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CRYOGENIC MECHANICAL PROPERTIES OF IRRADIATED ALLOYS

UNCLASSIFIED NERVA RESEARCH
AND DEVELOPMENT REPORT.

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PREFACE

This report was generated for presentation external to the NERVA project.

It is being published in this form prior to external publication for the general information of NERVA engineering personnel.

Cryogenic Mechanical Properties of Irradiated Alloys

J. R. Coombe and R. P. Shogan

ABSTRACT

Development of the Nuclear Engine for Rocket Vehicle Application (NERVA) requires that the combined effects of nuclear radiation, temperature and stress be considered. The NERVA reactor design requirements for material in this application of nuclear power to propulsion for extra terrestrial missions include temperatures from 40 to 5000° R in combination with high levels of nuclear radiation. The literature with rare exceptions does not include information on NERVA type materials at the neutron fluences, nuclear heat generation rates, and temperature environment inherent in the NERVA design. Consequently, experimental programs have been conducted to evaluate materials and generate design data.

The materials tested to date have included hot pressed block beryllium, titanium-5 percent aluminum-2.5 percent tin ELI (A110AT), and an aluminum alloy 2219.

These materials have been irradiated at liquid nitrogen temperatures (140° R) and tensile tested without any intervening warm-up. Some of the liquid nitrogen irradiated and tested material data as well as room temperature data are presented. The effect of temperature on radiation characteristics and subsequent material properties after cryogenic temperature irradiation is discussed.

The properties investigated have included ultimate tensile strength, 0.2 percent offset tensile and compressive yield strength, percent elongation and fracture toughness. Usually ductility and the decrease in the magnitude of this property as a function of irradiation is of more vital interest to the designer.

The experimental program conducted for some of the NERVA candidate materials is reported and areas of additional investigations for application to advanced NERVA designs are briefly discussed.

INTRODUCTION

The Nuclear Engine for Rocket Vehicle Application (NERVA) program applies nuclear energy to the objective of extra-terrestrial missions. The concept currently being considered uses a nuclear reactor to heat liquid hydrogen, the reactor coolant and propellant to approximately 5000° R developing over 1,100 megawatts of power. This paper deals with several of the non-fuel materials used in this application of nuclear power, the supporting radiation test program and the response of these materials to neutron irradiation as determined to date.

The end use of the reactor requires a highly efficient selection and application of materials. The extreme materials environment; temperature, stress, and radiation complicates this application, particularly since a high degree of reliability is required. Materials property data for reliability considerations must be defined to 99 percent at the 95 percent confidence level over the range of expected environment.

REACTOR ENVIRONMENT

The steady state temperatures that exist during reactor full power operation range from 40° R to 5000° R. Actual non-fuel reactor material temperatures range from 100° R to approximately 4000° F. Outside of the core, the materials generally operate in the cryogenic range to liquid hydrogen temperatures. During "cool-down" or between reactor runs, the temperature may approach 1000° R.

Stress levels can be relatively high even in materials such as the reflector since all non-fuel ^{materials} components are used as structural components. In addition, most components are subjected to high temperature gradients which compound the stress states.

Radiation levels that exist in the NERVA reactor are above 10^{14} n/cm²s (E>1 Mev). Fast neutron fluences exceed 10^{18} n/cm² (E>1 Mev) outside the core and 10^{19} n/cm² (E>1 Mev) inside the core. Thermal fluences (E<0.48 ev) are ^{above} 10^{19} n/cm². These fluences are well below those experienced in stationary power plant reactors but produce significant materials properties changes at cryogenic temperatures. Information on materials subject to this synergistic combination of temperature and radiation levels is not contained in the literature.

THE NERVA RADIATION EFFECTS PROGRAM

The NERVA Radiation Effects Program is intended to recognize any radiation effects problem which could become a significant hinderance to the successful development and design of the NERVA reactor and to support the designers in developing the most efficient design possible. Effort in this program has involved literature research, analysis and experimentation. The experimental irradiation program for reactor materials has generally consisted of ambient temperature irradiations in the National Aeronautics and Space Administration's Plum Brook reactor in a water-cooled capsule inserted adjacent to the core and ambient and liquid nitrogen (LN₂, 140°R) irradiations in the General Dynamics' Ground Test Reactor located in Fort Worth, Texas. In addition, the NERVA program has utilized liquid hydrogen for engine materials irradiations.

The LN₂ irradiations were in a large dewar next to the reactor closet allowing several hundred test specimens to be irradiated simultaneously. The specimens are subsequently transferred under LN₂ to an Instron tensile test machine to preclude warm-up prior to completion of the tests. Temperatures between 140°R and room temperature (540°R) are obtained by warming the specimens with a controlled flow of cooled gaseous nitrogen.

The primary effort to date has been expended in determining mechanical property data. This has consisted mostly of tensile testing although some compression

and fracture mechanics specimens of beryllium have been tested. A limited amount of physical property measurements including electrical resistivity and thermal conductivity have also been completed.

History

In general it is not expected that engineering materials would be significantly affected by fluences as low as those expected in the NERVA environment, that is 10^{19} n/cm² or less at room temperature or above. However, at cryogenic temperatures where point defects and small clusters are relatively immobile, significant effects have been reported by many investigators on such properties as electrical resistivity and shear strength of single crystals (1,2). One of the initial NERVA radiation effects programs indicated that the engineering properties could also be affected. Most of these results were reported previously (3).

Program Requirements

Strength generally increases with irradiation; but since this change cannot be taken advantage of by designers, it is subordinated as far as the NERVA program is concerned. Ductility, as measured by tensile elongation, has been the criterion for selection and evaluation of materials after irradiation. Present philosophy is to determine which materials show sufficient elongation (>5 percent) under operating environments to allow ductile design criteria to be used. Materials with ductility lower than 5% may then be candidates for application of brittle fracture design criteria, limited to more stringent design analysis or to operating temperatures where ductility is higher. A notable exception is the brittle S-200 beryllium which appears to decrease in strength at the lowest temperature.

Results of Irradiation Experiments

Several NERVA candidate materials tested, along with characterization information are identified in Table I. Table II shows the chemical composition of the metals.

Where possible, the materials data have been analyzed using the analysis of variance technique after separating it into balanced sets for test variables. The 0.05 level of significance was used to assess each effect. These data are presented as curves of average values with .95/.99 statistical tolerance limits which states that with 95 percent confidence at least 99 percent of the material population have values greater than the limits given; this has been defined as the "design allowable". In a few instances, the data are summarized as average values in tabular form. Discussion of the data is based on the average values. Test values are generally the average of three or more specimens.

S-200 Beryllium

Beryllium has been selected for use as the reflector for the NERVA reactors for many reasons including its high neutron scattering cross section and its strength to weight ratio. A hot pressed block type with a density of 1.85 gm/cc is used. Tensile and compression specimens were taken in the longitudinal or pressing direction from two locations (cores) of a large pressing. Both types were etched before irradiation. Brittle fracture specimens were in both the longitudinal and transverse directions from a single location. In the data reported, irradiation temperature was 140°R with an average neutron fluence of 7×10^{17} n/cm² (E>1 Mev). The statistical analysis of the ultimate tensile strength data shows that the irradiated data are significantly more variable than the unirradiated data. This is expected because of the extreme brittleness after irradiation. Core differences are significant only for the irradiated specimens. This variation is unexplained.

TABLE I

MATERIAL CHARACTERIZATIONALLOYS

<u>MATERIAL</u>	<u>FORM</u>	<u>STOCK SIZE</u>	<u>REMARKS</u>
Beryllium (S-200)	Hot Pressed Block (Ring Configuration)	50" Diameter 6" Wall	Specimens etched Density = 1.85 g/cc
Ti-5% Al-2.5 Sn ELI	Forging (Ring)	42" Diameter 2 1/2" Wall 1" Thick	Annealed 1500°F, 1 Hr.
	Sheet	1/8" Thick	Annealed 1500°F, 1 Hr.
Aluminum 2219 T852	Forging	7" Thick 24" Diameter	Age 350°F, 18 Hr.

TABLE II

CHEMICAL COMPOSITION OF METALS

WT. %

<u>ELEMENT</u>	<u>S-200 BERYLLIUM (%)</u>	<u>ELEMENT</u>	<u>Ti 5 Al-2.5 Sn ELI FORGING (%)</u>	<u>SHEET (%)</u>	<u>ELEMENT</u>	<u>Al 2219 (Typical) (%)</u>
Be	98.54	C	0.013	0.022	Cu	6.3
BeO	1.85	Fe	0.08	0.14	Fe	0.3
C	0.11	Al	5.05	5.0	Si	0.2
Fe	0.14	Ti	Bal.	Bal.	Mn	0.3
Al	0.09	N	0.01	0.011	Mg	0.02
Mg	0.02	H	0.008	0.012	Zn	0.1
Si	0.03	Sn	2.6	2.4	Ti	0.15
Mn	0.01	O	0.05	0.07	Al	Bal.

At room temperature the ultimate tensile strength of the irradiated beryllium is only slightly higher than the unirradiated values (not statistically significant) (Figure 1). The difference increases sharply with decreasing test temperature to 350°R where the irradiated strength begins to decrease. Below about 250°R the irradiated U.T.S. is lower than the unirradiated. This decrease in strength is credited to the ^{loss of} loss in ductility of the material below 350°R .

Analysis of the 0.2 percent offset yield strength data (Figure 2) showed no differences in core variability although the irradiated data is more variable than the unirradiated data. The irradiated yield strength is higher than the unirradiated at 540°R and increases sharply relative to the unirradiated as the test temperature is decreased. Below 350°R the plastic strain was less than 0.2 percent.

In compression the material is sufficiently ductile to measure the yield strength at the lower temperatures. The increase at 140°R was 271 percent after irradiation (Figure 3).

Total plastic strain in the one-inch gage section was determined from cross-head movement as indicated on the Instron chart. In this case the irradiated data was less variable due to the zero readings at the lower temperatures. There were no significant core-to-core differences.

Plastic strain is drastically reduced for the irradiated specimens below 450°R (Figure 4). No measurable plastic strain was detected below 350°R . After anneals of up to 1000 minutes at 340°R and 60 minutes at 240°R and 440°R , plastic strain at the 140°R test temperature could not be measured. Most of the damage was recovered after 60 minutes at 540°R .

A limited amount of testing has been completed on the fracture toughness properties of the beryllium. The specimens were taken from a large block pressing similar in composition and properties to those used in the other mechanical tests.

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Figure 1
 Beryllium Ultimate Tensile Strength
 8

Figure 2

Beryllium 0.2% Offset Yield Strength

612822-5B

Figure 3

Beryllium 0.2% Offset Compressive
Yield Strength

612822-12B

Figure 4
 Beryllium Plastic Strain

The results are shown in Table III. Wedge-opening-loading (WOL) type specimens were used. Attempts to precrack the specimens were unsuccessful because of the brittleness of the material. However pre-cracked unirradiated specimens of other designs gave results comparable to those from unirradiated WOL specimens. The K_{IC} values were slightly reduced at room temperature but greatly reduced at 140°R.

Titanium-5 percent Al-2.5 percent Sn ELI

Ti-5 percent Al-2.5 percent Sn ELI is an all alpha titanium alloy with extra low interstitial content. Previous testing (3) had reported that bar material specimens had been significantly affected by radiation. At 140°R average elongation values reported were reduced from 16.3 percent to 4.6 percent by irradiation to 6×10^{17} n/cm² (E>1 Mev).

In this experiment forged and sheet material were irradiated to average fluences of 1×10^{18} n/cm² (E>1 Mev) at 140°R. The statistical analysis showed that the variability in the data from test condition to test condition was similar. This allows a "pooled" or overall estimate of the standard deviation to be made.

At 140°R both ultimate and yield strengths were increased approximately 5 percent for the forging and 3.5 percent for the sheet with almost no increases at room temperature. The change in the measured elongation of the forging is shown in Figure 5. At 140°R the elongation had dropped from 17.8 percent to 10 percent. The sheet elongation, however, dropped only from 17.4 percent to 15 percent under the same conditions.

Aluminum 2219

Al 2219 is a heat treatable aluminum alloy used in the T852 condition. Tensile specimens, taken in the forging direction from a large pancake forging were irradiated at 140°R to 8×10^{17} n/cm² (E>1 Mev). Specimens were pulled at 140°R, 240°R, 340°R, 440°R, and 540°R.

TABLE III

TEST TEMPERATURE	K _{IC} TRANSVERSE ksi $\sqrt{\text{in.}}$		K _{IC} LONGITUDINAL ksi $\sqrt{\text{in.}}$	
	UNIRRADIATED	$6 \times 10^{17} \text{ n/CM}^2$	UNIRRADIATED	$6 \times 10^{17} \text{ n/CM}^2$
140°R	16.3	9.7	13.6	8.8
	17.2	8.2	15.9	10.1
	16.2		15.7	
340°R	19.1		17.7	
	18.4		16.9	
540°R	22.4	19.6	19.0	16.5
	22.5		21.2	

"POOLED" STANDARD DEVIATION $s = 1.167$
 $n = 10$

($E > 1 \text{ Mev}$)

612822-15B

Figure 5

Ti-5% Al-2.5% Sn ELI Forging Elongation

Figure 6

Al 2219 0.2% Offset Yield Strength

At 140°R after irradiation ultimate tensile strength had increased 6.6 percent. There was no change in the ultimate tensile strength at the higher test temperatures. The effect of irradiation on yield strength is shown in Figure 6. The increase was 26 percent at 140°R. No effect was found at 440°R or above.

Average measured elongation at 140°R decreased from 9.4 percent to 7.2 percent. At higher temperature, the effect was not significant. Notched tensile strength (K_t app. 6) was not affected.

SUMMARY

Data generated to date show that significant irradiation effects occur in NERVA engineering materials at cryogenic temperatures after fluences near 10^{18} n/cm² ($E > 1$ Mev). Generally small and for engineering purposes, unimportant increases in strength are found. The exception is S-200 beryllium where a decrease in strength is credited to the extreme neutron embrittlement. Decreases in ductility and expected decreases in fracture toughness for materials used in the reactor are more important to the reactor designers since they define the design criteria to be used.

The data given in the previous sections are a sample of the irradiation test programs being carried out by the Westinghouse Astronuclear Laboratory in support of the NERVA program. Many other materials and properties have been examined as well as various forms of materials (sheet, bar, etc.) and brazes and weldments. Extensive annealing studies have been completed. In addition, irradiation tests have been made on components and instrumentation.

Future plans include the tensile testing of new materials being considered for NERVA application, fracture toughness evaluation of materials showing less than 5 percent tensile elongation and thermal conductivity measurements on beryllium and various grades of graphite. Future tests will be at various fluences up to 10^{19} n/cm² ($E > 1$ Mev) permitting property versus fluence relationship development to the maximum application fluence.

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REFERENCES

- (1) McReynolds, A. W., et al, Phys. Rev. 98 p418 (1955).
- (2) Coltman, R. R., "Reactor Irradiation Studies at 4° K", Radiation Damage in Solids II, International Atomic Energy Agency, Vienna, pp 205-229 (1962).
- (3) Lombardo, J. J., et al, "Cryogenic Radiation Effects on NERVA Structural Materials", Effects of Radiation on Structural Metals, ASTM STP 426, Am. Soc. Testing Mats., pp625-652 (1967).