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MASTER

ANNUAL TECHNICAL PROGRESS REPORT
AEC UNCLASSIFIED PROGRAMS
GFY 1970

AEC Research and Development Report

Atomics International
North American Rockwell

P.O. Box 309
Canoga Park, California 91304

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Program:	Advanced Development Program
AEC Task:	15, High-Temperature Chemistry
Project Manager:	S. J. Yosim
Reporting Period:	Government Fiscal Year 1970
General Order: 7711	Subaccount: 53020 AEC Category: 05-05-01-00.0

I. PROJECT OBJECTIVES

The project is divided into two general areas; the study of fused salts and the study of metal/metal-salt solutions. The objective of the study of fused salts is to achieve an understanding of ionic melts (halides, oxides, oxysalts, and glass systems) by (a) establishing the nature of the species existing in the ionic melts, (b) determining the physico-chemical interactions between species, and (c) formulating systematic relationships between the physico-chemical properties of fused salt systems and the molecular parameters of the species.

The objectives of the metal/metal-salt study are to determine phase diagrams for, and the nature of interactions between, metals and their salts at high temperatures, to determine the species in those solutions and, finally, to predict the solubilities in metal-salt systems.

II. TECHNICAL PROGRESS DURING FISCAL YEAR 1970

A. PUBLICATIONS

The following papers were published:

1) "Electronic Conduction in Fused Salts," by L. F. Grantham and S. J. Yosim in "Molten Salts – Characterization and Analysis," Ed. by Gleb Mamentov, published by Marcel Dekker, Inc., 1969.

2) "Some Fundamental Concepts in the Chemistry of Molten Salts," by Milton Blander in "Molten Salts – Characterization and Analysis," Ed. by Gleb Mamantov – published by Marcel Dekker, Inc., 1969.

3) "A Redetermination of the Thermoelectric Properties of the Bi-$BiBr_3$ System," by J. D. Kellner, S. J. Yosim, and L. E. Topol, J. Phys. Chem. 73, 4419 (1969).

4) "The Electrical Conductivity of Aluminum Chloride Liquid and Supercritical Vapor," by C. R. Boston, S. J. Yosim, and L. F. Grantham, J. Phys. Chem. 51, 1669 (1969).

5) "The Electrical Conductivities of Molten $BiCl_3$, $BiBr_3$, and BiI_3 at High Pressure," by A. J. Darnell, W. A. McCollum, and S. J. Yosim, in J. Phys. Chem. 73, 4116 (1969).

6) "Electrical Conductivities of Molten Aluminum Chloride-Potassium Chloride Mixtures," by C. R. Boston, L. F. Grantham, and S. J. Yosim, J. Electrochem. Soc. 117, 28 (1970).

7) "Thermodynamics of the $Fm3m \rightleftharpoons Pm3m$ Transition in the Potassium and Rubidium Halides," by A. J. Darnell and W. A. McCollum, J. Phys. Chem. Solids 31, 805 (1970).

In Printing:

1) "Polymorphism in KCl-KBr and KCl-RbCl Solid Solutions at High Pressure," by A. J. Darnell and W. A. McCollum, J. High Temp. Science.

Submitted for Publication:

1) "Polymorphism in the KCl-KF and KCl-NaCl Systems at Elevated Pressures and Temperatures," by A. J. Darnell and W. A. McCollum.

B. TECHNICAL ACCOMPLISHMENTS

Several attempts were made to prepare polywater, but without success.

The first approach to synthesize polywater was by densification of mixtures of water and benzene and was based on the following rationale. The structure proposed for polywater (Lippincott, U. of Md. and N. B. S. 1969) consists of planar rings containing six oxygen atoms. Six hydrogen atoms are also in this ring space equally between the oxygen atoms. The other six hydrogen atoms are bound to the oxygen atoms in bonds perpendicular to the O-H-O bond. Oxygen p-orbitals are available for hydrogen-bonding. It is common knowledge that water and benzene are not miscible to any appreciable extent at ordinary conditions. We note that Schneider et al (1966) found that water and benzene become extensively soluble at elevated pressures. Furthermore a maximum

was found in the composition-vs-pressure isotherm at the composition $C_6H_6 - 6(H_2O)$. This hints that benzene may be interacting with a six-membered water molecule, perhaps the six-numbered ring of polywater suggested by Lippincott. Therefore the benzene-water system was examined to see if polywater could be stabilized from these solutions. For this purpose a "splat-quench" process was devised whereby miscible solutions of water and benzene (at high temperature and pressure) would be suddenly released to ambient conditions. The results from four separate tests, however, showed that this solution returns to a two-phase mixture of ordinary water and benzene. A very slight ($\sim$0.1%) decrease in density and an increase in refractive index of the water phase was noted. This, however, can be explained by a slight solubility of benzene in the water phase.

A second approach consisted of fractionally distilling water which had been previously pressurized. A 30-cc sample of water which was pressurized at 10 kbar in contact with amorphous silica was fractionated (at room temperature) and the last of three 1/4-cc portions of the distillate was collected and examined. The density and refractive index of these portions were not measurably different from the ordinary kind of water. On the basis of properties reported for polywater one would expect our process to concentrate any of this polymeric form into these last fractions. This fractionation would therefore increase our sensitivity by a hundredfold. In our refractive index measurements we should be able to detect polywater in amounts of 1 in 1000; hence less than 1 in 10^5 existed in this test.

The third approach to synthesize polywater was to splat-quench water from extreme pressure. The rationale for this approach was that water under the constraint of a pressure of 40 kbar approaches the density reported for polywater. It is possible that water could be in a polymerized form at these extreme conditions and that a sudden release of pressure might yield the polywater in a quenched form. Previous tests showed that water returned from these extremes by ordinary (slow) depressurization techniques has the usual properties. One accidental (rapid) decompression had yielded a sample with properties different from ordinary water. An apparatus to rapidly quench water samples from these extreme conditions was fabricated. The size of these samples would be approximately 100 times the volume of polywater samples

made by the capillary method. Several samples (~0.05 cc each) have been collected with this apparatus. Upon evaporation it was found that these samples left a small residue which was waxy in appearance but soluble in water. It is possible that this residue results from the decomposition of the gaskets used to retain the water in our apparatus. However, the substitution of different kinds of gasket materials still yielded a similar result. An experimental technique was subsequently developed using copper retainer or burst disks in place of these polymers. In this case none of the above effects was noted in samples quenched from pressures up to 40 kbar. A liquid with such an open structure as water might be expected to undergo significant changes in bonding at extreme pressures of 40 kbar. However, the pressure-quench experiments carried out here show that water rapidly and reversibly reverts to its original form.

III. EVALUATION OF EFFORT DURING FISCAL YEAR 1970

This project has been concluded.

Program:	Physical Research Program
AEC Task:	17, Electronic Structure of Metals and Alloys
Project Manager:	R. G. Breckenridge
Reporting Period:	Government Fiscal Year 1970
General Order:	7713 Subaccount: 54010 AEC Category: 04-40-03-01.1

Principal Scientists: R. G. Breckenridge, L. J. Barnes, S. L. Wipf, M. M. Nakata

I. PROJECT OBJECTIVES

This effort is devoted to acquiring knowledge of the electronic structure of metals and alloys (configuration of electronic energy states in momentum space) and the role of this structure in determining electrical, thermal, magnetic, vibrational, and alloying characteristics. Detailed information on the shape of the Fermi surface is provided by de Haas-van Alphen studies in magnetic fields up to 200 kilogauss, and the density of electronic states at the Fermi level is deduced from low-temperature specific-heat measurements. The latter also yield information on lattice vibrational modes and on the interactions involved in superconductivity and magnet ordering. Further characterization of magnetic interactions is accomplished by means of conventional magnetic susceptibility techniques. Considerable effort is devoted to the exploration of high-field superconductivity with emphasis on thermodynamic and transport characteristics, as well as on the electron-energy spectrum as deduced from point-contact tunneling measurements. These experimental investigations are correlated with current theory, and attempts are made to characterize quantitatively the relationship between superconductivity and the normal state electronic structure.

II. TECHNICAL PROGRESS DURING FISCAL YEAR 1970

Publications were as follows:

1) L. J. Barnes, "Tunneling at Point Contacts Between Superconductors," Phys. Rev. 184, 434 (1969)

2) H. J. Fink and A. G. Presson, "Superconducting Surface Sheath of a Semi-infinite Half Space and its Instability Due to Fluctuations," Phys. Rev. B. 1, 1091 (1970).

3) H. J. Fink and A. G. Presson, "Proximity Effect of Superconductors in High Magnetic Fields," Phys. Rev. B. 1, 221 (1970).

A. MEASUREMENT OF THERMODYNAMIC PROPERTIES WITH SUPERCONDUCTING WEAK LINKS (L. J. Barnes)

The temperature-induced Josephson ac effect has been further studied during this report period but the results are still inconclusive. The effect is observable but the difficulties of definitely eliminating spurious effects at these extremely low voltage levels are great.

B. THERMAL PROPERTIES OF SUPERCONDUCTORS (M. M. Nakata)

A program to measure the thermal diffusivity of selected superconductors below the critical temperature, and if possible in a magnetic field, has been in progress. A knowledge of the thermal diffusivity is essential in a calculation of the occurrence of magnetic instabilities. As indicated previously an extension of the flash-diffusivity technique which is normally used for very high temperature measurements to the ultra-low temperature regime seems feasible even if some unusual values of the material parameter and instrument characteristics are encountered. At high temperatures, for example, the thermal diffusivities are usually in the range of 0.01 to 1 cm^2/sec while at liquid helium temperatures they may become as high as 10^4 cm/sec. This means that an extremely short energy pulse must be used as well as a thick sample. Another complication arises from the requirement that the pulse should not raise the sample temperature above the critical temperature.

It has become clear in the development work that the key to a successful device lies in the development of a thermometer with a low heat content, very fast response time, high sensitivity, and good stability. It is well-known that the carbon-resistance thermometers currently widely used in low-temperature thermometry can satisfy some of these requirements, but their response time which is vital in this experiment is much too slow. Considerable effort was expended in developing a very thin film carbon-resistance thermometer that would have a rapid response. These were tested under pulsed conditions and performed very satisfactorily.

The apparatus was finally completely assembled and for its first trial a sample of pure niobium 0.8-cm-diam by 3.5-cm-long was prepared. The front face was coated with a thin layer of aquadag and a thin film carbon-resistance thermometer was fabricated on the back face. In the trial, good temperature measurements with an acceptable signal-to-noise ratio were obtained down to liquid-nitrogen temperature. As the temperature was lowered to the helium range the thermometer resistance increased and the signal-to-noise ratio decreased to an unusable value. The difficulty apparently is not in the system, however, and seems to be only with the amplifier that was available. Unfortunately the program terminated before a successful run could be made.

III. EVALUATION OF EFFORT DURING FISCAL YEAR 1970

This has been a rather frustrating work period since two important experiments, close to success, were not able to reach their goal. The thermal-diffusivity studies did show that the method is feasible and if possible a report will be written describing the work. Looking at the program in broader terms this project has been an outstanding success. The discovery of the high-field superconducting alloys is undoubtedly its major accomplishment but there were many other important contributions to studies of the Fermi surface and electronic properties of metals. The technical men involved have always been of the highest caliber and their work has been a credit to them, Atomics International, and the Atomic Energy Commission.

We regret that the program has been terminated at the end of this report period.

Program:	Physical Research Program
AEC Task:	18, Radiation Damage in Crystalline Solids
Project Manager:	R. G. Breckenridge
Reporting Period:	Government Fiscal Year 1970
General Order:	7714 Subaccount: 54040 AEC Category: 05-05-01-00.0

Principal Scientists: W. Bauer, D. W. Keefer, K. A. Herschbach, H. H. Neely, K. H. Thommen, D. D. Vawter, and A. Sosin

I. PROJECT OBJECTIVES

The materials requirements of modern technology demand an increased understanding of the effects of lattice defects on the physical properties of crystalline solids, and on their behavior when subjected to various kinds of radiation environments. Early recognition of the low thermal stability of some of the radiation-produced defects has resulted in emphasis on low temperature irradiation studies during the last 15 yr. These investigations have elucidated many important aspects of defect production and their properties, but concurrently have revealed the formidable complexity of radiation effects. While unanswered questions still remain in the domain of low-temperature radiation effects, the acquired insight now makes a study of radiation effects at higher temperatures a promising and desirable enterprise. The objective of this project is to study the production of defects in crystalline solids by radiation, and to attain an understanding of their structure and interactions with each other and with impurities and dislocations. Low-temperature electron irradiations are being used for the study of selected point-defect problems in metals, alloys, and semiconductors. On the other hand, recognition of radiation damage at high temperatures and high particle fluxes as a relevant but largely unexplored area has made it desirable to expand the scope of this project. The program now includes investigation of phenomena unique to a high temperature, high flux radiation environment. Pure metals are chosen for this study because their use should lead to an improved understanding of the fundamental processes. This in turn should be helpful for the development of materials of superior properties.

II. TECHNICAL PROGRESS DURING FISCAL YEAR 1970

Publications were as follows:

1) H. H. Neely and K. Herschbach, "Proton Induced Void Formation in Nickel," Bull. Am. Phys. Soc., 15, 775 (1970), APS Summer Meeting, Winnipeg, Manitoba.

2) H. H. Neely and K. Herschbach, "Void Formation in Nickel During High Temperature Proton Irradiation," submitted for publication to Radiation Effects.

3) H. H. Neely, "Damage Rate and Recovery Measurements on Zirconium After Electron Irradiation at Low Temperatures," to be published in Radiation Effects.

4) W. Bauer, H. H. Neely, and A. Sosin, "The Continuous Resistivity Recovery Spectrum of Aluminum and Copper in Stage I," submitted to Radiation Effects for publication.

5) W. Bauer, K. Herschbach, and J. J. Jackson, "Low Temperature Electron and Alpha-Particle Irradiation of Titanium," Phys. Rev. 185, 870 (1969).

6) W. Bauer, A. Anderman, and A. Sosin, "Atomic Displacement Processes in Gold," Phys. Rev. 185, 924 (1969).

7) K. Thommen, "Recovery of Low Temperature Electron Irradiation-Induced Damage in N-Type GaAs," Rad. Eff. 2, 201 (1970).

A. VOID FORMATION IN NICKEL DURING PROTON IRRADIATION (H. H. Neely and K. Herschbach)

During GFY 1969 an experimental program was established to study void formation in nickel during high-temperature proton irradiation. The first voids produced in the United States by charged-particle irradiation were observed during experiments done under this program in GFY 1970. A preliminary systematic investigation of the effects of temperature and helium content on void formation in pure nickel has been completed. In addition, an investigation of a specimen which had an excess-vacancy concentration due to prior irradiation at low temperature has been completed.

A presentation of these results was given at the American Physical Society Summer Meeting in June 1970. A paper titled "Void Formation in Nickel During High-Temperature Proton Irradiation" is being submitted to "Radiation Effects" for publication; the abstract is as follows:

"Pure Ni foils, doped with He from 0 to 28 appm, were irradiated with protons at temperatures in the range 0.3 to 0.6 T_m (T_m = melting point in °K) and void formation was studied. The influence of He doping, irradiation temperature, and alloying were investigated. For constant He content and proton fluence, void-number density and swelling are maximum at about 400°C while the void size increases with temperature. Most voids are octahedral in shape with no sign of truncation. Helium is required to nucleate voids, and lowering the stacking fault energy by alloying suppresses void formation completely. Present results suggest that void nucleation is inhomogeneous. Some implications of these findings are discussed."

The statistics of the nickel-void program are given in Table 1. The irradiations were all carried out to a total fluence of 1×10^{18} p cm^{-2}. Sections very near the end of range were investigated for electron microscopy.

The conclusions drawn from this investigation are:

1) Supersaturation of vacancies by irradiation is the driving force for nucleation and growth of voids.

2) There is a maximum in the void density and swelling at 400°C.

3) Void size is a gaussian distribution.

4) Nucleation is not homogeneous at the vacancy concentrations used in this investigation. There are very few voids nucleated with no helium present. Helium is required to stabilize vacancies for void growth.

5) Void densities, but not necessarily swelling, increase with helium concentration.

6) Voids in pure nickel are mainly octahedra. They are not truncated as is observed in stainless steel.

TABLE 1

NICKEL-VOID PROGRAM STATISTICS

Specimen	Temperature (°C)	Helium (ppm)	Calculated Vacancy Concentration (v/cm^3)	Void Density ($\times 10^{15}/cm^3$)	Volume Increase (%)	Average Size (Å)
VG-1-A	500	0	5×10^{22}	-	-	-
DN-21-3	500	0	2.2×10^{22}	small	-	-
DN-21-4			1×10^{22}	small	-	-
DN-10-4	500	9.1	1.1×10^{22}	2	0.03	60
DN-10-3			0.9×10^{22}	*	-	~30
DN-10-2			1.5×10^{22}	small†	-	-
DN-11-VG-B	500	6.4	1×10^{23}	2.7	0.12	85
DN-5-VG-A	500	0.35	$\geq 5 \times 10^{23}$	1.0	0.12	110
DN-4-VG-B	400	0.32	$\geq 5 \times 10^{23}$	6.9	0.35	90
VG-8-3	400	0	1×10^{23}	small	-	
DN-37-VG-A	300	0.5	1×10^{23}	0.5	0.001	40
DN-32-VG-A	400	7.0	1×10^{23}	5	0.12	80
DN-7-VG-A	400	28.0	1×10^{23}	19.1	0.15	60
DN-44-VG-A	400§	7.0	1×10^{23}	16.2	0.10	55

*Small average size, no count

†Analysis indicates 1/2% copper in lattice, voids are suppressed, many dislocation loops and tangles.

§Irradiation-doped, 200°C to 2.25×10^{17} p cm^{-2} then temperature increased to 400°C to a total fluence of 1×10^{18} p cm^{-2}.

B. DAMAGE RATE AND RECOVERY MEASUREMENTS ON ZIRCONIUM AFTER ELECTRON IRRADIATION AT LOW TEMPERATURES (H. H. Neely)

A paper on this subject has been submitted for publication in Radiation Effects, the Abstract being as follows:

"Resistivity change as a function of electron irradiation near 8°K and of annealing after irradiation has been measured on zirconium. Damage rates were measured as a function of incident electron energy from 0.70 to 1.9 Mev. A value of 24 ev for the displacement threshold energy was determined by extrapolation of the damage-rate curve to zero-damage production. A fit between the theoretical and experimental values of displacement cross-section was

achieved with an effective threshold energy of 28 ev, yielding 35 x 10^{-4} Ωcm/ fractional concentration for the Frenkel resistivity. The damage-rate curve indicates no tailing due to subthreshold displacements. Recovery in Zr is analogous to that of fcc and bcc element studies, but with six substages in Stage I. Substage I_f (analogous to I_e in other materials) was analyzed by using the serpentine plot, which gives an indication of long-range migration of an interstitial between 120 and 150°K, with an activation energy of 0.26 ev (second-order kinetics is assumed). Stage III is in the temperature range 250 to 310°K. The activation energy of Stage III was analyzed by use of the Meechan-Brinkman and second-order methods; this results in an average energy of 0.57 ev. The order of reaction kinetics was found to be a function of recovery."

C. RECOVERY OF LOW-TEMPERATURE ELECTRON IRRADIATION-INDUCED DAMAGE IN N-TYPE GaAs (K. Thommen)

A paper on this subject has been published in Physical Review, the Abstract being as follows:

"Undoped n-type GaAs was irradiated near 5 and 77°K with electrons having incident energies between 0.46 and 1.30 Mev. The recovery of the electrical resistivity and the Hall coefficient upon annealing from 4 to 520°K was monitored. Changes which occurred upon annealing below 200°K could be reversed by ionizing radiation. A small amount of irreversible ionization-induced recovery was observed after irradiation near 5°K. Major irreversible recovery stages were centered near 235 (Stage I), 280 (Stage II), and 520°K (Stage III). Recovery in Stages I and II obeyed first-order kinetics. The activation energies of Stages I and II were determined as 0.72 and 0.83 ev respectively. The carrier concentration changes per unit irradiation dose corresponding to the three recovery stages differed in their energy-dependence indicating that the defects which are removed in Stage III have the lowest threshold energy. The carrier-concentration changes per unit irradiation dose corresponding to Stages I and III were higher for irradiation near 5°K than for irradiation near 77°K.

D. LOW-TEMPERATURE ELECTRON AND ALPHA-PARTICLE IRRADIATION OF TITANIUM (W. Bauer and K. Herschbach, in conjunction with J. J. Jackson, Argonne)

A paper on this subject has been published in Physical Review, the Abstract being as follows:

"The recovery of point defects produced by 1.2-Mev electron and 40-Mev alpha-particle irradiation has been studied from 50 to 270°K. The recovery spectrum qualitatively resembles that of copper although it is shifted to higher temperature. The influence of varying irradiation dose, pre-irradiation at elevated temperatures, pre-deformation, and dilute alloying were also studied. The recovery below 150°K is dominated by the annihilation of Frenkel pairs with long-range or uncorrelated migration of the interstitial beginning at approximately 120°K. The recovery of annealed samples irradiated to relatively low dose is characterized by super-recovery. A model involving the migration of interstitial-hydrogen impurities from interstitial to substitutional sites is proposed to explain this phenomenon."

E. ATOMIC DISPLACEMENT PROCESSES IN GOLD (W. Bauer, in conjunction with A. I. Anderman and A. Sosin)

A paper on this subject has been published in Physical Review. The paper contains the results of gold single-crystal measurements and some relevant computer calculations on gold (Anderman sponsored by AFCRL). The Abstract is as follows:

"Experimental and theoretical results are presented which bear on the directional dependence of threshold displacement energy $T_d(\theta'\phi')$. The major experimental result is that the energy-dependence of the electron-damage rates measured in thin single crystals oriented along the three low index directions is nearly the same. With the assumption that $T_d(110)$ and $T_d(100)$ corresponded to local minima the data indicate $T_d(100) \sim T_d(110) \sim 36$ ev. A corresponding theoretical value of $T_d(100) = 36 \pm 2$ ev is found when a Born-Mayer-type potential with parameters derived by Anderson and Sigmund is used in computer calculations. Evidence is presented to show that experimentally derived threshold energies may not reflect true T_d values if they correspond to a local maximum in the threshold-energy surface, such as may be the case in the $\langle 111 \rangle$ direction."

The gold potential used for the calculation of $T_d(100) = 36 \pm 2$ ev is shown to be remarkably similar to copper potential used by the Brookhaven group in their calculations. If this comparison is valid, one may then carry over to gold the more extensive results of the Brookhaven group in copper. This would lead to the conclusion that $T_d(100) \sim T_d(110) \sim 36$ and correspond to minima, whereas $T_d(111)$ represents a local maximum and is heavily influenced by glancing collisions in easier displacement directions. These conclusions are largely in agreement with those reached by Sosin and Garr for copper single-crystal measurements.

In principle the above experiments could have been carried out with epitaxially grown films in the 1000Å range. While multiple-electron scattering can be ignored, glancing collisions would still play a role in such films. However, yet another facet involved in charged-particle irradiations of such very thin single-crystals becomes important. This phenomenon is generally known as channeling, but the connotation may be inappropriate when applied to electrons in single-crystals. When a charged particle enters a crystal parallel to a close packed direction it moves along a channel formed by rows of atoms. The particle's ability to interact with these atoms at a small impact parameter may be enhanced or suppressed when it is channeled, depending on whether its charge is negative (electrons) or positive (protons, positrons).

Displacements of atoms especially near threshold are caused by large-angle Rutherford scattering of electrons, a small impact parameter process. Recent experimental measurements of large-angle scattering of 50 kev electrons from single crystal copper foils indicate that the yield of scattered electrons at a fixed scattering angle is enhanced (over the off-axis yield) by as much as 25% when the electron beam is aligned with the ⟨110⟩ axis of the crystal.

The implication of these results to our work is that one may observe relatively larger damage rates in close-packed direction and not be able to distinguish the effects of channeling from those of a local minimum in the threshold displacement energy. Thus any attempt to quantitatively compare experiment with theory seems doomed for very thin crystals. The thickness of our samples was large enough that multiple-scattering inhibited channeling effects.

III. EVALUATION OF EFFORT DURING FISCAL YEAR 1970

The research activity has achieved outstanding research results in void formation with (1) the demonstration of voids in pure nickel, (2) nonhomogeneous void nucleation without helium to stabilize vacancies with 10^{18} p cm^{-2}, (3) data indicating a maximum in the void density and swelling at 400° C in nickel, and (4) quenching of voids with a small amount of an impurity atom (copper) with nearly the same characteristics as nickel. The experimental techniques have been so improved that the program is now in a position to secure detailed information on the study of void formation in pure and doped metals. The data obtained during this report period are an indication that accelerator irradiations to create voids in materials can easily simulate fast-neutron irradiation experiments. The basic information and experimental equipment in hand is an excellent approach to future results.

Since this is the final report on this program it is appropriate to express the appreciation of all the scientists who have worked on the project for the support provided by the AEC for the many years that the program has been in existence. The group engaged on this work has always been a leader in the field and its output includes many major technical contributions from a considerable number of very capable men. It is evident that the company and the men as well as the AEC have benefited by the opportunity to work in this fruitful and important subject area.