT/KBT                                                              1300
 0121                TBK=KBT                                                                   1310
 0122                TBKKK=KKKBT                                                               1320
 0123                KKBT1=LOCAT+1                                                             1330
 0124                KKBT2=KBT+LOCAT                                                           1340
 0125                KFLA=0                                                                    1350
 0126                AMV=0.0                                                                   1360
 0127                GMLOG=0.0                                                                 1370
 0128                DO 1040 J=1,KKKBT                                                         1380
 0129                BSUM=0.0                                                                  1390
 0130                BVAR=0.0                                                                  1400
 0131                BSS=0.0                                                                   1410
 0132                DO 1000 I=KKBT1,KKBT2                                                     1420
 0133                BSUM=BSUM+X(I)                                                            1430
 0134           1000 BSS=BSS+X(I)**2                                                           1440
 0135                BVAR=BSS-(BSUM**2)/TBK                                                    1450
```

```
      Y(J)=BVAR
      KKBT1=KKBT1+KBT
      KKBT2=KKBT2+KBT
 1040 CONTINUE
      AKT=KT-KKKBT
      GDF=TBK-1.0
      GLD=ALOG(GDF)
      SLD=ALOG(AKT)
      DO 1060 J=1,KKKBT
      IF (Y(J)) 1099,1057,1058
 1057 KFLA=1
 1058 AMV=AMV+Y(J)
      IF (KFLA) 1060,1059,1060
 1059 Y(J)=ALOG (Y(J))
      GMLOG=GMLOG+Y(J)
 1060 CONTINUE
      Z=AMV
```

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FORTRAN IV G1  RELEASE 2.0            MAIN                DATE = 78020          13/14/18   PAGE 0004

0153               KKKBT=KKKBT-1                                                                  1630
0154               IF (KFLA) 1061,1062,1061                                                       1640
0155          1061 BST=9999999999.                                                                1650
0156               KKKBT=999                                                                      1660
0157               GO TO 1100                                                                     1670
0158          1062 GMLOG=GMLOG/TBKKK                                                              1680
0159               GMLOG=GMLOG-DLD                                                                1690
0160               AMV=AMV/AKT                                                                    1700
0161               AMV=ALOG (AMV)                                                                 1710
0162               BST1=AKT*(AMV-GMLOG)                                                           1720
0163               BST2=1.0+(TBKKK+1.0)/(3.0*AKT)                                                 1730
0164               BST=BST1/BST2                                                                  1740
0165               GO TO 1100                                                                     1750
0166          1099 AKT=0.0                                                                        1760
0167               BST=-999999999.                                                                1770
0168               KKKBT=-999                                                                     1780
0169               Z=0.0                                                                          1790
             C  MAIN ANALYSIS OF VARIANCE STARTS 4EXCLUDING REP CALCULATIONS<                     1800
0170          1100 GO TO (1102,1101,1103),KDEV                                                    1810
0171          1101 WRITE (MPR,17) (OPTION(I),I=1,2),(ALF(I),I=1,M)                                1820
0172               GO TO 1104                                                                     1830
0173          1102 WRITE (MPR,17) (OPTION(I),I=3,4),(ALF(I),I=1,M)                                1840
0174               GO TO 1104                                                                     1850
0175          1103 WRITE (MPR,17) (OPTION(I),I=5,6),(ALF(I),I=1,M)                                1860
0176          1104 WRITE (MPR,15)                                                                 1870
0177               DO 1105 I=1,12                                                                 1880
0178          1105 MO(I)=0                                                                        1890
0179               K=1                                                                            1900
0180               MORTH=KO(1)                                                                    1910
0181               SSQ1=0.0                                                                       1920
0182               SSQT=0.0                                                                       1930
0183               MDG1=0                                                                         1940
0184               MDGT=0                                                                         1950
0185          1106 LNK=0                                                                          1960
0186               JNK=0                                                                          1970
0187               NUM=0                                                                          1980
0188               GO TO 1311                                                                     1990
             C  SEQUENTIAL COMBINATORIAL BINARY GENERATOR STARTS                                  2000
0189          1200 IF (KODE-2) 1203,1202,1203                                                     2010
0190          1202 MSHIFT=2                                                                       2020
0191               M1=M-1                                                                         2030
```

```
      GO TO 1205
 1203 MSHIFT=1
      M1=M
 1205 J=1
      DO 1206 I=1,M1
      IF (AND(JNK,MSK(I))) 8000,1206,1207
 1206 CONTINUE
      GO TO 1209
 1207 DO 1208 J=I,M1
      IF (AND(JNK,MSK(J))) 8000,1210,1208
 1208 CONTINUE
      J=M1-I+2
 1209 JNK=2**J-1
      NUM=NUM+1
      IF(M1-NUM) 4478,1211,1211
 1210 J=J-I-1
      I=I-1
```

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 0209                   JNK=JNK+2**I+2**J-1                                                      2210
 0210              1211 LNK=JNK*MSHIFT                                                           2220
                  C  COMBINATORIAL BINARY ANALYZER STARTS                                        2230
 0211              1311 NB=0                                                                     2240
 0212                   LEV=0                                                                    2250
 0213                   KR(1)=1                                                                  2260
 0214                   DO 1314 I=1,M                                                            2270
 0215                   IF (AND(LNK,MSK(I))) 8000,1312,1313                                      2280
 0216              1312 LVID(I)=0                                                                2290
 0217                   NB=NB+1                                                                  2300
 0218                   GO TO 1314                                                               2310
 0219              1313 LVID(I)=1                                                                2320
 0220                   LEV=LEV+1                                                                2330
 0221                   LV(LEV)=L(I)                                                             2340
 0222                   LVS(LEV)=I                                                               2350
 0223                   CHAR(LEV)=ALF(I)                                                         2360
 0224              1314 CONTINUE                                                                 2370
 0225                   NR = LEV+1                                                               2380
 0226                   IF (NR-13) 1315,1317,1317                                                2390
 0227              1315 DO 1316 I=NR,12                                                          2400
 0228              1316 CHAR(I)=BLANK                                                            2410
 0229              1317 DO 1318 I=2,LEV                                                          2420
 0230              1318 KR(I)=KR(I-1)*LV(I-1)                                                    2430
                  C                                                                              2440
                  C                                                                              2450
                  C  HARTLEY@S @SUM@ AND @DIFFERENCE@ OPERATORS START                             2460
 0231              2017 TKT=KT                                                                   2470
 0232                   NSKIP(1)=1                                                               2480
 0233                   DO 2020 I=2,M                                                            2490
 0234                   IF (LVID(I-1)) 2018,2019,2018                                            2500
 0235              2018 NSKIP(I)=NSKIP(I-1)*L(I-1)                                               2510
 0236                   GO TO 2020                                                               2520
 0237              2019 NSKIP(I)=NSKIP(I-1)                                                      2530
 0238                   GO TO 2020                                                               2540
 0239              2020 CONTINUE                                                                 2550
 0240                   IF (NP-1) 2021,2022,2021                                                 2560
 0241              2021 JDM=2                                                                    2570
 0242                   GO TO 2023                                                               2580
 0243              2022 JDM=1                                                                    2590
 0244              2023 KTS=KT                                                                   2600
 0245                   DO 2024 J=1,KT                                                           2610
```

```
      JNEST=J+LOCAT
 2024 Y(J)=X(JNEST)
 2025 DO 2060 I=1,M
      JC=0
      J=1
      M1=1
      NSK=NSKIP(I)
      LL=L(I)
      LL1=LL-1
      NSKLL1=NSK*LL1
 2026 IF (LVID(I) .NE. 0) GO TO 2028
      KCP=1
      GO TO 2031
 2028 KUP=2
      DL=LL
 2031 SOP=0.0
      M2=M1+NSKLL1
```

```
FORTRAN IV G1  RELEASE 2.0            MAIN               DATE = 78026           13/14/18   PAGE 0006
      0263                  M3=NSK                                                                  2790
      0264                  GO TO (2035,2039),KOP                                                   2800
      0265            2035 DO 2036 JJ=M1,M2,M3                                                      2810
      0266            2036 SOP=SOP+Y(JJ)                                                            2820
      0267                  Y(J)=SOP                                                                2830
      0268                  J=J+1                                                                   2840
      0269                  GO TO 2050                                                              2850
                      C   OPERATOR BRANCHES FOR ALTERNATIVE COMPUTATION &MEANS OR DEVIATES<         2860
      0270            2039 GO TO (2040,2044),JDM                                                    2870
      0271            2040 DO 2041 J=M1,M2,M3                                                       2880
      0272            2041 Y(J)=Y(J)*DL                                                             2890
      0273                  GO TO 2050                                                              2900
      0274            2044 DO 2045 J=M1,M2,M3                                                       2910
      0275            2045 SOP=SOP+Y(J)                                                             2920
      0276                  DO 2049 J=M1,M2,M3                                                      2930
      0277            2049 Y(J)=Y(J)*DL-SOP                                                         2940
      0278            2050 M1=M1+1                                                                  2950
      0279                  JC=JC+1                                                                 2960
      0280                  IF (NSK .GT. JC) GO TO 2058                                             2970
      0281                  M1=M2+1                                                                 2980
      0282                  JC=0                                                                    2990
      0283            2058 IF (M1 .LE. KTS) GO TO 2031                                              3000
      0284            2059 IF (KOP .EQ. 1) KTS=KTS/LL                                               3010
      0285            2060 CONTINUE                                                                 3020
      0286                  IF (NP) 2061,2061,2062                                                  3030
      0287            2061 GO TO (4278,2080),JDM                                                    3040
      0288            2062 IF(IPLOT.LT.1) GO TO 334                                                 3050
      0289                  WRITE(6,11) (OPTION(I),I=3,4),(ALF(I),I=1,M)                            3060
      0290             334 WRITE(6,13) CHAR                                                         3070
      0291                  IF (NP-1) 8000,4278,4280                                                3080
                      C   DEGREES-OF-FREEDOM CALCULATION STARTS                                     3090
      0292            2080 MDG=1                                                                    3100
      0293                  DO 2083 I=1,M                                                           3110
      0294                  IF  (LVID(I) ) 2081,2081,2082                                           3120
      0295            2081 MDG=MDG                                                                  3130
      0296                  GO TO 2083                                                              3140
      0297            2082 MDG=MDG*(L(I)-1)                                                         3150
      0298            2083 CONTINUE                                                                 3160
                      C   SUM-OF-SQUARES CALCULATION STARTS                                         3170
      0299                  SSQ=0.0                                                                 3180
      0300                  SKTS=KTS                                                                3190
```

```
      DO 2088 J5=1,KTS
 2088 SSQ=SSQ+Y(J5)**2
      SSQ=SSQ/SKTS
      SSQ=SSQ/TKT
      SMDG=MDG
      SQM=SSQ/SMDG
      IF (LEV) 2091,2092,2091
 2091 SSQT=SSQT+SSQ
      MDGT=MDGT+MDG
C  PRINTOUT OF VARIANCE ATTRIBUTABLE TO EACH FACTORIAL COMBINATION
 2092 WRITE (MPR,18) SSQ,MDG,SQM,CHAR
      IF (MORTH .LT. 1)          GO TO 4250
      IF (LEV .NE.1)             GO TO 4250
      IF (MORTH .GT. M)          GO TO 4250
      IF (LVID(MORTH) .NE. 1)    GO TO 4250
      IF (L(MORTH) .LE. 1)       GO TO 4250
C  OPTIONAL PARTITION INTO LINEAR THRU CUBIC COMPONENTS STARTS FOR
```

```
                 C   SPECIFIED MAIN EFFECT WHOSE LEVELS ARE MAGNITUDES IN ARITHMETIC      3370
                 C   PROGRESSION                                                          3380
 0316             3135 NN=L(MORTH)                                                        3390
 0317                  DN=NN                                                              3400
 0318                  OLIN=0.0                                                           3410
 0319                  OQAD=0.0                                                           3420
 0320                  OCUB=0.0                                                           3430
 0321                  OREM=0.0                                                           3440
 0322                  IF (NN-3) 3136,3137,3138                                           3450
 0323             3136 IG=1                                                               3460
 0324                  GO TO 3139                                                         3470
 0325             3137 IG=2                                                               3480
 0326                  GO TO 3139                                                         3490
 0327             3138 IG=3                                                               3500
 0328             3139 DO 3145 I=1,NN                                                     3510
 0329                  AA=I                                                               3520
 0330                  P=AA-(DN+1.0)/2.0                                                  3530
 0331                  OLIN=OLIN+P*Y(I)                                                   3540
 0332                  GO TO (3145,3140,3140),IG                                          3550
 0333             3140 PP=P*P-(DN*DN-1.0)/12.0                                            3560
 0334                  OQAD=OQAD+PP*Y(I)                                                  3570
 0335                  GO TO (3145,3145,3141),IG                                          3580
 0336             3141 PPP=P*(P*P-(3.0*DN*DN-7.0)/20.0)                                   3590
 0337                  OCUB=OCUB+PPP*Y(I)                                                 3600
 0338             3145 CONTINUE                                                           3610
 0339                  PKT=KT                                                             3620
 0340                  RD1=12.0/(PKT*DN*DN*(DN*DN-1.0))                                   3630
 0341                  F(K)=OLIN*OLIN*RD1                                                 3640
 0342                  GO TO (3152,3146,3146),IG                                          3650
 0343             3146 RD2=15.0*RD1/(DN*DN-4.0)                                           3660
 0344                  S(K)=OQAD*OQAD*RD2                                                 3670
 0345                  GO TO (3152,3152,3147),IG                                          3680
 0346             3147 RD3=140.0*RD2/(9.0*DN*DN-81.0)                                     3690
 0347                  T(K)=OCUB*OCUB*RD3                                                 3700
 0348             3150 IF (NN .LE. 4) GO TO 3152                                          3710
 0349             3151 JR(K)=NN-4                                                         3720
 0350                  ERDF=JR(K)                                                         3730
 0351                  IG=4                                                               3740
 0352                  OREM=SSQ-OLIN-OQAD-OCUB                                            3750
 0353                  R(K)=OREM/ERDF                                                     3760
 0354             3152 MO(K)=MORTH                                                        3770
```

```
      IGO(K)=IG
 4249 K=K+1
      MORTH=KG(K)
 4250 GO TO (2022,4280,1200),KDEV
C   IDENTIFICATION STARTS FOR FACTOR LEVELS OF INDIVIDUAL MEANS, DEVIATES
 4278 DO 4279 I=1,KTS
 4279 Y(I)=Y(I)/TKT
 4280 DO 4470 J=1,KTS
      N=J-1
      DO 4363 IG=1,M
 4363 LVID(IG)=0
      IF (LEV-1) 4469,4468,4364
 4364 DO 4365 KK=2,LEV
      I=LEV-KK+2
      LV(I)=N/KR(I)
      N=MOD(N,KR(I))
 4365 LV(I)=LV(I)+1
```

```
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0371                   LV(1)=N+1                                                        3950
0372                   DO 4366 IG=1,LEV                                                 3960
0373                   KK=LVS(IG)                                                       3970
0374              4366 LVID(KK)=LV(IG)                                                  3980
0375                   GO TO 4469                                                       3990
0376              4468 KK=LVS(1)                                                        4000
0377                   LVID(KK)=J                                                       4010
0378              4469 WRITE (MPR,19) Y(J), (LVID(I),I=1,M)                             4020
0379              4470 CONTINUE                                                         4030
0380                   IF(NP.NE.1)  GO TO 201                                           4040
0381                   IF(IPLOT.LT.1) GO TO 201                                         4050
0382                   IF(LEV.LT.1  .OR.  LEV.GT.2)  GO TO 201                          4060
0383                   GO TO (203,205), LEV                                             4070
0384               203 CONTINUE                                                         4080
0385                   DO 207 J = 1, KTS                                                4090
0386               207 XCOR(J) = J                                                      4100
0387                   WRITE(6,211) CHAR(1)                                             4110
0388               211 FORMAT(1H1,12(/),39X,26HA PLOT OF RESPONSE VERSUS ,A2,7HFOLLOWS) 4120
0389                   CALL PLOTB(IPLOT,XCOR,IX1,Y,IY1,KTS,9,ISIZE,ITYPE,IMODE)         4130
0390                   GO TO 201                                                        4140
0391               205 CONTINUE                                                         4150
0392                   DO 213 J = 1, M                                                  4160
0393                   IF(LVID(J).EQ.0) GO TO 213                                       4170
0394                   LEV1 = L(J)                                                      4180
0395                   JX = J + 1                                                       4190
0396                   GO TO 215                                                        4200
0397               213 CONTINUE                                                         4210
0398                   WRITE(6,231)                                                     4220
0399               215 DO 221 J =  JX,  M                                               4230
0400                   IF(LVID(J).EQ.0) GO TO 221                                       4240
0401                   LEV2 = L(J)                                                      4250
0402                   GO TO 223                                                        4260
0403               221 CONTINUE                                                         4270
0404               231 FORMAT(1H1,10(1HX) / 4H ZAP / 1X,10(1HX))                        4280
0405                   WRITE(6,231)                                                     4290
0406               223 KCX = 0                                                          4300
0407                   DO 217 J = 1, LEV1                                               4310
0408               217 XCOR(J) = J                                                      4320
0409                   CALL CORE (CHAR(1),1)
0410                   READ (10,219) AX(1)
0411                   CALL CORE (CHAR(2),1)
```

```
      READ (10,219) AX(2)
  219 FORMAT(A1)                                                         4350
      WRITE(6,225) AX(1),LEV2,AX(2)                                      4360
  225 FORMAT(1H1,12(/),33X,26HA PLOT OF RESPONSE VERSUS ,A1,4H FOR,      4370
     1 I4,11H LEVELS OF ,A1,8H FOLLOWS)                                  4380
      IF(IPGS.EQ.1)  GO TO 241                                           4390
      KBX = 0                                                            4400
      IMODE = 0                                                          4410
      DO 243 J = 1, KTS                                                  4420
      KBX = KBX + 1                                                      4430
      IF(KBX.GT.LEV1)  KBX = 1                                           4440
  243 XCOR(J) = KBX                                                      4450
      CALL PLOTB(IPLOT,XCOR,IX1,Y,IY1,KTS,9,ISIZE,ITYPE,IMODE)           4460
      GO TO 201                                                          4470
  241 NTIMES = KTS/LEV1                                                  4480
  218 CALL PLOTB(IPLOT,XCOR,IX1,Y(INTEX),IY1,LEV1,9,ISIZE,ITYPE,IMODE)   4490
  201 WRITE(MPR,12)                                                      4500
```

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0428          4475 GO TO 1200                                                                    4510
0429          4478 IF (NP) 4480,4480,411                                                         4520
0430          4480 IF (AKT) 4482,4482,4481                                                       4530
             C   PRINTOUT OF POOLED REP ERROR TERM STARTS                                        4540
0431          4481 MDG1=AKT                                                                      4550
0432               MDGT=MDGT+MDG1                                                                4560
0433               SSQT=SSQT+Z                                                                   4570
0434               SQM1=Z/AKT                                                                    4580
0435               WRITE (MPR,20) Z,MDG1,SQM1                                                    4590
             C   PRINTOUT OF TOTALS, HOMOGENEITY TEST, ORTHOGONAL PARTITION STARTS               4600
0436          4482 WRITE (MPR,21) SSQT,MDGT                                                      4610
0437               IF (BST) 4483,4486,4483                                                       4620
0438          4483 WRITE (MPR,22) BST,KKKBT                                                      4630
0439          4486 DO 4494 I=1,12                                                                4640
0440               IF (MU(I) .LE. 0) GO TO 4495                                                  4650
0441               MORTH=MU(I)                                                                   4660
0442               IG=IGU(I)                                                                     4670
0443               WRITE (MPR,23) ALF(MORTH),F(I)                                                4680
0444               IF (IG .LE. 1) GO TO 4494                                                     4690
0445               WRITE (MPR,24) ALF(MORTH),S(I)                                                4700
0446               IF (IG .LE. 2) GO TO 4494                                                     4710
0447               WRITE (MPR,25) ALF(MORTH),T(I)                                                4720
0448               IF (IG .LE. 3) GO TO 4494                                                     4730
0449               WRITE (MPR,26) ALF(MORTH),JR(I),R(I)                                          4740
0450          4494 CONTINUE                                                                      4750
0451          4495 WRITE (MPR,16)                                                                4760
0452               AKT=0.0                                                                       4770
0453               BST=0.0                                                                       4780
0454               Z=0.0                                                                         4790
             C   CALCULATION OF VARIANCES WITHIN NESTS STARTS <CYCLING<                          4800
0455          5010 IF (NEST) 51,51,5020                                                          4810
0456          5020 KYCLE=KYCLE+1                                                                 4820
0457               IF (KYCLE-1) 5040,5025,5040                                                   4830
0458          5025 KT=KT/L(M)                                                                    4840
0459               M=M-1                                                                         4850
0460               JSTA=MSTA-NEST                                                                4860
0461               WRITE (MPR,27) JSTA                                                           4870
0462          5040 LOCAT=(KYCLE-1)*KT                                                            4880
0463               IF (KEEP-LOCAT) 5060,5060,5050                                                4890
0464          5050 GO TO 412                                                                     4900
0465          5060 NEST=NEST-1                                                                   4910
```

```
      KYCLE=0
      IF (NEST) 51,51,5070
 5070 LOCAT=0
      GO TO 5020
 8000 WRITE (MPR,28)
      GO TO 51
 9000 IF (MEOF) 9001,9002,9001
 9001 END FILE MPR
 9002 CALL EXIT
      END
```

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