Summer 1983

Low Cost Neutron Detector

Sebastian K. Namukolo

University of Central Florida

Find similar works at: https://stars.library.ucf.edu/rtd

University of Central Florida Libraries http://library.ucf.edu

This Masters Thesis (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of STARS. For more information, please contact STARS@ucf.edu.

STARS Citation


https://stars.library.ucf.edu/rtd/703
LOW COST NEUTRON DETECTOR

BY

SEBASTIAN K. NAMUKOLO
B.Sc., University of Zambia, 1977

THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in the Graduate Studies Program of the College of Engineering University of Central Florida Orlando, Florida

Summer Term 1983
ABSTRACT

Neutron bombardment of bipolar transistors creates cluster defects in semiconductor material. The clusters are small volumes of semiconductor material containing several hundred atoms displaced from their proper lattice sites owing to collision processes. They act as recombination centers in transistor bases, reducing minority carrier lifetime and consequently reducing transistor current gain. The damage is permanent to the semiconductor device and can only be corrected by thermally annealing the transistor. Copious test data available on bipolar transistors d.c. gain \( h_{FE} \) response to incident fast neutron fluences confirm their mathematically derivable functional relationships. This report develops a neutron fluence detector system based upon the current gain \( h_{FE} \) degradation. An approximate model extending these results to include the effects of temperature is developed. A probe containing an npn silicon planar transistor with associated components to allow \( h_{FE} \) measurements is designed. A thermal sensor is also designed. More precise neutron data is obtained by correcting for d.c. current gain versus ambient temperature error. The design of the probe is the major contribution in this report. In addition to the computer simulation of the probe model a system architecture and implementation is presented. The detector system is comprised of the probe and associated data acquisition 1/0 circuitry.
A microcomputer processes the probe data to calculate the neutron fluence received.

Robert J. Martin
Supervisor of Research
ACKNOWLEDGEMENT

This research was made possible by continued support from Mr. Robert J. Martin and Dr. Brian Petrasko who spared a lot of their time in the guidance of the research directions, and for making available the computer facilities. My special thanks also go to Dr. Fred O. Simons, Jr. and Dr. Bruce Matthews who encouraged and cheered me on in the whole period of my study at the University of Central Florida. I would also like to thank Dr. Robert Walker who was the third member on the committee.
# TABLE OF CONTENTS

LIST OF TABLES ................................................. v
LIST OF FIGURES ............................................... vi

Chapter

I. INTRODUCTION ............................................. 1
II. THEORY ....................................................... 5
   Review of Nuclear Radiation on Semiconductor Devices .... 5
   Transistor Operation ........................................ 8
   Effects of Radiation on Transistor Operation ................ 10
   Current Gain ............................................... 10
   Lifetime Damage Constant .................................. 11
   Photocurrents and Leakage Currents ......................... 12
   Combined Neutron and Thermal Effects on Bipolar Transistor Gain ........................................... 20
III. PROBE DESIGN ............................................. 26
   Derivation of Equations ...................................... 26
   Transistor Selection from Graphs ............................ 32
   Radiation Resistant Characteristics ......................... 35
   Temperature Sensing ......................................... 36
   Bias Equations ............................................... 37
   Computer Simulation of Probe Circuit ......................... 40
IV. SYSTEM DESCRIPTION AND DESIGN ......................... 42
V. SUMMARY AND CONCLUSIONS ................................ 52
   Summary ..................................................... 52
   Conclusions ................................................ 53

Appendix

A. DESIGN PROCEDURE ........................................ 54
B. COMPUTER PRINTOUT, PROGRAM AND RESULTS .............. 55

LIST OF REFERENCES ....................................... 68

iv
LIST OF TABLES

1. Matrix Parameters .............................................. 9
2. Radiation Effects of Silicon Transistors ...................... 14
3. Particle Effects of Transistor Parameters .................... 15
4. Tabulated Transistor Parameters .............................. 31
LIST OF FIGURES

1. System Overview ................................................. 4
2. Primary Photocurrents of Transistors ...................... 13
3. Typical Results for $I_{CBO}$ Degradation .................... 16
4. Plot of $h_{FE}$ versus $\phi$ .................................. 17
5. Plot of $V_{CE\ SAT}$ versus $\phi$ ............................. 18
6. Plot of $I_{CES}$ versus $\phi$ .................................. 19
7. Mobility versus Temperature .................................. 22
8. Current Gain versus Frequency ................................. 27
9. $f_{\beta}$ versus $h_{FE}$ ........................................ 33
10. $\phi$ versus $f_{\beta}$ .......................................... 34
11. Probe Schematic ............................................. 38
12. Probe Schematic with Temperature Sensor .................. 39
13. Complete Action Flow ....................................... 44
14. System Block Diagram ....................................... 45
15. Sequential Controller ....................................... 46
16. ASM Legend .................................................. 47
17. ASM Flow Chart ............................................. 48
18. Data Acquisition Detail ..................................... 49
19. ROM Code ................................................... 50
20. Low Cost Neutron Detector Schematic ........................ 51
CHAPTER I
INTRODUCTION

Nuclear radiation has adverse effects on both equipment and living organisms. It is essential to monitor radiation levels in a nuclear environment to determine doses which equipment or living organisms can be safely exposed to without irreparable damage.

Particulate and electromagnetic radiation are modes of material radiation. Particulate radiation includes alpha particles, electrons, protons and certain fission fragments. Electromagnetic radiation includes x-ray, photon and gamma radiations. While protons, alpha particles, electrons and fission particles are charged, neutrons and photons are electrically neutral. The ability of radiation to penetrate matter varies as a function of energy, charge and mass. However, charged particles have much shorter penetration than do photons and neutrons of equal energy. Neutrons undergo hard-sphere scattering, and charged particles undergo Rutherford scattering. Fast and thermal neutrons describe two groups of neutrons according to the amount of kinetic energy they possess. Fast neutrons have kinetic energies which are greater than ten kilo-electron volts.

Lacking electrical interaction with atomic electrons and nuclei in matter, neutrons are capable of penetrating other materials for several millimeters. Because of their mass, neutrons undergo a series of collisions with the atoms of the target material and are subsequently
stopped. In the process of collisions, considerable damage is done to the crystalline atomic structure of the target material. These neutron-atomic interactions involve a direct encounter with an atom nucleus. The atom nucleus receives a high percentage of the incident neutron energy during such an encounter. As a result the atom is usually displaced from its position in the structure, forming a vacancy and a shifting of atoms to unexpected positions. Mathematical models of neutron-matter interaction have been developed for several materials. The crystalline structure disorganization accounts for the semiconductor degradation, which in bipolar junction transistors gives rise to the functional relationship of neutron fluence and the transistor d.c. current gain ($h_{FE}$).

The utilization of these neutron damaging effects on low cost quality bipolar semiconductor transistors and the availability of inexpensive but powerful digital computers forms the basis of the design of a low cost neutron fluence detector system.

This research paper presents a low cost neutron detection system using bipolar semiconductor transistors as detectors. The neutron fluence is calculated from the amount of current gain ($h_{FE}$) degradation of the semiconductor transistor sensors at the probe.

The probe, appropriately hardened to respond to neutron fluences possessing a minimum kinetic energy, should be sensitive enough to accurately estimate the number of neutrons above the threshold energy level which have been radiated in an area.

The probe consists of bipolar semiconductor transistor with associated components for the measurement of the d.c. transistor
current gain. Included in the probe circuitry is a thermal sensor constructed by connecting several diodes in series.

The data acquisition circuitry accesses the probe data, digitizes it, and sends it to the computer whose software processes the data and displays the results. An overview of the system is shown in figure 1.
Fig. 1. System overview.
CHAPTER II

THEORY

Review of Nuclear Radiation on Semiconductor Devices

Bipolar junction transistors in a nuclear environment containing gamma rays, x-rays, energetic electrons and high-energy neutrons undergo ionization effects which result in trapped charges, charge transfer, increased bulk conductivity and excessive minority carriers. These damage mechanisms may be further characterized as surface effects, increased junction leakage currents, parameter degradation, primary photocurrents and latchup conditions. Electrons possessing enough kinetic energies interact with the atomic electrons causing excitation and ionization in the incident materials. In semiconductors, ionization effects result also from the interaction with high energy photons (gamma rays) to produce charged particles, which in turn cause more ionization by electrostatic interaction with the electrons of the semiconductor. Primary photon interaction involves the photoelectric effect, the Compton effect, and pair production processes. Photons do not possess charge or mass, and penetrate to longer distances in the target material. Neutrons have no charge and no associated electromagnetic field and are not repelled by the positively charged atomic nuclei. Hence they penetrate close to the nuclei of the material through which they are travelling. They may be captured to form a new compound nucleus or may be scattered or deflected away from
the target nuclei in a process referred to as elastic scattering. In elastic scattering, some of the energy of the neutron is transferred to the target nucleus and appears as kinetic energy. These displacements are particularly relevant to single-crystal materials such as semiconductors, whose physical properties often depend on the perfection of the crystal lattice. The results of displacement are extra atoms inserted between lattice sites (interstitials) and unoccupied lattice site vacancies. Defect clusters produced exclusively by fast neutron bombardment are often associated with impurity atoms in the semiconductor, and are important because they do not readily anneal or disappear, as do simple defects. Lifetime degradation in transistors causes a decrease in power output and common emitter current gain. Other radiation effects on bipolar junction transistors include increases in surface charge density resulting from ionizing radiation, changes in majority carrier density and decreases in carrier mobility. Fast neutrons create cluster defects in semiconductor materials which in transistor bases act as recombination centers hence reducing minority carrier lifetime and resulting in reduced transistor current gain. An understanding of the dependence of radiation fluence on basic semiconductor properties is necessary for considering device behavior in radiation environment. The important properties in priority order are as follows:

1. Minority carrier lifetime $\tau$.
2. Majority carrier density $n$.
3. Majority carrier mobility $\mu$. 
Minority carrier lifetime $\tau$ is related to radiation fluence $\phi$ by the equation

$$\frac{1}{\tau} = \frac{1}{\tau_0} + \frac{\phi}{K(\rho_0, E_n)}$$

(1)

where $\phi$ is the neutron fluence in n/cm$^2$,

$E_n$ is the incident neutron energy,

$\rho$ is the semiconductor material resistivity, and

$K$ is lifetime damage constant which is a function of energy and type of radiation, base resistance injection level of semiconductor and semiconductor impurities.

This relationship applies accurately for integrated neutron fluxes from $10^9$ to $10^{16}$ n/cm$^2$.

Majority carrier density fluence relationship is given by

$$n = n_0 + \frac{\phi dn}{d\phi}$$

(2)

where $dn$ depends on base resistance, type and energy of incident radiation.

Majority carriers are influenced by defects which act as scattering centers decreasing their mobilities. These cluster defects remove a volume of semiconductor containing the cores of the cluster and the surrounding field region from the conduction path, thereby causing an effective decrease in mobility.

Mobility fluence relationship is given by

$$\mu = \mu_0 - \phi \frac{d\mu}{d\phi}$$

(3)
Transistor Operation

In a neutron environment, all semiconductor properties are subject to change and affect transistor operation. The dominant mechanism is the minority carrier lifetime $\tau$ degradation in the base region determined by cluster defects in the bulk base material. In this section the functional relationships of $\tau$ to current gain $\beta$, neutron fluence $\phi$, and damage constant $K$ are derived.

The intrinsic transistor at low frequencies is described by

\[ I_E = a_{11} \psi_E - a_{12} \psi_C \]  \hspace{1cm} (4)
\[ I_C = a_{21} \psi_E - a_{22} \psi_C \]  \hspace{1cm} (5)

Where
\[ \psi_E = \exp \left( \frac{qV_E}{KT} \right) - 1 \]  \hspace{1cm} (6i)
\[ \psi_C = \exp \left( \frac{qV_C}{KT} \right) - 1 \]  \hspace{1cm} (6ii)

$I_E$ is emitter current

$I_C$ is collector current

$V_E$ is emitter voltage

$V_C$ is collector voltage and

\( a's \) are the quasi-admittance matrix parameters

The matrix parameters are shown in Table 1.

In the equations,

\[ \sigma = \frac{1}{2} \sqrt{\left(\frac{n}{w}\right)^2 + \left(\frac{4}{L_p}\right)^2}, \quad K = \frac{N_{DE}}{N_{DC}} \]  \hspace{1cm} (7)
\[ n = \ln K, \quad L_p = D \tau \]  \hspace{1cm} (8)
Table 1: Functions of the Conductance Matrix Elements Applicable to Both Homogeneous-Base and Graded-Base Transistors

<table>
<thead>
<tr>
<th>Matrix Element Function</th>
<th>Exact Form</th>
<th>Approximate Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{a_{11}}{AD_{spn}}$</td>
<td>$\sigma \coth \sigma W + \frac{n}{2W}$</td>
<td>$\left(1 + \frac{W^2}{2L_p^2} + \frac{n^2}{2} + \frac{n^2}{8}\right)/W$</td>
</tr>
<tr>
<td>$\frac{a_{12}}{AD_{spn}}$</td>
<td>$\frac{\sigma \csch \sigma W}{\sqrt{k}}$</td>
<td>$\frac{1}{W\sqrt{k}} \left(1 + \frac{W^2}{6L_p^2} + \frac{n^2}{24}\right)$</td>
</tr>
<tr>
<td>$\frac{a_{21}}{AD_{spn}}$</td>
<td>$\sqrt{k} \sigma \csch \sigma W$</td>
<td>$\frac{\sqrt{k}}{W} \left(1 + \frac{W^2}{6L_p^2} + \frac{n^2}{24}\right)$</td>
</tr>
<tr>
<td>$\frac{a_{22}}{AD_{spn}}$</td>
<td>$\sigma \coth \sigma W - \frac{n}{2W}$</td>
<td>$\left(1 + \frac{W^2}{2L_p^2} - \frac{n^2}{2} + \frac{n^2}{8}\right)/W$</td>
</tr>
</tbody>
</table>
$W$ is the transistor base width.

$N_{DE}$ is donor density in the base near the collector.

$L_p$ is hole diffusion length.

$D_p$ is hole diffusion constant in the base.

$\tau$ is minority carrier lifetime.

From equations (4) and (5), the transistor gain is given by

$$\alpha = -\frac{a_{21}}{a_{11}} = \frac{\beta}{1+\beta}$$

Using expressions in Table 1, the expression for $1/\beta$ (current gain) is

$$\frac{1}{\beta} = \left[ \frac{1}{\sqrt{k}} \left( 1 + \frac{n}{8} + \frac{W^2}{2L_p^2} \right) + \frac{n}{2\sqrt{k}} \left( 1 + \frac{n}{24} + \frac{W^2}{6L_p^2} \right) \right] - 1$$

(9)

This applies for homogenous - base transistors ($k = 1, n = 0$) and graded base transistors ($k = 10, n = 2.3$). An important parameter in current gain is $\tau$, the minority carrier lifetime in the base. From equation (8), $L_p$ (the hole diffusion length in the base) is given by

$$L_p = \sqrt{D_p \tau}$$

and equation (9) may be written as

$$\frac{1}{\beta} = \left[ \frac{1}{\sqrt{k}} \left( 1 + \frac{n}{8} + \frac{W^2}{2D_p \tau} \right) + \frac{n}{2\sqrt{k}} \left( 1 + \frac{n}{24} + \frac{W^2}{6D_p \tau} \right) \right] - 1$$

(10)

In the next section, it will be shown how the transistor current gain $\beta$ is influenced by the neutron fluence $\phi$.

**Effects of Radiation on Transistor Operation**

**Current Gain $\beta$**

For transistors whose base lifetime has been substantially degraded by displacement damage, the minority carrier lifetime $\tau = K/\phi$ is presented in equation (1).
Substituting this value of $\tau$ in equation (10), we have

$$\frac{1}{\beta} = \left[ \frac{1}{\sqrt{k}} \left( \frac{1}{\Phi} + \frac{n^2}{\Phi} + \frac{W^2}{2Dp} \right) + \frac{n}{2\sqrt{k}} \left( \frac{1}{\Phi} + \frac{n^2}{24} + \frac{W^2}{6Dp} \right) \right] - 1$$  \hspace{1cm} (11)

where the current gain $\beta$ is expressed as a function of the neutron fluence and minority carrier lifetime $\tau$ through the damage constant $K = 2\tau\phi$.

Now

$$\frac{\beta^{-1} - \beta_{1}}{\beta} = \frac{1}{K} \left( \frac{W^2}{2Dp} \left( \frac{1}{\sqrt{k}} + \frac{n}{6\sqrt{k}} \right) \right)$$  \hspace{1cm} (12)

where the term $W^2/2Dp$ is calculated using a measured value of current gain cutoff frequency $f_a$. An expression applicable to both homogeneous and graded-base transistor is

$$\frac{W^2}{2Dp} = \frac{0.2[1 + (n/2)^4/3]}{f_a}$$  \hspace{1cm} (13)

The Lifetime Damage Constant $K$

The lifetime damage constant $K$, a property of the semiconductor and influenced by fluence is given by

$$K = \frac{0.2 \left( 1/\sqrt{k} + n/6\sqrt{k} \right) \left( 1 + (n/2)^4/3 \right) \phi}{f_a (\beta^{-1} - \beta_i^{-1})}$$  \hspace{1cm} (14)

or

$$K = \frac{0.2F(n)\phi}{f_a (\beta^{-1} - \beta_i^{-1})}$$

where $F(n)$ is unity for homogeneous-base transistors.

C.R. Viswanathan et al. have shown that the neutron damage constant varies as the emitter current density for bipolar transistors. The expression for constant $K$ was derived in terms of the rate of degradation of current gain as
where $f_T$ is the preirradiated gain-bandwidth product (MHz)

$\beta$ is the common emitter current gain.

$D$ is neutron fluence.

Displacement in the base region is the dominant mechanism affecting current gain in bipolar transistors, where in turn, the damage constant $K$ is strongly dependent on the emitter current density. This is due to the fact that the lifetime of a minority carrier depends on the injection level, and this lifetime deterioration under neutron irradiation is caused by increased recombination centers in the base due to displacement damage.

The change in $K$ as a function of emitter current density is given by

$$K = \frac{0.16/f_T^2(1/\beta)}{D}$$

(15)

$$K = 0.16/f_T^2 \frac{2(1/\beta)}{D}$$

Photocurrents and Leakage Currents

Transistor exposure to radiation also results in primary photocurrents $i_{pp}$ and radiation storage time $t_{SR}$ which are complicated functions of device geometry, diffusion constant and generation rate of hole-electron pairs. Typical photocurrents of some transistors are shown in figure 2.

Tables 2 and 3 show effects of radiation on silicon transistors, particle effects on transistor parameters and transistor parameter variations due to neutron irradiation.

Figures 3, 4, 5, and 6 show effects of radiation on silicon
<table>
<thead>
<tr>
<th>Device</th>
<th>Power Rating (W)</th>
<th>$f_T$ (MHz)</th>
<th>Collector-Base Primary Photocurrent at $10^{10}$ rad (Si)/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>2N2368</td>
<td>0.360</td>
<td>400</td>
<td>8 mA</td>
</tr>
<tr>
<td>2N706</td>
<td>0.300</td>
<td>400</td>
<td>50 mA</td>
</tr>
<tr>
<td>2N3244</td>
<td>1.0</td>
<td>175</td>
<td>400 mA</td>
</tr>
<tr>
<td>3TX002</td>
<td>60</td>
<td>150</td>
<td>7 A</td>
</tr>
<tr>
<td>2N1016B</td>
<td>150</td>
<td>0.03</td>
<td>200 A</td>
</tr>
</tbody>
</table>

Fig. 2 Primary photo currents of transistors. (Taken from Ricketts 1972)
Table 2  Radiation Effects on Silicon Transistors  
(Taken from Ricketts).

<table>
<thead>
<tr>
<th>Functions</th>
<th>Function Dependence on Radiation</th>
<th>Specific Examples and Radiation Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photocurrent, ( I_{pp} )</td>
<td>( \propto \gamma )</td>
<td>2.4 mA at ( 10^8 ) rads/sec for 2N2222</td>
</tr>
<tr>
<td>Radiation storage time, ( t_{SR} )</td>
<td>( \propto \log \gamma )</td>
<td>3.5 ( \mu ) sec at ( 10^{11} ) rads/sec for 2N2222</td>
</tr>
<tr>
<td>Forward current gain, ( \beta )</td>
<td>( \propto 1/\Phi )</td>
<td>Decreases 18% at ( 10^{12} ) n/cm² and 57% at ( 10^{14} ) n/cm² for 2N3736</td>
</tr>
<tr>
<td>Collector saturation resistance, ( R_{SAT} )</td>
<td>( \propto \Phi )</td>
<td>Increases approximately 38% at ( 10^{12} ) n/cm² and 63% at 10 n/cm² for 2N708</td>
</tr>
</tbody>
</table>
Table 3  Particle Effects on Transistor Parameters*  
(Taken from Ricketts).

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Simulation Method</th>
<th>Particle Energy</th>
<th>Effect at 25°C</th>
<th>Parameter Affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast neutrons</td>
<td>Reactor</td>
<td>&gt;0.1 MeV</td>
<td>Permanent</td>
<td>$h_{FE}$, $V_{CE(sat.)}$, $I_{CB0}$</td>
</tr>
<tr>
<td>Protons</td>
<td>Same simulation method as for neutrons</td>
<td>&gt;0.1 MeV</td>
<td>Permanent</td>
<td>$h_{FE}$, $V_{CE(sat.)}$, $I_{CB0}$</td>
</tr>
<tr>
<td>Electrons</td>
<td>Accelerator (Linac, etc.)</td>
<td>1-22 MeV</td>
<td>Transient to semi-permanent</td>
<td>$I_{BB}$, $h_{FE}$</td>
</tr>
<tr>
<td>Gamma and X-ray</td>
<td>Flash X-ray, superflash</td>
<td>300-699 keV, 1-6 MeV</td>
<td>Transient</td>
<td>$I_{BB}$</td>
</tr>
</tbody>
</table>
Fig. 3  Typical results for $I_{CBO}$ degradation (Taken from Ricketts).
Fig. 4. In plot of dc pulse current gain $h_{FE}$ versus fast-neutron dosage $h_{FE}$ goes down: $T_A = 25^\circ C$, $I_C = 10$ m A, $V_{CE} = 5$ V. (Redrawn from Ricketts).
Fig. 5 In plot of collector saturation voltage $V_{ce}$ (sat) versus fast-neutron dosage $O$, $V_{ce}$ (sat) goes up: 
$T_A = 25^\circ C$, $I_C = 10mA$ (Redrawn from Ricketts, 1972).
Fig. 6 In plot of leakage current $I_{ces}$ versus fast-neutron dosage $I_{ces}$ goes up:
$TA = 25^\circ C, V_{ce} = 6.0V.$  (Redrawn from Ricketts, 1972)
transistors for leakage current, for effects on $h_{fe}$, effects on $V_{CE(sat)}$ and for effects on $I_{CES}$ respectively.

**Combined Neutron and Thermal Effects on Bipolar Transistor Gain**

The previous sections discussed transistor's d.c. gain neutron response at room temperature. In this section, an approximate model is developed to extend these results, to include the effect of temperature.

The reciprocal common emitter d.c. current gain $h_{FE}$ at low and moderate current levels is approximated and rewritten as

$$\frac{1}{\beta} = \frac{W^2}{2DT} + \frac{\sigma_b W}{\sigma_e L_e} + \frac{SA_W}{A_b D} + \frac{W_n b}{2Dn_i} \left( \frac{W_{eb}}{\tau D} + \frac{SA_S}{A_e} \right) \exp \left( -\frac{qV_{be}}{2kT} \right)$$  \hspace{1cm} (17)

where $W$ is the base width.

- $D$ is the base diffusion constant.
- $\tau$ is the base minority carrier lifetime.
- $\tau_D$ is the minority carrier lifetime in the emitter base depletion region.
- $\sigma_e$ and $\sigma_b$ are the emitter and base conductivities.
- $L_e$ is the emitter diffusion length.
- $S$ is the surface recombination velocity.
- $A_S$ is the effective area for surface recombination.
- $A'_{sb}$ is the area of the surface depletion region of the emitter base junction.
- $A_e$ is the emitter area.
- $W_{eb}$ is the width of the emitter-base space charge region.
- $n_b$ is the base doping.
- $n_i$ is the intrinsic carrier concentration.
q is the electron charge.

$V_{be}$ is the base emitter voltage.

k is the Boltzman's constant ($8.62 \times 10^{-5}$ ev/°K).

T is the absolute temperature.

The first term of the above equation is the base transport loss which leads to the Messenger-Spratt neutron damage equation,

$$\frac{1}{\beta} = \frac{1}{\beta} + \frac{\phi}{2\pi f_T \kappa}, \quad K_D = 1/2\pi f_T$$

(18)

where $K$ is the lifetime damage constant $K = 1.6 \times 10^6$ cm$^2$/n-sec and $K_D$ is damage factor for the device.

The dependence of the factor $K_D$ on temperature is expressed by the empirical formula

$$K_D(T) = K_{D0} \left[1.1 - 0.1 \left(\frac{T}{T_0}\right)^4\right]$$

(19)

The temperature dependence of the base transport term prior to neutron exposure is estimated from the temperature dependence of mobility figure 7 and the Einstein relation ($D = kT\mu/q$) yielding

$$D = D_0 T_0 / T$$

(20)

The second term in equation (17) describes emitter efficiency. It is not significantly affected by neutrons however, due to the small initial lifetime and a square root dependence on neutron fluence

$$L_e^2 = D_T E$$

The current gain is dominated by the emitter injection efficiency for devices where

$W < 0.1 \sqrt{2D_T}$

(21)

In transistors, initial current gain is determined almost entirely by emitter efficiency prior to neutron exposure which leads to
Fig. 7 Mobility as a function of Temperature on Silicon. (Redrawn from Yang, 1978)
temperature dependence. For a uniformly doped emitter region, the current gain as determined by the emitter efficiency can be roughly estimated for heavily doped emitters as

\[ h_{FE} \propto \exp \left( -\frac{\Delta E_g}{kT} \right) \left( \frac{D_e}{D_b} \right) g_e \]  

(22)

where \( \Delta E_g = 3.4 \times 10^{-8} (N_d^{1/3} - 2.65 \times 10^6) \) eV.

Where using an emitter doping level of \( N_d = 6 \times 10^{19} \). The temperature dependence of gain is estimated as

\[ h_{FE}(T) = h_{FE0} \exp \left[ \frac{\Delta E_g}{k(1/T - 1/T_0)} \frac{D_e}{D_b} \right] \]  

(23)

\[ \frac{1}{h_{FE}(T)} = \frac{1}{h_{FE0}} \left( \frac{T}{T_0} \right)^x \]  

(24)

where \( x = \frac{\Delta E_g}{kT} + 1 \approx 2.6 \) at \( T = 300^\circ K \).

The third term of equation (17) represents surface effects at the non-space charge region only, while the fourth term is due to surface recombination effects in those regions of the base where depletion layers have formed near the surface.

After neutron irradiation,

\[ S = S_o + K_S \Phi \]  

(25)

where \( K_S \) is surface damage constant which varies with device type. The terms in \( S \) are

\[ S_o = \sigma_c V_{th} N_{st} \]  

(26)

where \( N_{st} \) is the surface trap density

\( V_{th} \) is the thermal velocity proportional to \( \sqrt{T} \) and

\( \sigma_c \) is the surface trap cross-section.

Surface terms have a small temperature dependence.

Using diffusion constant and intrinsic carrier concentration
dependence on temperature the remaining terms are described.

\[ \text{ni}(T) = T^{3/2} \exp \left( -\frac{E_g}{2kT} \right) \]  

(27)

\[ \text{no} = \text{ni} \left( 300K \right) = 1.5 \times 10^{10} \frac{\text{c}}{\text{cm}^3} \]

and

\[ E_g = 1.12 \text{ eV} \]

The resultant temperature dependence of the low current gain term is

\[ \frac{\Delta \frac{1}{h_{FE}}}{h_{FE}}(T) \approx \frac{W^2}{2D_0\tau_D} \left( \frac{T}{T_D} \right)^{\phi/2kT} \exp \left[ -\frac{qV_{be}/2kT}{T} \right] \frac{\text{To}}{T}^{1/2} \exp \left( -\frac{qV_{be}/2kT}{T} \right) \]

(28)

Which is approximated to

\[ \frac{\Delta \frac{1}{h_{FE}}}{h_{FE}} \approx \frac{W^2}{2D_0\tau_D} \left( \frac{T}{T_D} \right)^{-y+1} \]

(29)

Where

\[ A = \left( \frac{W_{eb}}{W_{TD}} \right) \left( \frac{\text{To}}{\text{no}} \right) \exp \left( E_g - qV_{be} \right) \left( \frac{1}{T} - \frac{1}{T_D} \right) /2k \]

\[ y = \left[ \left( E_g qV_{be} / 2kT_D \right) \right]^{-3/2} \]

Combining the neutron and temperature models for transistors where surface recombination is not significant, the resultant model for estimation of the neutron degraded d.c. gain is given as

\[ \frac{1}{h_{FE}} = \frac{\sigma_D W}{\sigma_e L_e} \left( \frac{T}{T_D} \right)^{-x} \left[ K_D(T) \phi + \frac{W^2}{2D_0\tau} \left( \frac{T}{T_D} \right) \right] \left[ 1 + A \left( \frac{T}{T_D} \right)^{-y} \right] \]

(30)

where \( x \) is 2 to 2.6 and \( y \) is 4 to 8.

The low current terms are proportional to \( A \). Prior to neutron exposure, terms proportional to \( A \) are multiplied by \( W^2/2D_0\tau \approx 1/f_T \) which is typically between 0.01 and 0.0005 for most transistors. As
1/f<sub>T</sub> approaches zero, the above equation reduces to emitter efficient term without neutron degradation.

Equation (30) is simplified to

\[
\frac{1}{h_{FE}} = \frac{1}{h_{FEO}} \left( \frac{T}{T_0} \right)^{-x} + K_D(T) \Phi \left[ 1 + A \left( \frac{T}{T_0} \right)^{-y} \right]
\]  

(31)

After heavy neutron exposure, terms proportional to \( K_D(T) \) predominate and the effect of the \( A \) term (which is highly temperature dependent) can be important.

For transistors operating at moderate current levels, near the peak of their gain curves, the combined thermal/neutron model can be further simplified by dropping the low current term:

\[
\frac{1}{h_{FE}} = \frac{1}{h_{FEO}} \left( \frac{T}{T_0} \right)^{-x} + K_D(T_0) \Phi \left[ 1.1 - 0.1 \left( \frac{T}{T_0} \right)^4 \right]
\]  

(32)

To utilize the model, the measured \( h_{FEO} \) (room temperature gain) and \( K_D(T_0) \) room temperature degradation are substituted in the equation.
CHAPTER III
PROBE DESIGN

Derivation of Equations

A transistor can be used as the central element in the design of a probe detecting neutron fluence. However, probe transistors must be appropriately selected to withstand the maximum irradiation expected without excessive damage. In this section, equations which facilitate the choice of the transistors are derived, and rules of their selection from given tables and graphs are discussed.

In the discussion following, these definitions are used, as shown in figure 8

where

$\alpha$ or $h_{fb}$ (alpha) is common-base ac forward current gain.

$\alpha_0$ (d.c alpha) common-base dc forward current gain.

(at low frequencies $\alpha \approx \alpha_0$)

$\beta$ or $h_{fe}$ (beta) common emitter ac forward current gain.

$\beta_0$ or $h_{FE}$ (dc beta) common emitter dc forward current gain at low frequencies, $\beta \approx \beta_0$.

$\alpha_c$ (alpha cut off frequency or common-base cut off frequency), frequency at which the value of alpha drops to 0.707 times its 1-KHz value.

$\beta_c$ (beta cut off frequency or common emitter cut off frequency),
Fig. 8 Current gain versus frequency.
frequency at which the value of beta drops to 0.707 times its 1kHz value.

$f_T$ (gain-bandwidth product), frequency at which beta is equal to unity. The variation of transistor current with injection level is described by the equation

$$\frac{1}{\beta} = \frac{\text{SWA}}{\frac{D}{p} A e} + \left[ \frac{\alpha_b W}{\sigma L e} + \frac{1}{2} \left( \frac{W}{L_p} \right)^2 \right] (1+Z)$$

(33)

The first term describes surface recombination. The second term describes injection efficiency and volume recombination, and the factor $(1+Z)$ multiplying $W^2/L_b^2$ treats bulk recombination as a bimolecular process.

A modified equation relating the transistor current gain degradation with fast-neutron fluence (derived by Messenger-Spratt) is given by:

$$\frac{1}{\beta_\phi} - \frac{1}{\beta_o} = 0.2\Phi + \frac{dI_{RE}}{dI_E}$$

(34)

Where $\beta_\phi$ is current gain at fast-neutron-fluence $\Phi$,

$\beta_o$ is initial gain,

$f_\alpha$ is alpha cutoff frequency,

$K$ is damage constant, which is a function of neutron energy, resistivity of the base region, injection level and temperature,

$dI_{RE}$ is term to account for recombination in the emitter-base space charge region.

Equation (34) shows that at low injection level, the second term will dominate because the base current increase is primarily due to increased carrier recombination in the emitter-base space-charge region.
For normal transistor operation, at intermediate injection levels, the first term will dominate because the increase in base current is due primarily to recombination in the neutral base region (base transport factor). The degradation of transistor current gain is represented by

\[
\frac{1}{\beta_{\phi}} - \frac{1}{\beta_0} = \frac{0.2\phi}{Kf_{\alpha}}
\]

where \( K = 1 \times 10^6 \text{ n/cm}^2 \text{ sec} \) for an npn transistor.

Assuming \( f_\alpha = \beta_0 f_\beta \), an equation predicting 50% degradation

\[
\beta_{\phi} = 0.5 \beta_0 \text{ of current gain}
\]

\[
\phi_{0.5} = 5 \times 10^6 f_\beta \text{ n/cm}^2
\]

Using this equation, the 50% beta degradation fluence of transistor may be calculated. In choosing high radiation tolerant transistors, it is best to choose transistors with both high initial current gain and high cut off frequency.

Table 2 shows calculated and experimental results, where the beta cut-off frequencies are calculated from the equation

\[
f_\beta = f_T / \beta_0 = f_a / \beta_0
\]

In addition to the 50% beta degradation level determination, the knowledge of the absolute beta of the transistor at a specific fluence level is helpful in selecting transistors.

A simple equation to calculate transistor beta at fluence

\[
\phi = 1 \times 10^{13} \text{ n/cm}^2
\]

which is rewritten as

\[
\frac{\beta_{\phi}}{\beta_0} = \frac{K f_{\alpha}}{K f_{\alpha} + 0.2 \phi \beta_0}
\]
where for \( K = 1 \times 10^6 \) n/cm² sec
\[
\Phi = 1 \times 10^{13} \text{n/cm}^2
\]

\[
\frac{\beta_\Phi}{\beta_o} = \frac{f\alpha}{f\alpha + 2 \times 10^6 \beta_o}
\]

or
\[
\beta_\Phi = \frac{\beta_0 f\alpha}{f\alpha + 2 \times 10^6 \beta_o}
\]

(39)

The last column of Table 2 shows calculated transistor beta at
\( \Phi = 1 \times 10^{13} \text{n/cm}^2 \) for neutrons with \( E > 10 \text{kev} \)

Other electrical parameters, which are a measure of the physical makeup of the transistor relate to radiation damage and are hence useful for evaluating the degradation in performance caused by a radiation environment.

The expression for the effect of exposure to integrated neutron flux on beta (the common emitter a.c. current gain designated by \( h_{fe} \) or \( \beta \)) is given in terms of the beta-cutoff frequency \( f_\beta \). Using
\[
f_\beta = (1-\alpha)f\alpha,
\]
where \( \alpha \) is the common base ac low frequency gain \( (h_{fb}) \), \( \alpha \) and \( \beta \) in turn are related by the expression \( \beta = \alpha / (1-\alpha) \) or \( \alpha = \beta / (1+\beta) \).

Thus \( f_\beta = (1-\alpha)f\alpha \) is rewritten as
\[
f_\beta = \frac{f\alpha}{(\beta+1)}
\]

(40)
or \( f_\beta \approx \frac{f\alpha}{\beta} \) for \( \beta \gg 20 \)

or \( f\alpha \approx \beta f_\beta \)

Using this result in equation (35) we get
\[
\frac{1}{\beta_\Phi} = \frac{1}{\beta_o} + 0.2 \frac{\phi}{\beta_o f_\beta}
\]

(41)
Table 4  Tabulated Transistor Parameters

<table>
<thead>
<tr>
<th>Transistor Number</th>
<th>Calculated $f_p$ (MHz)</th>
<th>Calculated $\phi_{0.5}$ (n/cm$^2$)</th>
<th>Exposure $\phi_{0.5}$ (n/cm$^2$)</th>
<th>$f_c$ or $f_T$ (MHz)</th>
<th>$F_0^a$</th>
<th>$\beta_0/\beta_0$</th>
<th>$\beta_0$ Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>2N918</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>600</td>
<td>20</td>
<td>0.93</td>
<td>18</td>
</tr>
<tr>
<td>2N930</td>
<td>0.2</td>
<td>$1 \times 10^{12}$</td>
<td>$5 \times 10^{11}$</td>
<td>30</td>
<td>150</td>
<td>0.09</td>
<td>13</td>
</tr>
<tr>
<td>2N2222</td>
<td>5.0</td>
<td>$2.5 \times 10^{13}$</td>
<td>$8 \times 10^{12}$</td>
<td>250</td>
<td>50</td>
<td>0.71</td>
<td>35</td>
</tr>
<tr>
<td>2N2369</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>800</td>
<td>80</td>
<td>0.83</td>
<td>66</td>
</tr>
<tr>
<td>2N2484</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>60</td>
<td>100</td>
<td>0.23</td>
<td>23</td>
</tr>
<tr>
<td>2N2857</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>1900</td>
<td>50</td>
<td>0.95</td>
<td>$47^b$</td>
</tr>
<tr>
<td>2N2907</td>
<td>6.6</td>
<td>$3.3 \times 10^{13}$</td>
<td>$2 \times 10^{13}$</td>
<td>200</td>
<td>25</td>
<td>0.80</td>
<td>20</td>
</tr>
<tr>
<td>2N3499</td>
<td>0.5</td>
<td>$2.5 \times 10^{12}$</td>
<td>$1 \times 10^{13}$</td>
<td>150</td>
<td>100</td>
<td>0.42</td>
<td>42</td>
</tr>
<tr>
<td>2N5071</td>
<td>1.0</td>
<td>$5 \times 10^{12}$</td>
<td></td>
<td>100</td>
<td>10</td>
<td>0.83</td>
<td>8</td>
</tr>
</tbody>
</table>
Letting $\beta_0$ to be rewritten as $x\beta_0$, where $1-x$ is the amount of degradation of $\beta_0$ that the circuit can tolerate, equation (41) is rewritten as

$$\frac{1}{x\beta_0} - \frac{1}{\beta_0} = 0.2x \frac{\Phi}{K}$$

Thus, $f_\beta = \frac{0.2x \Phi}{(1-x)K}$

and

$$\Phi = \frac{(1-x)Kf_\beta}{0.2x}$$

(42)

(43)

$f_\beta$ (beta-cutoff frequency) and $f_\alpha$ (alpha-cutoff frequency) are not specified. The gain-bandwidth product $f_T$ (the frequency at which $h_{fe}'$, or beta, is unity) is specified.

Where $f_T < f_\alpha$ and can be substituted for $f_\alpha$.

If not specified, $f_T$ is calculated by taking the product of the common-emitter small-signal current gain times the frequency of measurement; provided the frequency of measurement is above the beta-cutoff frequency, $f_\beta$. Common-emitter low frequency current gain $\beta$ or $h_{fe}$ is not often specified. However, $f_\beta$ is approximately $f_T/\beta_0$.

Transistor Selection from Graphs

The graphs of figures 9 and 10 facilitate the selection of transistors having the required resistance to the integrated neutron flux $\Phi$. The procedure for using these curves is as follows

1. $\beta(h_{fe})$ or $\beta_0$ from the data sheet is obtained.

2. $f_\alpha$ or $f_T$ is obtained or calculated from the data sheet.
Fig. 9 Plot of $f_B$ as a function of $\beta$ and $f_T$ (Taken from Ricketts)
Fig. 10  Beta-cutoff frequency as a function of integrated neutron flux (Taken from Ricketts).
3. Using figure 9 the value of \( f_B \) is obtained using the above steps 1 and 2, by entering the graph at the proper value of \( h_{FE} \) on the abscissa, going up to the proper curve for \( f_T \) and then reading \( f_B \) on the ordinate.

4. Using the value of \( f_B \) obtained above, graph of figure 10 is entered from the \( f_B \)-axis to the curve for the amount of degradation in beta which can be tolerated and the value of the integrated neutron flux which will cause that amount of degradation read off.

Radiation-Resistant Characteristics

In general the best radiation-resistant devices have the following characteristics:

1. High \( f_T \), which is the best indicator of base transit time.

2. High \( h_{FE} \) for a given transistor family; the higher the \( h_{FE} \), the higher the \( f_T \) and the more the \( h_{FE} \) can change before reaching a circuit design minimum.

3. Low \( L V_{CEO} \): The higher the starting resistivity, the more significant the change.

4. Small geometry: the smaller geometry consistent with current-carrying requirements and the shallower the device, the smaller the diffusion volume; thus the less susceptibility to transient radiation.

5. Low \( V_{CE(sat)} \): The lower saturation voltage requires epitaxial collector construction. Change in resistivity in the collector makes \( V_{CE(sat)} \) increase drastically and possibly cause the transistor to come out of saturation.
6. Operating at or near the $h_{FE}$ versus $I_C$ peak: In general, $I_C \log I_C h_{FE}$ will fall at a much faster rate and will reach a minimum value much faster than at the point where $h_{FE}$ will peak. This is caused by the surface contribution to low current $h_{FE}$, and the surface is most sensitive to radiation effects.

**Temperature Sensing**

Diodes can be usefully employed as Temperature Sensors. The bipolar junction formed by an n and p semiconductor has the following voltampere characteristic equation.

$$I_D = I_s \exp \frac{q(V_D - I_s R_s)}{NkT} - 1$$  \hspace{1cm} (44)

Where

- $V_D$ is diode voltage in volts.
- $I_D$ diode current amps.
- $k$ Boltzman's constant.
- $T$ Absolute temperature.
- $q$ electron charge.
- $R_s$ series resistance ohms.
- $I_s$ reverse saturation current amperes.
- $N$ recombination constant.

Bipolar diodes are related to temperature variations by the following relation

$$\frac{dV_D}{dT} = -2mV/°C$$  \hspace{1cm} (45)
where

\[ V_D \] is the voltage across the diode.

This property makes diodes temperature sensors.

The solution of the above equation is given by

\[ T = T_o - \frac{V_D(T) - V_D(T_o)}{2} \]  (46)

where \( T_o \) is the initial temperature and \( T \) is the final temperature.

**Bias Equations**

In order to estimate the neutron fluence a basic circuit to measure d.c. current gain is designed as shown in figure 11.

At room temperature, and normal current levels.

\[ h_{FE} = \frac{I_C}{I_B} \]  (47)

where

\[ I_C = h_{FE}I_B + (h_{FE} + 1) I_{co} \] collector current.

\[ I_B = \frac{V_{CE} - V_{BE}}{R_B} \] base current.

\[ I_E = \frac{V_{CC} - V_{CE}}{R_C} \] emitter current.

Using the above equation the preirradiation d.c. current gain is

\[ h_{FE0} = \frac{V_{CC} - V_{CE}}{V_{CC} - V_{BE}} \cdot \frac{R_B}{R_C} - 1 \]  (48)

where \( R_B \) and \( R_C \) are respectively base and collector resistors.

A complete probe basic circuit to carry out neutron fluence detection with temperature sensor is given in figure 12.
Fig. 11 Probe Schematic
Fig. 12  Probe Schematic with Temperature Sensor
This configuration describes the combined thermal/neutron transistor models in radio active environment. The transistor neutron response is described by equation (50).

\[
\frac{1}{h_{FE}} = \frac{1}{h_{FE0}} \left( \frac{T}{T_0} \right)^{-x} + K_D \left( T_0 \right) \Phi \left[ 1.1 - 0.1 \left( \frac{T}{T_0} \right)^4 \right]
\]

From which the neutron fluence \( \Phi \) is calculated as

\[
\Phi = \left[ \frac{1}{h_{FE}} - \frac{1}{h_{FE0}} \left( \frac{T}{T_0} \right)^{-x} \right] \frac{1}{K_D}
\]

where

\[
K_D(T) = K_D(T_0) \left[ 1.1 - 0.1 \left( \frac{T}{T_0} \right)^4 \right]
\]

and \( x \) is between 2 to 2.6.

Computer Simulation of Probe Circuit

The simple probe circuit describing the combined thermal/neutron transistor response was simulated on the computer to estimate the neutron fluence for different values of \( h_{FE} \) (degraded gain).

The following algorithm was followed.

1. Based on \( f_T \) at \( T_0 = 300K \) \( K_D(T_0) \) is calculated

\[
K_D(T_0) = \frac{1}{2\pi f_T K}
\]

2. Based on \( V_{CC} \), \( V_{CE} \), and \( V_{BE} \) pre-exposure measurements at \( T = 300K \) the value \( h_{FE0} \) is calculated from

\[
h_{FE0} = \frac{V_{CC} - V_{CE}}{V_{CE} - V_{BE}} \frac{R_B}{R_C} - 1
\]

3. \( V_D(T) \) is measured across the diodes from which the temperature \( T \) is calculated as

\[
T = T_0 - \frac{V_D(T) - V_D(T_0)}{2}
\]
4. Given $T$ as calculated above, $K_D(T)$ is calculated from

$$K_D(T) = K_D(To) \left[1.1-0.1 \left(\frac{T}{To}\right)^4\right]$$

5. After irradiation, $\Delta V_{CC}, \Delta V_{CE}$, and $\Delta V_{BE}$ are again measured and a new value of degraded $h_{FE}$ calculated.

6. Finally, the neutron fluence is calculated from

$$\Phi = \left[\frac{1}{h_{FE}} - \frac{1}{h_{FE0}} \left(\frac{T}{To}\right)^{-x}\right] \frac{1}{K_D(T)}$$

Basic program and results from the simulated design are as displayed in the appendix.
CHAPTER IV
SYSTEM DESCRIPTION AND DESIGN

In this chapter an overview of the design process of the integrated neutron fluence detector is discussed. This instrument involves a sequence of interactive decisions between the instrument hardware and a computer. Based on the computer simulation steps discussed in the previous section, the flowchart shown in figure 13 describes the system hardware and software interaction. Figure 14 shows the system block diagram describing the flowchart in terms of a functional block diagram consisting of the probe, input circuitry, (ASM) Algorithm State Machine and the computer.

Four lead wires carry $V_{CC}$ (power supply voltage), $V_{CE}$ (collector emitter voltage), $V_{BE}$ (base emitter voltage) and $V_D$ (average diode voltage) all measured in volts. This analog data is acquired by the input circuitry where it is digitized and under the supervision of the Algorithm State Machine control is sent to the computer where the value of the integrated neutron fluence is calculated.

The Digital Data Acquisition (Algorithm State Machine or ASM) controls input circuitry on the basis of its interaction with SEND Signal from the computer. It also controls the careful transfer of the digitized data to the computer.

On interaction with the SEND Signal, the ASM outputs COUNT Signal to the input circuitry to begin multiplexing data from the probe. On
the next clock (figure 1) the ASM outputs the LOAD Signal to hold the counter address and check DAVI (Datavalid) from the A/D of the input circuitry.

When the DAVI Signal becomes active, the ASM outputs the DAV2 (DATA VALID) to the computer to accept the data from the input circuitry, and checks for the data accepted (DAC) signal from the computer. As the DAC becomes active, the ASM lowers the DAV2 line and waits for the computer to lower the DAC line to complete the handshaking. The ASM next checks the DONE line. The four bytes of probe data are transferred to the computer at the end of which the input circuitry is reset. Figure 15 shows a general sequential controller. Figure 16 shows the ASM legend while figure 17 describes the flow of this Algorithm State Machine on interaction with conditional inputs. Figure 18 shows a part of the hardware at the input. Figure 19 is the general ROM code which would perform the control sequencing. And finally, figure 20 is the low cost neutron detector implementation.
Fig. 13 Complete Action Flow.
Fig. 14  System Block Diagram
Fig. 15 Sequential Controller.
Fig. 16 ASM - Legend (Redrawn from Peatman, 1980)
Fig. 17  ASM Flow Chart.
Fig. 18 Data Acquisition Detail.
### ROM CODE

<table>
<thead>
<tr>
<th>Function</th>
<th>S3</th>
<th>S2</th>
<th>S1</th>
<th>SEND</th>
<th>DAV1</th>
<th>DAV2</th>
<th>DAC</th>
<th>DONE1</th>
<th>NS3</th>
<th>NS2</th>
<th>NS1</th>
<th>LD.</th>
<th>CT.</th>
<th>DAV2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wait for SEND=1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Wt. for next clk.</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Wt for DAV = 1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>x</td>
<td>0</td>
<td>x</td>
<td>x</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Wt. for DAC = 0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>x</td>
<td>x</td>
<td>0</td>
<td>x</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>x</td>
<td>x</td>
<td>1</td>
<td>x</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Wt. for DAC = 1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>x</td>
<td>x</td>
<td>0</td>
<td>x</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>x</td>
<td>x</td>
<td>1</td>
<td>x</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Wt. for DONE = 1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>In. Self Start.</td>
<td>1</td>
<td>1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Legend

- **x** = don't care
- **Wt.** = Wait
- **clk.** = clock
- **In.** = Insure
- **LD.** = LOAD
- **CT.** = COUNT

Fig. 19 ROM CODE
Fig. 20 Low cost neutron detector, schematic.
CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

In Chapter II, the theory of the neutron fluence transistor interaction is discussed and important equations describing the functional relationship between the d.c. transistor current gain ($h_{FE}$) and the neutron fluence $\phi$ derived. It was found that minority carrier lifetime $\tau$ in the base region was the most important factor contributing to the transistor current gain degradation under neutron irradiation. The neutron fluence effects on transistors was intended to include the effect of temperature on the transistors being irradiated. It was from this combined neutron and thermal effects on the transistor gain that the probe model was based. Equation (32) describing the model was simulated on the computer, the results of which are shown in Appendix B.

In Chapter III, emphasis was placed on probe design and the selection of the probe transistors from the spec sheets to assure reliable counting operation up to a minimum current gain degradation below which the counting becomes unreliable and the probe transistor need be changed or annealed. The selection of the appropriate transistors was based upon theoretical consideration, mathematical analysis and graphical selection rules, as discussed.

Chapter IV presents a discussion of interface between the computer
and the probe. This digital data acquisition circuitry is essentially an (ASM) machine which supervises the reliable transfer of the probe data to the computer, for the fluence calculation.

**Conclusion**

This research paper looks at the mathematically and experimentally proven relationships between fast neutrons and semiconductor bipolar junction transistors and suggests a cheap method of neutron detection and counting. It has been proven that neutrons are the primary radiation source which degrades the direct current gain of a transistor and from the mathematical expression which describes this relationship, the neutron fluence is readily estimated. The system described uses a probe placed in a nuclear active environment to monitor the neutron levels by transmitting the data to a computer where the fluence is calculated and displayed. This instrument could be used for different applications depending on the design. It could be used domestically to monitor the neutron radiation in nuclear contaminated environments e.g. in cities near nuclear reactors, nuclear powered ships and submarines for personnel protection or it could be used to monitor neutron radiations which can damage equipment. Further development of the instrument would be in time shared applications where several probes placed in isolated places may be monitored centrally. This is an inexpensive way of neutron detection. Neutrons are normally difficult to detect but damaging. The availability of cheap but powerful computers, semiconductor bipolar transistors, and other integrated circuits makes the development and implementation of this instrument very economical.
APPENDIX A
DESIGN PROCEDURE

\[
h_{FE0} = \frac{10}{1.35 R_C} R_B - 1 \quad \text{(a)}
\]

Where \( h_{FE0} \) is the initial transistor d.c. current gain. \( R_B \) and \( R_C \) are the required base and collector resistors respectively.

\[
R_C = \frac{V_{CC} - V_{CE}}{I_C} \quad \text{(b)}
\]

Where \( V_{CC} \) is the supply voltage.

\( V_{CE} \) is the collector emitter voltage and \( I_C \) is the collector current. All known therefore \( R_C \) is calculated from (b) \( R_B \) is then calculated from (a).

\[
\frac{R_B}{R_C} = \frac{(h_{FE0} + 1) (1.35)}{10} \quad \text{(10)}
\]

Where

\[
R_B = \frac{1.35}{10} R_C (h_{FE0} + 1)
\]
LIST

SEBAST 23-JUL-83 12:20:52

100 REM NEUTRON DETECTOR SIMULATION PROGRAM
110 REM FROM: SEBASTIAN KUFKISA NAMUKOLO
120 REM TO: ROBERT J. MARTIN
130 REM
140 REM
150 REM
160 PRINT "This program simulates a Neutron Detector Model"
170 PRINT "in a radioactive environment. Calculates the"
180 PRINT "number of neutrons which have been radiated in"
190 PRINT "an area within a period of time."
200 REM***
210 REM***
220 REM***
230 REM***
240 REM***
250 DIM V(200),P(200),H(200)
260 PRINT "Definition of Key Parameters"
270 PRINT "-----------------------------"
280 PRINT
290 PRINT
300 PRINT "KDTD Initial Temperature Correction Factor"
310 PRINT "hFE0 Initial Current Gain"
320 PRINT "VDT Diode Voltage as a function of Temperature"
330 PRINT "KDT Damage Factor as a function of Temperature"
340 PRINT "hFE Subsequent Current Gain"
350 PRINT "PHI Neutron Flux"
360 PRINT "VCC Power Supply Voltage"
PRINT "VCEI Initial Collector-emitter Voltage"
380 PRINT "VBEI Initial Base-emitter Voltage"
390 PRINT "RB Base Resistance"
400 PRINT "RC Collector lead resistor"
410 PRINT "fT Transistor unit gain frequency"
420 PRINT "TG Temperature gradient"
430 PRINT "K Damage factor"
440 PRINT "To Initial Temperature in Kelvin"
450 PRINT "----------------------------------"
460 PRINT
470 PRINT
480 PRINT
490 PRINT "MATHEMATICAL MODEL OF PROBE"
500 PRINT "---------------------------"
510 PRINT "STEP 1"
520 PRINT "------"
530 PRINT "Based on the transistor unity gain frequency fT, at"
540 PRINT "room temperature, T0=300K, the initial temperature"
550 PRINT "correction factor KDTO=1/2*Pi*fT*K"
560 PRINT "Where K=1.6*10^-6 cm*cm/neutron*sec"
570 PRINT "----------------------------------"
580 PRINT "STEP 2"
590 PRINT "------"
600 PRINT "Based on VCC,VCEO,VBE0 pre-exposure measurements at T0=300K"
610 PRINT "hFEO=(VCC-VCEO)/(VCEO-VBE0)*(RB/RC)-1"
620 PRINT "From the diode measurements the temperature T is"
630 PRINT "T=T0, where k=-2, VDT and VDTO are diode"
640 PRINT "voltages at temperature T and 300K respectively."
650 PRINT "-----------------------------------------------"
660 PRINT "STEP 3"
670 PRINT "------"
680 PRINT "The transistor damage factor KDT as a function of"
690 PRINT "temperature is KDT=KDTO (1.1-0.1(T/T0)^4)"
700 PRINT "----------------------------------------"
710 PRINT "STEP 4"  
720 PRINT "-----"  
730 PRINT "From the new values of VCE and VBE the desired transistor\n740 PRINT "gain is hFE=((VCC-VCE)/(VCE-VBE)*(RB/RC)-1)"  
750 PRINT "----------------------------------------"
760 PRINT "STEP 5"  
770 PRINT "-----"  
780 PRINT "Neutron flux 0=1/KDT*hFEO(hFEO/hFE-1) N/cm²*cm"  
790 PRINT "=============================================
800 PRINT 
810 PRINT "DECLARATION OF FIXED DESIGN PARAMETERS"
820 PRINT "---------------------------------------"  
830 PI=PI  
840 K1=1.6*10^-6  
850 T0=300  
860 REM***  
870 REM***  
880 PRINT 
890 PRINT "PROBE CIRCUIT SIMULATION"  
900 PRINT "---------------------------------------"  
910 PRINT  
920 T$="Type of transistor in probe"  
930 PRINT "What is the type of transistor used in the probe";  
940 INPUT A$  
950 PRINT T$;"";A$  
960 REM***  
970 PRINT "What is the supply voltage";  
980 INPUT V1  
990 PRINT "The value of VCC is ";V1;" Volts"  
1000 PRINT "What is the Collector-emitter voltage";  
1010 INPUT V2  
1020 PRINT "Initial Collector-emitter is ";V2;" Volts"
1030 PRINT "What is the initial base-emitter voltage?"
1040 INPUT V3
1050 PRINT "Initial base-emitter voltage is ";V3;" Volts"
1060 PRINT "What is the base-emitter resistance?"
1070 INPUT R1
1080 PRINT "Base resistance value is ";R1;" Ohms"
1090 PRINT "What is the collector resistor value?"
1100 INPUT R2
1110 PRINT "Collector lead resistor is ";R2;" Ohms"
1120 PRINT "What is the diode voltage value?"
1130 INPUT V4
1140 PRINT "Diode voltage at room temperature T is";V4;" Volts"
1150 PRINT "What is the diode voltage at temperature T?"
1160 INPUT V5
1170 PRINT "Diode Voltage at temperature T is";V5;" Volts"
1180 PRINT "What is the transistor unity frequency gain?"
1190 INPUT F1
1200 PRINT "Transistor unity gain frequency is ";F1;" Hertz"
1210 PRINT
1220 PRINT
1230 REM** CALCULATION AND ANALYSIS OF PARAMETERS
1240 PRINT "DATA OUTPUT"
1250 PRINT "------------"
1260 K2=1/(2*PI*F1*K1)
1270 PRINT "KDTO=";K2
1280 REM** INITIAL CURRENT GAIN hFE0
1290 H1=V1-V2
1300 H2=V2-V3
1310 R3=R1/R2
1320 H3=H1/H2*R3-1
1330 PRINT "Initial current gain hFE0 is ";H3
1340 REM** CALCULATIONS OF TEMPERATURE ERROR FACTOR
1350 T1=-2
1360 T2=(V5-V4)/T1
1370 T3=T0-T2
1380 K3=1.1-.1*(T3/T0)^4
1390 K4=K2*K3
1400 PRINT 'The temperature correction factor KDT=';K4
1410 REM**
1420 REM**
1430 REM** NETRUN FLUX CALCULATIONS
1440 V6=2
1450 PRINT 'VCE Volts',' Neutron/cm*cm',' Tra hFE'
1480 FOR I=1 TO 100
1490 V6=V6+.09
1500 H4=V1-V6
1510 H5=V6-V3
1520 H6=H4/H5
1530 H7=H6*R3-1
1550 P3=(1/H7-1/H3*(T3/T0)^-2)*(1/K4)
1560 V(I)=V6
1570 P(I)=P3
1580 H(I)=H7
1590 NEXT I
1610 FOR I=1 TO 100
1620 PRINT ' V(I)',' P(I)',' H(I)
1630 NEXT I

READY
This program simulates a Neutron Detector Model in a radio-active environment. Calculates the number of neutrons which have been radiated in an area within a period of time.

Definition of Key Parameters

KDTO Initial Temperature Correction Factor
hFED Initial Current Gain
VDT Diode Voltage as a function of Temperature
KDT Damage Factor as a function of Temperature
hFE Subsequent Current Gain
PHI Neutron Flux
VCC Power Supply Voltage
VCEI Initial Collector-emitter Voltage
VBEI Initial Base-emitter Voltage
RB Base Resistance
RC Collector lead resistor
fT Transistor unit gain frequency
TG Temperature gradient
K Damage factor
To Initial Temperature in Kelvin
MATHEMATICAL MODEL OF PROBE

STEP 1

Based on the transistor unity gain frequency $f_T$, at room temperature, $T_0=300K$, the initial temperature correction factor $K_{DT0}=1/2\pi f_T K$

$K=1.6\times10^{-6} cm^3/\text{neutron}\cdot\text{sec}$

STEP 2

Based on $V_{CC}, V_{CEO}, V_{BEO}$ pre-exposure measurements at $T_0=300K$

$h_{FE0}=(V_{CC}-V_{CEO})/(V_{CEO}-V_{BEO})\times(R_B/R_C)-1$

From the diode measurements the temperature $T$ is $T=T_0$, where $k=-2$, $V_D$ and $V_{D0}$ are diode voltages at temperature $T$ and $300K$ respectively.

STEP 3

The transistor damage factor $K_D$ as a function of temperature is $K_D=K_{DT0}(1.1-0.1(T/T_0)^4)$

STEP 4

From the new values of $V_{CE}$ and $U_{BE}$ the degraded transistor gain is $h_{FE}=((V_{CC}-V_{CE})/(V_{CE}-V_{BE})\times(R_B/R_C)-1)$

STEP 5

Neutron flux $O=1/K_D h_{FE0}(h_{FE0}/h_{FE}-1) \text{ N/cm}^2\cdot\text{cm}$

DECLARATION OF FIXED DESIGN PARAMETERS
What is the type of transistor used in the probe? 2N2222A
Type of transistor in probe 2N2222A
What is the supply voltage? 12
The value of VCC is 12 Volts
What is the Collector-emitter voltage? 2
Initial Collector-emitter is 2 Volts
What is the initial base-emitter voltage? .65
Initial base-emitter voltage is .65 Volts
What is the base-emitter resistance? 55000
Base resistance value is 55000 Ohms
What is the collector resistor value? 2000
Collector lead resistor is 2000 Ohms
What is the diode voltage value? .6
Diode voltage at room temperature T is .6 Volts
What is the diode voltage at temperature T? 1
Diode Voltage at temperature T is 1 Volts
What is the transistor unity frequency gain? 300000000
Transistor unity gain frequency is 3.00000E+08 Hertz
DATA OUTPUT

KDTO = 3.31573E-16

Initial current \( \text{gain hFED} \) is 202.704

The temperature correction factor \( KDT = 3.31484E-16 \)

<table>
<thead>
<tr>
<th>VCE Volts</th>
<th>Neutron/cm*cm</th>
<th>Tra hFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.09</td>
<td>1.16220E+12</td>
<td>188.253</td>
</tr>
<tr>
<td>2.18</td>
<td>2.32639E+12</td>
<td>175.503</td>
</tr>
<tr>
<td>2.27</td>
<td>3.51304E+12</td>
<td>164.17</td>
</tr>
<tr>
<td>2.36</td>
<td>4.72280E+12</td>
<td>154.029</td>
</tr>
<tr>
<td>2.45</td>
<td>5.95636E+12</td>
<td>144.903</td>
</tr>
<tr>
<td>2.54</td>
<td>7.21442E+12</td>
<td>136.646</td>
</tr>
<tr>
<td>2.63</td>
<td>8.49772E+12</td>
<td>129.139</td>
</tr>
<tr>
<td>2.72</td>
<td>9.80703E+12</td>
<td>122.285</td>
</tr>
<tr>
<td>2.81</td>
<td>1.11431E+13</td>
<td>116.002</td>
</tr>
<tr>
<td>2.9</td>
<td>1.25069E+13</td>
<td>110.222</td>
</tr>
<tr>
<td>2.99</td>
<td>1.38992E+13</td>
<td>104.887</td>
</tr>
<tr>
<td>3.08</td>
<td>1.53208E+13</td>
<td>99.9466</td>
</tr>
<tr>
<td>3.17</td>
<td>1.67728E+13</td>
<td>95.3592</td>
</tr>
<tr>
<td>3.26</td>
<td>1.82562E+13</td>
<td>91.0882</td>
</tr>
<tr>
<td>3.35</td>
<td>1.97719E+13</td>
<td>87.1019</td>
</tr>
<tr>
<td>3.44</td>
<td>2.13210E+13</td>
<td>83.3728</td>
</tr>
<tr>
<td>3.53</td>
<td>2.29047E+13</td>
<td>79.8768</td>
</tr>
<tr>
<td>3.62</td>
<td>2.45241E+13</td>
<td>76.5927</td>
</tr>
<tr>
<td>3.71</td>
<td>2.61804E+13</td>
<td>73.5017</td>
</tr>
<tr>
<td>3.8</td>
<td>2.78750E+13</td>
<td>70.5873</td>
</tr>
<tr>
<td>3.89</td>
<td>2.96090E+13</td>
<td>67.8349</td>
</tr>
<tr>
<td>3.98</td>
<td>3.13841E+13</td>
<td>65.2313</td>
</tr>
<tr>
<td>4.07</td>
<td>3.32016E+13</td>
<td>62.7647</td>
</tr>
<tr>
<td>4.16</td>
<td>3.50630E+13</td>
<td>60.4245</td>
</tr>
<tr>
<td>4.34</td>
<td>3.89243E+13</td>
<td>56.0868</td>
</tr>
<tr>
<td>4.43</td>
<td>4.09276E+13</td>
<td>54.0728</td>
</tr>
<tr>
<td>4.52</td>
<td>4.29819E+13</td>
<td>52.1525</td>
</tr>
<tr>
<td>4.61</td>
<td>4.50890E+13</td>
<td>50.3195</td>
</tr>
<tr>
<td>4.7</td>
<td>4.72511E+13</td>
<td>48.5679</td>
</tr>
<tr>
<td>4.79</td>
<td>4.94703E+13</td>
<td>46.8925</td>
</tr>
<tr>
<td>4.88</td>
<td>5.17489E+13</td>
<td>45.2884</td>
</tr>
<tr>
<td>4.97</td>
<td>5.40894E+13</td>
<td>43.7512</td>
</tr>
<tr>
<td>5.06</td>
<td>5.64943E+13</td>
<td>42.2766</td>
</tr>
<tr>
<td>5.15</td>
<td>5.89663E+13</td>
<td>40.8611</td>
</tr>
<tr>
<td>5.24</td>
<td>6.15083E+13</td>
<td>39.5011</td>
</tr>
<tr>
<td>5.33</td>
<td>6.41232E+13</td>
<td>38.1934</td>
</tr>
<tr>
<td>5.42</td>
<td>6.68142E+13</td>
<td>36.935</td>
</tr>
<tr>
<td>5.51</td>
<td>6.95847E+13</td>
<td>35.7232</td>
</tr>
<tr>
<td>5.6</td>
<td>7.24384E+13</td>
<td>34.5555</td>
</tr>
<tr>
<td>5.69</td>
<td>7.53789E+13</td>
<td>33.4296</td>
</tr>
<tr>
<td>5.78</td>
<td>7.84103E+13</td>
<td>32.3431</td>
</tr>
<tr>
<td>5.87</td>
<td>8.15370E+13</td>
<td>31.294</td>
</tr>
<tr>
<td>5.96</td>
<td>8.47634E+13</td>
<td>30.2806</td>
</tr>
<tr>
<td>6.05</td>
<td>8.80944E+13</td>
<td>29.3009</td>
</tr>
<tr>
<td>6.23</td>
<td>9.50912E+13</td>
<td>27.4364</td>
</tr>
<tr>
<td>6.32</td>
<td>9.87685E+13</td>
<td>26.5485</td>
</tr>
<tr>
<td>6.41</td>
<td>1.02573E+14</td>
<td>25.6883</td>
</tr>
<tr>
<td>6.5</td>
<td>1.06512E+14</td>
<td>24.8547</td>
</tr>
<tr>
<td>6.59</td>
<td>1.10593E+14</td>
<td>24.0463</td>
</tr>
<tr>
<td>6.68</td>
<td>1.14822E+14</td>
<td>23.262</td>
</tr>
<tr>
<td>6.77</td>
<td>1.19210E+14</td>
<td>22.5008</td>
</tr>
<tr>
<td>6.86</td>
<td>1.23764E+14</td>
<td>21.7617</td>
</tr>
<tr>
<td>6.95</td>
<td>1.28494E+14</td>
<td>21.0436</td>
</tr>
<tr>
<td>7.04</td>
<td>1.33410E+14</td>
<td>20.3458</td>
</tr>
<tr>
<td>7.13</td>
<td>1.38525E+14</td>
<td>19.6674</td>
</tr>
<tr>
<td>7.22</td>
<td>1.43849E+14</td>
<td>19.0076</td>
</tr>
<tr>
<td>7.31</td>
<td>1.49397E+14</td>
<td>18.3656</td>
</tr>
<tr>
<td>7.4</td>
<td>1.55183E+14</td>
<td>17.7407</td>
</tr>
<tr>
<td>x</td>
<td>y</td>
<td>z</td>
</tr>
<tr>
<td>----</td>
<td>-----</td>
<td>-----------</td>
</tr>
<tr>
<td>7.49</td>
<td>1.61222E+14</td>
<td>17.1323</td>
</tr>
<tr>
<td>7.58</td>
<td>1.67531E+14</td>
<td>16.5397</td>
</tr>
<tr>
<td>7.67</td>
<td>1.74129E+14</td>
<td>15.9622</td>
</tr>
<tr>
<td>7.76</td>
<td>1.81037E+14</td>
<td>15.3994</td>
</tr>
<tr>
<td>7.85</td>
<td>1.88275E+14</td>
<td>14.8507</td>
</tr>
<tr>
<td>7.94</td>
<td>1.95870E+14</td>
<td>14.3155</td>
</tr>
<tr>
<td>8.03</td>
<td>2.03847E+14</td>
<td>13.7933</td>
</tr>
<tr>
<td>8.12</td>
<td>2.12237E+14</td>
<td>13.2838</td>
</tr>
<tr>
<td>8.21</td>
<td>2.21071E+14</td>
<td>12.7863</td>
</tr>
<tr>
<td>8.3001</td>
<td>2.30388E+14</td>
<td>12.3006</td>
</tr>
<tr>
<td>8.3901</td>
<td>2.40226E+14</td>
<td>11.8262</td>
</tr>
<tr>
<td>8.4801</td>
<td>2.50632E+14</td>
<td>11.3627</td>
</tr>
<tr>
<td>8.5701</td>
<td>2.61656E+14</td>
<td>10.9097</td>
</tr>
<tr>
<td>8.6601</td>
<td>2.73354E+14</td>
<td>10.4669</td>
</tr>
<tr>
<td>8.7501</td>
<td>2.85791E+14</td>
<td>10.0339</td>
</tr>
<tr>
<td>8.8401</td>
<td>2.99038E+14</td>
<td>9.61047</td>
</tr>
<tr>
<td>8.9301</td>
<td>3.13178E+14</td>
<td>9.19623</td>
</tr>
<tr>
<td>9.0201</td>
<td>3.28303E+14</td>
<td>8.79089</td>
</tr>
<tr>
<td>9.1101</td>
<td>3.44521E+14</td>
<td>8.39418</td>
</tr>
<tr>
<td>9.2001</td>
<td>3.61955E+14</td>
<td>8.00582</td>
</tr>
<tr>
<td>9.2901</td>
<td>3.80746E+14</td>
<td>7.62555</td>
</tr>
<tr>
<td>9.3801</td>
<td>4.01060E+14</td>
<td>7.25312</td>
</tr>
<tr>
<td>9.4701</td>
<td>4.23088E+14</td>
<td>6.88829</td>
</tr>
<tr>
<td>9.5601</td>
<td>4.47059E+14</td>
<td>6.53084</td>
</tr>
<tr>
<td>9.6501</td>
<td>4.73240E+14</td>
<td>6.18053</td>
</tr>
<tr>
<td>9.7401</td>
<td>5.01953E+14</td>
<td>5.83716</td>
</tr>
<tr>
<td>9.8301</td>
<td>5.33583E+14</td>
<td>5.50052</td>
</tr>
<tr>
<td>9.9201</td>
<td>5.68598E+14</td>
<td>5.17041</td>
</tr>
<tr>
<td>10.01</td>
<td>6.07573E+14</td>
<td>4.84666</td>
</tr>
<tr>
<td>10.1</td>
<td>6.51219E+14</td>
<td>4.52907</td>
</tr>
<tr>
<td>10.19</td>
<td>7.00431E+14</td>
<td>4.21748</td>
</tr>
<tr>
<td>10.28</td>
<td>7.56344E+14</td>
<td>3.91171</td>
</tr>
<tr>
<td>10.37</td>
<td>8.20428E+14</td>
<td>3.6116</td>
</tr>
<tr>
<td>10.46</td>
<td>8.94615E+14</td>
<td>3.317</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>----</td>
<td>----------------</td>
</tr>
<tr>
<td>10.55</td>
<td></td>
<td>9.8149E+14</td>
</tr>
<tr>
<td>10.64</td>
<td></td>
<td>1.0846E+15</td>
</tr>
<tr>
<td>10.73</td>
<td></td>
<td>1.2090E+15</td>
</tr>
<tr>
<td>10.82</td>
<td></td>
<td>1.3622E+15</td>
</tr>
<tr>
<td>10.91</td>
<td></td>
<td>1.5551E+15</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>1.8057E+15</td>
</tr>
</tbody>
</table>
LIST OF REFERENCES


