RADIATION RESEARCH AT MARSHALL SPACE FLIGHT CENTER

By

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SUMMARY

The status and scope of the Radiation Research Program at Marshall Space Flight Center are described in this report. The application of radiation to engineering problems and the effects of nuclear and space radiation on materials and components are discussed. Much of the progress made in the last year consists of the continued accumulation of engineering data. The Propulsion and Vehicle Engineering Laboratory has continued its testing of materials under reactor space radiation environments. The Astrionics Laboratory is concerned with the effects of radiation on electronic components and the development and calibration of instrumentation for the measurement of the radiation environment. The Research Projects Laboratory has been primarily concerned with the transport of radiation through shields and the aspects of radiation from the physical viewpoint. Appropriate contracts and publications in the field of radiation physics are referenced. Several applications of radiation for the solution of engineering problems are discussed briefly to indicate their feasibility and to provide contract and document references.

INTRODUCTION

Radiation research at the Marshall Space Flight Center (MSFC) is applied in nature and is distributed among organizational elements according to their missions and responsibilities. The effects of radiation on materials is studied by the Materials Division of the Propulsion and Vehicle Engineering Laboratory; the effects of radiation on electronic components is the concern of the Astrionics Laboratory, which is largely electrical engineering in composition. Radiation research is incorporated into existing studies and in laboratories as an integral part of a project or program. For example, a complete description of the dielectric properties must include a knowledge of whether these properties are moisture-, radiation-, or temperature-dependent. From the environmental viewpoint, radiation in the form of X-rays, gammas, neutrons, protons and electrons is just another environmental factor which must be considered by the engineer in his effort to produce equipment which will perform properly.

An effort is also being made to understand the basic transport of radiations through matter and of charged particles through electromagnetic fields. These studies are essential for an understanding and evaluation of problems in technical areas such as advanced propulsion concepts, nuclear power supplies for space applications, spaceship design, nuclear test facility planning, interaction of charged particles with space vehicles, space experiment planning and integration, thermonuclear power, Civil Defense and calibration requirements for radiation measuring instruments.

The presence of high energy charged particle radiation in space is of immediate concern for manned space missions and relative to hazards as a function of time, position and the amount and kind of shielding. These hazards extend to the spacecraft's components and materials exposed to space radiation. A recent example of such a problem was that of charge storage in dielectrics and subsequent Lichtenberg discharges which could produce electrical interference with spacecraft systems. Space experiments, whether or not they are concerned with radiation measurements, must be examined from the viewpoint of their sensitivity to radiations which are not of direct interest, but which may be naturally present in space or present because of radioisotopes in the spacecraft.

The interpretation of many space measurements requires an understanding of how the measured signal interacts with its environment on the way to the detector. The techniques of radiation transport are universally applicable to photons, whether they arise as thermal radiation from hot bodies, as gamma rays emitted from reactors, or as X-rays produced by solar proton bombardment of the lunar surface. The concepts of collisions and cross sections are useful not only on the microscopic scale but also on the planetary scale in the discussion of meteoroid populations.

Electrons, protons, neutrons and photons are the primary concern of this report. Energetic electrons and protons exist naturally in the space environment in the form of trapped radiation, solar flare ejections and cosmic rays. Neutrons and photons, the latter of which may be called X-rays, gammas or bremsstrahlung, depending on their origin, arise because of electron and proton interactions with spacecraft, the atmosphere of the earth, and the lunar surface, and may also arise from radioisotope and nuclear power supplies. Electrons and protons, being charged particles, interact with both matter and electromagnetic fields, whereas neutrons and photons are neutral particles and, for most purposes, interact only with matter.

This report is concerned with radiation research at MSFC and associated contractors. References to published work and NASA contract numbers are included as a guide for those whose interest extends to specific areas.

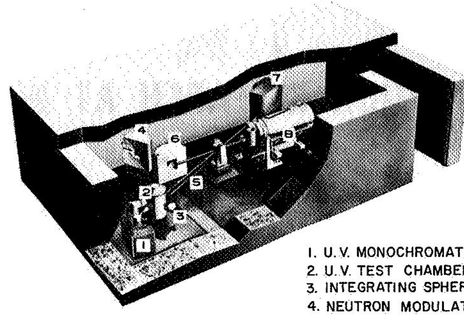
FACILITIES, PRESENT AND PLANNED

Facilities are usually justified and built because of highly specific program demands. Whether or not they have application to other situations depends on a number of factors such as the versatility of the facility and the associated personnel. As a rule, research facilities and personnel are expected to be more basic and general in orientation, although immediate program requirements may regiment and closely define the work for extended periods of time. The radiation facilities at MSFC are built around some type of radiation source, e.g., a Van de Graaff accelerator, a Co^{60} array, or an X-ray machine. With each radiation facility there must be enough equipment to guarantee safety and to permit measurement, definition, and calibration of the radiation environment produced in the facility. Personnel associated with the facility must have the specialized knowledge and training to use it efficiently and safely.

The location of a facility within an organizational segment does not preclude its use by outside personnel in an entirely different application. For example, Dr. Charlotte Lee of Alabama A & M College was permitted to use the Van de Graaff in the Materials Division for radiological studies.

THE VAN DE GRAAFF FACILITY

The Van de Graaff charged particle accelerator, located in the Materials Division of the Propulsion and Vehicle Engineering Laboratory, is a particularly versatile device for producing various kinds of radiation in energy ranges of interest in space application. The MSFC Van de Graaff Facility (Figs. 1 and 2) was designed for the multiple capability of simultaneously irradiating materials with ions, ultraviolet, infrared and possibly electrons in a vacuum environment. It can also be used to generate large quantities of X-rays by accelerating electrons into high-Z target material and neutrons by accelerating deuterons into a deuterium or tritium target.



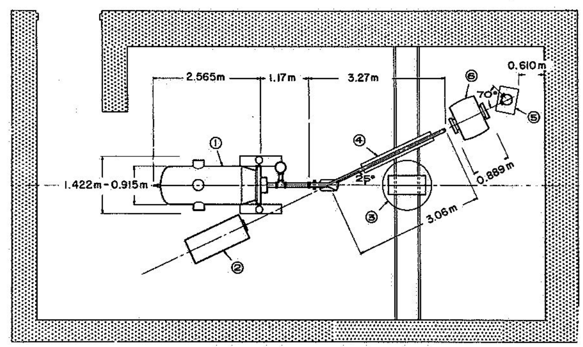


FIGURE 2. SCHEMATIC OF VAN DE GRAAFF FACILITY

ASTRIONICS RADIATION FACILITY

The radiation facility, located in the Instrumentation and Communication Division of the Astrionics Laboratory, is geared toward the testing of electronic components and the development and testing of various kinds of radiation instrumentation. The facility shown in Figures 3 and 4 will house in Hot Cell "B" a 20,000-curie Co^{60} source for gamma irradiations at the dose rate up to 4×10^6 roentgens per hour. Remote manipulators in both hot cells will permit assembly and arrangement of intense radioisotope sources needed for radiation effects testing and instrument calibration.

This basic radiation facility is supported by a large electronics organization with complete capability in all aspects of circuit design, digital techniques, flight instrumentation and environmental testing. The supporting equipment associated with this facility includes a 400-channel pulse height analyzer (RIDL Model 34-12B), a 2π proportional counter system (NMC Model PCC-10A) for radioactivity measurements, and a vacuum pumping system.

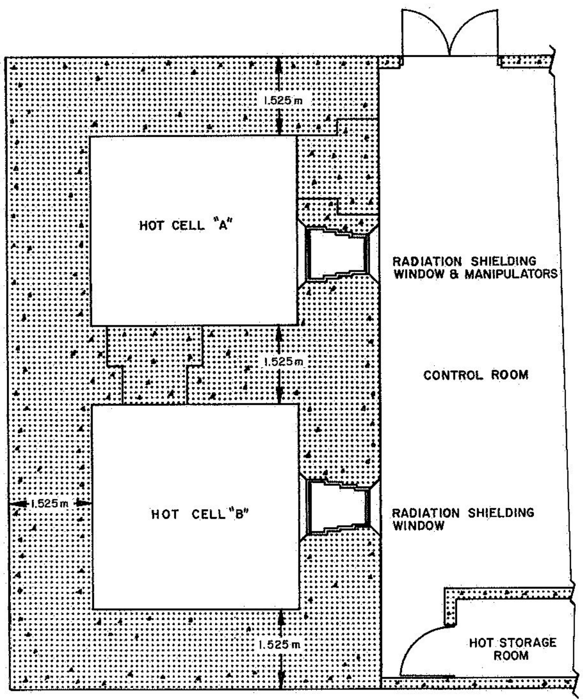


FIGURE 3. SCHEMATIC OF ASTRIONICS LABORATORY'S HOT CELL RADIATION FACILITY

Hot Cell "A" is presently occupied by a neutron generator (Texas Nuclear Model 9900). The device accelerates deuterons into a deuteron or tritium target, thereby producing in excess of 10^{11} neutrons per second from deuteron-deuteron and deuteron-tritium nuclear reactions. This device can also produce energetic protons from the deuteron-tritium reaction, and gamma rays from neutron capture and inelastic collisions.

Also available at this facility is an X-ray generator (Norelco Model MG-100) capable of operating up to 100 kiloelectron volts and producing 2.5×10^6 roentgens per hour at 10 centimeters and a collection of encapsulated sources, including a polonium-beryllium source delivering 1.9×10^6 neutrons per second.

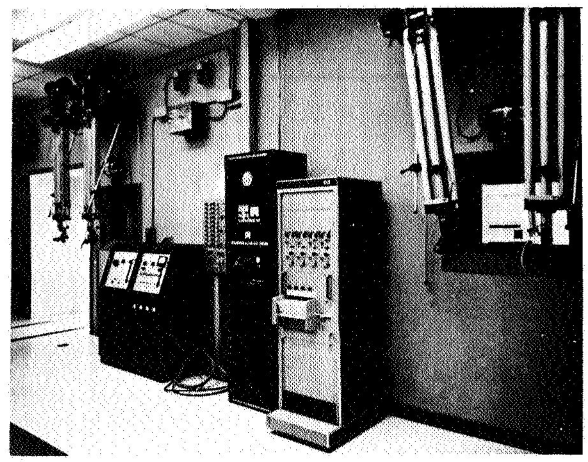


FIGURE 4. ASTRIONICS LABORATORY'S HOT CELL RADIATION FACILITY

OTHER RADIATION FACILITIES

A number of low-level radiation facilities are associated with special radioisotope applications such as shield evaluation, leak detection, instrument calibration, gas pressure and density measurements, and tracer applications. Table I enumerates a number of radioisotope users and their interests. Table II lists a number of radioisotope applications of interest to various R & D people who may or may not have radioisotopes with which to experiment. As a rule, each radioisotope on the premises has some storage facility associated with it and the necessary safety and application appurtenances such as film badges, radiation survey meters, radiation detectors and specialized electronics equipment.

RADIATION EFFECTS ON MATERIALS

The space environment contains several types of radiation which may change the bulk or surface properties of materials. The low-energy protons and alpha particles ejected by solar flares can change surface properties such as emissivity and absorptivity. The high-energy electrons and protons, produced by solar flares or present in the captured radiation belts or cosmic rays, can change the optical properties of lenses and windows and damage solar cells and photographic film. The ultraviolet radiation can promote chemical reactions and outgassing in organics. Neutron and gamma radiation arising from reactors used in nuclear stages for primary propulsion can present a serious materials problem, especially in the immediate vicinity of the reactor. For several years, the Materials Division of the

TABLE I. RADIOISOTOPE USERS AT MSFC

USER	No. of Sources	Purpose
A. M. Payne, R-TEST-IDT	16	Gas density measurements
H. D. Burke, R-ASTR-IMT	5	Instrument calibration and research
B. Corder, R-QUAL-AVR	3	Leak testing
A. Hafner, R-ASTR-IMP	2	Density measurements
R. Potter, R-RP-N	8	Electron density measurements
H. Hilker, R-QUAL	1	Leak testing
T. Knowling, R-P&VE-MEE	4	Instrument calibration
W. White, R-TEST	50	Density measurements in cryogenic fluids
C. Jacks, Emergency Planning	1	Civil Defense
E. Parrish, R-AERO	4	Gas density measurements
E. Donald, R-TEST	6	Gas density measurements
W. L. Kimmons, R-ASTR	1	Ionization pump

TABLE II. USES OF RADIATION SOURCES

Design and calibration of radiation detectors	Random number generators
Leak detection	Tracer techniques
Velocity indication	Wear, Ablation, Flow rates,
Damage studies	Chemical and Biological processes
Materials	Solid-state research
Components	X-ray techniques
Radiation effects	Proton shield evaluation
Materials	Gas density measurements
Electronic components	Saturn V test stand checkout
Radiation research	Inspection of components
Shielding	Liquid level indicators
Activation	Disconnect signals
Density measurement	Civil defense planning
Vacuum chamber	Ionization pump
Cryogenic fluids	

Propulsion and Vehicle Engineering Laboratory has been studying the effects of various kinds of radiation on materials important to space vehicles. These radiation effects are measured and described in the manner common to materials testing, i.e., as an integral part of a complete materials testing and development program which considers all possible environmental aspects, including radiation. Radiation testing of materials has followed two main lines: (1) that of evaluating materials in a nuclear rocket radiation environment, and (2) that of evaluating materials in a space radiation environment. In some cases, radiation damage in one situation can be related to that in another, but as a rule the change in components, materials, exposure times and environments involved does not permit easy and reliable extrapolation from one situation to another.

The combined effects of space environmental parameters on space vehicle materials has been studied under both inhouse and contractor effort [1] with emphasis on solving the problems of making appropriate in situ measurements of samples during simultaneous exposure to several environmental factors such as low temperature, vacuum, ultraviolet radiation, electrons and protons.

The combined effects of nuclear radiation, cryogenic temperature, and vacuum on the electrical properties of engineering materials has been studied in considerable depth and detail by Gause and McKannan [2, 3, 4]. The measurement of material properties during reactor irradiation is made difficult and expensive by the fact that the test equipment is damaged and activated, and by the requirement of remote operation and instrumentation. Consequently, most material tests have been made before and after irradiation. Materials recently tested [5] under combined nuclear radiation, cryogenic and vacuum environments are shown in Table III [6]. For testing details and lists of other materials tested, a contractor's report is recommended [7].

TABLE III. MATERIALS TESTED UNDER COMBINED NUCLEAR RADIATION, CRYOGENIC, AND VACUUM ENVIRONMENTS

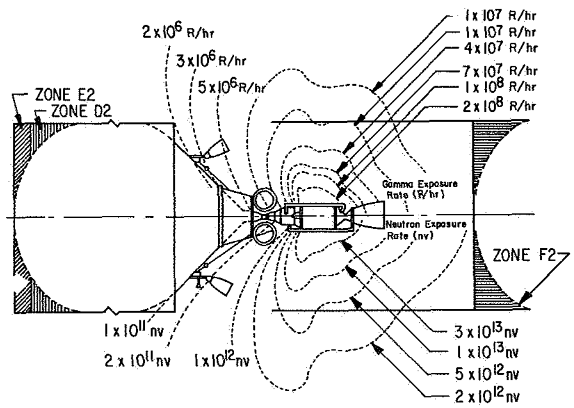
AEROBOND 430, EPOXY PHENOLIC ADHESIVE
LEXAN, POLYCARBONATE/GLASS LAMINATE
KYNAR, VINYLIDENE FLUORIDE PLASTIC
SILASTIC 1410, SILICONE ELASTOMER
MYLAR C, POLYESTER FILM
SYLGARD 182, SILICONE POTTING COMPOUND
Q94-002 FLUOROSILICONE SEALANT
PRP-2277 NEOPRENE ELASTOMERIC SEAL
PRP-19007 FLUOROCARBON ELASTOMERIC SEAL
PRP-737 ACRYLONITRIDE ELASTOMERIC SEAL
CRP-20-2 POLYURETHANE FOAM (CO_2 BLOWING AGENT)
CRP-20-2X POLYURETHANE FOAM (FREON BLOWING AGENT)
CRP-20-2X EPOXY FOAM (FREON BLOWING AGENT)

RADIATION EFFECTS ON ELECTRONIC COMPONENTS AND SYSTEMS

The effects of nuclear radiation on electronic components has been of design importance since the advent of nuclear fission power and was investigated with considerable resources during the development of the nuclear powered airplane. In the space environment, the familiar problems associated with the neutrons and gammas from nuclear power reactors are augmented by the presence of energetic electrons and protons and other high-energy charged particle radiations.

THE EFFECTS OF REACTOR RADIATION ON ELECTRONIC COMPONENTS

Interest in propulsion by nuclear heat exchanger rockets has resulted in studies [8] of the effects of reactor radiation on electronic components in environments such as that shown in Figure 5 [9].



ZONE	NEUTRONS (n) TOTAL EXPOSURE n/cm^2	NEUTRONS (n) PEAK RATE n/cm^2-sec	GAMMA (γ) TOTAL EXPOSURE R	GAMMA (γ) PEAK RATE R/hr
D-2	1.7×10^9	4×10^8	9.2×10^3	1.6×10^5
E-2	3.3×10^9	6.2×10^8	1.3×10^4	2.2×10^5
F-2	1×10^{12}	1×10^{11}	2.8×10^2	2.8×10^5

FIGURE 5. RADIATION FLUX FIELDS OF A NUCLEAR HEAT-EXCHANGER ROCKET

Emphasis has been placed on the study of the more susceptible semiconductor devices, the less sensitive electronic components such as resistors, capacitors, inductors and electron tubes, and the design of circuits "hardened" to radiation.

An example of the hardening process is shown in Figures 6 - 8. In Figure 6, an unhardened power supply showed severe degradation at 10^4 roentgens exposure. With some attention to component selection based on radiation testing histories and some

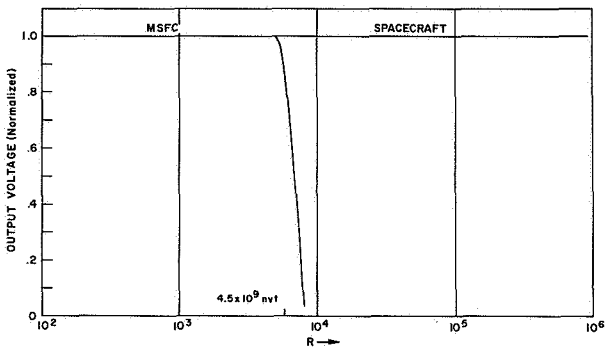


FIGURE 6. PERFORMANCE OF IRRADIATED UNHARDENED POWER SUPPLY

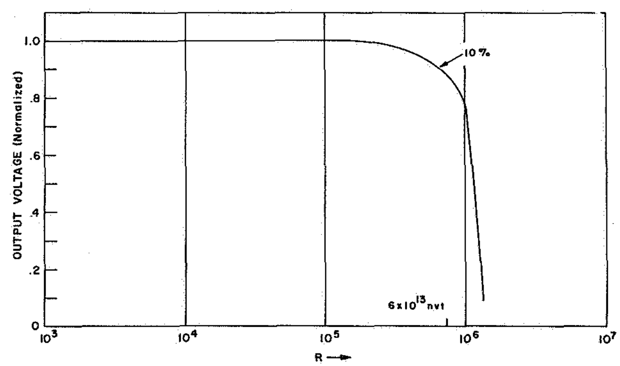


FIGURE 7. PERFORMANCE OF IRRADIATED HIGH-VOLTAGE POWER SUPPLY MODIFIED FOR RADIATION ENVIRONMENT

circuit redesign, power supplies can be hardened sufficiently to survive a 3×10^5 roentgens exposure, as shown in Figure 7 [10]. With a special effort at design for radiation survival and some sacrifices in what might be an optimum design without the radiation problem, it is possible to push the useful operation [11] of the system beyond an exposure of 5×10^6 roentgens or 10^{14} nvt (neutrons per square centimeter) as shown in Figure 8.

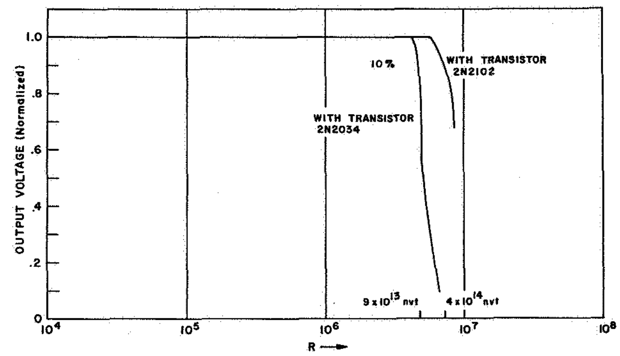


FIGURE 8. PERFORMANCE OF IRRADIATED SERVOAMPLIFIERS WITH SPECIAL DESIGN FOR RADIATION ENVIRONMENT

The study of problems existing for Saturn measurement components used in conjunction with a RIFT stage has proceeded with preliminary testing at the Georgia Nuclear Laboratories of Lockheed. Twenty-five out of twenty-eight units withstood ten times the levels expected in the reactor inflight test (RIFT) instrument unit [12]. A summary of the categories of devices tested is given in Table IV. Other items listed [13] included a large number of solid-state devices, capacitors, differential amplifiers, transistors, resistors, cables, batteries and exploding bridge wire parts. In future tests, emphasis will be placed on microelectronics and new devices which show promise of useful application.

TABLE IV. SATURN MEASUREMENT DEVICES IN A REACTOR RADIATION ENVIRONMENT

Temperature Gauge	AC Amplifier
Temperature Transducer	Microphone
Pressure Transducer	Emitter Follower
DC Amplifier	Accelerometer
Carrier Amplifier	Rate Gyro
Power Supply	Ion Chamber System
Leak Detector	Semiconductor Radiation Detectors

In a radiation environment some electronic elements such as transistors fail long before other transistors, supposedly identical, suffer significant radiation damage, resulting in failure of random components. Apparently there were deviations in materials or transistor production techniques which were not discernible in the initial tests but which later became important in the radiation environment. It would be desirable to separate these potential maverick elements from the group before they are used in components to be exposed to radiation.

In order to select transistors which are uniformly resistant to radiation, a study [14] of the relevance of various design and manufacturing features to radiation survival is under way. Particular attention is being paid to possible surface effects and auxiliary materials because failures have occurred long before the basic semiconductor properties should have changed under irradiation.

Another approach to improving radiation resistance is to go to new semiconductor materials. Silicon carbide amplifiers now being developed [15] are expected to survive an irradiation of 10^{14} to 10^{15} nvt at temperatures of 573° to 673° K.

THE EFFECTS OF CHARGED PARTICLE RADIATION ON ELECTRONIC COMPONENTS

Because of the low radiation doses associated with components afforded even a minimum of shielding by spacecraft shells and normal packaging envelopes, damage by the electrons and protons present in space has not been viewed as a serious problem for the average electronic circuit. However, some components such as solar cells and electrical cables are directly exposed to the radiation environment and some protection must be provided.

The damaging effect of charged particle radiation on solar cells has been studied both experimentally [16a] and theoretically [16b], and is presently guarded against by specially designed covers which incorporate good optical properties but probably more shielding than is necessary. If large solar arrays are used for propulsion power, more attention must be given to establishing minimum weight shields [17].

The storage of charge in dielectrics exposed to radiation has been studied for many years. In space, charge accumulation because of exposure to electrons and protons can easily cause spurious currents in the picoampere range. In addition, the charge storage distorts the local electric field, and if the field becomes intense enough, dielectric breakdown and spurious signal production can occur. Distortions of the local electric field by charge accumulation in dielectric paints used to achieve a proper heat balance can affect sensitive measurements of the space plasma. A large number of small Lichtenberg discharges in such paints might produce electrical noise which would interfere with satellite electrical systems.

SHIELDING AND TRANSPORT STUDIES

The study of the propagation of radiation through matter and force fields is of paramount interest in the fields of physics and astronomy, and is often designated by such names as radiation shielding or radiation transport. Radiation shielding research at MSFC is directed toward answering a number of operational and design questions: How much shielding should be applied to a solar cell which must operate for one year in a 1000-kilometer equatorial earth orbit? How long can an astronaut safely remain in stationary earth orbit without a solar flare storm cellar? How much shielding and what kind of material should be used to protect photographic film in a manned space vehicle designed for a three-week stay on the moon? What should be the amount, composition, and disposition of shielding for a manned Mars landing vehicle using nuclear rocket and nuclear electric propulsion? How do radioisotope power supplies interfere with radiation experiments? To answer such questions, one must know what kind of radiation is involved; how it is distributed with respect to time, energy and position; how it interacts with matter; and how much radiation exposure can be tolerated. These are not simple questions and can be attacked only by dedicated, competent and specialized study.

The uncertainties in shielding calculations can be associated with a lack of knowledge in the radiation environment, errors and omissions in computing the interaction of radiation with matter and fields, and errors in estimating the tolerance to radiation of the item to be shielded. Shielding interests at MSFC have been concerned primarily with transport problems, but have had to consider the other aspects to provide answers to questions of practical interest. In general, environmental data were obtained from compilations by specialists under joint NASA and DOD contract to accumulate, extrapolate, and refine radiation data available from U. S. and U. S. S. R. satellite measurements.

PROTON SHIELDING

The big uncertainties have been removed from the transport part of proton shielding, and the major concern is with computing refinements to economically handle the complex geometries normally associated with men and spacecraft. Machine costs can be reduced considerably by devising simplified analytical functions to represent the mass of physical data associated with proton energy spectra and penetration formulations [18]. Most of the interest in space shielding has been associated with high-energy protons [19] because of their great penetrating power and their capability of producing secondary radiations.

As the problems of proton shielding have become better understood and more stabilized, and as the capability to use specialized machine codes have become more widespread, demands for simplified, accurate and convenient compilation of computer input data have increased. Figure 9, taken from a recent study [20], shows the relative error incurred when a relatively simple and analytical expression is substituted for more accurate but highly cumbersome Bethe-Bloch formulation. Table V gives the eye and abdomen radiation doses [21] for an eight-man spacecraft using 2.54 and 19.3 centimeters of polyethylene shielding during a large solar flare. In these calculations, the emphasis is on a complicated geometry with simplified radiation data input. The effect of considering equipment and other new members in the calculation is in dramatic evidence.

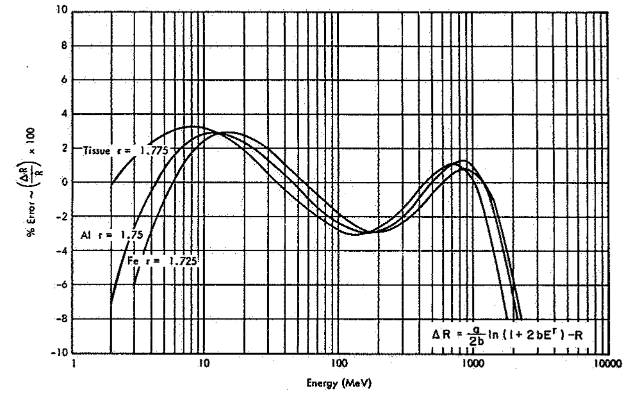


FIGURE 9. PROTON RANGE ERROR CURVE

TABLE V. EYE AND ABDOMEN RADIATION DOSES FOR AN EIGHT-MAN SPACECRAFT DURING A SOLAR FLARE

$$\frac{d\phi}{dp} = 5.675 \times 10^8 \exp(-p/80) \frac{\text{Protons}}{\text{cm}^2 - \text{MV}}$$

Detectors	1E	1A	2E	2A	3E	3A	4E	5E	5A	6E
19.3 cm Polyethylene										
Shield Only	2.87	2.87	1.49	2.07	3.00	2.51	2.36	1.59	2.08	1.62
Shield + Equipment	1.82	1.92	1.36	1.80	2.18	2.10	1.66	1.43	1.80	1.44
Shield + Crew + Equipment	1.17	0.29	0.78	0.20	1.24	0.30	1.28	0.82	0.20	0.84
2.54 cm Polyethylene										
Shield Only	203.	194.	98.0	122.	198.	165.	176.	107.	124.	105.
Shield + Equipment	83.5	95.5	91.6	96.5	116.	115.	88.6	98.1	97.4	89.5
Shield + Crew + Equipment	30.4	1.87	47.6	1.16	42.1	2.12	54.4	48.9	1.23	49.7

E = detector in eye
A = detector in abdomen
1 = middle crew member at instrument console
2 = crew member in top bunk, head under instrument console
3 = crew member in hatchway
4 = right crew member at instrument console
5 = crew member in top bunk, feet under instrument console
6 = crew member in bottom bunk, head under instrument console

The proton environment varies greatly with time [22], and many studies are concerned with the worst probable situations. Figure 10, taken from a recent calculation by M. O. Burrell, shows the proton dose for the three largest solar flares in the last solar cycle. Here again, simplified representations of the solar flare spectra and the proton range formulations were used.

ELECTRON AND BREMSSTRAHLUNG PENETRATIONS

The Monte Carlo work of Martin Berger [23] of the National Bureau of Standards has been reduced to a few simple equations which can be incorporated into

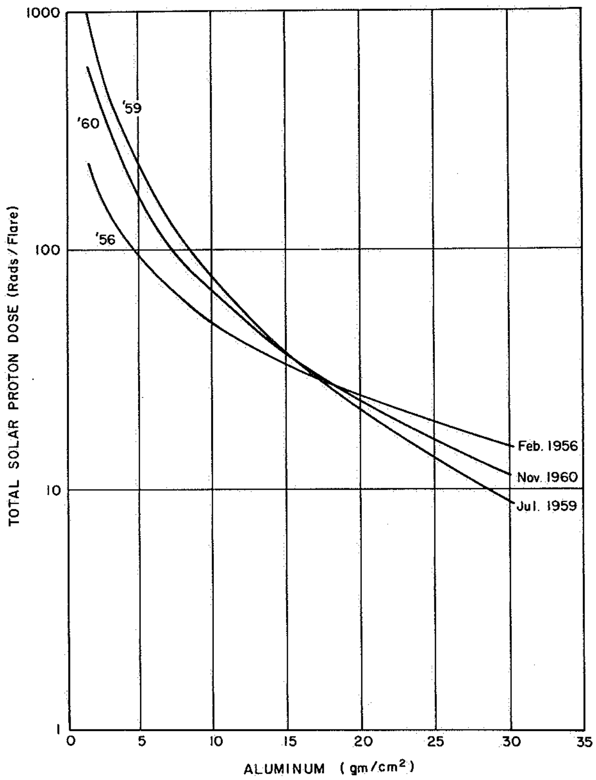


FIGURE 10. ACCUMULATIVE DOSE THROUGH VARIED THICKNESSES OF ALUMINUM FROM SOLAR PROTONS AND COSMIC RAYS

a computer code to calculate number, energy and dose penetrations for both normal and isotropically incident electrons. More sophisticated analytical codes have been written to calculate in a reasonable fashion the bremsstrahlung production and penetration in various materials. These codes are quite useful in obtaining realistic estimates of electron and bremsstrahlung doses in satellite orbits [24]. Results based on their application will be presented later in this report.

ELECTRON INTERACTIONS

The interactions of electrons with matter are extremely complicated and are of current concern to the studies of quantum electrodynamics and quantum field theory. Recently, M. E. Rose suggested that the picture might be further complicated by the facts that the electron sees a multipole nuclear field [25] and that bremsstrahlung emission can occur from both the electron and the nucleus. Because of its intrinsic difficulty, both theoretically and experimentally, the work on electron interactions has been characterized by intense interest and close cooperation by a highly select and specialized group of people. Experimental work has progressed at General Atomic [26] and Ling-Temco-Vought [27] and theoretical work has been done at General Atomics [26], National Bureau of Standards [28], and Union Carbide Corporation [29].

The agreement between theory and experiment has advanced satisfactorily as shown in Figures 11-13, [26, 27]. The experimental work has required painstaking effort to avoid background problems [30]. The theoretical effort has become quite involved in the truncation of series [31] for greatest accuracy, the sophistication of Monte Carlo techniques [32], and the evaluation of integrals which resist conventional approaches [33].

The interactions of electrons with matter are of basic importance for shielding of personnel and equipment on space vehicles from electrons in space. The present investigations were prompted by inadequacies in existing experimental data and theoretical methods.

An effort was undertaken to provide the shield designer with a straightforward, sufficiently accurate formula for establishing bremsstrahlung dose

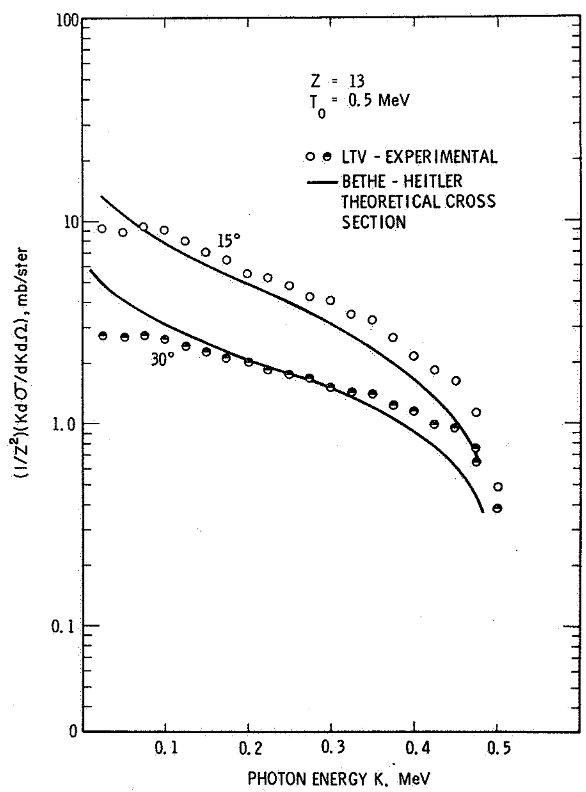


FIGURE 11. THIN TARGET DIFFERENTIAL CROSS SECTIONS

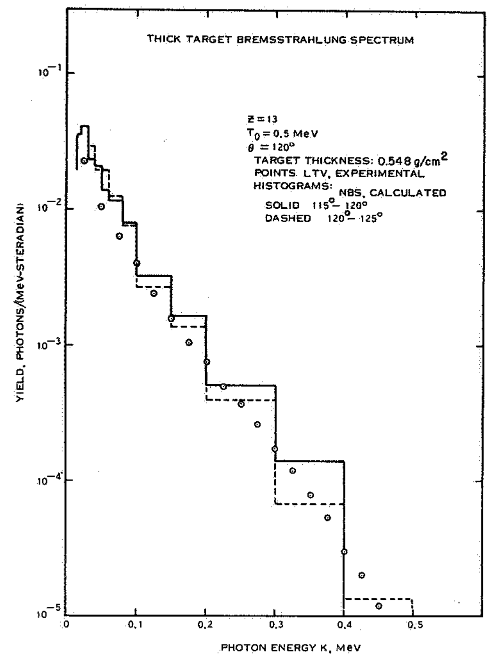


FIGURE 12. THICK TARGET BREMSSTRAHLUNG SPECTRUM

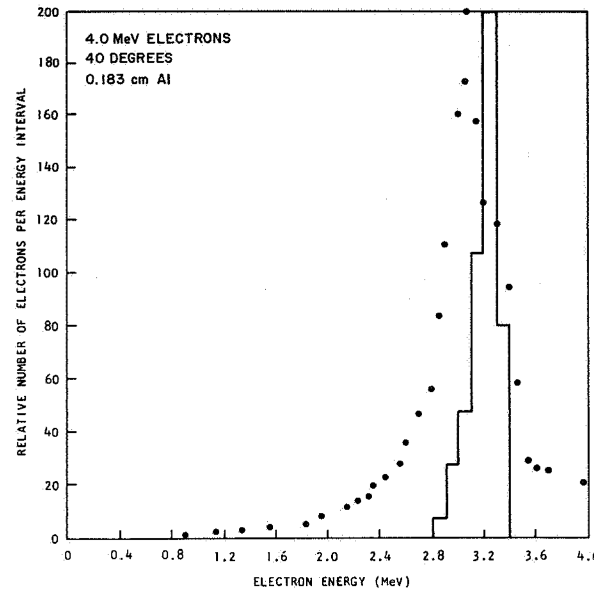


FIGURE 13. ELECTRON ENERGY SPECTRUM AT FORTY DEGREES FOR A 0.183-cm THICK ALUMINUM SLAB TARGET

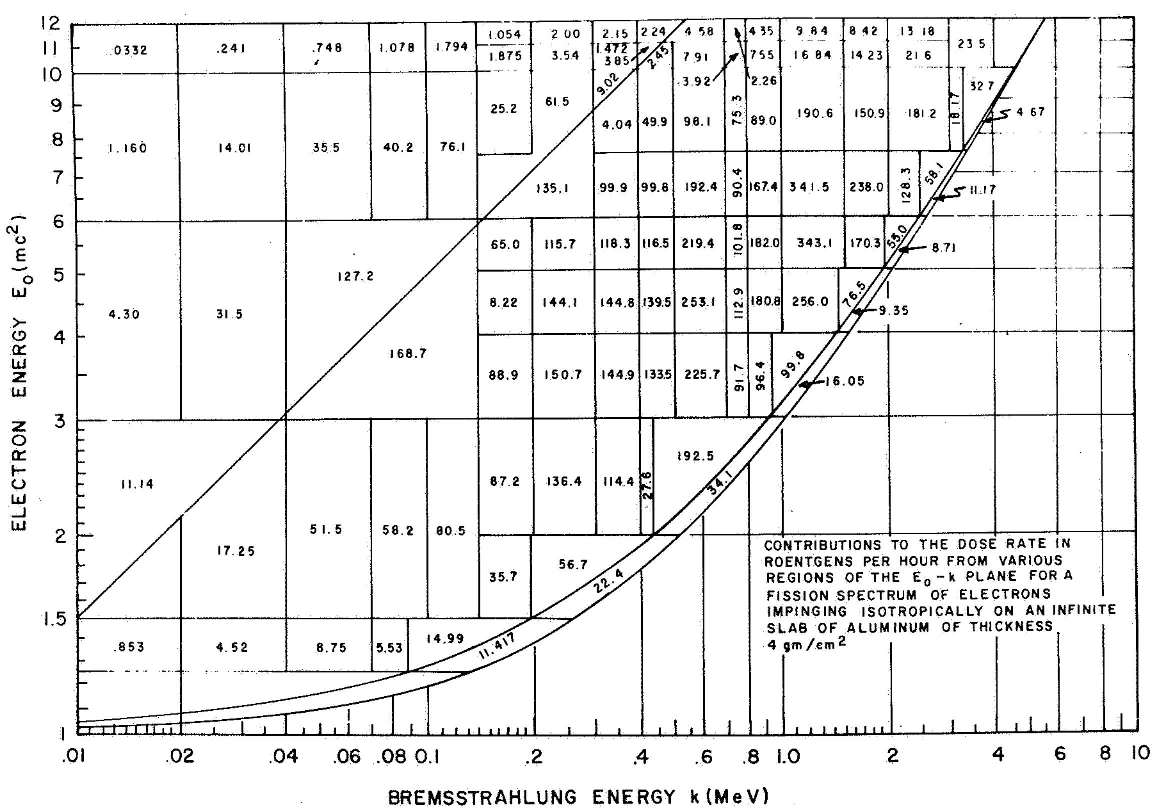


FIGURE 14. ERRORS IN BREMSSTRAHLUNG DOSE CALCULATION DUE TO INACCURACIES IN INPUT CROSS SECTION DATA

as a function of incident electron spectrum and shield parameters [34-35]. One of the essential problems was to estimate the errors incurred in the calculated result due to inaccuracies in the input bremsstrahlung production cross section data. Some of the results of this effort are shown in Figure 14 [35]. The detailed explanation of this work is in the process of being published. An interesting calculation associated with the above work was performed by M. O. Burrell and is shown in Figure 15. Here, the integrated proton flux at the end of each orbit is plotted and compared to an accumulative average. The high points are associated with passages through the South Atlantic anomaly.

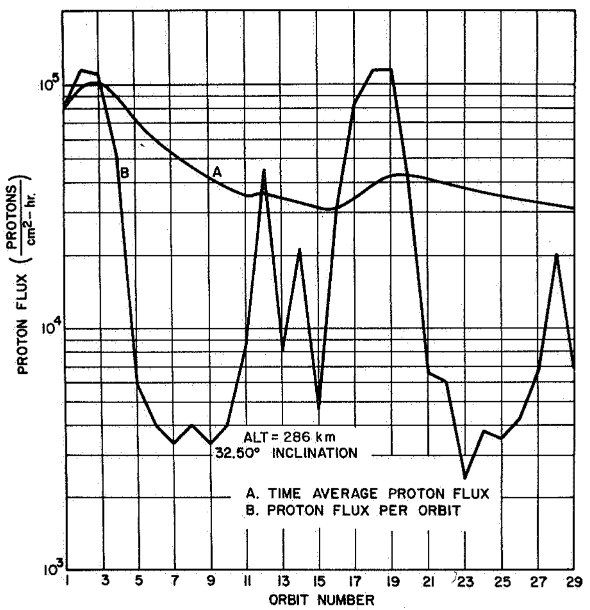


FIGURE 15. PROTON FLUX CURVES FOR EARTH ORBITS

REACTOR RADIATION SHIELDING

Comparison, Evaluation, and Shield Calculation Methods

Work was undertaken [37] to effect a comparison and evaluation of various shield calculation methods as applied to typical reactor systems for nuclear rocket propulsion. To this end, two simplified reactor-shield configurations were chosen, and insofar as possible, the same cross section input data were used in all calculations.

Three classes of calculation methods were employed: point kernel, discrete ordinates or angular segmentation, and stochastic or Monte Carlo. Two or more existing operational programs of each type were considered.

Criteria adopted for code evaluation include the following:

(a) Type and detail of data obtainable

(b) Flexibility for treatment of system configuration, radiation sources and types of radiation interactions

(c) Computer running time and time required for problem preparation

(d) Relative difficulty of operation

(e) Comparative accuracy of output.

Results of the study are presented in Lockheed-Georgia Report ER-8236, Evaluation of Methods for Computing Nuclear Rocket Radiation Fields.

Two figures relating to this work [38] are shown below. Figure 16 gives an outline of the two shield models which were used in the calculations. Figure 17 shows a dose rate traverse computed for configuration A, using five different calculational methods.

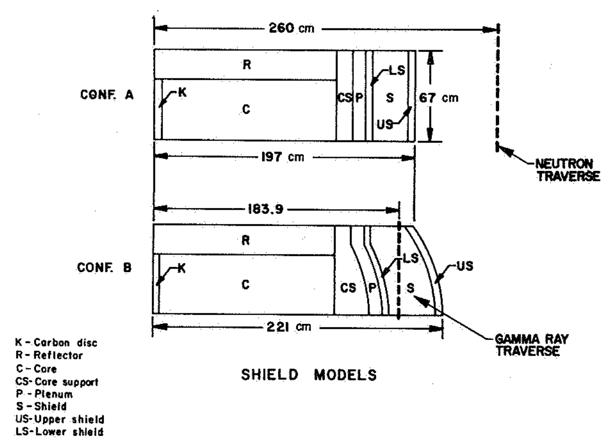


FIGURE 16. RADIATION SHIELD MODELS USED IN COMPUTING NUCLEAR ROCKET RADIATION FIELDS

A follow-on study is planned that will choose one or perhaps two of the most promising methods, convert these to Fortran IV, check them on MSFC computing equipment and train personnel in their operation.

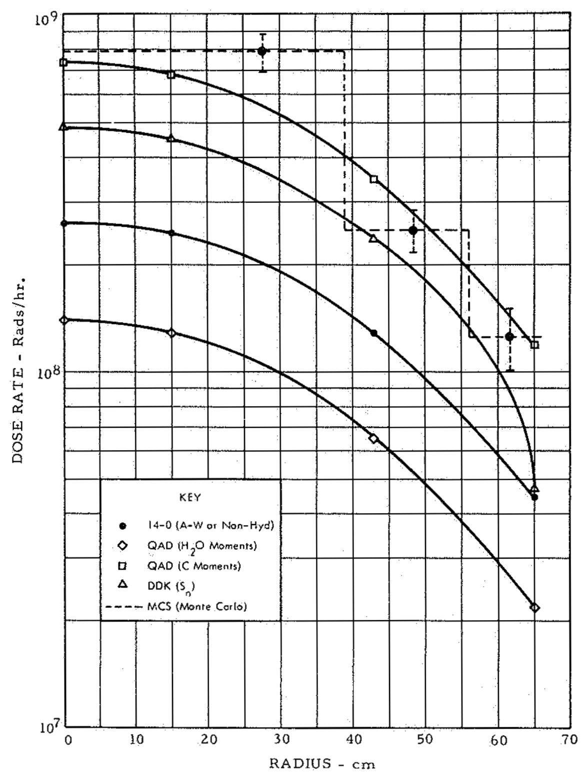


FIGURE 17. NEUTRON DOSE RATE TRAVERSE USING DIFFERENT CALCULATION METHODS

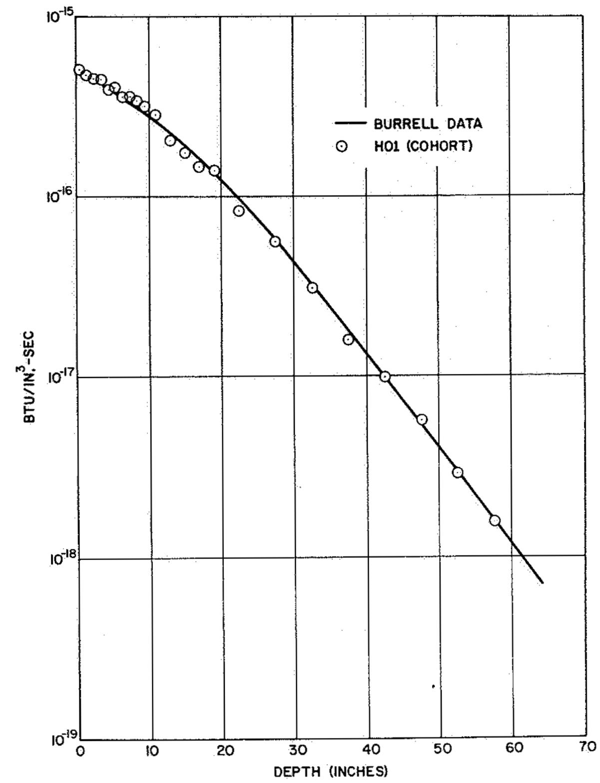


FIGURE 18. HEAT DEPOSITION VERSUS DEPTH FOR 7 MeV NEUTRONS IN A LIQUID HYDROGEN SLAB

Development of Machine Codes for Calculating Radiation Fields in Nuclear Rockets

The development of a Monte Carlo calculation program to predict the dose and heating inside and outside typical nuclear rocket reactor shield systems and in the hydrogen fuel tank has been in progress for several years. A current contract [39] with Radiation Research Associates, Fort Worth, should result in a completely checked-out Fortran IV version of the program (called COHORT) and in the training of MSFC personnel to operate the program on the MSFC computing equipment. Essentially all of the component routines have now been checked out, and some sample test problems have been run. One simple geometry problem is that of determining heat deposition in a semi-infinite slab of hydrogen. Results of this calculation for a normally-incident plane beam of 7-megaelectron-volt neutrons are shown in Figure 18 [40], together with results determined previously by Burrell [41] using his special purpose hydrogen heat deposition code.

Radiation Research is also planning to use COHORT on one of the sample configurations employed by Lockheed-Georgia in their shield evaluation study to obtain a direct comparison against other calculation methods.

ELECTROMAGNETIC SHIELDING

The research program on active or electromagnetic shielding has continued in two main areas: analysis of the motions of charged particles in magnetic fields, and advancement in the development of superconducting magnets that will be required for such shields.

Two types of active shields have been shown to be competitive with passive or bulk shielding from the standpoint of system mass: (1) The magnetic shield which employs purely magnetic forces to deflect charged particles away from a spacecraft, and (2) the plasma shield which repels positively charged particles electrostatically while being held in position around the spacecraft by a magnetic field. Magnetic shields have earlier been shown [42, 43] to be feasible and competitive provided the shielded volumes are large enough and allowable primary dose rates for extended missions are set low enough. Plasma shields, because they require much smaller magnetic fields and therefore lighter magnetic structures, could be considerably lighter than either passive or purely magnetic shields for all shielded volumes and dose rate requirements. However, the rather early state of research on the plasma shield concept and the fact that it has not yet been demonstrated that a successful plasma shield concept can be built prevents any firm predictions of the competitive positions of magnetic and plasma shields.

Charged Particle Motion

Several aspects of the theory of charged particle motion in axially symmetric magnetic fields were extended during the past year. A theoretical treatment of the problem of specifying the shielding capabilities of general axial field configurations, and application to some particular fields was published [44]. Figure 19 shows a number of limiting cases for charged particle exclusion from the vicinity of a pair of coaxial current loops whose symmetry axis is the vertical axis. This general work was also extended [45] to a case of geomagnetic interest - a dipole plus coaxial quadrupole. Related work was also carried out under the laboratory support contract. This work resulted in an annotated bibliography [46] of the literature on charged particle motion and magnetic shielding. More recent studies under this task [47] are considering the permissible particle fluxes in the vicinity of a dipole field (plus various equatorial current ring configurations) and of the fields of solenoids.

Development of Superconducting Magnets

Work to advance the physics and technology of large, high field superconducting coils was actively pursued over the past year with five contracts [48-52] covering a number of areas of investigation.

The chief topic of concern was the attempt to understand in detail supercurrent instabilities in

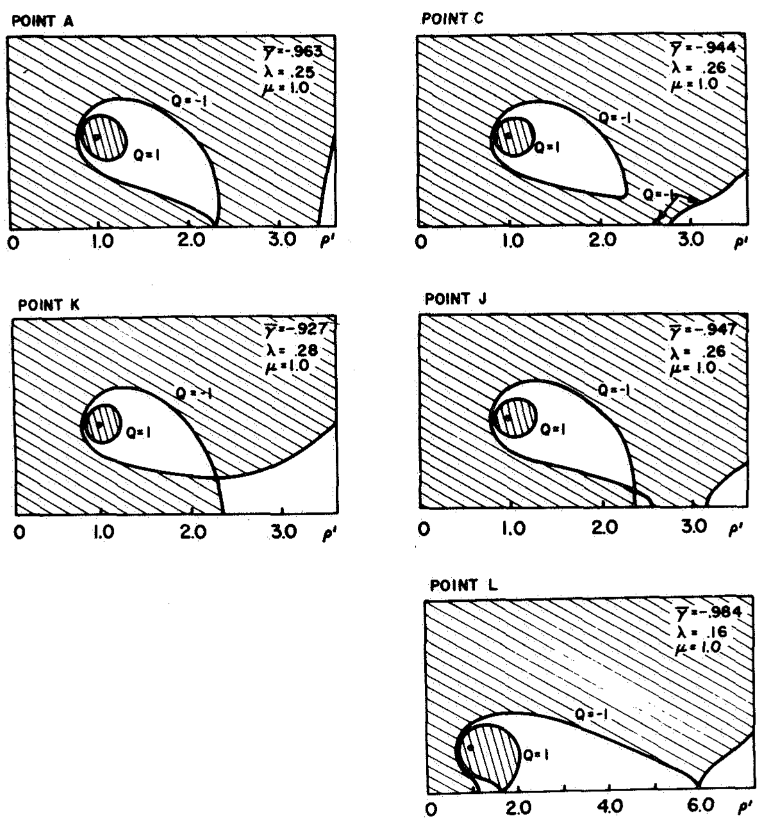


FIGURE 19. CRITICAL POINTS IN THE (ρ , θ) PLANE OF A DOUBLE-PARALLEL LOOP SYSTEM

superconductors. These instabilities, due to nonuniform flux motion through the magnetic windings as the field is changed, prevent the attainment of theoretically possible fields without the use of involved and expensive metallurgical and manufacturing methods. The effects on these instabilities due to metallurgical structure and history, conductor shape and winding configurations, and magnetic and thermal environment were the subject of considerable research effort [53-64]. Other work covered the changes in superconductive properties due to nuclear irradiation [55], microprobe techniques for mapping field and current distributions within coil windings [62, 63], flux pumping techniques for energizing high current windings by means of low current power sources [64], and use of the superfluid properties of Helium II to improve the cooling within tightly wound magnets without separate cooling passages [64].

Work performed under this program and by other organizations continues to advance the magnetic field strength and working volume of superconducting magnets as illustrated in Figure 20. The devices indicated by X are the more important of those tested or under construction during the past year. Shown also are the field-volume combinations which will be required for magnetic and for plasma shields. As magnet sizes and field strengths increase, problems of providing an environment of liquid helium for refrigeration, of providing structural strength to withstand the high magnetic forces, and of providing access to the useful high field region become correspondingly more serious, and costs rise accordingly - hence the small number of new devices.

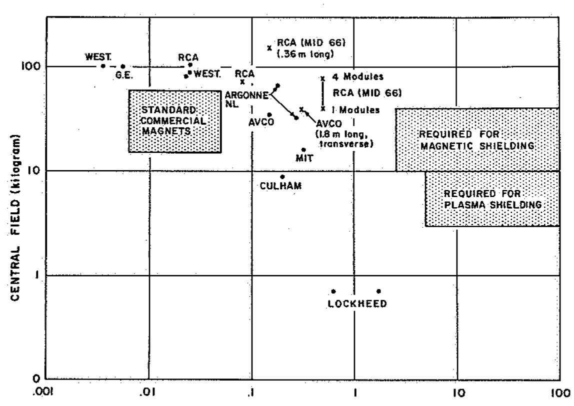


FIGURE 20. SUPERCONDUCTING MAGNETS, JANUARY 1966

The Plasma Shield Concept

The recent plasma shield work at Avco [65] has been characterized by active theoretical work and the construction of new experimental apparatus. Several lines of important collateral research seem to be developing along with the plasma shield. The plasma shield concept [66] shown in Figure 21 is as follows: By means of a strong magnetic field supplied by superconducting magnets, electrons are removed and excluded from the space vehicle, which assumes a positive charge. The electric field provided by the charge separation protects the spacecraft from energetic positively charged particles.

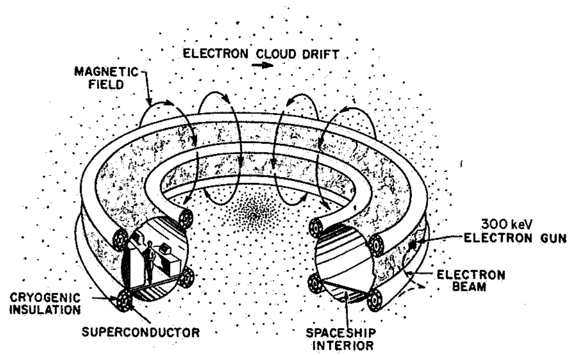


FIGURE 21. SCHEMATIC DIAGRAM OF A SPACE VEHICLE USING A PLASMA RADIATION SHIELD

The interesting feature of the plasma shield is that it establishes an electric potential hill on the inside of a magnetic field about which a cloud of electrons migrates. The electrons can move across the field to the positively charged region only by collisions with each other or with neutral gas atoms and ions. By measuring the rate of electron migration, it is speculated that gas pressures as low as 2.67×10^{-16} newtons per square meter can be measured.

By inverting the configuration so that electrons are on the inside of the magnetic field, there is created a potential well into which positive ions can be injected and contained at very high energies. This means that the plasma shield concept could evolve into a high-energy reaction chamber [67] useful for studying collision and nuclear processes. It is also possible to think of the device as a high voltage generator. The voltages which the developers think will be feasible are shown in Figure 22 [66].

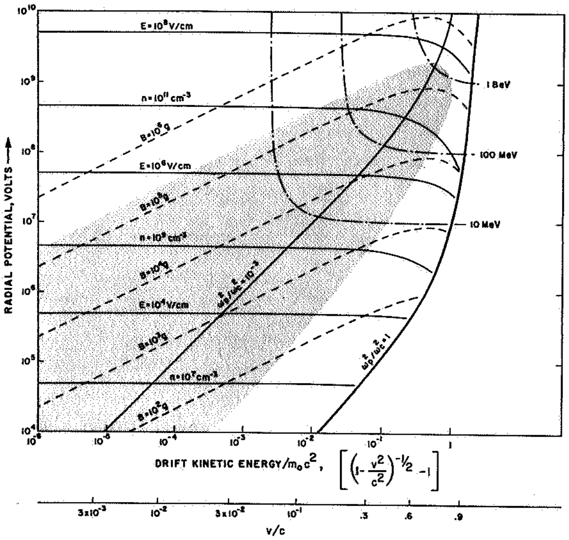


FIGURE 22. MAP OF ONE-METER ELECTRON PLASMA CONTAINMENT DEVICE

Another possibility consists of using the device as an oscillator at microwave frequencies [68] with the ability to radiate over a widely adjustable frequency range without wave guides and antennae.

PARTICLE POPULATIONS AND METEOROID DISTRIBUTIONS

The behavior of particle swarms has been studied (1) for the purpose of providing the physical framework for understanding measured distributions of meteoroids and dust particles and (2) for computing the relative hazards associated with dispersions by explosions in orbit and on the lunar surface. The relation of the distribution functions to such parameters as satellite motion, distance from the earth, meteoroid velocity and direction of injection has been discussed in a series of published papers [69-73]. Present work is concerned with the distribution of debris on the lunar surface by active seismic shots [74].

A recent study of bound orbits [75] published by Hale and Wright in the JGR, resulted in data such as that shown in Figure 23, which shows what happens to particles injected isotropically at various altitudes as a function of injection velocity. The most interesting feature of this study is the fact that the flux maximum for such distributions always occurs at less than 1.5 earth radii away from the center of the earth. The fraction of particles in surviving orbits to total particles injected isotropically at r_0 is shown in Figure 24 [75].

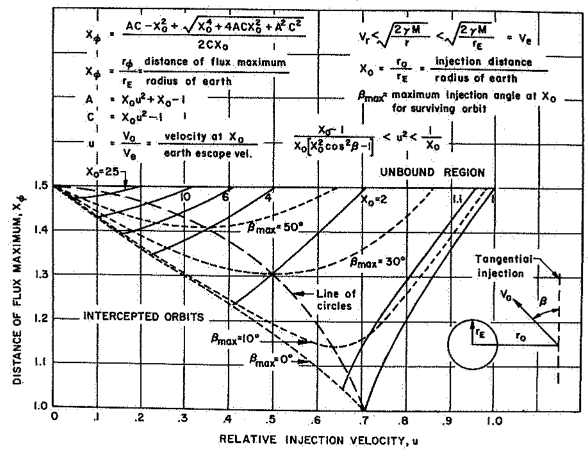


FIGURE 23. RADIAL DISTANCE OF FLUX MAXIMUM FOR BOUNDED PARTICLES

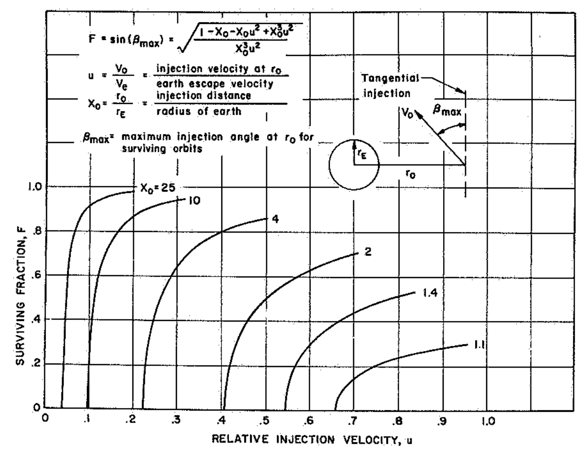


FIGURE 24. FRACTION OF PARTICLES IN SURVIVING ORBITS TO TOTAL PARTICLES INJECTED ISOTROPICALLY AT r_0

ELECTRONIC CHARGE STORAGE PHENOMENA

In order to learn more about the phenomena resulting from electronic charge storage in dielectrics in general and the observable effects in particular to be expected when Pegasus panels are subjected to the electron bombardment in the charged particle belts around the earth, a small experimental program was undertaken under contract with Lockheed-Georgia Nuclear Laboratories. To this purpose, a specially designed strontium-yttrium beta ray source was fabricated by the Isotope Division of the Oak Ridge National Laboratory. The source (Fig. 25) comprises

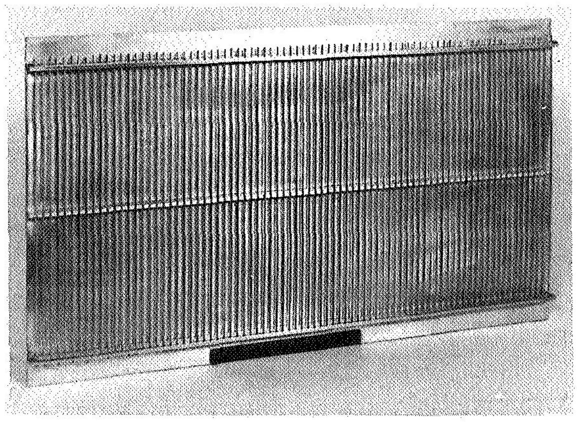


FIGURE 25. STRONTIUM-YTTRIUM BETA RAY SOURCE

80 tubes with an active length of about 20 inches (51 centimeters) and a total source strength of approximately 800 curies. Assembled in a rectangular array, the source provides an essentially uniform irradiation flux of about 5 x 10^8 electrons per square centimeter per second over an area of about 20 inches by 40 inches (51 centimeters by 102 centimeters) at distances a few centimeters from the tube surfaces.

The contractor, using this source, an environmental chamber constructed previously under an unrelated NASA contract, and one of the large hot cells available at the Dawsonville Nuclear Laboratories, assembled and instrumented an experimental arrangement to test a Pegasus panel under electric bombardment in a cryogenic and vacuum environment. A vacuum of 6.66 x 10^{-4} newtons per square meter was obtained, with temperature down to 208° K. Principal instrumentation consisted of an oscilloscope and camera to record pulse size and shape and a timing circuit. Typical circuit arrangements are shown in Figure 26.

For the experimental configuration employed, a multitude of pulses have been observed. The largest pulse seen was 2.4 volts; all others were below 2 volts, with the majority in the 50- to 200-millivolt range. Pulses of both polarities result, apparently independent of the impressed voltage. At 208° K a discharge rate of 1/2 pulse to 1 pulse per minute was observed. As the temperature is increased, the pulse rate decreases until at about 258° K no pulses are observed. The size of the pulses seems to indicate that the capacitor is breaking down only locally.

Hopefully a follow-on study can be conducted in which an environment more nearly like that

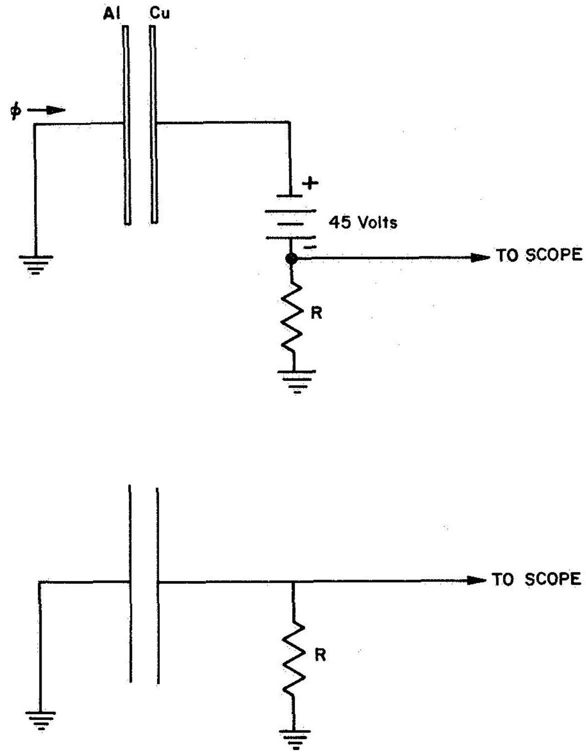


FIGURE 26. PEGASUS OSCILLOSCOPE CIRCUITS

encountered by Pegasus satellites can be simulated. In particular, plans are being made to vary the temperature through a cycle of 233° to 313° K, try to cycle the radiation intensity, use a filtering network such as that used in flight and perhaps test a "hit microplane" in the radiation environment. Additional measurements will help materially to understand the basic discharge mechanism, and successively smaller rings will be etched in one of the panels to effectively produce capacitors of different areas. Plans also specify the use of different panel thicknesses, different type capacitors, and to test more carefully for effects of temperature on pulse size and frequency.

PROJECT SUPPORT

ORBITAL AND TRAJECTORY CODES FOR RADIATION DOSE CALCULATIONS

The objective of this work was to develop computer codes that provide the integrated electrons and proton flares and energy spectra encountered by a spacecraft orbiting or traversing the trapped radiations surrounding the earth. First, the coordinates of the satellite as a function of time were computed from the six orbital elements defining the particular mission. These coordinates were then converted into the B-L coordinates of McIlwain's [76] using a

48-term expansion [77] for the magnetic field of the earth. Using the data compilation of Vette's [78], the magnetic coordinates were used to find energy spectra and fluxes for each coordinate point. A time integral of the radiation exposure was then made and penetrations were calculated.

Among the various project-oriented tasks undertaken by using the orbital and trajectory codes during the past year was the evaluation of the space radiation hazard in the SIV-B hydrogen tank, the radiation hazard and shielding requirements in a synchronous orbit, and the radiation dose analysis of six trajectories to the moon. The latter work was performed for NASA Headquarters after help in evaluating conflicting results obtained by two industrial contractors. Figure 27 represents a summary of the SIV-B workshop radiation hazard analysis. Figure 28 is a typical curve of the electron and bremsstrahlung hazard in a synchronous orbit, and Table VI gives the shelter weight requirements for a synchronous orbit where the radiation is about 40-rads skin dose and about 25 rads at the bone marrow. Figure 29 shows the radiation doses from electrons and bremsstrahlung for three different trajectories to the moon starting at a parking altitude of 200 kilometers above the earth. The important point of this graph is the extreme variations in radiation dose along different escape orbits through the trapped radiation belts.

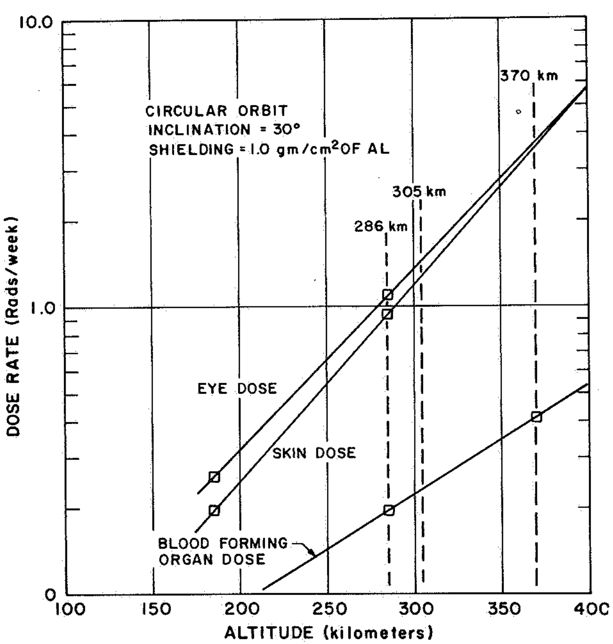


FIGURE 27. SPACE RADIATION DOSE FOR ONE WEEK EXPOSURE IN THE S-IVB HYDROGEN TANK

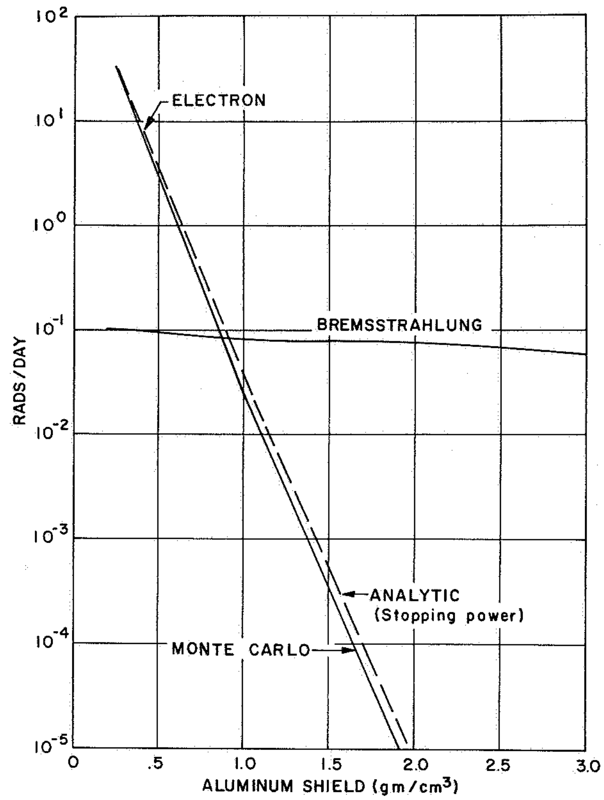


FIGURE 28. SYNCHRONOUS ORBIT ELECTRON DOSE

TABLE VI. SHELTER WEIGHT REQUIREMENTS FOR A SYNCHRONOUS ORBIT DUE TO ELECTRON AND BREMSSTRAHLUNG HAZARD

	$(CH_2)_n$	AL
INSIDE CM		
THICKNESS	10 cm	5.3 cm
MASS	1313 kg (2890 lbm)	1810 kg (3980 lbm)
OUTSIDE CM		
THICKNESS	15 cm	7.5 cm
MASS	2080 kg (4420 lbm)	2750 kg (6050 lbm)

NUCLEAR GROUND TEST MODULE

There were no specifically identified radiation studies associated with this effort, although the air scattering capabilities of the COHORT machine code were designed with possibilities such as ground testing of nuclear rockets in mind.

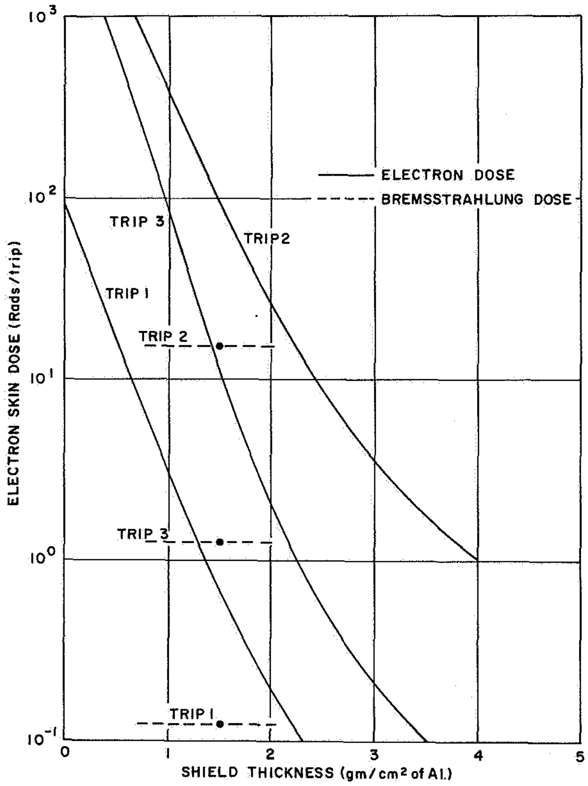


FIGURE 29. ELECTRON AND BREMSSTRAHLUNG DOSE CURVES

EXPERIMENT INTEGRATION

Experiments will be exposed to the radiation naturally present in space and to radiation associated with space power supplies using radioisotopes or reactors. In addition, the experiments may depend on other components such as solar cells or external cables that are also sensitive to radiation. Table VII lists other areas which will receive considerable attention in such experiments. It is probable that the interpretation of certain radiation measurements will require extensive analysis from the radiation transport viewpoint. For example, a measurement of neutron albedo from low orbit must be concerned with such factors as neutron production in the atmosphere by high energy protons, propagation of neutrons through the atmosphere and production of neutrons within the spacecraft itself. From the experiment viewpoint, the particular interest in radiation will depend on what is being measured, the degree of radiation exposure and whether or not the effects of radiation on other parts of the spacecraft are harmful to the particular experiment. No enlightening formula for predicting the importance of radiation to experiments can be given, but a number of specific examples are now past history. If radiation affects the temperature central surfaces, the experiment will suffer. If the solar cells are insufficiently shielded, they may be overexposed by radiation. If external points are good insulators, they may store charges and produce electric fields intense enough to interfere with interpretations of plasma measurements that are already difficult enough to interpret. If charged particle radiation is stored in dielectrics to the extent that catastrophic breakdown occurs, the electric signals produced could feed into the spacecraft logic system and cause spurious counts. Radiation-induced conductivity and spurious currents can also occur. These and other problems are associated with radiation in space, and there will undoubtedly be new experiments and new problems with even worse radiation environments.

TABLE VII. RADIATION AND EXPERIMENT INTEGRATION

SOLAR CELL DAMAGE
CHANGE IN TEMPERATURE CONTROL SURFACES
RADIATION PRODUCED IN SPACECRAFT
RADIOISOTOPE POWER SUPPLIES
RADIOISOTOPE APPLICATIONS
CHARGE STORAGE AND ELECTRICAL DISCHARGES
SPURIOUS CURRENTS
INDUCED CONDUCTIVITY
FILM DARKENING
ASTRONAUT EXPOSURE

PEGASUS DATA

Before the Pegasus satellites were launched, there was concern that the electrons in the Van Allen belts would be stored in the dielectrics of connecting cables and capacitors and that subsequent electrical discharges would be counted as meteoroid hits. The problem was circumvented by using the lowest possible orbits and designing the electronic circuitry to discriminate against pulses of the wrong size, shape, or polarity.

To confirm that electron fluxes were low enough to prevent spurious discharges, a simple two-threshold electron spectrometer (Fig. 30) was carried on each spacecraft. Much valuable data have been collected on the distribution of electron fluxes in the South Atlantic anomaly region of the radiation belts. A typical plot in B-L coordinates of Pegasus I data is shown in Figure 31, together with predicted fluxes for the same time period.

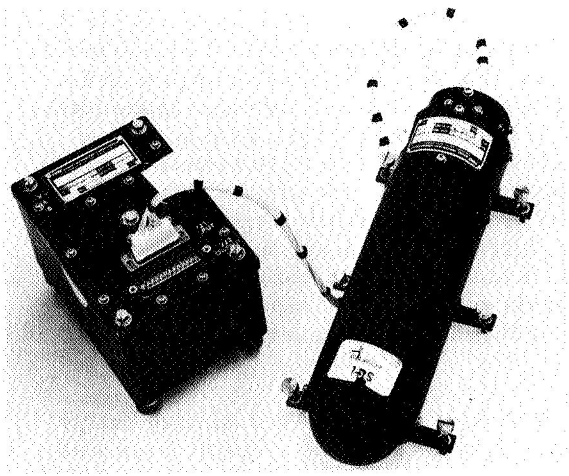


FIGURE 30. PEGASUS ELECTRON SPECTROMETER

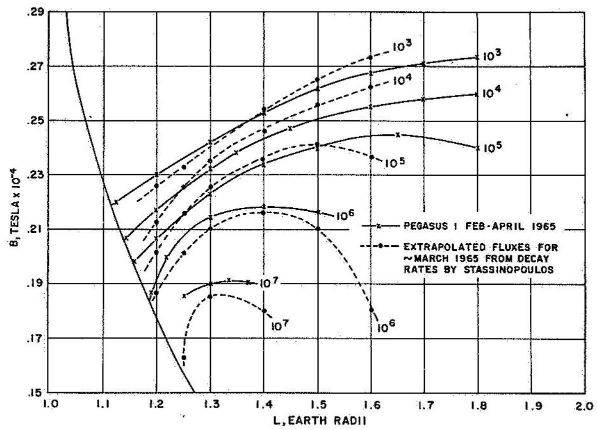


FIGURE 31. PEGASUS ISOFLUX CONTOURS FOR ELECTRONS

ADVANCED PROPULSION

Almost every advanced propulsion system for manned exploration envisions the use of nuclear power in some form and is motivated by the desire for longer voyages in space. An artist's concept of one such system is shown in Figure 32. The neutron and gamma radiation from the reactors must be shielded, and since greater distances are to be covered, man is exposed to space radiations for longer periods of time. In a recent paper [79], the radiation problems associated with a nuclear, nuclear-electric spacecraft were studied for a manned Mars expedition. Radiation sources considered were Van Allen belts, solar flares, cosmic rays, a nuclear heat exchanger reactor and a nuclear electric power supply. Because the flight was planned to occur during a period of relatively quiet sun, the dominant radiation dose came from the reactor systems. A typical reactor shield design is shown in Figure 33. Tungsten is employed primarily as an efficient gamma-ray shield; lithium is used primarily to attenuate neutrons. The shield is heavily contoured to reduce the weight of the system and is left unshielded in directions in which the radiation will neither strike personnel or equipment nor scatter off structural members of the spacecraft. Because of the shield shaping, personnel activities about the spacecraft would have to be carefully controlled. Specifications for the shield system are given in Table VIII.

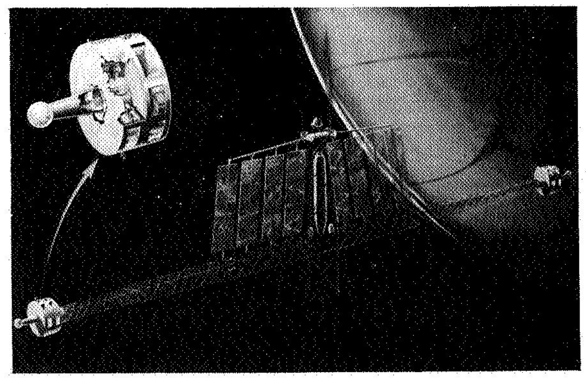


FIGURE 32. ELECTRIC SPACESHIP FOR MANNED MARS FLIGHT

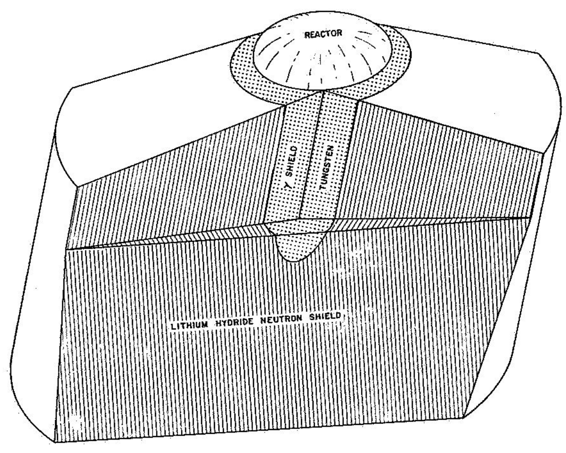


FIGURE 33. REACTOR SHIELD FOR ELECTRIC SPACESHIP

TABLE VIII. REACTOR SHIELD SPECIFICATIONS FOR THE NUCLEAR ELECTRIC SPACESHIP

REACTOR POWER (THERMAL)	134 MW
ELECTRIC POWER	20 MW
URANIUM LOADING (U^{233})	4.5×10^3 kg
REACTOR MASS	1.2×10^4 kg
LiH MASS	1.7×10^4 kg
TUNGSTEN MASS	3.3×10^4 kg
TOTAL REACTOR AND SHIELD MASS	6.2×10^4 kg

RADIOISOTOPE APPLICATIONS AND INSTRUMENTATION

The interposition of matter between a radiation source and a radiation detector reduces the signal received by the detector. Since the days of Roentgen, this phenomenon has had wide application for determining the distribution of matter in inaccessible places. The use of gamma rays to evaluate proton and electron shields is essentially the classical X-ray technique with emphasis on Compton scattering, which is sensitive to electron areal density, the determining factor in proton shielding. The diagnosis of scattered as well as transmitted radiation is also of importance in many applications. The value of radioisotope tracers was demonstrated extensively shortly after the fission process was brought under control and radioisotopes became easily available. The Mossbauer effect made possible the use of radiation sources to determine relative motion between a source and detector and introduced a new kind of velocity meter and accelerometer.

RADIOISOTOPE FUEL GAUGE

The determination of the amount of propellant in a tank under zero gravity conditions is not a straightforward matter. One way to do it is to "X-ray" the propellant mass by means of several radioisotope sources and radiation detectors and to compute the mass from the measured radiation attenuations [80]. How well this technique works has not been demonstrated under space conditions, but is expected to be tested on the LEM descent module in MSFC Experiment No. 3.

VAPOR QUALITY METER

To insure proper pressure regulation in a tank containing liquid hydrogen, it is necessary to vent the vapor boiling off because of heat leakage into the system. However, it is important to prevent the ejection of liquid along with the vapor as the liquid sloshes or undergoes redistribution because of vehicle motion or surface tension forces in a zero gravity environment. The purpose of the vapor quality meter is to measure the density of hydrogen in the hydrogen vent line and thereby determine if liquid is escaping. The vapor quality or Q-meter was developed for use with the LH_2 experiment on Vehicle 203, and may also be flown on Vehicles 501-503.

There are several designs of vapor quality meters. In one design [81] useful for large pipes, gamma radiation is scattered by the volume of interest according to the mass of hydrogen there. The scattered photons are reduced in energy and may be analyzed selectively to yield a signal proportional to the mass of hydrogen viewed jointly by the radioisotope source and radiation detector. In another design [82] useful for smaller pipes, the reduction of beta transmission from source to detector is analyzed to determine the quantity of liquid present in the vent line.

The extent to which radioisotope quality meters will be applied is not determined at this time, although their use appears certain. The addition of one Curie of Americium 241 in the meter using the gamma-scattering technique presents problems from the safety and interference viewpoints, and it may happen that the degree of application will depend on the development of a design which uses a very small beta source.

LEAK DETECTION

The use of radioisotopes for leak detection [83] is based on the assumption that a radioactive gas under pressure will enter a leaky component which has been previously outgassing in a vacuum. The leak rate is determined by how radioactive the component becomes and how fast it decays. So far the process seems to be well understood, but there is a problem of correlating the radioisotope method with mass spectrometer techniques.

RADIOISOTOPE STAGE SEPARATION INDICATOR

The use of radioisotopes to measure distance depends on the fact that the radiation intensity obeys the inverse square law, i.e., the intensity of radiation falling on a detector varies inversely as the square of the distance between source and detector. In one proposed system [84] the relative position between two planes (the interface between two stages) is to be determined by using three sources in one plane and six detectors in the other.

NEUTRON SPECTROMETER

A satisfactory method for measuring neutron spectra has not yet been developed although this problem has been attacked vigorously since nuclear fission was achieved. The RIFT program introduced the requirement of measuring neutron fluxes and energy spectra in a large nuclear stage filled with hydrogen and powered by a reactor operating in the gigawatt levels. In almost all cases the neutron spectrometer must operate in a gamma-ray background to which it must be relatively insensitive. Also, it must be designed so that it does not saturate in relatively high-level neutron and gamma fluxes or be too sensitive to spurious signals in a low-level radiation environment.

The neutron spectrometer under development [85] by IITRI uses the exoergic reaction ${}_0N^1 + {}_2He^3 \rightarrow {}_1P^1 + {}_1H^3$ + 800 kiloelectron volts in a small chamber filled with He^3 gas. To discriminate against noise, the chamber is divided into two parts (acting as proportional counters); a solid state detector is then placed on each end of the chamber. By adding the four pulse contributions and incorporating the proper coincidence requirements, a neutron spectrometer capable of operating in rather intense fields has been obtained. In a recent test [86] this device shows a count rate of 5×10^3 counts per minute in a gamma field of 10^6 roentgens per hour, or roughly 10^{11} photons per square centimeter per second. A neutron flux of 10^8 neutrons per square centimeter per second would produce roughly ten times this count rate. This reasonably good gamma discrimination will be necessary in the RIFT (or a similar) nuclear stage because liquid hydrogen is a poor gamma and good neutron shield, which means that neutrons will be counted in a strong gamma field.

CONCLUSIONS

The technology of radiation is common enough to provide a broad base in space engineering. The increased use of radioisotope power supplies and nuclear stations for space exploration could produce a greatly increased emphasis on the aspects of radiation interactions with materials and components, and the interference of radiation sources with scientific and engineering experiments. In addition, radiation would impose operational constraints on manned missions in space, more from the biological viewpoint than from the consideration of damage to equipment. It is possible that operational aspects of nuclear systems will require considerable additional attention because of the many interesting cosmological experiments concerned with the measurements of radiations that are very similar to those arising from radioisotopes used on spacecraft and from reactors used for propulsion and power supplies.

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