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RADIATION-EFFECTS STATE OF THE ART - 1965-1966

Donald J. Hamman, et al

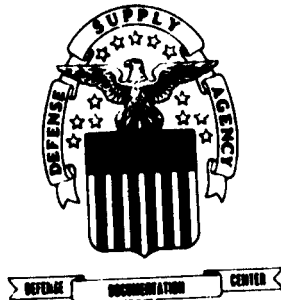
Battelle Memorial Institute
Columbus, Ohio

30 June 1966

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REIC Report No. 42
June 30, 1966

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**RADIATION-EFFECTS STATE OF THE ART
1965-1966**

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RADIATION EFFECTS INFORMATION CENTER
Battelle Memorial Institute
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Report on

⑥ RADIATION-EFFECTS STATE OF THE ART
1965-1966,

to

AIR FORCE SYSTEMS COMMAND
RESEARCH AND TECHNOLOGY DIVISION

⑪ 30 Jun 66 (⑫ 115 p.)

⑮ AF 33(615)-1124

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Report on
RADIATION-EFFECTS STATE OF THE ART
1965-1966

SUMMARY

Electronic Components and Equipment
(Including Semiconductors)

The major portion of the work described in reports received by the REIC during the past year was done in the area of semiconductors, which constitutes the most radiation-sensitive area outside of organic insulation. Many of the reports dealt with the characterization of the semiconductors in a radiation environment, although another activity that is becoming more and more prominent is the radiation hardening and testing of circuits and systems. The effect of space radiation has been of major concern during the past year.

Polymeric Materials

The major emphasis during the year has been on polymers and polymer systems for use in electrical insulation, dielectric materials, seals, and gaskets. Data obtained on the polyimide resins and polycarbonates were of particular interest. Radiation effects in vacuum and at cryogenic temperatures also received attention, although the volume of data is relatively small because of the lack of facilities available for such work. Fundamental studies of the mechanisms of radiation-induced reactions are continuing at approximately the same rate of effort as last year.

Lubricants, Flotation and Hydraulic Fluids

The REIC has not received any new information on fuels, hydraulic fluids, or flotation fluids during the past year.

Ceramics

The effort on radiation-effects studies on ceramics continued at about the same rate as last year. The radiation tolerance of ceramics as a class remained unchanged.

Space-Radiation Environment

Additional information clarifying electron and proton flux levels was obtained during the past year. Much effort has been directed toward the study of diurnal variations of radiation regions and the mechanisms causing these variations.

Neutron and Gamma Dosimetry

Recent work in nuclear dosimetry has been diverse, resulting in the improvement of specific concepts for particular situations rather than the introduction of new methods or general procedures. Basic problems plaguing the work have been interference from disparate background radiations, radiation-induced degradations of detector parameters, and insufficient response range for high exposure levels or high rates. Most studies have concerned solid-state neutron detectors, high-resolution solid-state gamma spectrometers, and luminescent dosimeters. Advances have appeared more as refinements of established techniques than as significant expansion of the capability of measuring radiations.

Structural Metals and Alloys

The changes in the physical properties of structural metals and alloys due to radiation continue to be of importance to reactor designers and operators. This section provides information about the radiation effects in ferritic and stainless steels, nickel-base alloys, and refractory materials and alloys.

There is a continuing need for in-reactor experiments for fatigue testing and creep studies.

General

The approximate status of development of materials for use in various radiation environments is presented in Figure A. The bracketed areas give some estimate of the radiation levels to be expected from various systems.

INTRODUCTION

This is the ninth state-of-the-art report on radiation-effects activities prepared from data processed by the REIC for the Air Force, the National Aeronautics and Space Administration, and the Atomic Energy Commission. The purpose of this report is to summarize progress and to review problem areas in radiation-effects activities. It is based on new information obtained during the past year and should be helpful to those responsible for planning and executing radiation-effects programs.

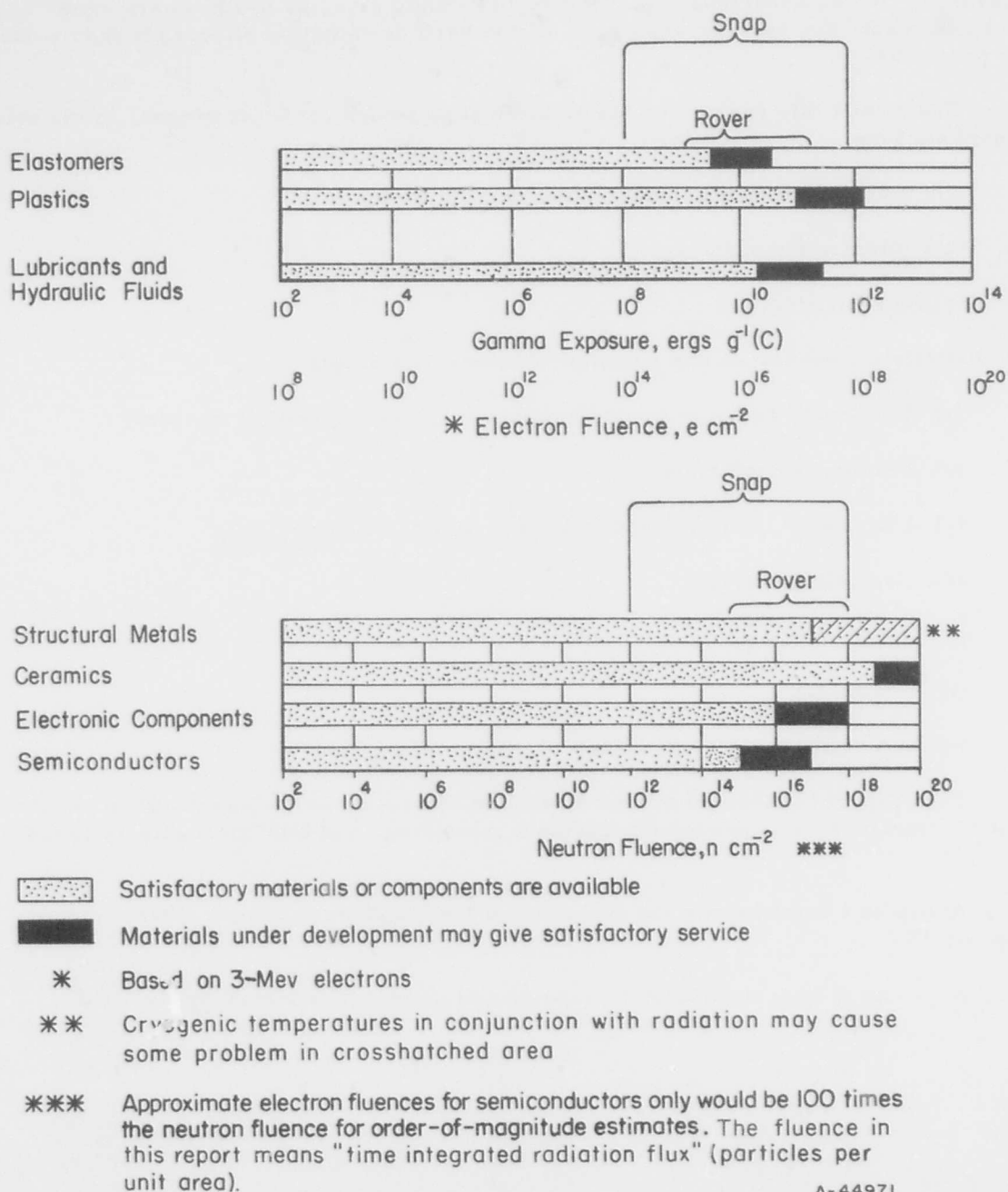


FIGURE A. STATUS OF MATERIALS IN RELATION TO RADIATION ENVIRONMENTS

The original intent of the annual State-of-the-Art report was to provide a summary of where the various classes of materials and components stood with respect to radiation tolerance. It was not intended that the report should give, as has been attempted in the past few years, the specific results of all the various radiation effects programs during the past year.

The report this year, then, is an attempt to return, at least in part, to the original report purpose.

The following topics are summarized:

- (1) The current state of the art
- (2) Programs in progress
- (3) Battelle's conclusions and recommendations concerning
 - (a) Electronic components and equipment (including semiconductors)
 - (b) Polymeric materials
 - (c) Lubricants, flotation and hydraulic fluids
 - (d) Ceramic materials
 - (e) Space-radiation environment
 - (f) Dosimetry
 - (g) Structural metals and alloys

This report is oriented around space and steady-state nuclear-radiation environments. Information on propulsion systems, shielding, and biological effects is not included.

Appendix I summarizes the operation of the REIC from June 1, 1965, through May 31, 1966.

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

SECTION A

ELECTRONIC COMPONENTS
AND EQUIPMENT (INCLUDING SEMICONDUCTORS)

SECTION A

ELECTRONIC COMPONENTS
AND EQUIPMENT (INCLUDING SEMICONDUCTORS)Introduction

This section summarizes the state of the art pertaining to radiation effects on electronic components, materials, and equipment. This summary is based on the information contained in the REIC files, with particular reference to radiation-effects information received during the period from June 1, 1965, to July 31, 1966. The purpose of this summary is to update the knowledge of managerial personnel and to acquaint technical personnel with the scope of information available at the REIC. For a more comprehensive coverage of this subject, the reader is referred to REIC Reports, No. 36 and 39 which deal, respectively, with nuclear and space radiation effects on electronic components and materials, including semiconductors.^(1,2) For detailed answers to specific radiation-effects problems, an information request should be submitted to the REIC either by mail or telephone.

The radiation environments of primary interest with respect to the effects produced on electronic components, materials, and equipment are the space-radiation and the steady-state nuclear-radiation environments.* Within each of these environments, radiation may cause degradation of performance or failure of active and passive components and materials with resultant effects on equipment performance. However, the amounts and kinds of radiation-induced degradation depend on the structure of the specific devices and the details of their application so strongly that only general observations are applicable to a state-of-the-art summary such as this. Thus, in the following discussions, no attempt will be made to report details of specific-device performance in specific environments. Rather, presentation of a general picture of the effects that may be expected to result from exposure of general classes of electronic components, materials, and equipments to the various radiations of the space-radiation or steady-state nuclear-radiation environments will be attempted.

Electron, proton, and bremsstrahlung radiations constitute the three types of radiation that are of primary concern for space-electronics applications. An important characteristic of this environment is that all three of its components are highly productive of ionization. The detailed composition of the space environment for various missions is considered elsewhere in this report and will not be repeated here.

The steady-state nuclear-radiation environment is generally characterized by neutrons with energies ranging from thermal to more than 10 Mev accompanied by gamma radiation. The neutron-energy spectrum, neutron-gamma ratio, neutron flux, and gamma exposure rate depend upon the radiation source, location of the area of interest with respect to the source and shielding; that is, the kind and amount of materials

*The pulsed-radiation environment is also of interest for some applications. However, because of the special characteristics of this environment and the excellent state-of-the-art coverage given to transient radiation effects on electronic components, materials, and equipment in the TREE Handbook, no summary of this area will be attempted in this report. Rather, those readers interested in the effects of pulsed radiation on electronic components, materials, and equipment are referred to the TREE Handbook which is available from the Defense Documentation Center (AD 472207 with a classified supplement AD 366383L).

located between the radiation source and area of interest. A generalized characterization of "the" steady-state nuclear-radiation environment is obviously impossible because of the many variables involved. For example, the radiation emanating from one type of isotope power system might be essentially pure gamma radiation, whereas a different system might produce a mixed gamma and neutron environment. Thus, it is necessary to consider separately the radiation effects associated with portions of the steady-state nuclear-radiation environment. Accordingly, the following paragraphs will consider the effects of thermal neutrons ($E < 0.1$ ev) or fast neutrons (minimum energy specified) in combination with gamma radiation as well as the separate effects of gamma radiation.

In general, the thermal neutrons do not make a great contribution to the radiation-induced damage of electronic components, materials, and equipments except by transmutation. In some cases, the radioisotopes produced can cause significant property changes (e. g. conductor conductivity changes, semiconductor impurity-concentration changes). Thermal-neutron bombardment has been used in manufacturing transistors to introduce a desired pattern of impurities by transmutation of silicon atoms to a phosphorus isotope. However, for general electronic applications having relatively remote and shielded locations with respect to the thermal-neutron source, available information shows that the contribution of thermal-neutron bombardment to the component, material, or equipment degradation is negligible in comparison to that resulting from fast-neutron and gamma-ray exposure. Of course, radioactivation of the materials by both thermal and fast neutrons may be a safety hazard for subsequent maintenance or handling and the resultant secondary gamma flux will add to the primary flux.

Many modern electronic systems utilize semiconductors which are highly dependent on the structure and order of their crystal lattice for their performance characteristics. Nuclear radiation, particularly the fast neutrons, causes lattice defects or disorders in the lattice structure and this damage degrades the semiconductor's characteristics. Available information indicates that this may be the most significant effect for electronic systems utilizing semiconductors and exposed to the steady-state nuclear-radiation environment.

Generally, the energy range of gamma radiation is such that energy is deposited through Compton interactions. Thus, ionization effects are the most significant results occurring when electronic components, materials, and equipment are exposed to gamma radiation. Since the gamma and neutron fields are usually mixed, the neutron-damage and gamma-induced-ionization effects occur concurrently.

It is recognized that the primary value of information about radiation effects on electronic components, materials, and equipment is that it provides a basis for predicting system performance in specific applications. Design efforts, component selection, the need for development of improved components, and many other decisions will be guided by such predictions. The accuracy of the predictions and the confidence that may be placed in them will depend upon the amount and quality of the radiation-effects information upon which the predictions are based and the pertinence of the information to the actual problem. Much of the remainder of this radiation-effects state-of-the-art summary will be directed toward making generalized predictions of expected performance for electronic components, materials, and equipments exposed to radiation environments on the basis of information contained in the files of the REIC. Such generalized radiation-effects predictions can serve to set boundaries on the extent and magnitude of some of the problems confronting those responsible for the design and manufacture of electronic equipment and systems intended for use in the space-radiation and the steady-state nuclear-radiation environments.

In the following discussions, the space and steady-state nuclear-radiation environments will usually be considered separately. However, it is desirable to state one basic generalization applicable to both environments; viz., all available radiation-effects information supports the prediction that significant effects of radiation on the performance of transistors and silicon controlled devices* can be expected to occur at particular fluences of gamma, X-ray, or bremsstrahlung radiation exposures well below those producing significant effects in most other electronic components. In general, the limiting factor with respect to the life of electronic equipments or systems utilizing semiconductors in the radiation environments will be their tolerance to loss of transistor gain or their dependence upon behavior of silicon controlled devices.*

In recognition of the above, a substantial portion of recent work on radiation effects has been concerned with establishing the physical mechanisms that are the fundamental causes for transistor and silicon-controlled-device sensitivity to radiation. Many of the papers presented at the IEEE Annual Conference on Nuclear and Space Radiation Effects held at Stanford University in July, 1966, were concerned with this problem. It appears that for injection transistors and most other semiconductor devices, the radiation effects of greatest significance are caused by radiation-induced lattice defects acting as recombination centers and decreasing the minority carrier lifetime in the base region. This results in degradation of various performance parameters of the semiconductor devices, with the most important being degradation of injection transistor gain, solar-cell power and silicon-controlled-device required gate voltage and holding current.

However, in addition to this bulk damage, irradiation of semiconductors can produce surface defects and can cause a surface charge buildup. These produce surface channels and surface recombination-generation currents which will cause device-parameter changes such as a decrease of transistor gain or an increase in field-effect transistor (FET) gate threshold voltage. Thus, even devices such as the FET, which has a performance relatively independent of radiation-induced bulk damage, may exhibit very significant performance degradation as a result of surface damage caused by irradiation. In fact, the available experimental evidence indicates comparable radiation sensitivities for FET's and injection transistors; that is, depending on the application, either type of transistor may be found to have the better tolerance to radiation but neither type will be as radiation resistant as most other electronic components.

Radiation Effects State of the Art for Electronic Components, Materials, and Equipment

Semiconductors

For most space applications, the components and materials which constitute the electronic equipments and systems will be shielded from direct exposure to the particulate radiation in space by the vehicle skin, structural members, etc. However, solar cells are an exception. If the solar cell, transparent shielding material, and adhesive are considered as a single electronic component, this part of the power supply is necessarily exposed directly to the space-radiation environment.

*Silicon controlled devices include: the silicon controlled rectifier, SCR; the silicon controlled switch, SCS; and the Schockley diode.

The degradation (decrease) of power output from silicon solar cells as a function of radiation fluence at first will depend upon the energy distribution of the incident protons and electrons, the intensity and spectral distribution of the effective illumination source, the cell structure, and cell resistivity. Once the radiation fluence is sufficient to produce about 15 percent degradation, and if the intensity and spectral distribution of the effective illumination source* remain constant, the degradation per decade of radiation fluence will be approximately constant until a fluence sufficient to cause about 85 percent degradation has been experienced. In this fluence range, the degradation rate is independent of type or energy of bombarding radiation, cell structure, and resistivity, depending only on the optical-absorption properties of light in silicon.

The effective illumination source for shielded solar cells may not remain constant as the radiation fluence increases but may show a continuing intensity decrease and spectral distribution change because of radiation-induced changes in the transmissivity and transmission spectral distribution for the shielding cover material and adhesive. On the other hand, the use of the shielding cover material will act to eliminate effectively the effects of lower energy protons (up to 20 Mev) on the basic cell and thus increase the threshold fluence for solar-cell power degradation. Use of appropriate shielding cover materials has been shown to extend significantly the useful life of even the most radiation-sensitive silicon solar cells in the space-radiation environment.

The fluence threshold for proton-irradiation damage in unshielded solar cells increases with cell resistivity and with proton energy. That for electron-radiation damage also increases with cell resistivity but decreases as electron energy increases. The radiation-damage threshold fluence also increases as the cell structure is changed from p/n silicon to n/p silicon, graded-base silicon, and p/n gallium arsenide, respectively. To illustrate the region of electron and proton fluences expected to produce significant solar-cell degradation, available information indicates that on a worst-case basis**, 25 percent degradation in shielded*** silicon-solar-cell power output will result for electron fluences ranging from 1×10^{13} to 8×10^{14} e cm⁻² or for proton fluences ranging from 6×10^{10} to 2×10^{12} p cm⁻². Similarly, 25 percent degradation in shielded p/n gallium arsenide solar cells would be expected for a worst-case electron fluence of about 6×10^{14} e cm⁻² or a worst-case proton fluence of about 2×10^{12} p cm⁻². Because the gallium arsenide cells will degrade much more rapidly (45 to 50 percent per decade of fluence) with increasing fluence than will silicon cells (approximately 20 percent per decade of fluence), 10 ohm-cm or graded-base silicon cells appear to be more radiation resistant than presently available gallium arsenide cells in applications where power-output degradations of 25 percent or greater are tolerable.

Ionization and surface defects as well as bulk damage in transistors are the result of exposure to either space radiation or steady-state nuclear radiation. The general mechanisms producing these radiation effects were summarized earlier. The bulk damage is generally the most significant for injection transistors and is evidenced by an approximately linear dependence of reciprocal common-emitter gain on fluence.

Radiation-induced ionization and surface defects can also cause changes in injection transistor gain as well as causing increases in leakage currents. These effects usually become significant at radiation fluences in the vicinity of the bulk-damage

*The effective illumination source defines the illumination impinging on the basic solar cell after any modification by the shielding cover material and adhesive.

**The worst-case assumptions are that all incident electrons have an energy of 3 Mev; all protons with energies less than 20 Mev are removed by the shield and all other incident protons have an energy of 20 Mev.

***It is assumed that the shielding material is unaffected by the radiation.

threshold, although for some transistor types and some applications, the effects may be significant at much lower fluences.

Bulk damage is not significant for field-effect transistors (FET's) of either the junction or metal-oxide-semiconductor (MOS) types because these are majority-carrier devices whose performance is essentially dependent on the minority-carrier lifetime. However, radiation-induced ionization and surface defects can cause changes in transconductance, increases in gate threshold voltage, and increases in leakage currents. These effects usually become significant at radiation fluences comparable to the range of injection-transistor bulk-damage threshold fluences. Again, for some applications and some FET types, significant radiation-induced performance degradation can occur at lower fluences.

The maximum transistor life in the radiation environments can be obtained by designing circuits that are as tolerant as possible to changes in transistor performance, especially decrease of injection transistor gain or increase of FET gate threshold voltage. Of course, such a circuit must also be insensitive to increases in leakage currents. In logic circuit design, reduction of fan-out requirements can substantially add to circuit life expectancy during radiation exposure.

In general, significant degradation of transistor performance as a result of electron irradiation can be expected for fluences ranging from 1×10^{12} to 1×10^{16} e cm⁻², depending upon the incident electron-energy distribution, transistor type, and the application requirements. Similarly, proton fluences ranging from 1×10^{11} to 1×10^{14} p cm⁻² or bremsstrahlung photon exposures of from 1×10^4 to 1×10^8 ergs g⁻¹ (C) may produce significant effects, depending on the incident-radiation energy distribution, transistor type, and the application requirements.

Whether a high-energy photon is a gamma photon or a bremsstrahlung photon makes no difference in the effects produced by the photon in an electronic component, material, or equipment. Of course, the photon energy is important. However, for most practical applications it is reasonable to assume that the energy distributions for bremsstrahlung photons in the space radiation environment and gamma photons in the steady-state nuclear-radiation environment are comparable. Thus, it should not be surprising that the range of gamma exposures from 1×10^4 to 1×10^8 ergs g⁻¹ (C) may produce significant degradation of transistor performance just as was observed for bremsstrahlung photon exposures.

In general, significant fast-neutron-induced degradation of transistor performance can be expected for fluences ranging from 5×10^{11} to 5×10^{15} n cm⁻² ($E > 1$ Mev) depending on the transistor type and the application requirements.

Silicon controlled rectifiers and the other pnpn switching devices can be considered to consist of overlapping npn and pnp transistors. As was the case for transistors, radiation can cause ionization and surface defects as well as bulk damage. The effects of radiation will be evidenced by increases in required gate current, holding current, and breakover voltage at fluences comparable to the bulk-damage threshold fluences for silicon transistors. Also, radiation-induced leakage currents and ionization currents at fluences well below those producing significant bulk damage can cause premature triggering and/or continuous conduction. The available information shows that these pnpn devices are highly sensitive to radiation and they are not recommended for use in a radiation environment. If their use is unavoidable, it should be expected that these devices

will be the limiting factors with respect to the radiation tolerance of the electronic equipment or system and that failure may be observed for fast-neutron fluences in the range from 10^{11} to 10^{13} n cm⁻² ($E > 1$ Mev). *

The extremely small size, light weight, and potentially high reliability of microcircuits make them particularly attractive for use in space electronic equipment and systems. Although a number of different microcircuit classifications are currently available (e. g., monolithic integrated circuit, hybrid thin film, etc.), all of them ultimately depend upon the semiconducting properties of silicon for their operation. Hence the ionization, surface-defect, and bulk-damage effects previously described for conventional transistors will also be observed for microcircuits. Radiation-induced conductivity changes in the silicon will affect microcircuit resistors and leakage currents, or radiation-induced changes in the dielectric properties of silicon may affect microcircuit capacitor performance.

Because of the relative newness of microcircuit technology and the rapid changes being made in microcircuit approaches, only a limited amount of radiation-effects data has been accumulated. The situation is complicated by the fact that microcircuit performance is necessarily specified in terms of circuit function, and thus there exists a wide variation in the parametric descriptions of performance for the various circuits.

Although of questionable validity, the practice of considering microcircuit elements separately to predict radiation effects on the circuit performance provides a limited basis for comparison with the effects expected for conventional circuitry. On this basis, available evidence indicates that, as expected, the microcircuit-transistor degradation is the most significant effect produced by radiation. In fact, none of the information available pertaining to irradiation of microcircuits gives any indication of the observation of a radiation-induced microcircuit failure that could be attributed to a component other than transistors.

The construction of the microcircuit transistor and the tolerance of the circuit design to transistor degradation are very important with respect to the radiation tolerance of the microcircuit. Where differences have been noted between radiation effects on energized and unenergized microcircuits, the unenergized circuits generally experienced the greatest degradation. No evidence has been found to indicate that any microcircuit-logic configuration (DTL, RTL, T²L, etc.) is inherently superior to any other with respect to radiation sensitivity.

The available information indicates that microcircuits employing transistors having the greatest possible gain-bandwidth products and utilizing circuit margins that provide the widest possible tolerance for transistor-gain degradation will have a minimum sensitivity to radiation. From the system-design standpoint, the permissible fan-out should be minimized, since this has a direct relationship to the output-transistor gain needed for satisfactory microcircuit performance. Also, the operating temperature of the microcircuits in the application is an important consideration, since temperature effects transistor gain. It appears that appreciable deviations from an operating-temperature range of from 20 to 30 C may be detrimental to the microcircuit performance.

*No information is available that establishes the electron or proton fluences producing silicon-controlled-device failure. However, because these radiation particles are highly ionizing, and the silicon controlled devices are generally very susceptible to premature triggering or continuous conduction caused by ionization, these effects may be expected to cause equipment or system failure at such low fluences as to seriously limit the value of such devices in space applications.

Since transistor degradation is the primary cause of radiation-induced microcircuit failure, the radiation-fluence ranges expected to produce significant microcircuit-performance degradation are those previously quoted for conventional transistors. Some limited evidence is available that indicates a space-radiation tolerance for some microcircuits slightly greater than that for their conventional counterparts.

Semiconductor diodes and rectifiers including Zener and voltage-reference diodes as well as PIN rectifiers will experience the same radiation-induced bulk damage and reduction of minority-carrier lifetime as occurs for transistors. Hence, there will be radiation-induced increases in forward-voltage drop and decreases in switching time and storage time. However, available information shows that although the radiation-induced minority-carrier-lifetime decrease will occur at the same radiation fluence levels that cause significant reductions in transistor gain, the increases in diode forward-voltage drop and reverse leakage current generally do not become significant until considerably higher fluence levels are experienced. When the utilization of these devices in circuitry is considered, it is generally believed that semiconductor diodes and rectifiers are about 1 to 2 orders of magnitude less sensitive to radiation than are transistors. In fact, the radiation-induced reductions in switching and storage times can be an advantage.

There is some information that shows a variability in the effects of radiation among individual high-voltage Zener diodes of a given type which might cause problems in critical applications. In general, however, radiation effects on voltage-reference and lower voltage Zener diodes should be insignificant for many applications since the initial voltage variation between individual specimens of a given type is usually much larger than the observed voltage changes resulting from irradiation.

Information available pertaining to the effects of space radiation on tunnel diodes shows that these devices may become inoperable for electron fluences of from 10^{17} to 10^{18} e cm⁻² ($E \approx 1$ Mev). It appears that, in general, these devices may be used for space applications without special precautions for space-radiation-induced parametric degradation.

Electron Tubes

The small size, lower power requirements, and generally higher reliability of semiconductors make them much more attractive than electron tubes for most space-electronics applications, particularly since the high-input-impedance FET's have become available. However, for certain specific space-electronic uses (e. g., low-level light sensors, television-camera tubes, high-power radar), no practical substitute for vacuum tubes has yet been found. Unfortunately, direct experimental information is not available to show the effects of electron, proton, or bremsstrahlung radiation on vacuum-tube structures, such as photomultiplier tubes, television-camera tubes, klystrons, magnetrons, or traveling-wave tubes. However, experience obtained in the nuclear-radiation environment indicates that these devices should perform adequately at space-radiation fluences exceeding those expected to cause failure of transistor circuitry.

A possible exception for some critical applications (star tracking, etc.) is the photomultiplier tube for which there will be a radiation-induced increase in dark current that depends approximately linearly on radiation flux. This radiation-induced dark current results from glass luminescence in the optical path and recoil electrons generated in the region of the photocathodes. Radiation-induced darkening of glass may also be significant for long-duration space missions.

In the steady-state nuclear-radiation environment, the gamma radiation can cause ionization effects in photomultiplier and other types of light-sensitive tubes similar to those described above for the space-radiation environment. However, the primary damage mechanism which limits the life of the light-sensitive tubes as well as the other types of electron tubes that employ glass for lead seals or envelopes is the failure of the glass during exposure to high-intensity nuclear radiation. The damage is characterized by the cracking of hard-glass envelopes or the fracturing of stressed areas in the immediate vicinity of the seal. The damage will be observed for most borosilicate envelopes and Kovar seals at thermal neutron fluences in the range of 10^{15} to 10^{16} n cm⁻². Boron-free glasses are less sensitive to this type of radiation damage and can tolerate neutron fluences as high as 10^{18} n cm⁻² even though there may be some increase in fragility.

Because of the reduced bulk of the glass envelope and the size of glass-to-metal seals, miniature and subminiature tubes have a higher radiation tolerance than the larger tube types. The ceramic tube types are quite insensitive to radiation and can withstand neutron fluences of up to 10^{16} n cm⁻² without significant damage. They may not suffer severe damage until the neutron fluence is about 2×10^{17} n cm⁻². Although some subminiature tube types may be operable for neutron fluences as high as 10^{18} n cm⁻², significant radiation effects have been observed for fluences as low as 10^{15} n cm⁻².

Transducers

The function of a transducer is the conversion of some physical measurement (e. g. , pressure, temperature, displacement, etc.) to a proportional electrical signal which can then be transmitted easily from the remote transducer location to a centrally located electronic system for processing. When radiation is present, it is usually possible to protect the central electronic system by shielding and/or distance, but usually the transducer will be exposed to the full radiation flux. In fact, the major reason for employing the transducers may be that the presence of radiation precludes the use of other means to obtain the desired measurement data. Thus, the effects of radiation on the performance of transducers can be critical to the success of space missions and such activities as the development and control of nuclear reactors.

Examination of the physical structures and materials employed in the construction of transducers shows that semiconductor sensing or compensation elements, piezoelectric crystals, and organic materials that may be used for seals, insulators, bonding adhesives, and potting are the most radiation-sensitive transducer parts. Depending upon the particular semiconductor properties that are important to the transducer performance, transducers employing semiconductor elements will be subject to the same effects of radiation as previously described for other semiconductor electronic components. Although no specific information is available to describe observed radiation effects for such transducers, it would be expected that radiation-induced bulk damage, surface defects, and surface leakage currents would result in transducer-performance degradation at radiation fluences comparable to those for other semiconductor components.

Transducers employing piezoelectric crystals or ceramics are primarily susceptible to radiation-induced ionization or thermal effects. The properties of insulation and bonding materials as well as the sensing element itself may change, introducing error into the transducer output. The use of charge-amplifier processing systems

rather than voltage-amplifier systems generally produces a significant reduction of radiation-induced measurement error. Radiation-induced resonant frequency changes for some crystal cuts will be of the order of 1 to more than 10 parts per million for radiation exposures as low as 5×10^7 ergs g^{-1} (C).

In general, the structural properties of organic materials (strength, elongation, etc.) degrade at lower radiation-exposure levels than do the electrical properties (insulation resistance, dielectric breakdown, etc.). Although radiation-induced ionization is the primary cause of organic-material degradation, the radiation damage may be dependent on other environmental factors such as temperature, surrounding atmosphere, etc. The available information shows that, in general, the radiation-induced degradation of transducers utilizing organic materials in their structure will occur in the radiation exposure range from 10^8 to 10^{12} ergs g^{-1} (C).

By replacing all of the organic materials with inorganic parts, considerable improvement in the radiation tolerance of transducers can be achieved. With proper design, the effects of radiation-induced ionization can also be minimized so that proton-, electron-, or neutron-induced transmutations or other material changes will be the dominant mechanisms for transducer degradation in low-flux environments. In general, satisfactory performance for such transducers can be obtained with neutron or proton fluences of from 10^{15} to 10^{18} particles per square centimeter and in some cases such as that of thermocouples, even with fluences orders of magnitude higher. Thus, it appears that transducers are available that can be employed successfully in most applications in the space-radiation environment and many applications in the steady-state nuclear-radiation environment.

However, some applications in the steady-state nuclear-radiation environment involve exposure to high radiation flux. In such cases, radiation heating poses a considerable problem. Depending upon the thermal paths within the transducers and the materials employed, differential thermal gradients appear as a result of the energy deposited by the high flux radiation. In some cases, localized internal temperatures can be sufficiently high to cause thermal or electrical breakdown of insulating materials or even melting. Differential thermal expansion can produce malfunctions or excessive transducer error. Temperature differences existing between sensing and compensating elements are another source of error. The obvious solution to this problem is through the use of shielding or distance to reduce the radiation flux and including thermal flow paths and/or cooling passages in the transducer design to assure that uniform internal temperatures are maintained and that material thermal limitations are not exceeded. However, for many applications, shielding is impractical and the redesign of the transducers is a difficult and time-consuming task. Although considerable progress has been and continues to be made, radiation heating of transducers remains the major problem for their application in high-flux radiation environments.

Piezoelectric Crystals

Quartz crystals employed as frequency-controlling elements in radio transmitters, receivers, etc., can experience resonant-frequency changes up to tens of parts per million as a result of space irradiation. However, the inherent shielding capabilities of the space vehicle, crystal packages, and oscillator packages may be sufficient protection for most space applications. In the available information, it is recommended that only positively aging crystals should be used in a radiation environment. Although crystal-controlled-oscillator frequency changes of from tenths to several parts per million may

be expected for electron fluences of from 6×10^{13} to 1×10^{15} e cm⁻², no significant frequency changes would be expected for 10-Mev proton fluences of at least up to 3.6×10^{12} p cm⁻² or for neutron fluences of up to 10^{18} n cm⁻². However, bremsstrahlung- or gamma-radiation exposure of 5×10^7 ergs g⁻¹ (C) can produce frequency changes of from 5 to 10 parts per million and bremsstrahlung radiation will probably be the major constituent of the radiation environment for quartz crystals in space applications just as gamma radiation is a major constituent of the steady-state nuclear-radiation environment.

Passive Electronic Components

Carbon-composition and carbon-film resistors are the most sensitive to radiation of the various resistive-component types. Significant changes in the resistance of these resistors may occur for fast-neutron fluences of about 10^{13} n cm⁻². The other resistor types do not exhibit significant permanent resistance changes until the fast-neutron fluence is in the range of from 10^{15} to 10^{16} n cm⁻².

Radiation-induced changes in capacitance, dissipation factor, and leakage resistance of capacitors result from damage to the dielectric material. The available information shows that (1) moderate changes in capacitor parameters may result from fast-neutron fluences ranging from 10^{12} to 10^{18} n cm⁻², depending on the capacitor type, and (2) the flux-dependent ionization effects which include induced voltages, low-resistance air-leakage paths, and resistance changes in insulating or dielectric materials and resistors will not generally be significant at the flux expected for space applications. These effects may be significant for high gamma fluxes sometimes encountered in the steady-state nuclear-radiation environment but they will disappear when the components are removed from the gamma flux.

Bremsstrahlung and gamma radiation can cause degradation of organic capacitor-dielectric material, but except for the types utilizing oil, radiation exposures up to 10^7 ergs g⁻¹ (C) should not produce significant effects on the capacitor performance. Ceramic, glass, and mica dielectric capacitors are the most radiation tolerant of the capacitor types. Severe damage can be expected for the various capacitor types for fast-neutron fluences in the range of from 10^{14} to 10^{19} n cm⁻². In general, the lower fluence values pertain to capacitors employing organic oils such as oil-impregnated-paper capacitors or oil-filled electrolytic capacitors. For these types, radiation causes the oil to degrade with the evolution of gas and the subsequent rupture of the container or hermetic seal because of the pressure buildup.

Recognizing that passive electronic components such as resistors, capacitors, etc., can (and usually will) be shielded from direct proton or electron bombardment in space applications, a major concern has been the effects on these components of the bremsstrahlung radiation generated in the shielding materials. On the basis of available information, ceramic, glass, and mica dielectric capacitors will be capable of tolerating bremsstrahlung or gamma exposures of at least 10^9 ergs g⁻¹ (C) without significant degradation, and severe damage would not be expected until the bremsstrahlung or gamma exposure exceeds 10^{12} ergs g⁻¹ (C). Thus, it appears that for most space applications, and many that involve the steady-state nuclear-radiation environment, the radiation tolerance of resistive and capacitive components will be adequate.

Vitreous-enamel insulations used for coils and transformers have capabilities similar to those of the inorganic dielectric materials used in capacitors. Most

radiation-effects tests of coils and transformers for electronic systems report that no significant effects were observed. It is only where high localized temperatures resulting from gamma heating are involved that problems may exist, and these problems are primarily thermal rather than radiation effects.

The effects of radiation on cables, connectors, hook-up wire, etc., are primarily dependent upon the insulating materials employed, though for some applications, conductivity changes in conductors resulting from transmutation or dislocation damage may be important. Because of the wide variety of materials and structures involved, general statements are difficult. However, it does appear that nearly all of these components can tolerate much more space radiation than can transistors.

Electronic Materials

As indicated previously, electronic equipment or system failure caused by radiation-induced degradation of transistors or silicon controlled devices generally occurs at particulate radiation fluences or bremsstrahlung and gamma radiation exposures much lower than those producing significant radiation effects in most other electronic components or materials. Although organic dielectric and insulation materials are widely recognized as being relatively sensitive to radiation damage with respect to their physical strength and dimensional stability, as well as their electrical qualities, the least radiation-resistant organic insulation from a generic standpoint possesses a radiation tolerance of up to 1×10^9 ergs g^{-1} (C) for gamma (or bremsstrahlung) radiation in a vacuum environment. At best, significant degradation of transistor properties would be expected for gamma- or bremsstrahlung-radiation exposures an order of magnitude lower than this. Some radiation-resistant organic materials can perform satisfactorily for gamma- or bremsstrahlung-radiation exposures approaching 10^{12} ergs g^{-1} (C) and inorganic insulating materials should not exhibit significant degradation of electrical properties for gamma- or bremsstrahlung-radiation exposures of up to about 5×10^{14} ergs g^{-1} (C).

It should be noted that, although information pertaining to electron and proton irradiation of the organic insulating materials is limited, comparable energy depositions from the particulate radiations would be expected to produce comparable damage; that is, the damage produced in an organic material by a radiation exposure of 10^{10} ergs g^{-1} (C) should be approximately the same irrespective of whether the type of radiation were bremsstrahlung photons, electrons, or protons. This follows from the observation that ionization is the primary cause of damage in these materials and the amount of ionization (which is proportional to the energy absorbed) is the important factor rather than the source of the ionization. On this basis it would be predicted (and available information confirms) that the contribution of neutron radiation from the steady-state nuclear environment to the degradation of the organic insulation and dielectric materials is negligible in comparison with the effects produced by the accompanying gamma radiation.

Inorganic insulating materials are much more radiation resistant than are organic materials. Available information, though limited, shows that space radiation will not produce significant effects with fluences or exposures well beyond those expected to destroy transistors. Inorganic insulators have been employed successfully for applications inside the core of nuclear propulsion reactors and their performance has been limited mainly by thermal considerations rather than radiation effects.

Except for the possibility of radiation-induced ionization effects, available information shows that metallic conductors will not be significantly affected by space-radiation exposure at normal equipment operating temperatures ($T \geq 245$ K). For applications involving extremely low temperatures such as might be obtained outside the space vehicle in shaded areas, heating of the conductors might be needed to avoid radiation-induced conductivity changes.

Information pertinent to the effects of electron and proton radiation on magnetic materials is very limited. However, the information available, as well as experience gained in the nuclear radiation environment, supports the prediction that the effects of proton bombardment will be insignificant for fluences of up to at least 10^{16} p cm⁻². No significant effects would be expected for electron fluences of up to at least 10^{17} e cm⁻² or for bremsstrahlung irradiation.

Changes in the properties of both metallic conductors and magnetic materials may result from radiation heating in high-flux environments and from transmutation or neutron-induced changes in composition and lattice structure. The significance of these effects is, of course, very dependent upon the particular application. In general, the fluence range producing significant neutron-induced property changes will be comparable to that producing significant changes in the structural properties of the pure metals involved, and these are well beyond those which would be expected to destroy most electronic components.

Electronic Equipment

Electronic equipment consists of a specific structure of electronic components and materials assembled to perform a specific function. Thus, the effects of radiation exposure will depend primarily upon the tolerance of the various circuit designs employed to the radiation-induced changes in electronic-component and material parameters. Because of the almost infinite variety of possible equipment designs, only broad generalities can be used to describe the radiation-effects state of the art for electronic equipment.

The available information shows that the most radiation-sensitive electronic components are semiconductors, followed by components that employ organic materials and piezoelectric crystals. Thus, the electronic equipment sensitivity to radiation will depend upon the tolerances allowed for radiation-induced changes in semiconductors, organic dielectric capacitors, piezoelectric crystals, and organic insulating materials. With the allowance of wide circuit tolerances to changes in transistor gain, and the use of the more radiation-resistant parts, electronic equipment should not experience significant radiation-induced performance degradation in the space environment for periods of time sufficient to accumulate electron fluences of 10^{15} to 10^{16} e cm⁻², proton fluences of 10^{13} to 10^{15} p cm⁻², or bremsstrahlung exposures of 10^6 to 10^8 ergs g⁻¹ (C). However, since the actual space environment in practical applications will usually involve concurrent electron, proton, and bremsstrahlung radiation, the actual equipment radiation-tolerance limits will be lower than those stated. This is because radiation damage is an accumulation of effects produced by the individual radiations.

Unfortunately, attempts to establish generalized techniques for predicting the cumulative effects of mixed radiation fields based upon effects observed for separate irradiations have not been too successful. The problem is further complicated by the

dependence of radiation-induced degradation on the energy distribution of the bombarding particles.

Electronic-equipment performance in the steady-state nuclear-radiation environment is subject to the limitations of the same types of radiation-sensitive components and materials as for the space-radiation environment. Also, transducers located remotely from the bulk of the equipment may be subjected to a much more stringent environment than are the other components and materials. The available information shows that equipment employing radiation-resistant transistors and having circuits that are very tolerant of transistor-gain degradation should perform satisfactorily for fast-neutron fluences up to the range of from 10^{13} to 5×10^{15} n cm⁻². The limiting range for vacuum tube equipment will be from 10^{15} to 10^{18} n cm⁻².

For equipment employing transducers, the radiation tolerance of the transducers may be the limiting factor since the radiation experienced by the bulk of the equipment may be quite low as a result of shielding or distance. The section of this report discussing transducers indicates the state-of-the-art radiation tolerance to be expected in such cases.

Programs in Progress*

Current programs on radiation effects on electronic components and materials are summarized below.

Aerospace Corporation is studying radiation damage in selected electronic materials and electronic piece parts.

American Bosch Arma Corporation is investigating transient radiation effects with regard to guidance and control electronics.

Battelle Memorial Institute, Columbus Laboratory, is studying the reliability of electronic components in a nuclear radiation environment.

Battelle Memorial Institute, Columbus Laboratory, is providing technical advisory services to study nuclear vulnerability of an advanced Avionics System.

Battelle Memorial Institute, Columbus Laboratory, is researching and preparing the Transient Radiation Effects on Electronics Handbook.

Battelle Memorial Institute, Columbus Laboratory, is studying the effects of electron radiation on digital integrated circuitry, silicon analog integrated circuits, metal-oxide-semiconductor integrated circuits, and micropower integrated circuitry.

*Detailed information on these programs is given in REIC Memorandum 29, "Compilation of Nuclear, Pulsed, and Space Radiation Effects Projects".

The Bendix Corporation is investigating the effects of ionizing radiation on a specific transistor type.

The Bendix Corporation is developing accurate nondestructive test procedures for use in predicting radiation damage to semiconductor devices without irradiation.

The Bendix Corporation is determining the applicability of available electronic components and circuit design concepts to military electronic requirements in the time period 1965-1975.

The Boeing Company is to expand prediction techniques for nuclear-radiation effects on electronics by both theoretical and experimental methods and to apply them to circuit and system hardening.

The Boeing Company is maintaining an awareness and survey of nuclear weapon effects on aircrew and airplane structures.

The Boeing Company is determining operational equivalence factors among various types of silicon transistors as function of fabrication technique and type and energy of radiation.

The Boeing Company is testing various types of monolithic and thin-film integrated circuits in ionizing radiation and neutron environments.

The Boeing Company is studying advanced guidance system radiation created by both offensive and defensive nuclear weapons.

Braddock, Dunn and McDonald, Inc., is making theoretical studies of circuit analysis including radiation effects in models of components.

Braddock, Dunn and McDonald, Inc., is doing analytical studies dealing with the hardening of missile system electronics.

Burroughs Laboratories is studying hardening data for processing equipment and timers from transient radiation.

Douglas Aircraft Company, Inc., is doing experimental studies of the response of the materials, components, and assemblies used in missile systems to pulsed radiation.

Douglas Aircraft Company, Inc., is making vulnerability reliability studies on components, assemblies, and systems, and attempting to generate appropriate codes.

Edgerton, Germeshausen and Grier, Inc., is investigating and measuring radiation-induced currents in dielectrics and metals used in nanosecond pulse measurement.

General Dynamics Corporation, General Atomic Division, is studying the defects likely to be responsible for the degradation suffered by silicon solar cells when exposed to high-energy nuclear radiation in space applications.

General Dynamics Corporation, General Atomic Division, will study the correlation between high-energy proton and high energy electron effects on silicon and germanium, solid-state electronic materials.

General Dynamics Corporation, General Atomic Division, is developing a program to demonstrate the procedures for radiation hardening of a typical semiconductor circuit as would be found in a missile guidance computer.

General Dynamics Corporation, General Atomic Division, is determining the effects by which a pulse of nuclear radiation affects the electrical characteristics of certain electrical parts and materials and developing models of electronic parts exhibiting optimum designs and materials for high radiation resistance.

General Dynamics Corporation, General Atomic Division, is studying the effects of pulsed gamma radiation on functioning dynamic electronic components and devices. A computer program to solve the complete set of semiconductor transport equations is also being developed.

General Dynamics Corporation, General Atomic Division, is formulating accurate models for describing the behavior of excess electrons and holes in semiconductor devices to predict the responses of these devices to a transient radiation environment.

General Dynamics Corporation, General Dynamics/Fort Worth, is conducting irradiation tests of NERVA components and materials for NASA.

General Electric Company is researching for the long-term testing of cylindrical diodes and the irradiation of fuel and insulator.

General Electric Company is studying low-noise traveling-wave tubes.

General Electric Company, Missile and Space Division, is working on the design and development of the Mack-12 R/V Program.

General Electric Company, Missile and Space Division, is studying radiation effects on reentry-vehicle heating, signature, and on electrical systems.

General Electric Company, TEMPO Division, is collecting, evaluating, and disseminating information and data on nuclear weapons effects, including electromagnetic-wave propagation and generation and EM pulse effects.

Hughes Aircraft Company is experimentally and theoretically determining the effects on electronics of a high-intensity source of fusion neutrons.

Hughes Aircraft Company is studying transient radiation effects in the missile guidance area primarily devoted to high-temperature, radiation-resistant microelectronics for these applications.

Hughes Aircraft Company is studying the effect of silicon diffused power transistor design parameters on radiation response.

Hughes Aircraft Company is determining the relative radiation sensitivity of various commercially available monolithic logic circuits for application in future missile guidance systems.

Illinois Institute of Technology Research Institute is doing experiments for measurement of nuclear, auroral, and ionospheric noise effects due to high-altitude nuclear weapons.

International Business Machines Corporation is studying the effects of pulses of nuclear radiation on passive electronic parts.

International Business Machines Corporation is developing and writing an automated digital computer program to determine the responses of electronic circuits to transient nuclear radiation.

Ion Physics Corporation is continuing optimization of the ion implantation junction formation technique for the fabrication of dendritic silicon solar cells.

Ion Physics Corporation is conducting a joint program with Solid State Sciences Laboratory to expand developed ion implantation techniques.

Ion Physics Corporation is studying the application of ion implantation techniques to fabrication of semiconductor devices and integrated circuits.

The Johns Hopkins University is studying the effects of transient nuclear radiation upon missile electronics.

The Johns Hopkins University is evaluating the components in circuitry for spacecraft.

Lockheed-Georgia Company is conducting experimental studies on the effect of reactor radiation on electronic equipment, circuits, and components.

Martin Company is measuring the characteristics of selected unijunction transistors when exposed to 1.5 Mev electrons ranging to 10^{16} electrons/cm².

Martin Company is preparing a state-of-the-art study of the effect of nuclear (permanent and transient) and space radiation in microelectronic circuit elements.

Martin Company is studying the transient and permanent effects of high-intensity pulsed nuclear radiation on insulated gate field effect integrated circuits.

Martin Company is testing Sprint Missiles for nuclear radiation effects.

Martin Company is testing transistors, diodes, capacitors and other selected electronic parts using pulsed radiation.

Martin Company is producing a radiation effects standardization program and preparing a radiation effects design manual.

Martin Company is investigating materials for hardened antennas and protective structures.

Martin Company is conducting an analytical and test program to verify that the nuclear radiation design requirements have been met on selected subsystems on the Sprint missile system.

Massachusetts Institute of Technology has a space-simulation, radiation-effects laboratory now in operation and is studying the effects on a wide range of semiconductor devices.

North American Aviation, Inc., is investigating radiation-induced electronic phenomena in insulating and dielectric materials.

North American Aviation, Inc., is studying the radiation effects which become dominant in microelectronic devices and circuits.

North American Aviation, Inc., is investigating the ionization phenomena produced in semiconductor materials and devices by radiation fields.

North American Aviation, Inc., is evaluating the effects of reactor-produced radiation on instrument compartment components utilizing SNAP shield test facility.

North Carolina State College is studying radiation-produced changes in the surface re-combination velocity of semiconductors and the dependence of present-day semiconductor defect performance on the surface of the materials employed.

Northrop Corporation is making specific numerical and analytical calculations of nuclear weapon electromagnetic effects.

Northrop Corporation is determining the design criteria which will result in hardened or isolated electronic circuits and components for use in communications or surveillance applications in a nuclear environment.

Northrop Corporation is developing improved analytical methods to accurately represent behavior of a semiconductor device in a transient radiation environment.

Northrop Corporation is designing, developing, testing, and fabricating a 70-channel FM multiplexed radiation-hardened recording system.

Northrop Corporation is conducting an investigation by measuring operational parameters, analyzing circuits, subjecting circuits to radiation environments, and analyzing the data.

Northrop Corporation is developing two prototype radiation-hardened, transducer-controlled FM oscillators.

Northrop Corporation is determining the rate of change by neutron irradiation of minority-carrier lifetime and carrier concentrations in silicon.

Northrop Corporation is studying the vulnerability of standard DTL logic gates under realistic load conditions and in a nuclear weapon environment.

Northrop Corporation is studying the radiation sensitivity of those properties critical to operation of semiconductors.

Old Dominion College will do theoretical investigations of defect annealing in irradiated semiconductors.

Philco Corporation is studying the causes of instability, high threshold voltage, and sensitivity to gamma radiation of MOS transistors.

Princeton University is conducting high-energy accelerator radiation-effects studies on transistors, diodes, epoxies, and elastomers.

Radio Corporation of America is studying radiation effects on semiconductor devices and circuitry for Tos satellites.

Radio Corporation of America is gathering up-to-date information on radiation effects on electronics and writing a state-of-the-art report and standards for use by design engineers.

Rand Corporation is continuing investigation on the effects of space radiation on the life-time of communication satellites.

Rensselaer Polytechnic Institute is studying electrical properties of transient radiation effects induced in silicon by ~50 Mev electron pulses.

Rensselaer Polytechnic Institute is studying defects induced in silicon and germanium by ~1 to 60 Mev electron radiation.

Sandia Corporation is evaluating transistors in a radiation atmosphere.

Sandia Corporation is investigating methods for measuring semiconductor device parameters which are significant in models for circuit analysis progress.

Sandia Corporation is continuing analytical and experimental investigations of radiation-induced secondary photocurrents in transistors.

Sperry Rand Corporation is providing radiation computer design techniques which will operate in high levels of nuclear flux and temperature, and which will withstand prompt gamma pulse radiation.

Sylvania Electric Products, Inc., is studying reactor irradiation of nonoperating vacuum tubes and other devices for qualification approval.

Texas Instruments, Inc., is by epitaxial means, constructing solar cells with a built-in field in order to reduce carrier transmit time.

TRW Systems is studying charged-particle-induced defect characteristics in silicon.

Tung-Sol Electric, Inc., is establishing a pilot-line production capability for producing nuclear-radiation-resistant electron tubes.

University of Illinois is investigating radiation effects in semiconductors.

University of New Mexico is studying the problems associated with the operation of microelectronic circuits in a pulsed radiation environment.

U. S. Air Force, Aerospace Research Laboratories, is providing information on the energy band structure of cadmium sulfide, utilizing electron bombardment to make tailored changes in the defect structures.

U. S. Air Force Cambridge Research Laboratory is determining atomic displacement thresholds and annealing behavior in pure elements.

U. S. Air Force Cambridge Research Laboratories is studying radiation damage in semiconductors using fast electrons.

U. S. Army, Electronics Command/Fort Monmouth, N. J., is studying transient radiation effects in electronics in the area of photoconductivity and related charge-transport effects induced by pulse radiation.

U. S. Army, Electronics Research and Development Laboratories is studying the essential performance characteristics of critical electronic materials, parts, devices, and circuits caused by exposure to nuclear radiation pulses of predetermined nature, intensity, and duration.

U. S. Army, Frankford Arsenal, is studying, theoretically and experimentally the radiation effects on fire control assemblies.

U. S. Army, Harry Diamond Laboratories, is to analyze entire systems response to transient nuclear radiation and to develop analytical techniques and test systems in laboratory radiation conditions.

U. S. Army, Harry Diamond Laboratories, is analyzing and testing selected materials, components, and subsystems in high-intensity radiation fields.

NASA, Goddard Space Flight Center, is studying the effects of space radiation on microelectronic circuitry.

A-21 and A-22

NASA, Goddard Space Flight Center, is studying the effects of simulated space radiation on higher power silicon controlled rectifiers.

NASA, Goddard Space Flight Center, is studying the effects of space radiation on silicon MOS-field effect transistors.

NASA, Langley Research Center, is studying charge storage and discharge in dielectric materials under steady electron and proton irradiation.

NASA, Lewis Research Center, is studying the radiation effects of 10-Mev proton and 1-Mev electron damage to silicon solar cells as a function of impurity levels.

NASA, Lewis Research Center, is studying the effects of impurities in base material and variations in design and processing on solar-cell performance.

USN, Naval Research Laboratory, is doing experimental studies on the effects of electrons and protons on solar cells, shields, and bonding materials.

USN, Naval Research Laboratory, is studying the effects of fast neutrons on ceramic and epoxy bonded, etched-foil strain gages.

SECTION B

POLYMERIC MATERIALS

SECTION B

POLYMERIC MATERIALSCurrent State of the Art

Polymeric-materials studies during the past year continued to be directed towards end items such as seals, gaskets, insulating and casting materials, and coatings. Limited work is continuing on combined environmental studies including vacuum and extreme temperatures, both elevated and low, combined with nuclear radiation. A few materials have been irradiated to higher doses than had been previously reported. A glass-reinforced epoxy resin containing an alumina filler retained 25 to 30 percent of its original mechanical properties at the absorbed radiation dose of 1.1×10^{14} ergs $\text{g}^{-1}(\text{C})$.⁽³⁾ Although the number of publications received during the past year was approximately the same as that received during the previous year, the rate of effort in the polymer area declined significantly as judged both by the reports received and the contracts in effect. Information is needed concerning the behavior of end items when subjected to radiation doses which severely degrade the polymer. In some cases, the operation of the end item is not impaired until after considerable degradation of the polymer. In other cases, performance is hindered with slight damage to the basic material.

Radiation Effects on Polymers

Figures B-1, B-2, and B-3 show the relative radiation stability of elastomers, thermosetting resins, and thermoplastic resins in air at ambient temperature. On the basis of information received during this year, the following changes or additions were incorporated into these figures. In Figure B-1, the dose for mild to moderate damage to polyurethane rubber has been extended to 1×10^{10} ergs $\text{g}^{-1}(\text{C})$, based on work done by Johnson and associates⁽⁴⁾. The radiation stability of poly(n-vinyl carbazole) has been incorporated into Figure B-2. Additional data are shown in Figure B-3. The radiation stability of Teflon FEP has also been incorporated into Figure B-3. In air it shows a radiation stability about two orders of magnitude greater than that for TFE (polytetrafluoroethylene). In vacuum their stabilities are approximately equivalent.

Two methods of studying radiation effects are of particular interest. Stucki and Newell⁽⁵⁾ at Lockheed examined the effect of radiation on the internal pressure of two epoxy resins. In this case, a small inductance transducer was encapsulated in the resin and changes in internal stresses were monitored. The second method consists of calculating the dynamic modulus of the material after continuously monitoring a miniaturized vibrating-reed apparatus in which the forced displacement of the clamped end and the resonance displacements of the free end of the polymer sample were recorded. This latter method is not new as the dynamic mechanical properties of polymers were studied at the University of Pennsylvania several years ago by Deeley, Woodward, and Sauer. However, these two methods provide means of continuously monitoring changes in properties while samples are under irradiation.

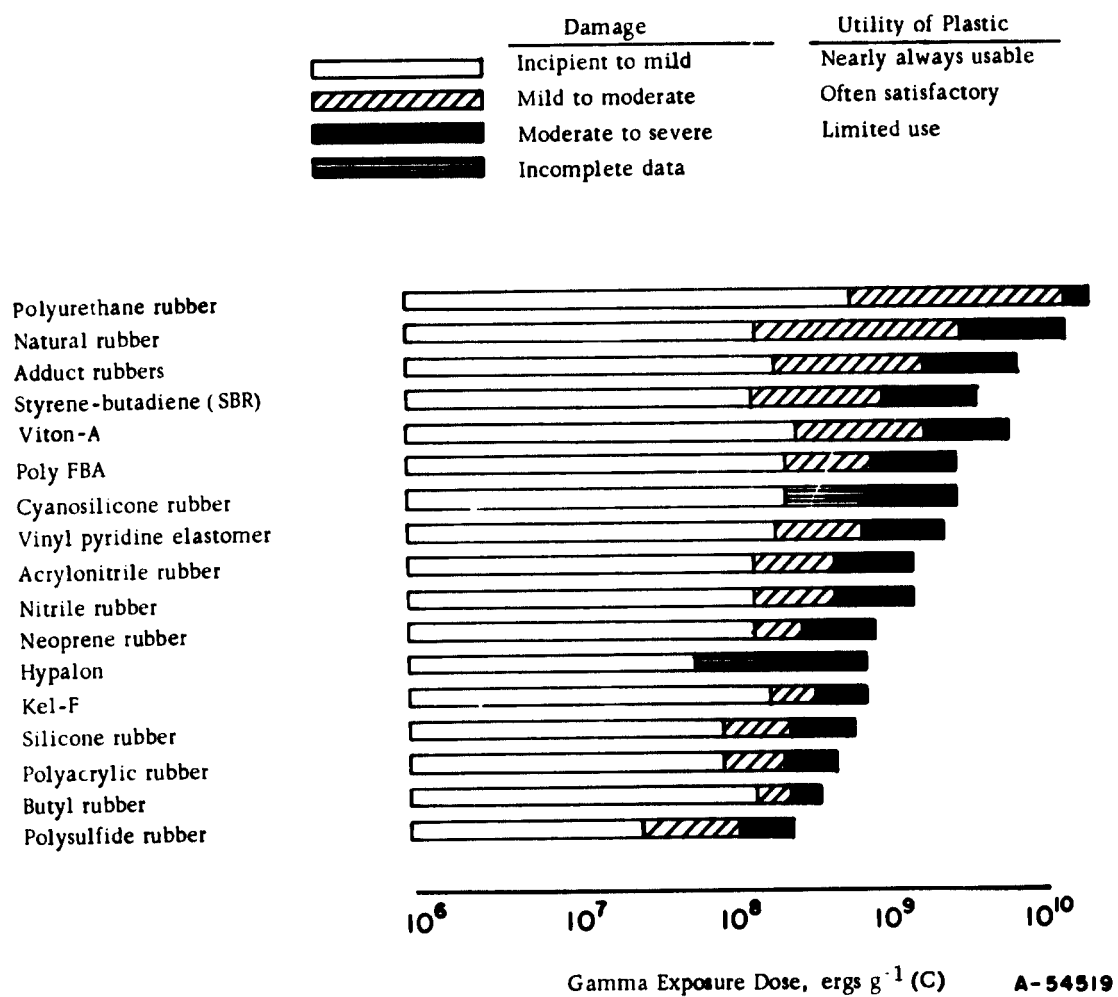


FIGURE B-1. RELATIVE RADIATION STABILITY OF ELASTOMERS

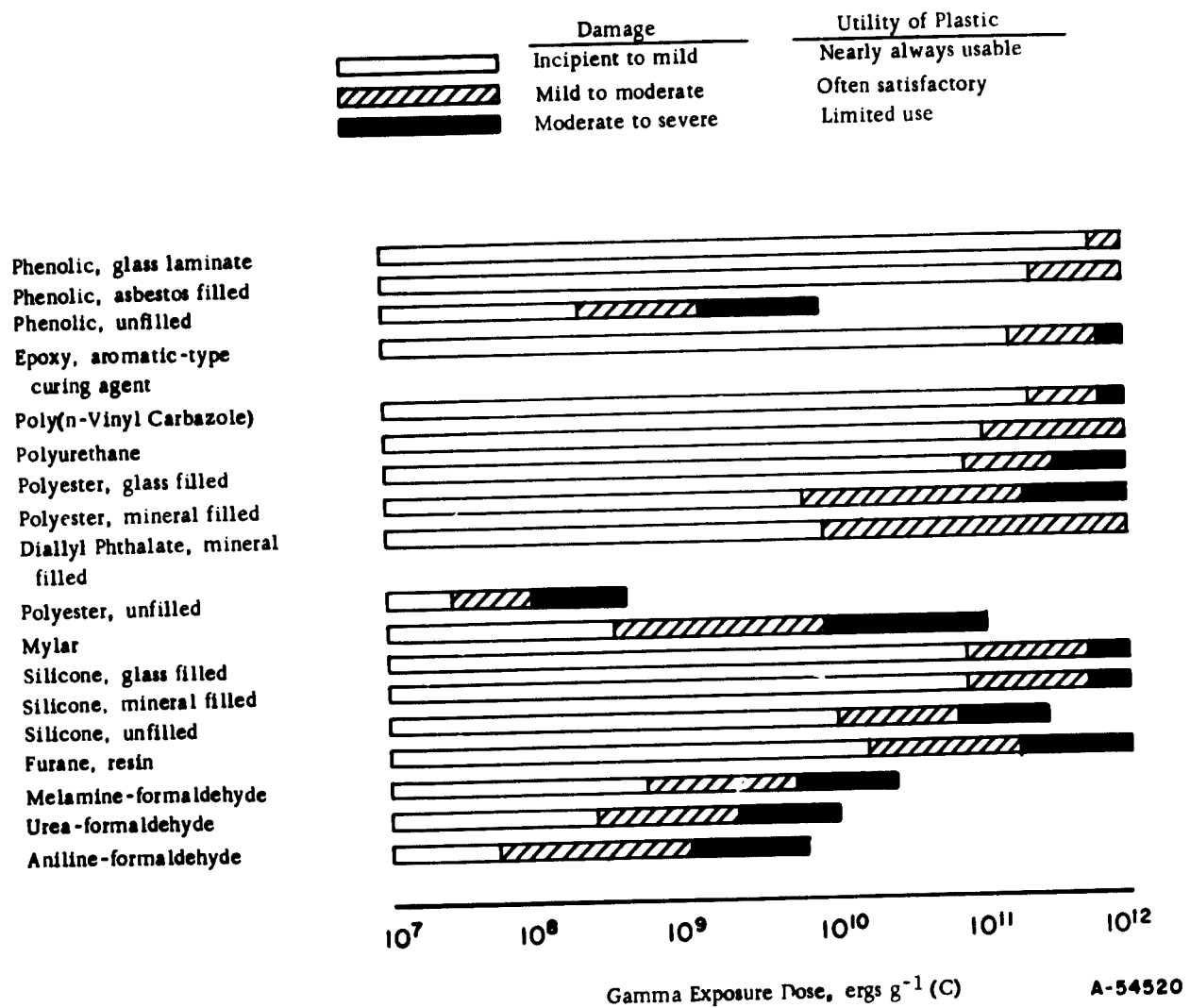


FIGURE B-2. RELATIVE RADIATION STABILITY OF THERMOSETTING RESINS

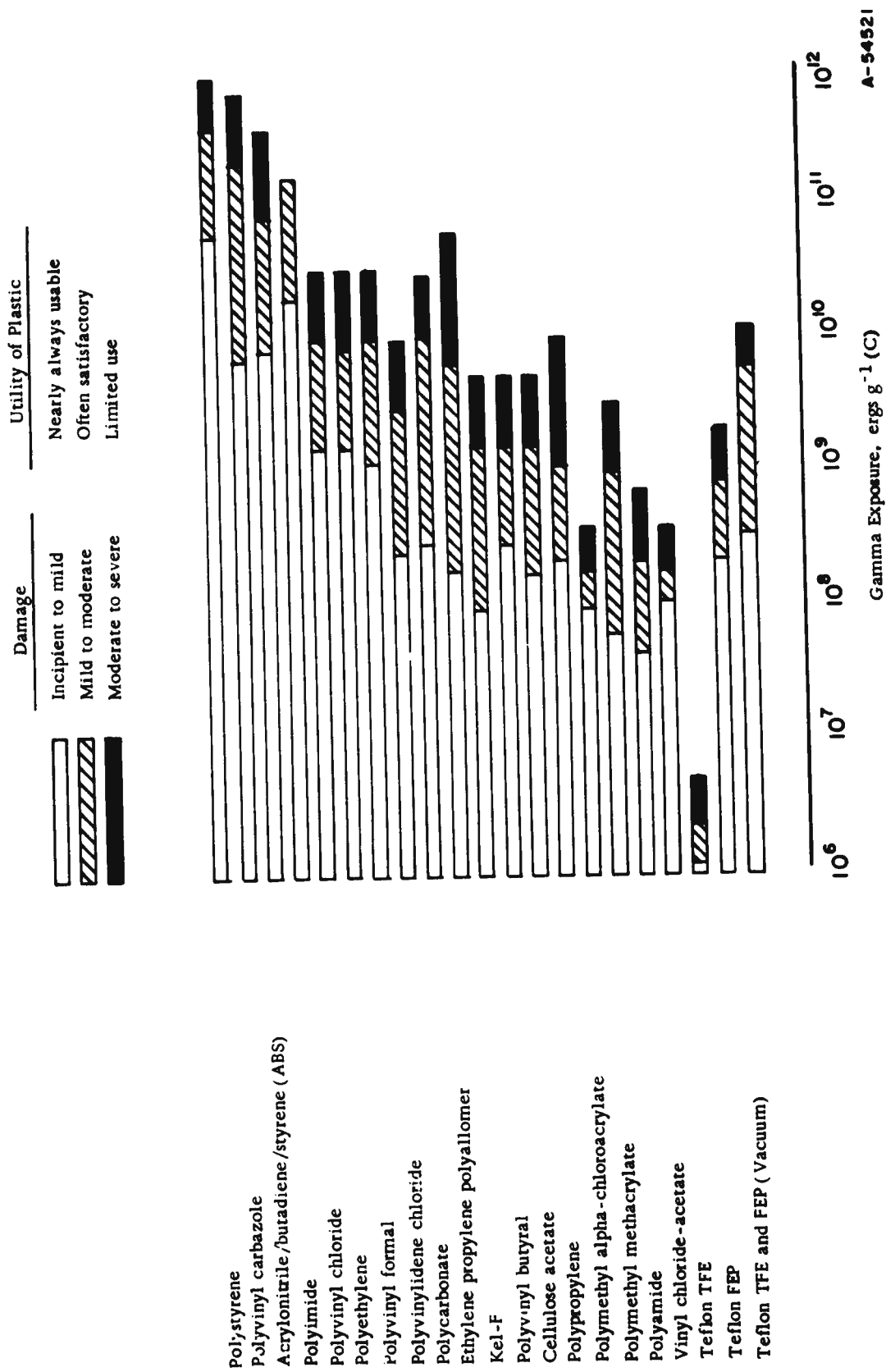


FIGURE B-3. RELATIVE RADIATION RESISTANCE OF THERMOPLASTIC RESINS

Radiation Effects on Components

Most of the irradiation work in the polymer area has been concentrated on determining the radiation stability of various components or systems. This, of course, is to be expected since it is the behavior of these various systems or hardware items in a radiation field which is important. The radiation levels to which these components are exposed is generally determined by the anticipated use. In some cases, the exposure dose is not as high as it would be advisable to employ considering the overall state of the art. The data merely confirm that which would be expected, rather than provide additional information.

Programs in Progress*

Current programs on radiation effects on polymers are summarized below.

Cook Electric Company is studying the effects of neutron and gamma radiation on nylon, dacron, and nomex cloth, tape, and strap for nose-cone recovery.

General Dynamics/Fort Worth, is measuring the effects of various environments on a select group of nonmetallic engineering materials.

Lockheed Aircraft Corporation is providing consultation in irradiation processing of wood products.

Radiation Applications Inc., is investigating dielectric properties of new copolymers of tetrafluoroethylene using Co^{60} initiation.

Rutgers State University is investigating the effect of structure, physical state, radiation environment, and temperature on the occurrence of molecular motion and polymer transitions.

Stanford University is studying radiation effects of epoxy reinforced with glass-fiber cloth loaded with pure alumina. Best properties shown at 3.25×10^{12} rads.

University of Georgia is determining concentrations of different kinds of olefins in many different irradiated polymers.

U. S. Army, Natick Laboratories, is continuing statistical evaluation of effect of experimental variables on irradiation-induced polymerization and irradiation-induced graft polymerization.

U. S. Naval Air Engineering Center is using gamma irradiation to enhance the properties of polymers and initiate polymerization.

*Detailed information on these programs is given in REIC Memorandum 29, "Compilation of Nuclear, Pulsed, and Space Radiation Effects Projects".

Conclusions and Recommendations

Investigations on radiation effects on polymers continue to be directed toward determining the radiation stability of components and systems under complex environments. The behavior of various plastics and elastomers in electrical applications has received the most attention, but interest in seals and in laminates is still in evidence. However, the rate of effort in the polymer area is continuing to decline. This is due in part to the limitations of polymeric materials in a radiation and high-temperature environment and, therefore, to an increasing need to bypass their use where possible. However, for many applications, polymeric materials show desirable advantages.

There is a significant trend in attempting to determine properties of polymers while under complex environmental conditions. Equipment has been modified or developed to obtain stress-strain data under these test conditions. Also, methods such as the incorporation of transducers in potting compounds and the use of a vibrating reed to determine variations in dampening of samples have been employed to obtain data on materials while being irradiated. There is a need for more of this type of effort and for correlation of these data with changes in mechanical and electrical properties.

Most of the requests for information which have been received during the year have been concerning the behavior of materials after they have been seriously degraded by radiation. There is a need for more information on the properties of elastomers and plastics under extreme environmental conditions. With such knowledge it may be possible to engineer around some of the problems.

Some new materials have been developed which show improved heat stability. These would be expected to have improved radiation resistance also. They include the polyphenylene oxides, the polysulfones, and similar materials. No information has been received as to their radiation stability. This information should be obtained.

As has been mentioned in previous reports, there is no means at present for channeling information to a central source according to methods by which materials have been successfully used for extreme environmental applications. This needs to be done.

SECTION C

LUBRICANTS, FLOTATION AND HYDRAULIC FLUIDS

C-1 and C-2

SECTION C

LUBRICANTS, FLOTATION AND HYDRAULIC FLUIDS

Current State of the Art

Research efforts in this area have been extremely low during the last several years. From the questions submitted to the Radiation Effects Information Center in this area during the past year, the lack of satisfactory flotation fluids for high-radiation environments seems to be an area of great concern. Conventional flotation fluids reach a threshold around 10^8 ergs $\text{g}^{-1}(\text{C})$, depending upon the amount of gas accumulation permissible within the gyro system.

Polyphenyl ethers are considered the best lubricating oils and hydraulic fluids for high-temperature, high-radiation environments. Solid-film lubricants are still more radiation resistant than the best radiation resistant greases. Solid-film lubricants should replace conventional greases in extreme temperature, nuclear environments and in most radiation-vacuum environments. Several greases have been successfully tested for use in vacuum to radiation exposures greater than the exposures expected during operation in space for periods over 1 year.

SECTION D

CERAMIC MATERIALS

SECTION D

CERAMIC MATERIALSSilica, Glasses, and SilicatesOptical Properties

The optical characteristics of glasses, silicates, and quartz crystals are the most important in considering the use of these materials in a radiation environment. Basic research investigations of defect structures in synthetic crystals and quartz indicate that the defects responsible for the C-band absorption are produced by direct Coulomb encounters between the radiation and the lattice constituents. (6) Investigations of some regularities in the variation of the Raman spectrum of alpha quartz when irradiated to a fluence of 7×10^{19} n cm⁻² indicate that the effect of a fluence of 6 to 7×10^{19} n cm⁻² is equivalent to the temperature of the alpha-beta phase transition. (7)

The spectral-transmission characteristics of fused silica specimens including Corning 7940, Amersil Infrasil, and Thermal American Spectrosil brands were studied over a range of temperatures prior to nuclear radiation and during thermal annealing of reactor-induced coloration following exposure to a fluence of 6×10^{17} n cm⁻² fast neutrons. The study revealed that the nuclear-reactor-induced coloration is more difficult to remove in the ultraviolet portion of the spectrum. Induced coloration in the ultraviolet is annealed out at temperatures between 700 and 900 C, and the rate of annealing corresponds to activation energies of between 2.2 and 2.8 ev in a first-order kinetic annealing process with a frequency factor of 10^{10} sec⁻¹. The three brands of silica in order of their degree of difficulty in removing the coloration were Amersil Infrasil, Corning 7940, and Thermal American Spectrosil. (8)

Spectral transmittance curves for Corning 1723, Owens-Illinois 650, Owens-Illinois 100, stretched Plexiglas, acrylic sheet, cross-linked methacrylate, copolymer styrene with divinyl benzene, Corning 0311 "Chemcor", and Corning 7940 were generated in a study of Apollo window materials. The materials were exposed to a simulated space-radiation environment consisting of combined low-energy protons of 50 kev and electromagnetic radiation with wavelengths of from 1216 Å in the extreme ultraviolet to 2 microns in the infrared. Degradation was found to occur at varying degrees in all materials tested, with Corning 7940 showing the least effect. For the Corning 7940, the decrease in transmittance was approximately 5 percent at 0.6 micron, near the middle of the visible spectrum. (9)

Light transmission in various optical materials was measured both before and after exposure to gamma radiation ranging from 2×10^7 R to 5×10^9 R. Corning 7940 showed the greatest radiation resistance, with its percentage of light transmission decreasing from 100 percent before irradiation to 89 percent after exposure to 5×10^9 R. Vycor exhibited the greatest degradation in its optical-transmission characteristics, its transmission decreasing from 99 percent before exposure to gamma rays to 0 percent after irradiation to 2×10^7 R. Light transmission at 4000 Å of unprotected dense flint-2, borosilicate crown-2, and Styron 690 also fell to 0 percent following irradiation, but varying amounts of light transmission were noted in these materials at higher wavelengths. (10)

Samples of various grades of silica, quartz, and radiation-shielding glasses were irradiated with 1.2 and 0.30-Mev electrons at total doses of up to $2.7 \times 10^{15} \text{ e cm}^{-2}$. All of the silica samples and the Solex glass showed almost no damage in wide-band transmission. Both plate glass and Feurex are very susceptible to radiation damage. The degree of degradation of fused quartz varies greatly from type to type; of the samples tested, Vycor showed the greatest damage. (11)

Borosilicate, flint, and barium crown glass and fused silica were irradiated to 10^6 rads carbon gammas and $10^{15} \text{ e cm}^{-2}$ (2.0-Mev electrons) to determine the effects of the radiation on the refractive indices of the samples in the 4000 to 7000 Å region. The refractive index changed by as much as 2 in the fourth decimal place in unprotected glasses, and by 6 in the fifth decimal place in cerium-protected glass sample. The values of refractive index change erratically as a function of time after irradiation in the unprotected glasses, and the changes diminish as the induced absorption decays with time. From the investigation it was concluded that for high-resolution cameras and television systems that are to be used in a space-radiation environment, unattended for long periods of time, index changes of the magnitude observed may result in degradation of image quality. (12)

Mechanical Properties

A ceramoplastic, Supramica 500, was irradiated in air at 75 F and 240 F with gamma exposures of 2.7×10^6 to 2.0×10^9 rads carbon. The study of the effect of radiation on the tensile, hardness, and specific-gravity properties indicated that Supramica 500 was not affected at the levels used. However, all specimens given heat treatment had tensile strengths somewhat lower than that of the 75 F specimens. (13)

In a study of the stress relaxation in quartz and vitreous silica produced by 40-Mev helium and 11-Mev protons, it was found that the vitreous silica crazed at approximately $10^{-3} \text{ c cm}^{-2}$ ($E = 1.8 \text{ Mev}$) of protons. Primary crazing consisted of typical polygonal craze areas, mostly rectangular, about 1 mm across. In the thin layers studied the crazing occurred at over 2-1/2 times normal breaking strength. (14)

Thermal Properties

The effects of charged particles on the thermal properties of zinc oxide/potassium silicate (Z-93) and zinc oxide/LTV-602 silicone (S-13) used as spacecraft coatings have been studied. The specimens were bombarded with protons having energies of 1 to 9 kev and 2.5 Mev and alpha particles having energies of 2 to 16 kev and 5.0 Mev to simulate a 230-day Earth to Mars flight environment. The damage thresholds for the Z-93 and S-13 coatings were 2×10^{14} and $8 \times 10^{14} \text{ p cm}^{-2}$, respectively. The estimated percentage changes in solar absorptances of the two paints due to the simulated-flight solar-wind fluence are 29 and 54 percent for S-13 and Z-93, respectively. (15)

Aluminum Oxide

Electron-spin resonance has been used to investigate the mechanism of radiation-induced damage in Al_2O_3 . The effects of radiation on the catalytic and electrical properties of Al_2O_3 and the optical properties of ruby crystals have also received considerable attention.

Electron-Spin Resonance

Both ultraviolet and gamma-ray irradiation of Al_2O_3 produce one resonance line with an isotropic g-value of 2.007 ± 0.005 and a line width of about 48 gauss at 77 and 300 K. For irradiations at 77 K, the growth of this resonance saturates at about 10^{16} spins/cm³ with an exposure of 10^5 rads gamma rays, indicating that the resonance arises from existing imperfections in the crystals. (16)

Reactor irradiation of Al_2O_3 for 1 hour at 70 C and 2×10^{15} fast n cm⁻² also produces the resonance line having an isotropic value of 2.007 ± 0.005 . Isochronal anneals of 1 hour at each temperature for 100 C intervals starting at 0 C show a linear decrease of absorption. After reactor irradiation of about 10^{17} fast n cm⁻², an additional paramagnetic center appears with a multiline spectrum and a g-value close to that of the free electron. (16)

Reactor irradiation followed by gamma-ray irradiation at liquid nitrogen temperature produces a three-line spectrum characteristic of a hole-like defect with three unpaired electrons. (16) This spectrum is attributed to interstitial O^+ . (17)

Irradiation of Al_2O_3 with 1.8-Mev electrons yields a multiline structure similar to that created by reactor irradiation but with greater overall splitting. (16)

Catalysis

If Al_2O_3 is gamma irradiated at -78 C at 2×10^{17} ev g⁻¹ min⁻¹ for 30 minutes, its catalytic activity in the H_2 - D_2 exchange reaction is increased sevenfold. (18) It has been suggested that the catalytic activity is affected by the concentration of trapped electrons or holes, which are altered by ionizing radiation and by subsequent annealing. (19)

Irradiation of Al_2O_3 to fluences of 10^{18} n cm⁻² at 50 C increases hydrogen adsorption. The specific surface area of 85 m² g⁻¹ of the Al_2O_3 is unchanged after irradiation; however, the shapes of the hydrogen adsorption isotherms are altered. The observed monolayer capacity for hydrogen indicates that at 78 K, hydrogen atoms are absorbed in one-to-one correspondence with the oxygen ions in the alumina surface. Nitrogen contamination has been detected. Nitrogen is displaced systematically as hydrogen is adsorbed at 78 K; this nitrogen-release phenomenon is enhanced by reactor irradiation. (20)

Electrical Properties

Irradiation of polycrystalline α -alumina at about 10^{16} n cm⁻² increases the electrical conductivity at room temperature. As the specimen temperature is increased, the relative effect of the radiation decreases until it becomes insignificant at temperatures above 767 K. (21)

Irradiations of Al_2O_3 to 6×10^{17} fast n cm⁻² at 95 C and at 2×10^{19} and 5×10^{19} fast n cm⁻² at 47 C reveal that the dielectric constant of alumina decreases slightly with neutron fluence. The dissipation factor appears to be more sensitive to fast-neutron fluence, rapidly increasing at irradiations between 6×10^{16} and 6×10^{17} n cm⁻², but decreasing at higher exposures. (22)

Ruby

Irradiation with gamma rays at fluences from 8.7×10^4 to 4.4×10^5 ergs g^{-1} (C) at 34 C causes the absorption spectrum of light-rose ruby crystals to change noticeably in both the visible and ultraviolet regions of the spectrum. The ruby becomes more dense in the red part of the spectrum after an exposure of 8.7×10^4 ergs g^{-1} (C); this density changes little even with comparatively large doses of radiation. (23)

An examination of the thermoluminescence of gamma-irradiated synthetic ruby over a smooth temperature variation from room temperature to 500 C shows one wide maximum of luminescence at 300 C that increases in intensity with increasing radiation exposure. Annealing at 500 C completely extinguishes the color produced by the irradiation, while heating to 250 C followed by slow cooling does not change the absorption spectra. (23)

Nuclear energy may be advantageously employed to increase the energy output of ruby laser crystals. Gamma irradiation of ruby crystals results in the formation of color and other centers associated with energy storage in the crystal which can be released either spontaneously or by light excitation. Thus, using a conventional pulsed system to pump the irradiated laser crystals, the energy output is significantly increased with no increase in the energy input. (24)

Magnesium Oxide

Recent investigations of radiation effects on MgO have included studies on crystal-structure damage. The effects of radiation on the catalytic properties, optical absorption, and electrical conductivity of MgO have also been investigated.

Growth

In MgO single crystals irradiated at 150 C at a neutron fluence of 3×10^{19} n cm^{-2} ($E > 1$ Mev), defect clusters account for about one-fourth of the macroscopic growth. (25) If, after the above irradiation, the MgO is annealed at 100 C intervals in the range 300 to 1200 C, the damage evidenced by lattice parameter and macroscopic expansion measurements steadily decreases. After annealing at 900 C for 1 hour, dislocation loops averaging 60 Å in diameter are observed. Annealing at higher temperatures causes these loops to increase in size and decrease in numbers. (26)

At a fluence of 4.3×10^{20} n cm^{-2} , the loops become so large that they degenerate into a tangle of dislocation lines. (27) This damage is resistant to annealing; after 1 hour at 1800 C, one-fourth of the irradiation growth is retained. (25)

X-ray growth slightly exceeds macroscopic growth at neutron fluences below 10^{20} n cm^{-2} in the range 75 to 100 C. At higher fluences, the macroscopic growth continues to increase at a reduced rate, but the X-ray growth decreases and rapidly becomes much less than the macroscopic growth. (28)

After irradiation to $3.1 \times 10^{19} \text{ n cm}^{-2}$, the lattice parameter is $4.2148 \pm 0.0001 \text{ \AA}$.⁽³⁾ The parameter increases linearly with exposure up to $7 \times 10^{19} \text{ n cm}^{-2}$, to reach a maximum at about $1.75 \times 10^{20} \text{ n cm}^{-2}$ and then fall away to almost zero at $4.5 \times 10^{20} \text{ n cm}^{-2}$.⁽²⁸⁾

Catalysis

Irradiation of MgO with gamma rays for up to 60 minutes at an intensity of $2.7 \times 10^7 \text{ ergs g}^{-1} (\text{C}) \text{ hr}^{-1}$ at -78 and 25 C increases the rate of ortho to para hydrogen conversion over MgO catalysts, especially when the oxide has been penetrated with oxygen at elevated temperatures. The catalytic activity does not seem to be related to the formation of paramagnetic centers observed in the electron-spin-resonance spectra. The adsorption properties of MgO for hydrogen and carbon monoxide appear unchanged by irradiation.⁽²⁹⁾

The catalytic activity of MgO powders for the hydrogen-deuterium exchange reaction, $\text{H}_2 + \text{D}_2 \rightleftharpoons 2\text{HD}$, is enhanced by ultraviolet irradiation, provided the catalyst is not completely degassed. Using electron paramagnetic resonance to study the irradiation-induced active sites on MgO, a correlation has been found between the V_1 center (a hole trapped at an anion adjacent to a cation vacancy) and the enhanced catalytic activity of MgO for the exchange reaction.⁽³⁰⁾

The fast irreversible chemisorption of oxygen at 25 C on neutron-irradiated MgO can be correlated with an S-center ESR signal which is irreversibly destroyed by oxygen. An S-center can be represented by an anion vacancy on the surface which is occupied by a single electron. These vacancies can be populated with electrons by using gamma irradiation, while neutron irradiation both creates and populates new vacancies. The amount of chemisorbed oxygen in this fast process agrees approximately with the number of S-centers. Impurity transition-metal ions cause increased chemisorption in both irradiated and unirradiated MgO. These ions lose electrons when MgO is heated at 350 to 550 C in the presence of excess oxygen.⁽³¹⁾

Optical Properties

MgO crystals were divided into two groups on the basis of optical absorption and thermoluminescence measurements. X-irradiation of the MgO produces an optical-absorption peak at 2.3 eV in Group I crystals and at 2.3 and 3.0 eV in Group II crystals. After irradiation, the thermoluminescence curves show a peak at 410 K for Group I crystals and at 410 K and 520 K for Group II crystals. By an optical bleaching method, the 2.3 and 3.0 eV absorption peaks are shown to be linked, respectively, with the 410 and 520 K thermoluminescence peaks.⁽³²⁾

The fine structure of optical-absorption bands in MgO irradiated with neutron fluences from $10^{16} \text{ n cm}^{-2}$ to $10^{18} \text{ n cm}^{-2}$ has been interpreted in terms of phonon creation and annihilation. Narrow absorption peaks having a constant spacing of 0.012 eV are tentatively associated with 1-, 2-, and 3-phonon processes. These phonon transitions become more pronounced as the temperature is lowered. There is a zero-phonon transition (electronic transition which occurs in color centers without transferring energy to the lattice phonons) which is characterized by its narrow width, its position on the low energy shoulder of the many-phonon absorption band, and its

temperature-dependent height and temperature-independent width. The absorption and luminescence spectra exhibit mirror symmetry about this line. (33)

Electrical Properties

Exposure of MgO to relatively high radiation intensities in the temperature range 100 to 800 K has served to delineate a region of appreciable delayed conductivity in the temperature range 600 to 800 K. (34)

Investigation of the relationship of the crystal current in MgO to the total electron exposure shows that the initial postbombardment conductivity builds up to a temperature-dependent saturation value. A model has been proposed that ascribes the postbombardment conductivity to charge carriers thermally emitted from a single trapping level, which predominates in a given temperature range. A study of postbombardment thermally stimulated conductivity reveals trap formation at 0.96, 1.20, 1.32, and 1.69 eV. Electron-induced conductivity measurements confirm the dependence of yield (crystal current/primary current) on trap occupation, which is a function of temperature and bombardment. (35)

Beryllium Oxide

The most important aspect of the irradiation behavior of BeO is dimensional expansion. Macroscopic growth in BeO is approximately linear with exposure, amounting to about 0.5 percent at a neutron fluence of 10^{21} n cm⁻². (36) Irradiation-induced changes in strength, elastic constants, and other properties are related to the grain-boundary separation types of expansion. The types of expansion occurring in irradiated BeO are lattice expansion, microcracking, helium bubbles, and defect clusters.

Lattice Expansion

Exposure to neutron fluences of from 1.7 to 5×10^{20} n cm⁻² ($E \geq 1$ MeV) at 100 C causes the c-axis to expand about 8 times as much as the a-axis. The initial rate of volume expansion (versus fluence) is 0.2 to 0.3 percent per 10^{20} n cm⁻². After an exposure of 1.7×10^{20} n cm⁻² is reached, the rate increases to about 0.36 percent per 10^{20} n cm⁻², amounting to approximately 3.3 percent at 10^{21} n cm⁻² ($E \geq 1$ MeV). Expansion is primarily in the c-axis at irradiation temperatures above 600 C. (37)

Microcracking

Cracking at the boundary between grains of unlike orientation is caused by stresses developed from the anisotropy of lattice expansion. The ultimate result is powdering of BeO at a volume expansion of about 6 percent. Microcracking occurs at relatively high fluences when small grain sizes and high irradiation temperatures are used.

Helium Bubbles

Helium is formed in (n, 2n) and (n, α) reactions in beryllium at a rate of about 0.36 cm³ helium/g BeO per 10^{21} n cm⁻² ($E \geq 1$ MeV). Bubbles form in the grain

boundaries at temperatures as low as 600 C. (37) In BeO irradiated to about 4×10^{20} n cm⁻² ($E \geq 1$ Mev) at 1000 C, bubbles are seen only on the grain boundaries. However, after annealing at 1400 C and above, bubbles also appear within the grains. (38) Specimens irradiated at 900 to 1000 C to a fluence of about 10^{21} n cm⁻² have an estimated bubble volume of 20 to 40 percent of a total expansion of about 1 percent. The apparent helium-diffusion rate, based on gross specimen dimensions, is about 10^{-8} to 10^{-9} per sec⁻¹ for specimens in which grain-boundary separation occurs. (37)

The (n, α) reaction in beryllium also produces tritium. At low temperatures (~100 C), the lattice expansion caused by tritium generation is linear with exposure to an exposure of about 1.5×10^{20} n cm⁻². At higher exposures, stresses from anisotropic growth causes cracking at the grain boundaries, which essentially converts the material to a powder at exposures from 5 to 6×10^{20} n cm⁻². (39)

Defect Clusters

At irradiation temperatures up to 600 C, interstitial clusters predominate; vacancy clusters predominate at higher temperatures. The size ranges up to 1200 Å at fluences of 1 to 2×10^{21} n cm⁻² ($E \geq 1$ Mev). The density appears to be 10^{15} to 10^{17} cm⁻³. (37)

In general, changes in properties are 3 to 5 times smaller in 500 to 700 C irradiations than in 100 C irradiations, and the property changes are smaller yet above 1000 C. (36) Radiation effects on the strength, elastic constants, and thermal conductivity of BeO have been investigated.

Strength

Irradiation increases the strength slightly until grain-boundary separation occurs, at which time the strength markedly decreases. This decrease is less with smaller grain size. Strength decrease begins at a volume expansion of from 0.4 to 1.0 percent, the latter value occurring at higher irradiation temperatures.

Elastic Constants

A small decrease in elastic constants of 1 to 2 percent, consistent with the decrease in density, occurs in the absence of grain-boundary separation. There is a decided decrease in the elastic constants of specimens involving grain-boundary separation. (37)

Thermal Conductivity

Irradiation damage has a negligible influence on thermal conductivity until the onset of microcracking, at which time the conductivity decreases significantly. The effects of microcracking on the conductivity may be reduced by annealing at moderately high temperatures. (40) Room-temperature conductivity falls to 50 percent of its unirradiated value at 3×10^{19} n cm⁻² and continues to fall at higher fluences. Unlike the unirradiated material, irradiated BeO shows little change in thermal conductivity with temperature. (36)

Graphite

Graphite is one of the ceramic materials receiving a considerable amount of study. The mechanism of the irradiation-induced growth of graphite and the results of subsequent annealing have been investigated in great detail, and the effects of radiation on graphite's electrical, thermal, and mechanical properties have also been studied.

Growth

For graphite samples irradiated at 30 C, bulk expansion is observed when the graphite is measured in the direction perpendicular to the direction of extrusion, and bulk contraction is observed when it is measured parallel. Perpendicular expansion decreases with increasing radiation temperature and neutron fluence, and contraction sets in at about 300 to 400 C with a neutron fluence of $6 \times 10^{20} \text{ n cm}^{-2}$.⁽⁴¹⁾ Perpendicular specimens exhibiting a greater initial expansion tend to show a lower expansion rate at the higher exposures.⁽⁴²⁾ The parallel contraction rate decreases with increasing radiation temperature, up to about 600 C. This rate is unchanged in the range 600 to 1000 C, and then increases above 1000 C.⁽⁴¹⁾ Contraction occurs at a higher rate for parallel specimens than for perpendicular specimens.⁽⁴²⁾

The axis increases rapidly with irradiation at room temperature, but with increasing irradiation temperature, this expansion is minimized. The axis contracts slightly at all irradiation temperatures.⁽⁴¹⁾

Changes in dimensions of polycrystalline and pyrolytic graphites irradiated at 170 and 200 C have been compared. At low crystal strains, axis crystal growth is absorbed by porosity so that the bulk volume changes in polycrystalline graphite are less than those in a single crystal. However, as crystal strain closes the porosity, the rate of bulk volume change of the polycrystalline material approaches and eventually surpasses that of the single crystal.⁽⁴³⁾

Alternate reirradiations and anneals can remove radiation damage from graphite. The ratio of growth during a reirradiation to the recovery during an anneal is independent over large ranges of both irradiation temperature and retained damage. This ratio is a linear function of exposure between anneals with a slope that is determined by the annealing temperature.⁽⁴⁴⁾

Electrical Properties

The electrical resistivity of nuclear graphites approaches a saturation value after relatively short radiation exposures. Radiation affects the electrical resistivity by producing changes in the number of charge carriers and scattering centers in graphite. At low exposures the resistivity rises approximately in proportion to the number of scattering centers because the increase in the number of positive holes is nearly balanced by the decrease in concentration of free electrons. However, after a short exposure, the number of free electrons is so small that it does not contribute significantly to the conductivity. From this point the resistivity remains constant as the increasing concentration of holes counteracts the decreasing mean free path between scattering centers.⁽⁴²⁾ The electrical resistivity of graphite is relatively insensitive to the irradiation temperature. However, both the initial resistivity and the fractional increase in

resistivity caused by irradiation are sensitive to the crystallinity of graphite, being greater for the more crystalline materials. (45)

Thermal Properties

The conduction of heat in polycrystalline graphite occurs primarily by lattice waves. Because radiation-induced defects act as scattering centers and thereby decrease the mean free path of the lattice waves, the thermal conductivity is decreased by irradiation. (46) The thermal resistivity of irradiated graphite rises to a saturation level with increasing exposure. This saturation point is reached at higher exposures for thermal resistivity than for electrical resistivity. Irradiation-induced increase in thermal resistivity is generally between 200 and 300 percent. The thermal conductivity of nuclear graphites depends on the degree of crystallinity, crystallite orientation, and the number and kind of defect structures. The more crystalline the graphite specimen, the higher the thermal conductivity and the larger the temperature coefficient. Irradiation reduces crystallite size and increases crystal defects, thus causing the initial sharp decrease in thermal conductivity. Heat treatments can remove many of the radiation-induced defects, thereby restoring much of the original thermal conductivity. (42)

Mechanical Properties

The values of Young's modulus for unirradiated graphite are in the range of 5 to 10×10^{10} dynes cm^{-2} . Irradiation with 4-Mev electrons at liquid-nitrogen temperature does not change the static Young's modulus. On subsequent annealing, the modulus remains constant until 200 K is reached. Above this temperature there is a sharp increase in modulus with a maximum at 275 K; the height of this peak varies as the square of the exposure. The dynamic Young's modulus increases with irradiation, with this increase varying as the square of the exposure. Annealing increases the dynamic modulus further until a maximum value is reached between 200 and 240 K. The modulus change then returns slowly toward its postirradiation value as the annealing temperature is increased to 360 K. (47)

Graphite samples loaded under tension at about 500 psi exhibit steady-state creep rates of 1 to 2×10^{-7} (psi) $^{-1}$ per 10^{20} n cm^{-2} for specimens parallel to extrusion and 4 to 5×10^{-7} (psi) $^{-1}$ per 10^{20} n per cm^{-2} for specimens perpendicular to extrusion. No evidence was found to indicate that the creep strain could be removed by annealing either with or without stress. The radiation-induced creep has been interpreted in terms of the removal of dislocation barriers. (48)

Diamond

Neutron irradiation of diamonds causes displaced carbon atoms to accumulate in the interstitial zones of amorphous carbon between mosaic blocks of diamond containing randomly distributed vacancies and interstitial carbon atoms. After annealing to 600 C, some of the interstitial carbon atoms return to normal structural sites, but the carbon in the amorphous intermosaic zones does not return to the vacancies. (49)

Neutron irradiation reduces the usual high anisotropy of grinding hardness by a large factor. Annealing in 200 C steps of 1 hour to 600 C restores about 30 percent of the hardness and hardness anisotropy. (49)

Irradiation to 10^{17} fast n cm⁻² does not affect the density of diamond; however, a decrease of 0.2 percent is observed upon irradiation to 10^{18} n cm⁻². Annealing to 600 C results in a recovery of 40 percent. (49)

The electron paramagnetic resonance signal of diamonds is proportional to total integrated fast-neutron radiation to 10^{18} n cm⁻². The EPR signal rapidly decreases after heat treatment. The line widths are independent of radiation up to 10^{17} n cm⁻² and also decrease after heat treatment. It is suggested that highly irradiated diamond is a mosaic of microcrystals separated by a cement of damaged, amorphous, diamond-like glass. (50)

The room-temperature electron-spin-resonance spectrum of diamonds irradiated by 2-Mev electrons has been analyzed into four systems, all of which show a g-value within 0.2 percent of the free-spin value. The room-temperature electron-spin-resonance spectrum of diamonds irradiated with fast neutrons at 50 C shows a broad absorption centered at $g = 2.00$, with a half-power width of about 80 gauss. The differences between the spectra induced by neutron and by electron irradiation are due to the fact that neutron irradiation produces localized regions of high defect concentration, so that the structure of the electron-induced absorption with a half-power width of about 70 gauss is smeared out by magnetic interactions between the pairs. (51)

Programs in Progress*

Current programs on radiation effects on ceramic materials are summarized below.

Associated Universities, Inc., Brookhaven National Laboratory, is studying the electrical properties of irradiated graphite.

Battelle Memorial Institute, Battelle-Northwest Laboratory, is studying the effects of radiation, and gas reactions of nuclear graphites and the development and testing of improved graphites.

Battelle Memorial Institute, Battelle-Northwest Laboratory, is to investigate fundamental properties of uranium ceramic materials, with special emphasis on high-temperature properties and in-reactor behavior.

General Dynamics Corporation, General Dynamics/Convair, is evaluating the radiation effects on spacecraft window materials.

General Dynamics Corporation, General Dynamics/Fort Worth, is studying threshold characteristics of reactor-irradiated laser-active media, including ruby, and possible irradiation-excitation mechanisms of lasering.

*Detailed information on these programs is given in REIC Memorandum 29, "Compilation of Pulsed, and Space Radiation Effects Projects", April 15, 1966.

General Electric Company, Nuclear Materials and Propulsion Operation, is to define the irradiation behavior of beryllium oxide in terms of the composition and micro-structure variables that contribute to extended radiation stability.

General Electric Company, Special Purpose Nuclear Systems Operation, is fabricating and irradiating UO_2 -W dispersion, fuel-clad thermionic emitter bodies and fabricating and laboratory testing vented fuel-clad thermionic emitter bodies.

General Electric Company, Vallecitos Atomic Laboratory, is to obtain the upper limit of Zircaloy-2 clad uranium dioxide fuel, both powder and pellet, in particular as it relates to the fraction of fuel that is in the molten condition.

Georgia Institute of Technology is to determine the effects of time, temperature, and radiation on the aging characteristics of natural and synthetic quartz resonators.

North American Aviation, Inc., is studying the effect of high-energy particle radiation on a variety of glasses to be used in the Apollo vehicle.

North American Aviation, Inc., is to study the effects of fast-neutron bombardment and helium on the properties and intrinsic behavior of pure and boron-doped single-crystal beryllium oxide.

North American Aviation, Inc., is to do basic and applied studies into the atomistic mechanism of irradiation damage in fueled zirconium hydride and materials and product development studies to apply fueled zirconium hydride at high temperatures in reactor fuel elements.

North American Aviation, Inc., is to perform a materials and product study to apply uranium carbide in reactor fuel elements.

North American Aviation, Inc., is to do basic and applied studies into the atomistic mechanism of irradiation damage in uranium carbides and other carbides containing uranium.

Northrop Corporation is testing and measuring the Hugoniat equation of state of five nose-cone-type materials over the pressure range 1 to 50 kilobars.

Oak Ridge National Laboratory is studying the behavior of graphite under irradiation and the development of improved reactor grades of graphite.

Pennsylvania State University is conducting radiation research on graphite.

Sandia Corporation is studying radiation effects in ferroelectric materials.

T R W Systems is doing a study program to determine the radiation-induced luminescence yield produced in infrared optical materials by 1 Mev electron.

Union Carbide Corporation is to determine the effects of neutron damage on the mechanical properties of highly ordered pyrolytic and single-crystal graphite.

University of Chicago, Argonne National Laboratory, is studying the effects of low-temperature radiation in hydrogen-bonded glasses.

University of North Dakota is studying radiation-induced changes in silica by X-ray diffraction methods.

Westinghouse Electric Corporation, Astronuclear Laboratory, is studying thermal-neutron and transient pulse irradiations of fueled graphite materials.

U. S. National Bureau of Standards is studying nuclear- and space-radiation effects on refractive properties of optical glasses.

SECTION E

SPACE-RADIATION ENVIRONMENT

SECTION E

SPACE-RADIATION ENVIRONMENTCurrent State of the Art

During the past year, additional information clarifying electron and proton flux levels has been obtained. J. Vette, et al.,⁽⁵²⁾ have continued to model inner and outer zone electrons utilizing available satellite information. Transition region and interplanetary radiation data have become available. Much effort has been directed toward the study of diurnal variations of radiation regions as well as toward mechanisms providing these variations.

Monitoring of the entire 11-year solar cycle will continue with the future launching of the next series of Pioneer spacecraft to provide data on the interplanetary magnetic field, low-energy charged particles, high-energy proton and alpha particles, and cosmic rays. Additional studies of solar radiation and the energy spectra and chemical composition of high-energy primary cosmic rays as well as the energy and intensity of electrons of galactic origin will be conducted by the Soviet Proton Satellites. Additional information on solar proton and inner Van Allen Belt protons will be obtained from the ESRO satellite series.

Transition Region and Interplanetary Data

A requirement for the existence of a Van Allen-type radiation belt around Mars would be a Martian magnetic field strong enough to trap particles. Magnetometer and radiometer measurements by Mariner 4 indicate that such magnetic fields are nonexistent.⁽⁵³⁻⁵⁵⁾

The traversal of the extended magnetospheric tail of the earth by Mariner 4 at a geometric radial distance of $\sim 3300 R_e$ failed to detect any effects of a magnetospheric tail during 7 days of flight within a geocentric angle between 1 and 5 degrees from its presumed centerline. L. A. Frank⁽⁵⁶⁾ has reported a region of energetic particle fluxes on the night side of the earth which at times extends out from the stable trapping zone to distances as great as 15 to 16 R_e . Beyond the boundary of the cusp at 13.5 R_e out to the apogee distance and to 32 R_e , energetic particle fluxes occurring in isolated patches or islands frequently have been found to occur.⁽⁵⁷⁾ (See Figure E-1.) These reach flux levels of $\sim 3 \times 10^7 \text{ cm}^{-2} \text{ sec}^{-1}$ for electrons having energies above 45 kev. Konradi also reported fluxes of protons $> 125 \text{ kev}$ in the islands.⁽⁵⁸⁾ In addition, detectors on several satellites have observed sudden counting-rate increases due to electrons in the kev energy range in the magnetosheath and upstream from it. Imp 2 results indicate that these spikes are time varying and are not spatially fixed. These islands and spikes are shown in Figure E-1.

Analysis of Venus data from Mariner 2 led to the conclusion that any radiation zones of trapped high-energy electrons are likely to be minor in comparison with the earth's.⁽⁵⁹⁾ From the properties of the protons in the solar wind, it was concluded that Mariner 2

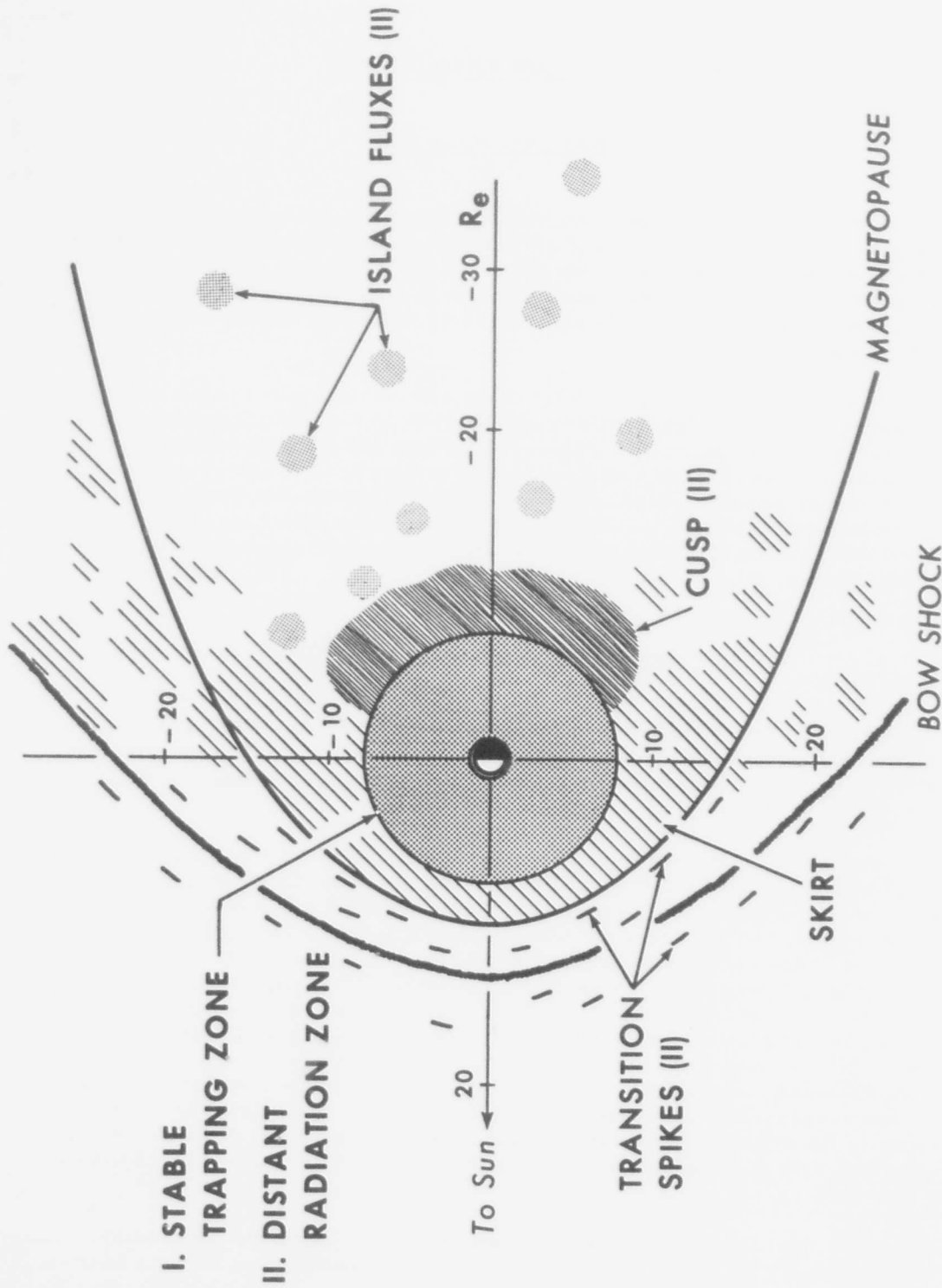


FIGURE E-1. SPATIAL LOCATION OF STABLE TRAPPING ZONE, CUSP, AND ISLAND FLUXES(57)

neither entered a magnetosphere of Venus nor penetrated any shock front or bow curve associated with its magnetosphere. (60)

Van Allen Radiation

Extensive work in the magnitude and diurnal variation of the electron flux beyond $5 R_E$ has been done with data from Explorer 14. In this study, the (B, L) coordinates were found to lose their effectiveness in organizing the observed omnidirectional intensities with $E > 40$ kev beyond $L \approx 6$. This was attributed to the distortion of the geomagnetic field by the solar winds. (61)

J. I. Vette has recently completed a modeling of the electron environment out to $6 R_E$ using the (B, L) coordinate system. (52) Integrated electron fluxes for various orbital positions are shown in Figures E-2 and E-3. Environment modeling for altitude regions greater than this is presently being done.

Observations of the temporal variations of electron ($E > 1.6$ mev) intensities near the geomagnetic equator in the outer radiation zone with Explorer 14 strongly suggests that an inward radial motion of energetic electrons from $L > 5$ begins the replenishment of energetic electrons in the outer radiation zone during the several weeks following a period of geomagnetic activity. It has been established that the diurnal variations of the outer radiation belt of the trapped electrons of energy $E \gtrsim 500$ kev is significantly reduced during times of low magnetic activity. (62)

Data from the polar-orbiting satellite 1963-38-C show the existence of a 27-day periodicity in the intensity of trapped electrons for $L \gtrsim 3.5$. These electron intensity variations have been shown to depend on properties of the solar wind and the interplanetary magnetic fields. (63)

Satellite Relay 1 has performed a thorough mapping of the energy spectrum and spatial distribution of protons in the inner zone. The proton flux has not changed markedly since 1958. (64) Generally, the low-altitude inner-belt proton flux has not been found to vary with the changes in atmospheric density due to solar cycle changes.

Investigations of the South Atlantic magnetic anomaly by satellites such as the Injun 1 have shown that a longitudinal dependence exists for trapped electrons at (B, L) points extending into the lower Southern atmosphere. This variation results from the precipitation and loss of trapped particles drifting through the anomaly. Electrons mirroring at B values which remain above ~ 350 km in altitude over the South Atlantic anomaly are not disturbed by the anomaly; about 90 percent of those that reach the 100 to 250-km region over the anomaly are lost, and all those electrons reaching an altitude of ≤ 100 km over the anomaly are lost. (65)

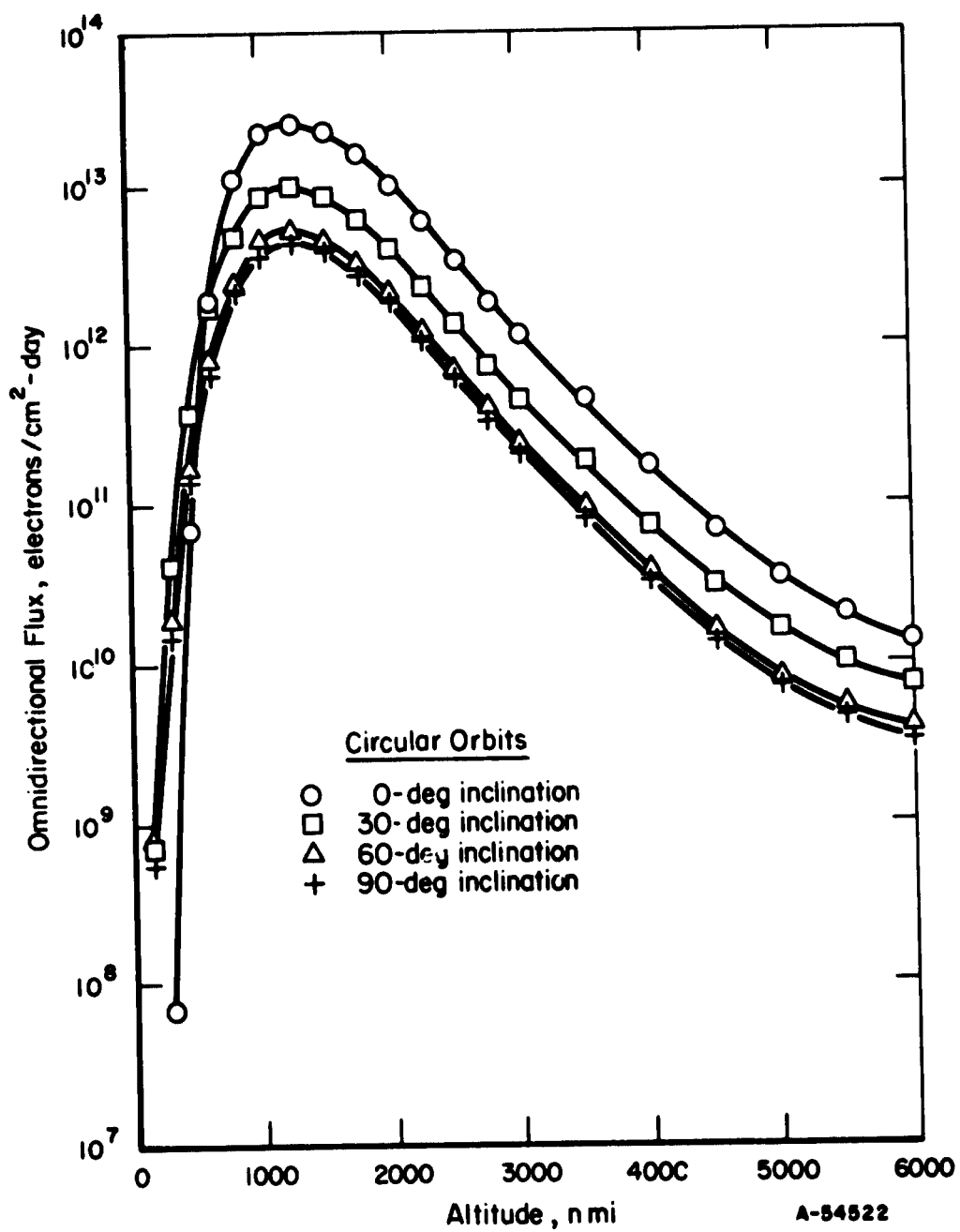
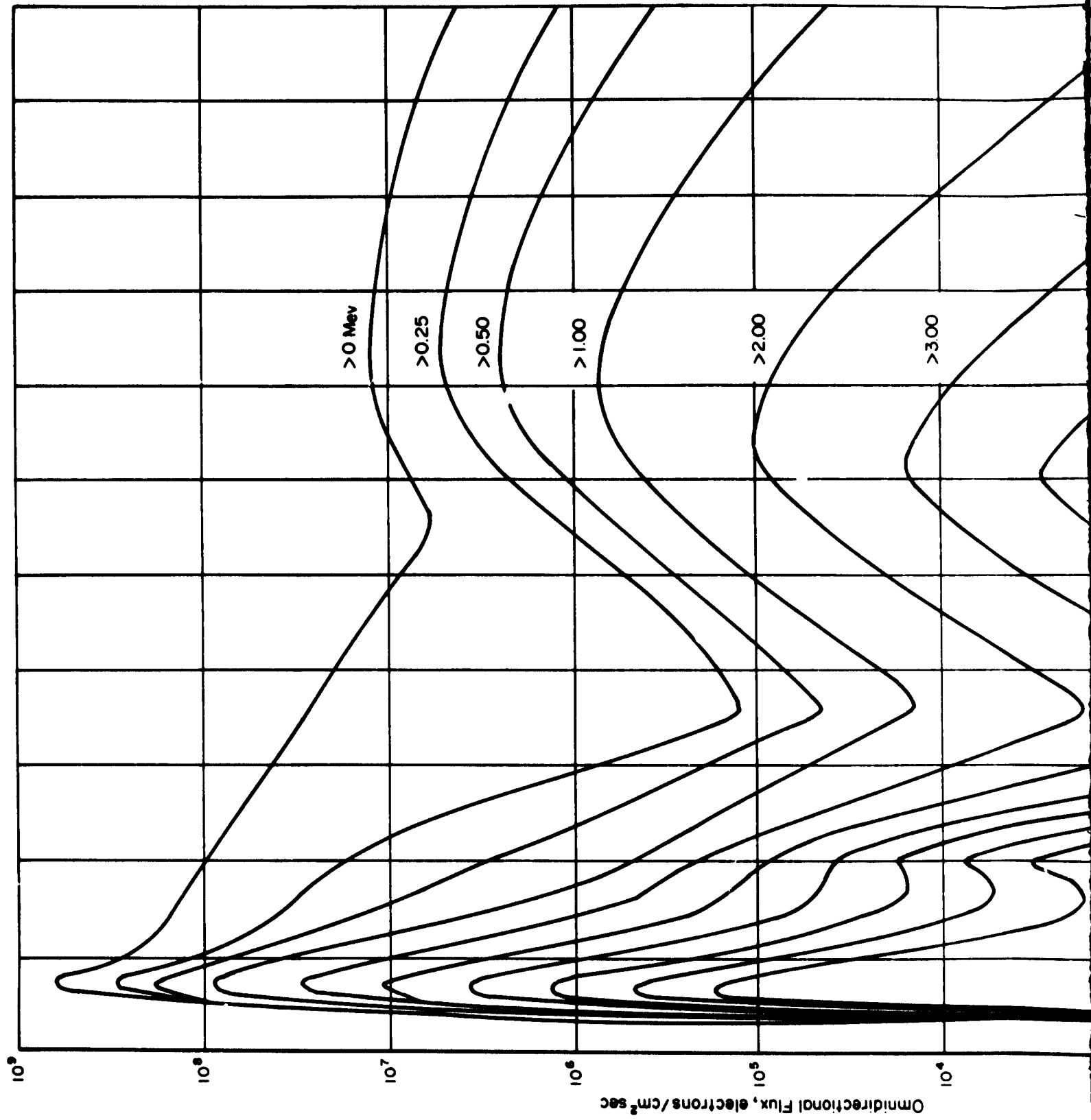


FIGURE E-2. ORBITAL INTEGRATIONS FOR ELECTRONS HAVING ENERGY ABOVE 0.5 MEV(52)



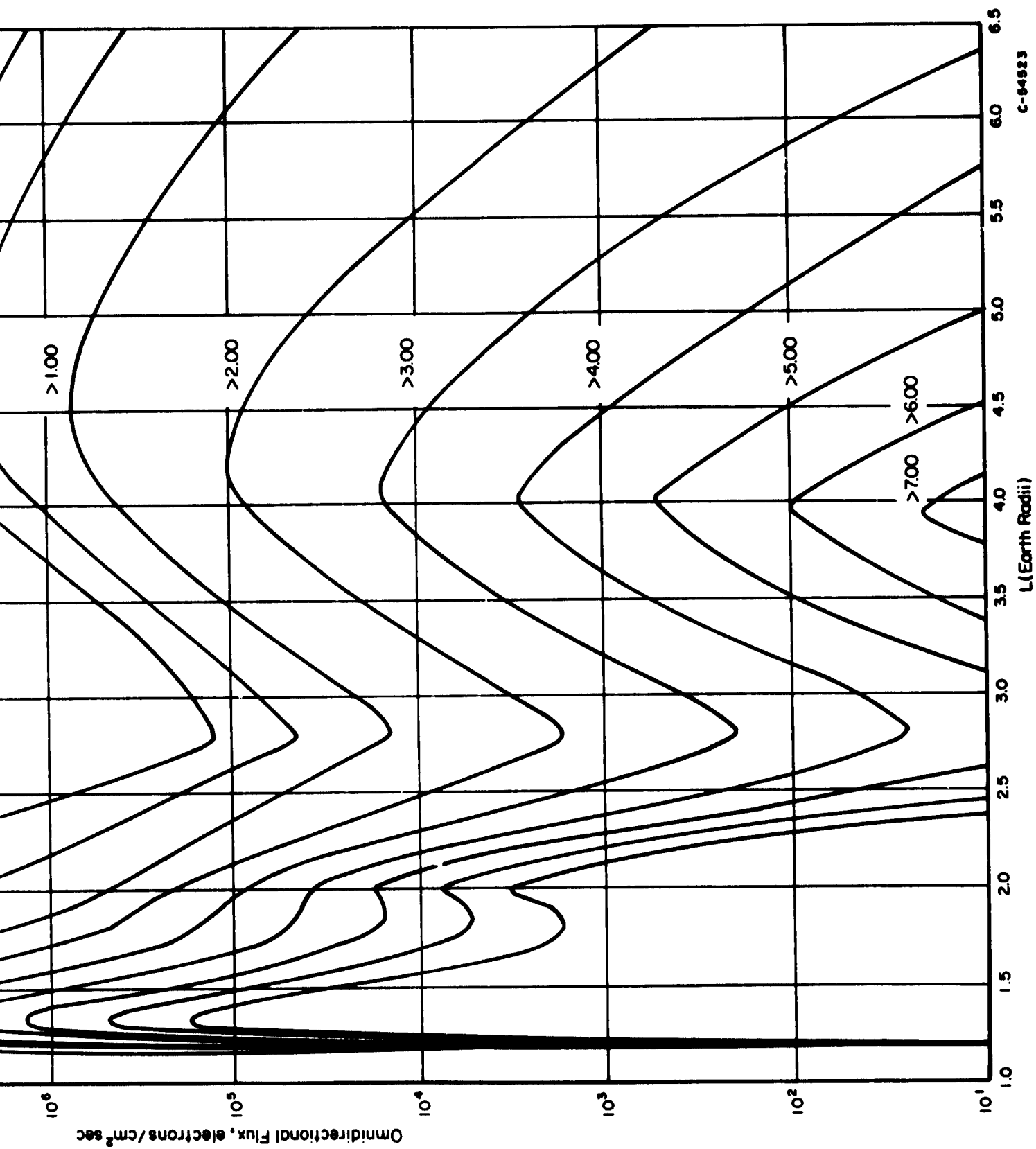


FIGURE E-3. OMNIDIRECTIONAL ELECTRON FLUX AT THE GEOMAGNETIC EQUATOR(52)

Programs in Progress*

Current programs in the field of space environmental studies are summarized below.

American Machine and Foundry Company is working with a soft X-ray and extreme ultraviolet solar radiation simulator.

Douglas Aircraft Company, Inc., is doing space radiation analysis and a determination of space radiation environment as a function of time and space.

Douglas Aircraft Company, Inc., is continuing theoretical and experimental work as related to nature and behavior of lunar surfaces.

Emmanuel College is evaluating radiation data attained in space for spectral distribution, magnetic effect,, and other solar and geophysical parameters of interest.

The Johns Hopkins University is studying the effect of geomagnetically trapped radiation on spacecraft components.

Litton Industries Incorporated is investigating sputtering effects on the moon's surface.

Ling Tempco Vought Aerospace Corporation is studying solar activity for optical and radio-frequency inputs for the Solar Particle Alert Network to provide the Apollo program with warnings of impending solar flare particle events.

Rand Corporation is investigating the effects of space radiation on the lifetime of communication satellites.

Union Carbide Corporation, Tarrytown, is doing cross-section calculations and study of space vehicle shielding.

University of Berne is studying radiation in space.

University of Lund is studying the charge spectrum of the primary cosmic radiation and of high-energy nucleus-nucleus collisions.

U. S. Air Force, Cambridge Research Laboratories, is investigating solar extreme ultraviolet and X-ray photon fluxes (XUV) and their interaction with the natural aerospace medium, vehicle surfaces, and exposed objects.

U. S. Air Force, Cambridge Research Laboratories, is studying the upper atmosphere and near space beyond the height of the F-layer using rocket probes and satellites.

*Detailed information on these programs is given in REIC Memorandum 29, "Compilation of Pulsed, and Space Radiation Effects Projects", April 15, 1966.

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SECTION F

NEUTRON AND GAMMA DOSIMETRY

SECTION F

NEUTRON AND GAMMA DOSIMETRYCurrent State of the Art

Recent work in nuclear dosimetry has been diverse, resulting in the improvements of specific concepts for particular situations rather than the introduction of new methods or general procedures. Basic problems plaguing the work have been interference from disparate background radiations, radiation-induced degradations of detector parameters, and insufficient response range for high exposure levels or high rates. Most studies have concerned solid-state neutron detectors, high-resolution solid-state gamma spectrometers, and luminescent dosimeters. Advances have appeared more as refinements of established techniques than as significant expansion of the capability of measuring radiations.

Neutron DosimetryDynamic Neutron Detector

Steady-State Applications. The quest for more thorough and accurate radiation measurements for better interpretation of radiation-effects studies demands more sensitive and flexible dosimetry systems, preferably operable continuously and simultaneously with long-term experiments. At the same time, the trend toward higher operating powers, temperatures, and pressures puts increasingly severe demands upon the integrity of the systems devised.

A number of techniques are applied to in-core measurements of radiation. The most common in-core device is the reliable ionization chamber, lined with boron-10 or uranium-235 (fission chamber) and perhaps a compensating fertile nuclide. Ion chambers exhibit signal rise times of several milliseconds and discriminate well against gamma rays. Most have linear working ranges to 10^{14} n cm⁻² sec⁻¹. Forster⁽⁶⁶⁾ designed chambers with life expectancies of 10^{21} n cm⁻² at 290 C and 1000 psi. Others appear reliable at temperatures up to 480 C in gamma fields of 10^8 R/hr.

Solid-state devices combine some of the advantages of ion chambers with a small physical size (e. g., 1-mm diameter by 0.5-mm thickness) for convenient access to operating radiation sources. They display an instantaneous response over a wide neutron-flux range with low gamma sensitivity. The neutron-detection mechanism is based on the liberation of charged particles by a neutron sensor (uranium-235, lithium-6, etc.). These charged particles in turn produce ion pairs in the silicon or germanium semiconductor devices. Such devices can be used for maps of neutron flux and/or spectra. (67, 68)

Two major problems with solid-state detectors threaten to limit their increased use. They are normally restricted to temperatures below about 200 C and are subject to rapid degradation due to lattice damage, being unreliable after exposure to about 10^{13} n cm⁻². Silicon carbide offers some improvements over silicon and germanium. It has sustained temperatures up to 800 C and neutron exposures of 10^{15} n cm⁻². Further increase of the damage threshold appears possible.

An important addition to the methods of in-core neutron-flux measurements was the introduction of self-powered beta-current detectors. These consist of two concentric electrodes which emit different current densities under neutron bombardment. Emitter electrodes made of rhodium or vanadium undergo radiative capture reactions to produce beta-active nuclides. The subsequent beta emission establishes a voltage drop between emitter and collector to power the device. Hilborn⁽⁶⁹⁾ improved the basic concept by insulating the electrodes with solid, inorganic, radiation-resistant dielectrics (e. g., MgC or Al₂O₃). This permits smaller, more rugged designs suited to high-temperature, high-flux environments. Units of 2-mm diameter are available for operation at 500 C in 10^{15} n cm⁻² sec⁻¹. Sensitivity is on the order of 10^{-20} amp per n cm⁻² sec⁻¹, with a burnout rate of 10^{-20} percent per n cm⁻². Response time of such detectors depends on the half-life of the beta-active emitter. For a rhodium emitter of 42-second half-life, the response rises to 63 percent in 60 seconds, following a change in neutron density, and to 99 percent in 280 seconds. Faster response can be obtained with such emitter isotopes as boron-12 or lithium-8, or by using the internal-conversion electron lines associated with prompt-gamma emission following neutron capture in such nuclides as Cd¹¹³, Sm¹⁴⁹, Gd¹⁵⁵, Gd¹⁵⁷, Dy¹⁶⁴, and Hg¹⁹⁹,⁽⁷⁰⁾ but at a sacrifice of sensitivity due to smaller reaction cross sections.

Thermoelectric devices have been applied to the measurement of core neutrons by means of the heat of nuclear reactions occurring in a neutron sensor. In thermocouple-type detectors (sometimes called neutron thermometers) heat is produced at the sensor (hot) junction by neutron reactions in a coating (e. g., uranium or boron) on the junction. The heat produced is proportional to the thermal-neutron flux. Stacks of thermoelements may be built to increase the emf generated by coating alternate junctions with uranium or boron. Sensitivities of 10^{-14} volt per n cm⁻² sec⁻¹ have been achieved with response linearity to 10^{14} n cm⁻² sec⁻¹. Time constants vary with design, ranging from 200 milliseconds⁽⁷¹⁾ to 10 seconds. Rispoli⁽⁷²⁾ reported a 32-junction Chromel-Alumel device, with boron as the sensor, which displayed linear response to more than 10^{12} n cm⁻² sec⁻¹ with a 3-second time constant. The device was compensated for gamma radiation and experienced little effort due to environmental temperature changes. A regenerative sensor such as natural uranium should serve to more than 10^{22} n cm⁻² if the severe nonnuclear environment and the mechanical integrity permit.

Transient Applications. The analysis of exposure-rate effects in transient-radiation-effects studies is only as reliable as the determination of the instantaneous dose rate. Dynamic dosimeters employed to monitor pulsed-radiation sources must respond accurately to high-intensity bursts of short duration. A brief survey of such dynamic devices appears to Reference (75). The normal procedure is to view and record the pulse shape from a dynamic gamma sensor while neutrons are monitored by integral dosimeters. The pulse shape determined by the gamma sensor is then applied to the activity of the integral neutron detector and assumption of direct proportionality determines the instantaneous neutron flux.

Perkins and Bailey⁽⁷³⁾ relate their experiences with pulsed-radiation dosimetry in which sulfur pellets served as fast-neutron detectors with corrections applied to the induced activity for changes in geometry and neutron scatter. Problems encountered with the silver-activated glass fluorods used for gamma dosimetry included continued activation by postburst residual gamma rays, and proper standardization of the rods, since discrepancies of 25 percent were noted between glasses of high and low mass numbers. The authors point out that the response of integral dosimeters must be normalized for pulse-width differences as well as for integrated-dose differences. Two bursts may produce the same total dose, and perhaps the same average dose rate, but differ considerably in their peak dose rates.

Summary. In summary, the present state of the art of dynamic in-core neutron-flux measurements recognizes ion chambers as the best and most convenient system. They are rated up to 10^{21} n cm⁻² in fields of 10^{14} n cm⁻² sec⁻¹ and 10^8 R hr⁻¹ gamma at 480 C and 1000 psi. Beta-current devices demonstrate linear signals without an impressed voltage in fluxes up to 10^{15} n cm⁻² sec⁻¹ and at temperatures up to 500 C. Sensitivity is adequate at 10^{-20} amp per n cm⁻² sec⁻¹, with excellent life potential due to a burnout rate of only 10^{-20} percent per n cm⁻². However, their long response time makes them unsatisfactory for control or for other applications requiring a rapid response.

Solid-state devices do not have the service life to make them useful for in-core neutron monitoring. The present damage threshold remains 10^{13} n cm⁻², with promise of extension to 10^{15} n cm⁻² by using silicon carbide. The simplicity and good sensitivity of thermoelectric monitor systems make them attractive for neutron fluxes up to 10^{14} n cm⁻² sec⁻¹ at very high temperatures. However, the problems inherent in ordinary high-temperature measurements are magnified in the radiation environment and realization of the 10^{22} n cm⁻² potential of these systems is difficult. Hawkings⁽⁷⁴⁾ has prepared a summary of in-core measurement methods which is an excellent source of further details and references.

Radioactivant Techniques

Radioactivant techniques comprise the most commonly used procedure for the determination of neutron fluxes and energy spectra. The importance of these techniques to radiation-effects programs warrants continued efforts to improve and expand the concept. Recent work has remained centered on the principal detector foils - e. g., sulfur, nickel, and uranium - and analysis of the data generated. The REIC state-of-the-art report of 1965⁽⁷⁵⁾ describes some of the approaches for reducing measured detector activities to descriptions of neutron-energy spectra. Determination of more accurate cross-section data for commonly used detector isotopes is paramount to significant improvement of spectral definition. Error analyses indicate that accurate cross-section data for a few detectors are more valuable and definitive than moderately precise data for many detectors. The American Society for Testing and Materials maintains a subcommittee on neutron dosimetry which has recognized the need for improved cross-section data and has urged more effort in this area. The subcommittee plans a review of current literature to evaluate the data available for several important reactions and will recommend differential cross-section values to be used for these reactions. A tentative method for measuring fast-neutron flux by analysis of the molybdenum-99 activity from the fast fission of uranium-238 is in the final stages of preparation by the subcommittee.

The (n,p) reaction in nickel-58 is a convenient monitor of fast-neutron exposure. The reaction product, cobalt-58, occurs in ground and isomeric states. Both states are subject to serious burnup due to their respective thermal-neutron-absorption cross sections of 10^3 and 10^5 barns. Martin and Clare(76) have considered the need for burnup corrections and concluded that at thermal-neutron fluxes above 10^{13} n cm⁻² sec⁻¹, determinations of fast-neutron flux by means of nickel are unreliable unless burnup corrections are determined for the particular irradiation facility and applied to the saturated cobalt-58 activity. The correction is dependent upon the neutron energy distribution of the facility because the energy distribution determines the branching ratio between the production of cobalt-58 and cobalt-58m.

For integration of the thermal-neutron exposure in long-term, high-temperature irradiations, Nyboe and Barr(77) have suggested a small cobalt wire dosimeter sealed in silica and placed in concentric molybdenum and graphite tubes. It would be useful to 10^{21} n cm⁻² at temperatures up to 1500 C. Chemical incompatibility demands separation of the molybdenum and graphite and the device is bulky for most in-capsule fuel experiments, being about 1.5 inches square.

Gamma-Ray Dosimeters

Luminescent Dosimeters

Luminescent dosimeters have become increasingly more important to dosimetry. They are small and rugged enough for general use. Cylinders 1 millimeter in diameter and several millimeters long are common and practical, but larger sizes and other shapes are available. Problems arise from variations of the response and characteristics noted within different batches of the same kind of glass or phosphor. Such variations are usually ascribed to differences in the raw materials used. Instability and nonlinearity of readers also affect reliability. These two conditions need not hinder the quality of the dosimeter systems, however, if the stock and the reader instruments are calibrated properly.

Radiophotoluminescence in silver-activated phosphate glass provides a measure of incident gamma dose. Gamma rays energize centers in the glass which will fluoresce upon subsequent exposure to ultraviolet radiation. The orange light that is emitted is measured by a fluorimeter equipped with proper optical filters, the photocurrent being proportional to the radiation exposure. This system is well developed and reliable. Fluorimeters are available commercially for several glass shapes, though the miniature cylinders are most prevalent. The practical lower limit for the phosphate glass appears to be about 10 rads, bounded by background fluorescence. With extreme care and effort to control background and fluorimeter instability, the range has been lowered(78, 79) to 10 mR + 15 percent standard deviation. The upper limit is determined by nonlinearity of response caused by optical darkening. The darkened glass attenuates the ultraviolet excitant leading to incomplete fluorescence. Small glass rods minimize this effect, permitting measurements to about 10^5 rads.

Response of radiophotoluminescent glass appears to be independent of exposure rate to at least 10^8 rad sec⁻¹, and perhaps to 10^{12} rad sec⁻¹.(80) Precision seems adequate, with standard deviations of about 5 percent attainable over the response range.

Extraneous effects which can lower the efficiency and reproductibility of radiophotoluminescents are temperature, dependence upon gamma-ray energy, response to neutrons in mixed radiation fields, and diminution of fluorescence centers. Response has been noted to vary directly with irradiation temperature and inversely with reader temperature. Low-energy gamma rays produce an overresponse correctable with metallic shields. Response to thermal neutrons is several times the response to an equivalent dose of cobalt-60 gamma rays but can be reduced by shields of lithium or boron. The effect of fast neutrons is slight. Postirradiation storage diminishes the fluorescence to about 80 percent of its original level after a year.

The two thermoluminescent materials of prime interest are calcium sulfate and lithium fluoride. Calcium sulfate is the more sensitive, having measured^(81,82) cobalt-60 doses down to $20 \mu\text{R} \pm 50$ percent standard deviation. Linearity of response exists to about 10^4 rads, but severe fading is a major disadvantage. Luminescence diminishes to one-half within several hours unless stored below room temperature.

Lithium fluoride has found the most extensive use as a thermoluminescent phosphor because of several advantages, including slight gamma-energy dependence, exposure-rate independence, and good signal retention during storage. The usable range extends from less than 100 mr to saturation at about 10^5 R, although response becomes supralinear before saturation.

When used in pairs, lithium fluoride dosimeters can provide a measure of thermal-neutron dose if one is enriched in lithium-6 and the other in lithium-7. The former responds to both gamma rays and to thermal neutrons, the latter responds only to gamma rays. The difference in luminescence therefore provides a thermal-neutron dose estimate.

Lithium borate is being investigated⁽⁸³⁾ as a thermoluminescent dosimeter in the form of powder in glass needles. The minimum detectable exposure has been 100 mR.

In summary, radiophotoluminescence permits measurement accuracies of a few percent, being limited by differences between different batches of glass, increases in the optical density, temperatures, fading, and reader instability. The upper limit of 10^5 rads restricts radiophotoluminescent phosphate glass to situations in which the integrated exposure is small, or the radiation is delivered in pulses, between which the dosimeters could be changed. This eliminates the surveillance of many radiation-effects tests by this technique. The same features are true of thermoluminescents but their very small energy sensitivity, their value to health physics, and their possible use as dosimetry standards warrants their continued development, with emphasis on the upward extensions of their range capabilities. This may entail searches for new materials of lower specific sensitivity and extensions of linearity by heat treatment or other processes.

Attix⁽⁸⁴⁾ has compiled a thorough review of the methods of luminescent dosimetry which is recommended for additional information and references.

Semiconductor Gamma Spectrometers

Solid-state devices are more sensitive to charged particles than to gamma rays, but application to gamma-ray spectrometry is continuing. Beech, et al.,⁽⁸⁵⁾ have

described a two-crystal coincidence spectrometer for gamma-ray analysis in which a silicon surface barrier diode serves as the primary detector with an annular plastic scintillator for detection of backscattered photons. The Compton background is low in the 50 square millimeter detector, and resolution is 16 kev for cobalt-60 and 14 kev for cesium-137. The peak efficiency for cesium-137 is 40 percent (that is, 40 percent of all counts registered are under the cesium-137 peak), but the total detection efficiency is small at only 5×10^{-9} counts per disintegration.

Brune, et al., (86) report an investigation of a germanium semiconductor spectrometer which permitted determination of cesium-134 in a cesium-137 standard source. It also analyzed the potassium-42 content of biological specimens containing strong sodium-24 sources and completely resolved niobium-94 and niobium-95 activities.

Five previously unreported gamma rays were revealed in the ytterbium-177 decay spectrum by a germanium spectrometer described by Tavendale and Ewan. (87) These instances are typical of the results being achieved with semiconductor gamma detectors. But their major advantage, high resolution, is at least partially offset by their low detection efficiency and cryogenic operating temperature.

Miscellaneous Gamma Dosimeters

The ferrous sulfate dosimeter system has served as a standard gamma-dose monitor for radiation-effects investigation because of its reproducibility, well-determined response characteristics, and simplicity. It has a linear response of from 5×10^3 to 5×10^4 R. A thorough review of the ferrous sulfate system was prepared by Burke(88) and is recommended for a further discussion of its merits and uses and for numerous references.

A proportional counter for X-rays from 5 to 35 kev with a resolution of 13.5 percent and a count-rate capability of 50,000 per second has been reported. (89) The counter is cylindrical and contains four beryllium windows. Two windows are diametrically opposite and are used for detection of beams of 5 to 14-kev X-rays. Two windows are axially opposite for detection of 14 to 35-kev beams. The second window of each pair serves as an exit port for unabsorbed X-rays, minimizing backscatter.

A quantameter (an ionization chamber with multiple parallel plates) for monitoring high-intensity, high-energy gamma beams has been tested(90) and found to respond linearly with primary quantum energies up to 1 Bev. Output of the quantameter, that is the integral charge collected, is proportional to the total energy deposited in the device; it did not saturate at a beam power of 2 megawatt.

Programs in Progress*

Current programs in the field of dosimetry are summarized below.

Associated Universities, Inc., Brookhaven National Laboratory, is to design and evaluate isotopic sources and irradiators and to study processes and dosimetry methods.

Bell Telephone Laboratories is smoking electron-measurement experiments.

Edgerton, Germeshausen, and Grier is to develop instrumentation for measuring the electric-field component of simulated nuclear electromagnetic pulse.

Emmanuel College is doing an analysis of photographic emulsions exposed to Van Allen radiation and high altitudes.

General Dynamics Corp., General Dynamic/Convair, is doing spectroreflectometer studies.

General Electric Company, Missile and Space Division, is studying semiconductor detectors with surface electric field controlled by the contouring principle.

General Electric Company, Radiation Effects Operation, is developing solid state and secondary emission radiation detectors for pulsed radiation environments.

Illinois Institute of Technology Research Institute is validating high-energy neutron cross sections for 28 activation threshold detectors using the Operation HENRE neutron generator.

Litton Systems, Inc., is to obtain a quantitative correlation between the variations in surface structure as determined by low-energy electron-diffraction measurements and sputtering yields as determined by the spectroscopic emission technique.

Lockheed Aircraft Corp. is determining the effects of electrons on Pegasus meteoroid detection panels.

Massachusetts General Hospital is studying solid chemical radiation dosimeters.

Moleculon Research Corp. is doing research and development into new techniques for measuring nuclear radiation at very high exposures and very high exposure rates using permanent radiation-induced effects in plastics, thermoluminescent salts, and glasses.

North American Aviation, Inc., is developing a systematic accurate method of determining neutron radiation environments by foil activations.

Northrop Corp. is developing a neutron detector system capable of determining the absolute neutron energy spectrum as a function of time.

*Detailed information on these programs is given in REIC Memorandum 29, "Compilation of Pulsed, and Space Radiation Effects Projects", April 15, 1966.

Oak Ridge National Laboratory is using the Dosimetry Applications Research Facility for the development of instrumentation and techniques for the use of threshold detectors and counters in neutron-dosimetry counting methods in gamma-ray dosimetry, and spectrometers in neutron and gamma-ray dosimetry.

Pennsylvania State University is concerned with improvements in sensitivity which can be achieved by the use of high electric fields and by radiative stimulation of electron traps.

Philco Corp., Western Development Laboratory, is providing the necessary personnel, facilities, materials, supplies, and services to design, develop, test, fabricate and qualify a Nuclear Particle Detection System for the Apollo vehicle.

Solid State Radiations, Inc., is developing a high altitude radiation instrumentation system (HARIS).

Solid State Radiations, Inc., is developing methods to produce Germanium PIN and surface barrier nuclear particle detectors for charged particles and γ rays.

Stanford Research Institute is to do X-ray flux and spectral measurements.

Texas Nuclear Corporation is to develop radiation dosimeters and radiation dosimetry for proton accelerator facilities.

Tracerlab is to develop a dosimetry system to measure electron exposures from 0.5 to 7×10^6 rad on a production line using remote readout.

University of California, Los Alamos Scientific Laboratory, is developing various radiation-detection devices for the Rover Program.

University of Wisconsin is to investigate thermoluminescent radiation dosimetry.

Westinghouse Electric Corporation is doing a feasibility study of a NAP radiation monitoring system using semiconductor rate-sensing devices.

U. S. Air Force, Special Weapons Center, is to develop instrumentation for use in AFSWC testing.

U. S. Army, Ballistic Research Laboratories, is to develop a neutron spectrometer capable of measuring neutron energies from 0.5 to 20 Mev from pulsed and steady-state sources.

NASA, Langley Research Center, is studying the effect of radiation on the degradation of solid-state radiation detectors.

U. S. National Bureau of Standards is developing a high-power fast-neutron field device.

U. S. Navy, Naval Research Laboratory, is studying the neutron response of $\text{Ca F}_2\text{:Mn}$ and other thermoluminescent dosimeters.

U. S. Navy, Naval Research Laboratory, is studying and designing a thermoluminescent dosimeter for unmanned space vehicles, capable of telemetering dose readings.

U. S. Navy, Naval Research Laboratory, is studying radiation characteristics of thermoluminescent dosimetry systems.

Conclusions and Recommendations

Suggestions of what dosimetry systems are available for particular applications appear in the text and in the references. These represent only a small portion of the techniques being practiced; the references and earlier REIC publications include many others.

Several devices are available for in-pile surveillance of neutron exposures. Radioactivants such as aluminum, phosphorus, sulfur, cobalt, nickel, iron, etc., can be used as integrating dosimeters for thermal and fast neutrons and neutron energy spectra. For measurements in harsh physical environments (low or high temperature, high vacuum, etc.), some of the common materials are not usable (e. g., aluminum, phosphorus, sulfur). Compounds or alloys which contain these elements, and which are impervious to the harsh environments are necessary. In addition they must be free of undesirable nuclear characteristics such as competing reactions which produce half-lives longer than that of the monitor isotope, and the inclusion in the compound or alloy of other elements which can yield the same reaction product as the monitor element. Small fission and ionization chambers and beta-current devices can be used as dynamic monitors except under pulsed conditions. Developmental effort in the area of dynamic neutron detectors for pulsed applications should be continued.

In the area of gamma dosimetry, the exposure limitations of current glass and chemical dosimeters are below the levels received in many high flux irradiations. Development of suitable in-pile dosimeters for exposures up to at least 10^{12} ergs g^{-1} (c) should be pursued.

Low (<100 kev)- and high (>10 Mev)-energy gamma dosimetries are becoming increasingly important. Techniques applicable to the efficient detection and spectral analyses of these energy regions are meager; development of such detectors and spectrometers is needed. Also important is the analysis of gamma spectra from pulsed reactors and considerable work is needed in this area.

SECTION G

STRUCTURAL METALS AND ALLOYS

SECTION G

STRUCTURAL METALS AND ALLOYSCurrent State of the Art

Radiation-induced changes in mechanical properties of structural materials are of extreme importance to people in the nuclear-reactor industry. Presently, the main emphasis is to test, evaluate, and select structural materials for application in fast reactors. Fast reactors require structural materials which can maintain strength and ductility after prolonged exposures to liquid metals at elevated temperatures and high stresses in a high fast-flux environment. These stringent mechanical-property demands have resulted in studying of irradiation performance of materials which had not been considered for application in thermal reactors. The materials which are currently receiving much interest for fast-reactor application are the alloys of vanadium, niobium, tungsten, molybdenum, and nickel. Considerable effort has also been expended in eliminating the elevated-temperature embrittlement of irradiated stainless steel and nickel alloys.

Stainless Steel

A considerable amount of research has been performed on the effect of irradiation on stainless steel during the past year. During recent years, it has been shown that irradiation temperature and testing temperature are both important in determining the mechanical properties of irradiated material. The trend appears to be that the most damage to the room-temperature properties results when the material is irradiated in the 200 to 400 C range. (91a, 92) This suggests that the irradiation-induced displacements are made more stable by irradiation in that temperature range. Irradiation above 500 C does not seem to affect the room-temperature properties of irradiated material. This is in good agreement with the annealing temperature that is required to remove irradiation-induced displacement-type damage. Low-temperature irradiations (~50 C) have been carried out to a fast-neutron accumulation of $2.1 \times 10^{22} \text{ n cm}^{-2}$. Testing of this material at room temperature and 316 C indicates that a saturation of irradiation effects on the mechanical properties occurs after an accumulated fast-neutron dose of $5 \times 10^{21} \text{ n cm}^{-2}$. (91b) No saturation effects in mechanical-property changes have been noted for austenitic stainless steel which has been irradiated at 200 to 400 C up to exposures of 10^{21} to $10^{22} \text{ n cm}^{-2}$. (91a)

Tensile tests on irradiated stainless steel below 400 C show increases in yield and tensile strength, with the yield strength almost equaling tensile strength at the saturation point. Total elongation of the material is reduced by about 50 percent. At elevated temperatures, (above 600 C) the irradiated specimens exhibit minor increases in strength accompanied by large reductions in ductility. Investigations of this elevated-temperature ductility decrease has received the most attention during the past year.

It has been previously found that failure in irradiated materials at elevated temperatures takes place by brittle intergranular fracture, while at low temperature, ductile transgranular fracture takes place. The cause of this fracture has been generally

attributed to formation of helium by various neutron-induced transmutations. (93) At low integrated mixed neutron fluxes the main source of helium is the reaction of thermal neutrons with boron-10 to produce helium and lithium. After an integrated thermal-neutron exposure of about 10^{21} n cm⁻², complete burnout of boron-10 has taken place but further helium production results in (n, α) reactions involving fast neutrons and metals such as iron, nickel, and chromium. The helium which is formed in these transmutations supposedly diffuses to the grain boundaries where it agglomerates in bubbles. Helium bubbles have been observed at the grain boundaries of irradiated stainless steel which has been tested at elevated temperatures. (91a, 94) The presence of helium bubbles at the grain boundaries supposedly changes the mode of fracture from ductile to brittle by providing sites for crack nucleation and also by reducing the effective grain-boundary area. Bombardment of austenitic stainless steel samples with alpha particles and lithium ions has been performed by the British. (95) On testing at 750 C, the bombarded samples showed a considerable ductility decrease. It was established that helium was the main cause in the ductility decrease since 100 times more lithium than helium was required to produce an equivalent ductility decrease.

Workers at Oak Ridge (96) and Harwell (93) have shown that the high-temperature ductility of irradiated material is dependent on helium content of the material. In these experiments, stainless steels containing varying amounts of boron were irradiated and then tested at elevated temperatures. Results of these experiments are shown in Figures G-1 and G-2. However, there are recent experimental data which suggest that there is no helium-dependent reduction in high-temperature ductility of irradiated stainless steel (Figure G-3). (91c) It has also been suggested that the helium produced in transmutation of boron is considerably more detrimental to elevated-temperature ductility than the helium caused by fast-flux transmutation of iron, chromium, and nickel. This is because boron precipitates at the grain boundaries of stainless steel; therefore, the transmuted helium resulting from boron-10 does not have far to diffuse in reaching the grain boundary. The fast neutrons produce helium uniformly throughout the matrix and considerable time is required for their diffusion to the grain boundaries. Attempts to remove the boron from grain boundaries and disperse it more evenly throughout the matrix have been somewhat successful. This has been accomplished by addition of titanium to the stainless steel. (96) Since titanium is a strong boride former, small particles of titanium boride are formed throughout the matrix and these particles act as trapping sites for the transmuted helium. The addition of 0.2 wt % titanium has resulted in improved ductility after irradiation, but further additions above that amount do not seem to have any effect. Another explanation for the improvement in elevated-temperature ductility of irradiated material with titanium additions may be the grain-size reduction accompanying addition of titanium. Stainless steels with small grain size have shown better elevated-temperature ductility after irradiation than have large-grained stainless steels. (97)

As previously mentioned, the fracture mode of stainless steel has been changed by irradiation. Instead of the formation of cavities at grain boundaries by vacancy diffusion, the fracture takes place by formation of wedge-type cracks which are supposedly promoted by helium bubbles. (91d) Aging of stainless steel before irradiation results in rounding of carbide particles at grain boundaries. These rounded particles have the effect of increasing the stress necessary for the formation and propagation of wedge-type cracks. (96) Increasing the carbon content from 0.02 to 0.06 percent has improved the elevated-temperature ductility of irradiated material by providing more carbide precipitates which anchor the helium atoms and prevent them from reaching grain boundaries. (98)

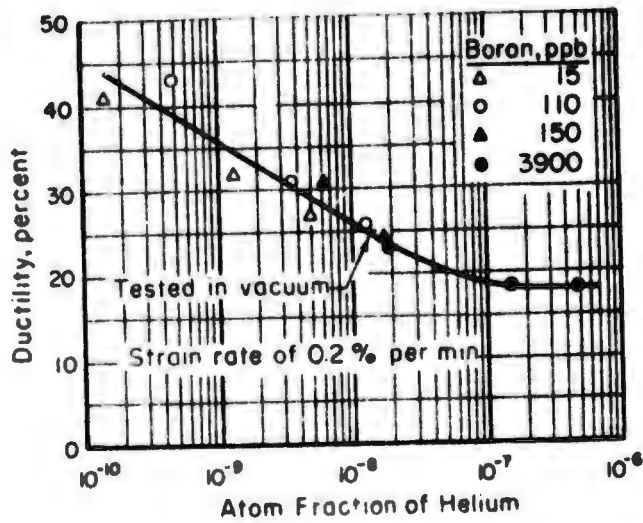


FIGURE G-1. IRRADIATION EMBRITTLEMENT OF BORON-STAINLESS STEELS AT 700 C AS A FUNCTION OF TOTAL HELIUM CONTENT⁽⁹⁶⁾

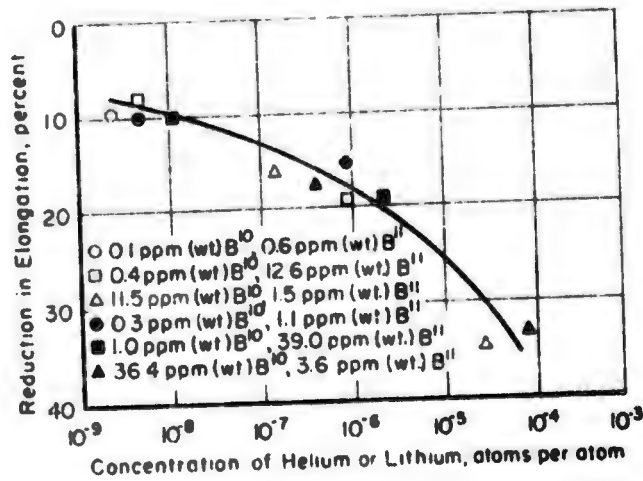


FIGURE G-2. TENSILE TESTS AT 750 C ON 20 PERCENT CHROMIUM, 20 PERCENT NICKEL, TITANIUM STABILIZED STEELS IMPREGNATED WITH B^{10} OR B^{11} IRRADIATED TO VARIOUS THERMAL-NEUTRON DOSES AT 40 C⁽⁹³⁾

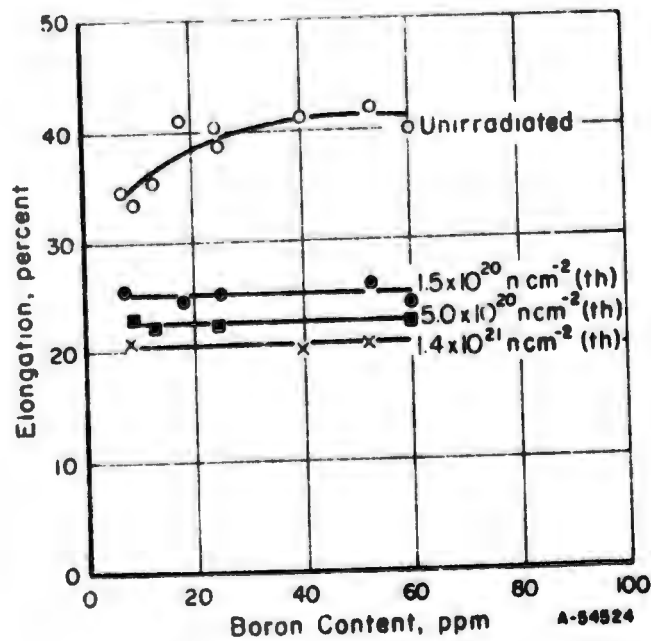


FIGURE G-3. EFFECTS OF NEUTRON IRRADIATION AT 45 C ON THE ELONGATIONS TO FRACTURE AT 750 C OF SOLUTION TREATED 18-10-Nb AUSTENITIC STEEL AS A FUNCTION OF BORON CONTENT (HELIUM PRODUCTION)^(91c)

A theory for the formation of helium-gas bubbles at grain boundaries of irradiated stainless steel has been formulated. (91e) This theory stipulates that a critical minimum bubble size and applied stress are necessary for growth of helium bubbles at a given temperature. The magnitude of stress is believed to be more important than temperature in causing the movement of bubbles. A low strain rate is expected to give more time for the formation of bubbles during testing, and consequently lower ductility is expected. Experimental results indicate that a lower strain rate results in lower ductility of irradiated stainless steel when tested at 650 to 750 C. (91f)

It had been previously shown that increasing the irradiation temperature from room temperature to 700 C did not result in ductility differences for specimens tested above 700 C. (99) However, it has recently been shown that increase of the irradiation temperature above 700 C results in decreased ductility when specimens are tested above 650 C. (98) This seems to indicate that the type of damage is diffusion controlled, with 700 C being the temperature where diffusion becomes significant. Annealing of irradiated specimens for 1 hour at 1350 C before testing does not improve the ductility at 750 C, rather, the strength of the material is reduced. (91b) The most prevalent theory at the present time is that irradiation above 700 C or annealing above that temperature results in more helium diffusing to the grain boundaries and also the bubble size is increased due to agglomeration. No saturation effects in elevated-temperature ductility decrease in irradiated stainless steel has been detected for fast-neutron accumulations of up to $3 \times 10^{22} \text{ n cm}^{-2}$ (91f) (Figure G-4).

The effect of irradiation on cold-worked Type 316 and 348 stainless steel has been investigated to a limited degree. (91a, 100, 101) Material which has been cold worked 25 percent has been irradiated at room temperature, 280 C, and 750 C. Limited transverse tests performed at temperatures from room temperature to 750 C show that testing of the unirradiated cold-worked specimens in the transverse direction results in considerable increase in strength and reduction in elongation. Irradiation of the cold-worked specimens results in minor increases in strength and decrease in ductility when tested at room temperature. For specimens irradiated at 280 C, the annealed specimens exhibit considerably better ductility than the cold-worked material at all temperatures from room temperature to 750 C. (Figure G-5). Both annealed and cold-worked specimens irradiated at 750 C exhibit similar strength and ductility characteristics at all testing temperatures. (Figure G-6). This indicates that recovery and recrystallization of the cold-worked material takes place during irradiation at 750 C. It has been shown that for the cold-worked material irradiated at 50 C, saturation in irradiation effects on mechanical properties takes place after an irradiation of about $2 \times 10^{20} \text{ n cm}^{-2}$. (91f) No saturation effect was detected for cold-worked specimens irradiated at 280 C after a fast-flux accumulation of $1.5 \times 10^{21} \text{ n cm}^{-2}$.

Prestraining of specimens before irradiation does not result in improved ductility at 650 to 700 C after irradiation. (91f) (Figure 4). Improved ductility was expected to result from precipitation of fine carbide particles at the dislocations caused by prestraining. These carbide particles were to act as trapping sites for helium atoms and thus prevent their migration to grain boundaries.

Comparison of in-pile and out-of-pile creep tests on Type 304 stainless steel indicates that the creep rates are almost the same. (91g) However, since total elongation is reduced by irradiation, the rupture life of the irradiated specimens is reduced by a corresponding degree.

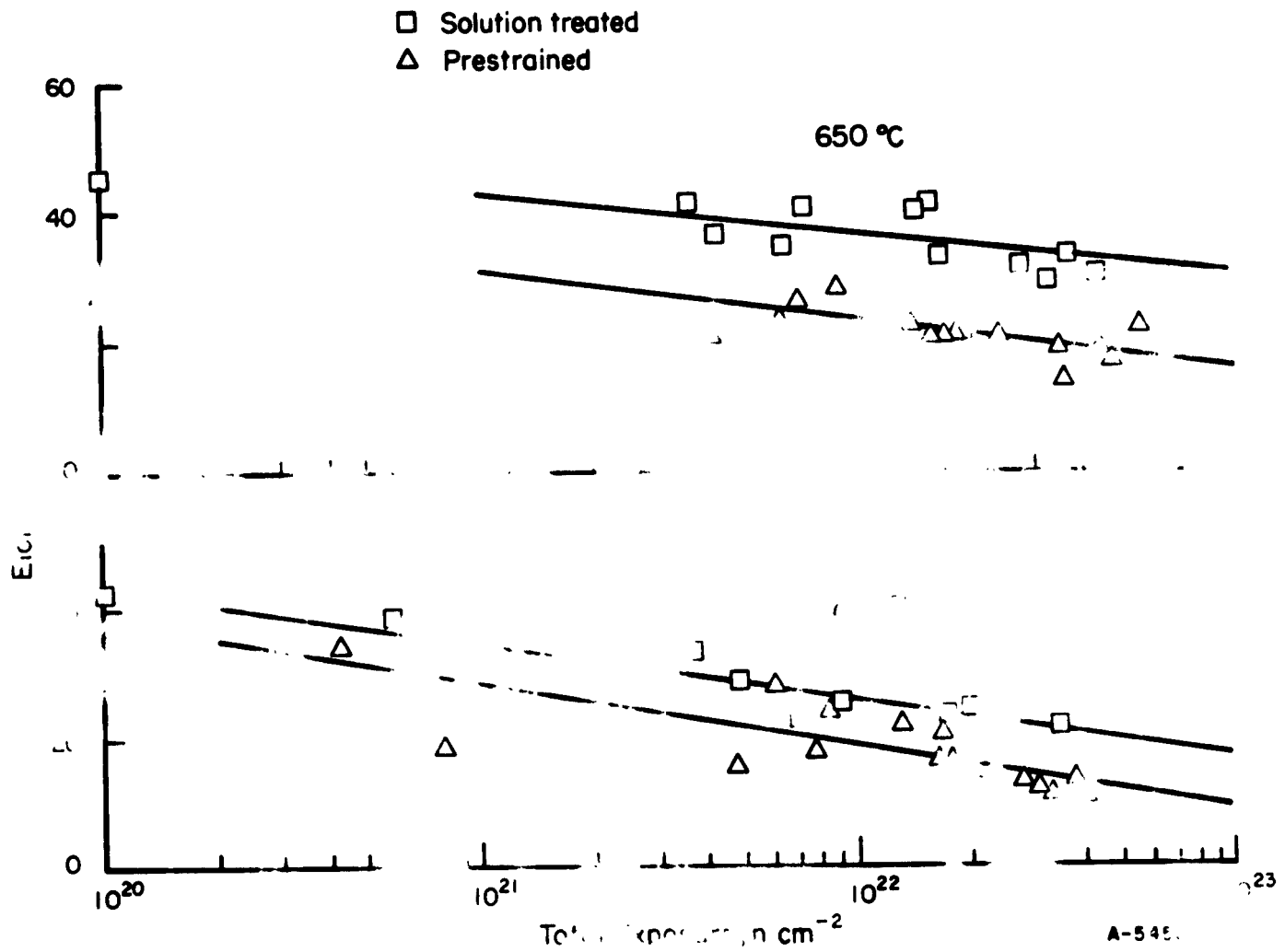


FIGURE G-1 DUCTILITY OF TYPE 304 STAINLESS STEEL AT 650 °C
 AND AFTER DIA TREATMENT TO 650 °C (910 °F)

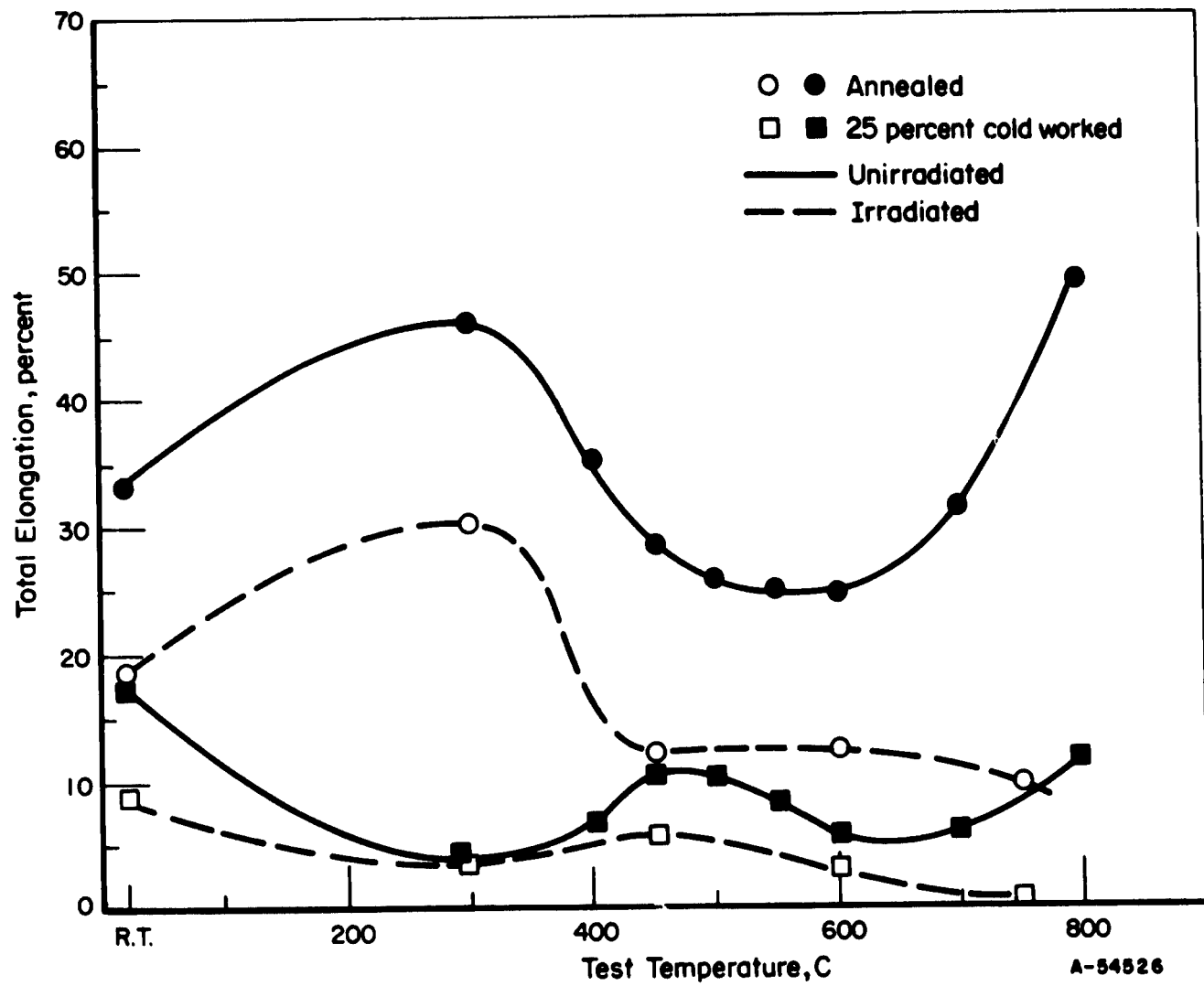


FIGURE G-5. EFFECT OF TEST TEMPERATURE ON THE DUCTILITY OF IRRADIATED AISI 316-L STAINLESS STEEL(100)

Irradiation temperature ~ 280 C.

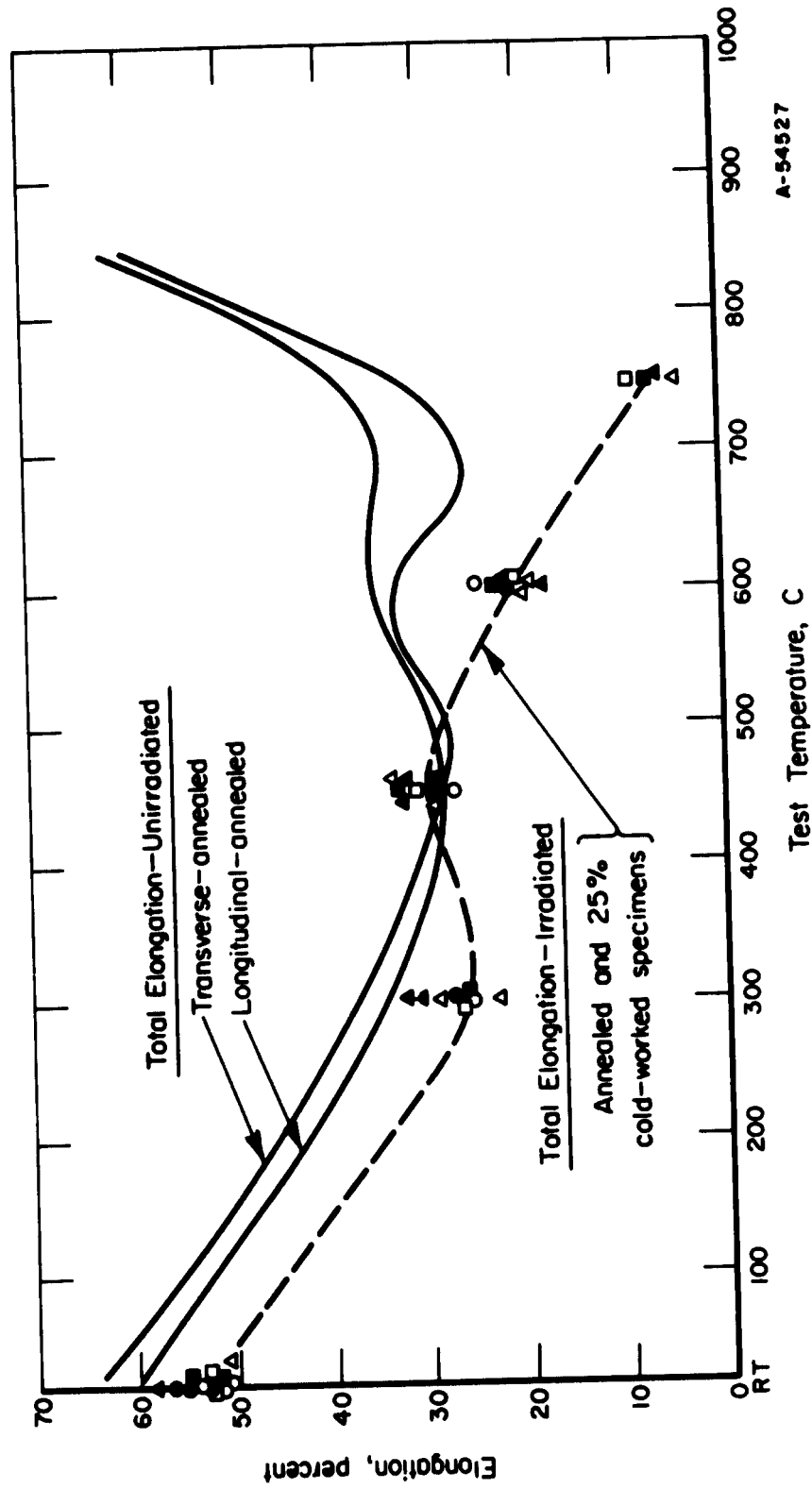


FIGURE G-6. EFFECT OF TEST TEMPERATURE ON THE DUCTILITY OF IRRADIATED TYPE 348 STAINLESS STEEL(101)

Irradiation temperature ~ 750 C.

There appears to be two distinctly different mechanisms which change the mechanical properties of stainless steel during irradiation. Irradiation of specimens below about 500 C results in a defect type of damage which increases strength and decreases ductility. Annealing or irradiating the stainless steel at about 500 C results in removal of this type of damage. Testing or irradiating the material above ~600 C results in drastic decreases in ductility which are accompanied with minor changes in strength. The second type of damage is presently attributed to formation of helium bubbles at the grain boundaries during irradiation at high temperature or their formation when the sample is heated to its testing temperature and also when the specimen is being stressed during testing. The second type of damage cannot even be annealed out at temperatures as high as 1350 C and it appears that annealing at high temperatures results in further deterioration of elevated-temperature properties. In evaluating the effects of elevated-temperature irradiation on stainless steels it must be borne in mind that significant property changes will result if the material is exposed to the same temperature conditions for equivalent times out-of-pile. Therefore, control specimens must be exposed to thermal histories similar to those experienced by the irradiated specimens during irradiation.

Nickel-Base Alloys

As the temperature requirements of reactor components have increased, more interest has been shown in nickel alloys. Nickel alloys generally have higher strength and corrosion resistance at elevated temperatures than have stainless steels.

Tensile tests have been performed on irradiated nickel alloys at temperatures up to 650 C. (91h, 102, 103) The alloys tested included both solution and precipitation hardened alloys which had been irradiated at 50, 280, and 740 C. The alloys irradiated and tested were Inconel 600, Inconel 625, Inconel 702, Inconel 718, Incaloy 800, Hastelloy C, and Hastelloy N. The maximum fast-neutron accumulation for these specimens is about $1 \times 10^{21} \text{ n cm}^{-2}$, with the thermal flux being about twice that. For interpreting the test results of the irradiated specimens, control specimens were given thermal treatment equivalent to that undergone by the test specimens during irradiation. The strength and ductility of the unirradiated materials decreased; this was attributed to aging of the material. It was found that the mechanical properties of materials irradiated at temperatures below 280 C and tested at room temperature did not differ significantly from those of the unirradiated controls given the identical thermal treatments. However, testing at 650 C of the materials irradiated at 280 C resulted in minor changes in strength accompanied by large reductions in ductility. Irradiating the materials at 740 C resulted in further reductions in ductility when tested at 650 C. Irradiation at 740 C was also found to cause a reduction in ductility in specimens tested at room temperature. In general, the poorest ductility and strength were exhibited by specimens tested at high temperatures after they had been irradiated at 740 C. The effects of irradiation on mechanical properties were found to increase with increasing fast flux, especially when the specimens were irradiated at 740 C.

Irradiations of nickel alloys have been carried out in predominantly fast fluxes and in mixed fluxes. (104) Inconel 625 and Hastelloy X specimens were irradiated at temperatures of 540 to 700 C and tested at 595 and 700 C. The results indicate that specimens irradiated in a mixed thermal and fast flux experienced larger decreases in ductility than did those irradiated in a predominantly fast flux. However, the specimens in the mixed flux were irradiated three times longer and at 700 C, while those in the

predominantly fast flux were irradiated at 540 C. These factors of time and temperature may cause a sufficient degree of aging to take place which may account for the differences in elevated-temperature properties of the materials irradiated in different fluxes.

British experience with PE-16, which is an age-hardenable nickel-base alloy, indicates that material which has been irradiated at 250 to 350 C in predominantly fast flux to neutron exposures of $3 \times 10^{22} \text{ n cm}^{-2}$ loses all of its ductility at 700 C but retains up to 10 percent total elongation at 650 C. (91f) The strength of the material was not changed by irradiation. (Figure G-7). These data indicate that 700 C may be a temperature limitation for irradiated nickel-base alloys.

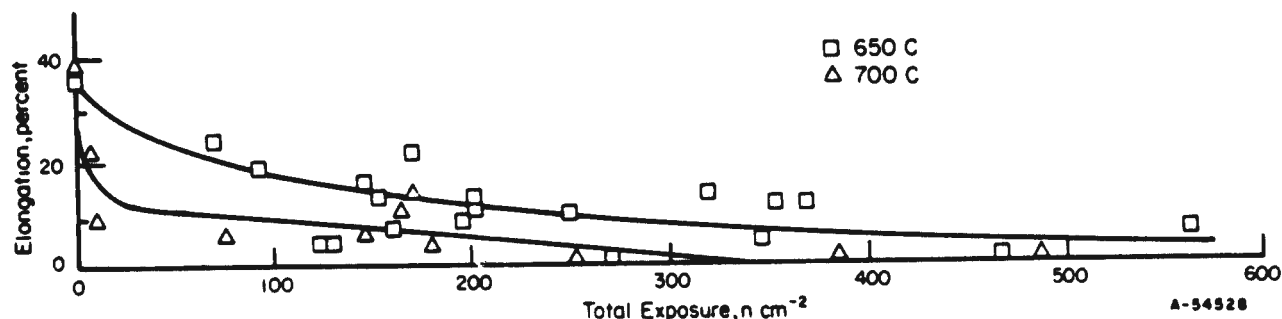


FIGURE G-7. ELONGATION OF FULLY HEAT-TREATED PE-16 AT 650 AND 700 C AFTER IRRADIATION AT 250 TO 350 C (91f)

In comparing the irradiation-induced ductility losses of nickel alloys at elevated temperatures with the ductility losses of stainless steels at equivalent temperatures and neutron fluxes, it is seen that the nickel alloys give considerably poorer performance. (Figure G-8).

The embrittlement of nickel alloys at elevated temperatures by irradiation has been attributed to helium formation by a mechanism similar to that experience in stainless steel. However, it must be remembered that these nickel-base alloys are metallurgically complicated and considerable strength and ductility was lost by overaging. Therefore, a possibility exists that irradiation-enhanced precipitation may play a significant role in the loss of ductility at elevated temperatures. The helium contribution can be discounted to a large degree, since the large number of precipitates available should be able to anchor the helium and prevent its agglomeration as bubbles at grain boundaries. (91h)

It has been shown that ductility of irradiated Hastelloy X-280 at 730 C can be improved by a factor of two by aging the solution-treated material at 815 C for 24 hours before irradiation. (105) The improvement in ductility is attributed to formation of fine precipitates during aging which act as sinks for the helium atoms and prevent their agglomeration as bubbles at grain boundaries.

Stress-rupture tests have been performed on irradiated Hastelloy-N at 650 (106-108) and 816 C. (106, 107) These specimens had received fast flux exposures of 5×10^{16} to $5 \times 10^{20} \text{ n cm}^{-2}$. It was found that the time to rupture was progressively reduced by increased fast-neutron exposure and this was attributed to a decrease in total

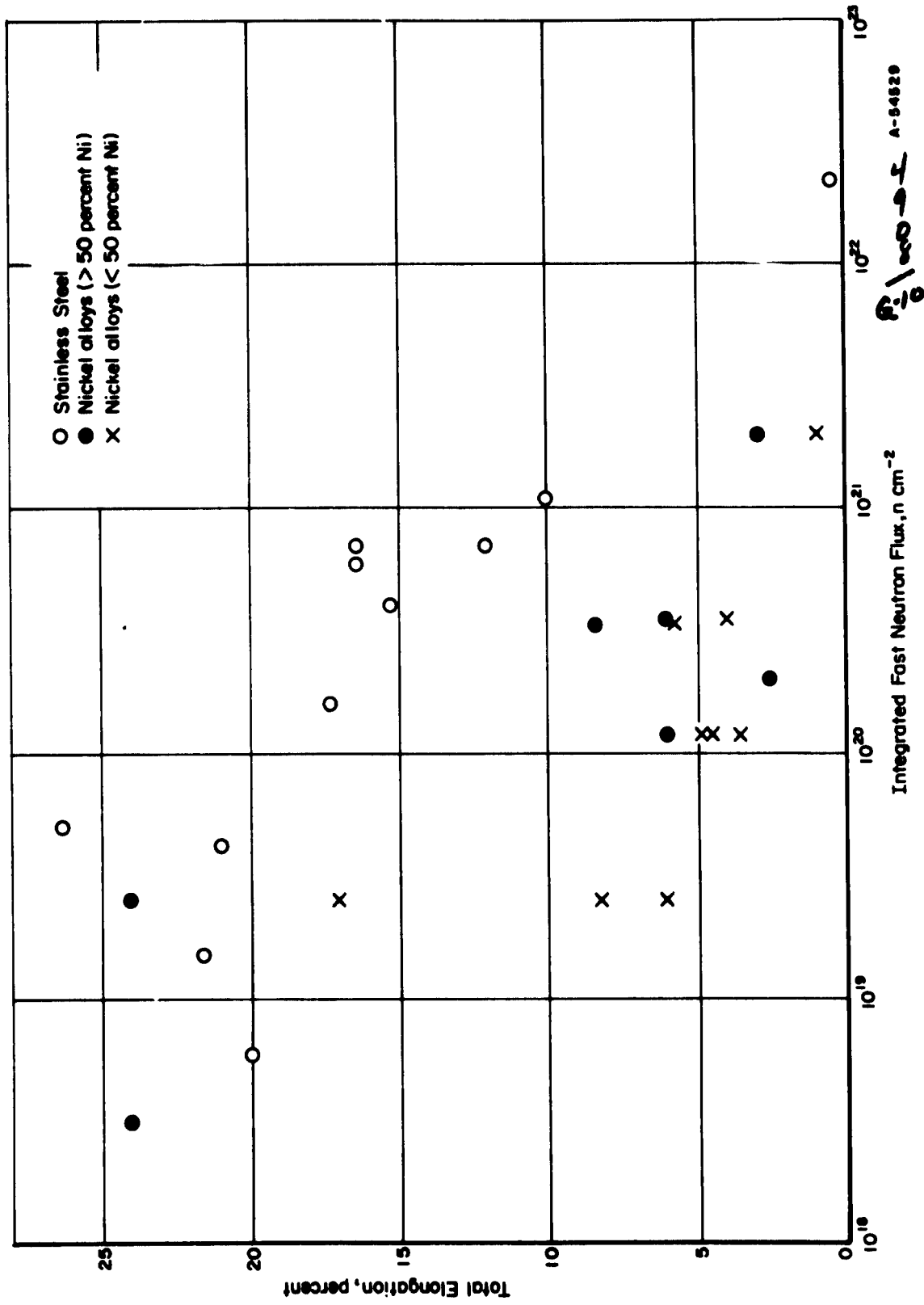


FIGURE G-8. EFFECT OF FAST-NEUTRON FLUENCE ON TOTAL ELONGATION OF IRRADIATED IRON AND NICKEL ALLOYS AT 700 TO 750 C

elongation of specimens before failure. At 816 C there was a smaller difference in life to rupture between irradiated and unirradiated specimens than had been observed at 650 C. Annealing of the irradiated specimens for 4 hours at 870 C did not improve the ductility or life of the specimens significantly. (107) It was found that material containing 7 ppm of boron exhibited considerably longer life than the alloy containing 40 ppm of boron. Therefore, the decrease in ductility in irradiated specimens is attributed to helium bubbles at grain boundaries. (108)

Pressure-Vessel Steels

Carbon and low-alloy steels are presently being used for pressure-vessel construction. The limiting factor in the use of these steels is the irradiation-induced embrittlement. This embrittlement results in the increase of the transition temperature where brittle instead of ductile fracture occurs. It has been shown that the ductile-to-brittle transition temperature in most carbon and low-alloy steels is linearly dependent on the fast-neutron accumulation (Figures G-9 and G-10). (109) The maximum shift in the transition temperature occurs when the irradiation temperature is about 200 C. Irradiation above that temperature removes most of the radiation damage and consequently the increase in transition temperature is smaller. Annealing of the irradiated material in the 350 to 400 C range results in almost complete restoration of the preirradiation mechanical properties. In comparing changes in ductile-to-brittle transition temperatures, great care should be taken to insure that the temperature changes are measured by the same criteria. The ductile-to-brittle transition temperature can be represented in the following ways:

- (1) The temperature where 50 percent of the fracture is due to shear
- (2) The temperature where 30 ft-lb of energy is required for fracture
- (3) The temperature at which a crack is initiated in a standard drop-weight test. (110)

The temperature from the drop-weight test is designated as nil-ductility temperature (NDT) and it has been shown to correlate with the temperature at which fracture occurs at 30 ft-lb of energy. (111)

Investigators at Harwell (112) have found that the irradiation induced changes in 0.24 percent carbon steel can be represented by the following formulas:

$$\text{Change in yield strength, } \Delta T_y(\text{psi}) = A(\phi t)^{1/2}$$

$$\text{Change in transition temperature, } \Delta T(\text{C}) = B(\phi t)^{1/2},$$

where A and B are material constants which vary with material composition and irradiation temperature, and (ϕt) is the fast-neutron exposure in units of $10^{18} \text{ n cm}^{-2}$.

There has been some speculation regarding the effect of neutron dose rate on irradiation-induced property changes. The settling of this question is of utmost importance because a reactor pressure vessel accumulates its fast neutron dose in about 40 years, while the specimens which are used to predict its behavior accumulate an

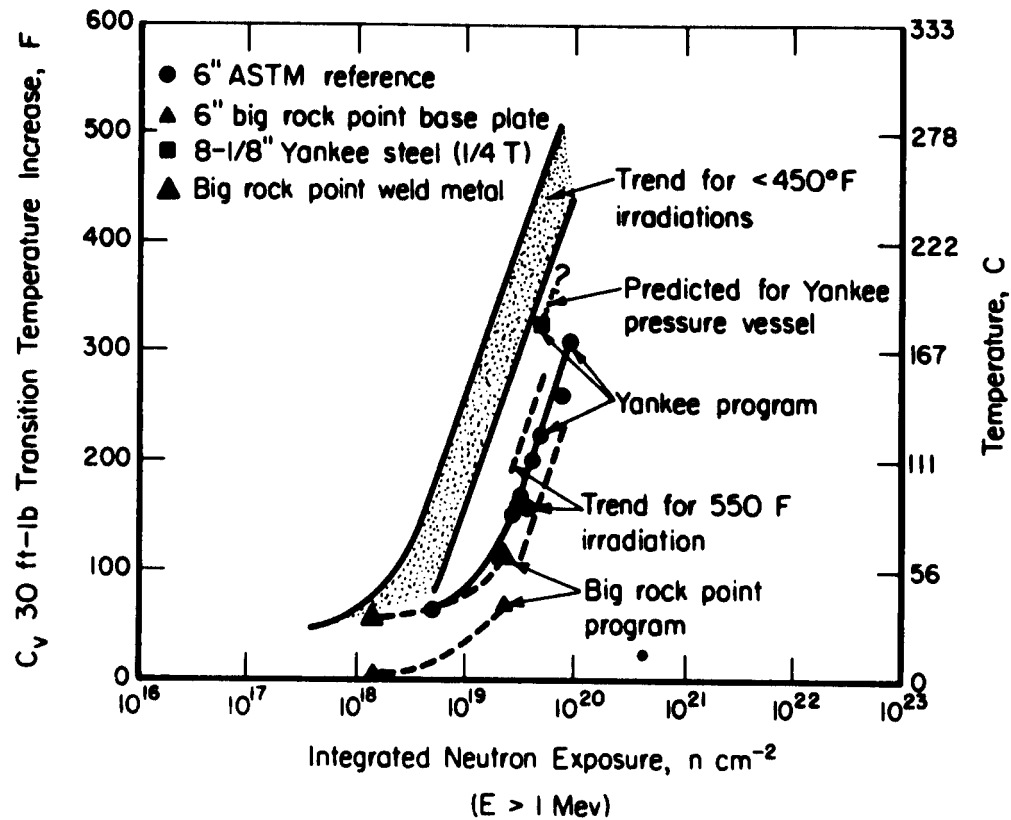


FIGURE G-9. CHANGE IN TRANSITION TEMPERATURES OF YANKEE AND BIG ROCK POINT PRESSURE VESSELS⁽¹⁰⁹⁾

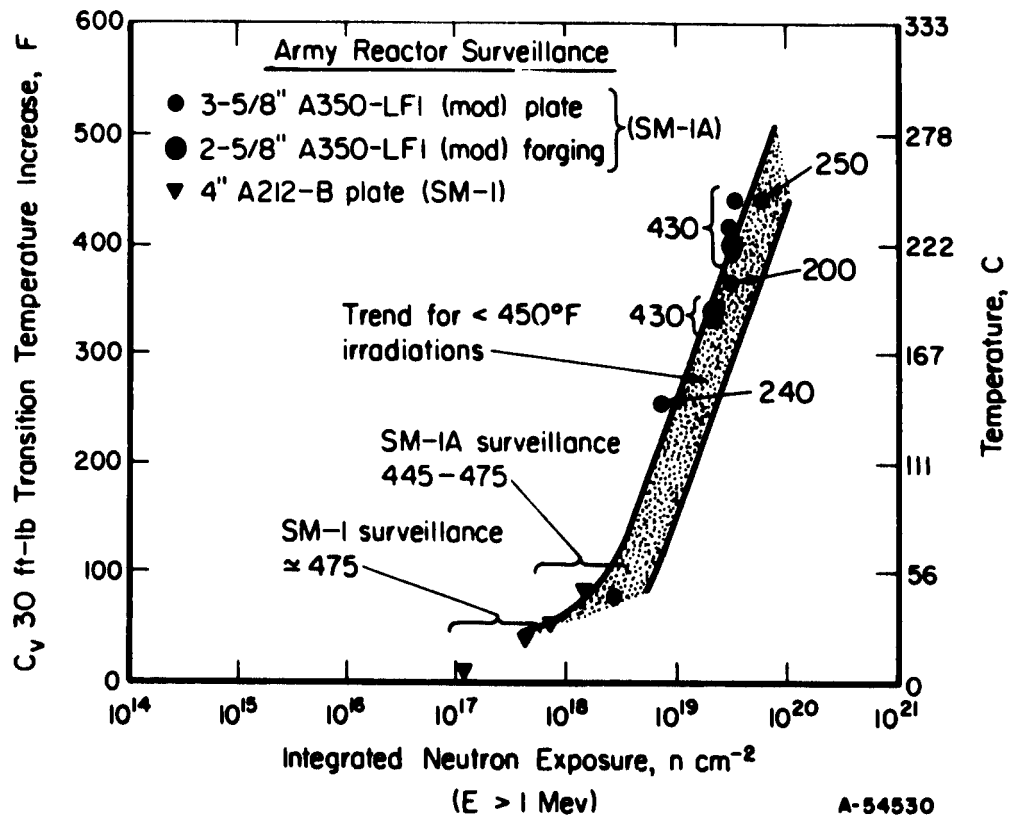


FIGURE G-10. CHANGE IN TRANSITION TEMPERATURES OF SM-1 AND SM-1A PRESSURE VESSELS⁽¹⁰⁹⁾

equivalent flux in a matter of months. However, recent studies have shown that no different irradiation-induced property changes are obtained at equivalent accumulated total fast fluxes with the dose rates varying up to a factor of 150. (94i, 113)

With increased pressure requirements in pressure vessels, it has become desirable to improve the performance of steels which are used for pressure-vessel construction. Therefore, medium-alloy steels with high yield strengths (80,000 to 180,000 psi) have been considered as substitutes for carbon and low-alloy steels. To determine the irradiation performance of the high-strength steels, the following steels were irradiated: 3.5 wt % and 7.5 wt % nickel-chromium-molybdenum steel, Armco SSS-100, 12 wt % nickel-5 wt % chromium-3 wt % molybdenum maraging steel, and 9 wt % nickel-4 wt % cobalt steel. (94j) Although only a limited number of tests have been completed on medium-alloy steels, the following conclusions can be made in comparing their performance with that of A212-B and A302-B, which are the most commonly used pressure-vessel steels at the present time.

- (1) The unirradiated high-strength steels have a lower nil-ductility temperature (NDT).
- (2) The high-strength steels undergo a smaller irradiation-induced increase in NDT.
- (3) The high-strength steels reach an earlier saturation limit in irradiation-induced property changes. This saturation limit is reached still earlier when the irradiation temperature is 290 C or above.
- (4) Lower radiation embrittlement is observed for the higher-strength steels after irradiation at 290 C.

To understand the mechanism of irradiation embrittlement, studies have been performed to determine the sensitivity of various metallurgical factors on irradiation embrittlement. The specific sensitivity to irradiation embrittlement in a given material has been attributed to interstitial content of the material. (113) It was also found that sensitivity to irradiation-induced change in NDT was a function of heat treatment. The irradiation effects on NDT of HY-80 and A350-LF3 steels could be varied considerably, depending on the heat-treatment-produced microstructure of the material. (91k) The smallest increases in NDT were experienced by materials which had been rapidly quenched and then tempered, while large increases in NDT were noted for materials which had been slowly cooled. It was therefore concluded that tempered martensite was less susceptible to irradiation-induced embrittlement than ferrite or bainite. Smaller amounts of residual elements were found to have no effect on susceptibility of low-alloy steel to irradiation embrittlement. (91k) Nickel content (from 4 to 8.4 percent) did not have any effect on irradiation susceptibility except in that it caused minor changes in the microstructure of the steel.

Figure G-11 illustrates the effect of grain size on increases in ductile-to-brittle transition temperature. (91l) It can be seen that a considerably better performance in reactor pressure vessels can be expected from fine-grained materials since they undergo a smaller change in ductile-to-brittle transition temperature.

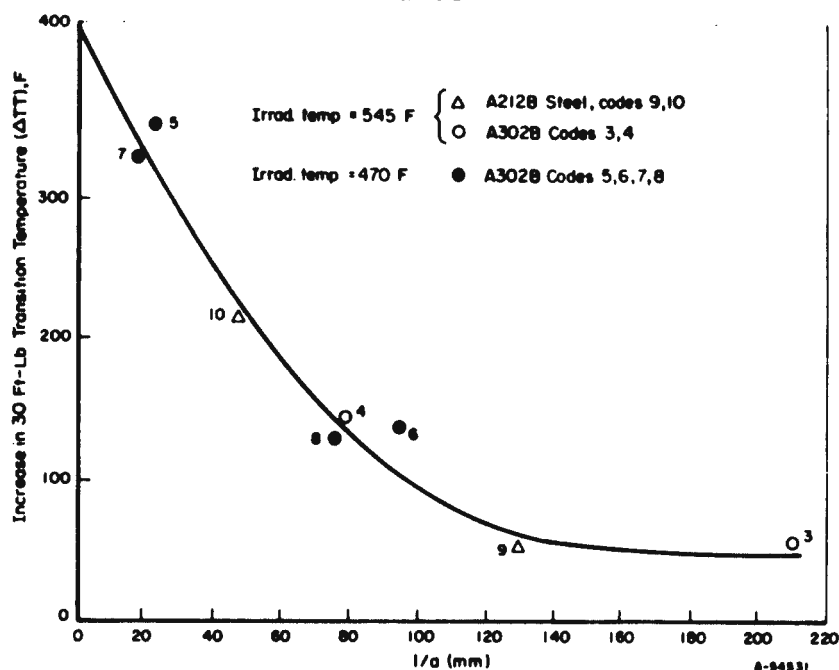


FIGURE G-11. INCREASE IN 30 FT-LB TRANSITION TEMPERATURE VERSUS RECIPROCAL GRAIN RADIUS FOR AN INTEGRATED EXPOSURE OF 3×10^{19} N CM² ($E > 1$ Mev) AT 470 TO 545 F(911)

It was found that stressing of ASTM A-302B steel during irradiation results in higher impact strength than was measured on material which was not stressed during irradiation. (114) This increase was noted even though the stressed steel received a fast-neutron exposure of 4.35×10^{19} n cm⁻², compared with an exposure of 2.64×10^{19} n cm⁻² received by the unstressed steel. Internal friction studies on irradiated materials indicate that irradiation enhances precipitation by providing sites for nucleation. (115, 121) Russian investigators have reported an irradiation-induced decrease in wear resistance in carbon steel irradiated to 1×10^{18} n cm⁻². (116) This result is not expected since hardness usually increases with irradiation.

For almost all power reactors which are in operation, a surveillance program is in progress which is designed to monitor irradiation-induced changes in properties of the pressure vessel resulting from operation. These surveillance programs usually employ Charpy V-notch specimens and tensile specimens which are located close to the pressure-vessel wall where they are expected to receive neutron fluxes and temperatures equivalent to those received by the pressure vessel. However, the construction of the pressure vessel prevents exact duplication of the irradiation conditions. Usually, the specimens are placed inside the pressure vessel where they receive an accelerated flux accumulation at somewhat higher temperatures compared with that experienced by the pressure-vessel wall. This is somewhat unfortunate, but it is deemed better than the other alternative of placing the specimens outside the pressure vessel where the rate of neutron accumulation and temperature are considerably lower. The purpose of accelerated neutron accumulation is to keep ahead of the neutron exposure of the pressure vessel so that the irradiation-induced property changes are known before the pressure vessel actually experiences them.

The first sets of surveillance capsules for the pressure vessels of Yankee, Army SM-1 and SM-1A, and Big Rock Point reactors have been tested. (109) The transition-temperature shift undergone by the surveillance specimens and the shift predicted by previous irradiation data are shown in Figures G-9 and G-10. Since the surveillance specimens for both Big Rock Point and Yankee Reactors were placed in front of the pressure-vessel wall, they were irradiated at a temperature somewhat higher than that experienced by the pressure vessel. Since the irradiation temperatures were somewhat higher, one would expect the shift in transition temperature to be lower. However, there appears to be good agreement between the data obtained in the surveillance program and that for test material irradiated at about 290 C, which is the estimated irradiation temperature of the surveillance specimens.

Zirconium Alloys

The main interest in Zircaloy-2 lies in its behavior due to a combination of irradiation effects and hydrogen pickup. The hydrogen pickup originates when water corrodes Zircaloy-2 resulting in the formation of ZrO_2 and hydrogen-gas release. A fraction (25 to 50 percent) of the released hydrogen diffuses into the Zircaloy-2 and forms zirconium hydride platelets. These plates have a somewhat detrimental effect on properties of the zirconium alloy. Figure G-12 illustrates the effects of hydrogen content and irradiation on impact strength of Zircaloy-2. (91m) It has been established that the effects of irradiation and hydrogen content are not additive and that the transition temperature approaches a limiting value.

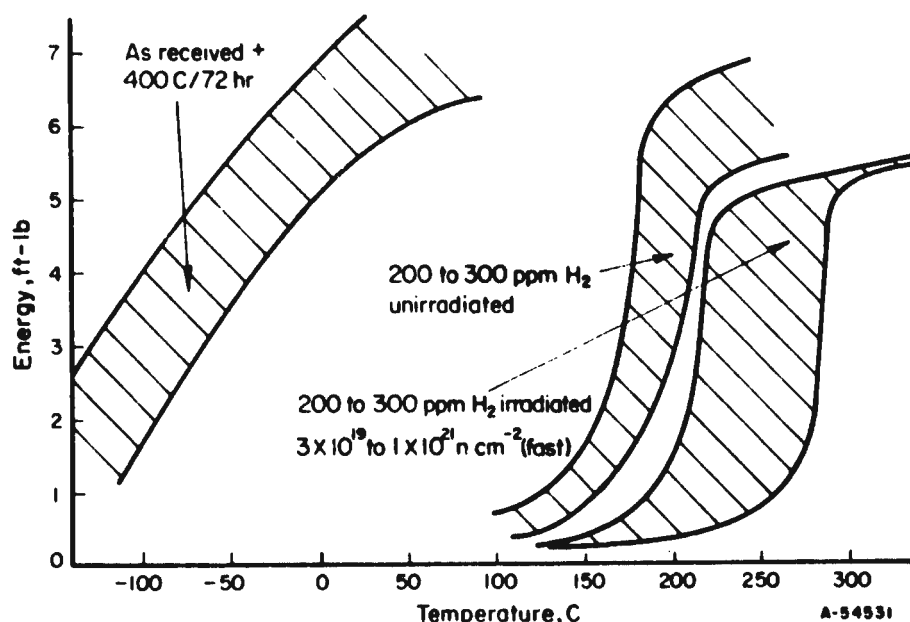


FIGURE G-12. EFFECT OF HYDROGEN AND IRRADIATION ON THE V-NOTCH IMPACT SPECIMENS OF COLD-WORKED ZIRCALOY-2(91m)

Indications are that specimens clad with Zircaloy-2 and irradiation at higher temperatures may be more stable than similar specimens irradiated at lower temperatures to the same neutron dose. This is due to the annealing out of irradiation damage in the

Zircaloy-2, which results in a considerable increase in ductility. With increased ductility, considerable straining of the cladding can be accommodated before failure occurs. Studies show that while only 1.5 percent strain can be accommodated before failure at an irradiation temperature of 350 C, a total of 7.5 percent strain can be accommodated before failure when irradiation occurs at 400 C. (91n) The above relationship was found to hold for cladding thicknesses of 20 to 30 mils. The above developments and a general interest in improving the performance in pressurized-water reactors have resulted in studies to determine Zircaloy properties at higher testing and irradiation temperatures. (91o)

Refractory Metals

Very few studies of irradiation effects on refractory metals have been undertaken. Limited high-temperature creep-rupture studies have been performed on tungsten, tungsten-25 wt % rhenium, and molybdenum. (117) In all cases, the material was irradiated at about 50 C, with the maximum fast-neutron accumulation being about $8 \times 10^{19} \text{ n cm}^{-2}$.

The irradiated tungsten specimens were found to undergo a five-fold increase in time to rupture at 1100 C when they had received an exposure of $8 \times 10^{19} \text{ n cm}^{-2}$. (117) A fast-neutron exposure of $1.6 \times 10^{19} \text{ n cm}^{-2}$ resulted in only a 30 percent increase in time to rupture. Increase in time to rupture for irradiated specimens was accompanied by a corresponding decrease in creep rate, with elongation at rupture being the same for both irradiated and control specimens. Annealing of the specimens for 1 hour at 1400 C before testing at 1100 C resulted in reduction of the rupture life from 5 fold to 3 fold above that of the control specimens. Testing of the irradiated specimens at 1700 C resulted in only a 9 percent increase in time to rupture. Since, at 1700 C, one expects the irradiation damage to be annealed out, the increase in rupture life is attributed to solution hardening of the matrix by transmuted rhenium and osmium atoms.

At 870 and 980 C, irradiated molybdenum specimens exhibited creep-rupture behavior identical to that of unirradiated specimens. (117) This indicates that irradiation damage was annealed out by the testing temperature. Consequently, creep-rupture tests were performed at 560 to 650 C and these indicated a large irradiation-induced increase in creep rate and consequently a reduction in time to rupture. The degree of creep-rate acceleration in irradiated material was found to decrease with increasing neutron exposure. This is attributed to a greater density of large vacancy clusters in the material which received a high neutron dose.

Irradiation of tungsten-25 wt % rhenium results in considerable improvement in rupture life when tested at 1100 C. (91p, 117) Again, no change in elongation is noted, and consequently, the irradiated specimens exhibit considerably lower creep rates. Testing of irradiated specimens at 800 C results in 100-fold reduction in creep rate compared with that of unirradiated controls. This is attributed to formation of a stable irradiation-induced defect which reacts differently with dislocations at 800 C than at 1100 C.

Limited tensile tests at room temperature and 1090 C have been performed on irradiated Cb-752, niobium-1 wt % zirconium, tungsten-25 wt % rhenium, TZM, and molybdenum. (91h) These specimens were irradiated at 50 C to a maximum fast-neutron accumulation of $5 \times 10^{20} \text{ n cm}^{-2}$. When tested at room temperature, the irradiated

refractory-metal specimens exhibited increases in yield and ultimate strength, as well as some decreases in ductility. Testing of the irradiated specimens at 1090 C resulted in restoration of preirradiation mechanical properties for CB-752, niobium-1 wt % zirconium, and molybdenum. This restoration of properties is attributed to annealing out of irradiation effects at the testing temperature. Increases in yield and ultimate strengths and a 40 percent reduction in total elongation were experienced by irradiated TZM and tungsten-25 wt % rhenium specimens tested at 1090 C. Increasing the fast-neutron exposure from 2.4×10^{20} to 5.6×10^{20} n cm⁻² resulted in progressive increases in yield and ultimate strength at 1090 C, but there was no significant change in total elongation.

Vanadium-titanium alloys have recently received consideration as cladding materials for fuel elements in fast reactors. Tensile tests have been performed on vanadium-titanium alloys containing chromium, niobium, or molybdenum and irradiated to a neutron exposure of 1.4×10^{21} n cm⁻² (>0.1 Mev). These tests were performed at 20, 200, 400, 650, and 750 C. These tests showed that (1) irradiation produces drastic reductions in elongation at room temperature accompanied by significant increases in yield and ultimate strength, (2) increasing the testing temperature results in annealing out of the irradiation-induced damage so that, at 650 and 750 C, the preirradiation mechanical properties are restored, and (3) increasing the titanium content of the alloys results in speedier recovery of preirradiation properties during annealing. Although the material contained significant quantities of boron, which was transmuted to helium by irradiation, no helium bubble-induced intergranular fracture was observed.

Programs in Progress*

Current programs on radiation effects on structural metals and alloys are summarized below.

Argonne National Laboratory is studying hydrogen embrittlement in irradiated steels and is determining irradiation-induced changes in mechanical properties of vanadium alloys.

Associated Universities, Inc., Brookhaven National Laboratory, is doing a fundamental study of neutron irradiation on the mechanical properties of iron and other bcc metals.

Battelle Memorial Institute, Battelle-Northwest Laboratory, is to study how irradiation affects the properties of molybdenum, nickel, and rhenium; how impurities perturb the damage state; and how thermally activated recovery processes operate.

Battelle Memorial Institute, Battelle-Northwest Laboratory, is to establish a better understanding of growth and fission-gas agglomeration processes in fuels.

Battelle Memorial Institute, Battelle-Northwest Laboratory, is to conduct a comprehensive investigation of the effects of irradiation and environment on the properties of reactor metals.

*Detailed information on these programs is given in REIC Memorandum 29, Compilation of Nuclear, Pulsed, and Space Radiation Effects Projects, April 15, 1966.

Battelle Memorial Institute, Columbus Laboratory, is to determine radiation induced property changes in 347 stainless steel after neutron exposure in the range of 5.2×10^{21} to 3.1×10^{22} n cm⁻².

Battelle Memorial Institute, Columbus Laboratory, is continuing its study on radiation-induced property changes in structural materials.

Battelle Memorial Institute, Battelle-Northwest Laboratory, is determining the radiation effects on the physical and mechanical properties of stainless steel, molybdenum, nickel-alloys, niobium alloys, and tungsten-rhenium.

The Boeing Company is performing experimental studies and investigations of ultra-violet-proton radiation effects on aluminum solar concentrator reflective surfaces.

Brookhaven National Laboratory is investigating the mechanism of radiation hardening and the effects of hardening on deformation and increase in the ductile-brittle transition temperatures of iron, iron alloys, and other bcc metals.

Clemson University is investigating the effects of radiation damage on solids (mainly metals) using a 0.4-Mev van de Graaff electron accelerator to induce damage.

Clemson University is determining the effects of 0.4-Mev electron irradiation on the physical properties of metals.

Douglas Aircraft Company, Inc., is studying the production of point defects in metals by heavy charged particle irradiation below 10 K and to investigate their behavior upon subsequent annealing.

Douglas Aircraft Company, Inc., is determining the effects of proton and electron bombardment at 5 K on noble metals and aluminum.

E. I. du Pont de Nemours and Co., Savannah River Laboratory, is to define the swelling behavior of uranium alloys containing small additions of Fe, Si, Al, Cr, and Mo over ranges of metal temperature and exposure of interest in advanced reactor technology.

General Atomic Division is studying the effect of substructure on irradiation stability of pressure-vessel steels.

General Dynamics Corporation, General Dynamics/Fort Worth, is investigating the effects of radiation and cryotemperature on the tensile properties of selected properties of Ni-Cr-Fe alloys, pressure-vessel steels, and Zircaloy.

General Electric Company, APED-San Jose, is determining the effect of nuclear irradiation on mechanical properties of nickel-base alloys.

General Electric Company, Knolls Atomic Power Laboratory, is to study the effects of radiation-damage programs directed toward metals being used or considered for use in any phase of naval reactor development programs.

General Electric Company, Knolls Atomic Power Laboratory, is determining the radiation effects on selected properties of Ni-Cr-Fe alloys, pressure-vessel steels, and Zircaloy.

General Electric Company, Nuclear Materials and Propulsion Operation, is studying the effect of radiation on the time, temperature, and stress-dependent properties of refractory metals and alloys.

General Electric Company, Nuclear Materials and Propulsion Operation, is determining the effects of irradiation on the time, temperature, and stress-dependent properties of refractory metals.

General Electric Company, Vallecitos Atomic Laboratory, is doing a detailed examination of nuclear fuel rods subject to average exposure of 25,000 Mwd/t or higher.

General Electric Company, Vallecitos Atomic Laboratory, is investigating stainless steel fuel-rod cladding failures.

General Electric Company, Vallecitos Atomic Laboratory, is developing an accurate nuclear-fuel-burnup analysis.

General Electric Company, Vallecitos Atomic Laboratory, is evaluating zirconium plus 1.15 wt % chromium alloy as nuclear-fuel-element cladding.

Lockheed Aircraft Corporation is determining the effects of reactor radiation on metals at cryogenic temperatures.

Lockheed Aircraft Corporation is measuring electron scattering cross sections of neutral mercury particles for electron energies between 0.1 volt and 5 volts using electron-beam techniques.

Massachusetts Institute of Technology is studying the radiation damage to bcc metals.

Materials Research Laboratory is developing test procedures for testing of fracture toughness of irradiated pressure-vessel steels.

NASA, Lewis Research Center, is studying the production of defects in metals and refractory compounds induced by electron and neutron bombardment.

NASA, Lewis Research Center, is studying the production of defects in metals and refractory compounds by electron and neutron bombardment.

North American Aviation, Inc., Atomics International Division, is studying the effects of electron radiation-produced lattice defects on the physical properties and electronic behavior of metals.

North American Aviation, Inc., Atomics International Division, is studying the effect of electron-radiation-produced lattice defects on the physical properties of electronic behavior of various metals.

Northwestern University is studying the effect of point defects on mechanical properties of metals.

Oak Ridge National Laboratory is to investigate the effects of irradiation in fast reactors on mechanical properties of iron and nickel-base alloys.

Oak Ridge National Laboratory is to determine the effects of reactor irradiation on the mechanical properties of stainless steels and nickel-base alloys.

Oak Ridge National Laboratory is studying irradiation-induced precipitation in iron and the effect of irradiation on mechanical properties of various structural materials.

Phillips Petroleum Company is investigating the corrosion rates of beryllium and aluminum in the MTR due to the pH of cooling water under actual operating conditions.

Phillips Petroleum Company is testing the effects of irradiation upon austenitic stainless steel and various aluminum alloys for changes in physical properties after irradiation in the MTR and ETR.

Phillips Petroleum Company is seeking the effect of irradiation on the fatigue properties of steels for nuclear reactors at high temperature (maximum temperature 550 C) when mechanically cycled in the irradiation field.

Phillips Petroleum Company is studying the effect of irradiation on the mechanical strength and dimensional stability of beryllium, the gas released during irradiation, and the influence of the gaseous atoms produced on the load-carrying capability of beryllium.

Phillips Petroleum Company is determining the in-pile fatigue properties of structural steels for high-temperature reactor uses.

Phillips Petroleum Company is studying the effects of irradiation on the physical properties of austenitic stainless steels and aluminum alloys.

Phillips Petroleum Company is determining the effects of irradiation on the mechanical strength, dimensional stability, and gas-release properties of beryllium.

University of Chicago, Argonne National Laboratory, is studying the swelling and growth of uranium, fission tracks in evaporated metal films, mechanical properties of metals, recovery of low-temperature-irradiated copper, and lattice defects of fcc metals.

University of Mississippi is investigating the radiation effects on the resistivity of binary alloys.

University of North Carolina is conducting electron-radiation-damage studies in gold, aluminum, and aluminum alloys at temperatures of 12 and 80 K.

University of Oklahoma is studying the effects of proton bombardment in the energy range 20 to 200 kev on aluminum and gold surfaces.

U. S. Air Force, Aeronautical Systems Division, is studying the effects of neutron radiation on the critical temperature of NbZr and Nb₃Sn using 14.1-Mev neutrons.

U. S. Air Force, Aeronautical Systems Division, is determining the effects of 14.1-Mev neutron irradiation on the critical temperature of NbZr and Nb₃Sn.

U. S. Air Force, Cambridge Research Laboratories, is investigating Young's modulus changes during annealing of electron-irradiated metals.

U. S. Air Force, Cambridge Research Laboratories, is investigating the effects of irradiation on the internal friction and Young's modulus in metals.

U. S. Naval Ordnance Laboratory is studying the effects of electron irradiation on the magnetic properties of magnetic materials.

U. S. Naval Radiological Defense Laboratory is doing experimental work with small steel structures to determine the shielding afforded by structures from fallout gamma radiation.

U. S. Naval Research Laboratory is to investigate the effects of neutron irradiation on the properties of reactor structural materials.

U. S. Naval Research Laboratory is evaluating radiation damage to advanced metallic materials having potential for future nuclear applications, devising methods for minimizing the effects of radiation, and determining mechanisms of radiation damage.

U. S. Naval Research Laboratory is studying the effect of heat treatment and composition on irradiation stability of steels.

Westinghouse Astronuclear Laboratory is determining the effect of irradiation on mechanical properties of various materials at cryogenic temperatures.

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- (114) Reynolds, M. B., "The Effect of Stress on the Radiation Stability of ASTM A302 Grade B Pressure Vessel Steel", Materials Research & Standards, 3 (8), 644-645 (August, 1963).
- (115) Damask, A. C., "Effect of Neutron Irradiation on Precipitation of Carbon in Alpha-Iron", Brookhaven National Laboratory, Upton, New York, BNL-8418, September, 1964, 20 pp.
- (116) Markouskii, E. A., and Krasnoshchekov, M. M., "Antifriction Characteristics of Neutron-Irradiated Steel", Atomic Energy USSR, 18, 72-73 (January, 1965).
- (117) Moteff, J., "Radiation Damage in Body-Centered Cubic Metals and Alloys", Paper presented at the AIME Symposium on Radiation Effects, Ashville, North Carolina, September 8-10, 1965.

APPENDIX I

OPERATION OF THE RADIATION EFFECTS INFORMATION
CENTER DURING 1965-1966

APPENDIX I

OPERATION OF THE RADIATION EFFECTS INFORMATION
CENTER DURING 1965-1966

The operation of the REIC during the 12-month period from June, 1965, through May, 1966, 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 November 1, 1966, through October 31, 1967, are briefly outlined.

Visitors

The following breakdown shows the number of visitors for the contract years 1965-1966, 1964-1965.

	<u>1965-1966</u>	<u>1964-1965</u>
Total Visitors	35	24
Industrial	1	18
NASA	12	0
Air Force	14	3
Army	4	0
Navy	1	1
AEC	2	0
Other Government		
Agencies	--	0
Foreign	1	2

Travel

During the 1965-1966 contract year, personnel from the REIC made 11 visits to 11 different organizations to keep abreast of current developments in radiation effects.

Technical Inquiries

The number of requests for information received by the REIC during the contract years 1965-1966 and 1964-1965 are listed below.

	<u>1965-1966</u>	<u>1964-1965</u>
Technical Requests	284	317
Nontechnical Requests	<u>486</u>	<u>555</u>
	770	872

Publications

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

Dissemination of Information

The REIC has continued to disseminate reports, memoranda, and accessions lists on both a total and accessions lists only basis. As of May 31, 1965, the total distribution required 922 copies and the accessions lists only required 95 copies.

Following is a breakdown of the distribution lists as of May 31, 1966.

<u>Organization</u>	<u>Total List</u>		<u>Accessions Lists Only</u>	
	<u>Addresses</u>	<u>Copies</u>	<u>Addresses</u>	<u>Copies</u>
NASA	41	42	3	3
Air Force	44	47	2	2
Army	40	43	3	3
Navy	22	26	4	4
Other Government Agencies	30	47	1	1
Industrial (Includes AEC)	650	717	55	82
	<u>827</u>	<u>922</u>	<u>68</u>	<u>95</u>

Operation of the Technical-Data File

The following breakdown describes the status of the REIC Technical-Data File as of May 31, 1966, after 9 years of operation. Figures for the previous year's operation are included for comparison.

	<u>Total as of May 31, 1966</u>	<u>Total as of May 31, 1965</u>
Documents Accessioned	32,335	27,756
Documents Extracted	16,695	14,826
Rejected Items	3,949	3,686

The rejected items may be categorized as follows:

	<u>Total as of May 31, 1966</u>	<u>Total as of May 31, 1965</u>
No Pertinent Information	1,938	1,870
No New Information	1,294	1,154
Duplicates	230	209
No Radiation Effects	<u>487</u>	<u>453</u>
Total Items Rejected	3,949	3,686

Future Plans

This is the last state-of-the-art report to be prepared by the REIC under Air Force monitorship. The coming year's operation is expected to be under the monitorship of the National Aeronautics and Space Administration.

Technical reports and memoranda to be considered for publication during the coming year may include the following subjects:

- (1) Space and nuclear effect on semiconductors
- (2) Dosimetry
- (3) Polymeric materials
- (4) Experimental procedures
- (5) Facilities survey
- (6) Semiannual contract compilation
- (7) Annual state-of-the-art report

Unclassified

Security Classification

14.	KEY WORDS	LINK A		LINK B		LINK C	
		ROLE	WT	ROLE	WT	ROLE	WT
	Radiation Effects Electronics Semiconductor Devices Polymers Lubricants Flotation Fluids Metals Ceramics Van Allen Radiation Dosimetry Bibliography Gamma Rays Neutron Radiation Electron Radiation Proton Radiation X-Ray Radiation Space Radiation Steel Stainless Steel Aluminum Oxide Beryllium Oxide Graphite Diamond Glass Electron Tubes Transistors Diodes Solar Cells Capacitors Resistors Microcircuitry Epoxy Resins Silicones Transducers Quartz Laminated Plastics Neutron Spectrum Neutron Spectrometer Nitrous Oxide Dosimeter Scintillators Thermoluminescent Dosimeter Polyurethanes Phenolic Resins Polyester Resins Fluoroethylene Polymers Magnesium Oxide						

Unclassified

Security Classification

APPENDIX II

LIST OF AVAILABLE REIC PUBLICATIONS

LIST OF AVAILABLE REIC PUBLICATIONS

Radiation Effects Information Center
Battelle Memorial Institute
Columbus Laboratories
Columbus, Ohio 43201

Requests for unclassified information or unclassified REIC published reports and memoranda should be sent:	Requests for classified REIC published reports and memoranda should be sent, via your contracting officer for endorsement, to the following address:
Radiation Effects Information Center Battelle Memorial Institute Columbus Laboratories 505 King Avenue Columbus, Ohio 43201 Attention D. J. Hamman	Defense Documentation Center Cameron Station Alexandria, Virginia 22314

Unclassified Reports

<u>Report Number</u>	<u>Title</u>
*6	A Survey of Current Research and Developments in the Field of Dosimetry (May 31, 1958), AD 157173
6 (First Addendum)	A Survey of Current Research and Developments in the Field of Dosimetry (March 31, 1959), AD 210766
*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) AD 265839
21	The Effect of Nuclear Radiation on Elastomeric and Plastic Components and Materials (September 1, 1961), AD 267890 (Supersedes Reports Nos. 3, 9, 13, and 17 and Momos Nos. 1, 3, 8, 13, and 17)
21 Addendum	The Effect of Nuclear Radiation on Elastomeric and Plastic Components and Materials (August 31, 1964), AD 454056 (Supersedes Reports Nos. 3, 9, 13, and 17 and Momos Nos. 1, 3, 8, 13, and 17)
23	Proton and Electron Damage to Solar Cells (April 1, 1962), AD 274954
27	The Effect of Nuclear Radiation on Ceramic Reactor-Fuel Materials (June 30, 1963), AD 414669
29	Effect of Nuclear Radiation on Metallic Fuel Materials (September 30, 1963), AD 420282
30	Effect of Nuclear Radiation at Cryogenic Temperature on Semiconductor Materials (September 30, 1963), AD 418420
31	Part I. A Survey of Irradiation Facilities (September 30, 1963), AD 418579 Part II. A Survey of Particle Accelerators (September 30, 1964), AD 447307
32	Space Radiation Damage to Electronic Components and Materials (September 30, 1963), AD 422325
33	Survey of Current Research and Developments in the Field of Dosimetry (September 30, 1963), AD 419304
35	Radiation Effects Experimental Procedures (August 31, 1964), AD 447977

*Out of Print in REIC: Available only from DDC, Defense Documentation Center, Cameron Station, Alexandria, Virginia
(Name changed from ASTIA, Armed Services Technical Information Agency).

<u>Report Number</u>	<u>Title</u>
36	Effects of Nuclear Radiation on Electronic Components Including Semiconductors (October 1, 1964), (Supersedes Report Nos. 1, 1A, 10, 10A, and 18), AD 454707
37	The Space Radiation Environment and Its Interaction With Matter (December 31, 1964) (Supersedes Memorandum No. 21), AD 456854
39	Space Radiation Damage to Electronic Components and Materials (January 31, 1966)
40	The Effect of Nuclear Radiation on Dispersion Fuel Materials, (January 1, 1966)
41	The Effect of Nuclear Radiation on Ceramic Coated-Particle Reactor-Fuel Materials (August 8, 1966)

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

*Out of print in REIC: Available only from DDC, Defense Documentation Center, Cameron Station, Alexandria, Virginia (Name changed from ASTIA, Armed Services Technical Information Agency).

II-3 and II-4

Unclassified Memoranda

Memorandum Number	Title
*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
24	A Selected Bibliography of Pulsed Radiation Effects (June 1, 1963), AD 615339
25	The Beneficial Uses of Radiation Effects (June 16, 1964), AD 601493
26	Radiation Effects on Glass: An Annotated Bibliography (September 15, 1965), AD 472139
28	Radiation Effects on Propellants and Explosives: An Annotated Bibliography (October 29, 1965), AD 474256
29	Compilation of Nuclear, Pulsed, and Space Radiation Effects Projects, (April 15, 1966), AD 481296

Classified Memoranda

Memorandum Number	Title
*1-C	The Effects of Nuclear Radiation on Fluorolubes and Other Gyroscope Fluids (Title Unclassified) (Secret) (September 5, 1958), AD 302126
*2-C	The Effect of Nuclear Radiation on Explosives and Solid Propellants (Title Unclassified) (Secret, Restricted Data) (June 15, 1959), AD 342563
*3-C	Dose-Rate Effects on Materials, Components, and Systems (Title Unclassified) (Secret, Restricted Data) (July 31, 1959), AD 341033

*Out of print in REIC: Available only from DDC, Defense Documentation Center, Cameron Station, Alexandria, Virginia (Name changed from ASTIA, Armed Services Technical Information Agency).

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5. AUTHOR(S) (Last name, first name, initial) Hamman, Donald J., Drennan, James E., Veazie, Walter H., Shober, Fred R., Leach, E. R., Broadway, Norman J., Gillette, Mrs. Helen C., Allgeier, J. P., Jr., Holt, Miss Judy C., and Kangilaski, M.		
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13. ABSTRACT Developments in the field of radiation effects on electronic components including semiconductors, polymeric materials, lubricants, flotation fluids, hydraulic fluids, structural metals and alloys, ceramics, space radiation environment, dosimetry, and ceramic and metallic fuel materials are reviewed. Programs currently being conducted in radiation effects are briefly given for each section of the report.		

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