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SOLID STATE NEUTRON DOSIMETER FOR SPACE APPLICATIONS

FINAL REPORT

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PROJECT SUMMARY

Personnel engaged in space flight are exposed to significant flux of high energy neutrons arising from both primary and secondary sources of ionizing radiation. Presently, there does not exist a compact neutron sensor capable of being incorporated in a flight instrument to provide real time measurement of this important radiation flux. We propose to construct such an instrument, as a final product of a Phase I and Phase II research effort, using a special PIN silicon diode which has the attractive property of being insensitive to the other forms of ionizing radiation

To establish the viability of this concept, research was conducted in several areas. First, studies were performed to determine the design and construction of a better reading system to allow the PIN diodes to be read with high precision. Second, the physics of the device was investigated, especially with respect to those factors which affect the sensitivity and reproducibility of the neutron response. Third, this information was then utilized to develop methods to achieve high sensitivity at low neutron doses. This included collaborating with Lake Shore Cryotronics, the manufacturer of the diodes, to produce and test special custom PIN diodes. Fourth, measurements were made to confirm that PIN diodes with enhanced sensitivity were sufficiently insensitive to other forms of radiation that reliable readings will be able to be obtained under all foreseeable flight conditions. Finally, the results of the studies were analyzed with respect to the known flight requirements in order to demonstrate feasibility, and a detailed plan for Phase II was prepared.

The research of the Phase I program demonstrated the feasibility of enhancing the PIN diode sensitivity to make possible the measurement of the low doses of neutrons encountered in space flights. We have successfully developed the instrumentation necessary for reading these devices and our study shows that it is possible to integrate it in a small package.

The new PIN diode will make possible the development of a very compact, accurate, personal neutron dosimeter. In addition to the specific NASA application described above, this device should have wide utility in commercial facilities such as power plants, accelerator facilities and industrial facilities using neutron activation analysis or neutron radiography in which significant dosages of neutrons may arise.

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A. Overview

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B. Background

1. Significance

With the increased interest in space missions and planned permanent human presence in space, there has emerged a specific need for a detailed understanding of the space environment and its effects on human beings. One factor that can have a very important impact on the physiological responses of astronauts is radiation exposure, and it is well known that the space radiation environment can cause significant dose levels inside a spacecraft (Atwell, Nachtwey, Parnel, Stauber).

Passive dosimeters flown during early space flights have shown that measurable doses can arise from a wide variety of radiation sources (ibid). Other experiments have confirmed that the types of radiation present inside the crew compartment during spaceflight include protons, electrons, X-rays, neutrons and heavy ions (ibid, Benton).

It is also known that the type of radiation and its intensity fluctuate widely due to factors such as altitude, inclination of orbit, and solar activity (Stauber). Theoretical models have been developed to understand the nature of this primary radiation and the predictions of these models have been experimentally verified. However, the interaction of the primary radiation with the shell of the space vehicle gives rise to a large variety of secondary radiation. While the primary radiation is itself hazardous to the human body, a number of the secondary emissions are even more biologically active in terms of absorbed dose than the primary particles from which they originated (Baily). This is particularly true of energetic neutrons that penetrate a space vehicle freely and yet collide with the numerous protons in the body tissue to produce densely ionizing recoil nuclei which are biologically up to ten times more damaging than lightly ionizing particles (ibid).

Because of the complex nature of the interactions involved, attempts to use theory to predict the detailed neutron flux inside a space vehicle from a knowledge of the ambient cosmic and trapped belt radiation has not been successful (Kovalev, Stauber). Therefore, neutron dosimeters are often included in the space dosimetry packages. However, the dosimeters flown aboard the space missions to date have been passive and unable to provide chronological data concerning the time course of the neutron dose throughout the flight. The passive neutron dosimeters are also sensitive to protons, and despite various techniques to correct for this effect, the quality of the data on neutron dose does not have very high precision (Benton, Parnell).

In order to obtain the data required to correlate the neutron exposure with other physiological responses, a neutron dosimetry system will be required which is accurate, dependable, provide the neutron dose information in real time and yet be portable enough to be placed inside the living compartment of the space vehicle.

Normally the research needed to develop, fabricate and calibrate a flight ready dosimeter to meet this need would be a complex multi-year project. However, RMD has recently completed a research program to develop a prototype gamma-proton radiation dosimeter for the Brooks Air Force Base which includes much of the interface and recording electronics which will be needed for constructing a flight dosimeter for NASA. By building on this previous research, it should be possible to concentrate most of the NASA work on the development of the new neutron sensor and its associated readout circuits and still achieve a near flight ready prototype by the end of the Phase II program.

We therefore initiated a research program which combined the results of our previous work with an additional research effort to develop a broad spectrum, real time, solid state, active dosimeter for neutron measurement. This instrument uses a solid state radiation detector and which is insensitive to gamma, beta, proton and heavy ion sources. The final instrument will be microprocessor based and will be capable of storing dose data as a function of time so that exposure can be studied during each segment of the flight path. Details of this topic are discussed in the Phase II proposal.

In Phase I of the program, we focused on the detector aspects of the instrument, the elimination of interference resulting from other types of radiation as well as on the conceptual design and specifications needed to define the final dosimeter. In Phase II of the program, research will be continued on the detectors and expanded into miniaturizing electronics.

2. Space Radiation Environment

In recent years there has been a rapid increase in the body of knowledge concerning the nature of radiation fields surrounding the Earth. The composition of this radiation field includes gamma rays, protons, electrons, neutrons, alpha particles and ionized atomic nuclei covering a broad energy spectrum ranging from less than 1 MeV to over 10^6 MeV. The intensity of the radiation fields depends on factors such as the altitude and latitude of the flight path and the current level of solar activity (ICRU, Silberberg) and can vary over several orders of magnitude.

The difficulty of ensuring radiation safety during space missions arises both from the nature of this environment and from limitations on the weight and material of flight vehicles. It is simply not possible to block all radiation from reaching the interior of the flight compartment. In addition, absorption of the high energy primary radiation by the vehicle shell results in the release of secondary radiation which is a major contributor to the dose experienced inside the living area. This environment, with its diversity of charged particles and numerous secondary interactions presents a formidable challenge to dosimetry.

The three major natural sources of exposure in the near Earth environment are the Earth's radiation belts, solar particle radiation and galactic cosmic radiation. It is worthwhile to briefly review the magnitude of the doses which can be expected from each of these sources of radiation. The Earth's radiation belts consist mainly of protons and electrons captured by the geomagnetic field, and the intensity of the flux is known to vary widely with altitude and angle of inclination of the orbit (Stauber). Current estimates of equivalent dose rates from proton exposures inside the vehicle range from less than mR/hr to greater than 40 rad/hr depending on the flight path. The expected energy of protons ranges from approximately 10 to 500 MeV (ICRU, Kovalev, Kovalev).

The intensity of the electron field surrounding the Earth varies dramatically with the altitude, latitude, and solar activity. Two distinct flux maxima surrounding the Earth are found at altitudes of 3,000 km and 22,000 km where the equivalent dose rate inside the vehicle can reach levels in excess of 4 rad/hr. Even with more desirable flight paths, the dose rate with the standard 1 to 2 g/cm^2 shielding is relatively high over most of the near Earth zone region (Atwell, Stauber). In this case the expected energy of beta rays inside a vehicle is between 1 and 10 MeV. High inclination missions ($> 50^o$) encounter both the South Atlantic Anomaly and the electron belt resulting in a significantly higher exposure (Atwell).

The second major source of exposure, the high energy radiation of solar origin, is composed mainly of protons and alpha particles. While the alpha radiation is generally blocked by the walls of the vehicle, calculations indicate that the dose equivalent for protons due to a solar flare event can range as high as 45 rads to the skin with 2g/cm^2 shielding for a 400 km polar orbit (ICRU). Since solar flares are not entirely predictable, the solar proton flux poses a radiation hazard that can occur anytime during the flight.

The third source of radiation, which originates from galactic sources, is composed mainly of protons with some alphas and heavier nuclei. The flux density of the fields is fairly uniform and undergoes relatively small changes with solar cycles. In near Earth orbits, the contribution of this source of radiation is further decreased due to mass of the Earth and the geomagnetic screening. The attenuation amounts to an approximate order of magnitude decrease from the intensity found in outer space. The calculated daily dose equivalent is estimated to be less than 7 mrem/day for near Earth orbits at low latitudes (O'Brien).

Low altitude and low inclination orbit is more desirable as a flight path from the point of view of minimizing radiation exposure to the flight personnel. For example, the space station program which is under development at NASA is being designed to operate between 333 km and 463 km above the Earth at an inclination of 28.5^o. For these missions, only the trapped protons of the inner zone are of most consequence. The intense region of the inner zone is the so-called South Atlantic anomaly between Africa and South America, where spiraling protons reach closer to the earth in their orbits than in other regions (Stauber).

The primary radiations discussed above interact with the spacecraft structure producing a variety of secondary radiation inside the vehicle. Some of the secondary radiations may even have a greater penetrating power than the primary radiation; for example, the Bremsstrahlung produced in the deceleration of electrons penetrating a spacecraft is highly penetrating. Trapped protons, on the other hand, are slowed and absorbed via ionization, or they interact producing neutrons, target spallation products, or recoil nuclei. Since the most significant fraction of radiation in the low earth orbits is protons, it is expected that a majority of the secondary radiation arises from interactions of protons. Among these secondaries, neutrons, being highly penetrating, can produce a significant dose inside the spacecraft. As an illustration, neutron dose measurements aboard the COSMOS 1129 and Space Lab 1 and 2 missions,(SL1 and SL2), are listed in Table 1 (Benton, Parnell).

TABLE 1
DATA INTEGRATED OVER SPACE LABS AND COSMOS MISSIONS

Neutron Energy	Fluence (cm^{-2}) SL1 and SL2	Equivalent Integrated Dose (mrem) SL1 and SL2	COSMOS 1129
Thermal	4.2 X 10^4	0.04	0.52
Resonance	1.5 X 10^6	7.30	7.40
High energy	7.6 X 10^5	45.00	125.00

These data, especially those that relate to the doses arising from the secondary neutrons caused by protons from the inner radiation belt, clearly indicate that the radiation dose from neutrons is significant, especially as the flights become longer. A dosimeter that can provide in real time both an integrated dose and dose rate information would be of major benefit, for without such equipment, large uncertainties in the determination of radiation exposure can occur. This can have profound consequences on the ability to ensure the safety of astronauts flying long space missions.

Several active dosimetry systems are in routine use for the measurements of charged particles and protons in particular. However, the lack of instrumentation for accurate real time measurement of neutron doses has led us to pursue research in this area.

3. Previous Neutron Detection Methods Used in Space Dosimetry

Over the past 30 years, a wide variety of both passive and active radiation detection devices and dosimeters have been flown on balloons, unmanned satellites and manned missions. From this experience, a solid data base has been developed concerning the nature of the radiation field surrounding the Earth. Mostly passive detectors have been employed to study neutrons and these provide an approximate estimate of the neutron exposure. In this section we limit ourselves to the discussion of neutron dosimeters flown aboard spacecraft.

Of particular interest are radiation dosimetry experiments that were conducted aboard the COSMOS and Space Lab missions (Benton, Parnell). These experiments were performed to assess the hazard to man and animals from the space radiation environment. Passive neutron dosimeters were used on COSMOS while both active and passive ones were used on the Space Labs.

The passive detectors were of three types; fission foil/plastic, fission foil/Cr^{39} and fission foil/mica. The detectors were mounted both inside and outside the spacecraft hull. The fission foil/plastic dosimeters consisted of foils of B^{10} and Li^6F which detected neutrons by the (n,He^4) reaction. The plastic, cellulose nitrate, was used to record the He^4 particle tracks for reading back on earth. The fission foil/mica dosimeters used foils of Bi^{209}, Th^{232}, Np^{237} and U^{238} to produce fission fragments by the (n,f) reaction. In this case, the tracks of emitted fission fragments were recorded using Muscovite mica. The fission foil/Cr^{39} dosimeters used Li^6 foils and, when used with and without Cd absorbers, could be used to estimate the dose due to epithermal and thermal neutrons.

By using these classes of dosimeters, some idea of the energy spectrum of the neutron fluence could be derived. The heavy fission foil/mica dosimeters were primarily sensitive to high energy neutrons, the Li^6F/plastic dosimeter to mid-range energies above 1-100 keV, the B^{10}/plastic foil to energies below 100 keV, and the Li^6F/Cr^{39} to epithermal and thermal energies.

Although passive neutron detector system is able to provide an estimate of the neutron exposure, the accuracy of measurement is limited because of several factors. Firstly, it is necessary to assume an energy spectrum for the neutrons in the resonance region in order to derive the effective response of the radiator detectors. Secondly, fission foil detectors are sensitive to the protons found in space. Since protons are the dominant primary particles in orbital flights, the majority of the fission fragment tracks on the mica samples are produced by protons. In addition, it is not possible to record the time course of the dose delivered to the inside of the spacecraft.

Recently attempts have been made to combine track etch and albedo dosimeters into a combination dosimeter capable of measuring neutron doses over a broad energy spectrum from 0.4 eV to 10 MeV (Baily). Such an instrument was used in NASA's Airborne Instrumentation Research Program to determine the neutron dose accumulated by high altitude flight personnel.

The albedo dosimeter consisted of the Hankins type, using one TLD-600 and one TLD-700 chip. The track etch portion of the dosimeter used one polycarbonate and one CR-39 dosimeter. Track etch dosimeters are insensitive to gamma rays but are sensitive to protons, whereas TLD-700 is sensitive to gammas and TLD-600 is sensitive to both protons and gammas. Thus, the sensitivity of the combination dosimetry system to other radiation types restricts its use for high altitude flights only.

Beside the neutron dosimetry techniques described above, there are a variety of systems currently used for personnel dosimetry, including photographic film, ionization chambers and thermoluminescent phosphors. The most common approach to making field measurements of a neutron dose and spectra is to use a Bonner sphere instrument. This instrument consists of a single neutron detector plus a set of five moderating spheres of various diameters. Measurements are taken sequentially with each moderator placed over the detector. By properly combining the count rate data from the detector when it is inside each sphere, an unfolding of the neutron spectrum can be accomplished, an estimate of the flux can be made and the average quality factor for the field can be determined (Awaschalom, Eisenhauer).

A recent telephone conversation with Dr. Gautam Badhwar of Johnson Space Center revealed the fact that a Bonner Sphere dosimeter for neutron measurements is currently under development at NASA. This system uses 5 Bonner spheres with gold foils in them. Analysis of the activation of gold foils will be used to estimate the neutron flux. Two other neutron detectors will be surrounded by gadolinium foil which absorbs epithermal neutrons so that the detectors are exposed only to be able to the thermal neutron component. With this instrument, NASA expects to measure neutron fluxes and doses with an error no larger than a factor of 3 or 4. However, the Bonner spheres are quite bulky and requires the monitoring of 5 separate detectors (Rogers).

Other active devices such as those based on the use of photomultipliers with either plastic or LiF scintillators have also been considered because of the high sensitivity, but have not found favor because of their high response to protons and the requirement for high voltage.

C. PIN Diodes as Neutron Detectors

PIN neutron diodes work on the principle that their forward impedance increases with neutron exposure due to damage introduced into the lattice by the radiation (Swartz). This damage occurs irrespective of whether the diode is conducting current, and thus the device provides an indication of the integrated dose that occurred up to the time of measurement. The diodes are read by periodically passing a fixed current pulse through them in the forward direction and measuring the corresponding voltage across the diode.

The PIN neutron diode was originally developed by a group at a small company with whom we collaborate, Lake Shore Cryotronics (LSC). This group, headed by Dr. Philip Swinehart, has produced these devices for commercial sale by the Harshaw Company. The units which are presently in use are sensitive to integrated fluxes of between one and 1000 rads.

As part of our research for the Air Force, we investigated the possibility of obtaining from Lake Shore diodes of the much higher sensitivity needed to meet the requirements of space flight applications. Although neither the diodes nor the high performance electronics necessary to achieve the desired performance were immediately available, the results of that study were sufficiently encouraging to indicate that it is indeed possible to modify the PIN diode system for useful flight dosimetry.

Figure 1 shows the data sheet which accompanies the commercial version of this diode. It features small size, low power consumption, and good stability. In addition, technical publications authored by Dr. Swinehart indicate that the response of the diode over a wide range of neutron energies (200 keV to 10 MeV) is flat to within a factor of two (Swinehart).

The key deficiency of this commercially available device is its low sensitivity. This deficiency arises from two problems. The first is the diode itself. The commercial version of the diode has a geometry and diffusion profile which leads to a high value of surface current and a relatively low change in voltage per unit dose.

The second of the deficiency arises from the performance of the electronics used to read the diodes. The reading system sold by Harshaw uses a train of three to five current pulses of 25 mA to interrogate the diode. They use this approach because they have found that the voltage generated across the diode by these pulses decreases with each pulse, but tends to stabilize somewhat after three to four pulses. This decrease in voltage is thought by Dr. Swinehart to be caused by the flooding of charge carriers annealing the device and he has conducted comparisons between devices annealed by such currents with those annealed thermally to confirm this hypothesis (Swinehart, private comm.)

Both of these limitations were addressed during the Phase I of the program. First, the diodes used were not the LSC commercial variety. The diodes were custom made for this research program and had different geometries and diffusion profiles. Second, an improved reader was developed which relies on current pulses which are of much shorter duration and of much lower intensity. This reader prevents the degradation of the diode interrogation pulse evident in the commercial diode reader system which limits the sensitivity of the reading to no better than a few hundred mR, a dose level far in excess of what is appropriate for a useful dosimetry system for space flight. Together, these advances lead to a sensor system which could provide the performance needed for the NASA flight dosimeter.

D. Summary of Background

The results of the research conducted by NASA and other groups clearly demonstrates the need for a dosimetry system capable of accurately measuring in real time the doses due to neutrons in the complex radiation environment in space. Although previous experiments flown aboard space vehicles have succeeded in obtaining a useful estimate of neutron dose, the detection systems used were primarily passive dosimeters which could not provide real time readout to show the time course of the radiation exposure. Furthermore, the sensitivity of these detector systems to high energy protons caused large uncertainties in the interpretation of the data.

During Phase I of the program, we utilized our experience in the development of dosimeter systems, both neutron and otherwise, to demonstrate the feasibility of enhancing the sensitivity of PIN diode as a neutron sensor and incorporating them into space flight dosimetry instrumentation. By the end of the Phase II program, a compact, flight ready instrument will have

DN-156 PIN DIODE NEUTRON DOSIMETER

Description

The Harshaw type DN-156 PIN Diode is a general purpose dosimeter for the measurement of fast neutrons. It is intended for use in a variety of applications, including personnel and tactical military dosimetry, neutron therapy planning in oncology, and dose effect studies. Its predictable performance characteristics, small size, mechanical ruggedness, and chemical inertness make it ideal for use in tough environments.

The PIN diode consists of a silicon chip with impurities diffused into its ends to provide P and N type regions, and an intrinsic region between. The forward voltage of the diode is a function of the accumulated neutron dose. Sensitivity to neutrons and temperature effect are determined by carefully controlling the minority carrier lifetime of the material, the dimensions of the chip, and the depth and purity of diffusion materials.

Features

- Sensitive—More than 5 millivolts per Rad
- Stable—Long-term zero drift less than 1 Rad
- Transparent to Gammas
- High Uniformity from Unit to Unit
- Small Temperature Effect Typically less than
  0.02 Rad/°C Undosed
  0.0045 x Rad Dose/°C Dosed
- Data Retention—Non-destructive readout
- Small—3mm diameter x 3.5mm long
- Easily Read—By pulsed current source/voltmeter. Reader available.
- Proven—More than 5000 built and tested.

Harshaw/Filtrol DN-156 PIN Diode Response to Neutron Dosage at Aberdeen Facility.

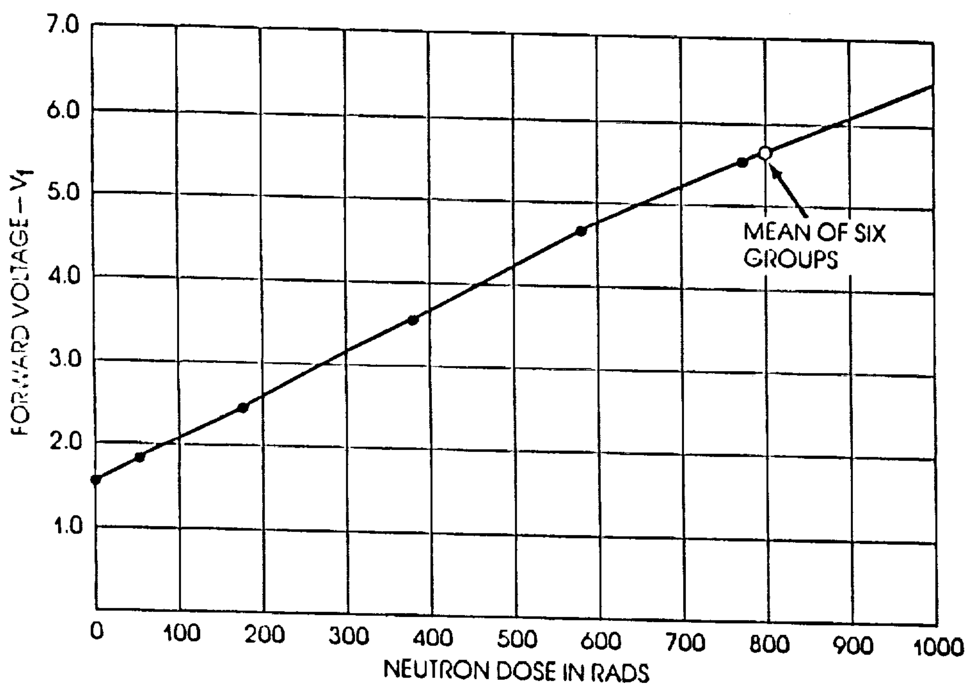

Figure 1 Prliminary specifications for the neutron sensitive diode.

been developed which will provide the performance needed for high quality in-flight neutron dosimetry. Such a unit will be capable of providing an accurate neutron dose and dose rate information throughout the flight.

II. THE TECHNICAL OBJECTIVES OF THE PHASE I PROGRAM

A. Overview

The specific objective of the Phase I program was to demonstrate the feasibility of enhancing the sensitivity of PIN diodes and developing an active neutron dosimeter system based on these devices. The final instrument will be insensitive to other types of radiation fields, be accurate and dependable, and yet be portable enough to be placed inside the crew compartment of the space vehicle.

To establish the viability of this concept, research was conducted in several areas. First, studies were performed to determine the design and construction of a better reading system that allows the PIN diodes to be read with high precision. Second, the physics of the device was investigated, especially with respect to those factors which affect the sensitivity and reproducibility of the neutron response. Third, this information was then utilized to develop methods to achieve high sensitivity at low neutron doses. This included collaborating with Lakeshore Cryotronics, the manufacturer of the diodes, to produce and test special custom PIN diodes. Fourth, measurements were made to confirm that PIN diodes with enhanced sensitivity were sufficiently insensitive to other forms of radiation that reliable readings will be able to be obtained under all foreseeable flight conditions. Finally, the results of the studies were analyzed with respect to the known flight requirements in order to demonstrate feasibility, and a detailed plan for Phase II was prepared.

The specific aims for Phase I of the program as stated in the Phase I proposal were as follows:

1. To conduct the studies needed to design and fabricate an improved diode reader.
2. To investigate the basic physics of the PIN diodes with respect to factors affecting sensitivity and reproducibility.
3. To explore methods of enhancing the sensitivity of the PIN diodes.
4. To confirm that the high sensitivity PIN devices are insensitive to other forms of ionizing radiation.
5. To develop a comprehensive plan for a Phase II program leading to a flight dosimeter.

These objectives were all met and it should now be possible to proceed with the final development of an improved instrument to measure neutron dose which will be particularly well suited for NASA applications.

III. PHASE I RESEARCH ACTIVITIES

A. An Improved Electronic Diode Reader

The earlier studies had shown that the PIN neutron diode could exhibit good sensitivity to high energy neutrons and at the same time be relatively insensitive to other forms of ionizing radiation. However, the studies also showed that the technology of reading the diode needed significant improvement.

As mentioned earlier, the physical process by which the diodes respond to neutron radiation is through defects generated by the neutrons in the silicon lattice. Thus, processes which tend to remove these defects reduce the apparent reading and lead to potential errors.

The most significant such processes are annealing due to temperature or charge injection. These processes involve the reduction of defects by either the movement of the lattice at elevated temperatures or by the flooding of the device with charge carriers, and are a direct result of the process by which the diodes are read. This makes the reader a very crucial part of the neutron dosimeter.

The commercial reading system developed by Lake Shore Cryotronics uses a train of three to five current pulses, each of 25 mA in amplitude and 10 milliseconds long, to interrogate the diode. They used this approach because they had found that the voltage generated across the diode by these pulses decreased with each pulse, but tends to stabilize somewhat after three to four pulses. However, this stability in reading is achieved at the expense of loss of reading resulting from self-heating and current injection annealing.

This loss in reading is insignificant when the diodes are used to measure very high neutron doses; however, for small doses that are expected in the space flight, which is in the range of 10 to 100 mRads, it introduces a sizable error. For this reason we investigated various reader ideas which rely on current pulses of much shorter duration and of much lower intensity. Our working hypothesis was that good results could be obtained if a single pulse of short duration was used to interrogate the diode rather than several pulses of long duration.

1. Design Requirements

The approach to reducing the amount of error introduced by the reader was to minimize the total current injected into the diode during the reading process. This was achieved by a combination of shortening the duration of the interrogation pulses as well as their amplitude. In order to explore these hypotheses more conveniently, an experimental diode reader was developed which provided the flexibility, convenience and sensitivity needed for these studies.

The signals needed to be measured were changes in the forward voltage drop across the diode. The starting value of this drop was in the range of three to five volts and the changes in the voltage due to neutron dose was expected to be on the order of a few millivolts. Thus the design requisites for the experimental diode reader include the following:

1) A pulsed current generator which could allow both the amplitude and duration of the current pulse to be varied over a very wide range to allow good experimental flexibility.

2) A pulsed current generator which would furnished a constant current over a range of impedances exhibited by the diodes with different geometries, and

3) An amplifier combined with the necessary timing circuitry to allow an analog to digital converter to be used to properly digitize the voltage pulse for storage an analysis by a computer.

Such a circuit was constructed and completed during the first part of the Phase I program and was used in the subsequent experiments described in this report. The details of the circuit design are discussed below.

2. System Hardware and Software

The goal of the instrument was to provide a flexible means of measuring the forward voltage of the diode as a function of radiation exposure. The hardware consisted of three sections, a pulse generator, an offset amplifier, and analog to digital convertor and a personal computer to store and analyze the data. Figure 2 shows a schematic diagram of the completed reader.

The pulse generator consisted of two subsections. The first provided a means of generating a set of one or more voltage pulses of preselectable constant width and the second a means to convert the resulting voltage pulses into current pulses of a preselected, constant amplitude.

The pulse generator used a one-shot (U3A) which produces a pulse whose width is determined by an adjustable resistor (R3) over a range of 5 microseconds to 5 milliseconds. It was triggered by an RS flip-flop which provided the sharp leading edge needed for a reliable trigger. This flip-flop was fired either manually using a push button as shown in the figure, or

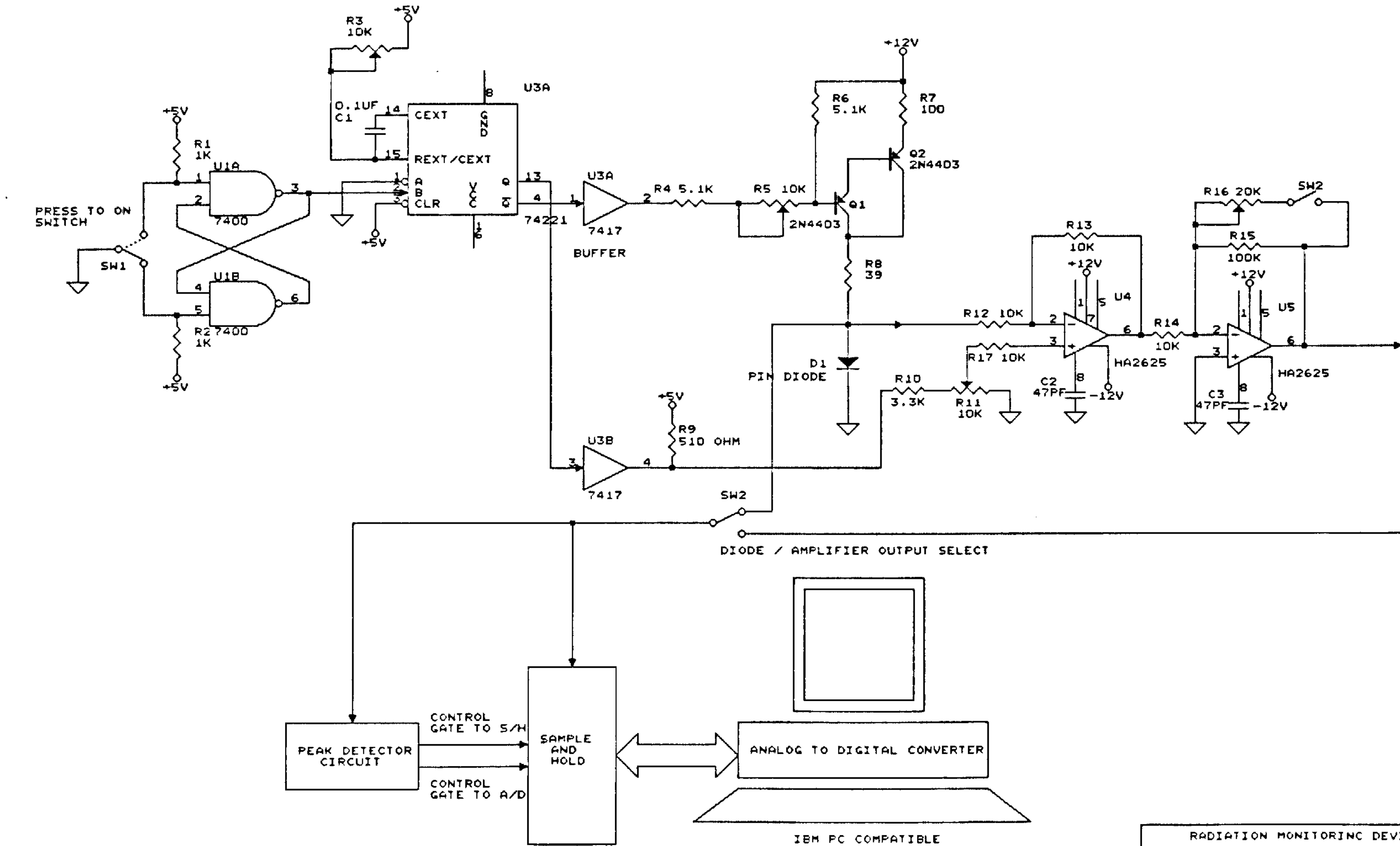

Figure 2 The neutron diode reader

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multiple times by a stream of trigger pulses generated by the computer. A buffer amplifier was then used as the output of this subsection.

It is important to note that the characteristics of a PIN diode in the forward direction are not quite as simple as might be assumed from an examination of the standard diode I-V curves. This distinction arises from the fact that the diode not only exhibits significant capacitance effects, but also displays other non-linear and time dependent behavior which arises from the trapping and detrapping of large numbers of carries. Thus, in order to drive the diodes with an precisely controlled, square current pulse, it was necessary for the constant current source to have a very low dynamic output impedance. For this reason, the current generator was designed to use a Darlington pair of transistors which had a current capability much higher than the 25 mA that was envisioned to be the maximum load.

The PIN diode to be studied (D1) was installed in the collector branch of the Darlington circuit and the current through it adjusted by means of the variable resistor (R5) which was in series with the base of the lead Darlington transistor.

Once this aspect of the circuitry was completed, testing was done to confirm that the current pulses produced and sent through the test PIN diode were, in fact, of both the time course and amplitude desired.

The function of the two-stage amplifier (U4, U5) which followed the PIN diode under test was to allow the signal to be readily read by the high speed, analog to digital convertor with sufficient resolution as to minimize errors due to the digitizing process. This was particularly important, since the baseline value of the forward bias voltage of the PIN diodes under these conditions was approximately 3 to 5 Volts, while the change in signal due to the neutron absorption was only in the millivolt range.

The first stage of the readout amplifier (U4) was used to allow a pulsed offset voltage which was coincident in time and shape with the diode signal to be subtracted from it. This was accomplished by sending the inverted output from the flip-flop though an attenuator (R11) into the opposite input of this first stage of amplification. By setting the attenuator to a value such that its impedance was equal to the forward impedance of the PIN diode prior to irradiation, the signal out of this amplifier represented only the difference in the forward voltage of the diode caused by the effects of the neutron irradiation. The second stage of amplification (U5) then magnified this voltage difference by a factor of ten.

The output of the amplifier circuit then drove the A/D convertor, including its triggering circuitry, which in turn fed the computer.

3. Computer System and the Analog to Digital Converter

In order to get measurements of high precision, it was necessary to analyze the diode signal using digital techniques. The digitizer used in the reader was a MetraByte, DAS-20, a high performance data acquisition and control system designed for use with the IBM compatible computers. It was capable of sampling analog waveforms with rates up to 100,000 samples per second and a resolution of 12 bits. For an input range of 10 Volts, this performance corresponds to a measurement accuracy of 2.44 mV, which, by itself, was not quite adequate for our purpose. However, with the gain of ten provided by the two stage amplifier described above, the accuracy of the measurement was raised to 0.244 mV, a level which was quite acceptable. The various modes of operation of the digitizer were controlled by means of the software.

For their operation, the ADC and S/H needed two control signals, one to initiate the sample and hold circuitry and the other to start the analog to digital conversion process. The signal pulse was used to generate both the control signals by feeding it into a peak detector circuit which in turn generated the control signals for the proper operation.

All of the timing of the data acquisition system was controlled by software developed under this program for this purpose. This software controlled the A/D board and passed the necessary parameters to it. It also controlled the input voltage range of the A/D converter, the acquisition period and frequency and also the format of the data. For most of these experiments, the control software was set so that the ADC sampled the diode signal every 10 microseconds for as long as the trigger input was active.

4. Reader Tests and Results

The sensitivity of the voltage measurement depends in large part on the performance and stability of the new instrumentation used to interrogate the diode and for this reason, the system was thoroughly checked over an extended period of time.

The results of the first test, which involved the use of a resistive load in place of the diode, confirmed that the output impedance of the Darlington circuit was sufficiently low that the magnitude of the interrogation current pulse was unaffected by the size of the load over the range of impedances of the various neutron diodes to be tested (60 Ohms to 200 Ohms).

Similar tests were also conducted in which a capacitor was placed in parallel to the resistive load to test the high frequency response of the circuit. Good results were also obtained under these conditions.

The third set of tests were designed to explore the effect of temperature on the accuracy of the diode reader. It is well known that the impedance of any silicon diode is a strong function of temperature and the instrumentation will eventually have to take this factor into account when translating the magnitude of the forward impedance of the PIN diode into cumulative neutron dose. For this reason, it was important that the reader itself did not have a significant temperature dependence. The results of this study indicated that over the range of temperatures experienced in our laboratory, the interrogation current remained constant to within 0.005%, which was suitable for these laboratory experiments. For the portable diode reader instrumentation to be developed during the Phase II program, steps will be taken to improve this performance so that the reader can be used over a much wider range of ambient temperatures.

The long term stability of the instrumentation was also checked. To within the accuracy of the digitizing circuitry, no significant drift was observed.

B. Initial Measurements of the Unirradiated PIN Diodes

1. Basic Wave Form

The diodes were read by passing a fixed current pulse through it in the forward direction and measuring the corresponding voltage across the diode. Because of the different charge carrier processes which occur in the diode, the voltage generated across the diode by the square interrogation current pulse does not have a simple shape, but rather has three distinct parts.

Figure 3 shows the output wave form of a typical PIN diode. Immediately after the inception of the current pulse, the voltage across the diode rises to a certain maximum depending upon the amplitude of the current and then decays exponentially to a stable asymptotic value. The exponential behavior is due to the conductivity modulation process which results in lowering the forward resistance of a PIN diode as the charge carrier density in the device is increased. The time required to assume the stable voltage depends on several factors including the resistivity of the starting material, the geometry of the device and varied between 160 microseconds to 1 millisecond.

The second part of the waveform is the steady state region in which the impedance tends to remain constant. The primary factor which affects this region is self heating due to the power dissipation caused by the pulse itself. It is for this reason that is of particular interest to keep the pulse width as short as possible and to minimize the number of pulses per interrogation. In the commercial diode reader, three to five pulses are used, each of duration 10 to 25 milliseconds. Part of the theme of the Phase I program was to determine whether the level of power could be reduced through reductions in the magnitude of the current, the width of the pulse or the number of pulses.

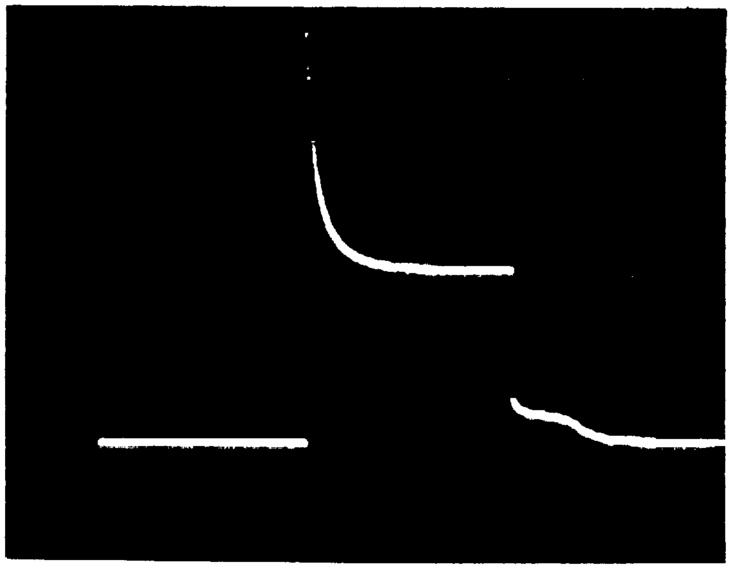

Figure 3. Output wave form of the diode reader applying a constant current pulse to a neutron sensitive PIN diode. The transients at the initial and trailing edge of the pulse is due to the trapping and detrapping of charge in the diode, not to the reader.

The final part of the wave form shows structure due to the trapping and detrapping of carriers raised into the conduction band by the passage of the current pulse. In principle, the measurement of this part of the waveform can provide information regarding the lifetime of the carriers in the silicon crystal, a property known to be affected by absorption of neutrons and the resulting damage to the lattice. Some experiments were done during the Phase I program to explore the possibility of using this information as an alternative means of reading the diode.

2. Minimization of Power Dissipation

As discussed in the background section of this report, the reader which is supplied commercially for use with the neutron sensitive PIN diodes interrogates the diode by forcing three separate, constant current pulses through the diode in the forward direction and measuring the value of the resulting voltage on the third and final pulse. This approach was adopted because it had been empirically found that the value of the forward impedance of the diodes increased as successive pulses were applied until reaching a steady state for the third and all following pulses. Furthermore, it had been found that the waveform of the voltage pulse was such that the best precision that could be obtained corresponded to an error in the neutron dose of more than 100 mR.

Since it was not cost effective to obtain for the program one of the commercial diode readers, it was necessary to rely on the reports of others as to the source of the problems associated with the presently available commercial reader. Based on our discussions with Dr. Swinehart, our collaborator and the inventor of the neutron sensitive, PIN diode, we hypothesized that one of the most likely causes of problems with the reader was associated with the high power or high current level introduced into the diode by the reader. For that reason, the new reader was designed to work with current pulses of lower value and shorter time. In particular, the commercial diode reader used current pulses which had an amplitude of 25 mA and a width of 10 milliseconds. In contrast, the new reader uses a pulse height of 10 mA and a width of 500 microseconds. Thus, the total charge pushed through the diode is reduced by a factor of 50.

A set of measurements was therefore conducted using a series of twenty current pulses. By using the digitizing electronics described earlier, it was possible to measure the magnitude of the resulting voltage pulses with good precision. To within the precision of the system, (+/- 200 microvolts), no changes in the diode base voltages were recorded. Thus, the new reader could make the desired measurement using only a single pulse, a situation which leads to both a much higher level of confidence as well as a simplification in the design of a flight dosimeter.

C. Response of PIN Diodes to Fast Neutrons

1. Experimental Measurements of Diode Sensitivity

The commercial PIN diodes show good sensitivity to only to neutron doses above 1 Rad. For these devices to be suitable for use in the space dosimeter, it is essential that their sensitivity be increased by at least two orders of magnitude. The primary goal of the Phase I program was to demonstrate that it is feasible to achieve this high level of sensitivity.

Experiments were therefore performed to use the improved diode reader to measure the response of the neutron sensitive PIN diodes, both custom and commercial grade, which were obtained from Lake Shore Cryotronics. The logic behind the experiments was that the diodes should not exhibit any changes as long as they were not being exposed to the neutron field. Once the exposure had begun, the diode reading should reflect changes proportional to the integral dose. During the course of irradiation, if the neutron field was withdrawn by removing the source, then the diode should show the same elevated reading with no droop as a function of time.

The neutron source used for the diode irradiation was a 500 mCi ^{241}Am-Be source. The source was enclosed within a lead pig to substantially eliminate the intense flux of 60 keV gamma rays emitted by the ^{241}Am. The source, when placed next to the diode, produced a maximum dose rate of approximately 90 mR/hr.

In a typical experiment, the diode was first irradiated continuously for several hours, then allowed to stand undisturbed, then irradiated a second time. This procedure was repeated one or more times, depending on the performance of the diode and the goal of the particular study. Measurements of the diode were made at appropriate intervals to track its response to the neutron flux.

Figure 4 shows the response of one of the custom diodes as a function of neutron dose. The graph shows the history of the forward voltage of the diode as a function of time with the figures above the individual points indicating the integral of the neutron dose in mR up to that point in time.

For the particular experiment shown, the diode was first exposed to a total dose of 270 mR. The source was then removed for a period of 2 hours and the irradiation then resumed until the integral dose reached 1900 mR. The behavior of the diode voltage after irradiation was then monitored for several additional hours.

As can be seen from the figure, the diode did not show any change in the reading before irradiation and, as expected, the output changed proportionally with the dose. The voltage across the diode did not change when the neutron field was removed which is in agreement with our hypothesis. The variations in the reading seen after the dose of 1900 mR are very small and are confined within the accuracy of the digitizer.

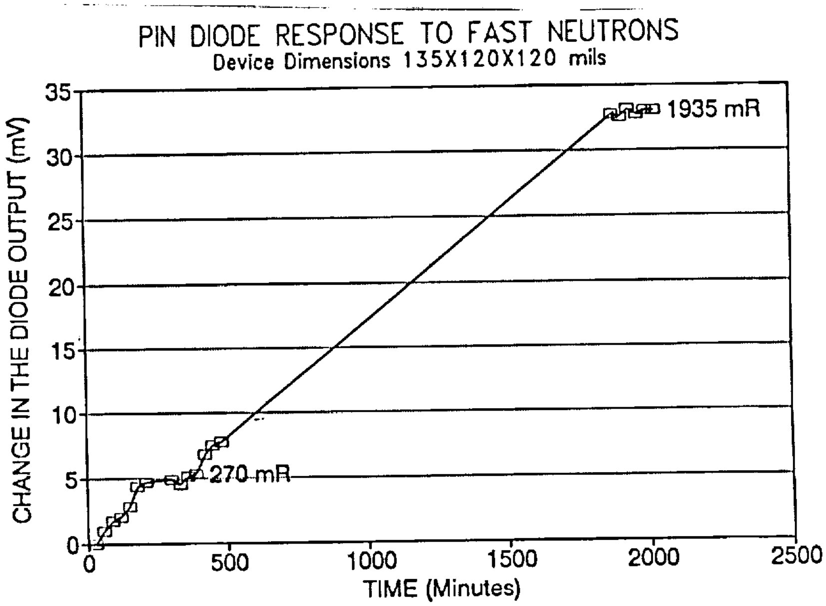

Figure 4. Response of a custom PIN diode to neutron irradiation. The forward voltage of the diode increases with exposure, not time.

2. Modification of PIN diodes to Improve Sensitivity

Prior to Phase I, it was already known that the sensitivity of PIN neutron diodes was determined primarily by the depth and profile of the junction, the purity of the diffusion materials, the lifetime of the minority charge carriers and the dimensions of the device. Furthermore, earlier theoretical studies conducted at Lake Shore Cryotronics indicated that for a given junction depth and profile, the sensitivity of the PIN diode as a function of the thickness of the intrinsic region has a distinct maximum arising from the diffusion length of the carriers. They had also determined experimentally that a similar maximum in sensitivity with respect to the cross sectional area of the diode exists, although the exact cause of this was not understood. Therefore it was believed that by experimenting with the thickness and cross section of the devices, it would be possible to extend their useful range down to the desired dose levels.

Previous studies were limited in part by deficiencies of the diode reader which have been discussed earlier. For this reason, new sets of diodes were prepared by Lake Shore to allow us to extend this work using the improved reader.

Custom produced silicon detectors were made in 16 different geometric configuration, comprising four different thicknesses (60, 85, 110 and 135 mil) and four different cross sections of the square base (ranging from 30x30 to 150x150 square mils).

Preliminary experiments with these devices showed that the diodes with dimensions of 135x70x70 mils showed the best sensitivity in the low dose ranges of interest. Further experiments of this type will be conducted in Phase II to determine the effects of different starting materials and surface preparations.

3. Measurements of a High Sensitivity Diode

The techniques described above were then applied to the measurement of the performance of the high sensitivity custom diodes. As will be described in more detail below, as expected, the

PIN diodes were quite sensitive to temperature and it was considered worthwhile to establish a means of maintaining the temperature very constant during the entire course of the study. For this purpose, a temperature controlled water bath was used.

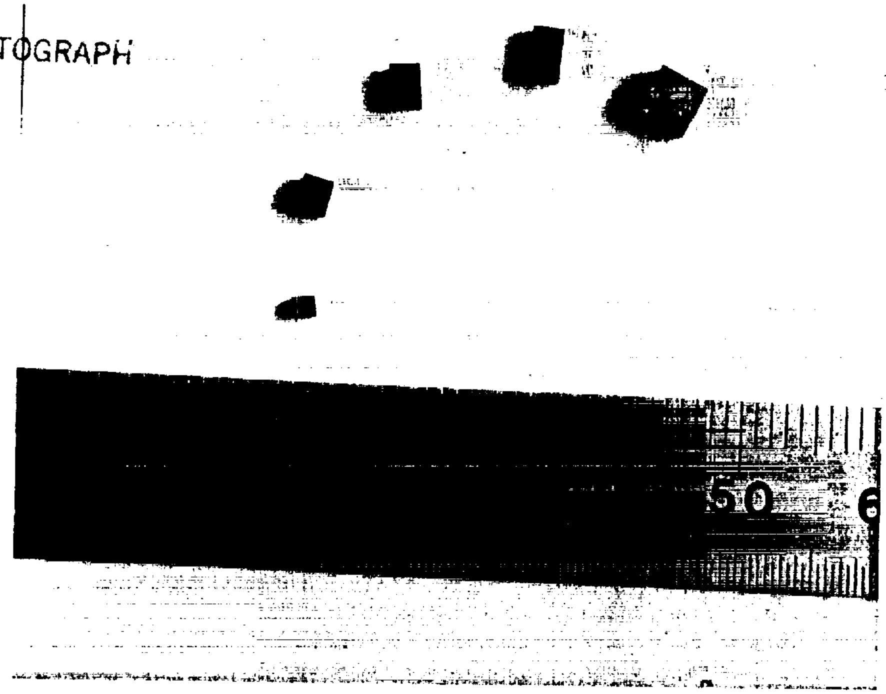

Figure 5. Several of the custom produced PIN diodes produced for this study by our collaborators Lake Shore Cryotronics. The diodes have both different geometries and different diffusion profiles.

The results of this study indicated the high sensitivity of the diode and are shown in Figure 6. The slope of the curve indicates that the diode produces a voltage change of 70 microvolts/mR. The inherent noise in the system, including that which arises from the digitizer was 240 microvolts. Thus, with the new reader, the diode could be read to within +\- 3 mR. This precision is a factor of thirty better than the performance of the commercially available diodes and instrumentation available prior to the Phase I development effort and exceeds that needed for useful flight applications.

D. Sensitivity of PIN Diodes to Other Forms of Radiation

One of the particularly attractive features of the PIN diodes for this application is its relative insensitivity to exposure to forms of ionizing radiation other than neutrons. Nevertheless, it is still the case that energetic photons and charged particles incident on silicon can cause displacement of the target atoms to occur and it was a goal of the Phase I program to reconfirm that the improved diodes would still be preferentially responsive to neutrons.

Since the cross-section for the interactions between silicon and ionizing radiation arising from sources other than neutrons is significant only at very high energies, experiments were

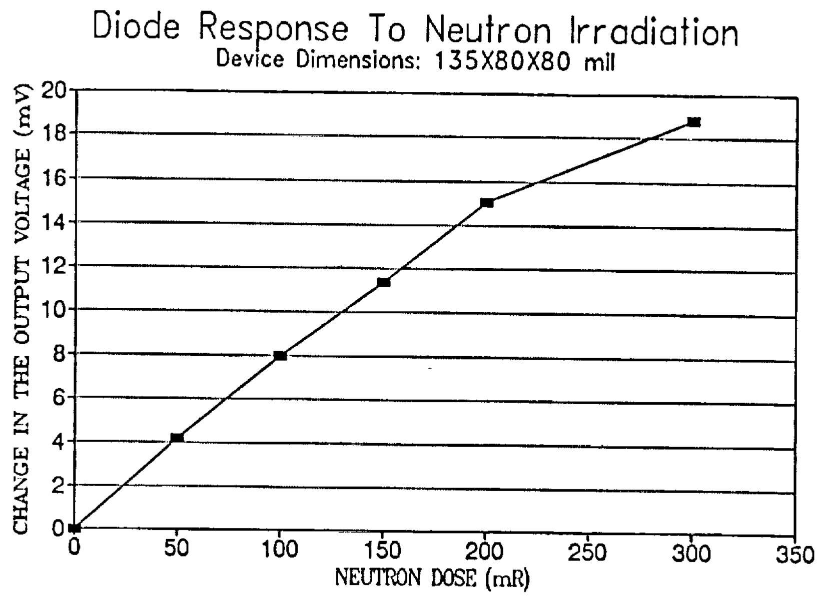

Figure 6. Response of a custom, high sensitivity PIN diode to low levels of neutron irradiation.

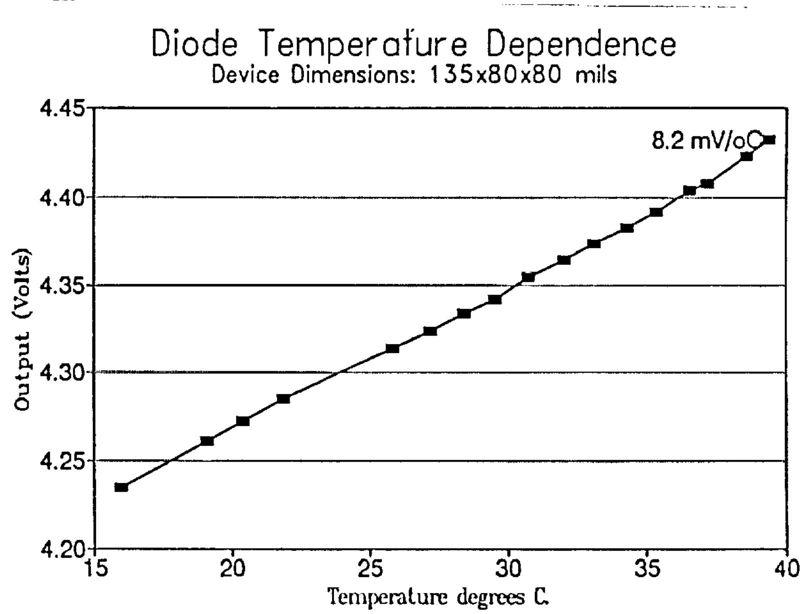

Figure 7. Temperature dependence of a high sensitivity PIN diodes. The device, which had dimensions of 135 x 80 x 80 mils was not optimized to minimize this dependence. With proper design, the temperature coefficient can be reduced to near zero.

designed to allow the diodes to be irradiated with sources which provided radiation fluxes of this type.

1. Sensitivity to Proton Irradiation

The preliminary measurements to determine the extent of the sensitivity of the diodes to proton irradiation were performed using three of the standard commercially available neutron diodes. Using the Harvard University Cyclotron facility, two of the devices were given a proton exposure of 11 R at beam energies of 20 and 148 MeV. Neither of these diodes showed any measurable response.

A third commercial device was then irradiated to 110 R dose at 148 MeV. In this case, a very small change in reading was obtained which corresponded to a neutron dose of less than 0.1 R. Therefore, the commercial devices appear to be over 1000 times less sensitive to energetic protons than to neutrons.

Experiments were then made at the Harvard Cyclotron using the high sensitivity diodes which had been custom made for this program. When irradiated with either of the two beam energies mentioned above, the response to the protons was less than 2% of that which would have arisen from a comparable dose to neutrons. This value indicates that while the increased sensitivity of the custom diodes does have some affect on their response to energetic protons, the absolute level of the response to protons is still so small that the devices will still perform extremely well in this type of mixed radiation field.

2. The Diode Response to Gamma Radiation

In the low earth orbit environment, the major source of gamma rays is the Bremsstrahlung produced by deceleration of energetic electrons as they collide with the space craft. The resulting gamma ray spectrum ranges from 0 to a maximum of few MeV. The Compton electrons produced by gamma rays in this energy range are expected to exhibit a Coulomb interaction with the shell electrons rather than a knock on reaction with the Si atoms and thus would not be expected to produce a measurable signal in the diodes. Nevertheless, for completeness, experiments were conducted to be sure that this was indeed the case.

An experiment was conducted in which a PIN diode was irradiated with Na-22 isotopic source which has gamma emission at 0.511 and 1.22 MeV. The diode was irradiated until a total dose of approximately 6 Rads was delivered. Even for such a high dose, the diode did not show any change in its output. This confirms that the PIN diodes are insensitive to the gamma radiation.

E. Factors Affecting Sensitivity and Reproducibility

The studies described above clearly show that it is possible to obtain very high sensitivity with the improved neutron diodes. However, there are still significant factors which must be addressed before the devices can be used in a practical flight dosimeter. Foremost among these is the undesirable sensitivity of PIN diodes to temperature.

1. Temperature Dependence of Neutron Sensitive Diodes

The temperature dependence of a PIN diode is the result of two separate phenomena, the positive temperature coefficient of resistance of the intrinsic silicon and the negative temperature coefficient of the PIN junctions. Since the former is dominant, the net result, the sum of these two components, is a temperature coefficient which is positive.

The width of the intrinsic region in a low sensitivity PIN diode is typically small and its temperature coefficient is counter balanced by the temperature coefficient of the junctions. Thus, these diodes exhibit a small or no temperature dependence. High sensitivity diodes, on the other hand, have a significantly large base width and therefore it is expected that these devices will exhibit increase in the forward voltage with temperature. The measurement of temperature coefficient for high sensitivity diodes was therefore undertaken and it was used to correct readings in the subsequent neutron sensitivity measurement.

Using the experimental setup described above, measurements were taken with the diodes immersed in the temperature controlled water bath. The temperature was measured using a thermometer that has an accuracy of 0.10 °C. The diode was interrogated by a current pulse of 25 mA and the forward voltage was measured at different temperatures over the range of 21 to 26 degrees centigrade.

The results of these measurements are shown in Figure 7. As can be seen from the graph, the relationship between the forward voltage and the temperature is linear in nature with a slope of 8.2 mV per degree centigrade. This temperature coefficient seemed rather high and in subsequent discussions with Dr. Swineheart of Lake Shore Inc., our collaborator and inventor of the device, it was concluded that it should be possible to lower this value by as much as a factor of 10 by modifying the design of the device. This will be discussed in more detail in the work plan for Phase II.

The presence of a significant dependence on temperature of the forward impedance presents a challenge in the design of a practical flight dosimeter since the ambient temperature will vary enough to affect the reading if some means of correction of this effect is not implemented. Even reducing the temperature coefficient of the diodes by the factor of ten discussed above, still limits the accuracy of the instrument to a few tens of mR, an useful, but less than ideal value.

To address this problem, several different methods of correcting for changes in temperature were considered. These included the use of a simple thermistor circuit to independently measure the temperature and provide an electronic correction to the output of the signal amplifier, the use of a second diode which was not sensitive to neutrons as a reference or the simultaneous measurement of the reverse impedance the same neutron PIN diode as an indicator of the temperature. Any of these approaches have the potential to provide an adequate means of compensating the readings with respect to temperature and are discussed in more detail later in this proposal.

2. Decay of the Diode Signal with Time

Another aspect of the diodes which was addressed was a report that the diodes could experience thermal annealing even at room temperature (Lake Shore Cryotronics). Thus the amount of voltage change recorded after a given exposure could be somewhat dependent on the time after exposure that the diode is read. According to this report, this thermal annealing causes the reading to follow the following equation in the commercial grade of the PIN diodes:

$$100 \times (\delta Vf(t) / \delta Vf(24)) = 111.2 - 3.942 \times \ln(t)$$

(where $\delta Vf(t)$ is the decrease in voltage across the diode after a time laps of t hours and $\delta Vf(24)$ is the decreased which would occur after 24 hours after irradiation. It has been reported that this relationship describes the signal decay for the commercially available, neutron PIN diode over a period from 30 minutes to one year with a precision of +3%. Thus, compared to the reading at 24 hours, the reading at time zero is 111%, at time one hour is 104%, and at time 2 days 96% and at time one year, 75%.

In the custom made PIN diodes used during the Phase I of the program, it was found that the PIN diodes did not follow the previously mentioned equation, and in fact, did not degrade at all. We hypothesize that the phenomenon reported for the commercial versions of the diode only occur at extremely high dose levels (10,000 R) and may not be relevant for the NASA application of flight dosimetry. Because of the obvious time constraints of the Phase I program a detailed study was not under taken. Further study of this possible time related phenomena will be undertaken during the Phase II of the research program to confirm that no correction for it will be required.

F. Summary of the Phase I Program

The new PIN neutron sensitive diode can make possible the development of a very compact, accurate personal neutron dosimeter for space flight applications. During Phase I of this program, significant improvements were made in both the design of these diodes and in the instrumentation with which to read them. These advances led to an improvement in sensitivity of a factor of thirty over the commercially available diodes. Based on the results of this effort, a comprehensive plan was formulated for a Phase II program which will lead directly to the completion of a fully functional field prototype. This prototype will be suitable for extensive testing by NASA personnel and able to be readily packaged for use in near term space missions.