University of New Hampshire

University of New Hampshire Scholars' Repository

Doctoral Dissertations

Student Scholarship

Spring 1964

NEUTRON ALBEDO MEASUREMENTS ON POLAR-ORBITING SATELLITES

JAMES HAROLD TRAINOR

Follow this and additional works at: <https://scholars.unh.edu/dissertation>

Recommended Citation

TRAINOR, JAMES HAROLD, "NEUTRON ALBEDO MEASUREMENTS ON POLAR-ORBITING SATELLITES" (1964). *Doctoral Dissertations*. 805.

<https://scholars.unh.edu/dissertation/805>

This Dissertation is brought to you for free and open access by the Student Scholarship at University of New Hampshire Scholars' Repository. It has been accepted for inclusion in Doctoral Dissertations by an authorized administrator of University of New Hampshire Scholars' Repository. For more information, please contact Scholarly.Communication@unh.edu.

This dissertation has been 65-956
microfilmed exactly as received

TRAINOR, James Harold, 1935-
NEUTRON ALBEDO MEASUREMENTS ON POLAR-
ORBITING SATELLITES.

University of New Hampshire, Ph.D., 1964
Physics, general

University Microfilms, Inc., Ann Arbor, Michigan

NEUTRON ALBEDO MEASUREMENTS
ON POLAR-ORBITING SATELLITES

BY
JAMES H. TRAINOR

B. S., University of New Hampshire, 1958

M. S., University of New Hampshire, 1959

A THESIS

Submitted to the University of New Hampshire
In Partial Fulfillment of
The Requirements for the Degree of
Doctor of Philosophy

Graduate School
Department of Physics

May, 1964

This thesis has been examined and approved.

John F. Johnson
Thomas J. Smith
Harry H. Hall
E. L. Lupp
D. H. Lambert

May 20, 1964
Date

ACKNOWLEDGMENTS

The author wishes to express his gratitude to Dr. John A. Lockwood for his guidance and suggestions during the progress of this study.

The assistance of Mr. Ludwig Katz and Mr. Don Smart of the Geophysics Research Directorate, Air Force Cambridge Research Laboratories, with the payload integration is greatly appreciated.

I am indebted to Dr. Douglas Miller of the Physics Department, Harvard University, for his assistance in arranging for the use of the FM cyclotron.

The use of the thermal-neutron-flux facility of the Portsmouth Naval Shipyard through the cooperation of Mr. Richard Bernard is gratefully acknowledged.

This research was supported by the Air Force Cambridge Research Laboratories, Office of Aerospace Research, USAF, under contracts AF19(604)-4552 and AF19(628)-2352.

TABLE OF CONTENTS

List of Tables	111
List of Illustrations	iv
Introduction	1
Instrumentation	8
Calibration	15
The Agena Satellite	24
Data Reduction and Interpretation	26
Results	32
Conclusions	43
Bibliography	45
Appendix I, Electronics	47
Appendix II, Calibration of the Charged Particle Detector	63
Appendix III, Calculation of Neutron Production	67
Appendix IV, Charged Particle Measurements	70

LIST OF TABLES

Number	Page
1. Satellite Designation and Ephemeris	7
2. $B^{10}(n, \alpha)Li^7$ Reaction Information	8
3. Characteristics of the Energy Spectra	22
4. Comparison with Theory	37
5. Comparison with the Measurements of Bame et al.	38
6. Component Values for the Low Voltage dc-dc Converter	47
7. A. Component Values for the High Voltage dc-dc Converter	51
B. Component Values for the Filter and Decoupling Circuitry	52
8. Component Values for the Amplifier	54
9. Component Values for the Pulse Discriminator.	56
10. Component Values for the Binary Scaler	58
11. Component Values for the Coincidence Circuit and the Blanking Univibrator	60
12. Component Values for the Anticoincidence and Output Circuits.	62
13. Examples of Charged Particle Enhancements	73
14. Real Time Acquisitions - Thule	75

LIST OF ILLUSTRATIONS

Number		Page
1.	The Differential Neutron Albedo Flux	3
2.	End View of the Detector Assembly	9
3.	Flight Package Showing the Detector Module . .	12
4.	Block Diagram of the Electronics System . . .	13
5.	Neutron Calibration	16
6.	Layout for Calibration	17
7.	Detector Response to a Neutron Pulse	19
8.	Gated Neutron Response vs. Latitude	33
9.	Mean Neutron Response vs. Latitude	34
10.	Low Voltage DC-DC Converter	48
11.	High Voltage DC-DC Converter	49
12.	Filter and Decoupling Circuits	50
13.	The Linear Amplifier	53
14.	Pulse Discriminator	55
15.	Binary Scaler	57
16.	Coincidence Circuit and Blanking Univibrator .	59
17.	Anticoincidence Circuit and Output Circuit . .	61
18.	Electron Calibration	64
19.	Proton Calibration	65
20.	Electrons After the Starfish Explosion	71
21.	Charged Particles over Alaska	77
22.	Neutron Response over Alaska, 310 km	78
23.	Neutron Reponse over Alaska, 230 km	79

INTRODUCTION

Neutrons are produced by the interaction of the primary and secondary cosmic radiation with nitrogen and oxygen in the atmosphere, and a fraction of these neutrons is able to leak out of the atmosphere, giving rise to the earth's neutron albedo. Since the free neutron has a half-life of ~ 12 minutes, decaying into a proton, an electron and an antineutrino, the decay of some of these neutrons within the magnetosphere can supply a portion of the protons and electrons trapped in the Van Allen radiation belts (Singer, 1959). Any evaluation of the neutron albedo as one of the sources of the trapped particles will require knowledge of the neutron flux, the energy spectrum and the angular distribution from the source, as well as the spatial and time variations.

Several theoretical calculations for the neutron albedo have been made, using neutron measurements in the atmosphere for their absolute normalization. Hess, Canfield and Lingenfelter (1961) originally calculated the neutron albedo spectrum at 44° N using a multigroup diffusion theory, and recently, Lingenfelter (1963) has refined the calculations. The essential differences between the two calculations are that (1) Lingenfelter has used an altitude dependence for his source function at the top of the atmosphere based on the star production measurements of Lord (1951) rather than a simple exponential fall-off;

(2) he has included the effects of inelastic scattering, thus moving many of the higher energy neutrons to lower energies; (3) he has used a weighted mean of sixteen measurements of thermal neutron fluxes by various experiments in the atmosphere at several latitudes as the source of his absolute normalization, rather than just the measurements of Hess, Patterson, Wallace and Chupp (1959); and (4) using the latitude variation of the primary cosmic radiation, normalized to the star production measurements of Lord (1951), he was able to construct the latitude variation of the neutron albedo for solar minimum and solar maximum. Newkirk (1963) has calculated the neutron flux at 57° N using the S_n approximation to transport theory, and his albedo flux prediction is in good agreement with that of Lingenfelter, although the spectral shape is somewhat different. At this time, the neutron flux and energy spectrum calculated by Lingenfelter are generally accepted as being the best calculations available. Lingenfelter's differential energy spectrum for the neutron albedo flux is shown in Fig. 1.

Several measurements of the earth's neutron albedo have been made with varying success. Bame et al. (1960, 1963) have measured the integrated neutron flux from thermal energies up to ~ 10 Mev using moderated $B^{10}F_3$ counters and moderated $Li^6I(Eu \text{ activated})$ scintillation counters on small rockets up to 120 km at 44.5° N. A further experiment by the same group used $Li^6I(Eu)$ scintillation counters within various thicknesses of polyethylene moderators.

THE DIFFERENTIAL NEUTRON ALBEDO FLUX

FIG. 1

These assemblies were mounted inside a pod which was ejected from an Atlas rocket over the South Atlantic ocean. The latter experiment allowed the neutron albedo flux to be measured at 36.5° N and 650 km and at 8.7° S and 320 km., and because of the differing energy responses of the detectors, the energy spectra of the albedo neutrons could be verified in a general manner. The fluxes measured at all three locations agree within the experimental uncertainties (25-50%) with the fluxes predicted by Lingenfelter (1963), and the spectral measurements are not inconsistent with Lingenfelter's spectrum, or for that matter, with the earlier spectrum by Hess et al. (1961). It should be noted that these experiments did not provide any means of rejecting neutrons produced in the detector assemblies by nuclear interactions due to the cosmic radiation. This effect was estimated to be $\sim 20\%$, and accordingly, this percentage was subtracted from the raw counting rates in all three measurements.

Measurements of the neutron albedo have also been made by Albert, Gilbert and Hess (1962) on a polar orbiting Agena satellite and by Williams and Bostrom (1964) on the Traac satellite. In both instances, the measurements fall consistently above the calculations of Hess et al. (1962) and some 5-10 times higher than the results of Lingenfelter. The experiment of Albert et al used a $B^{10}F_3$ counter within a plastic cylinder which served both as a moderator for the neutrons and as a scintillation detector for charged particles. The scintillator response was used

to blank the neutron data channel for 100 μ sec, thus separating the effects of neutrons produced in the detector assembly itself from the true albedo neutrons. However, it appears that the blanking time for the neutron channel was not long enough, so that a fraction of the locally-produced neutrons was counted. This effect was large enough to obscure the albedo results (private communication, W. N. Hess, November, 1963).

The experiment of Williams and Bostrom (1964) utilized an array of solid state detectors within a large polyethylene moderator. Some of the detectors were coated with 1 mg/cm² of B¹⁰ so as to respond to neutrons, while a few were used bare and served as charged particle monitors. No discrimination against neutrons produced in the moderator was provided in the experiment, and the detector was carried internal to the Traac satellite itself, so that their calculations to estimate the neutron production had to be carried out under far less than ideal conditions. The problem is enhanced, because their detector efficiency peaks at about 3 Mev where production effects should be large and it falls off by greater than a factor of 4 in the energy interval where Lingenfelter (1963) would predict a maximum albedo flux. The authors feel there is significance to their results, even though an uncertainty exists due to contributions from local production.

Information concerning the neutron albedo can also be obtained from experiments carried on balloon flights to

very high altitudes. Using this method, several experimenters have measured the total integrated neutron flux, the thermal neutron flux, and the flux of neutrons with energies greater than ~ 1 Mev (Soberman, 1956; Haymes, 1959; Smith et al., 1962; Haymes, 1964; Miles, 1964). If one extrapolates these neutron measurements to the top of the atmosphere using the results of Newkirk (1963) or Lingenfelter (1963), one can arrive at an estimate of the albedo neutron flux. These methods are always fraught with uncertainty, because the theoretical predictions of the neutron flux vs. altitude have not been experimentally verified in the region where they are used. These experiments and their results will be discussed more fully later.

The subject of this thesis is an experiment which was designed to measure the integrated neutron albedo flux with energies up to ~ 10 Mev as a function of latitude, longitude and time. It was intended that the experiment be carried external to a satellite to minimize the problem of local production of neutrons, and that the experiment provide for discrimination against neutrons produced in the detector assembly itself by the cosmic radiation. The detector consists of a $B^{10}F_3$ neutron counter, surrounded by a ring of charged particle proportional counters to identify protons and α particles which could produce neutrons in the detector assembly. The entire array of counters was encased in a cylindrical shell of paraffin, 1/2 inch thick, as a moderator for the higher energy neutrons. The pulse outputs from the

various counters are fed to a transistorized electronic system which performs the necessary logic functions and presents the reduced data to an interface compatible with the satellite telemetry system.

This experiment was carried into polar orbit on three Agena satellites in 1962. Table 1 gives the launch data, vehicle designations, apogee and perigee (Lange et al., 1963).

Table 1

Satellite Designation and Ephemeris

<u>Launch Date</u>	<u>Designation</u>	<u>Apogee (miles)</u>	<u>Perigee (miles)</u>
April 18	1962 lambda	178	120
April 28	1962 rho	226	110
July 21	1962 alpha eta	218	122

The orbital periods were ~ 90 minutes, so that a given orbit was repeated after 16 orbits or ~ 24 hours.

INSTRUMENTATION

The basic detector, shown in Fig. 2, consists of a $B^{10}F_3$ proportional counter for neutron detection surrounded by an array of ten proportional counters for charged particle detection. The neutron detector is one inch in diameter by three inches long, and is filled to 60 cm.Hg. pressure with BF_3 gas enriched to 96% B^{10} . Neutrons are detected through the $B^{10}(n,\alpha)Li^7$ reactions which are listed in Table 2 (Marion and Fowler, 1960). The net

Table 2

 $B^{10}(n,\alpha)Li^7$ Reaction Information

<u>Reaction</u>	<u>Q (Mev)</u>	<u>Branching Ratio</u>
$B^{10}(n,\alpha)Li^7$	2.792	.06
$B^{10}(n,\alpha)Li^7$	2.31	.94
$Li^7(\gamma)Li^7$	0.480	$\tau_{1/2} = 7.7 \times 10^{-14}$ sec

reaction energy is shared between the α particle and the Li^7 nucleus, ordinarily leading to a minimum of 2.31 Mev of energy liberated through ionization of the gas. The exception occurs when the reaction occurs near the counter walls, so that some of the energy is dissipated in the counter walls. A smearing of the pulse height distribution towards the lower energies occurs, because reactions

END VIEW

TUBE ARRANGEMENT:

(1-5) - Bank B Proportional
Counters

(6-10) - Bank C Proportional
Counters

(A) BF_3 Neutron Counter

(D) Paraffin cylinder
around tubes

END VIEW OF THE
DETECTOR ASSEMBLY
FIG. 2

occurring at the ends of the counter or near the center wire will produce smaller pulses, since the multiplication process in the gas doesn't fully develop in these cases. The counters possess a voltage plateau greater than 100 volts and a plateau slope of $\sim 1\%/100$ volts, using a 2 millivolt discrimination threshold. Pulses due to γ -ray or x-ray interactions and the passage of minimum ionizing charged particles are less than 1 millivolt and are thus rejected by the discriminator.

The charged particle detectors are $1/2$ inch in diameter by three inches active length, filled to 12 cm. Hg pressure with argon and to 48 cm. with methane. These were used as two banks of five counters in coincidence. Their plateaus center around 2250 volts for the proportional region, but in order to keep the counter dead time less than 10 μ sec, the counters were operated in the semi-proportional region. This improves the time response of the counter, but sacrifices the stability of the counting rate as a function of high voltage. In this instance, the counters were operated at 2100 volts with an operating slope of $\sim 30\%$ per 100 volts. Since the high voltage power supply was regulated to ± 5 volts over the expected variation of input voltage and ambient temperature, this leads to a $\pm 1.5\%$ uncertainty in the counting rates. This is completely negligible for this experiment.

The entire array of counters was encased in a cylindrical shell of paraffin 6 inches long by $1/2$ inch thick

which acted as a moderator for higher energy neutrons. The paraffin was contained in a thin aluminum shell which was sealed with epoxy. The epoxy used as the high voltage insulation and interstitial support for the counting tubes also acted as a moderator, especially at the ends of the cylinder. The efficiency of the detector for neutrons with energies in the range of 100 Kev to 10 Mev could have been improved by increasing the moderator thickness to 1 inch, but the available payload space prevented this choice. Fig. 3 shows the flight package and indicates the position of the detector module. The remaining space contained the electronic decks, individually foamed in a light plastic.

Fig. 4 shows the block diagram of the electronics system. The charged particle pulses are amplified, discriminated, and fed to a coincidence circuit with a resolving time of 5 μ sec. These coincidences are scaled and fed to the telemetry, and are also used to trigger a univibrator which blanks a neutron channel. This blanking time is set for 100 μ sec, which is greater than three times the half-life of neutrons in the overall detector, including the moderator. This half-life of the neutrons is discussed under CALIBRATION. Both the total output and the gated output of the BF_3 counter are scaled and fed to telemetry. In this manner, the effects of evaporation neutrons produced by protons and α particles interacting with the detector assembly can be removed and monitored. In addition, a channel is provided for monitoring the temperature inside

FLIGHT PACKAGE SHOWING DETECTOR MODULE

FIG. 3

BLOCK DIAGRAM OF THE ELECTRONICS SYSTEM FIG. 4

the package. Detailed schematics of the various circuits designed for and used in this experiment are given in APPENDIX I, along with performance criteria and tests.

CALIBRATION

The detecting system was calibrated by exposing the complete flight packages to fluxes of neutrons with $0 \sim E_n \lesssim 15$ Mev, protons with $0 \sim E_p \lesssim 160$ Mev, and electrons with $1 \text{ Mev} \lesssim E_e \lesssim 3$ Mev. In these calibrations, both the neutron and charged particle detecting channels were monitored to determine the response as a function of flux and energy. The proton calibrations were conducted at the Harvard University FM cyclotron and the electron calibration at the High Voltage Engineering Corporation. The neutron response was measured at the University of New Hampshire and at the thermal neutron flux facility at the Portsmouth Naval Shipyard.

Fig. 5 summarizes the neutron energy calibration. A 400 Kev Van de Graaff with a pulsed deuteron beam provided a source of nearly monoenergetic neutrons at 14.4 Mev, 5.2 Mev, 2.9 Mev and 110 Kev using tritium, copper, deuterium and carbon targets respectively. Calibrated radium-beryllium sources were also used, including tests with the detector mounted on the satellite. The two points arbitrarily plotted at 1 ev refer to calibration of the bare BF_3 counter and the finished packages in known thermal fluxes.

The actual calibration with the Van de Graaff was carried out as follows. Fig. 6 shows the placement of the flight package, the standard long counter (Hanson and

NEUTRON CALIBRATION

FIG. 5

LAYOUT FOR CALIBRATION
 FIG. 6

McKibben, 1947; Marion and Fowler, 1960) and a moderated BF_3 counter with respect to the Van de Graaff target. The neutron flux incident on the detector is determined by the activation of metallic foils or by the use of the monitors. The ratio of the detector's counting rate to the neutron flux incident on the detector is defined as the efficiency of the detector at that energy. The efficiency is denoted as $S(E)$ and has the units of counts/n/cm².

For the $T(d,n) \text{He}^4$ reaction, a thin copper foil (one inch in diameter, 1.338 gms) was mounted on the face of the detector and served as the absolute monitor of the neutron flux incident on the detector. Cu^{63} has a negative Q of 10.7 Mev for neutrons, and the resulting nucleus, Cu^{62} , has a half-life of 9.9 minutes, making this reaction a good monitor for neutrons above 10.7 Mev. The 9.9 minute half-life leads to moderate irradiation times, and yet is very convenient for subsequent counting of the induced activity in the foil.

Trial runs with the Van de Graaff in dc and pulsed modes of operation established that neutrons which had been scattered by the walls of the room were contributing significantly to the response of the package being calibrated. Fig. 7 shows the counting rate of the flight detector as a function of time after the beginning of the neutron pulse from the Van de Graaff. The counting rate reaches a maximum at the end of the neutron pulse, and then falls off exponentially with a half-life of $32 \pm 2 \mu\text{sec}$ until ~ 90

DETECTOR RESPONSE TO A NEUTRON PULSE FIG. 7

μsec after the end of the neutron pulse, where the scattered neutron flux is now contributing significantly to the counting rate. To eliminate the response to the scattered neutron flux, the detector output was electronically gated, so as to count only for a convenient $28 \mu\text{sec}$ after the beginning of the neutron pulse. The true number of counts due to the neutron pulse minus the response to the scattered neutrons is then given by the counts in the $28 \mu\text{sec}$ interval times a constant. This constant is the ratio of the areas A plus B to the area A as shown in Fig. 7, and is equal to $2.2 \pm .2$. This method assumes a $32 \mu\text{sec}$ exponential decay for the counting rate after the Van de Graaff pulse, and hence, assumes that the detector's response to the scattered neutrons is negligible until $\sim 90 \mu\text{sec}$ after the pulse. Further tests with a calibrated radium-beryllium source verify this assumption.

For the $D(d,n)\text{He}^3$ reaction, no convenient element exists which has a threshold for neutron activation sufficiently close to 2.9 Mev, such that activation by scattered neutrons would not be a serious problem. Thus, the flux incident on the detector had to be determined by the use of the standard long counter. The response of the long counter was monitored during the calibration with 14.4 Mev neutrons, so the long counter response could be directly related to neutron flux incident on the flight package at 14.4 Mev. The published long counter response as a function of energy (Hanson and McKibben, 1947; Marion and Fowler, 1960) extends only to 9 Mev, so the response of the long

counter at 2.9 Mev relative to that at 14.4 Mev had to be determined using a BF_3 counter within a cadmium-covered, paraffin moderator, 2 inches in thickness. The relative response of this detector is known (Hess et al., 1959). Actually, the response of the long counter for 14.4 Mev neutrons relative to the response at lower energies turns out to be just what one obtains by a smooth extrapolation of the published response as a function of energy.

For the $\text{Cu}^{63}(\text{d},\text{n})\text{Zn}^{64}$, $\text{Cu}^{65}(\text{d},\text{n})\text{Zn}^{66}$ and $\text{C}^{12}(\text{d},\text{n})\text{N}^{13}$ reactions, the standard long counter was used as the absolute flux monitor.

Prior to the assembly of a flight package, the bare BF_3 counters were calibrated at the Portsmouth Naval Shipyard in thermal fluxes known to 10%. After assembly, the completed flight packages were calibrated in thermal fluxes produced by using a huge paraffin box around the Van de Graaff target. In this case, the thermal flux was monitored by the activation of In^{115} , and could be determined to 15%. The two thermal measurements agree to $\sim 5\%$, verifying the accuracy of the activation analysis methods.

Using the calibration curve, Fig. 5, and the energy spectra given by Hess et al. (1961), Newkirk (1963), or Lingenfelter (1963), the conversion factors relating the BF_3 counting rate to the neutron flux can be calculated for each spectrum. Thus, if the differential neutron flux in neutrons/ cm^2 sec/Mev is given by $j(E)$ and the response of the detector is given by $S(E)$, then the mean response of

this detector is given by Eqn. 1.

$$\bar{S} = \int_0^\infty S(E) j(E) dE / \int_0^\infty j(E) dE \quad (1)$$

Table 3 lists the mean responses and gives some characteristics of each spectrum. Columns A and C refer to the energies above which 90% and 10% of the neutron flux are found respectively. Column B lists the energy corresponding to the maximum in the energy distribution, while Column D lists the predicted latitude effect.

Table 3

Characteristics of the Energy Spectra

<u>Spectrum</u>	<u>$\bar{S}$ counts/n/cm²</u>	<u>A Mev</u>	<u>B Mev</u>	<u>C Mev</u>	<u>D</u>
Hess et al. (1961)	.28	0.1	0.8	8	4.5/1
Newkirk (1963)	.34	0.003	0.45	6	---
Lingenfelter (1963)	.33	0.003	0.2	3.5	10.5/1

In addition to these calibrations, the response of the flight package to neutrons from a calibrated radium-beryllium source was determined. In this instance, both the source and the flight package were suspended by wires from the ceiling of a large room, so as to minimize the effects of scattering from the walls, floors, etc. Tests to determine the response of the detector as a function of

source distance verified that the response fell off as $1/r^2$, indicating that scattered neutrons were not a problem here. The mean energy of the neutrons from the radium-beryllium source is ~ 4 Mev (Marion and Fowler, 1960), intermediate to the neutrons from the deuterium and copper targets. Fig. 5 shows that the efficiency determined with the radium-beryllium source agrees with those determined using the Van de Graaff, activation foils, long counter, etc., thus lending consistency to the entire calibration.

Tests were also run with the radium-beryllium source to determine the directional response of the flight package. The response was found to be omnidirectional to better than 10%. This result was not expected, but the moderator thickness used was thinner than optimum for these neutrons. Thus, when a given flux is incident on the end of the detector, it sees a smaller but more efficient detector than it would see if the flux were incident on the sides of the detector.

Further tests were run using the radium-beryllium source, but with the flight package mounted on the Agena satellite. The results showed that the presence of the Agena vehicle did not modify the package calibration within the counting statistics of $\sim 5\%$.

THE AGENA SATELLITE

The Agena is a satellite used by the Department of Defense for investigations in space. It possesses active control systems such that a given side of the satellite always faces the earth. This experiment was mounted on a rear door looking down at the earth, and after ejection of the launch heat shield, less than 10% of the 2π solid angle facing the earth was obscured in any way. That portion obscured was at about 90° to the zenith line and should be unimportant for this experiment, since the top of the atmosphere at the horizon is at $\sim 75^\circ$ to the zenith line. Stated differently, the detector views the entire visible earth with no obstruction.

The Agena is a reasonable vehicle for neutron albedo measurements, even assuming a maximum weight of 2100 lbs. (Lange et al., 1963), provided the experiment is located on a door at the rear of the vehicle. This comes about because the vehicle is large and has a favorable mass distribution, as well as the fact that a small number of experiments are mounted on these doors with good spacing. The only material internal to the doors is the rocket engine itself, and the spacing is such that only $\sim 0.3\%$ of the evaporation neutrons produced in the engine enter the solid angle subtended by the detector. The effects of neutron production are discussed in more detail under RESULTS and in APPENDIX III.

Data retrieval from the Agena is carried out by the Lockheed Missiles and Space Company, Sunnyvale, California. Ordinarily they are funded under government contract to make up to 85 data acquisitions from the basic research experiments during the four- to five-day power life of these experiments. In the present case, information from the first vehicle was extremely limited because of noise in the data recordings. Information from the second vehicle was of good quality, but few data acquisitions were made. On the third vehicle, 85 data acquisitions were made over a period of five days. These were about evenly divided between real time acquisitions of ~ four minutes and tape recorder readouts of up to one orbit.

DATA REDUCTION AND INTERPRETATION

The experiment presents the data to the satellite telemetry system in a binary form. Each data output is sampled once per second by an electronic commutator and then fed to a real time transmitter and a tape recorder. Data are acquired at ground receiving stations in Hawaii, Alaska, California, New Hampshire and Greenland, both from real time transmissions and command readouts of the tape recorder. These data are on magnetic tape and are further processed by Lockheed Missiles and Space Company, separating the data of this experiment for all other information transmitted and correlating these data with the various ephemeris data. As they are finally received here, the data are a point by point reconstruction of the original binary data, printed on a strip chart with the proper time base.

The real time data can be read off these charts accurately for time intervals down to ~ 20 seconds, if the counting statistics justify this effort. However, the time base for the tape-recorded data is compressed by a factor of ~ 25 due to the high speed readout of the tape recorder, so that data can be accurately derived from the charts only for time intervals of ~ 4 minutes or more. This means that a counting rate recorded near the equator will be an average over at least 10° of latitude and 1 or 2 degrees of longitude, while one recorded at high latitudes will be an average over as much as 50° longitude and perhaps

1 or 2 degrees of latitude. Thus, if any sudden changes in counting rate occur, they may be observed in detail only in the real time data.

Using these time intervals, the uncertainty in any given time interval is ordinarily 1% to 2%, and as such, represents a negligible source of error in a flux determination. The statistical standard deviation in the number of counts in the usual time intervals ranges from 15% to 25% for the BF_3 counter, depending upon counting rate. In the final analysis of the data, many observations in a given latitude interval are averaged, thus improving the statistical validity of the data. In converting these average counting rates to neutron flux for a given spectrum, the uncertainty in the neutron energy calibration of $\sim 25\%$ must be included. Thus, the uncertainty in a given neutron flux is ordinarily $\sim 30\%$.

No temperature corrections need be applied to these data, since the flight temperature varied from 30°C to 10°C , while tests indicated that the response of the entire flight system varied less than $\pm 3\%$ over the temperature of -30°C to $+70^\circ \text{C}$.

A final point of concern is the proper interpretation of the data derived from this experiment. As already explained, a given observation might be the average of the counting rate while the satellite was traversing $\sim 10^\circ$ of latitude near the equator. However, at any instant, the detector sees neutrons coming from the entire top of the

atmosphere visible to it. The size of this source is large. An observer at the center of the earth would see the projection of this source as a circle centered about the satellite and with a radius equivalent to 14° of latitude.

The particular importance of any unit area of surface within this source is dependent upon the angular distribution of neutrons emerging from the unit area. The original theory of Hess et al. (1961) predicted that the neutrons emerging from such a unit area should have an angular distribution going as $\cos^2 \theta$, where θ is the angle measured from the zenith. The improvements made in this theory by Lingenfelter (1963) include an evaporation neutron source deeper in the atmosphere and the inclusion of the effects of inelastic scattering in the diffusion process. Both effects will tend to change the angular distribution of the neutrons from a $\cos^2 \theta$ distribution to one which is more omnidirectional. Lingenfelter has not yet been able to calculate this angular distribution, so one can only choose a specific distribution and investigate its effect.

A $\cos \theta$ distribution would imply that $\sim 90\%$ of the neutrons arriving at the detector at any instant came from a circular source region of radius equivalent to 7° of latitude. An omnidirectional source distribution would imply a neutron source nearly equal to the visible source, i.e., a radius equivalent to 14° of latitude.

The result of this angular distribution is that while the satellite may traverse 10° of latitude during a particular measurement, the detector is really averaging the neutron flux over $\sim 24^\circ$ of latitude ($10^\circ + 7^\circ + 7^\circ$), if the angular dependence goes as $\cos \theta$, and averaging over $\sim 38^\circ$ of latitude if the source is omnidirectional. This averaging should not affect measurements made near the equator or in the polar regions, since the primary cosmic-ray flux is approximately constant over latitude intervals comparable to or larger than the latitude intervals of interest here. One would expect the neutron albedo produced by the cosmic radiation to be approximately constant there also. However, at intermediate latitudes one would expect a smearing of the true shape of the latitudinal variation of the neutron albedo.

Up to this point, the gated counting rate of the BF_3 counter has been designated as the response to the albedo neutron flux and thus can be directly related to a flux for a given spectrum. This interpretation needs an additional qualification. Protons and α particles of the cosmic radiation can enter the detector assembly at the ends and pass completely through the assembly without being directly detected---- i. e., without passing through the charged-particle proportional counters. Some of these particles will interact with nuclei in the assembly and neutrons will be produced. Some of these neutrons will be detected. In evaluating the size of this production source,

the following points must be considered. (1) The solid angle through which this effect can occur is $\sim .4 \pi$ steradians or $\sim 10\%$ of the total solid angle. Since the primary cosmic radiation is isotropic, $\sim 10\%$ of the particles will enter through the ends of the detector assembly. (2) The calculations outlined in APPENDIX III show that $\sim 2/3$ of the neutrons produced in the detector assembly are produced by nuclear interactions in the counter walls. Thus a smaller fraction of the particles entering the detector assembly through the ends will produce neutrons as compared to those entering through the sides. (3) If an interaction does occur, charged particles in the fast cascade and/or the several charged particles evaporated from the residual nucleus may result in a charged-particle coincidence.

These three effects lead one to believe that the cosmic radiation entering the detector assembly through the ends will account for much less than 10% of the total neutrons produced in the detector assembly. Under RESULTS it is shown that the neutrons produced in the detector assembly account for 20% of the counting rate at the equator and 40% at the poles. Thus, the effect of neutrons produced by cosmic rays entering the detector assembly through the ends should be negligible here.

The next section of this thesis will be concerned with the results of the experiment. The results are presented in graphical form and are compared with the

calculations of Lingenfelter (1963) and the rocket measurements of Bame et al. (1960, 1963). Several previous attempts to measure the neutron albedo are also discussed. In addition, the results of several neutron experiments in the atmosphere are included, especially as to how they relate to the calculations of Lingenfelter.

RESULTS

The composite results of the gated BF_3 counting rates are shown in Fig. 8. The measurements of all three vehicles have been reduced to an altitude of 300 km using an altitude dependence of $R^{-3.2}$, where R is expressed in earth radii (Hess and Starnes, 1960). This amounts to a maximum correction of $\sim 4\%$. The error flags give the statistical standard deviation for each point. It should be emphasized that the data shown for July amount to only $\sim 15\%$ of the total data acquired on that flight, since, in general, trapped radiation and leakage contribute significantly to the measurements near apogee and throughout the entire trajectory over the Americas and Atlantic regions after the Starfish explosion on 9 July 1962. These effects are discussed in detail in APPENDIX IV.

Fig. 9 is a plot of the mean counting rate in the various latitude intervals. The error flags give the average deviations, and the number of observations contributing to each mean is given in parentheses. It should be noted that data presented in this way do not reflect the statistical weight of each observation. If a grand mean were to be used, the time duration of the data acquisition would affect the result more than positional and/or temporal variations. Such variations appear to be present, although the relatively small number and the limited geographical extent of the observations effectively mask any detailed structure. It is apparent, however, that there

GATED NEUTRON RESPONSE VS LATITUDE

FIG. 8

MEAN NEUTRON RESPONSE VS LATITUDE

FIG. 9

is a latitude variation of 3 to 1 in the gated neutron data.

When making neutron flux measurements in the presence of a charged particle background, local production of neutrons must always be evaluated. Since the difference between the gated and total neutron counting rates in this experiment is due to neutron production in the detector assembly, we can compare this measured quantity with the calculated production in the module due to the galactic cosmic radiation (see APPENDIX III). The calculations predict that production accounts for $\sim 23\%$ of the neutrons detected at the equator and $\sim 39\%$ of those detected at high latitudes. Stated differently, the calculations predict ratios between the total and gated neutron counting rates of 1.31 at the equator and 1.65 at high latitudes. These calculations cannot be considered to be accurate to better than 50%, but the ratios calculated are in surprisingly good agreement with the experimental values of $1.28 \pm .12$ and $1.72 \pm .36$ at high latitudes. Such agreement suggests that the calculations may be extended to the entire vehicle, where we find that the only additional, appreciable source is the Agena rocket engine. Since we do not know the internal details of the rocket engine, we assume, for a worst case, that it consists of solid nickel and neglect absorption. This calculation leads to less than 8% contribution to the counting rate at the equator and less than 12% at the poles, primarily because only

$\sim 0.3\%$ of the neutrons produced enter the solid angle subtended by the detector module. This contribution has thus been neglected.

Table 4 compares the present measurements with the calculations of Lingenfelter (1963). The means for both the gated and the total response of the detector are given. At low latitudes the measurements and the calculations agree within the listed uncertainties. At middle latitudes our measurement amounts to $\sim 1/2$ the calculated flux, however, and at high latitudes, to only $\sim 1/4$ the calculated flux. This discrepancy arises since Lingenfelter calculates a latitude variation of 10.4 to 1 at this time, while this experiment measures ~ 3 to 1 for the gated response of the detector.

Table 5 compares the measurements of Bame et al. (1960, 1963) corrected to 300 km, to the present measurements. The measurements of Bame et al. have already been corrected by 20% to account for local production (private communication, J. S. Bame, August 1963), and the flux is calculated for the spectrum of Hess et al. (1962). The third column lists the range of the present measurements near the appropriate latitude, and the number in parentheses indicates the ratio of gated to total response expressed as a percent. This gated response is calculated for the Lingenfelter spectrum and would be increased by $\sim 18\%$ for the spectrum of Hess et al. There is good agreement among the results near the equator, but the

Table 4

COMPARISON WITH THEORY

<u>Geomagnetic latitude</u>	<u>Gated flux neutrons/cm² sec</u>	<u>Total flux of 300 Km</u>	<u>Calculated flux (Lingenfelter, 1963)</u>
0-20	.085 $\pm$.03	.11 $\pm$.03	.11 $\pm$.02
20-30	.12 $\pm$.04	.16 $\pm$.05	.16 $\pm$.03
30-40	.13 $\pm$.04	.18 $\pm$.06	.27 $\pm$.05
40-50	.15 $\pm$.05	.21 $\pm$.07	.47 $\pm$.09
50-60	.17 $\pm$.05	.27 $\pm$.08	.75 $\pm$.15
60-70	.18 $\pm$.06	.31 $\pm$.08	.95 $\pm$.19
70-90	.24 $\pm$.06	.41 $\pm$.10	1.04 $\pm$.21

The neutron albedo flux deduced from the gated counting rate and the total counting rate of the BF₃ counter are compared with the fluxes predicted by Lingenfelter (1963).

Table 5

COMPARISON WITH THE MEASUREMENTS
OF BAME ET AL.

Neutrons/cm² sec at 300 Km.

<u>Geomagnetic latitude</u>	<u>Bame et al. (1960, 1963)</u>	<u>Present Experiment gated flux</u>
8.7° N	.10 ± .05	.074 to .10 (78%)
36.5°	.26 ± .11	.096 to .21 (74%)
44.5°	.34 ± .07	.092 to .22 (70%)

The measurements of Bame et al (1960, 1963) corrected to 300 Km (Hess and Starnes, 1960) are compared with the present measurements. The measurements of Bame et al have already been corrected by 20% to account for local production, and the flux is calculated for the spectrum of Hess et al (1961). The third column lists the range of the present measurements near the appropriate latitude, and the number in parentheses indicates the ratio of gated to total response of the BF₃ counter expressed as a per cent.

measurements differ by at least the experimental uncertainties at the higher latitudes. Part of this discrepancy might be explained by the fact that the present experiment measures a contribution to the total flux from local production at high latitudes which is greater than the 20% estimated by Bame et al., as well as the fact that the measurements were made at quite different longitudes. Simpson (1951) found a longitude variation of -1.5% per degree at 312 g/cm^2 in the atmosphere and at 41° magnetic latitude while going from 95° to 110° West geographic longitude.

The measurements of the neutron albedo by Albert, Gilbert and Hess (1962) on Agena satellites and by Williams and Bostrom (1964) on the Traac satellite have already been discussed. In the experiment of Albert et al., enough of the locally-produced neutrons were counted to obscure the albedo results (private communication, W. N. Hess, November 1963). The results of Williams and Bostrom are a factor of ~ 10 larger than the flux determined by this experiment. The authors feel there is significance to their results, even though an uncertainty exists due to contributions from local production (Williams and Bostrom, 1964). Further, there is apparent disagreement with an unexplained decrease of $\sim 50\%$ in the neutron measurements of Williams and Bostrom around 5 April 1962 to about 29 June 1962. Two flights of the present experiment occurred in this time period, and the third flight was launched on 21 July 1962. The results of all these flights, as shown in Fig. 8, are consistent and do not show any decrease.

Haymes (1964) has recently reported neutron measurements in the atmosphere up to 3.6 g/cm^2 using a proton recoil detector with a phoswich to identify neutrons in the energy range 1-8.5 Mev and to remove the effects of charged particles and γ rays. By extrapolating his results to the top of the atmosphere according to the theoretical calculations of Newkirk (1963), he finds a flux agreeing with the present results within the probable errors. However, only about 20% of the response of the present experiment is above 1 Mev for Lingenfelter's spectrum, so the agreement is fortuitous. It should be noted that no estimate of neutron production in the 3.2 kg detector unit (excluding the phoswich detector) or in the 2 kg aluminum container has been made.

The measurements of Haymes were carried out at 41° N while those of Williams and Bostrom were made at 40° N and 43° N at an altitude of 1000 km. Haymes detects neutrons with energies above 1 Mev, while the efficiency of Williams and Bostrom's detector peaks at $\sim 3 \text{ Mev}$ and falls by about a factor of 4 where Lingenfelter predicts a peak albedo flux at $\sim 200 \text{ Kev}$. Since $\sim 30\%$ of the albedo neutrons are above 1 Mev for Lingenfelter's spectrum, this means that Williams and Bostrom are looking primarily at neutrons above 1 Mev. Thus, one can roughly compare the two measurements. The flux measured by Williams and Bostrom is 7 times that measured by Haymes near the top of the atmosphere (3.5 mb pressure) and, indeed, even ~ 2 times that

measured by Haymes at the Pfozter maximum. Both of these statements are equivalent to saying that the flux at a distance from the source is greater than the flux very near the source. Thus, one is lead to believe that the measurements of Williams and Bostrum are seriously contaminated by locally-produced neutrons.

Recently, Miles (1964) has reported measurements of the slow neutron density in the atmosphere at 41° N using ionization chambers filled with $B^{10}F_3$ and $B^{11}F_3$. The difference in the response of the ionization chambers filled with the two gases is directly related to the slow neutron density. This experiment is different than other measurements in that (1) the detectors are much larger and, hence, the counting rate is much larger. Thus, the difference in the two counting rates has greater statistical significance. (2) The total weight of the balloon payloads was 6 kg, as compared to at least 50 kg payloads launched by other workers. This reduction in weight should decrease the effects of local production and moderation of neutrons.

Miles' results show that the slow-neutron density in the atmosphere has the same variation with altitude as Lingenfelter calculates, but that Lingenfelter's density is 50% larger than that measured. This comes about because Lingenfelter used the density measurements of Hess et al., (1959) as one of his sources of absolute normalization. These neutron density measurements were made at 44° N at a pressure altitude of 200 g/cm^2 in a B-36 airplane and are

~60% higher than the measurements of Miles. It is quite possible that neutron moderation in the airplane is responsible for the higher neutron densities of Hess et al. (Miles, 1964). Thus, it appears that the absolute normalization of Lingenfelter's spectrum may be in error at higher latitudes. A correction of 50% applied to Lingenfelter's calculated flux at 40° N bring his flux to $.21 \pm .04$ n/cm² sec, in good agreement with the present measurements of $.19 \pm .06$ n/cm² sec.

CONCLUSIONS

The present experiment has measured the earth's integrated neutron albedo at 300 km as a function of latitude. The results of the three flights of the experiment, as shown in Fig. 8 and Fig. 9, are consistent and show a mean neutron albedo flux varying from $.085 \pm .03$ n/cm² sec near the equator to $.24 \pm .06$ n/cm² sec near the magnetic poles.

Near the equator these measurements are in good agreement with the calculations of Lingenfelter (1963) and the rocket measurements of Bame et al. (1960, 1963). At higher latitudes the present measurements fall well below the calculations of Lingenfelter, but recent measurements by Miles (1964) show that the measurements which Lingenfelter used for his absolute normalization at 44° N are in error by $\sim 50\%$. If this correction is applied to Lingenfelter's flux at middle latitudes, good agreement is found with the present measurements. Two earlier measurements of the neutron albedo (Albert, Gilbert and Hess, 1962; Williams and Bostrom, 1964) which disagreed markedly with the present measurements are now known to be seriously contaminated with locally-produced neutrons.

In summary, there is now some agreement between measurement and calculation of the earth's neutron albedo, but there still exist sizable uncertainties in this flux and its latitudinal and longitudinal variations. These

uncertainties can be removed if more efficient neutron detection systems, such as the new He^3 proportional counters, are used, and if the neutron detectors can be well separated from the mass of the main satellite or rocket, so as to reduce the effects of local production of neutrons. It is apparent that any neutron albedo experiment must provide for the experimental separation of the albedo neutrons from those produced in the detector assembly by the cosmic radiation.

BIBLIOGRAPHY

- Albert, R. D., C. Gilbert and W. N. Hess (abstract)
J. Geophys. Research 67, 3537, 1962.
- Bame, S. J., R. W. David, J. P. Glore, and F. B. Brumley,
Bull. Am. Phys. Soc., (2), 5, 360, 1960.
- Bame, S. J., J. P. Conner, F. B. Brumley, R. L. Hostetter
 and A. C. Green, J. Geophys. Research, 68, 1221, 1963.
- Chen, F. F., C. P. Leavitt and A. M. Shapiro, Phys. Rev.,
99, 871, 1955.
- Dostrovsky, I., P. Rabinowitz, and R. Bivins, Phys. Rev.,
111, 1659, 1958.
- "General Electric Transistor Manual", Fourth Edition,
 Edited by the Semiconductor Products Dept.,
 General Electric Company, Syracuse, New York, 1960.
- Graveson, R. T., and H. Sadowski, I. R. E. Trans. on
Nuc. Sci., 5, 179, 1958.
- Hanson, A. O., and J. L. McKibben, Phys. Rev., 72, 673,
 1947.
- Haymes, R. C., Phys. Rev., 116, 1231, 1959.
- Haymes, R. C., J. Geophys. Research, 69, 841, 1964.
- Hess, W. N., J. Geophys. Research, 68, 667, 1963.
- Hess, W. N., E. H. Canfield, and R. E. Lingenfelter,
J. Geophys. Research, 66, 665, 1961.
- Hess, W. N., H. W. Patterson, R. Wallace and E. L. Chupp,
Phys. Rev., 116, 445, 1959.

- Hess, W. N., and A. J. Starnes, Phys. Rev. Letters, 5, 48, 1960.
- Lang, J. M. B., and K. J. LeCouteur, Proc. Phys. Soc. (London), A67, 586, 1954.
- Lange, O. H. and R. J. Stein, "Advances in Space Science and Technology", Supplement 1, Space Carrier Vehicles, p. 22, Academic Press, New York, 1963.
- Lin, W. C., D. Venkatesan, and J. A. Van Allen, J. Geophys. Research, 68, 4885, 1963.
- Lingenfelter, R. E., J. Geophys. Research, 68, 5633, 1963.
- Lord, J. J. Phys. Rev., 81, 901, 1951.
- Marion, J. B., and J. L. Fowler, "Fast Neutron Physics, Part I", Interscience Publishers, New York, 1960.
- Metropolis, N., R. Bivins, M. Storm, A. Turkevich, J. M. Miller, and G. Friedlander, Phys. Rev., 110, 185, 1958.
- Miles, R. F., J. Geophys. Research, 69, 1277, 1964.
- Newkirk, L. L., J. Geophys. Research, 68, 1825, 1963.
- Pieper, G. F., J. Geophys. Research, 68, 651, 1963.
- Simpson, J. A., Phys. Rev., 83, 1175, 1951.
- Singer, S. F., Phys. Rev. Letters, 3, 188, 1959.
- Smith, R. V., L. F. Chase, W. L. Imhof, J. B. Reagan, and M. Walt, Radiation Measurements with Balloons, ARL-TDR-62-2, 6571 st, Aeronautical Research Lab., Holloman AFB, New Mexico, 1961.
- Soberman, R. K., Phys. Rev., 102, 1399, 1956.
- Williams, D. J., and C. O. Bostrom, J. Geophys. Research, 69, 377, 1964.
- Williams, R. W., Phys. Rev., 98, 1393, 1955.

APPENDIX I

ELECTRONICS

1. Low Voltage dc-dc Converter. Fig. 10 shows the schematic for the low voltage dc-dc converter, and Table 6 lists the values for the components. This unit was designed specifically for this application by Anders Electronics, Inc., Needham, Massachusetts. It converts the regulated 28 volts supplied by the satellite to the 12 volts for which the electronics were designed. The efficiency of this unit is $\sim 72\%$ at a load of 2.6 watts.

Table 6

Component Values for the Low Voltage dc-dc Converter

R1, R6	1 K, 1/2 w	C1, C2	2.2 μ f, 35 V
R2, R5	470 , 1/2 w	C3, C4	100 μ f, 20 V
R3, R4	3.3 K, 1/2 w	C5	10 μ f, 35 V
R7	1 , 5 w	D1, D2	1N1695
R8	5 , 1 w	D3, D4	1N1692
Q1, Q2	CTP 1730	T1	UNT-1001

2. High Voltage dc-dc Converter. Figs. 11 and 12 show the high voltage power supply and the associated filter and decoupling circuitry. Table 7 lists the component

LOW VOLTAGE DC-DC CONVERTER
FIG. 10

FILTER AND DECOUPLING CKTS

FIG. 12

values. The basic 28 volts is converted to a 56-volt, 2 kc square wave, stepped up by the transformer to ~ 1500 volts, doubled and rectified, presenting ~ 2650 volts dc to the regulating and filter circuits. Primary regulation is provided by a Victoreen GV4S Corotron at the selected voltage. The high voltage is regulated to ± 5 volts over a temperature range of -30°C to $+75^{\circ}\text{C}$ and at an input voltage of 28 ± 3 volts. The overall efficiency of the unit was increased to $\sim 65\%$ by including a low voltage secondary to properly load the transformer.

Table 7

A. Component Values for the High Voltage DC-DC Converter

R1	10, 1/2 w	C1, C2	10 μf , 35 V
R2	47 K, 1/2 w	C3, C4	.03 μf , 3 KV
R3, R4	5.6 M, 1/2 w	C5, C6	.01 μf , 3 KV
R5	400 M, 3 KV	C7	0.1 μf , 100 V
R6	22, 1/2 w	C8, C9	150 μf , 15 V
R7	10, 1/2 w	D1, D2	1N2379
Q1, Q2	2N1233	D3, D6	1N646
T1	Rayco 0-3809B	V2	1N759A
V1	GV4S		

B. Component Values for the Filter and Decoupling Circuitry

R1	22 M, 1/2 w	C1	.01 μ f, 3 KV
R2	100 K, 1/2 w	C2	150 pf, 3 KV
R3	1 M, 1/2 w	C3	.001 μ f, 3 KV

3. Linear Amplifier. Fig. 13 shows the schematic of the amplifier and Table 8 lists the component values. This circuit is a modification of a circuit designed by Graveson and Sadowski (1958). The input emitter follower provides a high impedance to the counting tube and low impedance to the main amplifier input. Succeeding amplifier stages are each buffered by emitter follower stages to isolate amplifier input capacitance from the load of the previous stages. DC current feedback is used in each amplifier stage to stabilize the operating point as a function of temperature. Heavy ac current feedback is used to stabilize the ac gain, reduce the input time constant and improve the rise-time capability of each stage. The ac gain of ~ 600 is stable to 10% over the temperature range -30° C to $+75^{\circ}$ C.

4. The Pulse Discriminator. The discriminator is shown in Fig. 14 and the components are listed in Table 9. This circuit is a temperature-compensated, monostable multivibrator followed by an emitter follower for isolation and drive. It is a modification of a circuit given in the

THE LINEAR AMPLIFIER

FIG. 13

Table 8

Component Values for the Amplifier

R1	560 K	R17, R31	1.5 K
R2	470 K	R18, R32	6.8 K
R3, R11, R25, R44	10 K	R34	47 K
R4	100 K	R36 + R37	600
R5	470	R38	5.6 K
R6, R20	33 K	R42	680
R7, R21, R40	22 K	R43	3.3 K
R8, R22	1 K	C1	.01 μ f
R9, R23	330	C2	.1 μ f
R10, R24	4.7 K	C3	.5 μ f
R12, R19, R26, R33	10	C4	15 μ f
R13, R27, R35, R39	39 K	C5	6.8 μ f
R14, R28	15 K	Q1	2N417
R15, R29, R41	2.7 K	Q2-Q12	2N247
R16, R30	390

PULSE DISCRIMINATOR FIG. 14

General Electric Transistor Manual, Fourth Edition, 1960.

Table 9

Component Values for the Pulse Discriminator

R1, R3, R11	22 K	R13	1 K
R2, R4, R5	2.2 K	C1	.001 μ f
R6	18 K	C2	200 pf
R7	33 K	C3	56 pf
R8	2 K	C4, C5, C6	.01 μ f
R9	100	D1-D4	1N100
R10	3.3 K	Q1-Q3	2N396
R11	15 K		

5. The Binary Scaler. Fig. 15 shows the basic scaler and Table 10 gives the component values. Q1 functions as a switch, providing a negative pulse to the scaler, if a positive pulse must be counted. The scalers are stacked to provide the total scaling factor necessary. Each stage is capable of counting at 1 megacycle rates with a power dissipation of 12 mw.

BINARY SCALER
FIG. 15

Table 10

Component Values for the Binary Scaler

R1	12 K	R9	2.7 K
R2	100 K	C1-C4	56 pf
R3, R4	10 K	C5	.001 μ f
R5, R6	56 K	D1-D3	1N100
R7, R8	27 K	Q1-Q3	2N338

6. Coincidence Circuit and Blanking Univibrator.

Fig. 16 shows the coincidence circuit and blanking univibrators, and Table 11 gives the component values. The coincidence circuit is composed of two transistors with emitters and collectors common. Both transistors are normally turned on, and both must be turned off by pulses, if the common collector is to return to -12 volts and thus produce an output pulse. This pulse is then used to feed the scaling circuits and to trigger a univibrator. The time constants of the univibrator are chosen to produce a 100 μ sec negative pulse. Q5 is used as an emitter follower to apply this blanking pulse to the anticoincidence circuit.

COINCIDENCE CKT AND BLANKING UNIVIBRATOR

FIG. 16

Table 11

Component Values for the Coincidence Circuit and
The Blanking Univibrator

R1, R3	22 K	C3	500 pf
R2	2.2 K	C4	.011 μ f
R4, R6	6.8 K	C5	50 pf
R7	470	C6	.001 μ f
R8	39 K	D1, D2	1N100
R9	5.6 K	Q1, Q2	2N397
R10	8.2 K	Q3, Q4	2N338
C1, C2	.01 μ f	Q5	2N396

7. Anticoincidence and Output Circuits. Fig. 17 shows the anticoincidence circuit and the output circuit, and Table 12 gives the component values. Anticoincidence operation is obtained by the biasing of diode D1. Normally D1 is forward biased and a positive pulse from the neutron discriminator is passed to the scalers and counted. Q1 is used as an emitter follower, coupling the blanking pulse to the diode D1. In the presence of this blanking pulse D1 is back biased and will not pass the pulse from the neutron discriminator to the scalers.

ANTICOINCIDENCE CKT

OUTPUT CKT

FIG. 17

The satellite telemetry requires that signals be presented to it from a resistive source of a few thousand ohms, and that these signals shall not exceed 5 volts. Q2 and Q3 operate as a Darlington pair to isolate the scalers from the output load. R6 and R7 are a voltage divider to ensure that the output signal never exceeds 5 volts.

Table 12

Component Values for the Anticoincidence
And Output Circuits

R1	22 K	R8	1.2 K
R2	470 K	C1	100 pf
R3	10 K	C2	470 pf
R4, R6	5.6 K	C3	56 pf
R5	8.2 K	Q1	2N1254
R7	4.3 K	Q2, Q3	2N338

APPENDIX II

CALIBRATION OF THE CHARGED PARTICLE DETECTOR

The response of the cosmic-ray module to electrons is plotted in Fig. 18. The package was irradiated on different sides with $1 \text{ Mev} \lesssim E_e \lesssim 3 \text{ Mev}$ using a type K Van de Graaff accelerator. Since the actual flux of electrons on the package was a function of energy because of the beam sweeping arrangement, the average response was normalized to the counting rate observed above 2.5 Mev. This response is primarily due to accidental coincidence from bremsstrahlung. In the calibration the electron flux was measured and thus the product of the efficiency and geometrical factor for electrons $(\epsilon G)_e$, was determined to be 10^{-3} cm^2 , since

$$R = \epsilon G J \quad (2)$$

In Eqn. (2) R is the observed counting rate, ϵ is the efficiency for the radiation observed, G is the geometrical factor in cm^2 , and J is the omnidirectional flux through a sphere of unit cross section. Thus, for electrons

$$J(E_e > 1.5 \text{ Mev}) = 10^3 R \text{ electrons/cm}^2 \text{ sec} \quad (3)$$

where R is the coincidence counting rate.

The relative response of the coincidence detector for protons with $0 < E_p \lesssim 160 \text{ Mev}$ is shown in Fig. 19. The response is essentially zero below 50 Mev and is constant for proton energies greater than 80 Mev. We consider the

ELECTRON CALIBRATION
FIG. 18

PROTON CALIBRATION
FIG. 19

threshold to be 75 Mev where the response has decreased by 50%. The flux used was so small that reliable flux measurements could not be made. Thus, the geometrical factor must be determined by flight calibration using the known cosmic-ray flux at the equator. We estimate the primary flux at the equator to be 2×10^{-2} particles/cm² sec. ster. If we include a correction for the primary omnidirection albedo flux, which is about 50% at 200 km (Singer, 1958), the flux is 3×10^{-2} particles/cm² sec. ster. Using this figure we calculate

$$J(E_p > 75 \text{ Mev}) = 6R (\pm 50\%) \frac{\text{protons}}{\text{cm}^2 \text{ sec}} \quad (4)$$

where R is the true coincidence rate of the detector and J is the omnidirectional flux.

One must also consider the possibility that the observed counting rate is due to chance coincidence from an exceedingly high counting rate in the banks of counters. We estimate the threshold proton energy for penetration to a counter is $50 < E_p < 55$ Mev, and the geometrical factor is $\sim 7 \text{ cm}^2$. Therefore,

$$J(75 \geq E_p \geq 50 \text{ Mev}) = 65 R_c \frac{\text{protons}}{\text{cm}^2 \text{ sec}} \quad (5)$$

APPENDIX III

CALCULATION OF NEUTRON PRODUCTION

1. From geometry and known omnidirectional primary cosmic-ray fluxes, we can calculate the number of protons incident per second on the object of interest. This will be given by the product of the omnidirectional flux and the geometrical factor.

2. Find the mean path length seen by the protons by calculating the mean path (averaged over all angles of incidence) at representative points of incidence and then averaging these values. From this and published cross sections (Chen et al., 1955; and Williams, 1955) we calculate the probability of interaction. This gives the number of primary interactions per second.

3. Using mean primary proton energies of 20 Bev at the equator and 2 Bev at high latitudes, the Monte Carlo calculations of Metropolis et al. (1958) can be used to predict a mean excitation energy of the residual nucleus and the number of fast cascade particles as a result of the interaction. Calculations 2 and 3 can be done for the nuclei in the fast cascade, giving the mean excitation energy of the residual nuclei due to secondary interactions, etc.

4. These mean excitation energies can now be used with the Monte Carlo calculations of Dostrovsky et al. (1958) to predict the mean number of neutrons evaporated per interaction and the nuclear temperature. The work of

Lang and LeCouteur (1954) is informative here also, especially as concerns the energy spectra of the emitted-particles.

5. Thus, the number of neutrons produced per second is known. It is then a matter of geometry to calculate the fraction of these neutrons which enter the solid angle subtended by the moderator, thus giving the flux incident. In the case of the moderator and the detectors themselves, we estimate that the response is equivalent to 67% of the evaporation neutrons incident on the moderator.

6. However, these neutrons have a certain energy distribution with a mean energy of several Mev, and the present detector's efficiency for Lingenfelter's spectrum corresponds to considerably lower energies. Folding the detector efficiency into the evaporation neutron spectrum, we arrive at the final estimate of the effect of local production of neutrons.

In carrying out these calculations, the published information has been interpolated and extrapolated to values appropriate for the target nucleus and bombarding energy necessary here.

The cascade nucleons are assumed to have the same direction as the incident nucleon, but the evaporated neutrons are assumed to be emitted isotropically. Also, the primary cosmic radiation is considered to consist of protons only, with omnidirectional fluxes of $0.2 \text{ cm}^2 \text{ sec}$ at the equator and $2/\text{cm}^2 \text{ sec}$ at high latitudes. This is

consistent with the measurements of Albert, Gilbert and Hess (1962), who used a large scintillator which responded to protons with energies greater than about 40 Mev and electrons greater than about 8 Mev. It is also consistent with the charged-particle latitude variation measured by this experiment. It differs from the result of Lin, Venkatesan and Van Allen (1963) at lower latitudes, presumably because of the lower energy, charged-particle albedo which they can detect. This albedo is not an appreciable neutron production source here.

APPENDIX IV

CHARGED PARTICLE MEASUREMENTS

The solid curves on Fig. 20 represent the published data on electron flux measurements from Injun, Traac and Telstar satellites (Hess, 1963) in the two weeks after the Starfish explosion. Most of the data at larger B values are from the Traac satellite detector which has an electron threshold of 1.6 Mev (Pieper, 1963), quite similar to this experiment. The triangles represent electron flux measurements from this experiment and are deduced in the following manner. For the normal cosmic radiation we observe a ratio varying from 2.5 to 4 between the counting rates of the charged-particle and the BF_3 detectors near the equator. In the presence of electrons, $E_e > 1.5$ Mev, this ratio will increase, since the thresholds for photo-production of neutrons are in general > 10 Mev and cross sections are small.

In the region shown, ratios are commonly found which are greater than 10 and at times as high as 24. The excess charged particle counting rate is identified as electrons and converted to flux by Eqn. (3). These values are probably not good to better than a factor of 4. The variability of this electron leakage from trapped regions is apparent in all the data available for July. Actually, at L values less than $1.5 R_e$, electron fluxes have been observed as high as several thousand electrons/cm² sec at

ELECTRONS AFTER THE STARFISH EXPLOSION
FIG. 20

B values $\sim .4$ gauss during disturbed periods in July.

In a similar manner, the presence of protons with energies less than 50 Mev and greater than a few Mev manifests itself with reduced ratios between the counting rate of charged particle and the BF_3 detectors. Protons, $E_p > 50$ Mev, and electrons, $E_e > 1.5$ Mev, will offset this effect, so the picture is complicated. However, we are able in several instances to identify the effects of protons clearly. One example of such an event was recorded beginning at 1220 UT, July 22. The satellite was over the South Pacific at 350 km, $L \sim 5$, $\lambda \sim 60^\circ$ S and moving towards the equator. The charged particle counting rate abruptly increased by a factor of ~ 10 and the gated neutron rate increased by a factor of ~ 80 , probably due to evaporation neutrons produced in the detector module and on the vehicle.

Table 13 lists 8 events which were recorded where the counting rate in the detectors abruptly increased to many times the expected values. The factor by which the charged particle counting rate increased and the resulting ratio between the charged particle and gated neutron responses is given, as well as the ephemeris data, including the L parameters, geomagnetic position and altitude. Event A can definitely be ascribed to electrons, since the charged particle response increased by a factor of 8 while the neutron response remained essentially the same. Events

Table 13

EXAMPLES OF CHARGED PARTICLE ENHANCEMENTS

	Date	Time UT	Charged Particles	Ratio*	Ephemeris
A	7/21	0102-0108	X8	27	1.6-1.1 Re 38N-17N 57W-44W 211-205 Km
B	7/21	2103-2108	X10	7	3.8-8 Re 60S-72S 50E-67E 320-345 Km
C	7/22	1221-1232	X10	1	4-1.1 Re 57S-4S 56W-40W 370-388 Km
D	7/22	2148-2152	X10	4	1.4-2.1 Re 27N-41N 163W-156W 344-324 Km
E	7/23	1230-1240	X30	5-1.3	1.6-1.07 Re 33S-2N 50W-44W 389-385 Km
F	7/23	2052-2100	X20	3	1.7-1.1 Re 36N-7N 4E-12E 206-214 Km
G	7/24	1230-1242	X30	4	3.8-1.1 Re 57S-12S 64W-51W 376-388 Km
H	7/25	1105-1118	X6	2	3.9-1.1 Re 57S-9S 52W-34W 373-386 Km

* The ratio in column 4 refers to the ratio between the charged-particle and gated-neutron counting rates during the event.

C and E must have included large numbers of protons to account for the large increase in the neutron response, i.e., by a factor of 40 to 50 times, while the charged particle response increased by a smaller factor. The remaining events are consistent, with both electrons and protons being present. The events are of very short duration, since in several instances the vehicle traversed the same L region on the other side of the equator just a few minutes later and saw no effect whatsoever. The cause of this dumping from trapping regions is unknown, since we have not been able to find any solar or geomagnetic disturbances to account for this. Indeed, this entire period was a time of remarkably quiet solar activity.

Table 14 shows the data from the real time acquisitions at Thule, Greenland. For these data, L ranges from ~ 20 to 35 and back to ~ 20 , indicating that we are looking at radiation on field lines beyond the Van Allen belts. The counting rates from both the charged particle and gated neutron channels are shown. The charged particle response for orbit 25 is a factor of 2 above our earlier measurements and the neutron response is up by greater than a factor of 3, and hence the ratio is somewhat low. In the other instances, the charged particle response is quite variable, even though the standard deviations range from 3%-6%. It should be noted that the neutron response (~ 10 -15%) is far less variable and does not always appear to be correlated with the charged particle response. The

Table 14

REAL TIME ACQUISITIONS - THULE

Orbit	Universal Time	Local Time	Charged Particles counts/sec	Gated Neutrons counts/sec	Ratio
09	1418-1421	0915-1118	1.7	.38	4.4
11	1720-1725	0956-1337	2.6	.38	6.9
25	1425-1429	0913-1205	.82	.26	3.1
41	1432-1436	0917-1116	1.37	.39	3.5
42	1602-1608	0902-1320	1.71	.37	4.6
56	1306-1311	0803-1123	2.84	.29	9.8
57	1438-1442	0931-1150	2.56	.22*	12.6
58	1603-1614	1117-1246	2.77	.45*	6.3

asterisks after the counting rates for orbits 57 and 58 indicate that the response was variable to the extent of a factor of 2 during the passes. We mention this not only because it indicates that protons were coming in at the poles, but that the observed variations are consistent only if (1) there are electrons with $E > 1.5$ Mev at this time also, and/or (2) there is a modulation such that lower energy protons are not able to come in. The presence of protons just above threshold will result in an increased ratio, since they will be efficiently detected but will not produce as many neutrons as the normal cosmic radiation. This is especially so for orbits 56 and 57.

A different type of example can be demonstrated with data recorded over North America. Fig. 21 shows the charged particle data for two passes over Alaska at 310 km. Fig. 22 shows the corresponding gated neutron data. It is apparent that the difference between the charged particle data must be due mainly to electrons, since there is no correspondence between the charged particle counting rates and the neutron counting rates, but there are also protons present, since the neutron flux is 3 to 7 times that measured in the Pacific regions or that measured before the Starfish explosion. Fig. 23 shows the low altitude passes at the same station, and again, the neutron enhancement in the region $L \sim 3$ to 5 is evident. Data recorded in the same L region over the eastern United States show the same

CHARGED PARTICLES OVER ALASKA
FIG. 21

effect. Thus, one must conclude that protons with energies of at least a few Mev were in the region $L \sim 3-5 R_e$ in July, and they had pitch angle distributions such that some were mirroring below 200 km. This latter situation did not exist prior to the Starfish explosion.

Thus, one can summarize the charged particle measurements in July 1962.

1. Not only has the well-documented, large radial extension of electrons, as a result of the Starfish explosion, been observed, but we have also shown that protons in the region $L \sim 3-5$ were mirroring down to at least 200 km. This is a change from conditions prior to Starfish and implies the addition of large numbers of protons to the region or acceleration of the known population.

2. Leakage from the main artificial belt is commonly observed and found to be erratic.

3. Several instances of enhancement or dumping of charged particles, electrons and/or protons, have been observed. They are not apparently associated with obvious solar or geomagnetic events.

At this point, one can appreciate the difficulty in obtaining legitimate neutron albedo measurements in July, 1962. In general, the data are rejected if the charged particle to gated neutron ratio is too low or if the charged particle response is 50% greater than that expected from the galactic cosmic radiation. This obviously removes all data acquired over the Americas and the Atlantic regions.