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STUDY OF PROTON RADIATION EFFECTS ON SOLAR VEHICLE ELECTRONIC SYSTEMS

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STUDY OF PROTON RADIATION EFFECTS ON SOLAR VEHICLE ELECTRONIC SYSTEMS

By

Donald C. Latham

Richard J. Allen

Frank Phalen

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MARTIN MARTIN MARIETTA
ELECTRONIC SYSTEMS & PRODUCTS DIVISION Baltimore 3, Maryland

CONTENTS

I. INTRODUCTION

This report, a verbatim portion* of one volume of the Solar Probe final report (Engineering Report 13110-V) that was prepared by Martin's Space Programs Division under contract to NASA-Ames, comprises the radiation effects study as prepared by the Electronic Systems & Products Division of the Martin Company. The solar probe is designed to withstand the effects of solar radiation for one year on a mission carrying it to within 0.3 au of the sun.

The work to be accomplished under the contract was a four-month design study of a solar probe spacecraft; this effort included design of scientific experiments; mission analysis; spacecraft design, including power, subsystems, stabilization and control, communications and data handling, and structure and thermal control; ground support equipment; and reliability assurance, including radiation effects on all systems from both a nuclear power source and the natural environment.

The analysis presented in this report is concerned with radiation effects on the spacecraft electronic equipment. Consideration also was given to the problem of using a nuclear-fueled power supply as opposed to solar panels. The report gives shielding requirements and component selection criteria based on the estimated environment for the mission.

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* Chapter II of this report is Chapter IV of Volume V of the Solar Probe Report. References herein refer to other Chapters and Volumes of the Solar Probe Report.

II. TECHNICAL DISCUSSION

A. DESCRIPTION OF RECOMMENDATIONS

1. Class 4, 0.3-AU Mission

a. Requirements

It is required that all electronic equipment operate in both the natural and induced radiation environment encountered by the spacecraft during the 0.3-AU mission. Operation shall be for the intended one-year duration with a reliability that is compatible with that of the spacecraft, independent of radiation damage considerations. The case of the spacecraft design, which utilizes a nuclear power supply in place of a solar cell power supply, shall be included within the scope of the study.

b. Design philosophy

The approach has been to identify and evaluate the significant sources of radiation that represent a damage threat to the electronic components. The different types of radiation were reduced to an equivalent flux of one type (fission neutrons) to permit combining them additively for comparison with existing radiation damage test data on representative electronic components. Tradeoff studies were made of the degree of protection or increase in allowable dosages that could reasonably be obtained by component selection, component location, and circuit design techniques with a resulting savings in shielding weight. Recommended shielding thicknesses and materials were selected to bridge the gap between the allowable dosages and the predicted flux levels after the first three methods were fully exploited. The philosophy has been to add a shield as required to reduce the radiation intensity from the nuclear power supply, when it is used, and require no changes in other shields that are used for protection from external radiation. This, in effect, provides an added safety factor for increased reliability when the nuclear power supply is not used. Radiation damage to solar cells was studied as part of the solar cell power supply design, and is reported in Vol. IV, Chapter IV of this report.

Detail consideration of the effects that the neutron radiation from the nuclear power supply may have on the scientific experiments was not included in the radiation damage study. This must be the subject of a special design study to coordinate the necessary shielding requirements with the design of scientific experimental equipment that will be susceptible to the increased level of neutron background intensity.

c. Description of equipments

Minimum shielding recommendations are presented for protection against solar flare proton radiation and neutron radiation from the nuclear power supply. A shielding of 0.044-in. thick aluminum is recommended for complete enclosure of electronic components, or at least for all transistors and diodes and any IR detectors or thermistors that may be used. This is about the same thickness of typical electronic equipment cases necessary for the equipment to withstand the environment of launch preparations and the powered flight phase and therefore should not impose any serious weight penalty.

A shielding of 2.5-in. thick polyethylene is recommended in conjunction with a minimum separation of 30 in. between the electronic equipment and the core of a nuclear power supply. A smaller separation distance can be allowed for the few hours that will elapse between fueling of the power supply before launch and deployment of the satellite mechanisms.

Restrictions are placed on the selection of components, particularly transistors, to allow the use of only those having the highest radiation resistance. The selection of transistors is limited to the general classes of medium and high frequency germanium and high frequency silicon, and of these, only transistors that have been determined by tests to be capable of withstanding integrated flux values of at least 5×10^{12} neutrons/sq cm with failure rates not exceeding 0.01% can be used.

Demands are placed on circuit designs to provide reliable operation with decreased transistor common emitter current gain (β) to as low as 70% of the preirradiated value and similar degradation in other transistor parameters. Demands are placed on judicious placement of the above mentioned sensitive components to take advantage of the shielding effect from other components and materials to achieve a 50% reduction in the solar proton flux from this inherent shielding alone.

2. Changes for the Mission Away from the Sun

No changes are required from the standpoint of the radiation damage considerations. The predicted solar flare proton flux would be reduced by a factor greater than three, which would allow a sizable reduction in the thickness of the aluminum shielding or a relaxation in the selection criteria for transistors.

B. SUMMARY OF RADIATION DAMAGE STUDY

The only significant sources of radiation that threaten to cause damage to electronic components are the solar flare protons, with a predicted integrated flux of 1.27×10^{12} protons/sq cm, and the neutron radiation from a nuclear power supply, with a predicted integrated flux of 7.5×10^{12} neutrons/sq cm. The proton flux has been expressed in terms of an equivalent neutron flux using a proton-neutron damage equivalence of 6 for a total combined equivalent neutron radiation environment of 1.51×10^{13} neutrons/sq cm when the nuclear power supply is used. The maximum equivalent integrated flux that can be allowed for transistors to be used and still obtain the required component reliability is a flux of 5×10^{12} neutrons/sq cm. The total incident flux on the transistors is to be reduced to this equivalent flux by the use of 0.044-in. thick aluminum shielding, effective against the proton flux, and a 2.5-in. thick polyethylene shield, effective against the neutron flux.

Other demands are placed on the design of the electronic equipment in the areas of component selection, placement of susceptible components, and circuit design requirements.

Basic radiation damage mechanisms have been summarized, and consideration has been given to the implications of the possible use of advanced circuit fabrication techniques, such as hybrid circuits, integrated circuits, and radiation-hardened circuits. The objectives of a radiation test program necessary to support the Solar Probe design have been outlined.

As a cross-check of the feasibility of the Solar Probe to survive the solar flare proton environment, a comparison has been made with the integrated proton flux that some successful earth-orbiting satellites have encountered in the inner Van Allen belt.

Vanguard I has survived approximately 2 times the predicted solar probe flux. Telstar I experienced approximately 1/3 the proton flux predicted for the Solar Probe, in addition to an electron flux with a computed dosage of 600 rad/hr. The Telstar I electronics survived 7-1/2 mo., and eventual failure was attributed to the electron dosage, rather than the protons.

The references listed with this section of the final report were all used in the preparation of the radiation effects discussion and damage information.

C. DISCUSSION OF RADIATION ANALYSIS STUDIES AND RESULTS

1. Radiation Environment

The most significant external contribution to the radiation environment is the solar proton radiation that occurs at the time of major solar flares. The solar flare model that was recently directed by NASA/ARC (Ref. IV-1) for the Solar Probe was adopted as the basis of this study. The differential energy spectrum for this model is defined by the following relationships:

$$dN = 2.43 \times 10^{12} E^{-2} dE \qquad \text{for } E < 50$$

$$dN = 3.03 \times 10^{17} E^{-5} dE \qquad \text{for } E > 50$$

where

N = isotropic flux in protons/sq cm-yr at 1 AU

E = proton energy in mev.

Chapter II contains further discussion on the Ames model. The variations of the proton flux for distances closer to the sun were treated according to a $1/R^2$ relationship, where R is the distance between the sun and the spacecraft in astronomical units. The total integrated proton flux computed from the above relationships was multiplied by a time-averaged $1/R^2$ factor, which is 2.83 for the 0.3-AU mission trajectory. The result of these computations is a prediction of the total integrated solar proton flux during a one-year solar probe mission coinciding with a solar cycle maximum. The predicted total integrated flux is 1.27×10^{12} protons/sq cm-yr, for all energy levels above 5 mev. Energy levels below 5 mev have not been considered further, because the penetration range of 5-mev protons is only 0.05 gm/sq cm (corresponding to approximately 0. 007 in. aluminum), which is much less than the recommended minimum shielding thickness.

Radiation from the curium 244 nuclear power supply considered as a possible alternative to the solar cell power supply has been defined as the neutron and gamma fluxes listed below. The flux experienced by the electronic components is a function of the inverse square of the distance from the source, which is considered to be the center of the power supply package. The configuration of the spacecraft with the nuclear power supply will provide a separation of at least 30 in. except for a few hours during launch preparations and flight prior to deployment of the spacecraft mechanisms. Therefore, a 30-in. separation has been assumed in computing the following maximum flux levels that would be experienced by the electronic components in the absence of any shielding:

Type	Flux at 1 Meter From Source	Total Flux per Year at 30-in. Separation
Neutron	14×10^4 neutrons/sq cm-sec	7.5×10^{12} neutrons/sq cm
Gamma	4×10^{-1} rad/hr	6×10^3 rad

The energy spectrum of the neutron radiation is very close to a fission spectrum.

Other sources of radiation listed below are considered negligible for the reasons given:

(1) Secondary protons, neutrons and gamma radiation resulting from the primary solar protons are negligible, because they are present in such small intensities. Their flux levels are at least two orders of magnitude below that of the primary protons that penetrate the shielding, as will be discussed in connection with the shielding studies.

(2) Protons and electrons encountered while traversing the Van Allen belts and their secondary radiation are negligible because of the short time spent in the belts, and the fact that the shielding provided for solar proton protection will be more than adequate protection from the high intensity, low energy electrons.

(3) Cosmic radiation, consisting mostly of protons, is neglected because of the very low flux and the high energy, having greatly reduced damage effects.

(4) Solar plasma protons and electrons are neglected because of their very low energy levels, peaking at 1 to 2 kev, which are easily shielded.

(5) Solar electromagnetic radiation in the UV, IR, and X-ray spectrum are neglected, because they will be effectively shielded by the heat shield and solar proton shields.

Therefore, the only significant radiation sources remaining are solar flares and the nuclear power supply. From the latter, the gamma radiation can be neglected, because the total gamma flux is below the damage levels of the components likely to be used in the Solar Probe by at least three orders of magnitude.

2. Radiation Damage Mechanisms

At this point it is important to briefly consider some of the basic radiation damage theory in order to better understand the general problem of radiation effects on electronic components and the basis on which comparisons can be made between damage effects of protons and neutrons. A study of the damage mechanisms can shed some light on what effects are produced by the radiation encountered by the electronic equipment in the Solar Probe.

There are three general types of radiation effects on the materials that make up electronic components. These are:

Transient

Displacement

Chemical.

Transient radiation effects are due to excitation (including ionization) and de-excitation of electrons.

Displacement radiation effects are manifestations of atoms displaced from their normal lattice sites in crystalline solids.

Chemical radiation effects are due to molecular rearrangement occurring as a second stage to ionizing interactions.

Transient effects are associated with changes in electron states and thus they usually produce changes in the optical and electrical properties of materials. The perturbations are usually short-lived in most cases. Since relaxation times for electronic changes in most materials are usually very short, the transient effects are primarily a function of the radiation dose rate. They usually disappear after the radiation ceases and, hence, one observes a transient effect only in systems associated with a very rapidly varying flux of radiation such as that associated with a nuclear detonation. For noticeable effects on electronic circuits, dose rates of about 10^4 rad/sec are required. Such dose rates will not be encountered by the Solar Probe, therefore, it is not necessary to consider the transient effects.

Displacement radiation effects usually involve a sequence of events in which a nuclear particle enters the material, making a "collision" with the atomic nucleus and having sufficient energy transfer to cause the atom to be displaced from its normal lattice site. The displaced atom may move through the material, losing its energy through collisions with other atoms and, hence, displacing some of them. This sequence of events will eventually terminate when all the displaced atoms come to rest. The lattice defects may be thermally unstable, even at room temperature, and some of them may anneal. The annealing may eliminate the defect or form a secondary defect. These defects lead to macroscopic changes in the physical properties of the material.

The forms of charged primary radiation, such as protons or high-energy electrons, cause interaction with the atomic nuclei via the Coulomb electrostatic force between the nuclear charges and the charged moving particles. The number of displacements produced is a complicated function of the energy of incident particle which in turn determines a collision cross-section. The collision cross-section diminishes as the energy of the primary particle increases.

Neutrons interact with the nuclear force field and one can usually approximate the interaction as a hard-sphere collision. As with charged particle interactions, neutron interactions are energy-dependent. Neutrons of 1 mev, typical of fast neutrons in a reactor, can produce secondary displacement cascades amounting to hundreds of displaced atoms.

These displacement-induced effects can lead to several observable manifestations. These effects can cause serious, permanent damage to electronic components, resulting in degraded circuit performance, unless adequate precautions are taken. The important results of displacement radiation effects are:

(1) Changes in minority carrier lifetime, carrier mobility, and the effective doping level in semiconductors, primarily due to defect states introduced into the forbidden energy gap.

(2) Changes in mechanical properties causing some materials to weaken structurally or become brittle.

(3) Changes in thermal conductivity of materials due to photon interaction with the lattice defect centers. Silicon appears to be more susceptible to radiation effects than does germanium.

Chemical radiation effects are observed in various gases, liquids and organic solids. These effects usually result in changes in molecular configurations. An example of chemical effects is the radiation damage to teflon, which undergoes a process in which fluorine and other decomposition products are evolved and the polymer chains are broken. Chemical effects are not anticipated as a significant problem with the fluxes to be encountered by the Solar Probe.

3. Radiation Damage Equivalence

It can be assumed that the damage effects of the solar flare proton and power supply neutron radiation sources will be additive and that the combined effect can be evaluated if both types can be expressed in terms of a common equivalent flux, either a neutron or proton flux. It is by necessity that the choice of a common equivalent neutron flux be selected, because large quantities of test data on the effects of neutron radiation on electronic components is available compared to very little data on proton radiation effects. What little proton damage testing has been done has all been conducted at discrete energy levels, which cannot be considered representative of the energy spectrum of the solar flare model. On the other hand, most neutron damage testing has been conducted with a fission neutron spectrum, which is characteristic of most test reactors and is representative of the power supply neutron spectrum. Therefore, the fission neutron spectrum will be the basis for the common equivalent flux to be used, and the proton radiation will be expressed in terms of equivalent fission neutron flux.

Recent work (Refs. IV-2, -3 and -4) has established an equivalence, in terms of radiation damage to electronic devices, between various forms of nuclear radiation. The present data allow a correlation of proton, neutron, electron and photon radiation damages in semiconductor devices.

To establish a meaningful correlation criterion, it is necessary to consider:

(1) Particle type (i. e. , proton, neutron, electron, photon).

(2) Energy spectrum.

(3) Particle flux.

(4) Material under consideration.

(5) Time of exposure.

(6) Ambient conditions (temperature, effects of bias voltages, etc.).

It may be possible, in describing the characteristics of radiation for an equivalence of damage associated with ionizing radiation, to combine the first three items into a single quantity which is related to the total energy deposited in the material. Carbon is the standard for correlation of energy-deposited dose with units of ergs/gm.

The primary mechanism that has been investigated for establishment of the damage correlation is the reduction in the minority carrier lifetime associated with the semiconductor material. The governing relation between lifetime and flux is given by:

$$\frac{1}{\tau} = \frac{1}{\tau_0} + \frac{\phi}{K}$$

where

τ = minority carrier lifetime

τ_0 = original minority carrier lifetime

ϕ = particle-integrated flux

K = damage constant associated with a particular particle type, energy spectrum, and material characteristics.

The damage constant is related to impurity doping, natural impurities (such as oxygen), and material structure. These constants have been measured for a variety of devices.

The reduction of minority carrier lifetime results in a measurable loss of transistor forward current gain, beta. Hence, a convenient technique for measurement of bulk radiation effects, to obtain a damage correlation for different forms of nuclear radiation, is to measure transistor beta. In fact it can be shown (Ref. IV-5) that for transistors exposed to neutrons, the change in the inverse gain, $\Delta\left(\frac{1}{\beta}\right)$, is directly proportional to integrated flux, ϕ:

$$\Delta\left(\frac{1}{\beta}\right) = K' W^2 \phi$$

where W is the effective base width and K' is a proportionality constant that describes the relative radiation sensitivity of the device. Effective base width is related to the transistor alpha cutoff frequency, f_α, by

$$f_\alpha = 1.22 \frac{D}{\pi W^2}$$

where D is the diffusion constant of the semiconductor base material. These relations indicate the important relation that base width plays in the radiation tolerance of a transistor.

Further checks on the theory can be made through calculation of the expected defect density caused by dislocation radiation. The relation for defect density as a function of integrated flux is given by

$$N_d = \phi n_0 \sigma_d \gamma$$

where

ϕ = integrated particle flux

n_0 = atomic density (i.e., the number of atoms per unit volume)

σ_d = displacement cross-section and is a function of the incident particle energy, E, and the displacement threshold energy.

γ = average number of displacements, including primary and secondary.

Theoretical checks on the experimental methods agree within reasonable limits.

A summary of the results of the experimental testing and theoretical calculations on a series of transistors and diodes is given in the table below (Ref. IV-3). These are preliminary results but they appear to agree reasonably well with the work of other investigators.

Preliminary Particle Equivalence for Damage in Silicon Transistors and Diodes

Particle	Number of Particles/Sq Cm
10-mev protons	1.0
Moderated reactor spectrum neutrons	4
5-mev electrons	300
Cobalt-60--gamma rays	4000

These data indicate that a value of approximately 4 to 1, for fission neutrons to 10-mev protons, is a reasonable damage equivalence criterion. This number is especially useful since most neutron damage data are given for a reactor neutron spectrum and thus one can attempt to utilize the vast amount of neutron damage available on various transistors. The usefulness of these equivalences for relating the solar flare proton flux to neutron flux is limited by the fact that they apply only to specific energy levels.

With the displacement effects identified as the important damage consideration, attention must be given to this phenomenon in relating proton flux over a wide energy range to an equivalent fission neutron flux. A basis for doing this has been derived theoretically and verified by comparing neutron and discrete energy level proton test data collected on similar transistors (Refs. IV-4 and -6). It must be recognized that the proton-neutron equivalency cannot be precisely determined with the present state of knowledge, but the referenced method is the only one yet advanced that is adaptable to a wide range of energy levels, and it is in reasonably good agreement with equivalent relationships at discrete energy levels advanced by other authors (Refs. IV-2, -3, -5 and -7).

The basis for the equivalency relationship is the rates of lattice displacement production, which are directly related to the damage constants for semiconductor materials under neutron and proton radiation. The ratio of the displacement rates of protons and neutrons is considered a direct measure of the proton-neutron damage equivalent. The displacement rates (number of lattice displacement per centimeter along track of incident particle) are strongly dependent upon energy level and are different for silicon and germanium. For radiation composed of a spectrum of energy levels, an average displacement rate can be computed by adding the contributions made by increments of the energy spectrum, normalized to a unit particle. Average displacement rates have been computed for the fission neutron spectrum and for the solar flare proton spectrum, after shielding with a thickness of 0.3 gm/sq cm aluminum, which is the minimum recommended shielding as discussed later. The average displacement rates for both silicon and germanium and the resulting proton-neutron damage equivalency ratios are given in Table IV-1.

TABLE IV-1

Displacement and Damage Rates for Silicon and Germanium

Material	Damage Rate for Fission Neutrons	Damage Rate for Solar Flare Protons (shielded)	Proton/Neutron Damage Equivalence
Silicon	376 cm^{-1}	1245 cm^{-1}	$\frac{1245}{376} = 3.3$
Germanium	120 cm^{-1}	750 cm^{-1}	$\frac{750}{120} = 6.2$

Since it is expected that both germanium and silicon transistors and diodes will be used, a solar flare proton/fission neutron damage equivalence of 6 is used in this study to cover both types of materials. Using this factor, the total integrated solar flare proton flux expressed in terms of equivalent fission neutron flux is 7.62×10^{12} neutrons/sq cm, which will be shown later to be excessive for reliable operation of most classes of transistors.

4. Circuit Fabrication Techniques

The recommendations in this report have been based on conventional circuit components and fabrication techniques. It is obvious, however, that more sophisticated design, fabrication and packaging techniques may be used for the final construction of the probe. This appears to be very likely based on the weight and space requirements plus the rapid advances made in the field of integrated and hybrid thin-film circuits. This section discusses some of these more advanced methods of circuit fabrication in relation to the solar probe mission.

Methods. Five foreseeable circuit fabrication techniques to be considered for the Solar Probe are:

(1) Conventional semiconductor circuits fabricated on printed circuit boards.

(2) Integrated circuits fabricated almost entirely of semiconductor material (usually silicon). With this method even the resistors and capacitors are formed in the silicon block through diffusing techniques.

(3) Thin film hybrid circuits in which the passive components are metal film devices and the active elements are incorporated on the substrate in the form of semiconductor chips. Another method involves laying the passive film components over a prepared semiconductor substrate that contains the active devices.

(4) All metal film circuits which would utilize metal films, in conjunction with oxides, to form the active device as well as passive components.

(5) Advanced concepts such as TIMM (Thermionic Integrated Micro Module) circuitry. These are all metal and ceramic passive and active components that operate at approximately 600° C and are very radiation resistant.

Effects of fabrication methods on radiation tolerance. It is reasonable to assume that each of the five fabrication methods would yield system configurations whose responses to an identical radiation environment could be quite different. The conventional circuit method has been the subject of the most experimental testing and one can use it as a basis for comparison of the other techniques.

By comparison with conventional printed circuit boards, it appears that the all-semiconductor integrated circuit may well be more sensitive to nuclear radiation. Since even the passive elements are fabricated from semiconductor material and since isolating junctions are used to isolate active devices on the chips, one would expect to see radiation induced leakage current and junction degradation effects lead to circuit performance problems. Integrated circuits, however, lend themselves to space hardware because of their reduced size and weight.

The thin-film hybrid circuits using metal film resistors and capacitors on a glass substrate would probably have better passive component tolerance to radiation than the conventional lumped passive components. The disadvantage is that uncanned transistors, in the form of chips bonded in some fashion to the passive network, are used as the active elements, and thus the inherent shielding of the steel transistor can is lost. For the neutron environments this would not matter, as the can would not stop the primary particles. Due to a complete lack of experimental data on film hybrid circuits, one can only speculate as to their radiation tolerance. It is probably a fair statement, however, that thin-film hybrid circuits will not exhibit much, if any, greater radiation tolerance than conventional, high quality circuitry.

The all metal film circuit involving metal film active devices (if they are ever practically realized) should be extremely tolerant to nuclear radiation effects. This method appears promising enough that NASA Headquarters is funding two contracts for the development of thin-film active devices purely for the expected radiation tolerance of the final circuit configuration. It is too early to speculate if this effort will be successful, and this technique is not yet sufficiently developed to be considered applicable to the Solar Probe.

The final category of system fabrication falls into the area of unconventional devices and, in particular, the TIMM (Thermionic Integrated Micro Module) components. The concept behind the TIMM components is the utilization of the normally generated heat in an electronic circuit to heat a tube cathode to the temperature necessary to maintain electron emission. As a result, these units, including the passive components, operate at 580° C in normal operation. No heaters are required in the devices themselves and thus the units must be packaged to operate in a structure functioning at 580° C utilizing internally generated heat and/or other sources of heat. It has been shown

TABLE IV-2

Damage Thresholds

Component	Col. 1 Average Damage Threshold Flux (neutrons/sq cm)	Col. 2 Damage Flux for Selected Transistors, 0.01% Failure Rate (neutrons/sq cm)
Silicon transistors		
Low frequency	5×10^{11}	5×10^{10}
Medium frequency	10^{12}	5×10^{11}
High frequency	10^{13}	5×10^{12}
Germanium transistors		
Low frequency	10^{12}	10^{11}
Medium frequency	10^{13}	5×10^{12}
High frequency	10^{14}	10^{13}
Field effect transistors	10^{15}	
Tunnel diodes	10^{15}	
Silicon diodes	10^{13}	
Germanium diodes	10^{14}	
IR detectors	10^{13}	
Traveling wave tubes	10^{14}	
Vacuum tubes (miniature)	10^{14}	
Vacuum tubes (sub-miniature)	10^{15}	
Klystrons	3×10^{14}	
Resistors		
Wire wound	10^{19}	
Carbon composition	2×10^{15}	
Carbon film	10^{16}	
Potentiometers	2×10^{14}	
Capacitors		
Paper	10^{14}	
Ceramic	2×10^{15}	
Mica	10^{15}	
Plastic	10^{14}	
Tantalum	10^{17}	
Oil impregnated	10^{14}	
Electrolytic	4×10^{13}	
Air dielectric	2×10^{15}	
Quartz crystals	2×10^{15}	
PC boards	2×10^{15}	

that TIMM circuits have excellent stability, low power drain, an overall high thermal and electronic efficiency and high radiation resistance, having operated in environments up to 1 x 10^{18} neutrons/sq cm integrated flux with no effect on steady state characteristics. The TIMM components are not considered practical for use in the Solar Probe, because of the necessity of maintaining the high operating temperature.

In summary, each of the first three types of fabrication techniques, conventional circuits, integrated circuits and hybrid circuits have foreseeable application to the Solar Probe electronic systems. Conventional and hybrid circuits are expected to be comparable in terms of radiation resistance, but integrated circuits are expected to be more susceptible. Detailed attention has been given in this study to radiation effect on conventional circuit components, because, while it is somewhat representative of the other two techniques, it is also the only one for which radiation test data exists in any significant quantity.

5. Component Radiation Damage Thresholds

The damage thresholds representing average values of integrated neutron flux required to produce moderate performance degradation of commonly used electronic components are listed in Col. 1 of Table IV-2. Moderate degradation in the case of transistors is defined as 30% decrease in the common emitter current gain, β, which is believed to be the limit below which serious circuit design difficulties can be expected when this effect is superimposed on other normal transistor variations. It can be seen that the damage thresholds for all components, except for some transistors, diodes, thermistors, and IR detectors, are above the predicted flux levels of either the solar flare protons or the power supply neutrons by at least an order of magnitude, neglecting any shielding. This points out the commonly accepted conclusion that semiconductor devices are the components that are the most susceptible to radiation damage, and, therefore, they represent the determining considerations for shielding requirements.

When it is considered that large quantities of transistors (an estimated 500) will be used in the Solar Probe equipment, it is recognized that a low failure rate resulting from the radiation damage must be achieved for individual transistors, if the reliability of the mission is to be maintained. A goal for transistor failure rates of 0.01% has been established in order that the total mission reliability will not be significantly reduced as a result of radiation damage. It is recognized that to achieve this goal will require careful selection of transistor types that have been shown by tests to be the most radiation resistant in addition to all the other protection that can be afforded by the design. No exhaustive reliability testing in the presence of radiation has been conducted to determine what flux levels will produce failure rates as low as 0.01%, but a method has been developed for extrapolating test data taken on a small number of test samples to the 0.01% failure rate flux levels. This method involves plotting the available test data on Weibull probability plots and making a straight line extrapolation (Ref. IV-8). By the use of this method, it is apparent that transistors selected from among those that demonstrate the highest radiation resistance in each category will exhibit 0.01% failure rates at or above the flux levels listed in Col. 2 of Table IV-2.

6. Shielding Requirements

Shielding studies have been conducted for both the solar flare proton and power supply neutron fluxes using existing Martin computer programs.

The effects that can be expected from the proton radiation with various thicknesses of aluminum shielding are illustrated in Figs. IV-1 through IV-4. This shielding study was conducted using as the incident flux the NASA model for the 10 May 1959 solar flare, which is approximately described by the following differential energy relationships:

$$dN = 2.92 \times 10^{11} E^{-2.07} dE \quad \text{for } 5 < E < 60 \text{ mev}$$

$$dN = 6.42 \times 10^{14} E^{-3.95} dE \quad \text{for } E > 60 \text{ mev}$$

where

N = isotopic flux in protons/sq cm-yr at 1 AU

E = proton energy in mev.

Note: The coefficients in the above expressions are different from those quoted in Chapter II because they have been adjusted to convert from a steradian to an isotopic basis, and do not include time and distance factors.

This proton flux model, multiplied by coefficient constants for the 1-yr mission duration and the reduced distance from the sun, was used as the basis for this radiation damage study prior to receiving direction from NASA/Ames to use the model already quoted in Sect. C. The similarity between the two models, except for differences in coefficients, is apparent from the nearly identical value of the exponent of E in the range of energy levels below 50 mev, which constitutes 97.3% of the total integrated flux. This means that the energy distribution of the two models is very similar and that the shielding studies will apply to the

NASA/Ames model of the incident flux when the results are multiplied by an appropriate constant factor. The factor of 8.8 was computed, representing the ratio of integrated flux from the NASA/Ames model and the integrated incident flux curve of Fig. IV-1 over the predominant energy range. This comparison between the two models is illustrated in Table IV-3.

TABLE IV-3

Integrated Flux at 1 AU

Energy Range (mev)	NASA/Ames Model	Fig. IV-1 Incident Flux	Ratio	Percent of Total Flux
5 to 50	4.374×10^{11}	4.975×10^{10}	8.8	97.3
50 to 60	0.063×10^{11}	0.075×10^{10}	8.4	1.4
60	0.058×10^{11}	0.134×10^{10}	4.3	1.3

This factor of 8.8 is used to multiply the integrated fluxes after shielding obtained from the shielding study to equate them to the fluxes that would have been obtained using the NASA/Ames model as the incident flux. The results in either case must be multiplied by the average $1/R^2$ distance factor of 2.83 for the 0.3 AU mission.

The primary proton flux for various shielding thicknesses is shown in Fig. IV-1. The resulting integrated fluxes have been computed for shielding thicknesses of 0.1 and 0.3 gm/sq cm and converted to apply to the 0.3 AU mission by use of the above factors of 8.8 x 2.83. The results are presented in Table IV-4.

TABLE IV-4

Proton Fluxes

Shield Thickness (gm/sq cm)	Primary Proton Integrated Flux from Fig. IV-1 (protons/sq cm)	Primary Proton Integrated Flux 0.3 AU Mission (protons/sq cm)
0.1	2.78×10^{10}	6.92×10^{11}
0.3	1.46×10^{10}	3.636×10^{11}

A recommended minimum shielding thickness of 0.3 gm/sq cm, corresponding to 0.044-in. thick aluminum was selected as discussed later.

TABLE IV-5

Total Radiation Flux

Radiation Type	Nonshielded Integrated Flux	Shielding	Shielded Integrated Flux	Shielded Fission Neutron Equivalent
Solar flare proton	1.27×10^{12} protons/sq cm	0.044-in. Al plus inherent shielding	1.82×10^{11} protons/sq cm	1.09×10^{12} neutrons/sq cm
Power supply neutron	7.5×10^{12} neutrons/sq cm	2.5-in. polyethylene	3.55×10^{12} neutrons/sq cm	3.55×10^{12} neutrons/sq cm
		Total shielded fission neutron equivalent flux		4.64×10^{12} neutrons/sq cm

Similar computations have been made for the secondary neutron, proton and gamma fluxes that result from the primary protons for comparable shield thickness using the data presented in Figs. IV-2 through IV-4. In each case the resulting secondary flux is below the level of the primary proton flux by at least two orders of magnitude and may be neglected.

Shielding computations for the power supply neutron flux were based on the use of a polyethylene shield placed between the nuclear power supply and the electronic systems in conjunction with a physical separation between the two. The relationship of neutron dose rate as a function of polyethylene shield thickness is presented in Fig. IV-5 for a physical separation of one meter. A minimum shield thickness of 2.5 in. is recommended with a physical separation of 30 in. This combination will result in a total integrated neutron flux of 3.55×10^{12} neutrons/sq cm-yr, derived from the data on Fig. IV-5 and the relationship:

$$1 \text{ neutron/sq cm-sec} = 7 \times 10^3 \text{ rem/hr.}$$

The calculation of the total integrated neutron flux is:

2.5-in. shielding results in a dose rate of 9.5 rem/hr at a separation of 1 meter (from Fig. IV-5)

Dose rate at 30-in. separation

$$= 9.5 \text{ rem/hr} \times \left(\frac{39 \text{ in.}}{30 \text{ in.}}\right)^2 \times \left(7 \times 10^3\right)$$

$$= 1.122 \times 10^5 \text{ neutrons/sq cm-sec.}$$

Integrated dose over one year

$$= 1.122 \times 10^5 \text{ neutrons/sq cm-sec} \times 3.16 \times 10^7 \text{ sec/yr}$$

$$= 3.55 \times 10^{12} \text{ neutrons/sq cm-yr.}$$

The shielding effects and the resulting combined total integrated radiation flux expressed in terms of equivalent fission neutrons are summarized in Table IV-5. This summary utilizes the proton-neutron damage equivalence ratio of 6 described in Section C. It is also based on the assumption that additional inherent proton shielding from spacecraft structure and other components will be achieved by taking maximum advantage of this possibility in locating the semiconductors during the design. It is assumed that this additional shielding will reduce the proton flux incident upon the average transistor or diode by a factor of 2. All negligible radiation sources and types have been omitted from Table IV-5.

The significance of the total shielded fission neutron equivalent flux of 4.64×10^{12} neutrons/sq cm can be appreciated by referring back to the component damage threshold flux data presented in Table IV-2. It can be seen that properly selected transistors of the medium and high frequency germanium types and the high frequency silicon types can be used in this environment with a predicted failure rate of 0.01%. It is expected that this range of selection will allow sufficient design latitude for the solar probe electronic circuits and still remain within the necessary damage susceptibility limits required for high component reliability under this environment with the recommended minimum shielding thickness.

It should be noted that the solar flare proton flux contributes only about 20% of the limiting damage threshold flux 5×10^{12} neutrons/sq cm for the classes of transistors to be used. Therefore, the solar probes that do not use a nuclear power supply will have an added safety factor of nearly five times, which means that the solar flare intensity actually encountered could be up to five times the predicted flux without degradation of the mission reliability so far as the electronic components are concerned. An increase over the predicted solar proton flux by a factor of six with the nuclear power supply or by a factor of nine without it would result in a total integrated flux experienced by the transistors of approximately 10^{13} neutrons/sq cm. This could be expected to increase the failure rate of the transistors used from 0.01% to approximately 0.1%. This would result in a reduced reliability for the one-year mission, or the same reliability for a shorter mission of 3 to 6 months, long enough to get past the 0.3 AU point in the trajectory.

To obtain a gross check on the feasibility of surviving under the solar flare proton radiation environment, a comparison was made with the experience obtained from a few earth-orbiting satellites that enter into the inner Van Allen belt, which contains a high concentration of protons in roughly the same energy range. Two satellites were selected for comparison (Vanguard I and Telstar I) because each has a history of significant operating life in the inner Van Allen belt.

Based on the average altitude and inclination of the Vanguard I orbit, it was estimated that the average proton flux to which it is exposed has been 10% of the peak flux of the inner belt, which is approximately 6×10^{4} protons/sq cm-sec above 10 mev. The total integrated proton exposure above mev for the 5.5-year life of Vanguard I is computed as:

$$N = 6 \times 10^{4} \text{ protons/sq cm-sec} \times 0.1 \times 5.5 \text{ yr} \times (3.16 \times 10^{7}) \text{sec/yr}$$

$$= 1.04 \times 10^{12} \text{ protons/sq cm above 10 mev.}$$

The predicted total integrated proton flux above 10 mev for the Solar Probe 0.3 AU mission computed from the NASA/ARC model is 5.85×10^{11} protons/sq cm. This is approximately one-half the estimated flux experienced by Vanguard I, which is still functioning. Neglecting energy levels below 10 mev is justified because protons with lower energies will not penetrate the recommended shielding for the Solar Probe.

While Vanguard I has nowhere near the amount of electronic equipment or the degree of complexity planned for the Solar Probe, Telstar I is probably comparable on this basis. The total integrated proton exposure above 10 mev was similarly estimated as approximately 2×10^{11} protons/cm for the 7-1/2 month operating life of Telstar I. Actual measurements (Ref. IV-9) from Telstar I of integrated fluxes of 5.25×10^{10} protons/sq cm in the range of 26 to 34 mev and 1.3×10^{10} protons/sq cm above 50 mev are consistent with the estimated total above 10 mev. This estimated flux is approximately 1/3 the predicted Solar Probe flux. In addition to the proton flux, the Telstar I experienced an extremely damaging electron flux resulting from the Starfish test conducted the day before Telstar I launch. The electronic flux above 1.5 mev was one to two orders of magnitude greater than predicted and contributed a computed dosage of 600 rad/hr compared to 2 rad/hr proton dosage. The eventual failure of the Telstar I command decoder was attributed to the highly damaging electron dosage, rather than the protons.

The conclusion is that both satellites have operated in proton radiation environments that are comparable to the predicted Solar Probe environment without any evidence of failure caused by the proton flux, testifying to the fact that such a mission is feasible. Both satellites have, in addition, been exposed to electron radiation, which, at least since July 1962, has been potentially more damaging than the proton radiation.

7. Design Guide Rules

In addition to providing shielding, it is essential to observe other precautions in the design of the electronic equipment for use in the Solar Probe. These precautions include:

(1) Selection of radiation resistant components.

(2) Packaging for maximum inherent shielding of susceptible components.

(3) Circuit design techniques that will allow for predicted degradation of component performance.

The proper selection of components is one of the most important precautions. Selections should be made for maximum radiation resistance wherever possible in the interests of achieving higher reliability, even if the damage threshold flux quoted in Table IV-2 is well above the predicted flux. In the case of transistors, in particular, it must be recognized that there is large variation in the damage tolerance from one type to another within the various classes quoted in Table IV-2. This variation will even appear between transistors of the same type produced by different manufacturers. It is therefore essential in the case of transistors that radiation test data be obtained for each type used in the design to verify that it complies with the limiting failure rate for components at flux levels up to the allowable minimum of 5×10^{12} neutrons/sq cm. The following guide rules are listed as an aid in the selection of some of the more common electronic components.

a. Transistors

(1) One should use only diffused junction transistors in preference to grown junction or alloy junction types.

(2) The highest frequency (high alpha cutoff), thin-base units should be selected. All units should have alpha cutoff frequencies of at least 25 mc.

(3) The planar-type construction is preferred. Mesa units are also good.

(4) Vacuum encapsulation units are less affected by surface effects than are other types.

(5) Germanium transistors exhibit more neutron radiation resistance than do comparable silicon transistors. If the maximum temperature environment can be held to 40° to 60° C, as expected, then one should attempt to use germanium units throughout the system.

(6) Majority carrier devices such as field effect transistors have, in limited testing, exhibited from one to two orders of magnitude increased radiation tolerance over the ordinary bipolar equivalent. The use of field effect devices in various circuits must be done with caution since the device can be a source of radiation induced effects at the high impedance terminal which is characteristic of these devices.

b. Transformers

(1) Most transformers are reliable out to values of integrated neutron flux of 10^{15} nvt.

(2) Hermetically sealed units tend to have the poorer radiation resistance as they tend to rupture due to expansion of the potting compound.

c. Capacitors

(1) Mica, mylar and glass capacitors exhibit excellent radiation tolerance.

(2) Ceramic capacitors are somewhat better than either plastic or paper types.

(3) Wet-type capacitors should not be used. This includes oil filled or impregnated paper or metallized paper types, oil impregnated plastic and wet foil or wet slug tantalums.

d. Resistors

(1) Carbon composition resistors should be avoided if possible.

(2) Metal film and wire wound resistors are the most radiation tolerant resistor groups.

(3) Carbon film resistors are generally more radiation tolerant than carbon composition types and may be used sparingly.

e. Diodes and rectifiers

(1) Diodes usually begin to fail with noticeable increase in the forward resistance and decreases in reverse resistance.

(2) Germanium diodes should be used in preference to silicon.

(3) Selenium rectifiers are somewhat superior to silicon and germanium units.

(4) Zener diodes are noticeably affected by neutrons in the decade of 10^{14} to 10^{15} neutrons/sq cm. The effect is manifested in about 1% change in reference voltage. GaAs units appear to be superior to silicon zeners.

f. Printed circuit boards

Glass epoxy boards should be used throughout the system.

g. Insulation and wire

(1) The Boston Insulated Wire Company, Boston, Mass. has perfected a new insulated wire for extreme environments encountered by satellites. The B. I. W. Superjet Satellite Styles I and II appear to be the best qualified wire. Wire of this type is especially recommended for monitoring the boom-mounted experiments.

(2) For other insulation applications, use of flame-resistant, thermally stabilized, and irradiated, modified polyolefin is recommended. A second choice is "Durock" manufactured by Physical Science Corporation.

(3) Teflon in any form should be avoided.

(4) In general, inorganic components of laminates, such as glass cloth, mica, or asbestos are much more radiation resistant than the organic binders that are used with them.

(5) Polystyrene is exceptionally resistant to radiation damage.

In summary, we see that the engineer must choose the fabrication components and materials with exceptional care if one expects an overall high mission reliability. New data will undoubtedly become available by the time the probe is constructed, and it would be wise to resurvey the then known effects of radiation on devices and material.

It will be necessary to consider carefully the actual circuit layouts and system packaging configurations in order to take advantage of whatever material shielding the vehicle and other nonenvironment sensitive materials can provide. One possible construction worth considering is placing of the sensitive semiconductor elements inside a shielded container while leaving other components and parts relatively unshielded. At any rate, it is most important to seriously consider the layout and packaging problem in order to minimize the need for additional material that serves only as a shield. It will be necessary, in the design phase, to monitor and control the placement of semiconductor components to ensure that the 50% reduction in proton flux due to inherent shielding that has been assumed is actually experienced.

The following guide rules will serve as an aid to circuit designers to minimize the effects of radiation damage:

(1) High impedance circuits should be avoided. Junction leakage currents can be expected to increase sometimes by one or two orders of magnitude. Also, large value resistors tend to exhibit a greater percentage resistance change than low values.

(2) High feedback designs should be used for amplifier circuits to compensate as much as possible for component performance variations.

(3) Worst case design analysis must be employed to satisfy the designer that the circuits will continue to function in spite of the component variations from all environmental conditions and component aging. This need is especially important in a radiation environment in which the shielding requirements have been based on allowing a 30% degradation of transistor gain superimposed on all other sources of variation. Various analytical techniques have been developed for worst case design, some of which can be aided by the use of a computer. Experimental techniques have been used to good advantage to verify or supplement the analysis.

8. Test Programs

It is important that radiation damage tests be conducted as a part of the design and development phase of the Solar Probe program. Early in the program, testing should be aimed at obtaining more data in:

(1) Increasing the amount of test data on components under proton radiation.

(2) Compiling data of a statistical nature to permit component reliability predictions under radiation environments.

(3) Compiling data on new components that may have application to Solar Probe circuits.

(4) Investigation of radiation tolerance characteristics of latest fabrication techniques, such as hybrid and integrated circuits.

(5) Investigate further the influence of combined environments, particularly temperature and vacuum, on radiation damage effects.

During the design phase, radiation damage data should be generated, if not already available, for all semiconductors used in the circuit designs to verify that they possess adequate radiation resistance. Sufficient samples should be tested to permit reliability predictions. As time goes on, a list of "radiation qualified components" can be generated.

During the construction phase it will be necessary to continue radiation testing as a quality control measure. Consideration should be given to the use of pretesting of all semiconductors used in order to observe the trends of variation over integrated flux levels up to some small fraction of the predicted dosages. This method was used to good advantage for preselecting the most resistant components for the Telstar 1 satellite.

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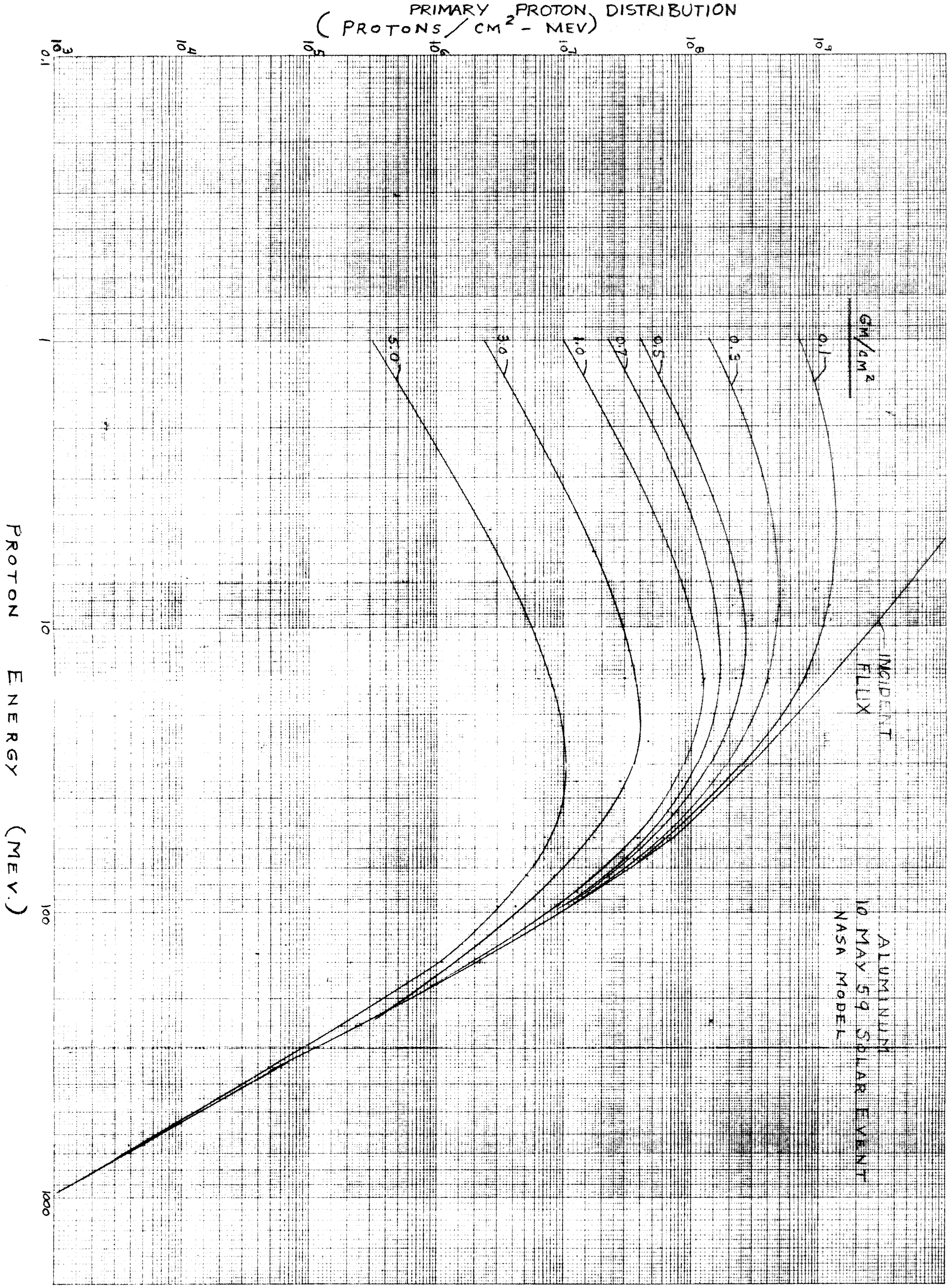

Fig. IV-1. EMERGENT DIFFERENTIAL PROTON ENERGY SPECTRUM WITHIN ALUMINUM SPHERICAL SHELLS OF VARIOUS THICKNESSES FOR THE NASA MODEL MAY 10, 1959 SOLAR FLARE EVENT.

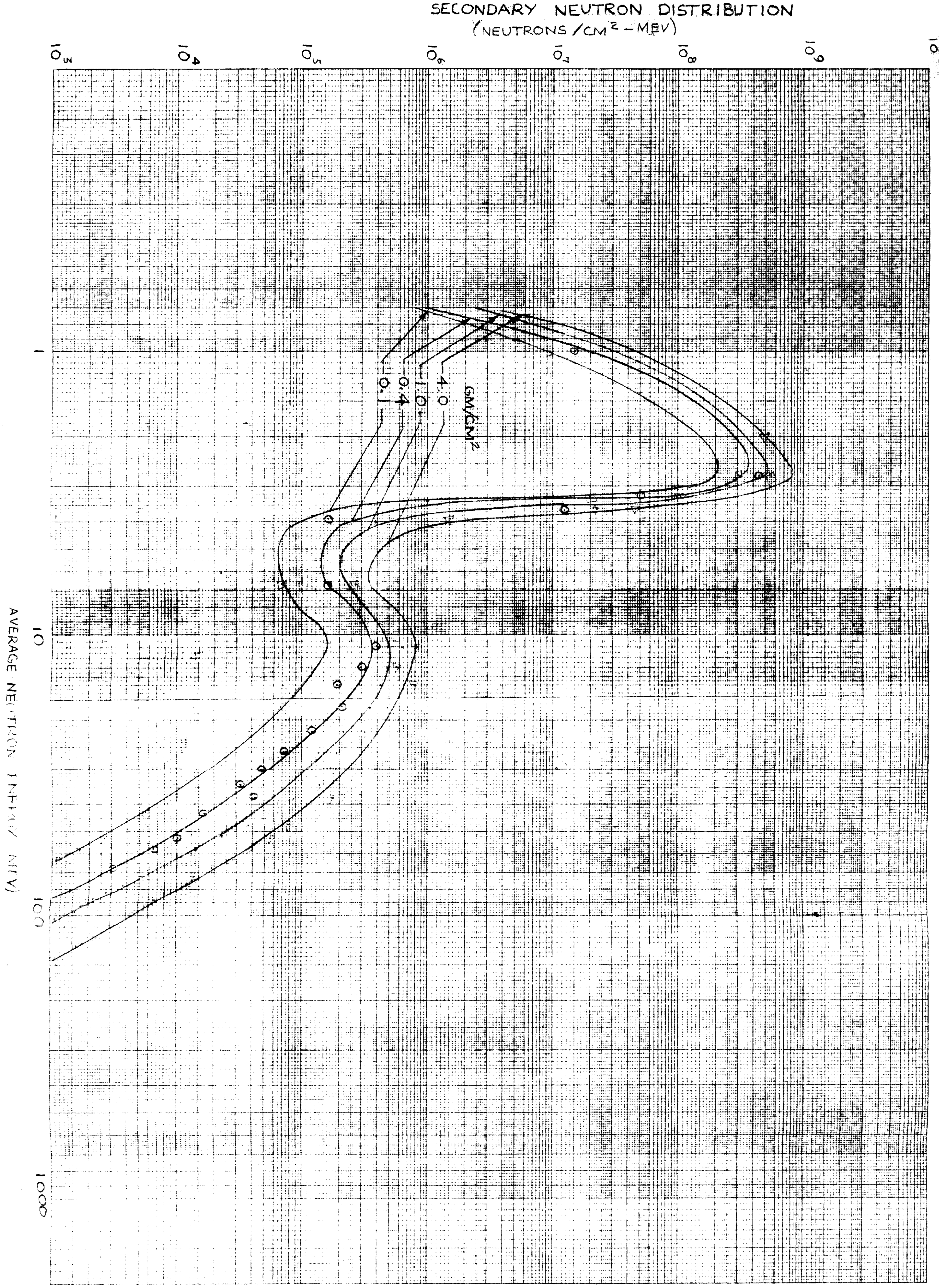

Fig. IV-2. EMERGENT DIFFERENTIAL SECONDARY NEUTRON ENERGY SPECTRUM WITHIN ALUMINUM SPHERICAL SHELLS OF VARIOUS THICKNESSES FOR THE NASA MODEL MAY 10, 1959 SOLAR FLARE EVENT.

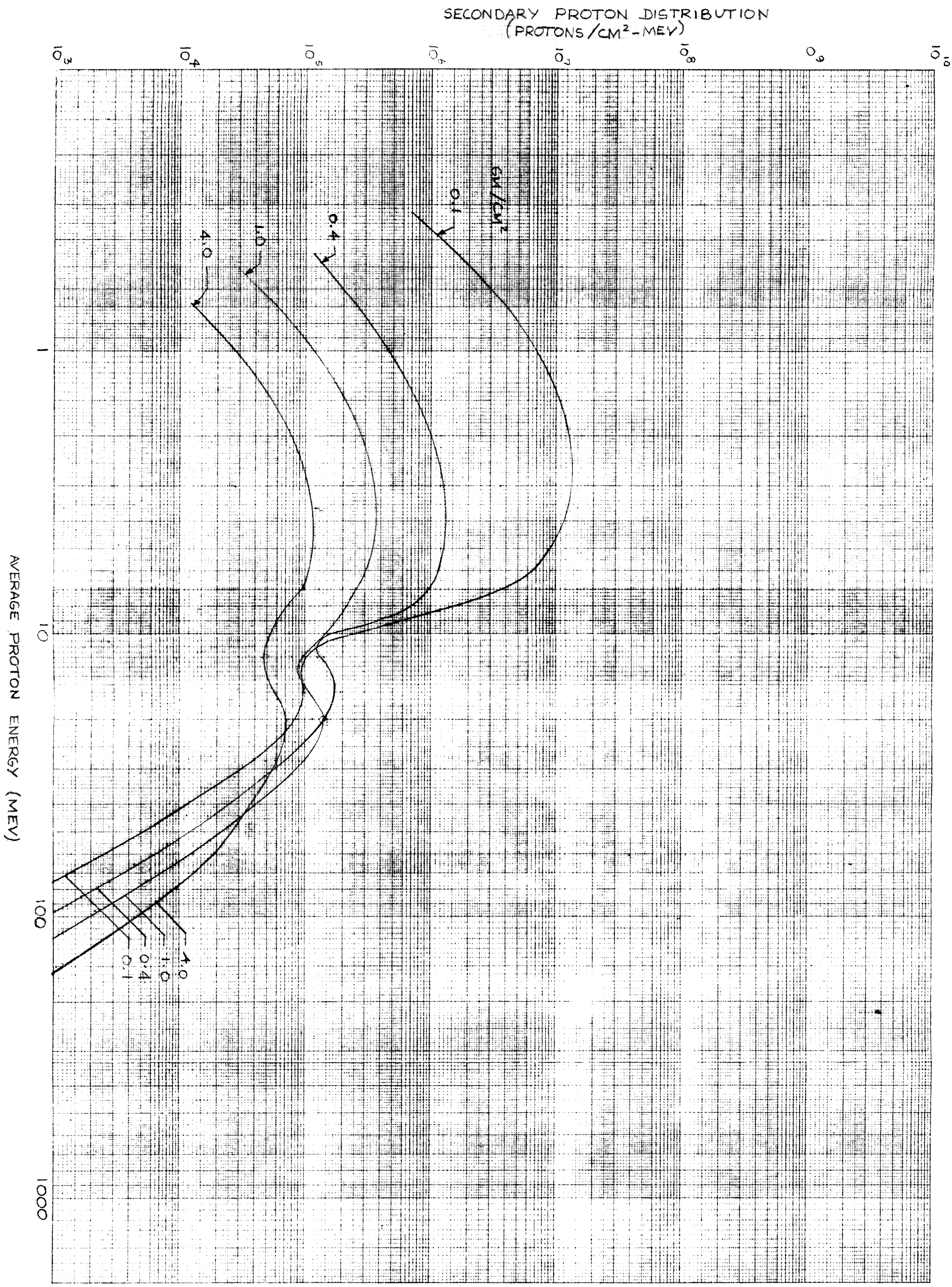

Fig. IV-3. EMERGENT DIFFERENTIAL SECONDARY PROTON ENERGY SPECTRUM WITHIN ALUMINUM SPHERICAL SHELLS OF VARIOUS THICKNESSES FOR THE NASA MODEL MAY 10, 1959 SOLAR FLARE EVENT.

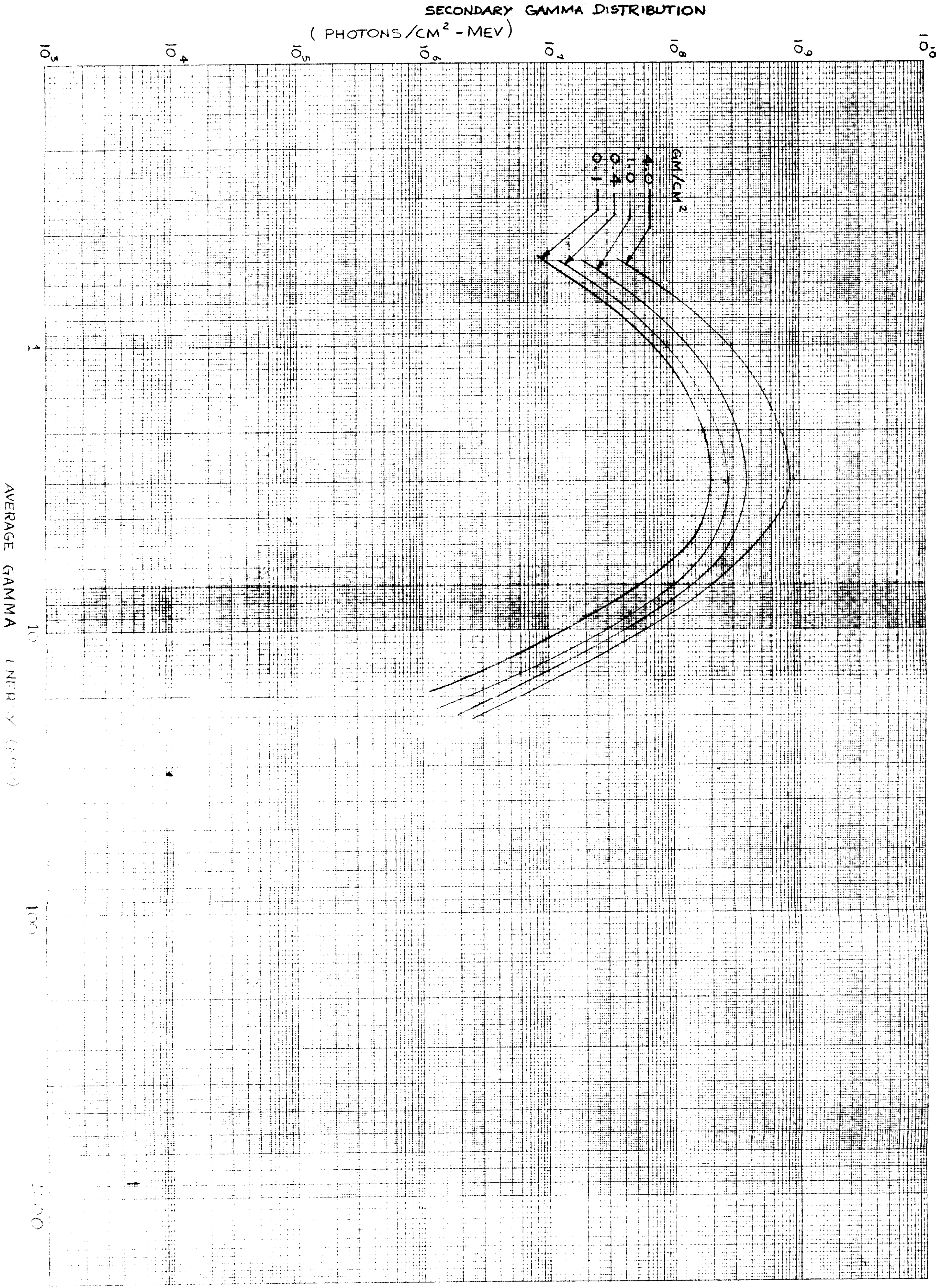

Fig. IV-4. EMERGENT DIFFERENTIAL SECONDARY GAMMA ENERGY SPECTRUM (GAMMAS FROM PROTON INELASTIC SCATTERING) WITHIN ALUMINUM SPHERICAL SHELL OF VARIOUS THICKNESSES FOR THE NASA MODEL MAY 10, 1959 SOLAR FLARE EVENT.

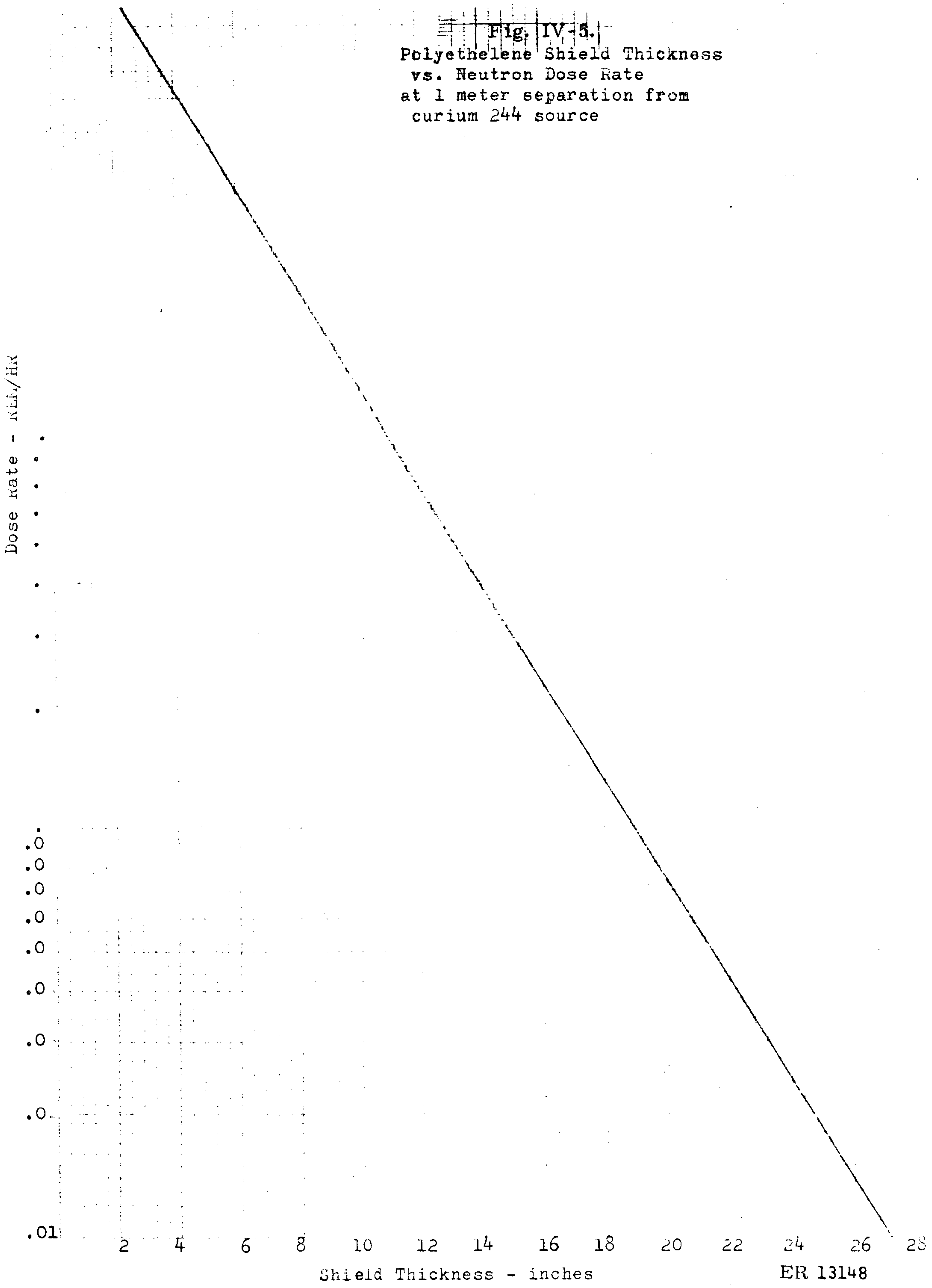

Fig. IV-5.
Polyethelene Shield Thickness
vs. Neutron Dose Rate
at 1 meter separation from
curium 244 source