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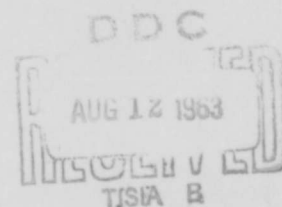
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**RADIATION-EFFECTS STATE OF THE ART
1962-1963**

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RADIATION EFFECTS INFORMATION CENTER

Battelle Memorial Institute

Columbus 1, Ohio

The Radiation Effects Information Center has been established at Battelle Memorial Institute by the United States Air Force to provide a means of placing radiation-effects data in the hands of designers and those conducting research and development. Access to the Center and to its reports is obtained through the Air Force. This report has been prepared pursuant to the provisions of Contract No. AF 33(657)-10085 [Continuation of AF 33(616)-7375], Task No. 738103, Project No. 7381 & 7634.

REIC Report No. 28
June 30, 1963

Report on

RADIATION-EFFECTS STATE OF THE ART

1962-1963

to

AIR FORCE SYSTEMS COMMAND

AERONAUTICAL SYSTEMS DIVISION

RADIATION EFFECTS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

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Note: This report was prepared by Battelle Memorial Institute under Contract No. AP 33(657)-10085 [continuation of AF 33(616)-7375] for use of the Air Force. The following Battelle staff members contributed to this report: D. J. Hamman, E. N. Wyler, W. E. Chapin, W. H. Veazie, Jr., F. R. Shober, F. J. Reid, B. P. Fairand, R. F. Redmond, Mrs. H. C. Gillette, and Mrs. E. G. Domingo.

Report on
RADIATION-EFFECTS STATE OF THE ART

1962-1963

SUMMARY

Generalized conclusions related to radiation effects on various materials, components, and systems include:

- (1) More experimental effort is still needed in studying combined effects of radiation and other environments. Of particular interest are the combination of radiation, extreme temperatures, and ultrahigh vacuum. In the ultrahigh-vacuum area the main interest should be concentrated on organic-materials. Although much is known concerning the loss of material due to evaporation and sublimation, very little is known concerning the effects of these material losses on the physical strength and electrical characteristics.
- (2) More research effort should be devoted to developing means for shielding materials, devices, and systems with known susceptibilities to radiation damage as a parallel effort, with research being conducted to increase resistance to radiation damage.
- (3) More information is needed concerning the effects of space radiations on materials, devices, and components.

Electronic Components and Equipment

During the 1962-1963 interval, reports available at REIC show that techniques and procedures for conducting radiation-effects research continue to improve. Because of wide variation in laboratory techniques for setting up experimental facilities and the recognition that combining of data generated becomes difficult, experimenters show a trend for standardizing procedures, and effort directed toward producing guides for conducting such research appears likely in the future. The main problem from the experimental-setup standpoint is with transient radiation experiments which appear to increase in quantity beyond the number of steady-state radiation experiments. The loss in relative position for research efforts associated with steady-state radiation experimentation has been supplemented with studies related to space radiation. The main effort for radiation-effects research, along with transient radiation studies, has been in connection with systems and subsystems. This effort continues to grow from both theoretical and empirical standpoints.

Few research programs directed toward determination of radiation effects for resistors were conducted during the report period. Most of the programs involving resistors are more closely related to system studies which involved most of the

electronic parts and were intended to determine whether problems would be encountered because of relatively low levels of exposure (10^{13} to 10^{15} n cm⁻²). Most areas of interest for resistors have been explored sufficiently, and, at the present time, tolerance for the radiation environment has been established between 10^{12} and 10^{16} fast n cm⁻² and from 10^6 to approximately 10^{10} ergs g⁻¹(C) for gamma radiation exposure.

Research experiments related to capacitors with a wide range of inorganic dielectric and insulation materials have not been emphasized during the report period. This is mainly because more concern has been shown for the less-radiation-tolerant paper and plastic-foil capacitors. The various impregnating materials such as mineral oil and bis-ether continue to be of interest in current research. Recent efforts have been devoted to the use of Mylar; however, current results for exposures up to 6.5×10^9 ergs g⁻¹(C) have not shown sufficient improvement over the conventional paper-dielectric units. In conclusion, the present state of the art for capacitors shows them to be capable of operation after exposures to between 10^{12} and 10^{18} n cm⁻² and 10^6 to 10^{11} ergs g⁻¹(C).

Early radiation study of unmounted crystals showed that they contained considerable tolerance to high-radiation fields. Subsequent studies of various crystals cut into a variety of configurations showed some crystal cuts to be more sensitive to radiation damage than others. Recent studies of mounted crystals with known orientations, showed them to be more susceptible to radiation damage than the unmounted crystals. Thus, the present studies are for mounted crystals with relation to space, steady-state, and transient radiation environments. Typical of these are experiments where crystals were subjected to radiation exposures of 10^{10} ergs g⁻¹(C) of gamma radiation and 1.6×10^{12} protons cm⁻². Proton radiation produced a negligible frequency shift. The gamma radiation (bremstrahlung) produced a large transient and permanent frequency change.

The threshold of radiation damage for most electron tubes has been well established during past years of radiation research studies. Certain special types such as magnetrons and klystrons have not been studied sufficiently to establish firm values of radiation exposure that will not prove damaging. Current studies deal mainly with the study of failure mechanisms, which is an encouraging step in the development of radiation-resistant electron tubes.

Information needed for establishing values of radiation tolerance for transducers is extremely scarce. When the need for radiation-effects information is recognized for transducers in telemetry applications, the wide variety of types and principles of operation associated with the device will bring about concern for the enormity of the problem. Some research is currently being conducted. However, because of the high degree of specialty associated with transducers, it may be many years before the state of the art will approach that of the resistor. Many types of pressure, temperature, vibration, shock, acceleration, and strain transducers have been irradiated in the past; however, the design of the systems needing them is far beyond the present state of the art of the conventional device. Research and development for high-temperature radiation-resistant transducers are proceeding at a slow pace, and their capabilities for surviving the environmental conditions mentioned will not be known in the immediate future.

Magnetic materials and permanent magnets can be considered as one of the most radiation-resistant parts of an electronic system. Results from transient radiation experiments show them as being unaffected at flux rates approaching 10^9 ergs g⁻¹(C) sec⁻¹. The threshold of radiation damage for magnetic material ranges between 10^{16} n cm⁻² and 10^{19} n cm⁻², with the nickel-iron types being most susceptible to radiation damage.

Much is known concerning the ability of organic and inorganic insulations to surviving in a nuclear environment. The main concern at the present time is for such plastics as Mylar and Teflon which have been valuable in nonnuclear environments for many electrical applications. Some studies have indicated that their tolerance to nuclear radiation has increased substantially in the space-simulated atmospheres. The more-radiation-resistant plastics such as silicone resin glass fiber and polyurethane glass fiber are believed to possess thresholds as high as 10^{11} ergs $\text{g}^{-1}(\text{C})$. Inorganic insulations continue to monopolize applications where extremely high levels of radiation fluxes are anticipated, and the general indications are that they can be used in fast-neutron flux conditions approaching 10^{20} n cm^{-2} .

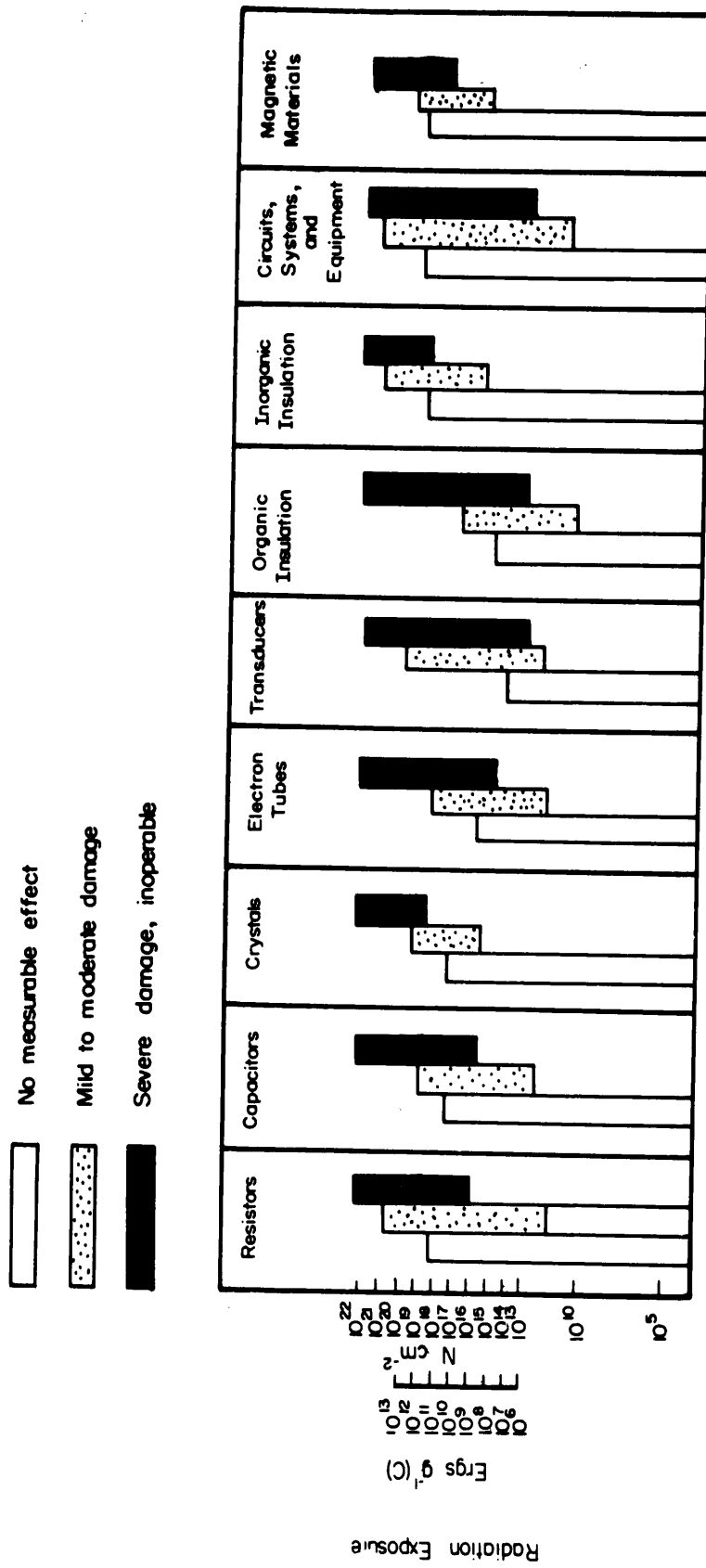
A considerable amount of effort is being devoted to known information on electronic parts and circuits in the design and evaluation of subsystems and systems. The approaches continue to follow lines established in previous years which consisted of using analog and digital computers to determine how the system will perform in the presence of steady-state and transient radiation fields. Some of the approaches are for a continued effort or radiation hardening before the final analysis is conducted. Other approaches involve actual irradiation of critical circuits after radiation-hardening processes have been completed. The main problem associated with systems and subsystems continues to be that they are far in advance in comparison to the component parts incorporated in them. Much more research is needed in the development of high-temperature radiation-resistant component parts.

Assessment of most component part and system capabilities is presented in Figure A. The bar-chart presentation was planned to show (1) radiation resistance to damage of the generic part or system, (2) what can be accomplished by judicious selection of known radiation-resistant component parts, and (3) areas where research and development are needed. The illustration does not include semiconductor devices (with the exception of the electronic parts such as transducers which now incorporate them for certain applications). In the preparation of the charts, the maximum and minimum flux levels for each class were ascertained on the basis of reactor-radiation experimental results. By aligning each bar representation so that the lower portions are neglected, the remaining portions represent the results of radiation hardening. The remaining darkened area, which represents "severe damage", then represents the need for research and development.

On the basis of the study of information made available in the 1962-1963 period, certain areas associated with electronic component parts need considerable research. It is recommended that the number of radiation-effects research experiments be increased substantially for telemetry transducers in particular. Other component parts requiring further study are resistors in high nominal resistance values, electrolytic capacitors, precision-wirewound and film potentiometers, magnetrons and klystrons, and sensitive switches.

Semiconductor Devices and Materials

The varied requirements for semiconductor devices in electronic equipment which will be subjected to a nuclear environment impose the greatest restrictions regarding the attainment of adequate radiation-resistant circuitry. At the present time, the



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FIGURE A. STATE-OF-THE-ART ASSESSMENT FOR ELECTRONIC PARTS AND SYSTEMS FROM A GENERIC STANDPOINT AS TO CAPABILITIES FOR RESISTING NUCLEAR-RADIATION DAMAGE

circuit-design engineer does not have devices utilizing material other than germanium or silicon, and he is constantly faced with the problem that radiation effects information rarely is available for the most up-to-date components.

As before, even though some devices may be operated to neutron exposures as high as $1 \times 10^{15} \text{ n cm}^{-2}$, most of the devices are limited to exposures of $1 \times 10^{14} \text{ n cm}^{-2}$ or less. In general, highest performance may be obtained by:

- (1) Use of germanium devices rather than silicon where other conditions will permit
- (2) Use of high-frequency (thin base) devices where possible
- (3) Use of diffused-base devices.

Polymeric Materials

As in previous years, most investigators are still concerned with the combined effects of radiation and vacuum in the space environment. No rigid conclusions can be drawn which would enable even types of coating polymers to be placed in an order of merit for resistance to vacuum volatilization. The conclusion that can be drawn is that vacuum losses of organic coating polymers over prolonged periods even at ordinary temperatures can be severe. The best organic materials to resist such losses appear to be straight (nonmodified) silicone resins and Kel-F (a polytrifluoromonoethylen).

Although the amount of research is quite voluminous, a great deal of coordination of effort and data is required before definite ratings and specifications can be formed. In some cases, redesigning of components and parts will also be necessary in order to use the advantages of the available materials. Many experimental data are presented from various programs.

Fuels, Lubricants, and Hydraulic Fluids

Studies during the past year indicate that lubricants, hydraulic fluids, and greases have been developed that are more resistant under dynamic conditions than predicted by static testing of several years ago. Studies are continuing in an attempt to obtain a lubricant that will perform well under space environmental conditions. Molybdenum disulfide is the current favorite for this application.

Structural Metals and Alloys

The radiation-induced property changes in structural metals and alloys continue to be of importance to reactor designers and operators. The summarization of data in this section reflects the increased use of structural materials in high-temperature applications.

This section also discusses the mechanism of radiation-induced property changes in ferritic, austenitic stainless steel, and high-temperature alloys.

Ceramics

BeO has received a great deal of attention during the past year. The experiments were conducted at several different temperature levels, and summarized results are presented. Other materials discussed are UO_2 , TiO_2 , MgO , Al_2O_3 , glasses, silicates, graphite, and diamond.

Space Environment

This section contains few changes from last year except for a more up-to-date description of the Van Allen regions.

Dosimetry

During the past year work has been directed toward development of better semiconductor detectors, with emphasis on wide depletion layer devices.

Experiments to measure response of various gamma dosimeters have been conducted. CaF_2 thermoluminescent dosimeters were also measured for fast- and thermal-neutron sensitivities.

General

Figure B illustrates, as a crude approximation, where we stand with respect to materials development for application to nuclear-powered vehicles. The gray areas on the graph indicate exposures at which currently available materials operate satisfactorily, whereas the black areas show the exposures where potential materials, now under research and development, may give satisfactory performance. The bracketed areas indicate the exposures expected in manned and unmanned flight vehicles. It should be emphasized that this chart represents a very crude approximation for permanent damage and does not consider any transient effects that occur during irradiation. In most cases it is possible to locate sensitive components and materials in a less stringent environment than shown by the upper limits of the vehicle environment. The chart refers primarily to materials, since, in general, systems will be dependent upon the material that comprises the weakest link. The bar for electronic components includes electron tubes, resistors, capacitors, etc., but does not include semiconductor devices.

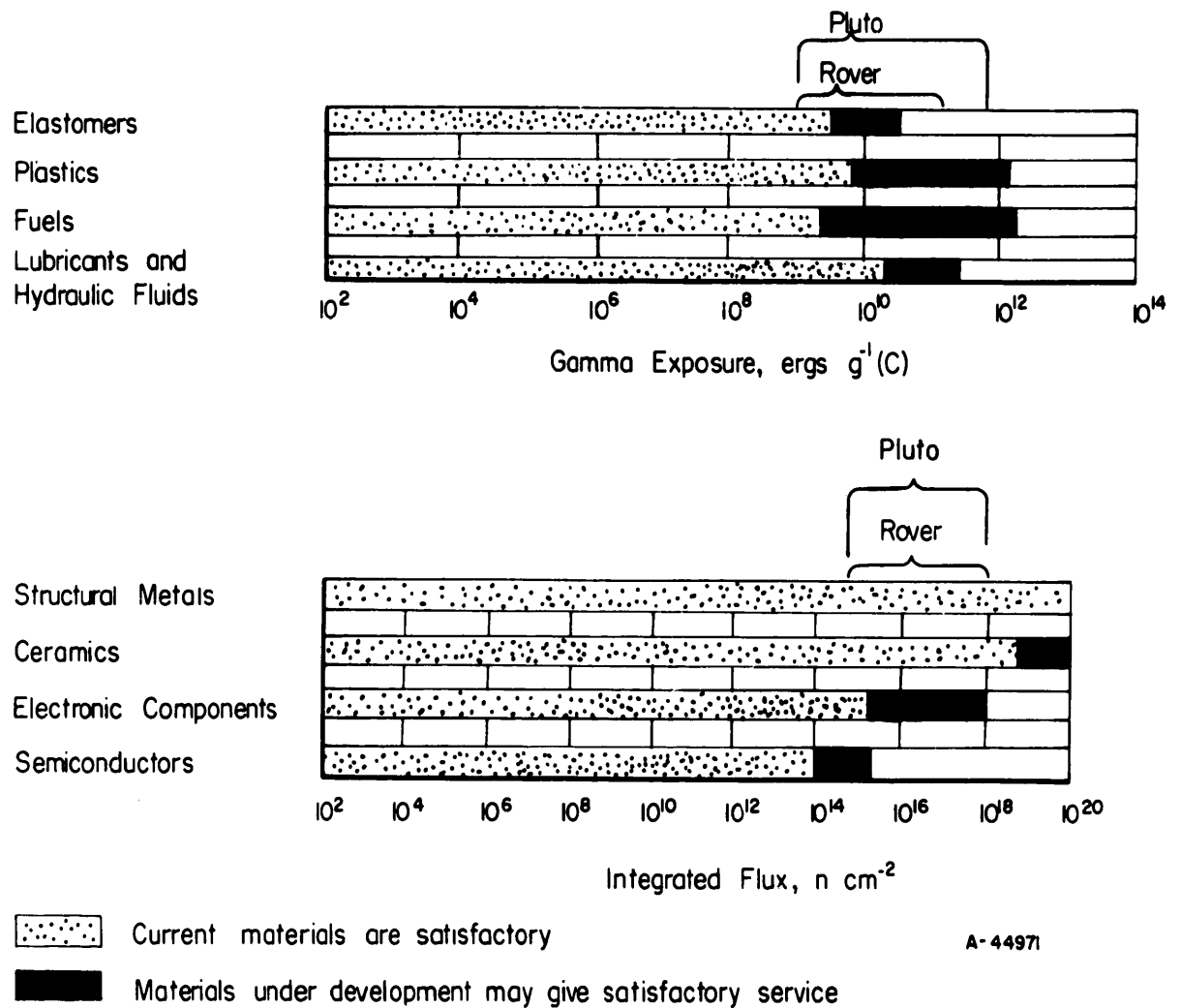


FIGURE B. STATUS OF MATERIALS IN RELATION TO NUCLEAR ENVIRONMENTS IN WEAPON SYSTEMS

INTRODUCTION

This is the sixth state-of-the-art summary of radiation-effects activities prepared by the Radiation Effects Information Center for the Air Force. The purpose of this report, based upon the data processed by the REIC, is to summarize progress and review problem areas in radiation-effects activities. This review should be helpful to those responsible for planning and executing radiation-effects programs. It is a revision and updating of the 1961-1962 Summary, based on new information obtained during the past 11 months.

This report summarizes briefly (1) the current state of the art, (2) recent results of radiation-effects studies, (3) programs in progress, and (4) Battelle's conclusions and recommendations in the following areas:

- (1) Electronic components and equipment
- (2) Semiconductor devices and materials
- (3) Polymeric materials
- (4) Fuels, lubricants, and hydraulic fluids
- (5) Structural metals and alloys
- (6) Ceramics
- (7) Space environment
- (8) Dosimetry.

This report is still oriented around steady-state nuclear-radiation effects; however, considerations regarding the less well-defined areas of pulse radiation and space radiation are included. Information on these latter two environments is still not sufficiently complete to permit more than general conclusions and recommendations.

Information on reactor-core materials, propulsion systems, shielding, and biological effects is not included in this report.

Appendix A summarizes the operation of the Radiation Effects Information Center for the period July 1, 1962, through May 31, 1963.

Appendix B lists the available reports and memoranda issued by the REIC.

ELECTRONIC COMPONENTS AND EQUIPMENT

Current State of the Art

Research and investigation into the effects of nuclear radiation during the past year show a definite trend toward an increase when compared with the 1961-1962 period. However, a considerable portion of the gains for radiation effects research has been for semiconductor devices and electronic equipment or systems. There is a definite diminishing in research support being shown for electronic component parts other than semiconductor devices.

In reviewing current reports, technical literature, and projects associated with radiation effects on electronic components, it appears that the subject matter can be divided into such categories as (1) resistive elements, (2) capacitors, (3) piezoelectric and quartz crystals, (4) electron tubes, (5) transducers, (6) magnetic materials, (7) electrical insulations, (8) circuits and systems, and (9) various special and miscellaneous electronic parts. When the above categories of electronic items are grouped according to component parts, systems, and equipment, it appears that a well-balanced program for conducting research on radiation effects is in effect. However, when the category associated with electronic component parts is further broken down into generic types, a tremendous unbalance becomes evident. Research on radiation effects to semiconductor devices is emphasized, and the remaining devices appear to be neglected.

The general trend during the past year has been to use all available information for radiation hardening of circuit designs and to publish and update radiation-effects handbooks for reference use. The approach appears to have had a reasonable measure of success and should be encouraged.

Resistive Elements

Most of the early experimentation conducted to determine resistor susceptibility to radiation damage has produced sufficient data and insight to electronic engineers and systems designers. Because of the wide range of resistor types available and the ideal broadness of radiation damage thresholds associated with each resistor type, the concern over the probability of failure in nuclear environments is minor when compared with other parts more susceptible to radiation damage. During the survey period involved, few experiments were conducted that included resistors. Those that did were designed such that resistive elements were part of a system and were not intended to expand the already saturated informational area associated with resistive elements. Other experiments^{(1)*} conducted during this survey period provided resistor manufacturers with nongeneric answers to inquiries associated with their own product. Research and development with the objective of improved resistor performance in the radiation environment is not being conducted according to a study of a recently published⁽²⁾ contract compilation. Where resistive elements are being irradiated in current research programs, the work is being done for specific environments associated with a system application, and the data are produced to gain assurance that resistance changes caused by the nuclear environment will not exceed the criterion of failure established during reliability studies.

*References are given at end of report.

In general, the state of the art for resistors indicates no pronounced change from what existed in previous years. The present state of the art is illustrated in Figure 1 for the most commonly employed resistors in circuit design and applications. It is realized that there are many factors involved in establishing threshold values of radiation damage for each of the resistor types. Much of the broadness indicated for each category of damage is caused by manufacturing variations of each generic type such as insulation materials, structural design, body enclosures, and winding schemes. One of the most critical characteristics that appears to show direct relation to susceptibility to radiation damage has been the resistance of the element. Generally, the most susceptible resistor to radiation damage is the one having the highest value in which it is manufactured. This is due mainly to the higher ratio of conductive particles to organic binder materials for carbon-composition resistors; extremely thin films in carbon- and metal-film resistors; and small-diameter wires for wirewound resistors and potentiometers. Therefore, estimates indicated in Figure 1 were oriented toward resistors, both fixed and variable, in nominal values that were less than their respective critical values.

In conclusion, resistors of all types shown exhibit thresholds of radiation damage from 10^{12} to 10^{16} n cm⁻² total fast-neutron flux and from 10^6 to approximately 10^{10} ergs g⁻¹ (C) of total gamma exposure. Severe damage can be expected for the group of resistors when they have been subjected to total exposures ranging between 10^{15} and 10^{19} n cm⁻² total fast-neutron flux and between 10^8 and 10^{12} ergs g⁻¹ (C) of total gamma exposure. Ordinarily, it would appear that resistor-type selection can be made for most levels of radiation and that no further research is needed in this area. This may be true for most nominal resistance values in each type. With restrictions placed on resistors with high nominal resistance values, gaps appear between most types. For example, when a low-wattage fixed-film resistor greater than 2 megohms is needed, the designer is forced to use a carbon-composition resistor that is more susceptible to radiation damage. A similar gap is encountered on borderline decisions between metal-film and wirewound resistors. Thus, some research is needed for development of resistors in high nominal resistance values that can withstand high-level exposures of nuclear radiation.

Capacitors

As in the case of resistors, the many types of capacitors have been thoroughly explored from the radiation-exposure standpoint. The main difference is that very slight overlap in nominal values exists between various types of capacitors, thus offering designers less option in their selections when a nuclear environment must be considered.

During the past years research and development was directed toward advancing the state of the art for oil-impregnated paper-dielectric capacitors. The early irradiation of this type of capacitor has shown that the main problem is related to outgassing of the oil impregnants. The earlier studies by the Admiral Corporation associated with the irradiations of foil-type capacitors using mineral oil and bis-ether as impregnating materials have been expanded⁽³⁾ to include Mylar as a dielectric medium. These studies were conducted to the point where the capacitors were exposed to approximately 6.5×10^9 ergs g⁻¹ (C). At this point, the paper dielectric was observed to become brittle and the Mylar exhibited indications of hydrolytic degradation. The treatment of Mylar specimens⁽⁴⁾ with isocyanate did not result in sufficient improvement in performance to be considered successful at this time.

No notable efforts have been devoted to capacitors such as the various ceramic, glass, mica, and enamel units. These have been accepted as the most radiation damage resistant of the capacitor family, and, therefore, the less resistant types of capacitors are receiving more attention.

For the most part, wet- and dry-electrolytic capacitors perform satisfactorily in radiation fields up to approximately $5 \times 10^{13} \text{ n cm}^{-2}$. At this point moderate changes in important parameters begin to occur. The radiation threshold for severe damage appears at approximately $10^{17} \text{ n cm}^{-2}$. This was indicated⁽⁵⁾ in some research experimentation where approximately half of a sample group developed short circuits at a total fast-neutron flux of $2.5 \times 10^{17} \text{ n cm}^{-2}$ and a total gamma exposure of $5.8 \times 10^{10} \text{ ergs g}^{-1} \text{ (C)}$.

The controversy concerning whether the wet-slug type of tantalum capacitor is superior to the dry type has not been resolved according to available literature. It is generally believed that the Teflon seals associated with the wet-slug type might be severely affected by ionizing radiation. Wet-slug units⁽⁵⁾ were exposed to fast-neutron fluxes between 8×10^{12} and $4 \times 10^{16} \text{ n cm}^{-2}$ with no apparent indications that the Teflon seals were affected. This supports current thinking that Teflon in the absence of oxygen is not as greatly affected by high-level ionizing radiation as has been observed when exposures took place in an oxygen-containing atmosphere.

In conclusion, the present state of the art for capacitors can be reflected in the bar chart shown in Figure 2. From a generic standpoint, mild to moderate changes can be expected to occur between 10^{12} and $10^{18} \text{ n cm}^{-2}$ for fast-neutron fluxes. Severe damage can be expected for various types in the entire group between 10^{14} and $10^{19} \text{ n cm}^{-2}$. Advancement of the state of the art, as mentioned, is being attempted for the paper and plastic-film capacitors by circumventing problems caused by outgassing of impregnants.

Piezoelectric and Quartz Crystals

Early radiation studies of quartz crystals in their raw unmounted stages indicated that effects of fast-neutron and gamma exposure were not severe at levels as high as 10^{16} and $10^{17} \text{ n cm}^{-2}$ and $10^{10} \text{ ergs g}^{-1} \text{ (C)}$. However, recent studies have indicated that mounted crystals in various cuts are less resistant to radiation damage than unmounted devices. Another problem which was considered very serious was the extreme sensitivity to flux rate. Exploration of neutron rate sensitivity is being carried out by using the 14-Mev linear accelerator at Argonne National Laboratory⁽⁶⁾. This electron source produced a fast-neutron exposure rate equivalent to $10^{15} \text{ n cm}^{-2} \text{ sec}^{-1}$ by bombarding a uranium target for 5 microseconds. During this study, 90 crystal units of the AT types ranging from 4 megacycles to 85 megacycles were irradiated. Several NT cuts at 50 kilocycles and 300 kilocycles in natural and synthetic quartz were also studied. The crystals were mounted in metal and glass enclosures. Differences in performance between the series-mode AT cuts and parallel-mode AT cuts were observed during the radiation pulses. No major frequency changes were observed for the series-mode AT cut crystals. The parallel-mode AT cut crystals showed momentary frequency shifts up to 5 kilocycles. The metal-encased crystals appeared quite sensitive to radiation pulses, whereas the glass-encased units were not greatly affected.

In line with the current interest in electron and proton irradiations of crystals, some studies have been conducted⁽⁷⁾ to determine their relative effects. Crystals were

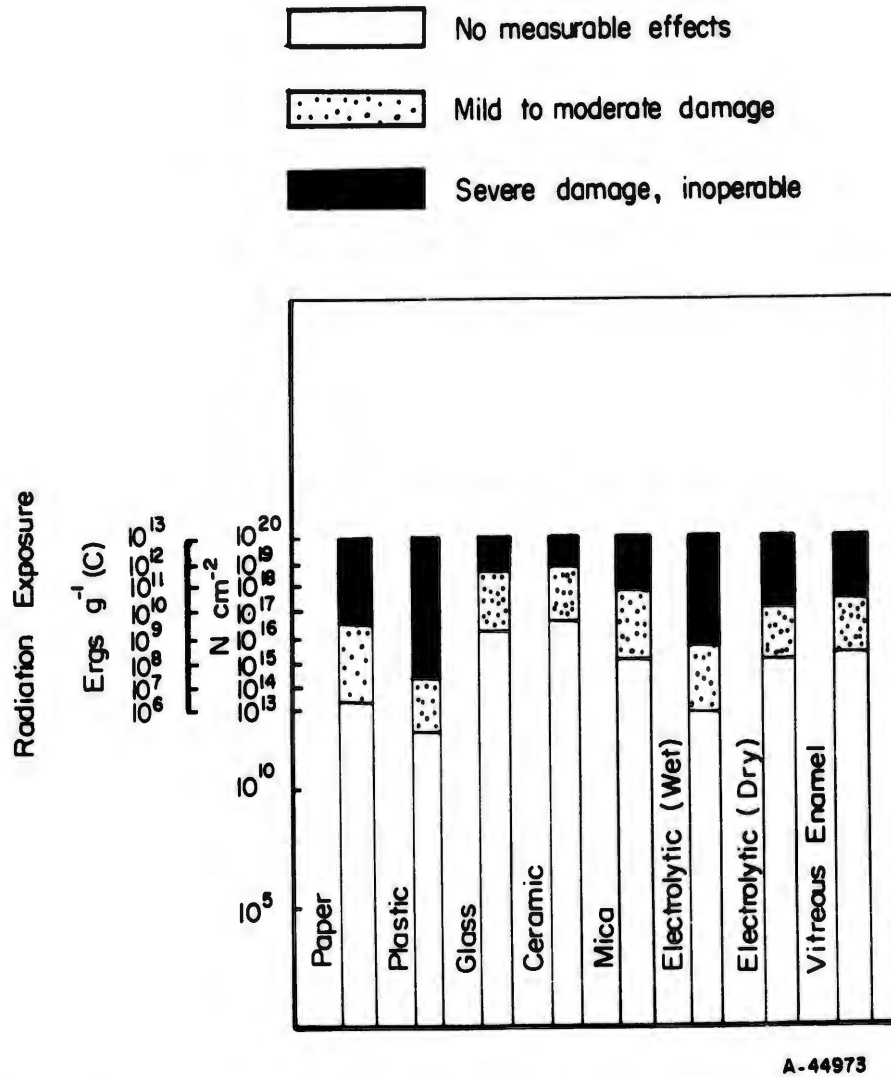


FIGURE 2. STATE-OF-THE-ART ASSESSMENT OF COMMONLY USED FIXED CAPACITORS WITH RESPECT TO ESTIMATED PERFORMANCE IN A RADIATION ENVIRONMENT

exposed to electron bombardment from a linear accelerator which produced radiation equivalent to 10^{10} ergs $\text{g}^{-1}(\text{C}) \text{ sec}^{-1}$. Other crystals were exposed to proton radiation bombardment produced by a cyclotron for a total exposure of $1.6 \times 10^{12} \text{ p cm}^{-2}$. The proton irradiation produced a negligible shift in frequency, and it was believed that the metal case absorbed most of the energy, thus permitting only a relatively small energy penetration to the crystal. The electron irradiation produced a large transient and permanent frequency change.

The state of the art for crystals may be advanced in the future because of continued research being conducted at the Admiral Corporation⁽⁸⁾. These studies involve a comprehensive program to evaluate current designs of quartz crystal units. Cyclotrons, linear accelerators, and pulse reactors are being planned for use as the radiation sources.

Electron Tubes

The primary damage mechanism which limits prolonged use of electron tubes in high-intensity radiation environment continues to be the damaging effects to the glass envelopes and the glass-to-metal seals. With the use of low-boron-content glass and the reduction of seal areas, the threshold of radiation damage has increased considerably. The problem of irradiated tubes being susceptible to shock and vibration damage remains.

Current interest in irradiation of electron tubes is being directed toward improving gettering action. Sorption and desorption rates are being investigated⁽⁹⁾. Similar programs of research⁽¹⁰⁾ sponsored by the Signal Corps at RCA are aimed at providing information on the type, quantity, and time periods of gas desorption and sorption in electron tubes. The objectives of the program are to reduce sorption and desorption by the careful selection of proper materials, design, and processing during tube manufacturing.

Interest has continued regarding space environments from the standpoint of electron radiation. In this instance⁽¹¹⁾ cold cathode diodes of the General Electric XD series were subjected to pulses of gamma radiation from the linear accelerator at General Atomics. The results of this experiment were compared with results obtained in Operation Plumbob, and the conclusions resulting from the study indicated that the diodes could find their application in nuclear-proofing circuits.

In conclusion, the state of the art for electron tubes has not shown any advancement. However, considerable research is being conducted to determine the nature of failure mechanisms and the means of producing electron tubes with greater radiation-damage resistance. Figure 3 shows the relative positions of various tubes commonly used in respect to their capabilities for operation in nuclear environments.

Transducers

In previous state-of-the-art reports, devices covered under the definition of transducers were mentioned as a weak link in electronic-circuit applications. Transducers, which fall within a special category of electronic parts, involve numerous electrical, thermal, and mechanical principles. The part played by transducers in the vital sensing

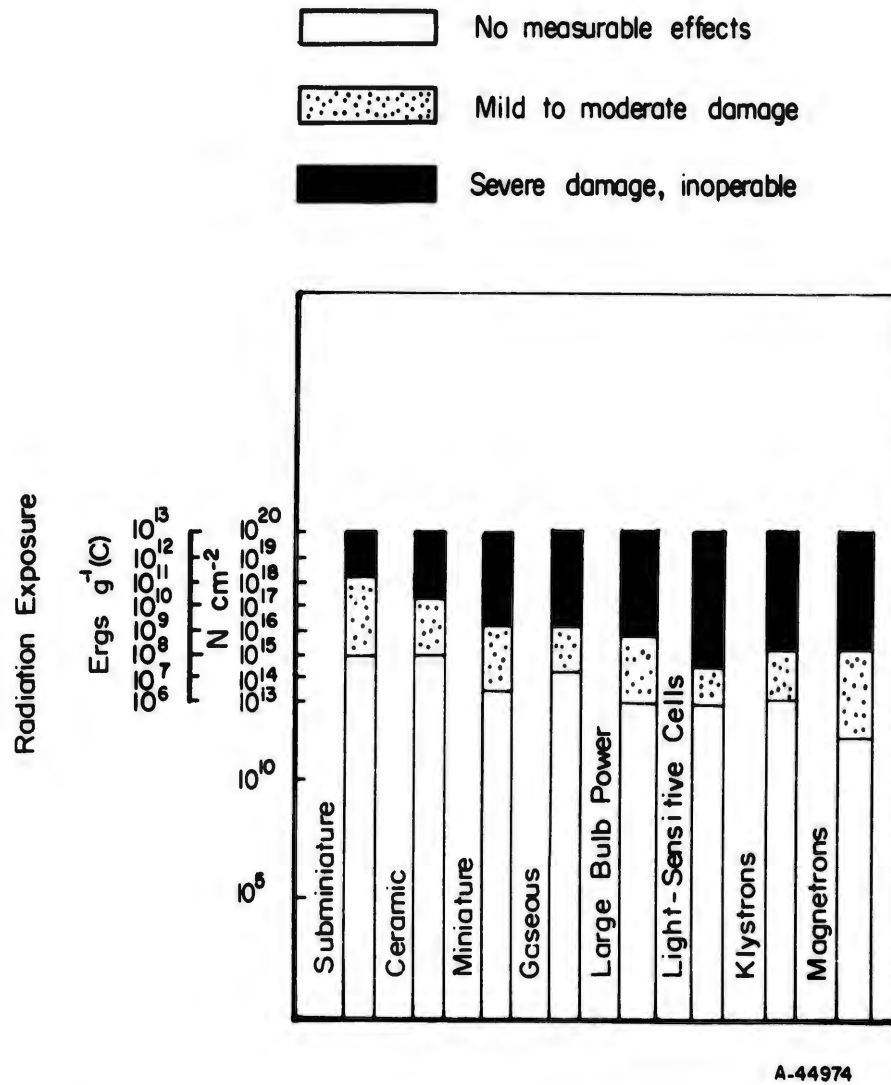


FIGURE 3. STATE-OF-THE-ART ASSESSMENT OF RADIATION-DAMAGE RESISTANCE FOR VARIOUS ELECTRON TUBES

and feed back devices is extremely important in the operation and monitoring of electronic circuits and electromechanical systems. They have become indispensable in nuclear-reactor control, space telemetry systems, and ground-based systems in the area of thermonuclear reactions.

In the field associated with transducers for telemetry applications, the need for both nuclear and nonnuclear information has become quite evident, as indicated by the increasing number of technical inquiries directed to the Radiation Effects Information Center. In response to the acknowledged need for transducer information, programs have been established to compile all available information that might aid designers. One of the most comprehensive studies⁽¹²⁾ was conducted by J. R. Burnett and others of the Bendix Corporation for the Aeronautical Systems Division. The main objective of this study was to determine transducer requirements for future nuclear-powered vehicles such as the nuclear rocket, nuclear ramjet, SNAP, and nuclear airplane. The results of this extensive study emphasized the lack of usable transducer information in both conventional and nuclear environments. Examination of the transducer requirements for the nuclear-rocket programs and comparison of system requirements with present capabilities have shown emphatically that a difficult problem exists in the area of damage to materials by combined effects of radiation, cryogenic temperature, and vibration.

In past years, application engineers and others have recognized the need for complete compilations of available transducers for both instrumentation purposes and telemetry applications. There is a recent publication of a series of telemetry transducer handbooks⁽¹³⁾ by H. F. Fisher, Jr., which consists of information describing available telemetry transducers and their applications in various aeronautical systems. From the instrumentation standpoint, the American Society of Instruments (ASI) has nearly completed the Asi Transducer Compendium and has indicated that its first edition will be available in mid-July, 1963.

Although radiation-effects information from transducers is extremely scarce, REIC has published, as REIC Report No. 25, information from all available sources, including pertinent contributions given in publications by Fisher and Burnet. The report, titled "The Effect of Nuclear Radiation of Transducers", presents information relative to the state of the art on the effects of nuclear radiation on various types of transducers that are becoming extremely important in present-day applications. The report consists of two sections. The first section contains information dealing with the concepts and characteristics of conventional transducers, with estimations of values of radiation thresholds. The second section of the report deals with information from reports available at the Radiation Effects Information Center on irradiation of various transducers and sensing elements. The objective of this report is to serve as a guide in developing a better understanding of the problems that must be solved prior to final selection of transducers to be used in nuclear environments.

Recognition of the scarcity of transducer radiation-effects information has resulted in an increase in research programs directed toward filling this information gap. Studies have been conducted⁽¹⁴⁾ recently to determine the effect of thermal-neutron irradiation on thermocouples and resistance bulb thermometers. In these experiments, the problem of transmutation of metals was of prime interest. Platinum and platinum-10% rhodium were selected for the thermocouple study. The thermocouples were exposed to a total thermal-neutron flux of approximately 3.5×10^{20} nvt at capsule temperatures between 1000 and 1180 F. Changes in thermal emf between 400 and 1800 F were observed within the range of +5.8 per cent to +81 per cent after irradiation.

Transmutation of materials normally used in resistance bulbs (copper, platinum, nickel, Manganin, and constantan) in this study showed that copper suffered the greatest change in composition, with nickel being least affected by transmutations.

On the basis of technical inquiries made at REIC, the general impression is that a complete understanding of transducers from the standpoint of definition, nomenclature, and types is somewhat limited. Technical articles have been extremely useful in contributing to a better understanding. In a recent article⁽¹⁵⁾, H. N. Norton described transducers for many presently used applications to inform the designer of transducer characteristics, thus reducing the problems of selection and obtaining maximum information from possible measurements.

Because of the lack of radiation-effects information, the estimation of thresholds has served as a stopgap so that potential users may be aware of possible weaknesses in various materials frequently used in transducer manufacturing. Although certain materials subjected to nuclear-radiation environments tend to change in physical and electrical characteristics, these changes are difficult to interpret in terms of measurement errors. In view of this situation, there has been an increase in radiation experiments for specific transducers. One of the early studies⁽¹⁶⁾ associated with transducer irradiation involved vibration pickups, accelerometers, resistance bulb thermometers, linear variable differential transformers, pressure transducers, and strain gages. These devices were given radiation exposures that totaled approximately 10^{13} n cm⁻² total fast neutrons and 10^9 ergs g⁻¹(C) for gamma radiation. The vibration pickups, pressure transducers, and resistance temperature bulbs were considered satisfactory at the radiation levels employed. The remaining transducers were damaged by the radiation exposure and their signal outputs were severely affected.

The most recent radiation-effects research for transducers has been conducted by Burnett⁽¹⁷⁾ and others at Edgerton, Germeshausen, and Grier, Incorporated. This series of studies consisted of calibrations made on CEC and Taber pressure transducers intended for application in PLUTO radiation environments. The CEC pressure transducers (Model 170824-0100) and Taber units (modified Model 185) were strain-gage pressure sensors that were specially designed to resist radiation damage. The maximum exposure used in irradiation of the CEC transducers was greater than 1×10^{18} ($E > 0.1$ Mev) fast neutrons, and 10^{12} ergs g⁻¹(C). The conclusions formed concerning the CEC units were that they showed excellent ability to operate for a large radiation exposure, with some limitation associated with zero shifting. The maximum exposures for the Taber units were established at 10^{15} n cm⁻² and 6×10^8 ergs g⁻¹(C). In this latter case, the radiation exposure rate (2×10^{11} n cm⁻² sec⁻¹) was limited by zero shift and the total exposure was limited by indications of permanent damage to the bonding materials.

Transducer technology appears to be progressing at a rapid rate. Much of the growth can be attributed to various aeronautical and space programs which have emphasized the extreme need for transducers that can withstand damage when exposed to elements of nuclear and high-temperature environments. The most important and critical fields of interest have been established by application to telemetry systems. At the present time, data of sufficient scope to make an accurate assessment of the state of the art are lacking. However, from what appears as good cooperation between manufacturers and users of telemetry transducers, the future can be considered optimistic. Transducer manufacturers have shown a willingness to remove and replace materials

that have been known to degrade rapidly following prolonged radiation exposures, and the newer series being produced specify that they can be applied in nuclear environments.

From a recent study of transducers made by REIC, some appraisal of radiation-damage thresholds was realized. The study made for displacement transducers provided sufficient insight so that the various applications and selections from a generic standpoint can be approached according to radiation levels shown in Figure 4. In this presentation, the point has been brought out that the sensors used for measurement of displacements vary quite broadly. In the case of pressure transducers, a somewhat similar treatment is shown in Figure 5. In both cases it may be noticed that the various types of sensors have widespread applications to other types of transducers. Thus, the problem that faces transducer application engineers will be to correlate known radiation-damage effects with losses or errors in the system output for each type of sensor used in the telemetering system.

Magnetic Materials

Magnetic materials are affected by nuclear radiation as indicated by changes in their structure-sensitive properties. The important properties, such as permeability, remanence, and coercive force, have been examined by many authorities on magnetic characteristics under conditions of both steady-state and transient radiation environments. The present state of the art for the field of magnetic materials indicates that the nickel-iron alloys change drastically in the important properties when irradiated to 10^{17} fast $n\text{ cm}^{-2}$. Other magnetic materials such as the silicon-irons, aluminum-irons, and Permendur show indications of changes at 10^{17} fast $n\text{ cm}^{-2}$; however, this represents the threshold of radiation damage.

Magnetic-material susceptibility to radiation damage has been examined at fast-neutron flux levels ranging between 10^{16} and 10^{18} $n\text{ cm}^{-2}$. In the earlier studies⁽¹⁸⁾, within the range of neutron flux exposures, such magnetic materials as the Ferramic F-1, S-1, and S-3, Ferroxcube 3C, and samarium- and yttrium-iron garnet were investigated. The procedure used involved measurement of hysteresis loops and complex permeability before and after irradiation, after room-temperature aging, and after a 500 C heat treatment. Ferromagnetic resonance line widths were measured in the yttrium-iron garnet and the Ferramic R group of ferrites. Hysteresis properties measured on magnet specimens exposed to flux levels less than 10^{18} $n\text{ cm}^{-2}$ showed insignificant effects from the irradiation. At 10^{18} $n\text{ cm}^{-2}$, significant changes in coercive force and remanence were noted. These changes were as great as 30 per cent. Regardless of these changes, the hysteresis loops were not severely affected. The subsequent treatment and aging were not effective in annealing of the radiation damage. The complex permeabilities of the Ferramic R-1, S-1, and S-3 changed appreciably. Exposures of 10^{16} and 10^{17} $n\text{ cm}^{-2}$ produced changes ranging between 10 and 50 per cent. In contrast, the complex permeability of samarium-iron garnet decreased monotonically as the exposure increased. When the exposure approached 10^{18} $n\text{ cm}^{-2}$, the complex permeabilities of samarium-iron garnet decreased 14 and 30 per cent. Aging and heat treatment of the samples exposed to 10^{18} $n\text{ cm}^{-2}$ annealed the radiation damage on the complex permeability in some instances, and in other cases this property showed further increases. Ferramic S-1 was not appreciably affected. Ferramic S-1 and S-3 showed an increase of 20 and 45 per cent, respectively. In the case of Ferramic R-1, the first complex permeability was slightly increased, whereas the second was restored to its initial value by the aging and heat treatment. In the case of the samarium-iron garnet,

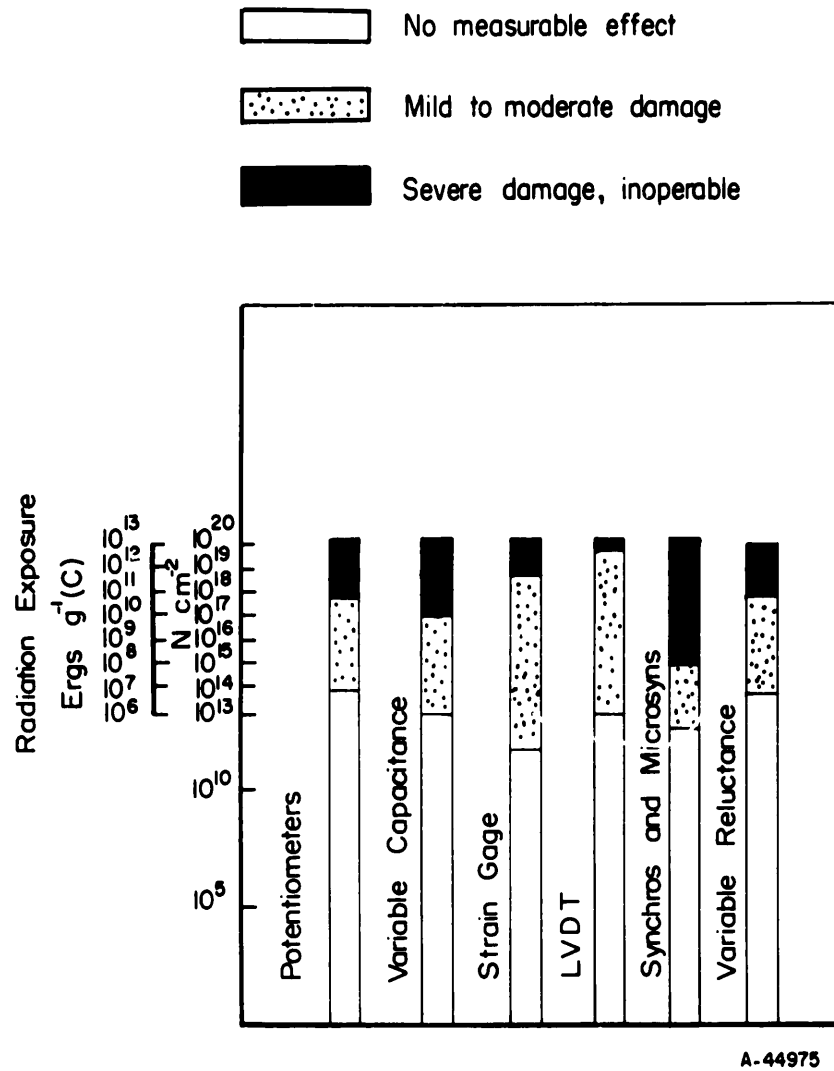


FIGURE 4. ESTIMATED EFFECTS OF RADIATION ON DISPLACEMENT TRANSDUCERS AS A FUNCTION OF FAST-NEUTRON AND GAMMA RADIATION EXPOSURE

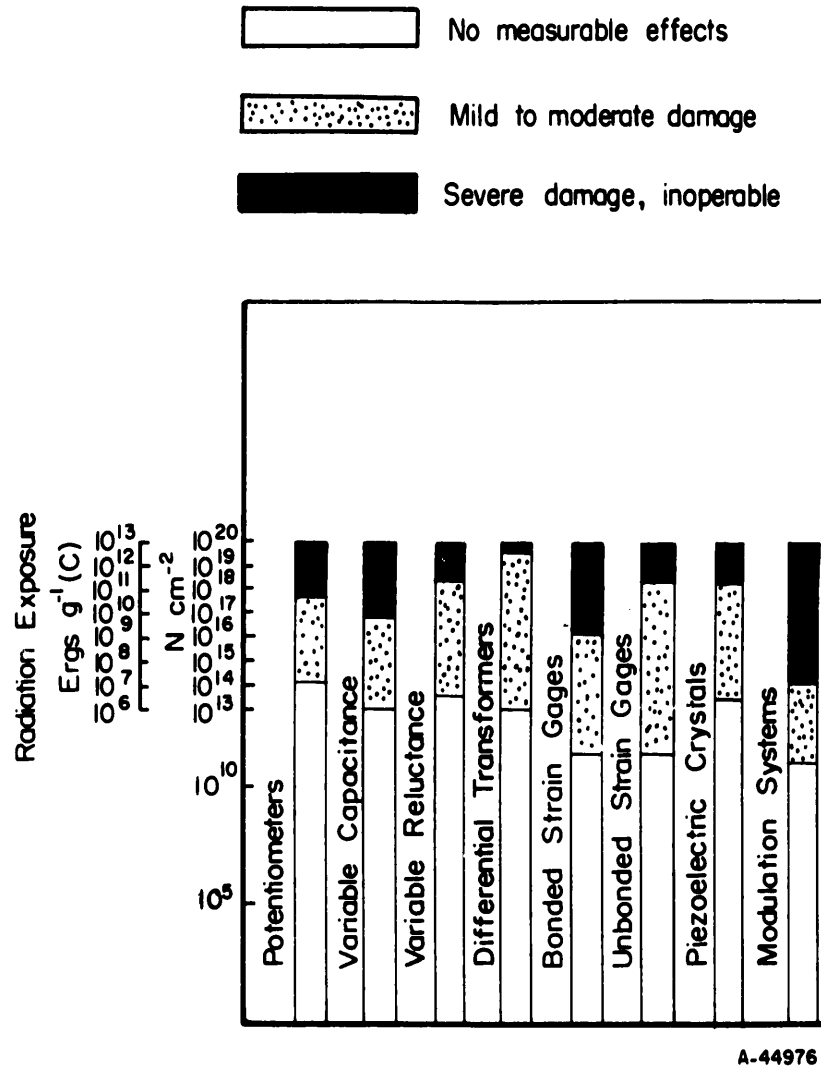


FIGURE 5. ESTIMATED EFFECTS OF RADIATION ON PRESSURE TRANSDUCERS AS A FUNCTION OF FAST-NEUTRON AND GAMMA RADIATION EXPOSURE

both complex permeabilities were restored to their preirradiated values after the treatments. The ferromagnetic resonance line widths of yttrium-iron garnet and Ferramic R-1 were not affected after 10^{18} n cm⁻² of fast-neutron exposure. Slight changes were observed in the line widths of the remaining samples. It was concluded that the devices using the tested magnetic materials were adequate for space applications that did not involve their use in the vicinity of propulsion reactions that were unshielded.

In some applications where the flux levels approach 10^{20} n cm⁻², the nickel-irons are undesirable. However, for various applications where the open-circuit magnetic-induction characteristic is the main important property, such permanent-magnet materials as the Alnicos II, V, and XII have been judged satisfactory at flux levels approaching 5×10^{20} n cm⁻². Sery(19), in reviewing the various magnetic materials, points out that Cunico I materials are more affected than the Alnicos. One problem for both the Alnico and the Cunico materials would be that of radioactivity because of their cobalt content if maintenance were required.

The use of the titanate-containing magnetic materials is becoming increasingly widespread. Studies conducted at the Stanford Research Institute facility(20) indicate that slight and moderate changes can be expected to such properties as complex permittivity and large signal hysteresis within exposure ranges of 10^{15} and 10^{18} n cm⁻². The magnetic materials studied consisted of BaTiO₃, 96 per cent BaTiO₃ + 4 per cent PbTiO₃, BaTiO₃ + 5 per cent CaTiO₃, and lead zirconate. The subsequent treatment after irradiation (room-temperature aging and 500 C heat treatment) showed that all of the measured properties were affected to some degree.

Continued studies(21) related to transient radiation effects to ferrite and tape-wound cores confirm earlier findings at the Sandia Pulse Reactor (SPR). No pulse radiation effects were detected in tests conducted with (1) Mg-Mn Ferrite, (2) Mn-Zn Ferrite, (3) Cr-Mn-Ni-Zn Ferrite, (4) 4-79 Mo Permalloy tape, and (5) High-Permeability Ferrite. During the same series, a sample of IBM heavy-duty magnetic tape contained all stored information after 30 SPR bursts. The tape also functioned properly when the original data were erased and new data written and reread from the tape.

In conclusion, magnetic materials incorporated in devices constitute one of the most radiation-resistant portions. Since all important properties are not changed drastically when exposed to radiation flux levels ranging between 10^{15} and 10^{20} n cm⁻², users can orient their design to take advantage of properties least affected. Lack of sensitivity, indicated by the SPR studies, shows that no problems exist for permanent magnetic materials when they are subjected to gamma pulses approaching 10^9 ergs g⁻¹ (C) sec⁻¹.

Electrical Insulations

In early radiation-effects investigations electrical insulation was recognized as a major problem. Much of the current knowledge associated with electrical insulation for use in radiation environments has been accumulated by radiation-effects technologists in their preparation of measurement circuits for basic components being irradiated. Additional radiation-effects data evolved from problems associated with the instrumenting of nuclear reactors where extremely radiation-resistant materials of the inorganic class are essential.

Although a considerable amount of information is available concerning radiation-damage thresholds for organic and inorganic materials, the bulk of the data contains physical and chemical effects which are difficult to interpret in terms of electrical properties. Thus, research has continued for the better electrical materials during the past year to establish accurate radiation thresholds. There have been attempts⁽²²⁾ to relate mechanical breakdown to electrical-insulation degradation. More specifically, mechanical and electrical tests were recently performed for specimens of insulation in sheet forms, insulative tubing or sleeving, and wire coatings. Sheet materials studied were (1) silicone-treated mica, (2) silicone-varnished glass fiber, (3) epoxy-coated glass fiber, (4) polyethylene terephthalate, (5) polyfluoroethylpropylethylene, (6) capacitor tissue (kraft paper), and (7) polytetrafluoroethylene. For the sleeving or tubing, the materials investigated were (1) silicone resin glass fiber, (2) polyurethane glass fiber, (3) polyvinylchloride, (4) silicone rubber, and (5) polytetrafluoroethylene. Insulation for magnet wire contained (1) polyurethane, (2) terephthalic, (3) silicone enamel, (4) polyvinyl Formal, (5) an isocyanate modified polyester, and (6) polytetrafluoroethylene. The results of the study indicated that few of the materials mentioned can be used in applications where the total exposure exceeded 10^9 ergs $g^{-1}(C)$ from both electrical and mechanical standpoints. The order of greatest resistance to radiation damage for each form coincides with the lowest itemizing numbers above. It was found that the radiation tolerance of electrical-insulation sheet, -tubing or -sleeving, and the magnet wire varied widely. The electrical properties showed degradation first with some materials, and mechanical properties more sensitive to radiation damage with other materials. It was concluded that in applications where no appreciable reduction in properties can be tolerated, selection of all classes tested is extremely limited for total radiation exposures exceeding 10^{10} ergs $g^{-1}(C)$. Otherwise, materials itemized as (1) show capabilities for withstanding damage to exposures as high as 10^{11} ergs $g^{-1}(C)$, and those listed as (2) can be rated at 10^{10} ergs $g^{-1}(C)$.

Heretofore, Teflon has been considered undesirable for use in the nuclear environment. In recent studies⁽²³⁾ Teflon has been found to retain many of its physical properties and good insulation qualities when exposures occurred in the absence of oxygen. Strips of Teflon tape exposed to gamma radiation in an ultrahigh vacuum retained superior high- and low-temperature characteristics, had nearly the same coefficient of friction in vacuum as in atmosphere, and had good dielectric properties. These findings indicate that Teflon can be useful in space applications.

Information associated with glass fibers and yarns has been limited primarily because many investigators make the assumption that the materials are highly resistant to radiation damage for most applications. As a result of the lack of interest, little is known concerning radiation-damage thresholds. The most recent available information⁽²⁴⁾ concerning results of irradiation of glass fibers for a series of discrete fast-neutron exposures ranging from 10^{12} to 10^{20} n cm^{-2} at 400 C indicated that the material was suitable for electrical insulation in nuclear reactors. It also indicated that there was no melting of the glass or any undesirable effects from nuclear heating.

The primary area where insulation problems occur is in research experiments conducted under transient radiation environments. Investigations are being conducted to observe radiation-induced current and voltages. A major part of these studies⁽²⁵⁾ is being conducted with pulsed radiation from the Kinetic Experimental Water Boilers (KEWB) reactor. These studies are considered extremely important because it is believed that results from past experiments on electronic devices were erroneous, and that

the signals measured were extraneous in nature and caused by the radiation pulse in parts of the test apparatus other than the test specimen itself.

A study of both organic and inorganic insulation materials was made on the basis of past and present results obtained from radiation-effects research programs conducted with insulation materials and electronic components using insulations (resistors, capacitors, wire and cables, etc. ,). The objective was to place the various materials in a relative position with respect to each other for use in radiation environments. The results of the study are shown in Figure 6 for organic materials, and Figure 7 for inorganic materials. It is realized that each factor such as physical strength, dielectric qualities, failure criteria, and other environmental conditions are extremely important in making proper selections; however, some insight can be gained through judicial application of the information for preliminary explorations.

Circuits and Systems

The general approaches for determining whether a system or circuit will function in a nuclear environment consist of (1) actually exposing the circuits and/or systems, (2) using available empirical information on radiation effects and establishing the maximum level of radiation tolerance on the basis of the weakest or most susceptible component, and (3) establishing comprehensive and complex computer programs which utilize empirical data and theoretical concepts related to system designs. Some recent methods for solution of the radiation capability problem have been simplified by establishing a reasonably firm level of the radiation environment and the identity of the component parts that will be required in the system's circuits. The next phase would be to examine each of the selected and preferred component parts to determine whether they possessed radiation tolerances within the prescribed radiation exposure level⁽⁵⁾. Component parts that are questionable or that possess no irradiation history are exposed to radiation levels above what has been indicated for their application. In essence, this latter method is a radiation hardening by proper-selection process which can be adapted adequately for systems planned for use in steady-state radiation environments where total exposures are less than 10^{15} fast n cm^{-2} and 10^{10} ergs $\text{g}^{-1}(\text{C})$.

Summarization of programs for the past year concerns research being carried on at the Flight Control Laboratory, Aeronautical Systems Division⁽²⁶⁾. This involves techniques being investigated in the design and evaluation of high-temperature radiation-resistant flight-control systems. Experimentation performed in actual reactor environments indicates that it is feasible for flight-control systems to be designed for certain nuclear applications. The results of the programs emphasize the need for further research in the development of high-temperature radiation-resistant components for use in flight-control systems. Some of these components needing an expansion in research are synchros, transducers, accelerometers, temperature amplifiers, and inertial components.

Specific programs being carried on by the Air Force that are typical of current research for systems consist of studies conducted at IBM's Space Guidance Center⁽²⁷⁾, the Aero-Space Division of The Boeing Company⁽²⁸⁾, and the Bendix Corporation, Systems Division⁽²⁹⁾. Research is being conducted at the International Business Machines Corporation to determine radiation effects on digital-computer circuits. Current reports on the IBM activity describe their efforts in circuit experiments utilizing known component effects to analyze and predict the behavior of circuits in pulsed

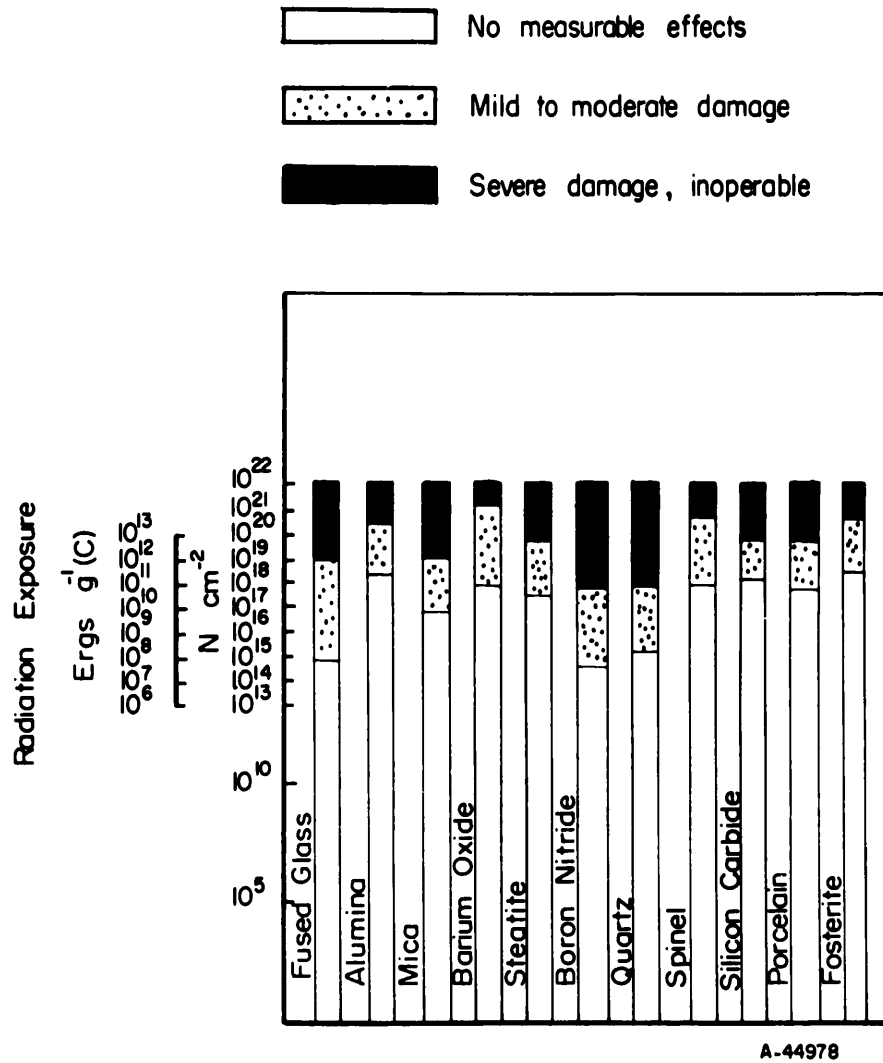


FIGURE 7. STATE-OF-THE-ART ESTIMATES OF RESISTANCE TO RADIATION DAMAGE FOR SOME COMMONLY USED INORGANIC INSULATION MATERIALS

radiation environments. During the past year, IBM scientists have established that, in a Godiva radiation pulse environment, the phenomena most likely to affect circuit operation are transient increases in transistor, diode, and capacitor leakage currents, and the permanent degradation in transistor gain. The effects of radiation on certain elementary circuits have been simulated on an analog computer, and the variation in component parameters was extracted from other elementary circuit configurations using digital-computer analysis. Of the elementary circuits that were investigated, the simplest were resistor-capacitor combinations. Such circuits were designed to test the applicability of the shunt-current generator model to circuit analysis.

The Boeing Company research activity is somewhat along lines similar to the IBM program. The Boeing program involves prediction of transient nuclear radiation effects to electronic circuits where electronic and radiation transfer functions of resistors, capacitors, and transistors have been developed empirically and are represented by analog circuitry. Single- and two-transistor circuits were simulated in a similar manner, and actual circuit tests were performed to check predicted analog results. The results of their preliminary studies show reasonable agreement. The Bendix program involves a study to determine effects of fission product gamma radiation on electronic parts and equipment. Their initial studies involve irradiation of completed circuit cards of such circuits as (1) flip-flop, (2) inverters, (3) time-delay circuits, (4) inverter gates and strobe output, and (5) driver amplifiers. Cobalt-60 sources are being considered for this research.

Miscellaneous

To a limited extent, special types of components have been evaluated in the nuclear-radiation environment. Of particular interest have been sensitive switches (microswitches) that find their application in instrumentation and controls for reactor experimentation. Minneapolis-Honeywell microswitches in Types 1SMi, 1SEi-3, V3-1, V3-1301, BZ-2R, BA-2R, 1EN1-6, 2EP2-E, 11S1, and 1HS1 were irradiated to gamma flux levels approaching 10^{10} ergs $g^{-1}(C)$. Examination and operation of the irradiated switches revealed degradations to rubber seals and slight losses in insulation quality of organic materials. Since these results have become apparent, high-temperature materials have been examined for use in microswitches that can be employed in radiation environments. The most radiation-resistant material applicable to microswitches was a glass-bonded mica. Since these findings, switches specified as radiation resistant have become available.

Another special applications area is associated with the TIMM's program being carried out by the General Electric Company(31, 32). The tube research program is continuing in areas of electrical and mechanical design, material evaluation, component fabrication and evaluation, module fabrication, radiation-effects studies, and data analysis. Some pulsed radiation tests were performed on active and passive circuit elements at the Sandia Pulsed Reactor, and steady-state radiation tests are planned for Battelle Memorial Institute. Their program of research has expanded into an investigation to develop metal-film resistors for 580 C operation.

Programs in Progress*

The current programs being conducted to use or generate data pertaining to the effects of radiation on electronic materials, component parts, and systems are described below:

General Dynamics is carrying on basic studies to determine the mechanisms involved in the gamma-radiation-induced voltage phenomena.

General Dynamics is studying means for calculating and reducing air ionization effects associated with electronic circuits.

General Dynamics is doing research to determine temperature dependence of radiation effects on dielectrics

International Business Machines Corporation has developed a computer (digital) which will withstand an integrated neutron flux of 10^{16} n cm⁻² and gamma exposures of 10^9 ergs g⁻¹(C). Part of the program involved radiation-effects experiments conducted at The Pennsylvania State University and Battelle Memorial Institute research reactors. These studies were conducted at levels of 10^{17} n cm⁻² for resistors, transistors, and transformers.

Northrup Aircraft, Inc. is engaged in studies pertinent to defining the space radiation environment for the purpose of developing specifications related to flight-control systems.

Litton Industries is conducting reactor research experiments on transistorized gyro preamplifiers in pulsed and steady-state radiation environments. This is being done to correlate the effect of neutron and gamma spectra with integrated exposure damage.

New York University is conducting research studies on high-energy radiation effects on materials for the purpose of explaining processes involving incident energy flows into optical, thermal, and electrical channels.

Philco Radio and Television is developing thin-film devices using tunneling for the active gain mechanism, thereby hoping to produce radiation-resistant devices.

Arizona State University is investigating effects of radiation on the electrical and optical properties of semiconductors and insulators.

Sandia Corporation is investigating effects of intense gamma radiation produced by nuclear weapons on materials and devices of exposed electronic circuits.

Brookhaven National Laboratory is studying radiation effects on the optical, ultrasonic, and magnetic resonance of insulators. This study includes effects of radiation on solid-state reactions, chemical effects of irradiation, and theoretical calculation of radiation damage.

*Detailed information on these programs, including contract numbers and sponsoring agencies, is given in REIC Memorandum 11-C, "Compilation of Nuclear, Pulsed, and Space Radiation Effects Projects" (Confidential), April 15, 1963.

Union Carbide Nuclear Company is conducting investigations pertaining to defects in insulators and their production of energetic radiation. The most important aspect of the study is the mechanism for defect production by ionizing radiation.

The Lockheed Georgia Nuclear Laboratory is exposing resistors, capacitors, semi-conductors and other component parts in the combined environments of radiation and vacuum.

Battelle Memorial Institute is exposing several thousand electronic parts to combined environmental conditions of radiation, temperature, and vacuum. Some units will be active and others passive.

General Dynamics is investigating the effect of various combined environments of radiation, vacuum, and cryogenic temperatures on engineering materials.

General Dynamics is studying the effects of reactor radiation on electronic systems with 6 months of exposure.

Bendix Aviation Corporation is investigating radiation effects on electronic parts and systems.

The U. S. Naval Research Laboratory has a program involving fast-neutron radiation effects on ceramic-bonded strain gages. Evaluation of lead-wire insulation is also included.

Battelle Memorial Institute is irradiating neutron detectors and various electronic components.

Sylvania Electric Products, Inc., is conducting irradiation studies on nonoperating vacuum tubes for qualification approval. They are also conducting radiation experiments with circuitrons in an operating condition.

Sperry Rand Corporation is performing experiments with the computer system for the WS107A-2 programs to determine the effects of pulsed radiation.

General Precision, Inc., is conducting a study to determine the means for hardening guidance and control systems for the MMTBM under conditions of transient radiation environments.

AVCO Research and Advanced Development is studying radiation hardening of instrumentation and telemetry systems for SLEIGHRIDE.

American Bosch Arma Corporation is concerned with radiation-effects studies on guidance and navigation equipment for global-range missiles.

International Business Machines Corporation is conducting a study concerned with evaluating guidance and control system techniques for a global-range missile. A portion of the study is being directed toward determining the vulnerability of various techniques to a nuclear-weapon environment.

NRA, Inc., is performing magnetic and related measurements associated with nuclear-weapons tests under PROJECT FISH BOWL.

Northrop-Ventura is conducting studies on the effects of prompt gamma radiation on guidance and control systems to make recommendations for hardening of specific circuits.

International Business Machines Corporation is performing a feasibility study of various missile guidance systems in a hypothetical defensive environment. This involves studies of environmental conditions caused by nuclear-weapon detonations and subsequent engineering estimates of the system vulnerability.

Kaman Nuclear is evaluating nuclear electromagnetic interference at high altitude, low altitude, and optical blackout. Thermal effects, X-ray effects and decoys, blast effects, and EMP are also included.

International Business Machines Corporation is under contract to investigate the effect of pulses of nuclear radiation on selected circuits from the TITAN II and the STINGS computers.

General Dynamics is studying the effects of short pulsed gamma radiation on dynamic electronic components, including vacuum tubes.

Hughes Aircraft Company is developing techniques for theoretical prediction of transient radiation effects on electronic systems.

International Business Machines Corporation is under contract to experimentally investigate the effects of pulse and steady-state nuclear-radiation effects on selected circuits from the Minneapolis-Honeywell X-15 flight-control system.

The Electronics Research and Development Laboratory at Fort Monmouth has an internal program for development of radiation-resistant electronic devices for use in computers and missile-guidance systems. LINAC, TRIGA and GODIVA are being considered for the experimental phase.

The Electronics Research and Development Laboratory at Fort Monmouth has an internal program for determining the nature, extent, and mechanisms of damage caused by nuclear radiation to electronic components, parts, materials, and electronic devices. The program will consist of evaluations and experimental investigations.

The Frankford Arsenal is conducting a theoretical and experimental program for studying the effects of transient radiation on electronic systems for fire control.

Harry Diamond Laboratories is conducting pulsed effects studies.

Harry Diamond Laboratories is establishing correlations between transient effects on specific circuits exposed to weapons tests and those observed in laboratory simulated conditions.

Harry Diamond Laboratories is doing internal research on nuclear-radiation effects on electronic materials and systems.

General Dynamics is investigating contributory radiation effects on electronic parts.

Bell Telephone Laboratories, Inc., is studying the vulnerability of the ZEUS/SPRINT systems from the nuclear-effects standpoint.

The Admiral Corporation is investigating the effects of nuclear radiation on the performance of precision military-type quartz resonators and oscillators in pulse nuclear experiments.

International Business Machines Corporation is studying the effects of transient radiation on magnetic and dielectric devices. Past work has involved memory devices and current work will involve pulse radiation effects on capacitors.

Northrop-Ventura is making an analysis of experimental data from OPERATION FISHBOWL to determine the long time motion of the debris as a function of the time and beta-ray injection into the geomagnetic field.

Northrup-Ventura is developing outlines of practical laboratory test methods for predicting radiation vulnerability of electric parts in present and future circuits.

General Dynamics is studying the physics of transient radiation effects and conduction mechanisms in ionized gases.

Hughes Aircraft Company is studying the development of new techniques to extend the peak current limitations of LINACs and the development of new electron accelerating techniques.

Hughes Aircraft Company is studying typical circuit design and component employment to aid in defining failure as related to missile-system vulnerability.

Kaman Nuclear is investigating the vulnerability of the Polaris re-entry system to nuclear environments.

General Dynamics is investigating the feasibility and potentialities of an accelerator-pulsed fast assembly.

The Defense Atomic Support Agency has an internal program for analyzing techniques related to protection of military electrical equipment and power systems from the electromagnetic pulse from nuclear detonations.

Kaman Nuclear is involved in studies of vulnerability to effects of nuclear detonations and the feasibility of fuzing.

General Electric Company, Tube Department is monitoring operational behavior of microwave devices in a pulsed radiation environment. Voltage-tunable magnetron oscillators are currently being investigated.

Georgia Institute of Technology is studying pulsed radiation effects on glass-enclosed quartz resonators at SPRF, and the results will be compared with subsequent weapons-effects tests.

Hughes Aircraft Company is conducting a study to determine and describe effects of nuclear radiation on passive electronic parts, devices, and circuits.

Sperry Microwave Electronics Company is conducting a study to determine effects of pulsed nuclear radiation on operating characteristics of the C-band beacon ferrite duplexers.

General Dynamics is conducting a study of contributory radiation effects of individual constituent parts of electronic components to the over-all radiation response.

ARINC Research Corporation is making a statistical analysis of magnetic-tape-recorded data on the effects of transient radiation on electron tubes and semiconductor devices.

General Electric Company, Receiving Tube Department is conducting research to determine the nature of basic mechanisms responsible for transient changes in operating characteristics of electron tubes subjected to pulsed radiation.

Northrop-Ventura is studying equipment design practices and techniques for establishing and defining nuclear environments for U. S. Army communications and surveillance equipment.

Northrop-Ventura is conducting a nuclear-effects study on dormant missile guidance and control systems.

Douglas Aircraft Company, Inc., has an internal program for development of methods needed to predict pressure-time histories. This study involves vehicles affected by shock waves and soft X-rays from nuclear explosions.

Douglas Aircraft Company, Inc., has an internal program involving calculation of standard nuclear-environment data, and application of nuclear-effects data to vulnerability studies, and to components, assemblies, and systems. This study is intended for use in vulnerability studies of optimum systems for specific missions, and general studies related to weapon concepts, trends, and detection.

Conclusions and Recommendations

The state of the art for radiation-effects research on electronic devices and systems indicates that there is a general increase in activity for each category, with the greatest effort being concentrated on the study and design of radiation-damage-resistant circuits and systems. Applicators of semiconductor devices such as diodes, transistors, and solar cells continue to be concerned over the vulnerability of the devices, as indicated by its relatively high position in per cent of total radiation-effects research programs. Of the electronic parts only, semiconductor devices comprise some 56 per cent of the research programs. In the over-all picture for electronic parts, circuits, and systems, 35 per cent is related to semiconductor devices, 27 per cent to other electronic parts, and 38 per cent to circuits and systems. This represents an increase (in comparison with 1961-1962 period) in semiconductor research and systems, with a strong indication that the remaining electronic parts have been sufficiently researched in the opinion of many.

In reviewing the current and completed programs associated with irradiation studies of electronic parts and equipment, it was found that there is a general increase

in quantity of such research programs in comparison with the period covered between July 1, 1961, and June 30, 1962. Approximately 61 per cent of the radiation-effects research that is being conducted involves transient-type radiation problems. A cross section study of organizations active in research programs indicates that, of the research on radiation effects, the U. S. Air Force is conducting or sponsoring 38 per cent; U. S. Army - 24 per cent; NASA - 11 per cent; DASA - 8 per cent; U. S. Navy - 7 per cent; AEC - 6 per cent, and nongovernmental organizations - 6 per cent. It is realized that these comparisons relate only to the number of active programs known at REIC, and that the magnitude and scope of research has not been taken into consideration for each organizational program.

Interest in the capability of the electronic components and systems to survive in space-radiation environments continues to expand at a rapid rate. Data generated in experiments through the use of nuclear reactors and gamma pools are being used as a stop-gap source. Experiments with cyclotrons and linear accelerators are increasing; however, the increase is slow. In view of the bulk of information and data made available from reactor and gamma pool experiments, many of the space electronics design engineers are attempting to seek direct conversion factors for converting neutron and gamma radiation-effects data to proton and electron radiation-effects data.

Although a considerable amount of data has been generated in connection with more common electronic components, much of the information is related to experiments with extremely small sample sizes. Since reliability requirements are being injected more strongly into electronic-system applications, many design engineers are desirous of combined radiation-effects and reliability information. In this respect, very few of the immense quantity of radiation-effects data can be used. The general trend for solving this problem is to select preferred and high-reliability parts as an initial approach and to follow up with determining the component part's vulnerability to radiation damage. In the absence of sufficient data, the component parts are irradiated to the radiation flux levels anticipated in their applications.

It has been mentioned that the research programs associated with electronic parts other than semiconductor devices have shown a second successive decrease in intensity. It is recognized that such components as resistors, capacitors, and electron tubes fall into saturated areas; however, certain types in each category have special parts in which no specific information is available. For resistors, there is a definite lack of radiation-effects data for precision potentiometers. In the area of electron tubes, data associated with magnetrons, electrometer tubes, and klystrons are extremely limited. In capacitors, information is not sufficient to determine whether the "wet" tantalum capacitor possesses greater resistance to radiation damage than the "dry" type, or vice versa. The radiation-effects information concerning transducers for instrumentation and telemetry applications is extremely limited. A recent study of the transducer state of the art (REIC No. 25) has shown that very little information is available to designers of telemetry systems, and a review of current research shows only a few programs that include any form of transducer. The need for transducer information, based on requests for technical information at the REIC, appears critical for such transducer types as (1) pressure, (2) temperature, (3) flow, (4) gyros, (5) strain and stress, and (6) velocity. Because of the lack of this needed information, many of the transducers are selected for application by estimating radiation threshold damage levels.

SEMICONDUCTOR DEVICES AND MATERIALS

Current State of the Art

In applications where semiconductor devices are exposed to radiation, three general classes of radiation effects are of potential concern: (1) displacement effects, (2) surface effects, and (3) ionization effects. Exposures of major practical interest have been fast-neutron and gamma radiation from reactor sources, electron and proton components of space radiation, and the high-intensity pulses of fast neutrons and gamma rays from nuclear-weapon bursts.

Displacement damage is the basic cause of radiation-induced degradation of the electrical characteristics of semiconductor devices, most commonly as a result of a reduction of minority-carrier lifetime and occasionally by changes in the electrical conductivity. Such damage that occurs at room temperature does not anneal to any substantial extent at temperatures below the practical upper limit for device operation and can be considered permanent. The exposures that can cause failures of semiconductor devices as a result of displacement effects cover a wide range. In general the most sensitive devices degrade sufficiently to cause circuit malfunction at exposures of $\sim 10^{11}$ fast $n\text{ cm}^{-2}$. Diodes and transistors can be selected to provide adequate radiation resistance to exposures of $\sim 10^{14}$ fast $n\text{ cm}^{-2}$ and in many cases to 10^{15} fast $n\text{ cm}^{-2}$, particularly if the circuits are designed to minimize degradation effects. The upper limit of satisfactory device operation using current semiconductor materials and device fabrication techniques is still $\sim 10^{16}$ fast $n\text{ cm}^{-2}$.

In transistors the most pronounced effect of displacement damage is reduction of current gain. The rate of decrease of current gain is proportional to K/f_α where f_α is the base transport frequency cutoff and K is a damage constant dependent on type and energy of the bombarding particle, nature of the semiconductor, and type and conductivity of the base material. As a consequence, low-frequency transistors, and silicon transistors degrade faster than comparable germanium transistors. Because of the large range of f_α encountered in transistors (~ 1 to 10^6 kc/sec) and the range of K -values, it is not surprising that transistor failure from radiation has been observed over an exposure range of approximately six orders of magnitude.

Recently, a thorough knowledge has been obtained of displacement effects produced by electron and proton radiation of silicon solar cells. Estimates of the electron spectrum in Van Allen radiation indicate a negligible number of electrons at energies above 1 Mev; hence, the active portion of a solar cell can be shielded from electrons with about 25 g cm^{-2} of a suitable transparent cover material. Shielding cannot shield out the energetic proton component. The most-radiation-resistant form of solar cell consists of a very thin n-type layer on a p-type base. In addition, to make less-radiation-sensitive cells, one can optimize the blue-light response at the expense of the red-light response. As a result, the blue sensitive n on p-type base silicon cells are about a factor of 20 more resistant to proton radiation than are the normal p on n cells. One can conclude that solar cells can be long-lived (1 to 10-year) power sources in satellites that encounter Van Allen radiation.

Little attention has been given to the physical nature and origin of radiation-induced changes in semiconductor surface properties and the associated changes in device characteristics; yet these changes have been frequently observed. The dominant effect is an

increase in the reverse current of a p-n junction. However, some observed changes in transistor current gain are of apparent surface origin. Although some of these effects decay in seconds, others persist for days. The degree to which surface effects are observed is sensitive to types of surface-coating materials, such as silicone greases placed on the semiconductor, to contaminants such as water vapor within the device encapsulation, and to the nature (or absence) of the gas within the encapsulation. Current knowledge does not permit any detailed correlation between radiation effects of surface origin and the physical nature of a semiconductor surface.

When a semiconducting junction is irradiated with gamma rays, hole-electron pairs are generated throughout the device volume as additional ionization is produced by Compton electrons, thereby causing an excess flow of current. For the very high radiation intensities that can be encountered from a nuclear-weapon burst, this radiation-induced current can be larger than the circuit signal level. A fair amount of success has been achieved in predicting the shape and magnitude of the excess current pulse from information about the expected radiation pulse and the basic geometry and electrical properties of the semiconductor device.

It has been determined recently that, in a transistor, radiation-generated hole-electron pairs can cause a secondary component of excess current in addition to the primary component of a single junction. This secondary pulse may reach a maximum at times greater than and endure much longer than the radiation pulse. It has been postulated that the production of carriers in the transistor will cause a temporary accumulation of majority carriers in the base region which tends to forward bias the emitter junction and thus produce the secondary current.

Programs in Progress

Arizona State University is investigating the effects of radiation on the electrical and optical properties of semiconductors and insulators.

Battelle Memorial Institute is investigating the irradiation of neutron detectors and electrical components.

Bell Telephone Laboratories efforts are currently being directed toward basic studies of radiation effects on germanium and silicon bulk material and devices. Also, radiation damage to solar cells is being studied, using a satellite to place the cells in the Van Allen belt.

Boeing Airplane Company is conducting a program to predict transient-radiation-damage thresholds for circuits from radiation data on components. From these data, circuits will be built and tested at Godiva and KUKLA facilities.

Brown University is investigating the unification of nuclear magnetic resonance techniques, electron-spin paramagnetic resonance techniques, and auxiliary techniques such as optical investigations used to study more thoroughly the mechanisms of defect formation in alkali-halides, semiconductor materials, and several noncubic materials.

Burroughs Corporation is conducting a study to ascertain whether the combined environmental effects of temperature and pulsed nuclear radiation on semiconductor devices are simply the sum of the two single effects or a complex interaction of the two. A statistical sample of four major device categories (two silicon and two germanium) will be exposed at various temperatures to various intensities of radiation pulses. In addition, radiation effects on thin-film tunnel emission devices are being studied.

Douglas Aircraft Company is conducting reactor exposure tests to determine effects of radiation and high-temperature annealing on various semiconductor components and circuits compensated for radiation damage.

Electro-Optical Systems, Inc., is investigating the feasibility of a radiation-resistant solar cell.

Exotech, Inc., is conducting a study to accumulate, review, and summarize existing data on the radiation damage created by high-energy electrons and protons to solar cells in space power systems.

General Dynamics Corporation, General Dynamics/Fort Worth is conducting basic studies to determine the mechanisms involved in induced voltage phenomena. A 2500-curie Cobalt-60 source is being used for the radiation field. In addition, radiation-effects experiments on semiconductors and semiconductor circuits are being conducted.

General Dynamics Corporation, General Atomic Division is studying the physics of radiation effects in silicon, germanium, and tellurium. This study includes the measurement of galvanomagnetic properties and excess carrier lifetimes as a function of radiation and subsequent annealing. Radiation effects on silicon solar cells are being studied to determine a correlation among types of defects produced, type of silicon used, and type of incident radiation. In addition the effects of short pulses of gamma radiation on semiconductor diodes, transistors, and optical and infrared detectors are being studied.

General Electric Company is devoting a portion of its program for the design and development of a communication-satellite vehicle to the effects of electron and proton radiation on solar cells. In addition, experimental studies on the behavior of microwave devices in a pulsed radiation environment are being conducted.

Hughes Aircraft Company is investigating the feasibility of mathematical and analytical prediction of the effect of pulsed radiation on circuits. These predicted effects will be based on the analysis of presently known radiation effects on components and circuits. The predicted effects will be tested by AFSWC at Godiva and gamma LINAC facilities.

Infrared Industries, Inc., is accessing the long-term effects of proton and electron radiation on PbS and InSb infrared detectors. A portion of the program is being devoted to determining the feasibility of simulating proton effects in solid-state materials and devices by electron bombardment.

International Business Machines Corporation is conducting investigations concerned with the experimental measurement and theoretical prediction of the electrical behavior of selected components exposed to high-intensity bursts of nuclear radiation. In addition, IBM has developed a digital computer which will withstand an integrated neutron flux of 10^{16} n cm⁻² and gamma exposure rates of 8.7×10^8 ergs g⁻¹(C) sec⁻¹. As part of this program a series of radiation-effects experiments were performed to determine the effects of large integrated neutron fluxes on electronic components (including tunnel diodes) and circuits.

Johns Hopkins University is performing experiments to study the effect of space radiation on solar-cell performance on the TRANSIT B4, the TRAAC, and the ANNA satellites.

Litton Systems, Inc., is investigating the correlation of neutron and gamma spectra versus integrated exposure on damage produced in transistorized gyro preamplifiers. Both pulse and steady-state reactors are being employed in this study.

Lockheed is testing electronic equipment and parts (including semiconductors) to radiation flux environments.

NASA, Langley Research Center, is studying electron damage to silicon solar cells with and without shields.

North American Aviation, Atomics International Division, is studying radiation damage in solids, yielding information on the effects of radiation on materials and providing a sensitive tool for investigating defects in solids. It is the objective of this project to study the production of defects in crystalline solids (including semiconductors) by radiation and to attain understanding of their structure, their interactions with each other and with impurities and dislocations, their effect on the physical properties of solids, and their recovery kinetics.

Northrop-Ventura is conducting a research program to determine transient radiation effects on electronic components and circuits.

Philco Corporation is developing thin-film devices utilizing tunneling for the active gain mechanism and studying radiation effects on these devices.

Purdue University is conducting fundamental studies of radiation effects on the electrical and optical properties of semiconductors, including compound semiconductors.

Radio Corporation of America is investigating the effects of high-energy electrons and high-energy protons on GaAs solar cells and silicon solar cells. In addition, the effect of proton radiation on transistors is being studied.

Sandia Corporation is employing two distinct approaches to predict the effect that permanent damage in semiconductor devices has upon systems or circuits. The first method is a parametric study whereby the behavior of the system is computed from the individual parameters associated with each component of the system. The second method involves statistical-analysis procedures whereby the probability of a system failure can be predicted as a function of flux.

Texas Instruments, Inc., is conducting experiments to observe the effects of 200-kv X-rays on semiconductor devices.

Union Carbide Nuclear Company, Oak Ridge National Laboratory, is studying radiation effects on semiconductors as a means of determining the fundamental nature of defects in solids. Materials being studied include the elemental semiconductors germanium and silicon, and compound semiconductors such as the sulfides of zinc, cadmium, and mercury.

University of Illinois is studying the nature and number of lattice imperfections introduced into crystalline solids by nuclear radiation at liquid-helium temperature and annealing above the radiation temperature. The materials being examined include GaSb, InSb, germanium, silicon, and various metals and alloys.

Harry Diamond Laboratories is conducting radiation-effects studies on electronic components and systems, with emphasis on transient effects.

U. S. Army Signal Corps, Solid State Devices Division, is studying transient effects and permanent damage to newly developed electron devices. Pulse and steady-state irradiations are being considered. Godiva, TRIGA, and KEWB facilities will be the sources used for the irradiation studies.

U. S. Naval Research Laboratories is conducting experimental studies of the effects of electrons and protons on solar cells.

Westinghouse Electric Corporation is evaluating the radiation tolerance of webbed dendritic solar cells for space applications.

Conclusions and Recommendations

The varied requirement for semiconductor devices in electronic equipment which will be subjected to a nuclear environment impose the greatest restrictions regarding the attainment of adequate radiation-resistant circuitry. At the present time, the circuit design engineer does not have devices utilizing material other than germanium or silicon, and he is constantly faced with the problem that rarely is radiation-effects information available for the most up-to-date components. It is noted that a great deal of progress has been made by investigations to predict damage as a result of displacement or ionization effects, thus providing many guidelines to aid the engineer in selecting reliable parts without testing each individual component. However, additional work on existing theories or in new areas will be fruitful in better defining damage mechanisms and thus aiding in the prediction of damage. For example, the current state of the art regarding the understanding (both theoretical and experimental) of surface effects leaves a great deal to be desired.

New device design and testing, as well as additional efforts in search of materials other than germanium and silicon for the active elements of diode and transistor-like devices, should be continued in a search for more radiation-resistant materials or device configurations. For example, should recent concepts of utilizing stimulated emission at p-n junctions to get transistor action without carrier diffusion across the base region be practical, lifetime degradation in the base region would no longer be the limiting radiation effect. Such a device would then be much more radiation resistant than the conventional transistor.

Conducting experiments which simulate the damage to be expected in devices exposed to nuclear-weapons bursts or to space radiation has its associated problems in producing an adequate facsimile of the true environment. As experimental conditions have more closely approached the actual environment, additional effects have been observed which were not previously predicted by extrapolations.

POLYMERIC MATERIALS

Current State of the Art

Although space environmental effects are still of interest in the area of polymers, a considerable amount of work has been conducted by such groups as General Dynamics/Fort Worth on reactor-radiation effects. Undoubtedly, these studies will eventually be extended and applied to problems encountered in the space environment.

Theoretical studies are still being conducted; however, several of them, veering toward applied research, are currently yielding results of a more practical and immediate interest.

Radiation Effects on Elastomeric Materials

Polyurethanes

General Dynamics/Fort Worth's investigations of the irradiation of several Adiprene, Genthane, General Tire Type R, and Disogrin samples at various exposure levels in the range of 2×10^9 to 1.7×10^{10} ergs $g^{-1}(C)$ plus associated neutron flux of 1.25×10^{15} to 8.5×10^{15} n cm^{-2} at -65, 80, 260, and 350 F permit a realistic characterization of their stress-strain behavior. The data indicate that all Adiprene-L and most Disogrin specimens predominantly degraded while all Genthane and General Tire Type R specimens predominantly crosslinked. Although polyurethane rubbers are among the most radiation-resistant rubbers, the ultimate tensile strengths and the ultimate elongations decrease at the higher radiation doses. (33, 34, 35)

The B. F. Goodrich Company⁽³⁶⁾ has found Estane VC rubber cured with dicumyl peroxide to be the most radiation-resistant vulcanizate tested so far in their program. Usually, rubber compounds without antirads require radiation exposure from 1.0×10^8 to 2.7×10^9 ergs $g^{-1}(C)$ to effect 50 per cent net compression set, and from 3.0×10^8 to 4.4×10^9 ergs $g^{-1}(C)$ when antirads are present. However, the Estane only requires 5.5×10^9 ergs $g^{-1}(C)$ to induce 50 per cent net compression set.

Adiprene-C exposed to high vacuum (10^{-6} mm Hg), ultraviolet radiation (2000 Å), and moderate temperature (300 F) had only a slight weight change, not exceeding 1 mg, and a small increase in differential swelling and permanent set. However, above 300 F, pyrolysis develops, resulting in marked stress decay. (37, 38)

Acrylonitriles

Goodrich has continued work on the development of radiation-resistant vulcanized rubber compounds; most of the recent work has been concentrated on an experimental elastomer of butyl acrylate/phenyl acrylate/vinyl benzyl chloride. Compression-set studies after exposure to 10^9 ergs $g^{-1}(C)$ of gamma radiation indicate that the phenyl ring has a protective effect in such acrylate rubbers. The inherent radiation stability of

such acrylate elastomers can be further enhanced by compounding with good conventional age resisters such as antioxidants and antiozonants. Increasing the amount of the curing agent, TETA (triethylene tetramine), also improves the radiation resistance of the BA/PA/VBC rubber compound. (39,40)

Another study, also conducted by Goodrich, involved the measurement of the effect of reinforcing agents, commercial carbon black, and nonreinforcing agents on the radiation resistance of Hycar 1001 vulcanizates with and without the antirad, Flexzone 6H. An attempt was made to correlate some of the basic properties of the reinforcing agent with radiation performance, namely, the structure index, surface area, acidity, oxygen content, hydrogen content, and the 200 per cent modulus of the compound. Carbon blacks with low oxygen contents, low surface area x hydrogen content products, and high pH values increase antirad protection; the opposite characteristics result in inhibition of antirad protection. Increasing the acrylonitrile content above 40 per cent is unprofitable in terms of the radiation resistance. (41,42,43)

The antirad effectiveness of Flexzone-3C, Sustane, and Solux in Hycar 1001 was also measured. Compression set at 5.23×10^9 ergs $g^{-1}(C)$ and the radiation exposure required for 50 per cent compression set indicate that Flexzone-3C affords the best protection to Hycar 1001. However, 5 phr is the optimum level for these antirads under these conditions. (44) Compression-set data for Hycar 1072 and Hycar 1000 x 145 at 5.23×10^9 ergs $g^{-1}(C)$ indicate that Hycar 1000 x 145 has the better radiation resistance of the two. In the presence of the antirad Flexzone-6H the Hycar 1072 shows considerably improved resistance to radiation-induced compression set. (45)

A low-temperature study was recently conducted on two Hycar 1001 nitrile rubber compounds, which received nine separate gamma radiation exposures ranging from zero to 10^{10} ergs $g^{-1}(C)$. The radiation-induced changes in modulus at room temperature were essentially the same for both stocks. However, the changes in modulus at -5 C were strikingly different as shown by the following comparison:

Radiation Exposure, ergs $g^{-1}(C) \times 10^{-9}$	Relative Modulus at R. T. (46)	
	Control Stock	Antirad Stock
0	1.0	1.0
10.45	3.5	2.0
Relative Modulus at -5 C		
0	1.0	1.0
0.87	1.5	1.2
2.61	3.1	1.6
5.22	110	3.2
10.45	550	22.7

The stress decay, weight loss, and elastic modulus of Hycar 1072, Hycar 4021, and Hycar 1042 show no apparent change at temperatures less than 225 F on exposure to ultraviolet radiation in vacuum; however, there was appreciable surface deterioration, as evidenced by dulling, cracking, permanent set, and unequal swelling. Above 300 F the bulk properties show significant changes, as pyrolysis becomes important and marked stress decay results. (37,38)

Several acrylonitrile-butadiene elastomers (Hycar 1001, Hycar 1052, Precision 103-95, and Duroid 3200) have been irradiated at ambient temperatures in JP-4 fuel and Oronite oil. Total exposure range was neutron: $1.9 \times 10^{15} \text{ n cm}^{-2}$ to $4.6 \times 10^{15} \text{ n cm}^{-2}$; and gamma: $4 \times 10^9 \text{ ergs g}^{-1}(\text{C})$ to $10^{10} \text{ ergs g}^{-1}(\text{C})$. The JP-4 fuel had a damaging effect even without irradiation, so that the measurement values from the irradiated specimen were very low. The compression-set data do not increase as uniformly as expected because of a bowing of the compression plates. When thicker plates are used, the compression-set data increase more uniformly. The tensile strength of materials compounded with Hycar 1001 generally increased with exposure, while those compounded with Hycar 1052 generally decreased. Because of such results, caution should be exercised in making general statements regarding the effect of radiation on a given type of elastomer without specifying the recipe. (33)

Silicone Rubbers

General Dynamics/Fort Worth, (33,35) has investigated the reactor irradiation of silicone elastomers in various media. Stress-strain data on the silicone elastomers, DC-80, DC-675, DC-916, LS-53, SE-361, and SE-551, that were irradiated in air at -65, 80, 260, and 350 F to exposures on the order of $10^{10} \text{ ergs g}^{-1}(\text{C})$ and $10^{15} \text{ n cm}^{-2}$ ($E > 0.33 \text{ Mev}$) indicate, with few exceptions, extensive radiation-induced crosslinking. The stress, when measurable at 50 per cent elongation, generally increased with increasing exposure. In most cases, the ultimate strength increased with exposure to a certain point and then decreased with increasing exposure. The increase is generally considered to be a continuation of the crosslinking that was not fully carried out by the usual curing process; the decrease is attributed to chain cleavage. Tear strength decreased with increasing exposure, and the tensile properties of the elastomers were sensitive to the test temperatures.

The performance of NSR-X5602 irradiated in different fluids is significant. Degradation in MIL-L-7808 was clearly indicated by the decrease in stress at 50 per cent elongation with exposure, while irradiations in Oronite 8515 and air resulted in an increase in stress at 50 per cent elongation with exposure. The highest exposure was $1.3 \times 10^{15} \text{ n cm}^{-2}$ ($E > 0.33 \text{ Mev}$) and $1.7 \times 10^9 \text{ ergs g}^{-1}(\text{C})$. Test results of gamma irradiated [exposure: $8.2 \times 10^9 \text{ ergs g}^{-1}(\text{C})$] LS-53 indicate that the material is not acceptable in OS-45 hydraulic fluid for either radiation or nonradiation conditions. (47-33)

The life of silicone elastomers and the extent to which they may be used in a radiation field is determined by the physical requirements, mainly elongation, of the application. Silicone elastomers may be usable for radiation exposures in excess of $5 \times 10^8 \text{ ergs g}^{-1}(\text{C})$ at room temperature or high temperatures, where high elongation is not required. The typical silicone rubber retains 50 per cent elongation after exposures of $5 \times 10^7 \text{ ergs g}^{-1}(\text{C})$ at room temperature, $10^7 \text{ ergs g}^{-1}(\text{C})$ at 150 C, or $5 \times 10^6 \text{ ergs g}^{-1}(\text{C})$ at 200 C. One radiation-resistant experimental silicone elastomer retained 50 per cent elongation after exposure of $9 \times 10^7 \text{ ergs g}^{-1}(\text{C})$ and 350 hours at 200 C. The dielectric properties are also unaffected by these radiation exposures. General Electric's investigation of silicone rubber used as insulation in an electrical connector showed some degradation of mechanical properties upon exposure to fast neutrons in excess of $10^{16} \text{ n cm}^{-2}$ ($E > 2.9 \text{ Mev}$) accompanied by gamma irradiation in excess of $10^{11} \text{ ergs g}^{-1}(\text{C})$ at 55 C. (48,49)

At moderate temperatures SE555-U showed severe surface deterioration on exposure to ultraviolet radiation in vacuum; however, Silastic LS63 and Silastic 916 showed only a slight permanent set, but no differential swelling. Above 300 F, pyrolysis develops, resulting in marked stress decay. (37,38)

Butyl Rubbers

Butyl 325 is considered to be one of the most radiation-resistant elastomer formulations. Tests revealed that it showed no alteration after 25 hours' exposure to ultraviolet radiation at 10^{-5} mm Hg ambient pressure. (37)

Natural Rubbers

The relationship between compression set induced by radiation and the degree of vulcanization for natural-rubber specimens and the ability of various additives to reduce radiation-induced compression set were determined at the Naval Radiological Defense Laboratory. (50) Compression set due to a 10^{10} ergs $\text{g}^{-1}(\text{C})$ exposure decreases linearly from 92 to 75 per cent as the degree of vulcanization increases from 5×10^{18} to 30×10^{18} . 9, 10-Phenanthrenequinone and 1,4-naphthoquinone functioned as antirads, reducing compression set moderately below that predicted from degree of cure.

Natural rubber exposed to high vacuum, radiation, and moderate temperature became hard and brittle on the surface. When the irradiated samples were released from tension, they developed a curvature, indicating permanent set of the top surface. Although there was very little stress decay, indicating little or no bulk chain scission at low temperatures, above 300 F bulk pyrolysis results in marked stress decay. (38)

Fluoroelastomers

Although the surfaces of Viton A and Viton B became hard and brittle on exposure to high-vacuum ultraviolet radiation, and moderate temperatures, they are two of the more radiation-resistant formulations. The effect of temperature becomes evident above 300 F when pyrolysis develops and marked stress decay results. (37,38)

Neoprenes

Neoprene W was exposed to high-vacuum ultraviolet radiation, and moderate temperatures at the Armour Research Foundation. The irradiated surfaces became hard and brittle. When the irradiated samples were released from tension, they developed a curvature, indicating permanent set of the top surface. They show very little stress decay, indicating little or no bulk chain scission at low temperatures; however, above 300 F bulk pyrolysis becomes important, resulting in marked stress decay. (38)

Chlorosulfonated Polyethylenes

Hypalon 30 exhibited good stress-strain properties up to a radiation exposure of 1.2×10^{15} n cm^{-2} and 3.1×10^9 ergs $\text{g}^{-1}(\text{C})$, after which all properties except ultimate strength underwent considerable change. (33)

High-vacuum ultraviolet radiation, and moderate temperatures caused Hypalon 40 to become hard and brittle on the surface. When the sample was released from tension, curvature developed, indicating permanent set of the top surface. There was little stress decay; however, above 300 F pyrolysis develops, resulting in marked stress decay. (38)

Radiation Effects on Plastic Materials

Thermosetting Resins

Epoxy Resins. At Aerojet General two specimens of several epoxy resins were subjected to a radiation exposure of 10^9 ergs $\text{g}^{-1}(\text{C})$, and five others were exposed to a vacuum between 10^{-4} and 10^{-6} torr for 16 days. Three of these five specimens were then irradiated to the specified exposure. Epoxy with unidirectional glass fibers and Sotchply 1009-25 deteriorated slightly from exposure to radiation, but the tensile strength increased slightly from exposure to the combined effects of vacuum and radiation. Type 181 glass fabric and epoxy E-787 resin also increased slightly in strength from exposure to the combined effects of vacuum and radiation. From these variations, it can be concluded that the epoxy resins' slight gains in strength from the combined effects of vacuum and radiation are probably through a curing mechanism. (51)

Mechanical and electrical tests on polymeric potting compounds have been made at Lockheed. Specimens have been exposed to pressures on the order of 10^{-7} mm Hg and temperatures up to 170 F for approximately 100 hours. Data are summarized in Table 1. Preliminary results indicate that several commercial epoxy formulations offer promise as encapsulants for electrical components in space environments. (52,53,54) Epon 828, which withstood SNAPSHOT (Satellite Nuclear Auxiliary Power Project) flux requirements of 10^{13} n cm^{-2} and 10^{10} ergs $\text{g}^{-1}(\text{C})$, is also satisfactory for use as a potting compound. (55) Results of work at the University of Illinois indicate that a radiation exposure of 10^{14} n cm^{-2} has no measurable effect on the mechanical behavior and fracture morphology of epoxy resins. (56)

Short-term-radiation studies have been made on epoxy laminates, which were exposed to combinations of radiation in ultraviolet and near ultraviolet range (2000 to 6000 Å) and to pressures near 10^{-6} mm Hg for up to 500 hours. Approximately 1 per cent of the laminate evaporated as plasticizer or other nonpolymerized substances. They lost approximately 10 per cent of their strength after the full 500-hour exposure. (57) Epon 828 also evolved a small amount of gases after exposure to X-rays. (58) Clear epoxy resins used to bond sapphire and quartz cover materials to silicon solar cells discolor severely under ultraviolet irradiation. (59)

Phenolic Resins. In a series of tests at Aerojet General, two specimens were subjected to a radiation exposure of 10^9 ergs $\text{g}^{-1}(\text{C})$ and five others were exposed to a vacuum between 10^{-4} and 10^{-6} torr for 16 days. Three of these five specimens were then irradiated to the exposure specified above. Significant variations were noted in the tensile strength of the following. Phenolic with chopped glass fibers and molding compound OPX-197 had slight deterioration from exposure to radiation, considerable deterioration from exposure to the combined effects of vacuum and radiation, and severe deterioration from exposure to vacuum only. Phenolic with chopped glass fabric and molding

TABLE 1. EFFECT OF HIGH VACUUM AND ELEVATED TEMPERATURE ON PHYSICAL AND

Material	Commercial Designation	Properties Before				
		Q-Value At 2.5 MC		Dielectric Constant and Power Factor at 10 KC		
		(1)(a)	(2)(a)	(1)	(2)	(3)(a)
Epoxy (flexible)	HYSOL 12-007	Q-143	Q-150	3.1	3.12	3.2
		Q-150	Q-155	0.0165	0.018	0.0335
Epoxy (filled)	HYSOL 3X	Q-139	Q-145	3.5	3.8	3.6
		Q-105	Q-113	0.0285	0.0378	0.0315
Epoxy-polyamide	EPOCAST 202/9615	Q-146	Q-152	3.2	3.5	3.13
		Q-150	Q-147	0.022	0.0355	0.0192
Epoxy	828/D	Q-145	Q-148	3.0	3.0	3.05
		Q-155	Q-148	0.007	0.0083	0.0082
Epoxy (solvent system)	DENNIS 1162	Q-105	Q-115	5.5	6.25	4.4
		Q-55	Q-65	0.102	0.11	0.063
Epoxy-polyamide	EPIBOND 1210/9615	Q-142	Q-146	3.4	3.7	3.45
		Q-131	Q-136	0.039	0.052	0.0355

(a) (1) Before conditioning.

(2) Conditioned at 10^{-6} mm Hg at 77 F for 48 hours.(3) Conditioned at 10^{-6} mm Hg at 170 F for 96 hours. Test results incomplete.

ELECTRICAL PROPERTIES OF TYPICAL PLASTIC POTTING COMPOUNDS⁽⁵²⁾

and After Test			Maximum Dimensional			Remarks
Hardness (Shore)			Change, %			
(1)	(2)	(3)	(1)	(2)	(3)	
78/73 (D)	80/75 (D)	81/78 (D)	-2.05 mold shrinkage	-2.93	-4.51	High shrinkage during cure and further contraction on R.T. -vacuum exposure. Good dimensional and electrical properties. Slight browning. Appears satisfactory.
82/81 (D)	85/82 (D)	86/84 (D)	-0.8 mold shrinkage	-1.24	-1.23	Fair electrical properties and dimensional stability but handling properties and viscosity are not satisfactory for potting resin. No visible change in appearance after vacuum exposure.
68/58 (D)	68/51 (D)	72/68 (D)	-1.9 mold shrinkage	-0.69	-1.18	Appears satisfactory. Slight browning.
82/81 (D)	85/83 (D)	65/83 (D)	-1.4 mold shrinkage	-0.52	-1.36	Good dimensional stability and electrical properties after conditioning, but high rigidity introduces excessive stress concentration throughout (particularly at corners). Not recommended.
56/49 (A)	52/58 (A)	86/72	-2.8 mold shrinkage	-1.39	-2.98	Not satisfactory. Solvent again caused curing difficulties and partially dissolved wire insulation. Resin cracked in center of cell after R.T. -vacuum test, and cracking was magnified by 170 F - vacuum exposure. Brownish discoloration also resulted after latter conditioning.
75/69 (D)	75/65 (D)	80/76	-0.8 mold shrinkage	-1.82	-1.16	Appears satisfactory. Printed-circuit broad coating also. No appreciable change after E. T. - vacuum exposure except slight bubbling on surfaces.

compound MX-2625 had slight deterioration from exposure to vacuum, radiation, and the combined effects of vacuum and radiation. Phenolic with chopped graphite fabric and molding compound MX-4551 had slight deterioration from exposure to radiation, and from the combined effects of radiation and vacuum. All of the phenolic resins tested were affected adversely by exposure to several or all of the environment conditions; this compares poorly with the performance of other phenolic resins previously tested. (51)

Polyester Resins. During studies on the exposure of polyester glass-reinforced laminates to combinations of ultraviolet radiation and pressures near 10^{-6} mm Hg, approximately 1 per cent of each laminate evaporated as plasticizer or other nonpolymerized substances. The flexural strength of the laminates increased after about 200 hours of exposure, which is attributable to crosslinking; after 500 hours it decreased somewhat but still exceeded the original strength. (57) The North Carolina State College of Agriculture and Engineering has reported that there were no significant changes in the breaking strength, elongation, and modulus of polyesters after irradiation to exposures in the range of 10^5 to 5×10^7 ergs $g^{-1}(C)$. (60)

The radiation exposure required to cause detrimental effects to polyester-backed magnetic tapes exceeds 200,000 times that termed 50 per cent lethal human exposure, according to engineers at Minnesota Mining and Manufacturing Company. Physical damage begins to appear after the exposure exceeds 4.23×10^9 ergs $g^{-1}(C)$. (61)

The effect of air on the irradiation behavior of polycarbonates is evidenced in General Electric (Hanford's) investigations. Other than increasing coloration, oxidation appears to have little effect on polycarbonates up to exposures of 10^{10} ergs $g^{-1}(C)$; they lose all of their strength after an exposure of 3.3×10^{10} ergs $g^{-1}(C)$ in air. (62)

The maximum total radiation exposure which polyethylene terephthalate electrical sheet insulation can tolerate has been estimated at 10^9 ergs $g^{-1}(C)$. A modified terephthalic acid base polyester stability was rated at 10^{11} ergs $g^{-1}(C)$; however, if reduction of electric strength to about 50 per cent of initial cannot be tolerated, the material must be downgraded one level to 10^{10} ergs $g^{-1}(C)$. (63) The Soviets have found that polyethylene terephthalate's static electrical conductivity increased about one order of magnitude after exposure to bremsstrahlung radiation and 10^{11} fast $n\text{ cm}^{-2}$. (64)

Film thickness has a decided influence on the effects of ultraviolet radiation on polyethylene terephthalate. Five-mil-thick film exposed to ultraviolet radiation and high vacuum had a fair appearance, although it had moderate brownish discoloration and was not quite as flexible as before irradiation. A 1-mil-thick film had brownish discoloration and disintegrated on handling after the same exposure as the 5-mil film see Table 2. (54, 53, 52, 65)

Thermoplastic Resins

Styrene Polymers and Copolymers. After exposure to bremsstrahlung radiation and 10^{11} fast $n\text{ cm}^{-2}$, the static electrical conductivity of polystyrene increased about one order of magnitude according to Soviet reports. (64)

TABLE 2. RESULTS ON STABILITY OF ORGANIC POLYMER FILMS TO ULTRAVIOLET RADIATION IN VACUUM⁽⁵²⁾

Material	Type	Thickness, mils	Ultraviolet Radiation Intensity ^(b) , cal/cm ² /min	Temp, F	Pressure, mm Hg	Exposure, hr	Results
Polyvinyl fluoride	Pigmented	3	0.6	80	3×10^{-7}	95	Slight darkening. No appreciable change in flexibility or tear strength. Excellent appearance.
Polyethyleneterephthalate	Clear	5	0.6	80	3×10^{-7}	95	Moderate brownish discoloration. Not quite flexible. Appearance fair.
Polyethyleneterephthalate	Clear	1	0.6	80	10^{-7}	91	Brownish discoloration. Film disintegrated on handling.
Polyvinyl chloride	Clear	6	0.6	80	3×10^{-7}	95	Brownish discoloration. Voids and blisters from exuded plasticizer. Poor appearance.
Tetrafluoroethylene	Clear	3	0.6	80	3×10^{-7}	95	Very slight discoloration. No appreciable change in flexibility, elasticity. General appearance very good.
Metallized polyethylene-terephthalate ^(a)	Al-coated one side	0.5	0.6	80	10^{-7}	91	No change.
Polyamide (oriented)	Clear	1	0.6	80	10^{-7}	91	Very slight discoloration. Good tear strength and tensile retention.

(a) This material is representative of the type used in the Echo I satellite.

(b) Intensity corresponds to 4 to 4.5 times solar ultraviolet intensity (2,200 - 4,000 Å) in space (zero air mass).

Polyvinyl Compounds. Systematic investigations have been conducted at the Danish Atomic Energy Research Establishment on the radiation-induced coloration in commercial polyvinylchloride film. The color intensity was studied as a function of: absorbed dose; color development caused by heat treatment under different conditions; fading effect of storage before and after heat treatment; oxygen content of the surrounding atmosphere; irradiation temperature; and film thickness. Results indicate a strong possibility of using this color change to measure gamma exposures in the $0.5 - 5.5 \times 10^6$ ergs $g^{-1}(C)$ range. A suitable procedure and well-standardized conditions give a reproducibility better than 10 per cent. Some preliminary experiments carried out with a 10-Mev electron linear accelerator show that the procedure proposed might also be useful for accelerator dosimetry. (66)

The Japanese have studied specimens of nonplasticized, rigid, and transparent polyvinylchloride sheets in six thicknesses, from 0.1 mm to 5.3 mm, irradiated with 1.4×10^2 ergs $g^{-1}(C)$, in order to derive the relationship between film thickness and optical-density changes. It was found that (1) the optical density tended to increase with increase in thickness; (2) the optical density gradually increased immediately after the termination of irradiation, subsequently decreased rapidly after a certain period of time, but finally increased once more until it reached a value larger than that immediately after irradiation; and (3) with increased thickness, the changes in optical density were retarded. (67)

In order to simulate the effects of thermal radiation from a nuclear blast, black polyvinylchloride sheet was subjected to a total thermal exposure of $1 \text{ cal cm}^{-2} \text{ sec}^{-1}$, at which exposure the samples fused. (68)

The radiation stability of polyvinylchloride tubing used for electrical insulation has been estimated at 10^9 ergs $g^{-1}(C)$ maximum total radiation exposure, and polyvinyl formal magnet wire insulation has been estimated at 10^{10} ergs $g^{-1}(C)$. However, if 50 per cent reduction in electric strength cannot be tolerated, both materials must be downgraded one level. (63)

Personnel at Lockheed have concentrated a considerable amount of effort on investigations of the effects of ultraviolet radiation and vacuum on polyvinylfluoride and polyvinylchloride. The fluoride had an excellent appearance; there was only a slight darkening, with no appreciable change in flexibility or tear strength. The chloride had a poor appearance, with discoloration, voids, and blisters from exuded plasticizer, as indicated in Table 2. (53,54,52)

Polyethylene. The influence of radiation exposures of 1.0, 2.5, 5.0, and 7.5×10^{17} n cm^{-2} on the stress-strain properties of polyethylene for tension, compression, bending, and shear stresses was determined. An increase in radiation produced the following effects: decreased elastic strength, fracture strength, ductility, resilience, and toughness, but increased stiffness and creep resistance in tension; increased elastic strength, stiffness, creep resistance, and resilience in compression; decreased modulus of rupture, ductility, and toughness, in bending; decreased elastic strength, modulus of rupture, ductility, resilience, and toughness, but increased stiffness, in torsion. In general, the tests show a decrease in most short-time properties with an increase in radiation exposures for tension, bending, and torsion, and an increase in short-time properties for compression. (69,70)

The tensile strength of uniaxially and biaxially oriented samples of polyethylene decreases while the modulus of elasticity increases with increasing gamma radiation exposures of 4.36×10^8 ergs $\text{g}^{-1}(\text{C})$, 1.39×10^9 ergs $\text{g}^{-1}(\text{C})$, and 7.99×10^9 ergs $\text{g}^{-1}(\text{C})$ at 78 F. The combined effects seem to indicate that the gamma radiation essentially destroys the macromolecular orientation and thus reduces the tensile strength to that of unoriented solid, but with a relatively higher elastic modulus as a result of the occurrence of crosslinking. (71)

The transmission of helium, nitrogen, methane, and propane has been studied in samples of a high pressure, branched polyethylene irradiated to an exposure of 8.77×10^9 ergs $\text{g}^{-1}(\text{C})$ in air. Infrared analysis indicates that oxidation, unsaturation, and crosslinking resulted from irradiation. The apparent solubility constants were uniformly higher by 40 per cent in the irradiated film as compared with the values in the unirradiated film. No reduction in crystallinity or the apparent energies of activation for diffusion was observed upon irradiation. A thermodynamically consistent increase in the apparent heats of solution was observed. The reduced apparent diffusion constants in the irradiated samples evidently arose from the mild crosslinking which had occurred in the amorphous phase. (72)

Constituents in the United States, Russia, and Japan have investigated the radiation-induced changes in polyethylene's electrical properties. The Soviet literature has reported that polyethylene films had an increase in the static electrical conductivity of about one order of magnitude after exposure to bremsstrahlung radiation and 10^{11} fast n cm^{-2} . In the case of polyethylene, when the temperature increased from 20 to 87 C, the radiation conductivity increased by a factor of about 30, and it fell sharply when the temperature was reduced, until at -57 C it was lower than 10^{18} ohm $^{-1}$ for a radiation intensity of 2.16×10^5 ergs $\text{g}^{-1}(\text{C}) \text{ hr}^{-1}$. (73,64) From Japanese investigations of the temperature (190 to 300 K) and exposure-rate (10^5 to 10^7 ergs $\text{g}^{-1}(\text{C}) \text{ hr}^{-1}$) dependence of the radiation-induced conductivity in polyethylene, it is concluded that the thermal electrons are dominant as charge carriers above 230 K, but fast electrons are dominant below that temperature. (74) Polyethylene-sheet electrical insulation has an estimated radiation stability of 10^{10} ergs $\text{g}^{-1}(\text{C})$, but if a reduction in electric strength to about 50 per cent of initial cannot be tolerated, the material must be downgraded one level. (63)

Polyethylene irradiated in vacuum at room temperature up to an exposure of 8.77×10^9 ergs $\text{g}^{-1}(\text{C})$ showed no change in the nuclear magnetic resonance line shape, indicating that it retains its original structure. (75) However, when polyethylene is exposed to ultraviolet light, both scission and crosslinking occur and the tensile strength and elongation decrease. (65)

Fluoroethylene Polymers. Teflon studies were conducted to determine the magnitude of the oxygen-associated radiation damage and the differences in radiation resistance among the fluorocarbon polymers, i. e., TFE Teflon, FEP Teflon 100, and Teslar. The thinner specimens of TFE degraded somewhat more than thicker ones, indicating that the rate of diffusion of oxygen through the Teflon is the most likely factor in this degradation. Batch variation can be seen in the control data for different thicknesses of TFE. Teflon 100 apparently has considerably more radiation resistance in air than TFE of the same thickness. An unexpected result was the extremely good radiation resistance of the Fiberglass-reinforced Teflon. This material retained some of its flexibility as well as 40 per cent of its tensile strength at a radiation exposure of 7.9×10^{15} n cm^{-2} and 1.2×10^{10} ergs $\text{g}^{-1}(\text{C})$. (33)

The conductivity induced by gamma radiation from a Cobalt-60 source has been measured for Teflon as a function of temperature, exposure rate, and applied voltage. The exposure rates range from about 10^5 to 10^7 ergs $\text{g}^{-1}(\text{C})$ hr^{-1} and the temperatures from 190 to 300 K. Below about 240 K the induced current at thermal equilibrium was independent of temperature, although it was slightly increased with decreasing temperature.⁽⁷⁴⁾ An increase in the static electrical conductivity of about one order of magnitude and destructive phenomena, i. e., disintegration into fine platelets and evolution of gases, were observed in Fluorofilm-3 and Fluorofilm-4 when irradiated with bremsstrahlung radiation and 10^{11} fast n cm^{-2} .⁽⁶⁴⁾ The general appearance of tetrafluoroethylene on exposure to ultraviolet and vacuum was very good. It showed slight discoloration, with no appreciable changes in flexibility and elasticity (see Table 2).^(53,54,52) Reviews of space-environment effects on Teflon resins continue to appear; one of the most recent is by E. I. du Pont de Nemours and Company, Incorporated.⁽⁷⁶⁾

Acrylics. Acrylic textiles had no significant changes in their breaking strength, elongation, and modulus on exposures in the range 10^5 to 5×10^7 ergs $\text{g}^{-1}(\text{C})$; a material produced by the graft polymerization of acrylonitrile to cotton cloth is also resistant to attack by microorganisms and to heat degradation.⁽⁶⁰⁾

In an effort to develop new space expandable structures using plastics with radiation-induced plastic memory, Radiation Applications, Incorporated, has investigated polyethylene-acrylate copolymers. Samples receiving 2.5×10^7 ergs $\text{g}^{-1}(\text{C})$ or more (the largest exposure studied was 8.5×10^7 ergs $\text{g}^{-1}(\text{C})$ of radiation for flat sheets and 2.0×10^8 ergs $\text{g}^{-1}(\text{C})$ for mesh) always showed complete restoration (within the limits of observation) after transparency developed in the polymer under restoration heating conditions. Increasing the radiation exposure causes a noticeable decrease in the restoring force of the copolymer. Under comparable conditions, Zetafin 30 irradiated with 5×10^7 ergs $\text{g}^{-1}(\text{C})$ moved 32.7 to 34.4 g, while Zetafin 30 irradiated with 10^8 ergs $\text{g}^{-1}(\text{C})$ moved only 15.2 to 15.7 g. This effect is probably due to the low G-value for crosslinking for the acrylate component compared to polyethylene.⁽⁷⁷⁾

When polymers of methyl methacrylate are subjected to radiation from a Cobalt-60 source, in exposures of 8.46×10^7 to 8.46×10^8 ergs $\text{g}^{-1}(\text{C})$, the polymer molecule was cleaved as shown by a decrease in intrinsic viscosity and by the amount of gases liberated. When polymethyl acrylate is irradiated, gelation rather than loss in intrinsic viscosity occurs at the lowest exposure used [8.46×10^7 ergs $\text{g}^{-1}(\text{C})$].⁽⁶⁵⁾

The tensile strengths of polyethylene-allyl acrylate and polyethylene-allyl methacrylate systems irradiated to exposures up to 4.6×10^6 ergs $\text{g}^{-1}(\text{C})$ rise markedly at the lower exposures. At the highest exposure used, they had higher tensile strengths than monomer-free polyethylene after 7.5×10^7 ergs $\text{g}^{-1}(\text{C})$.⁽⁷⁸⁾

Polyamides. HT-1, an experimental nylon, has excellent retention of tensile properties following exposure to beta and gamma radiation. In fact its strength is unaffected by 3.3×10^{10} ergs $\text{g}^{-1}(\text{C})$ of gamma radiation. Its vast superiority over Dacron and nylon 66 is illustrated by the results after exposure at the Brookhaven Pile for a total of 1.69×10^{11} ergs $\text{g}^{-1}(\text{C})$. HT-1 retained 45 per cent of its original tenacity, whereas Dacron became radioactive and nylon 66 crumbled.^(79,80) The breaking strength, elongation, and modulus of nylon 66 were also adversely affected in relatively short periods on exposures in the range of 10^5 to 5×10^7 ergs $\text{g}^{-1}(\text{C})$.⁽⁶⁰⁾

Polyamid-H film electrical insulation was unaffected by an exposure to Cobalt-60 irradiation for 27.25 hours to 4.1×10^9 ergs $\text{g}^{-1}(\text{C})$. Mechanical-property tests, performed after a 100-hour irradiation in the GTR at General Dynamics/Fort Worth, show that Polyamid-H film retained 76 per cent of the original ultimate elongation after exposure to 1.6×10^{10} ergs $\text{g}^{-1}(\text{C})$, and underwent a 30 per cent increase in ultimate tensile strength. After exposure to 4.0×10^{10} ergs $\text{g}^{-1}(\text{C})$, the ultimate elongation was reduced to 48 per cent of the original value and ultimate tensile strength increased by only 20 per cent over the original value. (58)

Continuous exposure to intense ultraviolet radiation tends to craze and embrittle nylon. The effect shows up first in the reduction of ultimate elongation. This is usually accompanied by a decrease in impact strength and an increase in stiffness. However, the resin retains its strength for a considerable period of time after its elongation has been affected. Nylon 66 can be protected from this type of attack by compounding finely divided 1 and 2 per cent carbon black in the base resin. Even a relatively small amount of carbon black affords some degree of protection. (81,65) However, on exposure to ultraviolet radiation and vacuum, polyamide resin has a very slight discoloration, and good tear strength and tensile retention. Of several materials tested (see Table 2) it showed the least change. (53,54,52)

Polypropylene. To determine the effect of isotacticity on radiation effects, isotactic and atactic polypropylene were irradiated in vacuum with Cobalt-60 gamma rays to a total exposure of 9.09×10^6 ergs $\text{g}^{-1}(\text{C})$, and the chemical effects produced by the irradiation were studied. The gases liberated were mostly hydrogen and methane, with the methane yield greater for the atactic sample. The intrinsic viscosity of both types of polypropylene initially decreased rapidly with exposure until the gel point was approached when a minimum was reached. (82)

The internal friction and the dynamic modulus of isotactic polypropylene samples subject to varying degrees of pile irradiation have been studied at low audiofrequencies and over the temperature range from 100 K to over 400 K. The radiation exposures varied from 5.4×10^{17} to 1.4×10^{19} n cm^{-2} . For exposures up to about 3×10^{18} n cm^{-2} , one observed change is a decrease in the temperature at which the final upswing in damping and drop in modulus occurs, presumably as a result of defects produced in the crystallites by the irradiation. As the radiation increases above 3×10^{18} n cm^{-2} , all evidence of crystallinity is lost. The results of density determinations and of solvent-extraction studies of the irradiated material confirm the simultaneous occurrence of crosslinking and of crystalline degradation upon pile irradiation of polypropylene. (83)

Isotactic polypropylene filament samples were irradiated in the presence of air as well as in vacuum at room temperature. The densities of the samples were almost unchanged by irradiation in vacuum, but considerably increased in the case of irradiation in air. The degree of shrinkage at the flow temperature of the irradiated filament as well as the flow temperature decreased with increase in exposure, except for a sample irradiated 9.3×10^9 ergs $\text{g}^{-1}(\text{C})$ in vacuum. The tensile strength and elongation at break decreased after irradiation in vacuum, especially in air. Young's modulus and elastic recovery at room temperature did not change with exposure. The changes in these properties by irradiation are presumed to be dependent on the presence of oxygen. (84,60)

Silicones. A survey conducted by Dow Corning indicates that silicone resins are generally more radiation resistant than other silicones. Radiation exposures of 10^9 ergs $\text{g}^{-1}(\text{C})$ at room temperature or 10^8 ergs $\text{g}^{-1}(\text{C})$ at high temperatures have little effect on the physical or electrical properties of silicone fluids. Because of viscosity increase, a low-viscosity dimethyl silicone fluid may be usable as a dielectric coolant for exposures up to 10^8 ergs $\text{g}^{-1}(\text{C})$ at room temperature. Phenylmethyl silicone fluids are usable for much larger exposures. Radiation at high temperatures, in the range of 150 C to 200 C, will decrease these radiation effects to about one-half the room-temperature effect. Silicone compounds are affected in a manner similar to silicone fluids by radiation. The phenylmethyl-based compounds gel after radiation exposures of 4×10^7 ergs $\text{g}^{-1}(\text{C})$ at room temperature, 2×10^7 ergs $\text{g}^{-1}(\text{C})$ at 150 C, or 10^7 ergs $\text{g}^{-1}(\text{C})$ at 200 C. The expected life of a dimethyl-based compound is about one-half of this. Electrically, neither compound is significantly affected by radiation in excess of the gelation exposure. (48)

Sealants and Gaskets

The effects of several integrated fluxes of 10^9 ergs $\text{g}^{-1}(\text{C})$, 10^{15} n cm^{-2} and 10^{10} ergs $\text{g}^{-1}(\text{C})$, 10^{16} n cm^{-2} at 72 - 95 F on the hardness, tensile strength, per cent elongation, peel strength, and thermal rupture properties of four high-temperature sealants, one prefabricated fillet material, and 7 Thiokol-based compounds were determined. The general strength characteristics of sealants EC-1520, EC-1605, and EC-1610 were improved after exposure to both fluxes. On the other hand, a trend was noted in that the strengths of PR-1422 and IE-1240 (prefabricated fillet) were adversely affected by radiation. EC-1520, EC-1605, and EC-1610 without a top coating of EC-776 showed more improvement after irradiation than when coated, while uncoated PR-1422 and IE-1240 showed less degradation than when coated. Among the fuel-tank sealants, EC-1520 appeared to be least affected by nuclear radiation. Overall, these materials were not affected to such an extent as to preclude their use in a nuclear-powered aircraft. (85,86)

A three-compartment chemical self-sealant package for aerospace vehicles, developed at Hughes Aircraft Company, seals a "meteoroid" puncture 0.140 inch in diameter. Only two of the compartments of this package contain reactants; the third is left empty. Any of several polyurethane and epoxy reactions are workable with this system. Several polyurethane and a few polysulfide and silicone reactions have been evaluated with respect to their potential use as space-applied assembly sealants. An unfilled polyurethane system, which cures within 6 hours at room temperature under vacuum conditions, appears promising for this use. (87) Silicones, fluoroelastomers, chlorosulfonated polyethylenes, polychloroprenes, chlorobutyl and chlorobutyl-polychloroprene blends, polysulfides, and polyurethane have also been studied for possible use in preventing and controlling meteoroid damage and the potential air leakage due to penetration. After exposure to seven different irradiation conditions, including gamma or combined gamma [10^8 and 10^9 ergs $\text{g}^{-1}(\text{C})$] and ultraviolet radiation in vacuum or air for times of 16 and 100 hours, the tensile strength, 100 per cent modulus, ultimate elongation, and hardness were determined, supplemented by analysis of the gases generated during the irradiation tests and visual examination of the specimens. For most of these elastomers, the primary reaction seemed to be crosslinking, with only minor amounts of chain scission. (88)

After irradiation with 10^9 ergs $g^{-1}(C)$ in air, the ultimate tensile strength of Viton B O-rings was reduced from 2638 psi to 2339 psi and the ultimate elongation was reduced from 372 per cent to 287 per cent. As a result of the irradiation in Oronite 8515 hydraulic fluid, the ultimate tensile strength was reduced to 1771 psi and the ultimate elongation was reduced to 227 per cent. However, superior high-temperature hose and seal components can be obtained with the Viton compounds by derating standard components or by designing specifically for radiation conditions. (58,47)

Stress-strain measurements of acrylonitrile-butadiene copolymer (NBR), acrylonitrile-butadiene/styrene-butadiene copolymer (NBR/SBR), chloroprene (CR), and Viton A O-rings before and after gamma radiation exposures of 0, 5, 10, 50, and 100×10^8 ergs $g^{-1}(C)$ rated these control gasket stocks' radiation resistance as follows: NBR > NBR/SBR > CR > Viton A. Measurements of compression set during irradiation rated the four vulcanized control rubber compounds' radiation resistance in the decreasing order NBR/SBR > CR > NBR > Viton A. The NBR/SBR vulcanizate with 3 phr of Antioxidant 4010 is the most radiation-resistant practical rubber compound tested so far in the B. F. Goodrich investigations. (36) O-rings fabricated of Precision 2277 Special, a neoprene with five pph of Antiox 40.0, were irradiated in air and also in 4P3E hydraulic fluid with an estimated exposure of 10^9 ergs $g^{-1}(C)$. The ultimate tensile strength increased slightly from 1984 psi to 2047 psi, and the ultimate elongation decreased from 254 per cent of the original length to 141 per cent of the original length after irradiation in air. As a result of the irradiation in hydraulic fluid, the ultimate tensile strength was reduced slightly to 1940 psi and the ultimate elongation was reduced to 138 per cent of the original length. (58)

Adhesives

Table 3 itemizes the various commercially available adhesives subjected to environmental testing and their corresponding cure cycles. Nine test specimens were exposed for over 1100 hours to a pressure of the order of 10^{-6} mm Hg and temperatures of 200 - 250 F, and irradiated for a total exposure of approximately 3×10^9 ergs $g^{-1}(C)$ with periodic leakage testing. Results indicate that the adhesives were quite stable in this environment with the exception of a modified phenolic-supported film adhesive, which leaked badly. In general, difficulty was experienced in fabricating specimens having leak-tight glue lines with the supported-film-type adhesive. Although different in kind than the charged-particle radiation existing in the Van Allen belts, the effects approach high-energy electron and proton effects. (52,53,54)

Coatings

The more recent coatings research has been almost completely centered on the requirements of paint coatings in withstanding space environment and in providing some measure of passive temperature control in spacecraft by radiation balance.

The Aeronautical Systems Division has prepared a wide variety of tailored coatings to meet the demands of selective solar absorptance values for short-term exposures to the space environment. A white silicone-alkyd coating gave 0.20 - 0.85 values when various amounts of a black enamel were added. Only small changes in optical properties were noted when the coatings were exposed to vacuum-thermal or ultraviolet radiation

TABLE 3. RESULTS OF EXPOSURE TESTS OF ADHESIVES TO VACUUM, ELEVATED TEMPERATURE, AND HIGH-ENERGY RADIATION⁽⁵³⁾

Adhesive	Type	Form	Leak Rate, cm ³ /sec (measured with helium leak detector)			
			After Exposure of 865 Hr at 200 F Plus 312 Hr at 250 F and 10 ⁻⁶ mm Hg	After Additional Exposure to 3.4 x 10 Roentgens of Gamma Radiation From Co ⁶⁰ Source in Air	After Additional Exposure of 50 Hr at 250 F and 50 Hr at 300 F and 10 ⁻⁶ mm Hg	After Temp Cycling at -80 to 200 F (10 Cycles)
Aerobond 422	Epoxy-phenolic	Supported film	2 x 10 ⁻⁵	4.7 x 10 ⁻⁶	5 x 10 ⁻⁷	2 x 10 ⁻⁶
HT-424	Epoxy-phenolic	Supported film	Large ^(a)	Too large to measure	Too large to measure	--
HT-424-F	Epoxy-phenolic	Primer only	10 ⁻⁶	2 x 10 ⁻⁵	4 x 10 ⁻⁷	1.3 x 10 ⁻⁶
EC-1648	Epoxy-polyamide	2 pt liq	10 ⁻⁶	9 x 10 ⁻⁶	4 x 10 ⁻⁷	9 x 10 ⁻⁷
EC-1386	Epoxy	1 pt liq	10 ⁻⁶	4 x 10 ⁻⁶	2 x 10 ⁻⁷	1.8 x 10 ⁻⁶
Epon 901/B-1	Epoxy	2 pt liq	10 ⁻⁶	1.4 x 10 ⁻⁷	2 x 10 ⁻⁷	2 x 10 ⁻⁶
Epon 8/A	Epoxy	2 pt liq	10 ⁻⁶	2.3 x 10 ⁻⁷	5 x 10 ⁻⁷	7.5 x 10 ⁻⁷
A-1	Epoxy	2 pt liq	10 ⁻⁶	2 x 10 ⁻⁵	2.5 x 10 ⁻⁷	9 x 10 ⁻⁷
Q3-0079	Silicone	1 pt liq	10 ⁻⁶	1.5 x 10 ⁻⁷	5 x 10 ⁻⁸	4.5 x 10 ⁻⁶

(a) Leak in specimen bonded with HT-424 was detected after the first 21 hours of exposure.

environments. Stabilization of certain organic coatings to the effects of ultraviolet radiation was accomplished by incorporating novel ultraviolet absorbers into the coating system. Additions of protective absorbers, particularly hydroxybenzoylferrocene, into a white silicone alkyd and acrylic have enabled the formulations to withstand the effects of ultraviolet radiation to a higher degree than the basic formulations themselves. (89)

The Naval Air Material Center has exposed 20 experimental and specification aircraft organic protective-coating systems to 1.2 Mev of gamma radiation. Significant degradation of color and film properties was noticed in most systems after a 8.0×10^9 ergs $\text{g}^{-1}(\text{C})$ exposure. Promising radiation-resistant topcoats were: white MIL-E-5556 enamel; MIL-R-3043 high-bake phenolic; a commercial, white amine-catalyzed Epon; an experimental white silicone-alkyd; and an experimental white all-silicone. High-pigment loadings aided in reducing degradation effects in some coatings. (90)

Two Acryloid A-10 formulations, one with zinc sulfide and the other with basic white-lead carbonate, were selected for continuing investigations at the Naval Research Laboratory. On exposure to ultraviolet radiation in a vacuum, a considerable decrease in the reflectance of the white-lead formulation was noted, but the zinc sulfide formulation was very resistant to a change in optical properties, and, in at least one instance, has proven superior to all silicone formulations. Reflectance measurements show only a slight increase in the reflectance of a coating by increasing the pigment volume above 40 per cent. Since this small, if any, increase in reflectance and resistance to discoloration from exposure is obtained at a great sacrifice in the coating's other properties, pigmentations above 40 per cent are not recommended. (91,92) Lockheed's results of exposure tests to determine the stability of temperature-control surfaces and thin films of organic polymers under ultraviolet radiation and high vacuum are summarized in Table 4. Of the commercial, white organic-base paints, the acrylic-base paints proved more resistant to visible yellowing than either the epoxy- or silicone-base paints. (52,53,54)

Programs in Progress*

Current programs on radiation effects on elastomers and plastics are summarized below.

Degradation Mechanisms

B. F. Goodrich Company is determining the mechanism of radiation damage of elastomers and of antirad action in inhibiting radiation damage, and is also studying aircraft rubber compounds and components in radiation environments.

Moleculon Research Corporation is determining the mechanism of polymer degradation on exposure to intense thermal and high-energy radiation.

*Detailed information on these programs, including contract numbers and sponsoring agencies, is given in REIC Memorandum 11-C, "Compilation of Nuclear, Pulsed, and Space Radiation Effects Projects" (Confidential), April 15, 1963.

TABLE 4. RESULTS OF EXPOSURE OF COMMERCIAL MATERIALS TO ULTRAVIOLET RADIATION AND VACUUM (53)

Test	Exposure Time, hr	Material Type		Substrate(a)	Curing Cycle	Visible Changes	Measured Radiation Characteristics			
		Vehicle	Pigment				Before		After	
							α	ϵ	α	ϵ
1	46	Epoxy A Silicone A	TiO ₂ , tinted TiO ₂ , untinted	D-15 D-15	Air dry 1 hr, 250 C	Yellowed Slight yellowing	0.25 0.29	0.85 0.83	0.37 0.29	0.87 0.82
2	80	Epoxy A Acrylic	TiO ₂ , tinted 50% TiO ₂ , 50% talc	D-17 D-17	Air dry Air dry	Yellowish brown Very slight yellowing	0.22 0.26	0.83 0.73	0.39 0.33	0.82 0.78
		Acrylic Silicone B	Carbon black Aluminum	D-17 B	Air dry 1 hr, 250 C	Very slight change Slight crackling	0.94 0.21	0.81 0.20	0.92 0.31	0.79 0.25
3	26	Epoxy B Silicone A Silicone A	TiO ₂ , untinted TiO ₂ , untinted TiO ₂ , untinted	D-17 B D-15	Air dry 1 hr, 250 C 1 hr, 250 C	Yellowish brown Yellowish brown	0.24 0.30	0.83 0.83	0.37 0.33	0.85 --
	(at 20S)	Acrylic A Acrylic	50% TiO ₂ , 50% talc 50% TiO ₂ , 50% talc	D-17 D-17	(each coat) Air dry Air dry	Yellowish brown Very little change Very little change	0.30 0.27 0.27	0.81 0.73 0.73	0.34 0.32 0.35	0.78 0.76 0.75
4	12	Epoxy B Silicone A Silicone B	TiO ₂ , untinted TiO ₂ , untinted TiO ₂ , tinted	D-15 B D-15	Air dry 1 hr, 250 C 30 min, 200-230 C	Yellowish brown Yellowish brown Yellowish brown	0.26 0.30 0.25	0.86 0.81 0.83	0.31 0.29 0.33	0.84 0.83 0.83
	(at 20S)	--Anodic coating-- --Anodic coating--	-- --	-- --	-- --	No change No change	0.23 0.18	0.06 0.09	0.28 0.38	0.07 0.14
5	100	Silicone A Silicone B Acrylic	TiO ₂ , untinted TiO ₂ , tinted 50% TiO ₂ , 50% talc	B D-15 D-17	1 hr, 250 C 30 min, 200-230 C Air dry	Yellowish brown Yellowish brown No change	0.30 0.26 0.26	0.81 0.84 0.74	0.33 0.37 0.35	0.84 0.83 0.76
	(at 20S)	Epoxy B Silicone B	TiO ₂ , untinted TiO ₂ , tinted	B D-17	Air dry 30 min, 200-230 C	Yellowish brown Very dark brown	0.26 0.31	0.86 0.83	0.36 0.60	0.82 0.83

(a) Code: D-15 - Dow 15

D-17 - Dow 17

B - Bare Metal.

New Polymer Studies

Douglas Aircraft Company, Incorporated, is continuing the development and evaluation of coating materials, pressure-sensitive tapes, and elastomers with high thermal radiation reflectance properties as protection against the nuclear-explosion environment.

General Dynamics/Fort Worth is investigating the effects of the various combined environments of nuclear radiation, vacuum, and cryotemperatures on engineering materials.

General Dynamics/Fort Worth is studying the radiation tolerance of adhesives, elastomers, electrical insulations, structural plastics, and thermal insulations.

General Dynamics/Fort Worth is also studying the kinetics of radiation-induced chemical reactions.

North Carolina State College, School of Textiles, is modifying textile fiber properties by radiation-induced graft polymerization.

The Pennsylvania State University is studying the effect of radiation of the dynamic properties of high polymers.

The Pennsylvania State University is also conducting a 3-year study on the effects of radiation on the properties of various polymers in order to arrive at an understanding and explanation of radiation-induced processes.

Radiation Applications, Incorporated, is studying the mechanism of radiation-induced gelation in polymer-monomer mixtures.

Sandia Corporation is studying the dynamic mechanical properties of irradiated elastomers.

Stanford Research Institute is investigating radiation-induced reactions in swollen polymers.

U. S. Army, Radiation-Chemistry Laboratory, Natick Laboratories, is investigating the effects of experimental variables on radiation-induced polymerization.

U. S. Army, Materials Research Agency, Rock Island Arsenal, is developing elastomers with improved functional properties by novel grafting techniques.

U. S. Navy, Air Engineering Center, is obtaining viscosity and transmission data for nylon 66 after nuclear, ultraviolet, and thermal irradiation.

U. S. Navy, Bureau of Ships, is studying the radiation polymerization of acetylene derivatives.

United States Rubber Company is determining the effect of electrons on filament-elastomer composites while held under tension in a vacuum.

The University of Georgia is studying the infrared spectra of plastics and elastomers after nuclear irradiation.

The University of Minnesota is planning to study the effects of atomic radiation and molecular orientation on the mechanical behavior of linear solid high polymers.

Conclusions and Recommendations

Most investigators are still concerned with the combined effects of radiation and vacuum in the space environment on polymeric materials. Especially those materials which will be used as insulation, gaskets, sealants, coatings, etc., in nuclear-powered space vehicles are receiving more attention.

No rigid conclusions can be drawn which would enable even types of coating polymers to be placed in an order of merit for resistance to vacuum volatilization. The conclusion that can be drawn is that vacuum losses of organic coating polymers over prolonged periods even at ordinary temperatures can be severe. The best organic materials to resist such losses appear to be straight (nonmodified) silicone resins and Kel-F (a polytrifluoromonochloroethylene). Apart from silicone resins, most of the vehicles suggested for heat-resistant paints are based either on soluble silicates or on titanium esters. (93, 94)

Although the amount of research is quite voluminous, a great deal of coordination of effort and data is required before definite ratings and specifications can be formed. In some cases, redesigning of components and parts will also be necessary in order to use the advantages of the available materials.

FUELS, LUBRICANTS, AND HYDRAULIC FLUIDS

Current State of the Art

Several systems studies during the past year have shown that the materials in the lubricant, hydraulic fluids, and greases area which have been developed for use in a radiation environment will perform at higher exposures of radiation under dynamic testing conditions than predicted by static testing studies of several years ago. Polyphenyl ethers continue to be the accepted lubricant for a radiation environment. Space-simulation studies continue in search of a lubricant which will perform well at the extreme temperature variations in space as well as under the high-vacuum environment of space. Molybdenum disulfide of the solid-film lubricants continues to be selected for immediate uses in space studies.

Fuels

The situation with respect to radiation-resistant fuels has not changed for several years. JP-4 is generally accepted as an auxiliary fuel. The thermal stability of JP-4 is the most critical property even though all its properties change significantly in a radiation environment. Significant gum content increases resulted from mock-up, in-source fuel-system studies at a gamma irradiation exposure of about 5×10^9 ergs $\text{g}^{-1}(\text{C})$, however, no filter plugging or malfunctioning resulted.

Shell has announced that hydrocarbon fuels can be protected from radiation damage by adding small amounts of an aromatic compound to the fuel. Optimum blending offers protection which is 85 per cent effective. (95)

An interesting sidelight this year has been the use of gamma radiation to enhance fuel properties. Gamma irradiation has been found to be just as effective as benzoyl peroxide when used as an initiator for the peroxidation of kerosene. (96) JP-5 was treated by gamma irradiation to an exposure of 1.3×10^5 ergs $\text{g}^{-1}(\text{C})$ at a rate of 4.3×10^4 ergs $\text{g}^{-1}(\text{C}) \text{ hr}^{-1}$. This treatment was used to reduce the particle size of the unstable constituents and to improve combustion and burning rate. (97)

Lubricants and Hydraulic Fluids

In the "1000 F Hydraulic Systems Program" by Republic Aviation Corporation⁽⁹⁸⁾, mix phenoxyphenyl ether has been irradiated at various temperatures under both dynamic and static conditions. In the dynamic tests the system was arranged so that the bulk fluid was subjected to a gamma exposure of 7×10^8 ergs $\text{g}^{-1}(\text{C}) \text{ hr}^{-1}$, and a fast- and thermal-neutron flux of about 10^{14} n $\text{cm}^{-2} \text{ hr}^{-1}$. During the test, pump-inlet temperature was held at 600 F and the actuator outlet temperature at 800 F. Dynamic-test results indicated that, within the limits defined for the fluid life, operation of the system under combined high-temperature and nuclear environment is feasible. In the static irradiation tests, samples were irradiated for 10 hours at an approximate gamma rate of 10^9 ergs $\text{g}^{-1}(\text{C}) \text{ hr}^{-1}$, and the fast- and thermal-neutron flux commensurate with the gamma flux in the NARF reactor. Little effect was noted in the fluids irradiated below 400 F. Viscosity, however, increased very gradually up to 700 F and then began increasing rapidly until, at 800 F, the change was considerable.

The effects of vacuum irradiation at room temperature on the lubricity of Molykote X-15, a dry film with inorganic binder; Electrofilm 66 C, a dry film with organic binder; Shell ETR-H, a grease; and GE F-50, an oil; were investigated at the Nuclear Aerospace Research Facility. (99) Small servomotors with bearings packed with the lubricants were subjected to a vacuum pressure of 5×10^{-7} torr, and were irradiated for 35.3 hours to a total exposure of 1.05×10^{15} n cm⁻² ($E > 2.9$ Mev), 1.06×10^{14} n cm⁻² thermal neutrons, and 7×10^9 ergs g⁻¹(C) gamma irradiation. Both motors containing Molykote X-15 failed to start after 12 and 13 hours of irradiation, but operated sporadically for a few cycles toward the end of the irradiation. One of the motors containing GE F-50 failed after 24 hours of irradiation. The other motor containing GE F-50 and one containing Shell ETR-H showed symptoms of failing at the end of the irradiation. The motors remained in the vacuum environment for a total of 52 hours after the start of the vacuum irradiation. At the end of this time, only the two motors containing Electrofilm 66-C and the two motors containing Shell ETR-H would run consistently. During the 1963 program at General Dynamics (100), three of these lubricants will be retested at lower temperatures. Two new materials, which have showed good resistance to high-vacuum environment, will also be tested.

The aromatic additives as radiation protectors, which were reported in the Shell work above (95), were also reported as being useful in hydrocarbon lubricants. A Shell Oil patent describes radiation-resistant lubricants consisting of nonasphaltogenic organic compounds stabilized with 0.1 to 10 weight per cent added asphaltenes. (101)

Dow Corning F-60 damping fluid used in a magnetic flux valve gelled, causing the valve to become inoperative after being irradiated for 19 hours at a reactor power level of 1.5 megawatts. The flux valve is utilized in aircraft primary navigation systems for detecting the angles between the horizontal component of the earth's magnetic field and the line of flight of the aircraft. The irradiation was continued for 24 hours and 14 minutes, during which time the valve received a total gamma exposure of approximately 2.6×10^{10} ergs g⁻¹(C) and an integrated neutron flux of approximately 2.4×10^{15} n cm⁻² ($E > 2.9$ Mev). A steady linear increase in the pressure of the flux valve case was recorded. After gelation the damping fluid continued to liberate gas. At gelation the pressure in the valve case was measured at 40.5 psi at 97 F, and at completion of the irradiation the pressure had built up to 50 psi at 97 F. (102)

A recent patent issued to the AEC, described the use of a thiopolyether lubricant such as 16,19-dioxa-13,22-dithiatetatriacontane in a medium subject to a reactor environment with a neutron flux of up to 10^{12} n cm⁻² sec⁻¹. (103)

In a three-part study by Westinghouse (104), of bearing and lubricant materials for the high-vacuum environment of space, Duroid 5813, TFE containing glass-fiber reinforcement and MoS₂ powder filler, was the best plastic self-lubricating material. It exhibited a low outgassing rate at temperatures from 160 to 360 F. Of the dry-powder materials tested after degassing in vacuum from -60 to 1000 F, the outgassing rates of molybdenum disulfide and tungsten diselenide were low at 760 F; however, the lowest outgassing rate at 760 F was that of 40 per cent Ni-60 per cent C carburized composite material.

In a vacuum environment of 1×10^{-7} to 2×10^{-8} mm of Hg, bearings of 204 size 20-mm bore incorporating self-lubricating retainers made of PTFE-glass fiber-MoS₂, bronze-PTFE-MoS₂, and silver-PTFE-WSe₂, operated satisfactorily for 100 hours. The bearing with the PTFE-glass fiber-MoS₂ retainers was exposed to temperatures of 100 to 160 F during vacuum testing, whereas the other two materials were exposed up to 400 F. (105)

Bearings made of cermets LT-1B and LT-2, and alloys F-48 and René 41 lubricated with a clad silver-palladium alloy, molybdenum disulfide used in cavities, and bonded molybdenum disulfide, were tested for friction, wear, and load capacity in a vacuum of 1×10^{-5} to 1×10^{-6} mm Hg at temperatures of from -90 to 1750 F. The wear of the cermet bearings lubricated by MoS₂ in a cavity was the best of the materials tested at high and moderate temperatures during the life tests of 5000 cycles; however, the wear approached that of unlubricated bearings at -90 F. (106)

After an extensive study by NASA, gold-plated stainless steel ball bearings and carbon brushes with a molybdenum disulfide core lubricant were used in the electric-field meter which was flown in the Explorer VIII satellite launched on November 3, 1960. These components were designed with a life expectancy greater than that of the available battery power supply. (107)

Greases

Cal Research nuclear-resistant grease NRRG No. 335 was used in the LPR-10 drum system tested by Litton Systems. (106). The system successfully operated without degradation throughout irradiation to a neutron exposure of $1.3 \times 10^{16} \text{ n cm}^{-2}$ ($E > 2.9$ Mev) and a gamma exposure of $10^{11} \text{ ergs g}^{-1}(\text{C})$. (108)

Programs in Progress*

The following organizations are engaged in active radiation-effects studies on lubricants and hydraulic fluids.

General Dynamics/Fort Worth is studying the radiation effects on mix-phenoxy-phenoxy benzene and the effectiveness of oxidation-inhibiting additives for uses at oil temperatures of 500 to 550 F.

General Dynamics/Fort Worth is testing for the radiation effects on solid-film lubricants which are usable to 1000 F in the absence of radiation.

General Dynamics/Fort Worth is studying various lubricants under vacuum-irradiation environment to determine the effects on lubricants in nuclear-powered space vehicles.

Conclusions and Recommendations

The use of low-level exposure of gamma irradiation to improve properties and to process lubricants has been noted in several patents. This patent search has continued at a steady pace over the past 2 years even though contract research has been extremely limited.

Many studies have been conducted on space-simulation effects on lubricants; however, few new conclusions have been reached in the past year. There is still a need for more information on lubricants in a combined environment of high temperatures, vacuum, and radiation, such as the work reported by General Dynamics.

STRUCTURAL METALS AND ALLOYS

Current State of the Art

The radiation-induced property changes in structural metals and alloys continue to be of importance to reactor designers and operators. The operating conditions of reactors are changing to achieve greater powers, and consequently require metals to operate at higher temperatures. The effect of higher temperature operation introduces additional problems related to corrosion, compatibility, and strengths. Not only are the short-time properties of considerable importance but the long-time properties such as creep become a predominant factor influencing the reactor life for many of these materials. The summarization of data given in this report reflects this increased use of structural materials in their higher temperature application. One will find that many of the investigations are now concerned with irradiation at elevated temperatures, i.e., in the range of 1000-2000 F. The use of structural materials for this temperature application requires that the effect of neutrons on mechanisms of strengthening such as age-hardening, solution-hardening, and high-melting-point alloys be considered. This section discusses mechanisms of radiation-induced property changes in ferritic steels, austenitic stainless steels, and high-temperature alloys. Some data are given for these materials.

Mechanisms of Radiation-Induced Property Changes

Seitz⁽¹⁰⁹⁾ discusses the influence of induced property changes from radiation related to the interstitial atoms and vacancy sites that result from particle bombardment of metals. The bombardment of metals by particles such as electrons, protons, or deuterons and neutrons is reviewed. A simplified model postulates a displacement mechanism in which the bombarding particle collides with an atom within a metal lattice site, displacing the atom from its site and into an interstitial position, thus leaving a vacancy or point defect at the original site. Calculations of particle energies sufficient to cause displacement of the atoms have been found to range in values between 15 and 40 electron-volts (ev). Studies have been carried out to determine the E_d or the energy sufficient to cause an atom displacement in specific solids. Work with copper has indicated that 22 ev is a reasonable number for the E_d of that metal. Table 5 shows calculations of the number of displacements for copper produced by three different particles: electrons, deuterons, and reactor neutrons. The energies of these particles are of the same order of magnitude. The table shows how these total energies consist of several components, that is, primary kinetic energy, the energy related to the atom displacement, and that contribution of energy associated with the vibrational energy per primary knocked-on atom. It can be seen that reactor neutrons have sufficient energy to displace the greatest number of atoms in copper, i.e., approximately 500. These 500 displaced atoms are only those participating in primary collisions between the neutron and the atom. Additional atoms are displaced by the 500 atoms which receive sufficient energy from the primary particle to cause subsequent atom displacements. These displacement energies and energies related to particle bombardment have been experimentally determined by measurement of changes in resistivity after particle bombardment.

TABLE 5. DISPLACEMENT CALCULATIONS FOR COPPER⁽¹¹²⁾
 $E_d = 22$ ev

Particles	Primary Kinetic Energy, ev	No. of Atoms Displaced Per Primary	Vibrational Energy Per Primary, ev
1.4 Mev electrons	28	1.25	22.5
9 Mev deuterons	170	6.2	150
Reactor neutrons (~0.8 Mev)	2.5×10^4	500	2.2×10^4

Work at Oak Ridge National Laboratory⁽¹¹⁰⁾ on copper bombarded with neutrons at liquid-helium temperatures has suggested that the radiation effects from neutrons are slightly different than those resulting from electrons or deuterons. Their experimental results show that annealing after this bombardment is nearly continuous, and more gradual, not exhibiting peaks that apparently result from bombardment from other particles. In some respects, the results appear to suggest that the migration of interstitial atoms and perhaps other rearrangements occur in a relatively localized heated zone formed by each primary displaced atom. Brinkman⁽¹¹¹⁾ has suggested that the localized displacement region in the crystal, in which the primary atom was displaced by a neutron, deposited energy in a radial arrangement, and a portion of the disorder is "quenched in" during the cooling period following the irradiation.

Table 6⁽¹¹²⁾ gives a comparison of concentrations of vacancy-interstitial combinations produced by equal fluxes of three types of particles: electrons, deuterons, and neutrons. In all instances, it is seen that the calculated values are larger than the experimentally determined values. This overestimation of the number of displaced pairs implies that the probability of ejection of an atom from its site is substantially less than unity when the best threshold energy value, in this case 22 ev, is used.

Simons, Koehler, and Balluffi⁽¹¹³⁾ suggest that the states of defection produced by irradiation at relatively high temperatures is not necessarily equivalent to that produced by irradiation at the liquid-helium temperatures followed by warming to the higher temperatures.⁽¹¹⁴⁾ Annealing after a low-temperature irradiation facilitates mutual interaction of the radiation-produced defects. Similarly, irradiation at the elevated temperature also favors defect interaction. Therefore, the steady-state concentration of defects produced by irradiation at elevated temperature may be quite small. If the radiation-induced defects produce the property changes per se, then one would expect the relatively small effect of irradiation at elevated temperatures. However, at elevated temperatures, the conditions favor the interaction of these defects formed with substitutional atoms or with other defects, such as dislocations. The radiation-induced property changes therefore may be greater than anticipated, depending somewhat upon the material under consideration and the extent of defect interaction.

TABLE 6. OBSERVED AND CALCULATED FRACTIONS OF ATOMS DISPLACED IN COPPER, WHEN $\Delta\rho$ (1 PER CENT) IS ASSUMED TO BE 3.0×10^{-6} OHM-CM

Density of bombarding particles in each case, $10^{17}/\text{cm}^2$, (112)

Bombarding Particles		
Kind	Energy, Mev	C_{obs}
Electrons	1.4	$2.2 \times 10^{-6} = C_{\text{calc}}/2.7$
Deuterons	9	$6.7 \times 10^{-4} = C_{\text{calc}}/6.0$
Neutrons	~ 0.8	$4.0 \times 10^{-6} = C_{\text{calc}}/18$

Annealing following irradiation at low temperature presents a rather complex spectrum, which appears to be similar for the electron-irradiated, or deuteron-irradiated materials. The annealing appears to result from the recombination of close vacancy interstitial pairs. There also appears on the annealing curve for copper a peak which may result from the migration of interstitials over a large number of atomic distances with an energy of migration of about 0.11 ev.

Sosin⁽¹¹⁵⁾, in looking at the effects of radiation with regard to mechanisms, suggests that until there is a better understanding of the nature of atomic interaction, the possibility of accurately predicting radiation effects is remote. There appears to be a notable acceleration in studies which will yield reliable data on interatomic interaction. However, it is unlikely that the radiation-damage theory will be fully developed until the knowledge in this area is more complete. Radiation-damage investigations should not be postponed until this development takes place. Sosin also refers to data already reported concerning the apparent discrepancy between observed and predicted amount of damage for different types of bombarding particles. It is his opinion that the form of the probability function is almost solely responsible for the discrepancy for the relatively low energy particles, for example, in the electron-irradiation experiments. Variances related to the higher energy irradiation materials may result from insufficiency of the cascade theory. In the case of neutron irradiation, full knowledge of the spike phenomena appears to be very important. These mechanisms are of less importance in the proton and deuteron irradiation. In this respect Sosin agrees with the work of Simons, Koehler, and Balluffi⁽¹¹³⁾, and Seitz⁽¹⁰⁹⁾.

Wechsler and Berggren⁽¹¹⁶⁾ point out that the emission of a captured gamma ray upon thermal neutron absorption also delivers sufficient recoil energy to the atom to produce atomic displacements. The effects and the magnitude of these effects on the properties of materials have not been fully investigated. Oak Ridge is continuing experiments in this area to evaluate the effect of displacement related to gamma-ray recoils.

In other studies related to the fundamental properties of radiation effects, Muss and Townsend⁽¹¹⁷⁾ have studied internal friction and Young's modulus of irradiated

tungsten. These measurements were made as a function of temperature, and irradiation was carried out in a 13.7-Mev deuteron flux. Their experimental work showed that the modulus changes with bombardment can be made to fit a simple dislocation pinning model reasonably well. The effect of immobile radiation-induced vacancies on Young's modulus in tungsten is observed to be -0.44 per cent per atomic per cent of vacancies, compared with Dienes' prediction of -1.0 per cent. Further studies of point defects formed by radiation interaction with existing defects reported by Westmacott, Roberts, and Barnes⁽¹¹⁸⁾ show that both vacancy clusters and interstitial clusters which form during bombardment attract their own kind and repel the other, such that each grows almost independently by a process involving both climb and slip. Thin films of zone-refined aluminum were bombarded at 80 C with a flux of 1.6×10^{10} fission fragments $\text{cm}^{-2} \text{sec}^{-1}$. Defects were observed after about 30 seconds of bombardment. For longer times of exposure, the defects enlarge into dislocation loops. These two pieces of experimental evidence show that point defects formed by radiation interact with existing defects, such that radiation-induced property changes result.

Carbon and Low-Alloy Steels

The application of pressure-vessel steels and other high-strength steels that are utilized in pressure vessels of power reactors continues to provide an interesting problem. As reported previously, the transition temperature for brittle-to-ductile fracture is increased as a result of irradiation. Many studies are continuing in this area to show the extent of the increase of this transition temperature, the effect of annealing, and the effect of subsequent irradiation of these annealed materials. The extensive use of surveillance programs to ascertain the condition of these irradiated pressure vessels has become a common practice. It is thought that, by the use of surveillance-type programs, some measure of the radiation-induced property changes can be detected from time to time in samples made from the pressure-vessel steels and irradiated in testing reactors. In some instances an accelerated program is used, that is, the samples are irradiated in the reactor core position and achieve their total fast flux exposures in times somewhat less than the pressure vessel would under normal operations. This provides a lead time to determine the extent of damage occurring in the pressure vessel itself.

Steele and Hawthorne⁽¹¹⁹⁾ have shown that the transition temperature for ductile-to-brittle fracture for the ferritic pressure-vessel steels is increased as a function of neutron exposure. The maximum extent of damage or radiation-induced changes appears also to be a function of the temperature of the energy spectrum of the neutrons. They have shown that theoretical studies are sufficiently developed to reveal the effects of these various differences, and hence programs are needed to evaluate and to follow the changes of properties in pressure-vessel materials as a result of irradiation. The method for resolving these uncertainties involves the exposure of specimens of the appropriate steel at specific points within reactors. This technique is nominally called a surveillance program. Procedures for conducting surveillance programs and tests have been suggested by a recent ASTM Tentative Recommended Practices-E185-61T. The need for these data have been emphasized to the extent that over one-half of the civilian reactors now in operation or in stages of development have planned surveillance programs. A summary of the existing reactors and the scheduled surveillance programs is shown in Table 7.

TABLE 7. SUMMARY OF PRESSURE VESSEL SURVEILLANCE PLANS FOR 21 U. S. S. REACTORS(119)

(From compilation by A. B. Holt, USAEC)

Reactor	Pressure - Vessel Material	Belt Line Flux for Life, n cm ⁻² (>1 Mev)	Surveillance		Surveillance Material	Specimens		Flux Accumulated to Date (> 1 Mev)
			Planned or Under Way			Charpy	Tensile	
Reactors Now in Operation								
Vallecitos BWR ASTR(a) Dresden SM1 Yankee PWR RER(a) SMIA	A212-B	5.4 x 10 ¹⁸	No	--	--	--	--	3.2 x 10 ¹⁷
	SA240-S	6.4 x 10 ¹⁸	No	--	--	--	--	--
	A302-B	9.2 x 10 ¹⁸	Yes	Representative	428	24	24	5.8 x 10 ¹⁶
	A212-B	1.0 x 10 ¹⁹	Yes	Representative	24	4	4	1.47 x 10 ¹⁸
	A302-B	2.04 x 10 ¹⁹	Yes	Original and representative	168	192	192	6.4 x 10 ¹⁷
	A302-B	6.0 x 10 ¹⁹	No	--	--	--	--	--
	Not operating	7.49 x 10 ¹⁹	No	--	--	--	--	--
	A350-LF-1(Mod.)	8.05 x 10 ¹⁹	Yes	Original (plus A201 and A212-B)	84	14	14	Startup: 3/1962
	A350-LF-3	2.13 x 10 ²⁰	No	--	36	3	3	5.4 x 10 ¹⁸
	PM-2A							
Reactors Not Yet in Operation								
Vallecitos ESR Humbolt Bay Pathfinder Hallam Piqua N. P. Consolidated Edison Bonus N. P. Saxton Elk River Big Rock Point Carolinas Enrico Fermi	A212-B	5.6 x 10 ¹⁷	No	--	--	--	--	Not applicable
	A302-B	1.0 x 10 ¹⁸	Yes	Original	Not indicated	Not indicated	Not indicated	Not applicable
	A212-B	1.14 x 10 ¹⁸	Yes	Not indicated	135	90	90	Not applicable
	304 Stainless	2.0 x 10 ¹⁸	No	--	--	--	--	Not applicable
	A212-B	3.4 x 10 ¹⁸	Yes	Representative	144	24	24	Not applicable
	A212-B	7.6 x 10 ¹⁸	No	--	--	--	--	Not applicable
	A212-B	9.13 x 10 ¹⁸	Yes	Original	120	--	--	Not applicable
	A212-B	9.5 x 10 ¹⁸	Yes	Original	156	24	24	Not applicable
	A302-B	1.9 x 10 ¹⁹	Yes	Representative	240	240	240	Not applicable
A302-B	1.24 x 10 ¹⁹	Yes	Original	Not indicated	Not indicated	Not indicated	Not applicable	
Zircaloy-4	1.4 x 10 ²¹	Yes	Not indicated	Not indicated	Not indicated	Not indicated	Not applicable	
A240-45	3.6 x 10 ²¹	No	--	--	--	--	Not applicable	
304 Stainless								

(a) Test reactors.

The extent of the radiation-induced property changes in typical, pressure-vessel steels is illustrated in Figures 8 and 9, where the increases in the ductility transition temperature for A212-B steel resulting from irradiations are shown. Other steels of this category may show slightly more or less depending on radiation exposure and temperature, but all show a definite increase in transition temperature.

It is suggested by Steele that for a surveillance program to be of value to investigators and prospective designers of reactors, it should include the following:

- (1) The specimens used should include samples from a particular heat of steel of which the reactor component was constructed. If the same heat of steel is not available, the next best choice is to use the same type of steel from a different lot.
- (2) It is also suggested that the radiation-induced property changes can be determined from the postirradiation testing of standard Charpy V-notch impact specimens and tensile specimens. With known changes in tensile and notch ductility, some measure of the effect of neutron damage can be detected.
- (3) All ferritic steels will need protection from corrosion during the irradiation. In addition to protection from corrosion, instrumentation should be included to detect the temperature of irradiation. This can be accomplished with either thermocouples or some low-melting-point metals or eutectic alloys.
- (4) In order that the property changes detected have meaning to the designer, a careful measure of the neutron exposure must be ascertained. Several methods are used for this detection, among which is the threshold detector. A number of such detectors are available, including pure nickel, pure iron, and pure titanium.

Discharge of these irradiated specimens from their strategically located positions within the reactor can map the radiation changes that are occurring within the pressure-vessel wall. Samples are discharged at periods of sufficient length that one can predict the condition of pressure vessels.

A surveillance-type program on the Yankee Atomic Electric Company for their reactor vessel is the subject of a recent paper by E. Landerman⁽¹²⁰⁾.

It is suggested that, in addition to the surveillance-type programs, all control samples be maintained at the irradiation temperature where possible. This practice may detect any changes related to thermally activated processes, and may illustrate that what has previously been believed to be radiation-induced damage results from some metallurgical change. Another area of question in regard to surveillance programs is whether an unstressed surveillance specimen represents a reactor component where a state of stress exists during irradiation. It has been shown recently by Murr and Shober⁽¹²¹⁾ that the state of stress during irradiation in a reactor component may influence the extent of property changes related to ductility of stainless steel. So far as is known, no effort has been made to determine this effect within the ferritic steels.

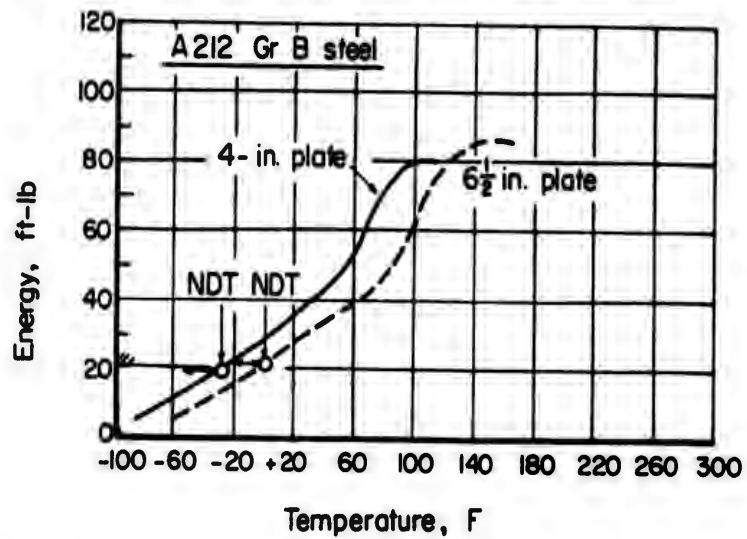


FIGURE 8. INITIAL NOTCH DUCTILITY CHARACTERISTICS OF 4-IN. AND 6-1/2-IN. A212-B STEEL⁽¹¹⁹⁾

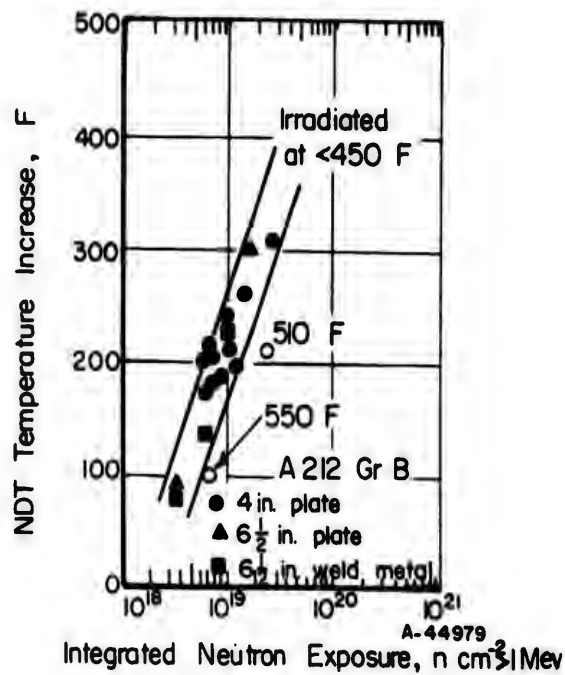


FIGURE 9. INCREASE IN THE NDT TEMPERATURE FOR A212-B STEEL RESULTING FROM IRRADIATION⁽¹¹⁾

The extent of these radiation-induced property changes in ferritic steels has been investigated to a lesser degree with respect to the temperature of irradiations. Some of the pressure vessels as indicated by Hawthorne and Steele⁽¹¹⁹⁾ show that the temperature of irradiation will reduce slightly the extent of the ductility increased transition temperature, but that the annealing following is somewhat less effective. A more recent study on the effects of temperature during irradiation was made on two low-alloy steels by Lowe.⁽¹²²⁾ These were steels irradiated in the range of 2.8×10^{18} to 2×10^{20} n cm⁻² ($E > 1$ Mev), and over a temperature range from room temperature to 1700 F. One steel was a 1-1/4 w/o chromium-1/2 w/o molybdenum, balance iron. The other steel was 2-1/4 w/o chromium-1 w/o molybdenum, balance iron. The postirradiation examinations were conducted at room temperature and included tensile tests and impact tests on the bulk of the irradiated samples. The effect of the irradiation temperature is given in Tables 8, 9, and 10. Figure 10 shows the effect of irradiation on the tensile properties at room temperature. The properties show an effect of irradiation up to temperatures above 725 F. However, at irradiation temperatures between 900 and 1100 F, there appears to be no irradiation effect. For the specimens irradiated above 1100 F, there again appears to be some effect of irradiation. Mr. Lowe suggests that the second increase in yield strength and tensile strength may be associated with microstructural changes. The impact specimens were of the subsize variety, and the data from these indicate that irradiation temperatures in excess of the stress-relief range need to be achieved before any appreciable temperature effect is noted. The temperature effect indicated that above a given temperature an increase or decrease in temperature ductility was less prevalent.

A recent paper by Nichols and Harries⁽¹²⁶⁾ reviews recent developments from irradiation programs on ferritic pressure-vessel steels in Great Britain. An attempt was made to study and determine the effects of both irradiation and metallurgical variables in accelerated flux tests on the radiation hardening and embrittlement of the ferritic steels. A summary of the results or conclusions follows:

- (1) Radiation-induced increases in room-temperature tensile yield stresses ($\Delta\sigma_y$) and notched slow-bend and impact transition temperatures (ΔT) are given by the following relationships:

$$\Delta\sigma_y = A_1 (\phi t)^{1/2}$$

$$\Delta T = A_2 (\phi t)^{1/2},$$

where ϕt is the integrated neutron flux in units of 10^{18} n cm⁻²

A_1 and A_2 are constants which depend on irradiation and metallurgical variables.

- (2) The temperature of the irradiation has no effect on changes in yield stress and transition temperatures of silicon-killed mild steels at temperatures up to those at which the annealing of damage occurs during irradiation.
- (3) Fine-grain steels show smaller changes in impact transition temperatures than coarse-grained steels, when irradiated under the same conditions.

TABLE 9. MECHANICAL PROPERTIES OF ANNEALED 2-1/4 Cr-1 Mo STEEL IRRADIATED AT ELEVATED TEMPERATURES AND TESTED AT ROOM TEMPERATURE⁽¹²²⁾

Specimen	Neutron Flux, n cm ⁻² (> 1 Mev)	Irradiation Temperature, F	Tensile Strength, psi	Yield Strength, psi	Fracture Strength, psi	Total Elongation, %	Uniform Elongation, %	Reduction in Area, %	Hardness, R _A
Standard ^(a)	0	R. T.	82, 600	49, 100	121, 200	34	18	69	55.9
2A-1	3.5 x 10 ¹⁹	700	153, 200	124, 000	219, 500	19	8	54	67.8
2A-2	8.5 x 10 ¹⁹	1000	83, 900	49, 700	242, 300	29	13	69	65.0
2A-3	1.1 x 10 ²⁰	725	157, 800	135, 900	201, 000	19	5	58	70.5
2A-4	1.5 x 10 ²⁰	900	74, 800	46, 800	86, 900	32	14	68	61.0

^(a) Average of several specimens.

TABLE 10. MECHANICAL PROPERTIES OF NORMALIZED AND TEMPERED 2-1/4 Cr-1 Mo STEEL IRRADIATED AT ELEVATED TEMPERATURE AND TESTED AT ROOM TEMPERATURE(122)

Specimen	Neutron Flux, n cm ⁻² (> 1 Mev)	Irradiation Temperature, F	Tensile Strength, psi	Yield Strength, psi	Fracture Strength, psi	Total Elongation, %	Uniform Elongation, %	Reduction in Area, %	Hardness, RA
Standard(a)	0	R. T.	146,700	104,700	193,000	20	5	61	62.5
2T-1	6.0 x 10 ¹⁹	975	148,000	120,000	271,000	22	8	64	67.2
2T-2	6.3 x 10 ¹⁹	975	146,000	128,000	197,000	19	6	70	66.6
2T-3	6.6 x 10 ¹⁹	1050	111,600	98,000	289,000	22	8	69	67.0
2T-4	6.7 x 10 ¹⁹	650	170,000	154,200	171,900	18	18	1	70.5
2T-5	8.5 x 10 ¹⁹	850	159,200	130,800	177,500	20	6	57	70.0
2T-6	1.0 x 10 ²⁰	800	169,500	157,800	203,000	18	5	57	70.5
2T-7	1.6 x 10 ²⁰	925	150,300	138,500	174,900	20	5	57	69.0
2T-8	1.7 x 10 ²⁰	950	151,700	137,000	192,000	21	6	64	67.0
2T-9	1.9 x 10 ²⁰	1025	107,100	92,900	145,000	22	6	72	66.1

(a) Average of several specimens.

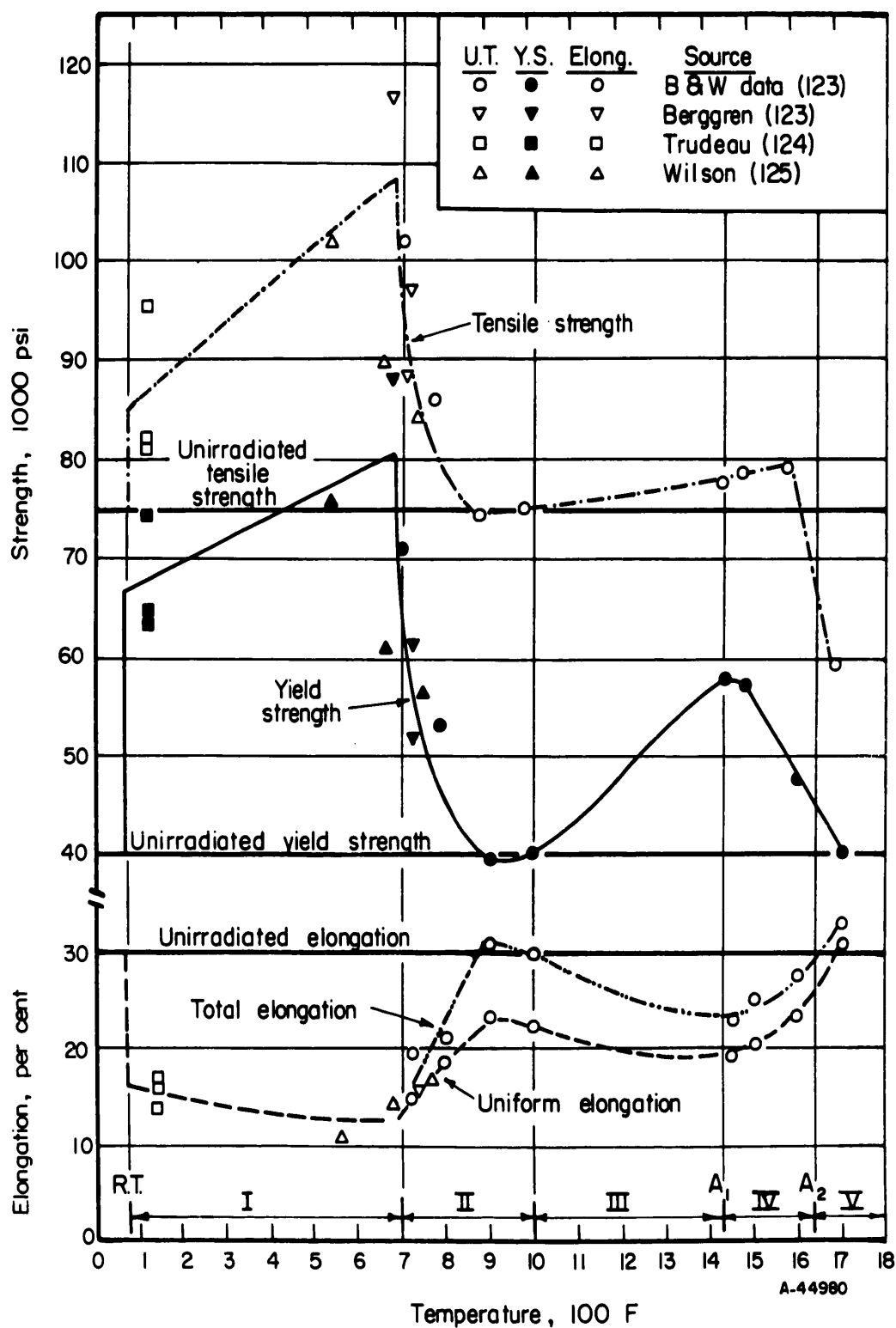


FIGURE 10. EFFECT OF ELEVATED-TEMPERATURE IRRADIATION ON FERRITIC STEELS⁽¹²²⁾

- (4) Work hardening or prior strain of approximately 2 per cent has no effect on radiation embrittlement of pressure-vessel steels over a rather wide range of irradiation temperatures.
- (5) Postirradiation annealing in an attempt to recover radiation hardening in carbon steels occurs with the activation energy for self-diffusion of iron. Iron is approximately 3.1 ev.
- (6) The pronounced increases in the magnitudes of the radiation hardening and embrittlement in aluminum grain size controls in low-alloy steels irradiated at temperatures of 50 to 130 C appear to be due to clustering of vacancies.
- (7) An instrumentation of load recording equipment on the Charpy machine has enabled the impact load deflection curve to be determined, and a relationship between the dynamic and static yield strengths to be compared before and after irradiation.

The results from work conducted in Sweden by Cibois, LeMaire and Weisz⁽¹²⁷⁾ on pressure-vessel steel similar to an A302B steel after ambient-water-temperature irradiations to about $5.6 \times 10^{19} \text{ n cm}^{-2}$ indicate certain changes in properties. Two types of specimens were used in this investigation: a subsize tensile-test specimen, and a Charpy V-notch specimen. The steel was studied for four different positions of the plate, and three different metallurgical conditions were included in the study. Those structures associated with the different conditions were the ferritic structure for the base and cold-worked metals, a sorbitic structure for the metal quenched in oil, and a bainite structure for the superheated metal. Although radiation hardening and embrittlement were detected for this low-alloy steel, the data were not as easily correlated with an empirical relationship as shown by previous workers. It was also noted by these investigators that prior cold work did not affect the radiation hardness of the steel, but seemed to influence a complex phenomenon occurring on the irradiated specimen tested in the so-called blue brittle range.

Stainless Steel

Austenitic Stainless Steel

As a result of less extensive use of stainless steel for load-bearing members in reactors, radiation effects in stainless steel have received less attention. However, certain reactor components needing to combine the properties high-temperature strength and corrosion resistance do call for the use of stainless steel. Austenitic stainless steels have found use primarily as pressure tubing within the reactor core of existing power and test reactors. A number of programs are in progress to study the radiation-induced property changes in stainless steels. Shober and Murr⁽¹²⁸⁾ have reported results from irradiations on 347 stainless steel for exposures up to $1.1 \times 10^{22} \text{ n cm}^{-2}$. These results show that radiation-induced property changes are not appreciably greater after $1 \times 10^{21} \text{ n cm}^{-2}$ exposure than they were at $1.0 \times 10^{20} \text{ n cm}^{-2}$. These results are given in Table 11. More recent unpublished data on the room-temperature fatigue properties of 347 stainless steel after irradiation to $1.1 \times 10^{22} \text{ n cm}^{-2}$ show increased fatigue strength over the unirradiated material. Murr and Shober⁽¹²⁹⁾ also report the

TABLE 11. COMPARISON OF TENSILE PROPERTIES FOR UNIRRADIATED, IRRADIATED, AND IRRADIATED AND ANNEALED TYPE 347 STAINLESS STEEL AT 75 AND 600 F⁽¹²⁸⁾

Total Integrated Fast Flux, n cm ⁻² (a) (< 1 Mev)	Condition	0.2 Per Cent Offset Yield Strength, 1000 psi	Ultimate Tensile Strength, 1000 psi	Total Elongation, per cent in 1.1 in.	Reduction of Area, per cent
<u>Test Temperature, 75 F</u>					
0	Unirradiated	34.5	87.7	61.8	75.0
0	Unirradiated	36.0	90.0	62.6	73.5
0	Unirradiated	34.5	89.5	66.3	72.0
0(b)	Unirradiated	38.3	92.5	63.4	75.0
0(b)	Unirradiated	38.7	92.8	64.7	76.0
0(b)	Unirradiated	39.3	92.4	64.7	75.6
5.7×10^{21}	As irradiated	104.0	112.0	34.5	68.5
5.7×10^{21}	As irradiated	88.7	111.5	32.7	75.0
1.2×10^{22}	As irradiated	103.5	112.0	30.9	75.0
1.2×10^{22}	As irradiated	109.0	113.0	30.9	78.0
5.7×10^{21}	Irradiated and annealed at 1800 F, 1 hr	33.0	86.6	55.5	75.0
1.2×10^{22}	Irradiated and annealed at 1800 F, 1 hr	33.8	87.0	61.0	77.0
<u>Test Temperature, 600 F</u>					
0(b)	Unirradiated	26.9	73.8	36.4	71.0
0(b)	Unirradiated	28.5	66.5	34.9	71.6
0(b)	Unirradiated	28.0	65.9	34.9	69.4
5.7×10^{21}	As irradiated	81.8	83.0	14.5	64.2
5.7×10^{21}	As irradiated	80.0	84.0	16.35	75.0
1.2×10^{22}	As irradiated	86.8	89.0	13.25	68.0
1.2×10^{22}	As irradiated	85.3	87.5	11.85	75.0
5.7×10^{21}	Irradiated and annealed at 1800 F, 1 hr	28.2	64.3	30.0	77.0
1.2×10^{22}	Irradiated and annealed at 1800 F, 1 hr	27.4	65.0	31.7	75.0

(a) Values based on $\text{Fe}^{54} \rightarrow \text{Mn}^{54}$ and $\text{Ni}^{58} \rightarrow \text{Co}^{58}$ reactions.

(b) Tests made by Knolls Atomic Power Laboratory.

effects of neutron radiation on 347 stainless steel pressure-tube components after irradiation in an atmosphere of water and elevated temperature. Indications are that the combined effects of stress and/or temperature produce greater property changes in materials than unstressed ambient-reactor-temperature irradiation. These data are shown in Table 12.

Hinkle⁽¹³⁰⁾ and co-workers at Oak Ridge have reported the results from an investigation of the burst properties of a number of materials, including 347 stainless steel. Stress-to-rupture data are obtained from static pressure-tube tests at elevated temperatures. It was observed that failure times were less in the reactor than if the tube were subjected to the static pressure and temperature outside of the reactor.

Several additional programs are in progress, that is, stainless steels are being irradiated to evaluate the effects of irradiation at elevated temperatures. ORNL is irradiating tensile samples over the temperature range from 500 to 1300 F. Hanford is irradiating a number of 347 and 348 samples at the temperature of approximately 550 F. Subsequent evaluation will be made of the radiation-induced property changes for materials in these programs.

Precipitation-Hardening Stainless Steels

General Electric Company, Nuclear Material Propulsion Operation, has investigated the short-time tensile and creep properties of A286 stainless steel. This is a precipitation-hardening stainless steel which exhibits superior elevated properties to the solid solutioning alloys. Their results indicate that the short-time properties after irradiation at elevated temperatures, i. e., 1000 to 1600 F, are not appreciably altered by elevated-temperature irradiation. However, the stress-rupture properties of A286 are decreased as a result of irradiation. The stress-rupture properties were determined at the same temperatures as materials that had been irradiated. The mechanism responsible for this deficiency in stress-rupture properties has not been determined.

Other Materials - Inconel-X, Hastelloy X and René 41

Hinkle⁽¹³⁰⁾ has investigated the tube burst properties in the reactor for Inconel and Inconel X, and found that the reactor environment decreases the stress-rupture properties for these materials also. Hastelloy X irradiated at elevated temperatures by GE-NPO and tested in short-time tension and stress to rupture also shows a reduction in the creep strength after irradiation at elevated temperature. Postirradiation annealing of the Hastelloy before creep testing did not seem to alter the as-irradiated properties. René 41 did not show any appreciable effect from irradiation at elevated temperatures, except for a slight increase in yield strength and ultimate strength. Insufficient samples were tested in stress rupture to evaluate the effect of elevated-temperature irradiation.

C. R. Cupp⁽¹³¹⁾ reviewed the effects of radiation on precipitation-hardening alloys for a number of systems at a recent ASTM symposium. The effects of radiation on the precipitation-hardened alloys are unpredictable; in some instances it appears to cause a redissolution of the precipitates, while in other cases the precipitation is enhanced and properties are changed accordingly.

TABLE 12. TEST RESULTS OBTAINED ON IRRADIATED TENSILE

Specimen	Approximate Temperature of Irradiation, F	Fast-Neutron (>1 Mev) Flux Exposure ^(a)		Temperature of Test, F
		Instantaneous, n cm ⁻² sec ⁻¹	Integrated, n cm ⁻²	
<u>Gas Jacket</u>				
LT-4-L-1	120	0.91 x 10 ¹⁴	1.8 x 10 ²¹	75
LT-4-I-2	120	0.8 x 10 ¹⁴	3.5 x 10 ²¹	75
LB-3-H	120	3.4 x 10 ¹⁴	6.5 x 10 ²¹	75
Control	--	0	0	75
LT-3-L	120	3.1 x 10 ¹⁴	2.0 x 10 ²¹	750
LT-3-I	120	2.4 x 10 ¹⁴	4.5 x 10 ²¹	750
LT-3-H	120	2.7 x 10 ¹⁴	5.1 x 10 ²¹	600
Control	--	0	0	750
<u>Inner Loop</u>				
ST-3-L	510	1.0 x 10 ¹⁴	1.9 x 10 ²¹	75
ST-2-I	625	2.0 x 10 ¹⁴	3.9 x 10 ²¹	75
ST-2-H	735	3.7 x 10 ¹⁴	7.1 x 10 ²¹	75
ST-2-L	540	1.1 x 10 ¹⁴	2.1 x 10 ²¹	750
SB-2-I	740	2.7 x 10 ¹⁴	5.1 x 10 ²¹	750
SB-2-H	760	3.6 x 10 ¹⁴	6.9 x 10 ²¹	750
Control ^(b)	--	--	--	70
Handbook data ^(c)	--	--	--	750
<u>Inner Loop</u>				
ST-7-L	540	0.87 x 10 ¹⁴	1.7 x 10 ²¹	75
ST-7-I	675	2.9 x 10 ¹⁴	5.6 x 10 ²¹	75
ST-7H ^(d)	735	1.7 x 10 ¹⁴	3.3 x 10 ²¹	75
SB-7-L	700	1.2 x 10 ¹⁴	2.3 x 10 ²¹	750
SB-7-I	760	1.9 x 10 ¹⁴	3.7 x 10 ²¹	750
SB-7-H	760	3.4 x 10 ¹⁴	6.5 x 10 ²¹	750
<u>Inner Loop</u>				
ST-4-I	680	0.0091 x 10 ¹⁴	1.7 x 10 ¹⁹	75
SB-5-I	760	0.52 x 10 ¹⁴	1.0 x 10 ²¹	75
SB-4-H	760	--	--	75
ST-5-H	735	2.7 x 10 ¹⁴	5.3 x 10 ²¹	75
ST-5-L	510	2.6 x 10 ¹⁴	5.0 x 10 ²¹	750
SB-3-I	760	--	--	750
ST-5-I	670	1.2 x 10 ¹⁴	2.3 x 10 ²¹	750
ST-3-H ^(e)	735	--	--	750
SB-5-H	760	0.89 x 10 ¹⁴	1.7 x 10 ²¹	750
<u>Inner Loop</u>				
ST-3-I ^(f)	670	0.49 x 10 ¹⁴	9.00 x 10 ²⁰	75
SB-6-I	760	--	--	75
SB-3-H	760	3.4 x 10 ¹⁴	6.50 x 10 ²¹	75
ST-6-H	735	3.3 x 10 ¹⁴	6.30 x 10 ²¹	75
ST-6-L ^(g)	510	0.047 x 10 ¹⁴	9.00 x 10 ¹⁹	750
SB-4-I	760	--	--	750
ST-6-I	670	2.4 x 10 ¹⁴	4.60 x 10 ²¹	750
ST-4-H	735	--	--	750
SB-6-H	760	3.3 x 10 ¹⁴	6.3 x 10 ²¹	750

(a) Exposures based on Mn⁵⁴ ratio.

(b) From McInnes Company, reports on sample cut from as-machined J-10 pressure tube.

(c) Metals Handbook, Vol 1, Eighth Edition, p 503.

(d) Only 1.5 mg of sample was analyzed. Small weighing errors could have caused large changes in analysis of exposure. Sample should have duplicated ST-2-H.

SPECIMENS MACHINED FROM SECTIONS OF THE J-10 LOOP⁽¹²⁹⁾

0.2 Per Cent Offset Yield Strength, 10 ³ psi	Ultimate Tensile Strength, 10 ³ psi	Fracture Strength, 10 ³ psi	Uniform Elongation, per cent	Total Elongation, per cent	Reduction of Area, per cent
<u>Initial Test Run</u>					
100.0	103.5	191.0	>18.0	31.0	54.6
95.2	101.3	192.5	>14.8	26.0	57.0
102.5	108.0	226.0	>18.6	25.0	60.5
46.8	99.7	--	> 8.5	50.4	61.8
62.5	66.7	118.0	--	13.5	54.0
65.4	69.3	123.0	7.7	11.5	54.6
71.8	73.3	115.0	9.0	12.5	48.3
36.5	67.6	--	--	26.2	62.9
<u>Initial Test Run</u>					
132.0	135.0	215.0	1.2	4.3	53.5
143.0	145.0	231.0	1.2	6.5	54.5
143.0	149.0	250.0	2.0	10.3	58.2
103.0	103.0	124.0	0.6	4.5	42.7
115.0	115.0	138.0	0.7	1.5	40.8
120.0	120.0	175.0	0.8	3.5	52.5
52.5-60.7	91.3-93.0	--	--	53-61	58-72
40-50	70-80	--	--	45-50	--
<u>Duplicate Test Run</u>					
130.0	134.0	247.0	2.0	6.5	59.1
139.5	144.8	264.0	1.8	10.6	59.8
143.0	147.0	278.0	1.0	9.4	61.5
115.3	115.3	239.0	0.6	4.2	64.0
123.0	123.5	162.0	0.7	4.2	45.5
123.6	125.8	150.0	0.8	4.1	40.5
<u>Annealed for 1 Hr at 1000 F</u>					
77.5	99.0	190.0	>16.0	35.5	58.7
72.3	98.0	183.0	>20.0	44.3	56.2
69.4	94.5	193.5	>15.0	38.0	59.1
75.0	96.0	208.0	>14.0	41.0	63.3
47.5	64.0	101.0	>18.0	24.0	50.2
55.0	75.4	108.5	14.2	21.2	50.8
58.0	71.4	118.5	11.9	19.5	55.2
87.5	88.5	122.5	1.1	7.5	47.3
54.4	69.2	117.5	11.1	16.6	55.8
<u>Annealed for 1 Hr at 1800 F</u>					
51.4	85.5	145.0	>26.0	42.9	49.9
38.4	87.8	132.0	>24.0	49.0	37.1
55.8	86.5	130.0	>25.0	51.0	42.9
36.5	77.5	121.0	>25.0	41.2	36.9
20.8	61.0	95.0	>27.0	35.9	46.3
44.7	65.4	120.0	18.0	23.4	58.0
33.0	62.5	87.5	>21.5	26.2	42.9
43.6	61.5	96.2	14.5	20.1	53.6
27.2	62.5	172.0	>28.0	41.2	67.3

(e) Erratic thermocouple operation resulted in annealing temperature below 1000 F.

(f) Annealing temperature went to 1930 F for 2 min, then decreased to 1800 F in about 6 min.

(g) Annealing temperature went to 1950 F for 3 min, then decreased to 1800 F in about 7 min.

Current Programs

An effort has been made by the Division of Reactor Development of the AEC to coordinate programs and correlate data being generated on AEC-DRD supported programs on radiation effects on structural materials. Cooperation is maintained between nine sites and working committees composed of members from the various sites to standardize, where possible, radiation experimentation and reporting techniques in an attempt to provide more meaningful data. Work being conducted under this group's coordination includes the following. Workers at Argonne National Laboratory are studying dosimetry techniques to compare radiation-induced property changes with the neutron spectrum. The use of the manganese-54 activity in the iron-base materials can provide a measure of neutron exposure. These dosimetry measurements and damage indexes are related to the changes in properties of impact specimens from the carbon steels.

Battelle Memorial Institute is continuing its irradiation surveillance program on 347 stainless steel, a program whose objective is to determine the changes in tensile properties, fatigue properties, and impact properties after exposures as great as 3×10^{22} n cm⁻². The current status of this program is that irradiations have been achieved as high as 1.5×10^{22} n cm⁻², and property changes have been determined for exposures as great as 1.1×10^{22} n cm⁻². Extensive use of nickel and iron dosimetry is made in this particular program.

Brookhaven National Laboratory is conducting a study of the effects of radiation on the plastic and fracture properties of reactor structural materials, with the work centered primarily on the carbon, low-alloy, and stainless steels. Preliminary studies have been made on high-purity iron. The effects of exposures of approximately 1×10^{20} n cm⁻² at temperatures below 100 C, and at 100, 200, 300, and 350 C, are being determined. The effects of alloying elements and impurities on the irradiated iron-polycrystallines have been determined. Electron-transmission studies and microscopy studies to determine dislocation distributions are also under way. Some limited studies on the determination of the effects of radiation on the properties of high-purity tantalum and columbium are being made.

General Atomic is studying the effects of radiation on the A-302B pressure-vessel steel. They expect to irradiate various materials to several levels of exposure and test these materials under biaxial stress conditions. Four types of specimens are being investigated over the temperature range of -50 to +350 F. These specimens include tensile, tube, notched tensile, and impact specimens.

General Electric, Hanford Laboratories is conducting studies on a number of materials. These rather extensive studies include the oxidation tests of nickel-base alloys in CO₂ under reactor conditions, in-reactor creep of Zircaloy-2 in the 250 C and 30,000-psi stress range, irradiation in a hot-water loop facility of a number of tensile and bend specimens of Zircaloy-2, AM350, 304, 348, and 410 stainless steels. The total radiation exposure for these materials will be in range of 5×10^{19} to 4×10^{21} n cm⁻². Fast-flux dosimetry is obtained from iron, titanium, and nickel monitors that are encapsulated along with the samples. The control samples for these radiation tests are subjected to a similar thermal history as the irradiated materials to provide a standard for comparison of radiation effects. Fast-neutron spectra calculations are

made for a number of reactor lattice positions. Environmental studies designed to provide data for understanding the chemical processes controlling the rate and the extent of corrosion and/or embrittlement reactions in reactor structural materials are under way. Several fundamental studies are being made to study the effect of impurity content on materials during irradiation; materials such as high-purity molybdenum, iron, and nickel are anticipated for this program.

The Naval Research Laboratory's objectives are primarily to detect and observe the notched ductility properties of several reactor steels under irradiation and study recovery of properties by postirradiation heat treatment. The effects of cyclic irradiation-annealing treatment are also under way. The Mechanics Division of the Naval Research Laboratory has undertaken a program and is currently making studies to determine the fracture toughness of materials in terms of the notched parameters. A measure of the yield strength of the same materials will be made. Materials used in this particular program include A212B and 350LF (PM-2) steels. Both of these steels are pressure-vessel steels and are currently being used as construction materials in nuclear reactors.

The General Electric Nuclear Materials Propulsion Operation is continuing radiation-effects investigations in the area of elevated temperatures. The effects of radiation on the rupture strength of A-286, Hastelloy X, and René 41 irradiated and tested at temperatures as high as 150 C have been investigated. Additional investigations are being carried out on these materials. The total exposures for most of these materials fall in the range of 1×10^{20} to 1×10^{21} n cm⁻². The results of the work indicate that short-time properties are not adversely affected by irradiations at elevated temperatures followed by subsequent testing at the same temperature. However, the long-time properties or creep-rupture properties are somewhat decreased as a result of irradiation. A reduction in ductility is noted. Studies are under way to make calculations and observations related to any metallurgical changes occurring in aged materials during irradiations at elevated temperatures.

Oak Ridge National Laboratory studies are primarily in the fundamental area to study effects of radiation defects in metals. These studies are based upon increases in resistivity and hardnesses observed during irradiation and related to room-temperature deformation characteristics. The short-time creep properties of several materials are being studied as parts of other programs. For example, the stress-to-rupture tube-burst tests on Zircaloy-2, 304 stainless steel, and a columbium-1 zirconium alloy have been made.

Phillips Petroleum Company has initiated a program to study the in-reactor fatigue properties of certain structural materials. The work to date has primarily consisted of the designing and initiation of construction of equipment to conduct these tests. In addition to these induced property changes in reactor materials, a comprehensive study of dosimetry is being made. The effects of fast-neutron exposures on reaction rates of a number of dosimeters have been studied. The evaluation of wire- or foil-type dosimeters for fast-neutron irradiation are under investigation, and a number of experimental points have been determined.

Programs not a part of the AEC-DRD coordinated effort include work at Lockheed to determine the effects of radiation at cryogenic temperatures on the properties of a wide variety of structural alloys, surveillance programs for the Dresden, Yankee, Virginian and Carolina, Rock Point, and Elk River power reactors, and a large number of fundamental programs.

Recommendations

Future studies in both areas of basic and applied research are recommended. It is believed that, although these suggestions are not all inclusive, they represent definite needs for a better understanding of radiation-induced property changes and determination of design parameters for reactor designers.

In the area of the fundamental studies on radiation effects, it is recommended that further investigations be directed toward programs:

- (1) To learn more of the role of focusing collisions
- (2) To study and determine factors governing the clustering of interstitial atoms
- (3) To show that ordered lattices disorder much more during deuteron bombardment than can be explained by the simple theory of displacements alone
- (4) To relate radiation effects on the basis of the point-defect production and interaction with existing dislocations.

In the area of applied research or determination of radiation-induced property changes in materials, additional studies should be made:

- (1) To determine and evaluate the effect of neutron radiation rates
- (2) To study the combined effect of temperature and neutrons
- (3) To learn more about metallurgical processes such as aging, recovery, and recrystallization during irradiation
- (4) To study the property changes of more materials during irradiation after a postirradiation annealing
- (5) To learn whether there is some level of neutron exposure after which changes in properties are very small
- (6) To determine the effectiveness of surveillance-type programs
- (7) To establish empirical relationships by which the effects of long-time irradiation may be extrapolated.

CERAMICS

Current State of the Art

Experimentation and development of theoretical models for radiation effects and mechanism of radiation damage during the past year indicate a greater increase in interest in ceramic materials for nuclear applications.

Ceramic Oxides

Among the miscellaneous ceramic oxides investigated during the past year were uranium dioxide, titanium dioxide, magnesium oxide, Forsterite, and Steatite.

R. M. Carroll⁽¹³²⁾ investigated the effect of 10^{18} n cm⁻² on the electrical-resistance activity of single-crystal uranium dioxide. The electrical resistivity was found to decrease by a factor of 200 as soon as irradiation began. This decrease was caused by the ionizing radiation rather than fission-product impurities, since in the initial portion of irradiation the resistivity could be increased by removing the specimen from the flux. After 24 hours of radiation, the change of the resistivity was irreversible.

An experimental investigation has been conducted by L. Stubbel⁽¹³³⁾ to determine the effect of 10^{15} to 10^{18} fast n cm⁻² on the electrical resistivity of titanium dioxide. Measurements of the resistivity as a function of temperature were made on reduced ceramic and single-crystal titanium dioxide samples, both before and after irradiation. The measurements were made over the temperature range of -70 to 200 C on samples which had been irradiated at the Oak Ridge National Laboratory. Extensive plotted data show that essentially no change in resistivity was produced by the radiation exposures.

The irradiation of sintered magnesium oxide specimens to 2.2×10^{20} fast n cm⁻² at 400 C was investigated by Elston⁽¹³⁴⁾. This exposure caused an increase in the magnesium oxide lattice parameter of from 4.2115 ± 0.0008 Å to 4.2150 ± 0.0008 Å. The crushing strength of the less dense specimens was substantially unaffected by irradiation. However, the crushing strength of the more dense magnesium oxide was increased from about 5 to about 10 metric tons cm⁻² by irradiation. The results of his experimentation suggest that closer examination of magnesium oxide as a potential reactor moderator material might be beneficial.

Frisco⁽¹³⁵⁾, in a continuation of his study on dielectrics for satellites and space vehicles, has studied Forsterite, Alsimag-243, and Steatite. No drastic changes were found in the electrical properties of the Forsterites during a 95-hour X-ray exposure period. The dielectric-constant and dissipation-factor values remained constant. Slight changes in d-c resistivity were noted. Steatite showed high resistivity to X-ray radiation. Its a-c properties were virtually unaffected by radiation, but showed some variation during recovery in air. The d-c resistivity data indicate that no steady increase in conductivity was exhibited. A spread in results and the fluctuations over a long period of time are typical of d-c resistivity measurements, particularly with ceramics. Only a slight change in color was noted in X-ray irradiated samples.

Aluminum Oxide

Sintered aluminum oxide powder was irradiated at 35 to 40 C with 2×10^{20} n cm⁻² ($E \geq 2.9$ Mev).⁽¹³⁶⁾ The results of impact tests indicated that there was little change in impact strength of the irradiated specimen as compared to the control. The impact specimen showed a small increase in hardness (2 to 11 per cent) which could be annealed out at 400 C after 114 hours.

Corrs AD 86 Ceramic (86 per cent Al₂O₃ plus MgO₂, and SiO₂) was investigated by Electro-Optical Systems, Incorporated⁽¹³⁷⁾ to determine the effects of vacuum ultraviolet radiation and/or ultravacuum on electrical resistance of the material. A 98 per cent decrease in electrical resistance was observed which annealed out upon removal from the radiation environment.

Sapphire cover slips were used to shield the solar cells in the Telstar satellite.⁽¹³⁸⁾ After 2 weeks in space the least heavily shielded cell with 20-mil sapphire showed a decrease in current output of 10 ± 2 per cent. The cells with 25 and 30 mils of sapphire shielding showed decreases of 5 ± 2 per cent.

Thermoluminescence of gamma-irradiated sapphire and ruby was studied at the University of Utah.⁽¹³⁹⁾ The light-induced glow curves in the sapphire have the form of a second-order decay process. Light-induced thermoluminescence in gamma-ray damaged ruby shows an afterglow long after the crystal has reached room temperature. The specimens were subjected to a gamma-ray field of 10^6 ergs g⁻¹(C) hr⁻¹.

Beryllium Oxide

Six different compositions of BeO were investigated by General Electric, Nuclear Materials and Propulsion Operation (Table 13).⁽¹⁴⁰⁾ The compositions were as follows:

AOX grade BeO
 UOX grade BeO + 0.5 weight per cent MgO
 HPA high-purity BeO
 HPA high-purity BeO + 0.5 weight per cent MgO
 UOX grade BeO
 UOX grade BeO + 3.0 weight per cent ZrO₂.

The most significant aspect of radiation effects in BeO is expansion of the crystal lattice which is reflected in the expansion of polycrystalline bodies. Expansion of the lattice is anisotropic in the two crystallographic axes, c-axis expansion being approximately eight times that of the a-axis. Estimations of expansion rates are 0.27 per cent of the c-axis and 0.03 per cent of the a-axis at dosages of 10^{20} n cm⁻² ($E \geq 1$ Mev).

The maximum radiation exposure which BeO can withstand is determined by its ability to retain liberated helium without undue property changes, or loss of helium through diffusion to pores or free surfaces. Gas bubbles were observed in a specimen irradiated at 1000 C to 3.4×10^{20} n cm⁻² ($E \geq 1$ Mev).⁽¹⁴¹⁾ The strength and elastic constants of BeO exposed to 4×10^{20} n cm⁻² ($E \geq 1$ Mev) are essentially unchanged unless grain-boundary separation occurs.

TABLE 13. DIMENSIONAL, VOLUME, MODULUS-OF-RUPTURE, AND ELASTIC-CONSTANT CHANGES IN EXTRUDED BeO IRRADIATED AT APPROXIMATELY 1000 C⁽¹⁴⁰⁾

Specimen(a)	Exposure, 10 ²⁰ n cm ⁻² (b) (E > 1 Mev)	No. of Samples	Average Change From Unirradiated Values, per cent				Room-Temperature Modulus Rupture	Room-Temperature Young's Modulus	Room-Temperature Shear Modulus
			Increase in Length	Increase in Diameter	Increase in Volume	Decrease in Density			
AOX	2.4 - 3.0	6	0.15	0.28	0.71	0.71	-7	-2	-1
	3.1 - 3.5	11	0.20	0.30	0.83	0.83	-11	-2	-2
	3.6 - 4.0	7	0.20	0.36	0.93	0.92	-16	-2	-2
HPA	2.5 - 3.0	1	0.33	0.34	1.0	1.0	-77	Could not measure, unable to resolve frequency	
	3.1 - 3.5	1	0.37	0.34	1.1	1.1	-81		
	3.6 - 4.0	1	0.46	0.42	1.3	1.2	-91		
UOX	2.5 - 3.0	6	0.23	0.19	0.65	0.60	0	-1	-2
	3.1 - 3.5	6	0.26	0.22	0.75	0.71	-8	-1	-2
	3.6	2	0.27	0.27	0.81	0.80	-15	-1	-2

(a) The HPA specimen has a grain size of 80 microns, while the AOX and the UOX are of 20-micron size. All specimens have a density of 2.90 g cm⁻³.

(b) Exposure rate, 1 to 2 x 10¹⁴ n cm⁻² sec⁻¹ (E > 1 Mev).

The following tabulation summarizes the effect of radiation on thermal conductivity of AOX - BeO specimens:

Exposure ($E \geq 1$ Mev)	$K_{\text{irradiated}}/K_{\text{unirradiated}}^{(140)}$		
	75 C	150 C	250 C
8.6×10^{18}	0.84	0.91	0.92
2.0×10^{20}	0.40	0.43	0.46
3.7×10^{20}	0.32	0.33	0.34

Anisotropic expansion of the crystal lattice was caused by the formation of point defects and defect clusters created by neutron collisions and generation of the gases He and H³ from neutron absorption. The expansion as a result of the gas generation is reduced in elevated-temperature irradiation by thermal annealing of the defects.

Dimensional and volume changes in BeO at 100 C are summarized in Table 14:

TABLE 14. DIMENSIONAL AND VOLUME CHANGES IN BeO AT 100 C⁽¹⁴⁰⁾

Specimen ^(a)	Exposure 10^{20} n cm ⁻² ($E \geq 1$ Mev)	Dimensional Expansion, per cent		Decrease in Bulk Density, per cent ^(b)	Increase in Volume, per cent ^(c)
		Length	Diameter		
AOX	0.086	0.03	0.08	0.1	--
	2.0	0.36	0.5	1.3	1.4
	3.7	1.14	1.4	3.4	3.9
	4.0	1.45	1.7	4.2	4.8
	8.1	Intact; disintegrated on handling			
HPA	0.082	0.02	0.08	0.1	--
	3.6	1.6	1.1	3.6	3.8
	4.0	1.3	1.5	4.2	4.3
	7.8	Powder			
UOX	0.061	0.02	0.08	0.1	--
	3.2	1.1	0.8	2.7	2.7
	4.1	1.6	1.2	3.9	4.0
	6.0	Not	2.1	5.8	--
Measurable					

(a) Fifteen to 20-micron grain size and density 2.9 to 2.95 g cm⁻³.

(b) Measured by hydrastatic weighing.

(c) Computed from dimensional changes.

General Electric Company⁽¹⁴¹⁾ investigations on BeO specimens of 5-micron grain size showed that they retained about 25 per cent of their unirradiated strength on irradiation at 600 C to 1.5×10^{21} n cm⁻² ($E \geq 1$ Mev). Comparable reductions in strength occurred in larger grain-size materials at as little as 1/5 this exposure.

J. E. Lee of the Oak Ridge National Laboratory⁽¹⁴²⁾ irradiated cylindrical BeO specimens in the ETR at 1.0×10^{20} to 2.5×10^{21} n cm⁻² ($E \geq 1$ Mev) over the temperature range 100 to 1025 C. After irradiation, the specimens were observed by X-ray diffraction, petrographic microscopy, electron microscopy, and metallographic methods,

since the specimens had been dissolved for determination of helium and tritium liberation. Severe irradiation damage was found to occur in specimens irradiated to the highest neutron exposure and the lowest temperature ranges. Specimens receiving as much as $1.5 \times 10^{21} \text{ n cm}^{-2}$ at approximately 100 C disintegrated into powder. Fractures were observed in specimens irradiated at $2.6 \times 10^{21} \text{ n cm}^{-2}$ at 800 to 950 C. Some specimens were found to remain intact after intermediate exposures and intermediate temperatures. Linear dimensional increases of 0.5 to 4 per cent were observed. This effect was found to increase with neutron exposure and to decrease with temperature. Thermal conductivity of the samples decreased substantially as irradiation exposures were increased, as indicated by 50 to 100 per cent increases in radial temperature differences. Gas analysis of irradiated BeO indicated that internally generated helium is retained even at high temperatures up to a fast-neutron exposure of $1.6 \times 10^{21} \text{ n cm}^{-2}$.

In later reports Lee⁽¹⁴³⁾ extended his investigation to irradiation of BeO without additives to exposures in the range 1.0×10^{20} to $3.6 \times 10^{21} \text{ n cm}^{-2}$ at temperatures from 110 to 1100 C. Postirradiation examinations were made on densities, grain size, porosity, and dimensional changes of both hot- and cold-pressed specimens. Lattice defects were found to be minimized by a thermally activated process at temperatures above 440 C, the changes in bulk physical properties could not be closely correlated with the radiation temperature and exposure. A neutron-flux effect, which is greater than the annealing rate, was indicated by the increase in the range of volume expansion and thermal conductivity decrease in fluxes above $3.5 \times 10^{14} \text{ n cm}^{-2} \text{ sec}^{-1}$. Grain-boundary separations primarily account for the observed changes in the physical properties.

The effect of radiation on the refractive indices of BeO were also investigated at the Oak Ridge National Laboratory.⁽¹⁴⁴⁾ The specimens were irradiated at 120 C to $1.5 \times 10^{21} \text{ fast n cm}^{-2}$ at the Engineering Test Reactor. The preirradiation index values were 1.719 and 1.733. The postirradiation index values were 1.700 and 1.712, respectively. The indices were returned to normal by annealing at temperatures as low as 650 C. The results of this experimental effort show that the determination of refractive indices is a good nondestructive method of measuring the extent of radiation damage to BeO and also the extent to which thermal annealing affects recovery of this property.

R. L. Hamner⁽¹⁴⁵⁾ prepared high-purity BeO with carefully controlled properties for irradiation studies in the Engineering Test Reactor. The studies were designed to evaluate BeO as a reactor moderator material considering the effects of density, grain size, and temperature on BeO irradiated at $10^{21} \text{ n cm}^{-2}$ ($E \geq 1 \text{ Mev}$). The bulk density of BeO bodies was affected markedly when the rate of heating to the sintering temperature in a hydrogen atmosphere was widely varied.

Beryllium oxides were irradiated with 1.7 to $2 \times 10^{21} \text{ n cm}^{-2}$ ($E \geq 1 \text{ Mev}$) at temperatures of 550 to 1000 C by Tobin.⁽¹⁴⁶⁾ The specimens irradiated at 800 to 980 C showed no evidence of disintegration. However, those irradiated at 570 to 770 C seemed to be fragile. Thermal diffusivity and thermal conductivity decreased 15 to 40 per cent during irradiation. MgO and bentonite additions depressed this tendency somewhat. Compressive strengths after irradiation were 50 to 67 per cent lower than the initial values. Bentonite addition tended to lessen the magnitude of this decrease. On the basis of this investigation, it was determined that there is no definite advantage of using BeO with a 99 per cent theoretical density over moderate density in moderator applications.

Atomics International⁽¹⁴⁷⁾ is investigating BeO - MgO ceramics; but, to date, has studied only temperature environments.

Elston⁽¹³⁴⁾ investigated the effect of 2.5×10^{19} to 2.0×10^{20} fast n cm⁻² on beryllium oxide. Table 15 summarizes the results of the compressive strength measurements.

TABLE 15. EFFECT OF NEUTRON EXPOSURE ON COMPRESSIVE STRENGTH OF BeO⁽¹³⁴⁾

Fast Flux, n cm ⁻²	Compressive Strength at 20 C, metric tons cm ⁻²
None	20
2.5×10^{19}	15.3
6.0×10^{19}	4.5
9.0×10^{19}	1.4
2.0×10^{20}	Powder

The effects of irradiation of 9×10^{19} n cm⁻² on crystal parameters of sintered beryllium oxide have also been studied by Elston as a function of the fast integrated flux, of the irradiation temperature, and of the density. The disintegration of sintered beryllium oxide irradiated to greater than or equal to 2×10^{20} n cm⁻² at any temperature below 100 C is attributed to the increase of the c-parameter, which is greater than the increase of the a-parameter. Microscopy of specimens shows how the loss of the intergranular cohesion is produced in the sintered samples. This study has demonstrated the importance of stresses which appear in hot-pressed beryllium oxide compacts. These stresses, which are caused by the anisotropic deformation of crystals under the influence of neutrons, result in the fragmentation of specimens and in their loss of cohesion. The elastic energy contained in the compacts which have been irradiated and which have preserved some of their cohesiveness seems to be a rather considerable part of the Wigner energy.

The effects of 1×10^{19} n cm⁻² at 75 to 100 C, and 1.5×10^{20} n cm⁻² at 500 to 650 C, on hot-pressed beryllium oxide were investigated by Hickman⁽¹⁴⁸⁾. An anisotropic lattice expansion occurred. The lattice expansion at irradiation temperatures of 500 to 600 C is almost a factor of three smaller than that for equivalent neutron exposures at 75 to 100 C. The annealing behavior of the lattice parameter changes is described, and it is shown that temperatures of 1400 to 1500 C are required for complete recovery from the damage. Hickman suggested that defect clusters are formed in the basal plane of the hexagonal beryllium oxide lattice.

Beryllium oxide was studied by Frisco⁽¹³⁵⁾ in a combined X-ray and vacuum environment. Two specimens subjected to 50-kv X-rays resulted in widely different results for the two specimens. It was concluded that the effects of vacuum X-ray exposure on the electrical properties of BeO depend on the presence of impurities and surface contaminants. The X-ray radiation caused severe discoloration in BeO from white to dark gray. This effect could be important in applications where emissivity is a design consideration.

A simple model for the fracture strength of irradiated BeO has been developed by Clarke.⁽¹⁴⁹⁾ The model predicts that the fracture strength will decrease rapidly within a fairly narrow range of radiation-induced strain. The model states that the magnitude of this strain is dependent on the inverse of the square root of the grain size.

Glasses and Silicates

Investigators at Bausch and Lomb⁽¹⁵⁰⁾ have continued the irradiation of lead silicate glass (BNL-EDF-1) and optical crown glass (VNL-BSC-1). The electron and gamma-ray irradiations were made with the specimen in air at approximately 22 C. The electrons had an energy of 1.5 Mev and a current of 10 μ a. In the frequency range considered, the dielectric constant was not affected by electron or gamma irradiation or by heat treatment. In most cases, the deviations from the untreated sample were less than 1.0 per cent. There appeared to be a small increase at a low frequency in some samples, which was in no case larger than 2 per cent. The dielectric loss tangent was, on the other hand, affected by radiation. Particularly at low frequencies and immediately after irradiation, the loss tangent was considerably enhanced. Most of this enhancement annealed after a period of about 24 hours. A comparison of several glasses after the same electron irradiation indicates the following significant features: (1) glasses that exhibit heat discharge show the greatest increase in the loss tangent after electron irradiation; (2) phosphate glass shows the largest increase and also will spontaneously discharge during electron irradiation at the smallest exposure, while Pyrex and fused silica can be discharged after a prolonged period of irradiation; (3) after discharging, an apparent permanent increase in the loss tangent was observed in lead silicate glass. One other characteristic of the lead silicate and phosphate glasses, not observed in the Pyrex and silica, is a small rapid variation in the loss tangent 100 minutes after the irradiation period. Subsequent irradiations showed that both time dependence and final value of the current were altered. The data generated do not support a space-charge hypothesis. There is agreement with the hypothesis that the polarization effects occur in the bulk of the glass. The bulk polarization processes, which have long temperature independent relaxation times, may furnish a mechanism by which charge and energy are stored.

The effects of gamma irradiation on the electrical conductivity of glasses and the applicability of the irradiated glasses to semiconductive glass or radiation dosimeters were investigated by Sugiura, Murakami, and Tanaka.⁽¹⁵¹⁾ Ten kinds of glasses were irradiated to a maximum of 8.7×10^8 ergs $g^{-1}(C)$. The electrical conductivity of each sample was measured by a vacuum-tube voltmeter for the range of low resistance values and by a vibration-reed electrometer for the high resistance values. The results showed that no change occurred in the electrical conductivity of the glasses subjected to the maximum radiation.

Vargin and Stepanov⁽¹⁵²⁾ have studied the effect of gamma-ray radiation on Na_2O and $Al_2O_3-SiO_2$ glasses. Their study indicated that the introduction of small quantities of aluminum oxide in glass compositions results in sharp decreases in the intensity of all absorption bands. Replacement of SiO_2 by aluminum oxide causes the bands to completely disappear at 5 and 5.6 ev. The thermal bleaching of glasses irradiated to 2.8×10^9 ergs $g^{-1}(C)$ shows that the thermal stability of bands at 2 and 2.6 ev increases with the introduction of aluminum oxide.

The formation of color centers in sodium silicate and quartz glasses by the action of gamma irradiation was studied by Byurganovskaya and Orlov.⁽¹⁵³⁾ They investigated the dependence of the intensity of the induced absorption bands in fused quartz and sodium silicate glasses on the gamma-radiation exposure as well as the influence of cerium, antimony, arsenic, manganese, iron, and lead additives on the properties of the absorption bands of sodium silicate glasses. The glasses were irradiated at room temperature with steadily increasing exposures to 8.7×10^9 ergs $\text{g}^{-1}(\text{C})$. The rate was 7.9×10^5 ergs $\text{g}^{-1}(\text{C}) \text{ hr}^{-1}$. Deviations were noted in the dependence of the optical absorption curves on the radiation exposure in the case of fused quartz and sodium silicate glass treated with Fe_2O_3 at exposures of approximately 8.7×10^6 and 8.7×10^7 ergs $\text{g}^{-1}(\text{C})$. It was suggested that these deviations were due to the presence of impurities or specific melting conditions.

Exposure of glass to ionizing radiation produces holes and free electrons which are trapped to form various kinds of color centers similar to those introduced in the alkali halides.⁽¹⁵⁴⁾ It is postulated in this report that most of the visible induced absorption is due to possible whole centers which can be annihilated by cerous ions. Although some models have been accepted for some centers induced in quartz and fused silicons, it is premature to specify any models for centers induced in complicated glasses due to the many factors involved in the processes of formation and the annihilation of these centers. The effect of multivalent ions, such as cerium, as additives to glass, is of practical importance since such additions suppress the induced physical coloration normally observed for glasses subjected to ionization radiation.

Electron-spin paramagnetic resonance spectra have been obtained at room and liquid-nitrogen temperatures for several alumino-silicate glasses and one soda alumino-silicate glass which have received X-ray or neutron irradiation.⁽¹⁵⁵⁾ Two distinct types of resonance were observed in alumino-silicate glass after X-ray irradiation. One is partially resolved into six equally spaced lines with a separation of 8.1 gauss between adjacent lines; the other resonance is an asymmetric line with a width of approximately 18 gauss between inflection points of the absorption curve. The latter resonance is more readily observed after heating the sample to 350 C, at which temperature the resonance exhibiting the six equally spaced lines disappears. Neutron irradiation of all the glasses to 3×10^{17} thermal n cm^{-2} produces the same spectra as X-ray irradiation except for the addition of a single sharp intense line which is ascribed to trapped electrons in the silica network.

Pilkington Brothers, Limited⁽¹⁵⁶⁾, have investigated the effect of gamma irradiation on the optical absorption of lead silicate glass. The absorption spectra of samples irradiated from 10^6 to 10^{10} ergs $\text{g}^{-1}(\text{C})$ may be divided into two Gaussian-shaped absorption bands centered at 2.54 ev and 3.36 ev. The positions of the peaks of these bands do not change with the radiation exposure or with the time after the irradiation ceases. The widths of the bands at half the maximum absorption value also remain constant.

Pilkington Brothers, Limited⁽¹⁵⁷⁾, have also subjected glass yarns to total neutron exposures of 10^{12} to 10^{20} n cm^{-2} at temperatures up to 400 C. This investigation had the objective of determining the suitability of glass fiber as electrical insulation in reactors. There was no melting of glass or any undesirable effects from nuclear heating.

Hardtke⁽¹⁵⁸⁾, in preliminary studies, has subjected Cabal-type glasses to Co^{60} radiation at room temperature. The charge displacement below 320 C, i. e., the time integral of the electrometer current prior to its inversion, is at its maximum of about 10^{-8} coulomb-cm² after a 25-hour exposure at 9.1×10^6 ergs g⁻¹(C) hr⁻¹. It was found that the total charge displaced below 320 C is directly proportional to the temperature gradient applied to the samples for the three gradients tested. Irradiation with 1 Mev electrons produces similar charge displacements, but at a much lower exposure. Comparable charge displacements with Co^{60} radiation require 200 times greater exposures than the Van De Graaff radiation. This implies that the Co^{60} secondary electron exposure rate is only 0.5 per cent that of the primary gamma radiation 2 inches away from the 220-curie Co^{60} source employed in these studies.

Investigators at the Owens-Illinois Glass Company⁽¹⁵⁹⁾ have investigated the effects of 100-kv electrons on glass films. They showed that the radiation and heating effects of the electron beam introduced crystallization in thin films of baria titanate alumina silica glass.

Research by Primak and Edwards⁽¹⁶⁰⁾ of Argonne National Laboratory on vitreous silica has shown that, when samples are irradiated in a nuclear reactor, three effects caused dimensional changes: homogenization effect is assigned to fast neutrons (approximately 3×10^{20} n cm⁻²); compaction is assigned mainly to fast neutrons (approximately 3×10^{19} n cm⁻²); and a dilatation is caused by ionization. They irradiated three grades of silica - Optosil, GE 101, and GE 103 - in the CP-5 reactor to investigate the possibility of homogenizing silica by irradiation. They found that a generalized symmetrical internal stress pattern developed which was greater than the local "inhomogeneities in the silica".

Studies have been conducted by Truell⁽¹⁶¹⁾ on radiation effects in alpha quartz using reactor radiation and Co^{60} radiation. Both types of radiation put a peak in the ultrasonic attenuation-temperature curves in the area between 250 and 300 C. These peaks disappear on annealing, but other effects do not disappear.

Investigators at Rutgers⁽¹⁶²⁾ have studied the lattice defects in natural and synthetic quartz crystals induced by exposure to 1×10^{19} to 1.5×10^{20} n cm⁻². Crystals irradiated at the highest level exhibited a considerable degree of crystal energy, as revealed by the extinction contour lines shown in the electromicrographs.

Induced color of various kinds of shielding window glass by gamma-ray irradiation was studied at the Tokyo Metropolitan Isotope Center.⁽¹⁶³⁾ With 23 ± 3 C as the irradiation temperature, 8.7×10^6 ergs g⁻¹(C) hr⁻¹ as the exposure rate, and 8.7×10^6 to 8.7×10^8 ergs g⁻¹(C) as total exposure, the coloration increases gradually.

Volume resistivity of glass and its change by gamma-ray irradiation are shown in Figures 11 and 12. Resistance of high-density glass is found to become minimum - hence the current becomes maximum - at the exposure of 8.7×10^7 ergs g⁻¹(C) and increases as the exposure increases, but the resistance of medium-density glass decreases gradually. Change of the resistance was found to be exponential and the charge always positive at any exposure. This indicates that glass is electrized by radiation. On the other hand, linearity is established between the quantity of space charge and the exposure in a range of 8.7×10^6 to 3.5×10^8 ergs g⁻¹(C).

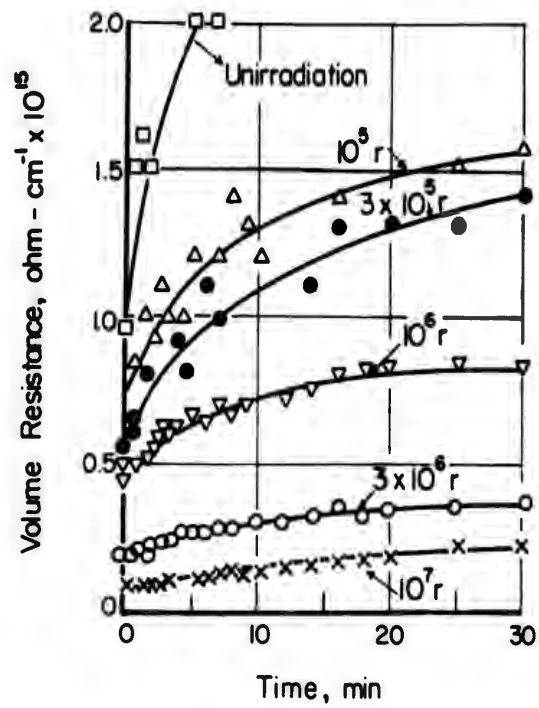


FIGURE 11. VOLUME RESISTANCE CHANGE WITH TIME OF IRRADIATED MEDIUM-DENSITY GLASS⁽¹⁶³⁾

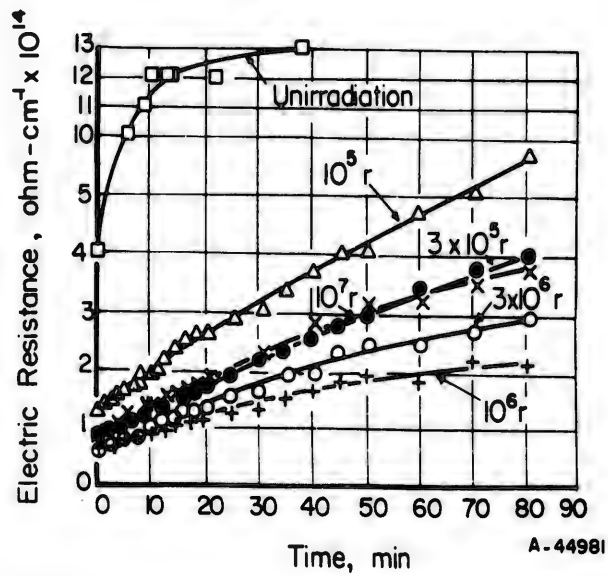


FIGURE 12. VOLUME RESISTANCE CHANGE WITH TIME OF IRRADIATED HIGH-DENSITY GLASS⁽¹⁶³⁾

This study demonstrates the physical properties of shielding window glass and the effect of radiation, and possibly suggests the means of preventing breakdown by radiation of glass.

A bibliography of 500 references on radiation effects on glass has been compiled by Comstock and Ferrigno⁽¹⁶⁴⁾, and would be helpful to those interested in such a comprehensive listing.

Graphite and Diamond

Research during the past year on graphite as a reactor material has been conducted by United States, British, French, Danish, and Japanese scientists.

Hanford⁽¹⁶⁵⁾ has continued its radiation-effects research on polycrystalline moderator graphite in a radiation environment. Their hypothesis concerning the mechanism of radiation-induced contraction is being tested by measuring the dimensional stability of nonconventional graphite materials such as pyrolytic graphite and low-permeability graphite. As a result of reactor radiation at high temperatures, conventional graphite contracts in both orientations. Pyrolytic carbon contracts in the direction parallel to the planes and expands perpendicular to the planes. The maximum radiation exposure for these specimens was $6 \times 10^{20} \text{ n cm}^{-2}$ ($E \geq 0.18 \text{ Mev}$), and the temperature was approximately 650 C. The effect of radiation on the coefficient of thermal expansion was most pronounced in the transverse direction with a change from 23×10^{-6} inches per inch per °C to 20×10^{-6} inches per inch per °C over the range 25 to 425 C after $6 \times 10^{20} \text{ n cm}^{-2}$. From these data it may be inferred that radiation causes a decrease in circumference of pyrolytic carbon shells but a slight increase in thickness.

The electrical resistances and Hall coefficients of polycrystalline graphite, neutron-irradiated graphite, chemically doped graphite, and neutron-irradiated chemically doped graphite were measured by Montet⁽¹⁶⁶⁾ over a range of magnetic fields at liquid-nitrogen and liquid-helium temperatures. The empirical equivalence of acceptor concentrations in irradiated graphite and in chemically doped graphite obtained by matching Hall coefficients was found to be a function of the temperature of measurement. This observation may be explained in terms of temperature-dependent trapping efficiencies of the electron traps introduced chemically or by neutron irradiation. This explanation affords some understanding of the electrical properties of the complicated neutron-irradiated chemically doped graphite. The temperature variation of the resistances and Hall coefficients of the graphites studied may be reasonably well understood on the basis of the phenomenological theory of transport properties. Anomalous variations with magnetic field of resistances and Hall coefficients were observed at low temperatures in some of the graphites studied.

Measurements of radiation damage were made in NPR and KC graphite using a 2 Mev Van De Graaff electronic accelerator and liquid-nitrogen temperatures to 150 C.⁽¹⁶⁷⁾ Measurements included those of changes in length, lattice spacing, and resistivity upon electron irradiation. It was found that significant quantities of ozone were produced when irradiations were done using liquid nitrogen as a coolant.

A 0.03 per cent change in thickness was measured for KC graphite exposed to the electron beam for 242.5 minutes, with a 0.13 per cent change after 1235 minutes.

The resistance of NPR graphite was found to increase nonlinearly with exposure. Because of the hazards of the ozone liberation, heating of the sample, sensitivity to temperature shocks, and mechanical stresses, the experiments were discontinued.

Reynolds and Thrower of the Atomic Energy Research Establishment⁽¹⁶⁸⁾ reported on their investigation of irradiating natural crystals of graphite in the Dido and Pluto reactors at 0.5 to 1×10^{20} n cm⁻². At 650 C the defects produced in graphite crystals increased in size but not in density and, at approximately 5×10^{20} n cm⁻², a new population of uniformly distributed fine damage began to appear. The new defects were similar to those characteristic of 150 C irradiation and coarsened on annealing at 1200 C.

Gain⁽¹⁶⁹⁾ reported at the IAEA Symposium in Venice, Italy, on the results of irradiation experiments on natural and artificial graphite at three temperature intervals ranging from 70 to 150 C, 300 to 400 C, and 500 to 650 C. Samples received neutron exposures up to 5×10^{21} n cm⁻² ($E \geq 0.17$ Mev). Results obtained during these investigations indicate that, in addition to the dependence on the irradiation temperature and the neutron exposure, a strong influence is exerted by the basic materials, the treatment during production, and the density of the material.

Other work by Thrower and Reynolds⁽¹⁷⁰⁾ on neutron irradiation of graphite indicated that etch pits form during the preparation of specimens irradiated to 10^{20} n cm⁻². In microstructural studies these etch pits were identified with a complex dislocation structure along grain boundaries.

British Pile Grade A Graphite and highly oriented natural material prepared from high-purity natural graphite were irradiated at 450 C up to 6.26×10^{20} fast n cm⁻². The results show that irradiation at 450 C produces a contraction in both directions relative to extrusion, the magnitude of the contraction being approximately twice as large parallel as perpendicular.

As an alternative to the theory developed by Hanford Atomic Products investigators, Kelly, Jones, and James⁽¹⁷¹⁾ propose that dimensional changes at lower temperatures are explained in highly graphitic materials on the basis of dimensional changes in the graphite crystals alone (see reference 165).

Rappeneau⁽¹⁷²⁾ investigated the effects of irradiation temperature on the amount of energy stored in graphite with reference to samples from the French G1 and G2 reactors. At a given irradiation temperature, the energy liberated by the irradiated graphite increases proportionally to the exposure. This linear relationship is valid only for small exposures. At relative low irradiation temperatures (30-70 C), there is a peak of energy release near 200 C. As the irradiation temperature increases, this energy peak diminishes and it disappears at an irradiation temperature of about 200 C.

The amount of energy stored for a constant exposure of 2×10^{20} n cm⁻² decreases rapidly as the irradiation temperature increases from 50 to 300 C. These results agree with the results obtained by other investigators.

Investigators at the Danish Atomic Energy Research Establishment⁽¹⁷³⁾ studied the effects of 4×10^{19} n cm⁻² on reactor-quality graphite. An effect is clearly demonstrated from measurements of electrical and thermal resistivity, Young's modulus, and dimensional changes, which can be interpreted in terms of a dominant process in the damaging mechanism with an activation energy for thermal annealing of 1.2 ev.

Sato(174) investigated the use of measuring the propagation velocity of pulsed ultrasonic waves in graphite as a means of determining elastic modulus. The ultrasonic method has the unique advantage of being easily applied to test pieces of all shapes and forms and at all temperatures, even those up to approximately 1600 C. Extruded, press-molded-from-pitch coke specimens were subjected to irradiation levels of 5.8×10^{20} n cm⁻². The specimens were subjected to mechanical tests and tests for determining elastic modulus. A close correlation between the two properties was revealed, indicating the possibility of estimating mechanical strength from the elastic modulus, irrespective of the radiation exposure. This work throws light on elastic recovery through the determination of the elastic modulus following isochronal and isothermal annealing.

Nightingale(175), Engle(176), Schweitzer(177), and Leveque(178) have reviewed radiation effects on graphite. Engle's review provides extensive thermal-conductivity data curves and tables as a comparison of various research programs. Schweitzer presents radiation-damage models as part of his review. A new model of radiation-damage graphite was proposed in an article written by Iwata and Suzuki. (179)

Investigators at the University of Michigan(180) have studied the effects of radiation on the density, hardness, and other physical properties of diamonds. Figures 13 and 14 summarize the results of the density and hardness studies.

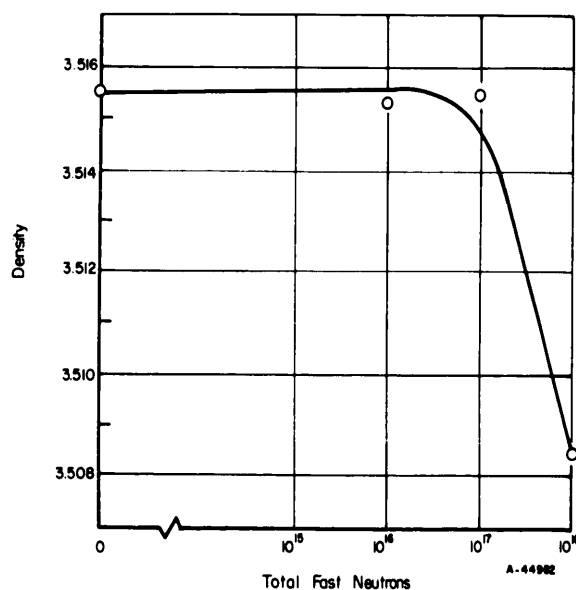


FIGURE 13. DENSITY OF NEUTRON-IRRADIATED DIAMONDS

The annealing of two diamonds which have been irradiated to 10^{18} n cm⁻² restored the transparency of the specimens only slightly. The general effect of irradiation is found to be roughly proportional to the reduction of the transmission (Table 16).

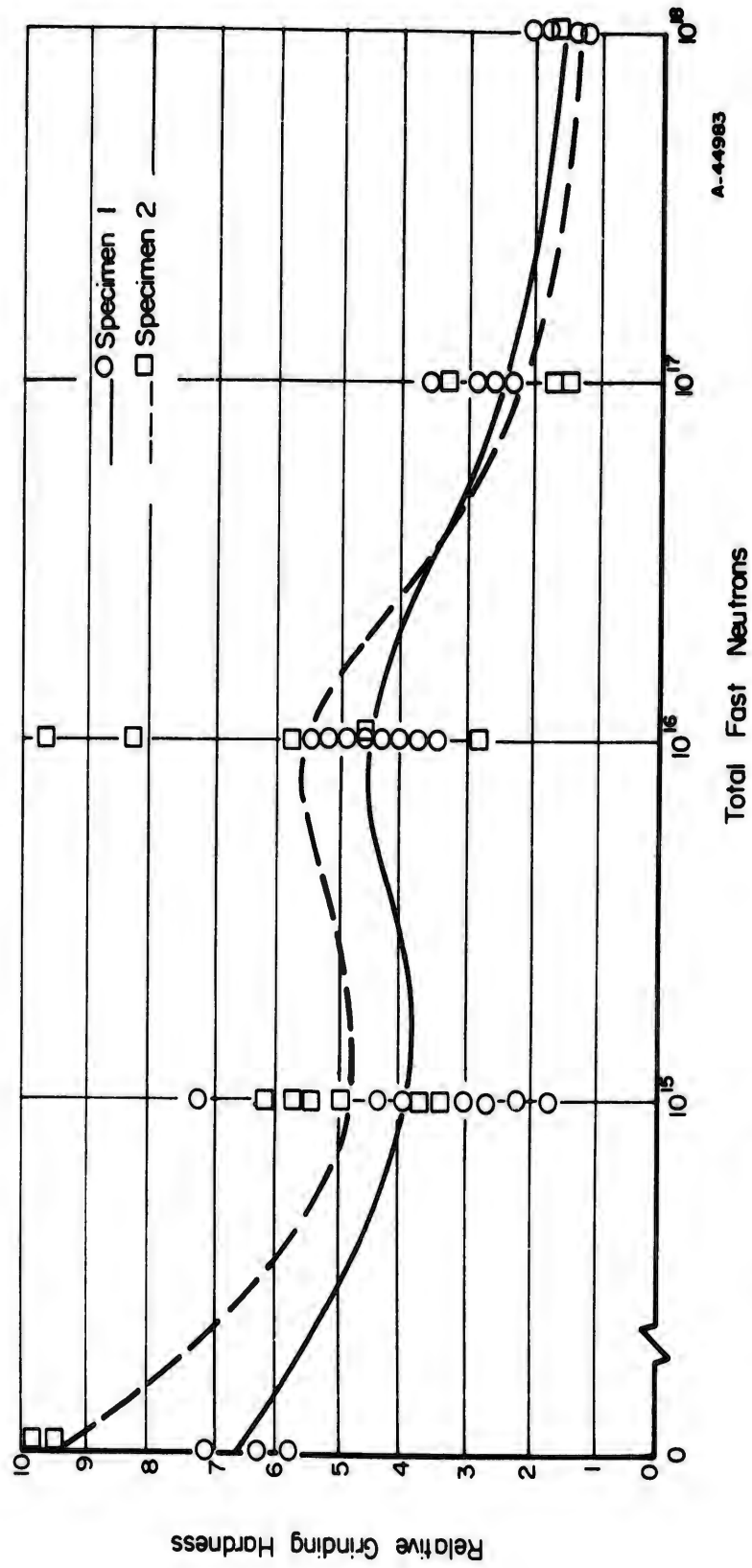


FIGURE 14. HARDNESS OF NEUTRON IRRADIATED DIAMONDS

TABLE 16. TRANSMISSION OF IRRADIATED DIAMOND

Total Fast Neutrons, $n\text{ cm}^{-2}$	Sample 1 (3.18 MM Thick)	Sample 2 (3.04 MM Thick)
2×10^{13}	99%	99%
2×10^{14}	95%	95%
2×10^{15}	77%	75%

The dependence of optical absorption upon radiation exposure suggests a general possibility of using diamond as a material for measuring exposure in a reactor experiment.

Diamonds irradiated with $3 \times 10^{20} n\text{ cm}^{-2}$ ($E \geq 1\text{ Mev}$) at approximately 70 C exhibit properties characteristic of a crystalline solid containing point defects. (181) The Debye-temperature factor was found to be unchanged by irradiation. There is pronounced radiation annealing but little thermal annealing during irradiation, as evidenced by the independence of the damage on exposure rate and the decrease of the damage rate with exposure. A model is proposed by the investigator for the damage structure which requires approximately 100 atoms to be displaced per primary, of which approximately 2-1/2 never recombine with their vacancies that are too distant.

Clarendon Laboratory investigators (182) found that the paramagnetic-resonance spectrum of neutron-irradiated diamond was similar to that produced by electron irradiation.

Programs in Progress*

Current programs on radiation effects in ceramics are summarized below.

U. S. Air Force, Aeronautical Systems Division, is studying electron-irradiation effects on infrared optical materials.

Bausch and Lomb Optical Company is doing research on lead silicate and optical glass.

Brookhaven National Laboratory is investigating electrical properties of irradiated graphite and damage mechanisms.

General Electric Company, Hanford Atomic Products Operation, is doing research on basic damage and annealing effects of reactor graphite.

General Electric Company, Nuclear Materials and Propulsion Operation, is investigating the physical and mechanical properties of irradiated beryllium oxide.

*Detailed information on these programs, including contract numbers and sponsoring agencies, is given in REIC Memorandum 11-C (Confidential), April 15, 1963.

General Electric Company, Research Laboratory, is studying damage mechanisms in mica.

Oak Ridge National Laboratory is continuing investigations on irradiation of beryllium oxide and graphite as moderator materials.

The Pennsylvania State University is studying the mechanisms of fission gas diffusion in graphite.

Phillips Petroleum Company is doing research on graphite damage as an index to the integrated damaging neutron flux.

National Aeronautics and Space Administration, Lewis Research Center, is doing research on the production of defects in refractory compounds by electron and neutron bombardment.

National Bureau of Standards is developing a high-temperature calorimeter for the precise measurement of heats of solution or reaction of neutron-irradiated quartz and silica.

Naval Air Engineering Center is investigating thermal-radiation resistance of nonmetallic materials.

University of Connecticut is conducting research on radiation effects in metal oxides by electron spin resonance.

Johns Hopkins University is investigating the electrical properties of dielectric materials including ceramic oxides.

Conclusions and Recommendations

The new internal research task initiated in 1962 at the Aeronautical Systems Division has indicated an awareness of the necessity of combined electron and vacuum data for satellite optical systems. While the Atomic Energy Commission investigations on basic mechanisms of radiation damage in reactor ceramics are extremely important, more emphasis is needed on combined environmental studies. Combined environmental data and information on proton-electron and neutron-gamma radiation, X-rays, ultra-violet radiation, temperature, vacuum, vibration, and shock are necessary to assist the design engineer in his quest for materials for advanced designs.

Continuation of research orientated along the lines of that being conducted at Johns Hopkins University⁽¹³⁵⁾, if expanded into other types of radiation, vibration, and shock, could provide needed design data.

SPACE ENVIRONMENT

Current State of the Art

There has been little change in the state of the art in the last year except for some better descriptions of the Van Allen radiations.

Van Allen Belts

During the past year experimental findings, particularly from Explorers 12 and 14, have contributed greatly to the description of the charged particles trapped in the earth's magnetosphere. The more recent Explorer 14 data have essentially confirmed the Explorer 12 data, particularly in regard to the outer-belt electron fluxes. As discussed in last year's report, the picture of the radiation belts has undergone some modification.

Van Allen's group⁽¹⁸³⁾ has recently reported some preliminary results from Explorer 14. The values given in Table 17 are quoted from this reference. According to these authors, the earlier erroneous values inferred for the electron fluxes in the outer belt were due to the neglect of penetrating electrons rather than protons as implied in last year's report. Data from Explorer 14 also confirm the finding from Explorer 12 which indicates a sharp boundary for the trapped particle zone at about $R_E = 70,000$ km.

In connection with the Van Allen belts, the artificial belt created last year by the 'Starfish' weapons test should be mentioned. On July 9, 1962, a 1.4-megaton weapon was exploded 250 miles above Johnston Island in the Central Pacific. Subsequently, various radiation detectors carried by satellites noted counting rates larger and more persistent than were anticipated. Reference (184) gives a collection of papers dealing with the measurements of the particles trapped from the 'Starfish' event. As a result of the nuclear detonation, fission products ejected electrons by beta decay into trapped trajectories. The artificial radiation belt apparently has maximum intensity at an altitude of about 750 miles at the geomagnetic equator. The peak intensities measured are about 10^9 electrons $\text{cm}^{-2} \text{sec}^{-1}$. These electrons seem to have a spectrum consistent with the spectrum of fission-product betas. A median energy of about 1 Mev is characteristic of such a spectrum. It is not clear yet how long these trapped electrons will persist, but estimates of several years have been reported.

Solar-Flare Radiations

No new data concerning recent solar-flare events have been published. This situation will more than likely continue for several years until the current cycle of solar activity begins to rise. Foelsche⁽¹⁸⁵⁾, however, has reviewed the better-known recent solar events from a radiation-hazard and shielding standpoint.

The over-all flare picture has therefore remained unchanged; i. e., the solar flares represent a serious radiation hazard for manned space missions but the solar-flare data are rather inadequate for optimum shield design.

TABLE 17. PARTICLE FLUXES⁽¹⁸³⁾ NEAR GEOMAGNETIC EQUATOR AS A FUNCTION OF DISTANCE FROM EARTH'S CENTER (R_E)

R_E , km	Electrons		Protons	
	Energy	Flux, electrons $\text{cm}^{-2} \text{sec}^{-1}$	Energy	Flux, protons $\text{cm}^{-2} \text{sec}^{-1}$
20,000	$\geq 230 \text{ kev}$	$\leq 4 \times 10^4$	$\geq 500 \text{ kev}$ $\geq 4.5 \text{ Mev}$	$4(\pm 2) \times 10^6$ $\leq 1.5 \times 10^4$
31,000	$\geq 40 \text{ kev}$ $\geq 230 \text{ kev}$ $\geq 1.6 \text{ Mev}$	1×10^8 $\leq 5 \times 10^6$ 1×10^6		
39,000	$\geq 40 \text{ kev}$ $\geq 230 \text{ kev}$ $\geq 1.6 \text{ Mev}$	1.5×10^8 $\leq 1.5 \times 10^6$ 2×10^5		
55,000	$\geq 40 \text{ kev}$ $\geq 230 \text{ kev}$ $\geq 1.6 \text{ Mev}$	2×10^7 $\leq 3 \times 10^4$ $\leq 1.5 \times 10^3$	$\geq 500 \text{ kev}$	$\leq 5 \times 10^4$
65,000	$\geq 40 \text{ kev}$ $\geq 230 \text{ kev}$ $\geq 1.6 \text{ Mev}$	1×10^6 $\leq 6 \times 10^3$ $\leq 2 \times 10^2$	$\geq 500 \text{ kev}$	$\leq 1.5 \times 10^4$
75,000 to 103,000	$\geq 40 \text{ kev}$	$\leq 5 \times 10^2$	$\geq 500 \text{ kev}$	$\leq 5 \times 10^2$

DOSIMETRY

Current State of the Art

During the past year considerable work has been orientated toward the development of better semiconductor detectors, with particular emphasis on wide-depletion-layer solid-state devices capable of detecting high-energy charged particles.

Experiments to measure the response of various types of gamma dosimeters in a mixed neutron-gamma environment have been conducted by Smith and Benck.⁽¹⁸⁶⁾ They tested films, glass microdosimeters, cobalt glass plates, thermoluminescent dosimeters, and formic acid chemical dosimeters. Fast (fission)-neutron and thermal-neutron sensitivities of a CaF_2 thermoluminescent dosimeter were obtained, and the fast-neutron sensitivities of two high-range films (548-0 and 649) were determined. There were insufficient data for the other dosimeters to draw conclusive remarks.

Pulsed-Radiation Dosimetry

Experiments have shown that a miniature MgO radiation detector (MgO-RAD)⁽¹⁸⁷⁾ is capable of measuring pulses of gamma radiation from 0.2 to 60- μ sec duration and intensities to 10^{10} ergs $\text{g}^{-1}(\text{C})$. Tests in the energy range from 300 kev to 24 Mev indicate that the device is energy independent.

Because of its very fast time response, a Cerenkov detector appears to be applicable for the measurement of high-intensity gamma fluxes which change rapidly with time. Personnel at Lawrence Radiation Laboratory⁽¹⁸⁸⁾ have investigated the Cerenkov response of two transparent solids, quartz and Lucite, to gamma and fast-neutron irradiation. They conclude that Lucite is a satisfactory solid for use in Cerenkov detectors. They found that the speed of response of Lucite is a factor of 30 to 40 times greater than for a fluor.

Glass Dosimeters

Cobalt glass dosimeters have been used to measure gamma exposure and thermal-neutron flux at the Triga Mark F pulse reactor.⁽¹⁸⁹⁾ The dosimeters were calibrated with the 2000- and 50,000-curie National Bureau of Standards Co^{60} sources from approximately 5×10^5 to 5×10^9 ergs $\text{g}^{-1}(\text{C})$. The dosimeters appeared to be exposure rate independent between approximately 5×10^6 and 5×10^7 ergs $\text{g}^{-1}(\text{C}) \text{ sec}^{-1}$. The (γ, α) reaction of boron present in the cobalt glass was used as a thermal-neutron flux monitor. Three glass slides were stacked in the form of a sandwich, with the outer slides acting as a thermal-neutron shield for the inner slide.

Chemical Dosimeters

Several types of chemical dosimeters have been developed which are applicable to cases where high exposures are anticipated. One dosimeter in particular may be used in the mixed radiation environment of a reactor.

An aqueous solution of oxalic acid⁽¹⁹⁰⁾ is the only suitable aqueous chemical dosimeter for measuring radiation exposure in a reactor. This chemical dosimeter can be used up to exposures of 1.6×10^{10} ergs g⁻¹(C), and the dosimeter is not made radioactive by neutrons. Preliminary experiments with 10-Mev electrons from a linear accelerator indicate that the radiation yield is not noticeably affected by exposure rates up to 10^{12} ergs g⁻¹(C) sec⁻¹.

The development of a chemical dosimeter⁽¹⁹¹⁾ which depends on the color change induced in titanium sulfate by gamma-ray irradiation has been investigated for application to exposures $> 10^8$ ergs g⁻¹(C). Using a method of photodensity measurement, exposures up to 10^{10} ergs g⁻¹(C) have been estimated.

Cesium nitrate⁽¹⁹²⁾ is an excellent inorganic chemical dosimeter for measuring high-intensity radiation according to Tung-Ho Chen and Everett R. Johnson of Stevens Institute of Technology.

Powdered di-alanine⁽¹⁹³⁾, which is similar to biological systems in absorbing radiation, has been fabricated to form solid-state dosimeters. The irradiated powder exhibits good stability, with no measurable change in the number of free radicals created 14 days after irradiation and only a 5 per cent decay 90 days after irradiation.

Scintillators

The high definition and efficiency of glass scintillators have led four British scientists⁽¹⁹⁴⁾ to build an all-glass alpha-particle detector from cesium-activated LiO₂-MgO-SiO₂. This thin all-glass detecting screen can record weak alpha-particle fluxes in a strong radiation background with a high discriminating power.

Through the use of a selected photomultiplier and logarithmic-spiral light pipe⁽¹⁹⁵⁾, the resolution widths of lithium-containing and boron-containing glass scintillators have been significantly improved. Resolution widths of 9.5 per cent for 5.02 per cent lithium-containing glass and 30 per cent for 13.81 per cent boron-containing glass have been obtained.

Organic scintillators can be used as fast-neutron spectrometers⁽¹⁹⁶⁾ in a mixed neutron-gamma field by pulse-shape discrimination between the electron pulses (produced by gamma absorption) and the slower decaying proton pulses (produced by fast neutrons). Using an organic scintillation detector⁽¹⁹⁷⁾, Texas Nuclear Corporation has developed a neutron-gamma ray spectrometer which gives spectral information in a mixed radiation environment for neutron energies between 0.7 Mev and 15 Mev, and gamma energies between 0.25 Mev and 4 Mev.

Ionization Chambers and Fission Counters

Possible in-core neutron sensors for nuclear-rocket reactors have been investigated by Paul E. Brown.⁽¹⁹⁸⁾ The severe physical environment (for example, temperatures ranging from -235 to +2600 C) and nuclear environment (fluxes as high as 10^{16} n cm⁻² sec⁻¹ for several minutes) preclude the use of most conventional ionization chambers and fission chambers. Tests have been performed on economically available fission counters and ion chambers by Pratt & Whitney^(199,200) at temperatures as high as 700 F.

No apparent change in sensitivity or significant increase in noise level was observed for the fission counters. Data obtained from the tests on the ion chambers indicate an increase in leakage current of about 1 decade per 75 degrees. On the basis of the environment confronted in nuclear rockets, Brown decided that a promising concept for an in-core neutron sensor would be a graphite ion chamber with BeO insulators. With appropriate choice of coatings on the internal electrode, this chamber could conceivably be used as a compensated ion chamber, uncompensated ion chamber, fission counter, or proportional counter.

A quartz-fiber integrating-type ionization chamber⁽²⁰¹⁾ designed for automatic, remote measurements of ionizing radiation is available from Electro-Optical Systems, Inc. This chamber was originally developed for use in spacecraft. Its output signal, consisting of pulses at a frequency proportional to incident flux, can vary from one pulse in 7 hours to 100 per second (equivalent to a flux range from 0.01 Mr hr⁻¹ to 50 R hr⁻¹), and the instrument tolerates temperatures from -50 C to +150 C.

Foil Detectors

The "sandwich method" or thick-foil technique^(202, 203, 204) can be used to measure the resonance neutron spectra at the selected resonance energies of several foil detectors. In this method a thin foil having a strong isolated resonance activation cross section is covered on both sides by thick layers of the same material which is thin in all neutron-energy regions except in the neighborhood of the resonance. The difference in activation of a thin foil with and without filters is a measure of the neutron flux at the resonance energy. Typical detectors are In (1.46 ev), Au (4.9 ev), W (18.8 ev), La (73.5 ev), and Mn (337 ev).

Hsiang-Lin Pai and others⁽²⁰⁵⁾ have used an iterative procedure to determine the resonance flux spectrum which is given by the general expression $\phi(E) = B/E^N$, where B is a constant independent of energy and $0 \leq N \leq 1$. For their first approximation to the spectrum they assume $N = 1$.

Lanning and Brown⁽²⁰⁶⁾ have measured the fast-neutron energy spectral distribution, using the threshold detector technique and a modification of the Hartman method. Their analytic expression for the differential spectrum is represented by an orthogonal polynomial expansion with an experimental energy-weight function.

The Trice step-function method for measuring fast-neutron flux has been reportedly improved upon by Armour Research.⁽²⁰⁷⁾ Their method, which is basically one of iteration, departs from the step-function method primarily in three respects: it does not presuppose that the unknown flux spectrum is shaped like a fission spectrum; it determines detector limits from a sensitivity curve; and it does not assume that high-energy foil measurements alone determine flux spectrum accurately.

Semiconductor Dosimeters

The rapid and significant development of semiconductor detectors in the last 3 years has led to their wide acceptance and use as charged-particle detection devices. Their compactness, shock resistance, and low power requirements have made them particularly suitable as detectors in space exploration.

Radiation-damage effects in semiconductors limits their use in high radiation fields. Silicon p-n junction detectors as well as silicon surface-barrier detectors irradiated with 10^{13} fast n cm⁻² were observed to show catastrophic increases in leakage current and noise. (208)

P-n junction detectors and lithium drift detectors exposed to gamma rays up to approximately 2×10^9 ergs g⁻¹(C) by A. R. Jones (209) exhibited losses in sensitivity, and in some cases the detectors became too noisy to measure their sensitivity to gamma rays.

A long-tube method (210), whereby a target of fissile material is placed at one end of a long evacuated tube and a semiconductor sensor at the other end, was used in measuring in-core neutron fluxes in the 1-Mw swimming-pool reactor at McMaster University. This increased the detector lifetime by as much as a million times.

The effects of long-term vacuum on commercial surface-barrier and diffused-junction silicon radiation detectors have been determined at the Aeronautical Research Laboratories (211). Measurements of reverse leakage current, RMS noise voltage, alpha-particle resolution, and dead layer were obtained in a vacuum of approximately 10^{-6} mm of mercury for a duration of approximately 6 months. The tests indicated that the surface-barrier detectors had somewhat better energy resolution and consistently thinner dead layers than the diffused-junction type. The extended high-vacuum tests showed that both diffused-junction and surface-barrier detectors were capable of operating in high vacuum for long periods of time and of maintaining excellent resolution and pulse-height stability.

Processes have been developed (212) whereby lithium drift semiconductor detectors can not be made with depletion layer widths up to 5 millimeters thick at 100 volts bias. These detectors are capable of stopping 2-Mev electrons, 30-Mev protons, and 140-Mev alpha particles.

A method of doping p-type silicon crystals by ion bombardment to produce solid-state detectors has been used at Argonne National Laboratories (213); 9000-ohm-cm p-type silicon was bombarded with 10-kev phosphorus ions from the Argonne electromagnetic isotope separator. The desired impurity introduced into the crystal can be precisely controlled by monitoring the ion beam current. Acceleration of the ions to low energies results in shallow junctions a few hundred angstroms below the surface, and owing to the discrete range of the ions the depth will be well defined. Detectors with very thin dead layers can be obtained by this process.

Solid State Radiations (214) has investigated the use of silicon solid-state devices as possible fast-neutron detectors. Their work included the development of a proton-recoil spectrometer utilizing a semiconductor detector, application of neutron charged-particle converter materials to semiconductor surfaces to make them neutron sensitive, and the use of lithium drift detectors as threshold detectors. The advantages of using the semiconductor detector over the proportional counter or scintillation detector in the proton recoil spectrometer are the available high resolution and simplicity of the experimental setup. The spectrometer is capable of yielding good results at least up to the 5-Mev threshold for the $\text{Si}^{28}(\text{n},\text{p})\text{Al}^{28}$ and $\text{Si}^{28}(\text{n},\alpha)\text{Mg}^{25}$ reactions. Use of coated detectors for measurement of neutron energy is essentially limited to U^{238} , Th^{232} , or Np^{237} fission threshold detectors which cover a limited energy range and have relatively poor

sensitivity. Because of its low inherent sensitivity, the potential use of the Li^6 drift detector as a neutron spectrometer is marginal.

Depletion-layer detectors have proved to be good charged-particle detectors; however, they are generally unsatisfactory as gamma-ray detectors. Bulk photoconductivity devices are being investigated as possible gamma-ray detectors.⁽²¹⁵⁾ The most promising materials now available are CdS and CdSe single crystals, though considerable attention is being focused on GaAs. Crystals of CdS are commercially available with a sensitivity to Co^{60} gamma radiation of 10 microamperes per 100 ergs $\text{g}^{-1}(\text{C})$ per hour.

Dosimeters for Space Application

In the interest of the solar physics program at the Goddard Space Flight Center⁽²¹⁶⁾, a detector for low-energy gamma-ray astronomy experiments has been developed. A study of nuclear reactions occurring in the solar atmosphere which generate gamma radiation in the energy range of 0.1 to 3 Mev is desired. Possible reactions that could be studied by use of this detector are bremsstrahlung produced by relativistic electrons in the solar atmosphere, positron annihilation radiation, and deuteron formation through neutron-proton capture reactions. The detector consists of a CsI (Tl) crystal 2 inches long by 1 inch in diameter which is inserted into a well of a CsI (Tl) crystal 8.75 inches long by 5.75 inches in diameter. The small crystal is viewed by a single photomultiplier tube, and the large crystal is viewed by four photomultiplier tubes. The outputs from the two crystals are run in anticoincidence.

A high-energy gamma-ray telescope⁽²¹⁷⁾ was successfully placed in orbit by Explorer XI and recorded data from 22 gamma rays with energies >50 Mev. These measurements may help to determine the direction from which galactic cosmic rays arrive at the earth. The detector consisted of a sandwich crystal scintillator that contains alternate slabs of cesium iodide and sodium iodide about one radiation length thick. A photomultiplier detects the light pulse that accompanies the production of the electron-positron pair in the sandwich scintillator. One or both of the electron-pair members then enter a Lucite Cerenkov counter, and the Cerenkov radiation is detected by two photomultiplier tubes. The output of both the scintillation detector and the Cerenkov counter is connected in coincidence. A plastic anticoincidence scintillator which surrounded the telescope was used to discriminate between gamma rays and cosmic rays.

A double gamma-ray spectrometer developed at Goddard Space Flight Center⁽²¹⁸⁾ will be used to study variations of the positron intensity in interplanetary space and the earth's radiation zone. Sensitive elements of the detector consist of two optically separated CsI (Tl) crystals, each completely embedded in a block of scintillating plastic, and a third small CsI (Tl) crystal which rests at the bottom of a conical well machined in the joined scintillator blocks.

Direct measurements of the radiation absorbed at five points on an astronaut⁽²¹⁹⁾ are possible with a set of tissue - equivalent ionization chambers developed by Hughes Aircraft. The system is completely transistorized except for electrometer tubes and weighs only 20 pounds. Automatic calibration is provided every 2 minutes during its 150-hour or greater lifetime.

A proton detector which essentially consists of a solid-state ionization chamber with multimicrosecond response⁽²²⁰⁾ was launched with Transit IV-A. This device which

is also applicable to the detection of electrons, neutrons, alphas, heavy ions, and fission fragments was developed by Solid State Radiation, Inc.

Conclusions and Recommendations

Because of its possible application for the measurement of high-intensity gamma fields of short duration, continued development of the Cerenkov counter is considered important. The development of a small steady-state gamma dosimeter for measuring gamma exposures $>10^{10}$ ergs-g $^{-1}$ (C) in a mixed neutron-gamma field would be valuable.

The importance of the adequate specification of nuclear environment in data reporting and its necessity in the prediction and correlation of radiation-effects data are re-emphasized.

The recommendations which have been made in previous years still stand:

- (1) All gamma exposures should be reported in terms of the field through its interaction with a reference material, the unit agreed upon being ergs per gram absorbed in carbon [ergs g $^{-1}$ (C)].

Gamma spectrum information, when available, should be reported in photons cm $^{-2}$ sec $^{-1}$ Mev $^{-1}$.

- (2) Fast-neutron fields should be described by the number flux (n cm $^{-2}$ sec $^{-1}$).

The neutron-flux energy distribution should be reported.

- (3) Thermal-neutron exposures should be described by the (nv $_0$).
- (4) Where the total energy absorption has been calculated, it should be reported.
- (5) The terms "absorbed dose" and "absorbed dose rate" will be used in those cases in which the energy absorbed in a material is reported. Otherwise, the terms "exposure dose" or "exposure dose rate" will be used.

The methods used to measure the radiation field should be clearly defined. For example, if the threshold foil technique is used to measure fast-neutron spectrum, the cross-section energy thresholds and any other information pertaining to the method of data analysis should be reported.

REFERENCES

- (1) "Radiation Resistant Wirewound Resistors", Aviation Week, 75 (25), 89 (December 18, 1961).
- (2) Nuclear Radiation Effects Projects (Title Unclassified)(Confidential) April 15, 1963, REIC Memo 11-C.
- (3) "Evaluation-Development of MIL-C-14157B Capacitors for Nuclear Radiation Environments", Admiral Corp. , Chicago, Illinois, NObsr-77612, August 21, 1961, Final Report, 122 pp, Avail: ASTIA, AD 265046.
- (4) Pfaff, E. R. , "Evaluation - Development of MIL-C-14157 Capacitors for Nuclear Radiation Environment", Admiral Corp. , Chicago, Illinois, NObsr-77612, NP-10547, July, 1961, Scientific Report No. 8, 76 pp.
- (5) Hamman, D. , Chapin, W. E. , "Study of Reliability of Electronic Components in a Nuclear Radiation Environment", from Battelle Memorial Institute, for Jet Propulsion Laboratory, Final Report, June 22, 1962.
- (6) Donovan, A. , Fueyo, A, and Schlueter, A. , "Effects of Nuclear Radiation on Quartz Crystal Units", Admiral Corp. , Chicago, Illinois, Report No. 1, September 30, 1961, Interim Final Report, May 23, 1960 - August 22, 1961, DA-36-039-SC-85322, 200 pp, Avail: ASTIA.
- (7) Gerstein, B. , Schlueter, A. , and Fueyo, A. , "Effects of Nuclear Radiation on Quartz Crystal Units", Admiral Corp. , Chicago, Illinois, March 30, 1962, Second Quarterly Progress Report, DA 36-039-SC-85322, 150 pp, Avail: ASTIA.
- (8) Gerstein, B. , Schlueter, A. , and Fueyo, A. , "Effects of Nuclear Radiation on Quartz Crystal Units", Admiral Corp. , Chicago, Illinois, June 30, 1962, Third Quarterly Progress Report, February 23 - May 22, 1962, DA-36-039-SC-85322, 100 pp, Avail: ASTIA.
- (9) Johnson, E. R. , "Unclassified Literature Survey on Effects of Nuclear Radiation to Electron - Tube Materials", Stevens Institute of Technology, Hoboken, New Jersey, Report No. 5735-4, November 30, 1961, Final Report, August 1 - November 30, 1961, DA-36-039-SC-87382, 25 pp, Avail: ASTIA.
- (10) Stern, H. A. , and Free, J. J. , "Radiation - Induced Gas Effects on Electron Tube Materials", Radio Corporation of America, Electron Tube Division, Lancaster, Pennsylvania, Second Quarterly Progress Report, October 1 - December 31, 1961, DA-36-039-SC-89121, 22 pp, Avail: ASTIA.
- (11) Talbert, A. J. , and Wilkin, N. D. , "Pulsed Gamma Initiation of Breakdown in Gas Tubes", Diamond Ordnance Fuze Labs, Department of the Army, Washington, D. C. , DOFL TR-961, July 10, 1961, Technical Report, DA-507-06-011, 21 pp, Avail: ASTIA, AD 261821.

- (12) Burnett, J. R., Courtois, D. A., Johnson, M. C., and Magee, R. M., "Transducers for Nuclear Vehicles", The Bendix Corp., Research Laboratories Division, Detroit, Michigan, ASD-TDR-62-551, January 24, 1962, Final Report, Vol. II, AF 33(616)-8077, 306 pp, Avail: ASTIA.
- (13) Fisher, H. F., Jr., "Telemetry Transducer Handbook", Radiation Inc., Melbourne, Florida, WADD-TR-61-67, October, 1962, Technical Report Vol. II, Supplement 3, AF 33(616)-8309, 200 pp, Avail: ASTIA.
- (14) Ross, C. W., "Effect of Thermal Neutron Irradiation on Thermocouples and Resistance Thermometers", Communication and Electronics (61), 192-196 (July, 1962).
- (15) Norton, H. N., General Dynamics/Astronautics, San Diego, California, "Transducer Selection", Space/Aeronautics, Technical Reference Series, October, 1962, pp 51-65.
- (16) Bradford, E. W., "Irradiation Tests of Selected Transducers", General Dynamics, Fort Worth, Texas, NARF-61-42T, MR-N-265, December 15, 1961, AF 33(657)-7201, 58 pp.
- (17) Burnett, J. R., Azary, Z. P., and Froelich, R. S., "Calibration of Pressure Transducers for Pluto Radiation Environments", Edgerton, Germeshausen & Grier, Inc., Santa Barbara, California, EGG-TN-29, March, 1963, 39 pp.
- (18) Taimuty, S. I., and Mills, J. S., "Effects of Radiation on Ferroelectric and Ferrimagnetic Materials: Part II - Ferrimagnetic Materials", Stanford Research Institute, Menlo Park, California, AFCRL-351, (Part II), June 15, 1961, Final Report, AF 19(604)-4141, 71 pp, Avail: ASTIA.
- (19) Sery, R. S., Lundsten, R. H., and Gordon, D. I., U. S. Naval Ordnance Laboratory, "How Radiation and Heat Affect Permanent Magnet Materials", Materials in Design Engineering, 55 (1), 90-92, 133 (January, 1962).
- (20) Wright, L. G., Rosen, C. A., and Taimuty, S. I., Stanford Research Institute, Menlo Park, California, "Radiation Effects in Ferroelectric Materials", paper presented at the AIEE Summer General Meeting, Denver, Colorado, June 17-22, 1962, 10 pp, Avail: AIEE as CP-62-1077.
- (21) "Study of Effect of High-Intensity Pulsed Nuclear Radiation on Electronic Parts and Materials", International Business Machines Corp., FSD Space Guidance Center, Owego, New York, IBM-62-521-14, Quarterly Progress Report No. 8, April 1 - June 30, 1962, DA-36-039-SC-85395, 33 pp, Avail: ASTIA.
- (22) Rogers, J., and Craig, C. L., Sperry Gyroscope Co., Division of Sperry Rand Corp., Great Neck, New York, "Degradation of Electrical Insulation From Reactor Irradiation", paper presented at the AIEE Summer General Meeting, Denver, Colorado, June 17-22, 1962, 12 pp, Avail: AIEE as CP 62-1297.
- (23) "Radiation-Resistance of Teflon Resins in Vacuums is Verified", Journal of Teflon, 3 (8), 2 (September - October, 1962).

- (24) Barker, R. S. , "Irradiation on Glass Yarns", Pilkington Brothers Limited, Lancashire, England, IT-95, December, 1961, 9 pp.
- (25) Saur, A. J. , Zack, J. F. , Jr. , and Anderman, A. I. , "Transient Radiation Effects in Electronic Materials", North American Aviation, Inc. , Atomics International, Canoga Park, California, AI-7506, July 27, 1962, First Quarterly Report, February 1 - April 30, 1962, MIPR-R-62-16-SC-00-93, 27 pp, Avail: ASTIA
- (26) Smalley, V. G. , and Polishuk, P. , "Radiation Effects to Flight Control Systems", paper presented at the International Symposium on Aerospace Nuclear Propulsion, October 23-27, 1961, Las Vegas, Nevada, ASD, WPAFB, Ohio.
- (27) "Radiation Effects Study of Digital Computer Circuits", International Business Machines Corporation, FSD Space Guidance Center, Owego, New York, IBM-62-521-16, June 29, 1962, Vol 1, Final Report, AF 33(616)-8341.
- (28) "Prediction of Transient Nuclear Radiation Effects in Electronic Circuits", The Boeing Company, Aero-Space Division, Seattle, Washington, D2-9878, January, 1962, AF 33(616)-7804.
- (29) Magee, R. M. , "Study to Determine Effects of Fission Product Gamma Radiation on Electronic Parts and Equipment", The Bendix Corp. , Bendix Systems Division, Ann Arbor, Michigan, BSC-31975, June, 1962, Progress Report No. 1, March 1 - May 31, 1962, NObsr-87267.
- (30) Hocraffer, V. D. , "Permanent Effects of Gamma Radiation on Various Switches", Minneapolis-Honeywell Regulator Company, Microswitch Engineering Test Laboratory, Freeport, Illinois, LTR 15027-1, December 30, 1960.
- (31) "Research and Investigation on Radiation Resistant, High Temperature Thermionic Circuitry", General Electric Company, Owensboro, Kentucky, Interim Engineering Report No. 5, April 1 - June 30, 1962, AF 33(616)-8096.
- (32) Schmidt, F. J. , "Research and Investigation on Radiation Resistant, High Temperature Thermionic Circuitry", General Electric Company, Receiving Tube Department, Owensboro, Kentucky, Interim Engineering Report No. 3, October 1-December 31, 1961, AF 33 (616)-8096.
- (33) Wattier, J. B. , Newell, D. M. , and Morgan, L. L. , "Effects of Reactor Radiation on the Engineering Properties of Elastomers and Plastics", General Dynamics/Fort Worth, Nuclear Aerospace Research Facility, Fort Worth, Texas, NARF-62-5T, FZK-9-174, June, 1962, AF 33(657)-7201, 115 pp, Avail: ASTIA.
- (34) Johnson, P. M. , and Fritz, E. G. , "Stress-Strain Behavior of Irradiated Polyurethane Elastomers", General Dynamics/Fort Worth, Nuclear Aerospace Research Facility, Fort Worth, Texas, NARF-62-2T, MR-N-293, February 23, 1962, AF 33(657)-7201, 29 pp, Avail: ASTIA.
- (35) Fritz, E. G. , and Johnson, P. M. , "Tensile Behavior and Molecular Characteristics of Irradiated Elastomers", General Dynamics/Fort Worth, Nuclear Aerospace Research Facility, Fort Worth, Texas, NARF-62-8T, MR-N-294, July, 1962, AF 33(657)-7201, 43 pp, Avail: ASTIA.

- (36) Born, J. W. , "Nuclear Radiation Resistant Polymers and Polymeric Compounds", B. F. Goodrich Company, Research Center, Brecksville, Ohio, WADC TR 55-58, Part VII, March, 1962, Technical Documentary Report, April 1, 1960 - May 31, 1961, AF 33(616)-7491, 205 pp, Avail: ASTIA, AD 276227.
- (37) Miller, C. D. , "Ultraviolet Radiation Degradation of Elastomers in a High Vacuum", Illinois Institute of Technology, Armour Research Foundation, Chicago, Illinois, ASD-TR-61-84, Technical Report, May, 1960 - May, 1961, AF 33(616)-7310, 20 pp, Avail: ASTIA, AD 268994.
- (38) Miller, C. D. , "Degradation Study of Elastomers", Illinois Institute of Technology, Armour Research Foundation, Chicago, Illinois, ASD-TR-61-84, Part IV, December, 1961, Technical Report, May - December, 1961, AF 33(616)-7310, 24 pp, Avail: ASTIA, AD 277057
- (39) Born, J. W. , "Nuclear Radiation-Resistant Polymers and Polymeric Compounds", B. F. Goodrich Company, Research Center, Brecksville, Ohio, March 15, 1962, Quarterly Progress Report No. 6, December 1, 1961 - February 28, 1962, AF 33 (616)-7491, 18 pp.
- (40) Born, J. W. , "Radiation-Resistant Polymers", B. F. Goodrich Company, Research Center, Brecksville, Ohio, May 1, 1962, Fourteenth Monthly Summary Report, January, 1962, AF 33(616)-7491, 6 pp.
- (41) Born, J. W. , and Gibbs, C. F. , "Radiation-Resistant Polymers", B. F. Goodrich Company, Research Center, Brecksville, Ohio, October, 1961, Twelfth Monthly Summary Report, AF 33(616)-7491, 11 pp.
- (42) Born, J. W. , "Nuclear Radiation-Resistant Polymers and Polymeric Compounds", B. F. Goodrich Company, Research Center, Brecksville, Ohio, December 15, 1961, Quarterly Progress Report No. 5, September 1, 1961 - November 31, 1961, AF 33(616)-7491, 23 pp.
- (43) Born, J. W. , "Radiation-Resistant Polymers", B. F. Goodrich Company, Research Center, Brecksville, Ohio, December, 1961, Thirteenth Monthly Summary Report, AF 33(616)-7491, 11 pp.
- (44) Born, J. W. , Paxton, T. R. , and Mooney, E. E. , "Radiation-Resistant Polymers", B. F. Goodrich Company, Research Center, Brecksville, Ohio, Eighteenth Monthly Summary Report, July, 1962, AF 33(616)-7491, 7 pp.
- (45) Born, J. W. , Paxton, T. R. , and Mooney, E. E. , "Radiation-Resistant Polymers", B. F. Goodrich Company, Research Center, Brecksville, Ohio, Twentieth Monthly Summary Report, September, 1962, AF 33(616)-7491, 10 pp.
- (46) Born, J. W. , "Radiation-Resistant Polymers", B. F. Goodrich Company, Research Center, Brecksville, Ohio, July 11, 1962, Sixteenth Monthly Summary Report, April, 1962, AF 33(616)-7491, 5 pp.
- (47) Collins, C. G. , "Combined Radiation - Temperature Effects on Hose and Seal Elastomers (Milestone Report)", General Electric Company, Aircraft Nuclear Propulsion Department, Cincinnati, Ohio, DC-60-12-95, November 30, 1960, 40 pp.

- (48) Dexter, J. F. , and Curtindale, E. G. , "The Effects of Gamma Radiation at Elevated Temperatures on Silicone Dielectrics", paper presented at the AIEE Summer General Meeting, Denver, Colorado, June 18-22, 1962, 25 pp, Avail: AIEE, CP-62-1241.
- (49) Kaufman, A. B. , and Gardner, L. B. , "Passive Components in a Hypernuclear Environment", Litton Systems, Incorporated, Woodland Hills, California, ASD-TN-61-99, August, 1961, Technical Note, AF 33(600)-41452, 27 pp, Avail: ASTIA, AD 269239.
- (50) Shelberg, W. E. , and Pestaner, J. F. , "Effect of Cure Upon Crosslinking, Chain Scission, and Compression Set in an Irradiated Rubber Vulcanizate", U. S. Naval Radiological Defense Laboratory, San Francisco, California, USNRDL-TR-547, January 10, 1962, Technical Report, 24 pp.
- (51) Gray, P. D. , O'Donnell, J. D. , Cornelius, G. K. , Brass, R. A. , and Kortenhoeven, J. L. , "Rockets in Space Environment Phase II: Individual Component Investigation", Aerojet-General Corporation, Azusa, California, AGC-2263, April 11, 1962, Phase Report, October 1, 1961 - March 30, 1962, AF 04 (611)-7441, 200 pp, Avail: ASTIA.
- (52) Blackmon, P. H. , Clauss, F. J. , Ledger, G. E. , and Mauri, R. E. , "Materials Evaluation Under High Vacuum and Other Satellite Environmental Conditions", Lockheed Aircraft Corporation, Missiles and Space Division, Sunnyvale, California, January, 1962, Technical Report, AF 04(647)-787, 40 pp, Avail: ASTIA, AD 270279.
- (53) Clauss, F. J. , Mauri, R. E. , Smith, E. C. , and Drake, S. , "Evaluating the Behavior of Materials Under Space Conditions", Lockheed Aircraft Corporation, Missiles and Space Division, Sunnyvale, California.
- (54) Clauss, F. J. , Mauri, R. E. , Smith, E. C. , and Drake, S. , "Evaluating the Behavior of Materials Under Space Conditions", 1961 Proceedings of the Institute of Environmental Sciences, National Meeting, Washington, D. C. , April 5-7, 1961, pp. 475-488.
- (55) Armstrong, E. L. , "Radiation Resistant Electronic Components for SNAPSHOT", prepared for Third Spare Parts Groups Meeting, Sunnyvale, California, November 15-16, 1961, 6 pp, Avail: ASTIA, AD 273908.
- (56) Feltner, C. E. , "On the Mechanical Behavior and Fracture Morphology of Epoxy Resin", University of Illinois, Department of Theoretical and Applied Mechanics, Urbana, Illinois, TAM-224, August, 1962, Nonr-2947(02)(x), 24 pp, Avail: ASTIA, AD 287159.
- (57) "Reinforced Plastics in Space", *Plastics Technology*, 8 (3), March, 1962, pp 23-25.
- (58) Kerlin, E. E. , Smith, E. T. , "Investigation of Combined Effects of Radiation and Vacuum on Engineering Materials", General Dynamics/Fort Worth, Nuclear Aerospace Research Facility, Fort Worth, Texas, FZK-147, June 4, 1962, Quarterly Progress Report No. 2, February 9 - May 8, 1962, NAS8-2450, 123 pp.

- (59) Baicker, J. A. , and Faughnan, B. W. , "Radiation Damage to Silicon Solar Cells", Radio Corporation of America, RCA Laboratories, David Sarnoff Research Center, Princeton, New Jersey, July 31, 1961, Summary Report, July 1, 1960 - July 1, 1961, NAS5-457, Avail: NASA.
- (60) Armstrong, A. A. , Jr. , and Rutherford, H. A. , "Modification of Textile Fiber Properties by Gamma Radiation", North Carolina State College of Agriculture and Engineering, Raleigh, North Carolina, NCSC-2477-6, January 1, 1962, Annual Report, November 1, 1960 - October 31, 1961, AT (40-1)-2477, 100 pp.
- (61) "Polyester Tapes Withstand Radiation", Missiles and Rockets , 11 (11), 23 (September 10, 1962).
- (62) Giberson, R. C. , "Gamma-Radiation Effects on Polycarbonate Resin", Modern Plastics , 39 (8), 146-228 (April, 1962).
- (63) Rogers, J. , and Craig, C. L. , "Degradation of Electrical Insulation from Reactor Irradiation", paper presented at the AIEE Summer General Meeting, Denver, Colorado, June 17-22, 1962, 12 pp, Avail: AIEE, CP-62-1297.
- (64) Bazin, A. P. , "Effect of the Bremsstrahlung Radiation from a 25-Mev Betatron and of 14-Mev Neutrons on the Electrical Conductivity of Polymeric Dielectrics", Soviet Physics-Solid State , 4 (10), 2213-2216 (April, 1963).
- (65) Cowan, J. C. , "After Dry, What? A General Survey", Official Digest , 34 (449), 561-574 (June, 1962).
- (66) Maul, J. E. , Holm, N. W. , and Draganic, I. G. , "The Use of Polyvinyl-Chloride Film for Co⁶⁰ Radiation Dosimetry", Danish Atomic Energy Commission, Research Establishment, Riso, Denmark, Riso-31, December, 1961, 39 pp, Avail: Library, Danish AEC, Riso, Roskilde, Denmark.
- (67) Asada, T. , Kawanishi, M. , and Ishii, K. , "Discoloration of Poly(vinyl Chloride) by γ -Ray Irradiation", Memorial Institute of Scientific and Industrial Research, Osaka University, 18, 111 (1961).
- (68) Evans, D. J. , "A Comparison of the Damage Sustained by Textiles and Other Materials on Exposure to the Heat from a Nuclear Explosion and from an Arc Source", Ministry of Aviation, Explosives Research and Development Establishment, Waltham Abbey, Essex, England, ERDE 13/M/61, May 29, 1961, Technical Memorandum, 5 pp, Avail: ASTIA, AD 267141.
- (69) Marin, J. , and Griesacker, P. B. , "Effect of Radiation on Creep of Polyethylene", Journal of Applied Polymer Science , 7 (1), 133-141 (January, 1963).
- (70) Marin, J. , and Griesacker, P. B. , "Effect of Radiation on Tension, Compression, Bending, and Shear Properties of Polyethylene", Journal of Applied Science , 7 (1), 153-169 (January, 1963).
- (71) Hsiao, C. C. , and Yang, J. W. , "Effect of Initial Straining and γ Irradiation on Strength of Polyethylene", Journal of Applied Physics , 33 (9), 2870-2872 (September, 1962).

- (72) Bixler, H. J. , Michaels, A. S. , and Salame, M. , "Gas Transmission in Irradiated Polyethylene", *Journal of Polymer Science, Part A*, 1 (3), 895-919 (March, 1963).
- (73) Vul, B. M. , "The Effect of Gamma Radiation on the Electrical Conductivity of Insulators", *Soviet Physics-Solid State*, 3 (8), 1644 (February, 1962).
- (74) Yahagi, K. , and Danno, A. , "Gamma-Ray Induced Conductivity in Polyethylene and Teflon Under Radiation at High Dose Rate", *Journal of Applied Physics*, 34 (4), Part 1, 804-809 (April, 1963).
- (75) Komaki, A. , Yano, S. , Yoshida, H. , and Okamura, S. , "Effect of Free Radicals on the Proton Resonance of Irradiated Polymers", *Journal of the Physical Society of Japan*, 17 (3), 581 (March, 1962).
- (76) Jolley, C. E. , and Reed, J. C. , "Teflon Resins in the Space Environment", *Space/Aeronautics*, 39 (2), 105-109 (February, 1963).
- (77) Odian, G. , Bernstein, B. S. , Mann, T. , et al. , "The Use of Radiation-Induced Plastic Memory to Develop New Space Expandable Structures", *Radiation Applications Incorporated, Long Island City, New York, RAI-305*, April 4, 1962, Quarterly Report, January 1 - March 31, 1962, NASr-78, 106 pp.
- (78) Odian, G. , Bernstein, B. S. , Binder, S. , and Connolly, R. , "A Study of the Mechanism of Radiation-Induced Gelatin in Monomer-Polymer Mixtures", *Radiation Applications Incorporated, Long Island City, New York, RAI-304*, March 8, 1962, Quarterly Summary Report, November 1, 1961 - January 31, 1962, AT(30-1)-2816, 21 pp.
- (79) Sieron, J. K. , "New Materials for High Temperature Pneumatic Tires", *USAF, Aeronautical Systems Division, Wright-Patterson AFB, Ohio, ASD-TR-61-615*, November, 1961, 22 pp, Avail: ASTIA, AD 271504.
- (80) Hargreaves, G. , "Molecular Changes in Polyamide and Elastomeric Polymers Due to Nuclear, Ultraviolet and Thermal Radiation", *U. S. Naval Air Material Center, Aeronautical Materials Laboratory, Philadelphia, Pennsylvania*, June 15, 1962, Fifth Progress Report, December 16, 1961 - June 15, 1962, 10 pp.
- (81) O'Toole, J. L. , and von Toerne, T. R. , "Effect of Environment on Design Properties of Nylon", *Machine Design*, 34 (16), 143-148 (July 5, 1962).
- (82) Dole, M. , "Radiation Effects in Ordered Polymers", *Northwestern University, Evanston, Illinois, ARL-62-311*, March, 1962, Final Technical Report, AF 33 (616)-5826, 55 pp, Avail: ASTIA, AD 277185.
- (83) Sauer, J. A. , Merrill, L. J. , and Woodward, A. E. , "Dynamic Mechanical Studies of Irradiated Polypropylene", *Journal of Polymer Science*, 58 (166), Part 1, 19-28 (April, 1962).
- (84) Sakurada, I. , and Kimura, F. , "Effects of γ -Ray Irradiation on Filament of Isotactic Polypropylene", *Bulletin of the Institute of Chemical Research, Kyoto University*, 39, 226-235 (May, 1961).

- (85) Price, H. M. , "Materials - Tank Sealants - Irradiation of Two Fluxes and One Temperature - Effects of", General Dynamics/Fort Worth, Fort Worth, Texas, FTDM-1904, November 2, 1962, AF 33(657)-7248, 35 pp, Avail: ASTIA, AD 288562.
- (86) Price, H. M. , "Material - Effects of Nuclear Radiation on Certain Fuel Tank Sealants and Pressure Sealants", General Dynamics/Fort Worth, Fort Worth, Texas, FTDM-2505, November 2, 1962, AF 33(657)-7248, 28 pp, Avail: ASTIA, AD 288936.
- (87) Tuckerman, A. J. , and Yurk, J. F. , "Development of Self-Sealants and Sealants For Aerospace Vehicles", Hughes Aircraft Company, Culver City, California, December 1, 1962, Second Quarterly Report, August 15 - November 15, 1962, AF 33(657)-9171, 24 pp.
- (88) Heitz, R. M. , Hunter, R. W. , and D'Anna, P. J. , "Research on Elastomeric and Compliant Materials for Aerospace Sealants", Northrop Space Laboratories, Hawthorne, California, ASD-TDR-62-709, NSL-62-35-1, August and October, 1962, Technical Documentary Report, Final Report, May 1, 1961 - April 30, 1962, AF 33(616)-8258, 182 pp.
- (89) Hormann, H. H. , "Improved Organic Coatings for Temperature Control in a Space Environment", USAF, Aeronautical Systems Division, Nonmetallic Materials Laboratory, Wright-Patterson AFB, Ohio, ASD-TDR-62-917, February, 1963, Technical Documentary Report, August 1, 1961- July 31, 1962, 54 pp, Avail: ASTIA.
- (90) Ohr, J. , "Effects of Gamma Radiation on Various Organic Protective Coatings", Paint Industrial Magazine, 76 (9), 11-15 (1961).
- (91) Field, D. E. , Cowling, J. E. , and Noonan, F. M. , "The Properties of Paints as Affected by Ultraviolet Radiation in a Vacuum - Part 2", U. S. Naval Research Laboratory, Chemical Division, Washington, D. C. , NRL-5737, March 8, 1962, Interim Report, 28 pp, Avail: OTS.
- (92) Field, D. E. , Cowling, J. E. , and Noonan, F. M. , "The Ultraviolet Degradation of Organic Coatings - Part 4 - Radiation in a Vacuum", U. S. Naval Research Laboratory, Chemistry Division, Washington, D. C. , WADD-TR-60-703, Part 4, July, 1962, Technical Report, July, 1960 - January, 1961, MIPR 33(616)-61-10, 31 pp, Avail: ASTIA, AD 287109.
- (93) Gaumer, R. E. , and McKellar, L. A. , "Thermal Radiative Control Surfaces for Spacecraft", Lockheed Aircraft Corporation, Missiles and Space Division, Sunnyvale, California, LMSD-704014, March, 1961, Technical Report, January 1 - December 31, 1960, AF 04(647)-563, AF 04(647)-564, AF 04(647)-558, 70 pp, Avail: ASTIA, AD 264127, and AD 288365.
- (94) Whitby, L. , "The Design of Paint Coatings for Spacecraft", Lockheed Aircraft Corporation, Missiles and Space Division, Sunnyvale, California, LMSD-703026, June, 1960, Technical Memorandum, AF 04(647)-347, 50 pp, Avail: ASTIA, AD 266890.

- (95) "Protection of Hydrocarbon Liquids From Radiation Damage", *Materials in Design Engineering*, 55 (5)(May, 1962).
- (96) Klang, M. , and Dragut, A. , "Initiation of Peroxidation of Kerosene by Ionizing Radiation", *Intern. Chemical Engineering*, 2 (1), 68-73 (January, 1962).
- (97) Matos, S. R. , and Johnson E. J. , "Performance of Irradiated and Chemically Treated JP-5 Fuel with Inhibited Red Fuming Nitric Acid", Picatinny Arsenal, Dover, New Jersey, PA-TR-1-61, NP-11219, DL-TR-1-61, 1961, Avail: ASTIA, AD 268931.
- (98) "Investigation of Techniques for 1000 F Hydraulic Systems. Part II. Nuclear Environment", Republic Aircraft Corporation, Farmingdale, Long Island, New York, ASD-TDR-62-674, Part II, March 1, 1963, Technical Documentary Report, February, 1961 - November, 1962, AF 33(616)-7454, 56 pp.
- (99) Kerlin, E. E. , "Investigation of Combined Effects of Radiation and Vacuum and of Radiation and Cryo-Temperatures on Engineering Materials. Vol 1. Radiation-Vacuum Tests", General Dynamics/Fort Worth, Nuclear Aerospace Research Facility, Fort Worth, Texas, FZK-161-1, January 5, 1963, Annual Report, November 9, 1961 - November 8, 1962, NAS8-2450, 340 pp.
- (100) Kerlin, E. E. , and Smith, E. T. , "Measured Effects of the Various Combinations of Nuclear Radiation, Vacuum, and Cryotemperatures on Engineering Materials", General Dynamics/Fort Worth, Nuclear Aerospace Research Facility, Fort Worth, Texas, FZK-163, March 15, 1963, Quarterly Progress Report, November 9, 1962 - February 28, 1963, NAS8-2450, 104 pp.
- (101) Gordon, B. E. , and Weir, F. E. , "Radiation-Resistant Lubricant Composition", Shell Oil Company, U. S. Patent 3,041,282, June 26, 1962.
- (102) Ingram, R. D. , "Reactor Irradiation of a Magnetic Flux Valve", paper presented at the AIEE Summer General Meeting, Denver, Colorado, June 17-22, 1962, 17 pp, Avail: AIEE as CP-62-1259.
- (103) Bolt, R. O. , "Method of Opposing Irradiation-Induced Viscosity Increase in Employment of Organic Fluids", USAEC, U. S. Patent 3,005,760, October 24, 1961.
- (104) Bowen, P. H. , "Analytical and Experimental Study of Adapting Bearings for use in an Ultra-High Vacuum Environment", Westinghouse Electric Corp. , East Pittsburgh, Pennsylvania, AEDC-TDR-62-51, February, 1962, Technical Documentary Report, Phases I, II, and III, AF 30(600)-915, 70 pp. Avail: ASTIA, AD 272555.
- (105) Bowen, P. H. , "Dry Lubricated Bearings for Operation in a Vacuum", *ASLE Transactions*, 5 (2), 315-326 (November, 1962), presented at the Annual Meeting of the American Society of Lubrication Engineers.
- (106) Brown, R. D. , Burton, R. A. , and Ku, P. M. , "Research on High-Temperature Bearings", Southwest Research Institute, San Antonio, Texas, ASD-TR-61-705, August, 1962, Technical Report, March 10, 1960 - March, 1962, AF 33(616)-7209, 71 pp.

- (107) Flatley, T. W., and Evans, H. E., "The Development of the Electric Field Meter for the Explorer VIII Satellite (1960 ξ), NASA-Goddard Space Flight Center, Greenbelt, Maryland, NASA-TN-D-1044, April, 1962, 35 pp.
- (108) Kaufman, A. B., Newhoff, H. R., and Gaz, R. A., "LPR-10 Drum Performance in a Nuclear Environment", Litton Systems, Inc., Guidance and Control Systems Division, Woodland Hills, California, 27 pp.
- (109) Seitz, F., "Effects of Irradiation on Metals", *Science* 138 (3540), 563-571 (November 2, 1962).
- (110) Blewett, T. H., Coltman, R. R., Klabunde, C. E., and Noggle, T. S., "Low-Temperature Reactor Irradiation Effects in Metals", 28 (6), 639-644 (June, 1957).
- (111) Brinkman, J. A., "On the Nature of Radiation Damage in Metals", *Journal of Applied Physics*, 25 (8), 961-970 (August, 1954).
- (112) Silsbee, R. H., "Focusing in Collision Problems in Solids", *Journal of Applied Physics*, 28 (11), 1246-1250 (November, 1957).
- (113) Simons, R. O., Koehler, J. S., and Balluffi, R. W., "Present Knowledge of Point Defects in Irradiated Face Centered Cubic Metals", presented at the IAEA Symposium on Irradiation Damage in Solids and Reactor Materials, Venice, Italy, May 7-11, 1962, University of Illinois Technical Report No. 21, February, 1962.
- (114) Corbett, J. W., Smith, R. B., and Walker, R. M., "Recovery of Electron-Irradiated Copper. I. Close Pair Recovery", *Physical Review*, 114 (6), 1452-1459 (June 15, 1959).
- (115) Sosin, A., "Mechanisms of Atomic Displacement Induced by Irradiation", presented at the Fourth Pacific Area National Meeting of the ASTM, Los Angeles, California, October 1-5, 1962.
- (116) Wechsler, M. S., and Berggren, R. G., "Irradiation Embrittlement of Reactor Pressure Vessels", article prepared for publication in *Nuclear Safety*, June, 1962.
- (117) Muss, D. R., and Townsend, J. R., "Internal Friction in Young's Modulus in Irradiated Tungsten", *Journal of Applied Physics*, 33 (5), 1804-1807 (May, 1962).
- (118) Westmacott, K. H., Roberts, A. C., and Barnes, R. S., "The Growth of Dislocation Loops During the Irradiation of Aluminum", AERE Metallurgy Division, AERE-R-4096, July, 1962.
- (119) Steele, L. E., and Hawthorne, J. R., "Surveillance of Critical Reactor Components to Assess Radiation Damage", NRL Report 5830, September 7, 1962.
- (120) Landerman, E., "Surveillance Test on Structural Materials in Nuclear Reactors", presented at the Fourth Pacific Area National Meeting of the ASTM, Los Angeles, California, October 1-5, 1962.
- (121) Murr, W. E., Shober, F. R., Liebermann, R., and Dickerson, R. F., "Effects of Large Neutron Doses of Elevated Temperature on Type 347 Stainless Steel", BMI-1609, January 21, 1963.

- (122) Lowe, A. L., Jr., "Effects of Irradiation on Two Alloy Steels at Elevated Temperatures", presented at the Fourth Pacific Area National Meeting of the ASTM, Los Angeles, California, October 1-5, 1962.
- (123) Berggren, R. G., and Wilson, J. C., "Recent Data on the Effects on Neutron Irradiation on Structural Metals and Alloys", ORNL-CF-56-11-1, January 30, 1957, Contract W-7405-eng-26, paper presented at the 6th Annual Meeting of the AEC Welding Committee at Oak Ridge, Tennessee, September 25-26, 1956.
- (124) Trudeau, L. P., "Effect of Neutron Irradiation on Mechanical Properties of Ferritic Steels and Irons", Second United Nations International Conference on the Peaceful Uses of Atomic Energy, 1958.
- (125) Wilson, J. C., and Berggren, R. G., "Effects of Neutron Irradiation in Steels", Proceedings of the American Society for Testing Materials, 55, 689 (1955).
- (126) Nichols, R. W., and Harries, Z. R., "Brittle Fracture and Irradiation Effects of Ferritic Vessel Steel", presented at the Fourth Pacific Area National Meeting of the ASTM, Los Angeles, California, October 1-5, 1962.
- (127) Cibois, Lemaire, and Weisz, "Contribution to the Study of Irradiation Embrittlement and Hardening of Steel and Zircaloy-2 for Pressurized Components", presented at the Fourth Pacific Area National Meeting of the ASTM, Los Angeles, California, October 1-5, 1962.
- (128) Shober, F. R., and Murr, W. E., "Radiation-Induced Property Changes in AISI Type 347 Stainless Steel", presented at the Fourth Pacific Area National Meeting of the ASTM, Los Angeles, California, October 1-5, 1962.
- (129) Murr, W. E., and Shober, F. R., "Annealing Studies on Irradiated Type 347 Stainless Steel", Battelle Memorial Institute, Columbus, Ohio, BMI-1621, March 6, 1963, W-7405-eng-92.
- (130) Hinkle, N. E., "Effects of Neutron Bombardment on the Stress Rupture Properties of Structural Alloys", presented at the Fourth Pacific Area National Meeting of the ASTM, Los Angeles, California, October 1-5, 1962.
- (131) Cupp, C. R., "The Effects of Neutron Irradiation on Precipitation-Hardening Alloys", presented at the Fourth Pacific Area National Meeting of the ASTM, Los Angeles, California, October 1-5, 1962.
- (132) "Gas Cooled Reactor Program", Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL-3372, February 1, 1963, Semi-Annual Progress Report for the period ending September 30, 1962, W-7405-eng-26, 49 pp.
- (133) "An Investigation of the Electrical and Optical Properties of Semi-Conductors and Insulators Which Have Been Irradiated by Fast Neutrons", Arizona State University, Tempe, Arizona, TID-17912 Final Report, Contract AT(11-1)-715, January, 1963.
- (134) Elston, J., "Behavior of Neutron-Irradiation Sintered Beryllium Oxide", AEC TR-5140, 1962.

- (135) Frisco, L. J. , "Dielectrics for Satellites and Space Vehicles", John Hopkins University, Dielectrics Laboratory, Baltimore, Maryland, Report No. 3, Final Report, March 1, 1959, to February 28, 1962, DA-36-039-SC-78321, Avail: ASTIA.
- (136) "Second Progress Report for the DOR Design Studies", Danish Atomic Energy Commission, RISO Report No. 49, September, 1962, p 55.
- (137) Moore, H. R. , Bernstein, H. , and Reynolds, R. S. , "A Source and Detector of Radiation in the Wave Length Region 1500-50 Angstroms Suitable for Radiation Effects Studies on Materials in Vacuum. Part II- A Study of Vacuum Ultraviolet Radiation Effects on Materials in Vacuum of Order 10^{-9} mm Hg", Electro-Optical Systems Inc. , Pasadena, California, WADD-TR-60-371 Part II, December, 1962.
- (138) "Telstar in Orbit Supplies Valuable Data", Engineering, 194 (5026), 221 (August 17, 1962).
- (139) Gabrysh, A. F. , Eyring, H. , LeFebre, V. , Evans, M. D. , University of Utah, Salt Lake City, Utah, "Thermoluminescence and the Influence of γ -Ray Induced Defects in Single-Crystal α - Al_2O_3 ", Journal of Applied Physics, 33 (12), 3389-3391 (December, 1962).
- (140) "High Temperature Materials and Reactor Component Development Programs, Vol. I, Materials", General Electric Company, Nuclear Materials and Propulsion Operation, Cincinnati, Ohio, GEMP-177A, February 28, 1963, Second Annual Report, AT(40-1)-2847.
- (141) "High-Temperature Materials Program", General Electric Company, Nuclear Materials and Propulsion Operation, Cincinnati, Ohio, GEMP-18A, December 14, 1962, Progress Report No. 18, Part A, September 15 - November 15, 1962, AT(40-1)-2947, 37 pp, Avail: OTS.
- (142) "Reactor Chemistry Division Annual Progress Report", Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL-3262, May 11, 1962, W-7405-eng-26, p 153.
- (143) "Gas-Cooled Reactor Program", Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL-3372, February 1, 1963, Semiannual Progress Report for the period ending September 30, 1962, W-7405-eng-26, p 269.
- (144) "Reactor Chemistry Division Annual Progress Report", Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL-3262, May 11, 1962, for the period ending January 31, 1962, p 156.
- (145) "Metals and Ceramics Division Annual Progress Report", Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL-3313, August 16, 1962, W-7405-eng-26, p 67.
- (146) Tobin, J. M. , "Some Effects of Neutron Irradiation on Selected Beryllia Materials", General Dynamics Corporation, General Atomic Division, San Diego, California, GA-2648, April 30, 1962.
- (147) "AEC Unclassified Programs Quarterly Technical Progress Report", NAA-SR-7333, January - March, 1962.

- (148) Hickman, B. S. , "X-Ray Diffraction Studies of Irradiated Beryllium Oxide", Journal of Nuclear Materials, 6, 190-198 (July, 1962).
- (149) Clark, F. J. P. , "A Model for the Strength of Irradiated Beryllium Oxide", Atomic Energy Research Establishment, Harwell, England, AERE-R-4275, February, 1963.
- (150) Aboaf, J. A. , Hensler, J. R. , Kreidl, N. J. , and Lell, E. , "Irradiation Damage to Glass", Bausch and Lomb, Incorporated, Rochester, New York, TID-17227, October, 1962, AT(30-1)-1312.
- (151) Sugiura, T. , Murakami, K. , Tanaka, H. , "The Influence of γ -Irradiation on the Electric Conductivity of Glasses", Yogyo Kyokai Shi, 70, 28-31 (January, 1962).
- (152) Vargin, V. V. , and Stepanov, S. A. , "The Effect of Gamma Irradiation on Na_2O and Al_2O_3 - SiO_2 Glasses", Dokl. Akad. Nauk. , SSSR, 147 (3), 609-611, 1962, available in translated form as AEC-TR-5616.
- (153) Byurganovskaya, G. V. , and Orlov, N. F. , "Formation of Color Centers in Sodium Silicate and Quartz Glasses Under the Action of Gamma Radiation", Optics and Spectroscopy, 12 (2), 151-154 (February, 1962), translated from Optika i Spektroskopiya.
- (154) Bishay, A. , "A Review of Some Gamma Radiation Effects on Glass", Argonne National Laboratories, Argonne, Illinois, TID-17776, November, 1962, paper presented at the First Arab Chemistry Conference, Cairo, Egypt, November, 1962.
- (155) Lee, S. , and Bray, P. J. , "Electron-Spin Paramagnetic Resonance Studies of Irradiated Alumino-Silicate Glasses", Physics and Chemistry of Glasses, 3 (2), 37-42 (April, 1962).
- (156) Barker, R. S. , and Richardson, D. A. , Pilkington Brothers Limited, Lancashire, England, "Effects of Gamma Irradiation on the Optical Absorption of Lead Silicate Glass", 1962 Conference on Radiation Effect on Glass, Rochester, New York, Summary Paper No. 15, p 2.
- (157) Barker, R. S. , "Irradiation on Glass Yarns", Pilkington Brothers Limited, Lancashire, England, IT-95, December, 1961, 9 pp.
- (158) Hardtke, F. C. , "Thermoelectricity in Irradiated Glass", Physical Review Letters, 9 (8), 339-341 (October 15, 1962).
- (159) Baak, J. , et al. , "Irradiation of Glass Films With a 100 KV Electron Beam", Physics and Chemistry of Glasses, 3 (2), 46-49 (April, 1962).
- (160) Primak, W. , and Edwards E. , "Radiation-Induced Dilatations in Vitreous Silica", Physical Review, 128 (6), 2580-2588 (December 15, 1962).
- (161) Truell, R. , "Investigation of Irradiation Effects in Solids", Brown University, Providence, Rhode Island, January 28, 1963, Annual Report, 1962, AT(30-1)-1772.

- (162) Weissmann, S., Imura, T. R., Nakajiman, K., and Wisnewski, S., "Lattice Defects of Quartz Induced by Fast Neutron Irradiation", Rutgers-The State University, New Brunswick, New Jersey, NYO-10444, September, 1962, AT(30-1)-2937.
- (163) Yamamoto, K., and Tsuchya, M., "Electric Characteristics of Gamma-Ray Irradiated Shielding Window Glass," Journal of Applied Physics, 33 (10) (October, 1962).
- (164) Comstock, M., and Ferrigno, P., "Effects of Radiation on Glass", Brookhaven National Laboratory, Upton, New York, BNL-6513, October 24, 1962, AT (30-2)-Gen-16.
- (165) Yoshikawa, H. H., "Radiation Behavior of Graphite Materials", General Electric Company, Hanford Atomic Products, Richland, Washington, HW-SA-2814, October 25, 1962.
- (166) Montet, G. L., "Low Temperature Galvanomagnetic Properties of Graphites", Argonne National Laboratory, Argonne, Illinois, TID-16243, UAC-6477, May, 1962, W-31-109-eng-38.
- (167) Myers, I. T., "Radiation Damage in Graphite by High-Energy Electrons", General Electric Company, Hanford Atomic Products, Richland, Washington, HW-75428, October 29, 1962, AT (45-1)-1350.
- (168) Reynolds, W. N., and Thrower, P. A., "Irradiation Damage in Graphite", International Atomic Energy Agency, Symposium on Radiation Damage in Solids and Reactor Materials, Venice, Italy, IAEA-SM-25/56, May 7-11, 1962.
- (169) Gain, R., "Comparison of Irradiation Damage in Artificial and Natural Graphite at Different Irradiation Temperatures", IAEA Preprint SM-25/3.
- (170) Thrower, P. A., et al., "Microstructural Changes in Neutron-Irradiated Graphite", Atomic Energy Research Establishment, Metallurgy Division, Harwell, England, AERE-R-4007, March, 1962.
- (171) Kelly, B. T., Jones, D., and James, A., "Irradiation Damage to Pile Grade Graphite at 450 C", Journal of Nuclear Materials, 7 (3), 279-291 (December, 1962).
- (172) Rappeneau, J., "Energy Emission from Irradiated Graphite - Effects of the Radiation Temperature", Journal of Nuclear Materials, 6 (1), 107-118 (1962).
- (173) Bridge, H., Gray, B. S., Kelly, B. T., and Sorensen, H., "An Effect of Flux Level and Flux Spectrum on the Accumulation of Damage in Reactor Irradiated Graphite", International Atomic Energy Agency, Symposium on Radiation Damage in Solids and Reactor Materials, Venice, Italy, IAEA-SM-25/50, May 7-11, 1962.
- (174) Sato, S. "Ultrasonic Pulse Method", IAEA Preprint SM-25/17.

- (175) Nightingale, R. E. , "Radiation Effects in Graphite", General Electric Company, Hanford Atomic Products, Richland, Washington, May 11, 1962, AT(45-1)-1350.
- (176) Engle, G. B. , "High-Energy Neutron Induced Changes in Carbon and Graphite", General Dynamics Corporation, General Atomic Division, San Diego, California, GA-2802, September 20, 1962.
- (177) Schweitzer, D. G. , "Fundamental Studies of Radiation Damage in Graphite", Brookhaven National Laboratory, Upton, New York, BNL-745, April 17, 1962.
- (178) Leveque, P. , "Reactor Radiation Effects on Graphite", Preprint S5-09.
- (179) Iwata, T. , and Suzuki, H. , "A New Model of Radiation Damage to Graphite", IAEA Preprint SM-25-19.
- (180) Denning, R. M. , "Quantitative Hardness of Irradiated and Non-Irradiated Diamonds", University of Michigan, Ann Arbor, Michigan, TID-17406, November 19, 1962, AT(11-1)-760.
- (181) Keating, D. T. , "Initial Phases of Damage in Neutron-Irradiated Diamond", Bulletin of the American Physical Society, 8 (3), 252 (1963).
- (182) Harris, E. A. , "Damage Centers in Irradiated Diamond", Bulletin of the American Physical Society, 8 (3), 252 (1963).
- (183) Frank, L. A. , Van Allen, J. A. , Whelpley, W. A. , and Craven, J. D. , "Absolute Intensities of Geomagnetically Trapped Particles With Explorer 14", Journal of Geophysical Research, 68, 1573-1579 (1963).
- (184) Hess, W. N. , Editor, "Collected Papers on the Artificial Radiation Belt from the July 9, 1962, Nuclear Detonation", Journal of Geophysical Research, 68, 605-758 (1963).
- (185) Foelsche, T. , "Current Estimates of Radiation Doses in Space", National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia, NASA-TN-D-1267, July, 1962.
- (186) Smith, R. J. , and Benck, R. F. , "Fission Neutron Effects on a Variety of Gamma Dosimeters", Nuclear Defense Laboratory, Army Chemical Center, Maryland, NDL-TR-37, August, 1962, Technical Report, January - June, 1962, 8 pp, Avail: ASTIA.
- (187) Saelens, R. G. , "Tiny Gamma Detector for High-Intensity Radiation", Nuclearonics, 20 (9), 60, 62, 64 (September, 1962).
- (188) Doyle, J. E. , Dickenson, W. C. , "The Cerenkov Response of Lucite and Quartz to Gamma and Fast Neutron Radiation, University of California, Lawrence Radiation Laboratory, Livermore, California, UCRL-7032, July 5, 1962, W-7405-eng-48, 26 pp, Avail: OTS.
- (189) Johnson, W. T. K. , "Extended Application of a Cobalt Glass Dosimeter", Diamond Ordnance Fuze Laboratories, Washington, D. C. , DOFL-TR-1050, June 5, 1962, 25 pp, Avail: ASTIA.

- (190) Draganic, I. , "Oxalic Acid: The Only Aqueous Dosimeter for In-Pile Use", *Nucleonics*, 21 (2), 33-35 (February, 1963).
- (191) Shiokawa, T. , "A New Chemical Dosimetry for Measuring Higher Level Gamma Rays Using A Titanium Sulphate Solution", *Nature*, 195 (4841), 592-593 (August 11, 1962).
- (192) "Cesium-Nitrate Chemical Dosimeter", *Nucleonics*, 21 (4) (April, 1963).
- (193) Bradshaw, W. W. , and Cadena, D. G. , "The Use of Alanine as a Solid Dosimeter", *Radiation Research*, 17 (1), 11-20 (July, 1962).
- (194) "Three Uses for Glass Scintillators", *Nucleonics*, 20 (9) (September, 1962).
- (195) Thomas, G. E. , and Bollinger, L. M. , "Two Recent Advances in Slow-Neutron Detectors", *Bulletin of the American Physical Society*, Ser. 2, 7 (6), 411 (June 19, 1962).
- (196) "Organic Phosphors Identify Particles", *Nucleonics*, 20 (5), 64 (May, 1962).
- (197) Hall, J. D. , and Ashe, J. B. , "Neutron-Gamma Ray Spectrometer", United States Air Force, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, ASD-TDR-62-52, April, 1962, January 1 - December 15, 1961, 25 pp, Avail: ASTIA, OTS.
- (198) Brown, P. E. , "In-Core Neutron Sensors for Nuclear Rocket Reactors", Radio Corporation of America, Camden, New Jersey, NP-11862, 1962, 3 pp.
- (199) Patalon, W. , "PWAR-11C Intermediate and Power Range Neutron Flux Sensors", Pratt and Whitney Aircraft (Canel), PWAC-675, June 27, 1961, Technical Information Memo, AT(11-1)-229, 9 pp.
- (200) Patalon W. , "PWAR-11C Startup Range Neutron Flux Sensor", Pratt and Whitney Aircraft (Canel), PWAC-674, June 22, 1961, Technical Information Memo, AT(11-1)-229, 7 pp.
- (201) "New Product of the Week: Ionization Chamber", *Missiles and Rockets*, 12 (2), 47 (January 14, 1963).
- (202) Judd, A. M. , "Neutron Flux Measurement by Resonance Actuation of Foils", TRG-Report-399(D).
- (203) Ehret, G. , "The Determination of Epithermal Neutron Spectra by Means of Resonance Probes (Sandwich Method)", AERE-Trans-906.
- (204) Golubev, V. I. , et al. , "The Use of Resonance Detectors for the Investigation of Neutron Spectra in Fast-Neutron Reactors", *Atomnaya Energiya*, 11 (6), 522-527 (December, 1961).
- (205) Hsiang-Lin Pai, et al. , "Measurement of Epithermal Neutron Spectra by Resonance Detectors", *Nuclear Science and Engineering*, 9 (4) (April, 1961).

- (206) Lanning and Brown, "Calculated and Measured Neutron Energy Spectral Distributions Using the Threshold Detector Technique", WAPD-T-1380, September, 1961.
- (207) "More Accurate Way to Measure Neutron Environment", Nucleonics, 20 (7), 58 (July, 1962).
- (208) Newell, W. , et al. , "Radiation Damage Effects in Semiconductor Nuclear Particle Detectors", Solid State Radiations Inc. , Los Angeles, California, August, 1960, Final Report, DA-49-186-ORD-1013, 52 pp.
- (209) Jones, A. R. , "Measurements of Gamma Radiation Damage to p-n Junction Gamma Ray Detectors", Atomic Energy of Canada, Limited, Chalk River, Ontario, Canada, CRRD-1102, September, 1962, 7 pp.
- (210) Ajdaucic, V. S. , et al. , "Measuring In-Core Neutron Fluxes With Semiconductors", Nucleonics, 21 (1), 60-62 (January, 1963).
- (211) Weiss, W. L. , and Whatley, E. M. , "Effects of Long Term Vacuum on Commercial Silicon Radiation Detectors", Oak Ridge Technical Enterprises Corporation, Oak Ridge, Tennessee, ARL-62-416, August, 1962, Final Technical Documentary Report, October 1, 1961 - May 24, 1962, AF 33(616)-8397, 137 pp, Avail: ASTIA, OTS.
- (212) Hallam, J. W. , and Williams, R. L. , "Solid State Charged Particle Silicon Detectors", Radio Corporation of America, Victor Research Laboratories, Montreal, Canada, ARL-62-406, August, 1962, Final Technical Report, June 1, 1961 - May 31, 1962, AF 33(616)-8373, 15 pp, Avail: ASTIA as AD 289009, OTS.
- (213) Alvager, T. , and Hansen, N. J. , "Doping of Crystals by Ion Bombardment to Produce Solid State Detectors", The Review of Scientific Instruments, 33 (5), 567 (May, 1962).
- (214) Zimmerman, E. L. , "The Application of Semiconductor Radiation Detectors to the Observation of Fast Neutrons", Solid State Radiations Inc. , Los Angeles, California, ASD-TDR-62-838, December, 1962, April, 1961 - August, 1962, AF 33(616)-8340, 52 pp, Avail: ASTIA, OTS.
- (215) Clayton, C. G. , and Whittaker, J. B. , "Bulk Photoconductivity Detectors Suitable for Gamma Radiation", Nucleonics, 21 (4), 60-64 (April, 1962).
- (216) Frost, K. J. , Rothe, E. D. , "A Detector for Low Energy Gamma-Ray Astronomy Experiments", National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland, NASA-TN-D-1693, March, 1963, 7 pp, Avail: OTS, NASA.
- (217) "High-Energy Gamma-Ray Telescope", Nucleonics, 20 (10), 69 (October, 1962).
- (218) Cline, T. L. , and Serlemitsos, P. , "A Double Gamma-Ray Spectrometer to Search for Positrons in Space", National Aeronautics and Space Administration, Washington, D. C. , NASA-TN-D-1464, October, 1962, 10 pp, Avail: NASA.

- (219) Baily, N. A. , and Hoalst, K. M. , "Dosimetry of Space Radiations", *Nucleonics*, 21 (4), 70, 72-73 (April, 1963).
- (220) Collins, A. H. , "SSR Detectors are Small, Sensitive", *Missiles and Rockets*, 10 (8), 26-27 (February 19, 1962).

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APPENDIX A

OPERATION OF THE RADIATION EFFECTS INFORMATION
CENTER DURING 1962-1963

APPENDIX A

OPERATION OF THE RADIATION EFFECTS INFORMATION
CENTER DURING 1962-1963

The operation of the REIC during the 11-month period from July, 1962, through May, 1963, is summarized by listing (1) visitors, (2) travel, (3) technical inquiries, (4) publications, (5) dissemination of information, and (6) operation of the Technical-Data File. In addition to this summary, future plans for the period July 1, 1963, through June 30, 1964, are briefly outlined.

Visitors

The following breakdown shows the number of visitors for the contract years 1962-1963 and 1961-1962.

	<u>1962-1963</u>	<u>1961-1962</u>
Total Visitors	44	60
Industrial	33	51
Air Force	2	6
Army	--	2
Navy	--	--
AEC	7	1
Other Government Agencies	2	--

Travel

During the 1962-1963 contract year, personnel from REIC made 21 visits to 23 different organizations to keep abreast of current developments in radiation effects.

Technical Inquiries

The number of requests for information received by REIC during the contract years 1962-1963 and 1961-1962 are listed below.

	<u>1962-1963</u>	<u>1961-1962</u>
Technical Requests	243	165
Nontechnical Requests	585	930
	828	1095

Publications

In addition to monthly unclassified accession lists and regular classified accession lists, the REIC has published the reports and memoranda listed in Appendix B.

Dissemination of Information

The REIC has continued to disseminate reports, memoranda, and accession lists on both a classified and an unclassified basis. As of May 31, 1963, the unclassified distribution required 663 copies and the classified distribution required 69 copies.

Following is a breakdown of the distribution lists as of May 31, 1963.

<u>Organization</u>	<u>Unclassified List</u>		<u>Classified List</u>	
	<u>Addresses</u>	<u>Copies</u>	<u>Addresses</u>	<u>Copies</u>
Air Force	26	29	11	13
Army	21	23	13	20
Navy	17	19	7	10
Other Government Agencies	31	50	5	8
Industrial (Includes AEC)	482	542	12	18
Total	577	663	48	69

Operation of the Technical-Data File

The following breakdown describes the status of the REIC Technical-Data File as of May 31, 1963, after 6 years of operation. Figures for the previous year's operation are included for comparison.

	<u>Total as of June 30, 1962</u>	<u>Total as of May 31, 1963</u>
Documents Accessioned	2853	1714
Documents Extracted	8924	9951
Rejected Items	3249	3403

The rejected items may be categorized as follows:

	<u>Total as of June 30, 1962</u>	<u>Total as of May 31, 1963</u>
No Pertinent Information	1987	2018
No New Information	677	779
Duplicates	155	158
No Radiation Effects		18
Total Items Rejected	2819	2973

Future Plans

The following reports and memoranda are either planned or are being considered for publication during the coming year:

- (1) An addendum to REIC Report No. 10, "The Effect of Nuclear Radiation on Semiconductor Devices"
- (2) An addendum to REIC Report No. 18, "The Effect of Nuclear Radiation on Electronic Components"
- (3) An addendum to REIC Report No. 20, "The Effect of Nuclear Radiation on Structural Metals"
- (4) An addendum to REIC Report No. 21, "The Effect of Nuclear Radiation on Elastomeric and Plastic Components and Materials"
- (5) The annual "Radiation-Effects State of the Art Report"
- (6) The biannual listings of nuclear-radiation-effects projects
- (7) A state of the art report on the effects of radiation on propellants and explosives
- (8) A report on radiation-effects testing techniques and data reporting
- (9) A report dealing with the correlation between reactor and space radiation effects
- (10) A report covering radiation effects that improve, rather than damage, devices and materials
- (11) Addendum to REIC Report No. 26, "Transient Radiation Effects on Electronic Components and Semiconductor Devices".

APPENDIX B

LIST OF AVAILABLE REIC PUBLICATIONS

LIST OF AVAILABLE REIC PUBLICATIONS

Radiation Effects Information Center
Battelle Memorial Institute
Columbus 1, Ohio

Requests for unclassified information or unclassified REIC published reports and memoranda should be sent:

Radiation Effects Information Center
Battelle Memorial Institute
505 King Avenue
Columbus 1, Ohio
Attention E. N. Wyler

Requests for classified REIC published reports and memoranda should be sent, via your contracting officer for endorsement, to the following address:

ASD (ASRCE-3, Mr. Robert G. Merkle)
Wright-Patterson AFB, Ohio

<u>Report Number</u>	<u>Unclassified Reports</u> <u>Title</u>
1	The Effect of Nuclear Radiation on Semiconductor Materials (December 20, 1957), AD 147399
1 (First Addendum)	The Effect of Nuclear Radiation on Semiconductor Materials (March 31, 1959), AD 210758
*6	A Survey of Current Research and Developments in the Field of Dosimetry (May 31, 1958), AD 157172
6 (First Addendum)	A Survey of Current Research and Developments in the Field of Dosimetry (March 31, 1959), AD 210766
10	The Effect of Nuclear Radiation on Semiconductor Devices (April 30, 1960), AD 240433 (Supersedes Memos Nos. 4, 5, 6)
10 (First Addendum)	The Effect of Nuclear Radiation on Semiconductor Devices (July 15, 1961), AD 262081
16	Survey of Irradiation Facilities (February 28, 1961), AD 256953
17	The Effect of Nuclear Radiation on Structural Adhesives (March 1, 1961), AD 256954 (Supersedes Reports Nos. 7 and 11)
18	The Effect of Nuclear Radiation on Electronic Components (June 1, 1961), AD 260303 (Supersedes Reports Nos. 2, 8, 12, 14, and 15 and Memos Nos. 2, 7, 12, 14, and 20)
19	The Effect of Nuclear Radiation on Lubricants and Hydraulic Fluids (May 31, 1961), AD 261278 (Supersedes Report No. 4)
20	The Effect of Nuclear Radiation on Structural Metals (September 15, 1961), AD 265839 (Supersedes Report No. 5)
21	The Effect of Nuclear Radiation on Elastomeric and Plastic Components and Materials (September 1, 1961) AD 267890 (Supersedes Reports Nos. 3, 9, and 13 and Memos Nos. 1, 3, 8, 13, and 17)
23	Proton and Electron Damage to Solar Cells (April 1, 1962)
24	Radiation Effects State of the Art 1961-1962 (June 30, 1962), NASA N62-16454
25	The Effect of Nuclear Radiation on Transducers (April 19, 1963)
26	Transient Radiation Effects on Electronic Components and Semiconductor Devices (April 19, 1963)

*Out of Print in REIC; Available only from ASTIA, Armed Services Technical Information Agency, Document Service Center, Arlington Hall Station, Arlington, Virginia.

Classified Reports

<u>Report Number</u>	<u>Title</u>
1-C	The Effect of Nuclear Radiation on Hydraulic, Pneumatic, and Mechanical Systems for Subsonic, Transonic, and Low-Supersonic Speed Aircraft (Title Unclassified) (Secret, Restricted Data) (May 31, 1958)
1-C (First Addendum)	The Effect of Nuclear Radiation on Hydraulic, Pneumatic, and Mechanical Systems for Subsonic, Transonic, and Low-Supersonic Speed Aircraft (Title Unclassified) (Secret, Restricted Data) (March 31, 1959)
1-C (Second Addendum)	The Effect of Nuclear Radiation on Hydraulic, Pneumatic, and Mechanical Systems (Title Unclassified) (Secret, Restricted Data) (September 15, 1960)
2-C	The Effect of Nuclear Radiation on Ceramic Materials (Title Unclassified) (Secret) (June 30, 1959). AD 157173
2-C (First Addendum)	The Effect of Nuclear Radiation on Ceramic Materials (Title Unclassified) (Secret, Restricted Data) (June 15, 1961)
4-C	The Effect of Nuclear Radiation on Electrical and Electronic Systems (Title Unclassified) (Secret, Restricted Data) (March 15, 1960)
6-C	The Effects of Nuclear Weapon Bursts and Simulated Bursts on Electronic Components (Title Unclassified) (Secret, Restricted Data) (May 31, 1961)

Unclassified Memoranda

<u>Memorandum Number</u>	<u>Title</u>
*9	The Effect of Nuclear Radiation on Glass (November 30, 1958), AD 207701
10	Format for Reporting Radiation Effects Data (May 15, 1959), AD 218251
*11	The Effect of Nuclear Radiation on Hydrocarbon Fuels (November 30, 1958), AD 207702
*15	The Effect of Nuclear Radiation on Hoses and Couplings (March 31, 1959), AD 225504
*16	The Effect of Nuclear Radiation on Refrigerants (June 30, 1959), AD 219510
*18	The Effect of Nuclear Radiation on the Performance of a Hydraulic Flight Control System (June 15, 1959), AD 219512
21	Space Radiation and Its Effects on Materials (June 30, 1961)
23	Radiation Dosimetry: An Annotated Bibliography (September 15, 1961), AD 265523

Classified Memoranda

<u>Memorandum Number</u>	<u>Title</u>
1-C	The Effects of Nuclear Radiation on Fluorolubes and Other Gyroscope Fluids (Title Unclassified) (Secret) (September 5, 1958), AD 302126

*Out of Print in REIC; Available only from ASTIA, Armed Services Technical Information Agency, Document Service Center, Arlington Hall Station, Arlington, Virginia.

B-3 and B-4

<u>Memorandum Number</u>	<u>Title</u>
2-C	The Effect of Nuclear Radiation on Explosives and Solid Propellants (Title Unclassified) (Secret, Restricted Data) (June 15, 1959)
3-C	Dose-Rate Effects on Materials, Components, and Systems (Title Unclassified) (Secret, Restricted Data) (July 31, 1959)
10-C	Nuclear Radiation Effects Projects (Title Unclassified) (Confidential) (March 31, 1962)
11-C	Compilation of Nuclear, Pulsed, and Space Radiation Effects Projects (April 15, 1963).

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