CONF-850103--10

No. 023

CONF-850103--10

DE85 012887

SWELLING AND TENSILE PROPERTIES OF EBR-II-IRRADIATED TANTALUM ALLOYS FOR SPACE REACTOR APPLICATIONS*

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*Research sponsored by the Office of Space Nuclear Projects, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with the Martin Marietta Energy Systems, Inc.

†Clearance review from the Defense Advance Research Projects Agency required for publication.

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ABSTRACT

The tantalum alloys T-111, ASTAR-811C, Ta–10 W, and unalloyed tantalum were examined following EBR-II irradiation to a fluence of 1.7×10^{26} neutrons/m^2 (E > 0.1 MeV) at temperatures from 650 to 950 K. Swelling was found to be negligible for all alloys; only tantalum was found to exhibit swelling, 0.36%. Tensile testing revealed that irradiated T-111 and Ta–10 W are susceptible to plastic instability, but ASTAR-811C and tantalum were not. The tensile properties of ASTAR-811C appeared adequate for current SP-100 space nuclear reactor designs. Irradiated, oxygen-doped T-111 exhibited no plastic deformation, and the abrupt failure was intergranular in nature. The absence of plastic instability in ASTAR-811C is encouraging for alloys containing carbide precipitates. These fine precipitates might prevent dislocation channeling, which leads to plastic instability in many bcc metals after irradiation.

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INTRODUCTION

Designs of current space reactors must meet stringent system lifetime, mass, and volume requirements as set by the SP-100 Project. These limits require candidate reactor power systems to operate at temperatures at which only refractory alloys based on Nb, Mo, Ta, or W can be considered.

The irradiation effects data available for these alloys are considered inadequate. The purpose of the work reported in this paper is to provide an evaluation of previously irradiated tantalum alloys as a means to assess the effects of irradiation on tantalum alloys in particular and candidate refractory alloys in general. Results of the evaluation are intended to aid in the SP-100 Program concept down-selection process scheduled for July 1985 and to provide initial guidance to reactor designers during the ground engineering systems (GES) phase of the Program.

Tantalum alloys have been studied as part of the U.S. Liquid Metal Fast Breeder Reactor (LMFBR) program for use as control rod materials. Tantalum was rejected for this application due to excessive nuclear decay heat. As a result of that decision, an EBR-II irradiation experiment for the neutron absorber program completed irradiation but was never examined. This experiment provided tensile specimens of T-111 (Ta–8W–2Hf) and ASTAR-811C (Ta–8W–1Re–1Hf–0.025C) for the present evaluation. The availability of these specimens resulted in about a two-year saving in the time required for fabrication and irradiation. The EBR-II experiment also contained Ta–10 W and unalloyed tantalum. These alloys were also examined to a limited extent to provide a comparison with the two alloys of primary interest.

The present investigation addresses swelling, tensile, and fracture behavior. Swelling resulting from the irradiation of metals and alloys is a concern even in nonfuel structural materials. Two major problems can result from swelling in a reactor system. Swelling of fuel cladding can cause fuel pin bowing, restricting heat transfer and altering flux shape, and stresses can develop due to differential swelling in temperature and flux gradients [Gilbert et al. (1977)]. Although irradiation creep will sometimes relieve swelling stresses, both of these phenomena may be limiting for some design and operating conditions. It is necessary to characterize swelling so that it can be accounted for in the design of nuclear reactors operating in the swelling regime. The effects of irradiation on tensile properties and on fracture mode must be known to design a structure that will be exposed to radiation. Since there are only sparse data available on swelling and tensile properties of irradiated T-111 and ASTAR-811C at relevant temperature and fluence levels [Wiffen (1984)], the present investigation was initiated.

NEUTRON IRRADIATION

The irradiation experiment was designed and fabricated as part of the LMFBR program for irradiation of tantalum alloys for use as neutron absorbers. The experiment was constructed at the Oak Ridge National Laboratory and subsequently installed in the EBR-II in Idaho, beginning irradiation on June 17, 1973. Although the tantalum alloy absorber program was discontinued, the irradiation vehicle, subassembly X-185, was allowed to remain in the reactor until September 24, 1974, having accumulated an exposure of 16,806 MWd. It was then stored at ORNL until 1984 when the specimens were determined to be of interest to the SP-100 program.

The tantalum alloys were irradiated in two Mark B-7 pins with specimen holders arranged in tandem along the axes of the capsules. The specimens were fit tightly into holes in cylindrical holders in a helium environment with filler pieces to assure uniform heat conduction from the entire specimen. Nuclear heating in the specimens and in the tungsten and stainless steel holders provided the required elevated irradiation temperatures. The holder configuration is illustrated in Fig. 1. Each holder was surrounded by a gap containing helium, and the width of the gap determined the irradiation temperature. Since no access to the irradiation capsule interior was possible, temperatures were calculated with a two-dimensional heat transfer analysis using the Heating V computer code of Turner, Elrod, and Simon-Tov (1977). Temperature calculations were performed following the irradiation so that the calculated nuclear heating rates from each reactor cycle could be used. Both maximum and mean heating rates were used to calculate selected specimen temperatures. Calculated temperatures appear in Table 1.

Neutron fluences were determined from calculated values for each reactor cycle as provided by the EBR-II neutron physics group [Grimm (1984)]. Total fluences were arrived at by adding the fluence for each cycle. Displacement cross sections were computed from data from Doran and Graves (1976). Values for displacements per atom are shown with fluences for the center position of each specimen in Table 2. The fluence values are in the range considered relevant to space reactors which are estimated to have maximum end-of-life exposures of about 2×10^{26} neutrons/m^2 ($E > 0.1$ MeV).

SPECIMEN PREPARATION

The specimens were prepared from alloys obtained in rod form with chemical compositions given in Table 3. The alloys were annealed for the times and temperatures shown in Table 4. Hardnesses and grain sizes of the annealed materials are also given in Table 4. Interstitial impurity contents are provided in Table 5. These values were not affected by the annealing. Cold-worked specimens of T-111 and Ta–10 W were produced by cold swaging the annealed material to 26% reduction of area prior to machining. In addition, a number of specimens of T-111 were doped with oxygen by exposure to an environment of 1.3×10^{-3} Pa oxygen pressure at 1098 K for 25 h to achieve levels of 360 to 450 wt ppm (4100–5100 at. ppm) measured by weight gain during the doping treatment.

SWELLING MEASUREMENTS

Swelling was determined from length measurements of the specimens. The precision of this measurement is estimated to be ±0.06% change in volume which is more precise than can be obtained from immersion density measurements on specimens of this size, where precision is estimated to be ±0.2% volume change. Certified micrometers were used for the measurements of the specimens before and after irradiation. The specimens were rotated end for end for three measurements, which were averaged. Isotropic volume swelling is very closely approximated by $3\,\Delta L/L$ where ΔL is the change in length and L is the preirradiation length.

Values of length changes and of volume swelling in unalloyed tantalum are tabulated in Table 6, and all swelling measurement results are summarized in Table 7. Since measured swelling values in the three alloys are all close to zero, the measurements on individual specimens are not given. These results lead to the following general observations:

1. There is no systematic variation of swelling with either temperature or fluence.

2. Only unalloyed tantalum in the annealed condition shows measurable swelling larger than the estimated error limit and the standard deviation of the measurements.

3. Oxygen-doped T-111 and ASTAR-811C demonstrated minor densification.

TENSILE TESTING

The cylindrical specimens had an overall length of 47 mm and a reduced gage section 28.58 mm long and 3.170 mm in diameter. These specimens were tested on a fully remote Instron universal testing machine equipped with an ion pumped vacuum furnace. Both irradiated and unirradiated specimens were tested on the same remote machine in order to avoid any differences in temperature distribution, environment, or the testing machine. A strain rate of 3.0×10^{-4} s^{-1} was used for all tests, but the chamber pressure varied from 7×10^{-6} to 1.3×10^{-4} Pa, and short temperature equilibration times were used to minimize exposure at high temperatures.

The potential for interstitial contamination during testing, especially by oxygen, was initially a concern. To address this concern, specimens of T-111 and unalloyed tantalum were analyzed by 14 MeV neutron activation analysis. Oxygen levels were found to be unchanged by exposure during the test to within the ±50% accuracy of the measurements.

The results of the tensile tests are shown in Table 8. For the purpose of discussion, the alloys will be compared with T-111 for which strength and ductility have been plotted in Figs. 2 and 3, respectively. As Fig. 2 shows, T-111 exhibits irradiation strengthening of about a factor of 2.3. Evidence of partial recovery is observed at 925 K. Figure 3 illustrates that radiation embrittlement occurred for all temperatures investigated as evidenced by a severe reduction in uniform elongation. This nearly complete absence of strain hardening will be referred to as plastic instability. Total elongation, although lowered by a factor of 3 by irradiation, still remains above 4%, which should be adequate for all SP-100 applications.

The effect of cold work can be seen from Table 8. T-111 with 26% cold work has been irradiated and tested under conditions similar to the annealed material. As expected, cold work raises the strength of unirradiated material by about 50%. Prior to irradiation, the ductility of the cold-worked material is only about one-third that of annealed T-111 as measured by total elongation, but following irradiation they are equivalent. Uniform elongation is very small for both conditions. This appears to be a mild form of the plastic instability that has been observed for irradiation of other bcc metals and alloys. The load drop observed in the tensile curves of the irradiated material is more abrupt than that observed in cold-worked material, and the values of uniform elongation are not as low, but the data indicate that 26% cold work has nearly exhausted the unirradiated material's ability to work harden.

ASTAR-811C (Fig. 4) has a higher strength than T-111 in the unirradiated condition, but strengthens to about the same level as T-111 upon irradiation. The elongation plot in Fig. 5 shows that ASTAR-811C, although embrittled by irradiation, does not have as low a uniform elongation as T-111. The tensile curves for ASTAR-811C do not exhibit the severe plastic instability observed in irradiated T-111.

As expected, unirradiated tantalum, plotted in Fig. 6, is only about one-third as strong as T-111 and ductility values are higher (Fig. 7). It does not, however, suffer from plastic instability or any form of limited uniform elongation; uniform elongation remains above 4% for irradiated material.

The alloy Ta—10 W was also examined to a limited extent. By comparing Figs. 2 and 8, it is seen that the alloy is slightly weaker than T-111 prior to irradiation and about 40% weaker following irradiation. The alloy's apparently lower sensitivity to irradiation is not reflected by ductility (Fig. 9). Although total elongation is slightly higher than that of T-111, plastic instability with resulting small values of uniform elongation is observed.

Although not illustrated because of the small number of specimens, 26% cold work of Ta—10 W has the effect of strengthening the alloy 50% for unirradiated and 20% for irradiated material. However, the ductility is changed very little by cold work, and the plastic instability problem is worsened.

A limited number of specimens of T-111 were doped with oxygen prior to irradiation. The specimens were exposed to a partial pressure of 1.3×10^{-3} Pa of oxygen at 1098 K for 25 h, which was shown by weight gain measurements to introduce an average of 400 wt ppm (4500 at. ppm) oxygen into the gage section of the specimen. The method has previously been validated by Inouye and Liu (1974) with neutron activation analysis. Doped specimens were irradiated at 753 and 853 K. As shown in Table 8, the unirradiated specimens exhibited 15 and 25% elongation at 753 and 853 K, respectively, but the corresponding irradiated specimens fractured in the elastic portion of the tensile curves with no macroscopic plastic deformation (Fig. 10).

DISCUSSION

Swelling Behavior

As with any fast spectrum reactor, swelling of fuel cladding and structural materials will be an important concern in a space reactor. Little is known about swelling in refractory metals and several phenomena that are peculiar to bcc alloys do not occur in austenitic alloys. However, many phenomena observed in the larger data base for austenitic stainless steels are also expected to take place in refractory metals. Swelling in stainless steels occurs for irradiation at temperatures from 0.3 to 0.5 of the melting point, T_m, in fast reactors. However, limited data on refractory metal alloys compiled by Wiffen (1984) indicate that this range may be lower, starting at 0.2 to 0.25 of the melting point. This corresponds to 650 to 820 K for tantalum base alloys. If further research with more accurate temperature measurements shows that swelling behavior is similar to that of stainless steels and that 0.5 T_m is the projected swelling upper limit, then swelling will be a concern at temperatures as high as 1600 K.

Swelling in austenitic stainless steels is found to exhibit an incubation fluence, usually near 3×10^{26} neutrons/m^2 ($E > 0.1$ MeV), or 15 dpa. Below this fluence, swelling is low; above the incubation fluence, swelling is nearly linear with fluence, sometimes increasing at a rate as high as $5\%/10^{26}$ neutrons/m^2 ($E > 0.1$ MeV), as pointed out by Garner (1984). Incubation fluence is a function of irradiation temperature and alloy composition, with minor element chemistry (therefore, heat-to-heat variation) having a major effect according to Garner (1984). The linear swelling rate is less sensitive to alloy chemistry and is nearly independent of temperature over a 200 to 300 K temperature range.

Since all of the alloys examined in this study exhibited swelling below 0.5%, it is possible that the incubation fluence may not have been reached. This has both favorable and unfavorable implications, but the data are encouraging for space power reactors. If the incubation fluence for tantalum alloys is greater than the end-of-life fluence for a space reactor, swelling will not be a problem. This appears to be the case for current designs. However, since the highest fluence reached in this experiment was 1.7×10^{26} neutrons/m^2, 2.2 dpa, if the end-of-life fluence were to be raised to significantly higher levels at a future time, the swelling could still limit reactor life if the incubation fluence is $\geq 1.7 \times 10^{26}$ neutrons/m^2. A linear extrapolation of swelling from the present data is not justified.

Previous irradiation of unalloyed tantalum by Wiffen (1977) shows higher swelling than observed in the present investigation in the same temperature range (Fig. 11). Since the fluence was 2.5×10^{26} neutrons/m^2, the higher swelling (2.4%) might have resulted from exceeding the threshold fluence. The discrepancy may also have resulted from temperature uncertainties in the earlier experiment. Nonetheless, the present investigation does show that in the temperature range investigated, T-111, ASTAR-811C, and Ta–10 W are not expected to swell for a fluence as high as 1.7×10^{26} neutrons/m^2 ($E > 0.1$ MeV), producing damage levels of 2.2 dpa, which is approximately the end-of-life exposure for SP-100 designs.

Mechanical Behavior

The most interesting behavior observed in this investigation was the very early onset of plastic instability, where uniform elongations of less than 0.2% were observed. Only ASTAR-811C and unalloyed tantalum did not exhibit this behavior, and unalloyed tantalum is too weak to be of use as a reactor structural material. This phenomenon is illustrated in Fig. 12 where representative tensile curves for irradiated and unirradiated T-111 are shown. The unirradiated specimen shows serrated yielding, then a large amount of plastic deformation followed by fracture. In contrast, the irradiated specimen demonstrates a very abrupt load drop immediately following the elastic portion of the curve. Plastic deformation continues with necking until fracture occurs with several percent total elongation. This phenomenon has been observed on many occasions in bcc metals as reviewed by Wiffen (1984). Although transmission electron microscopy remains to be done in the present investigation, previous research by several investigators, for example, Wiffen (1973), has shown the phenomenon to be accompanied by channels cleared of irradiation-produced defects. Channel deformation, as it is called, results from dislocation motion clearing a channel along slip planes which results in a locally soft band. This is believed to be the cause of the abrupt drop in strength immediately following the onset of plastic deformation. Figure 13 shows the fracture surface of a specimen with only 0.18% uniform elongation. Despite such limited uniform elongation, the fracture surface reveals complete ductile rupture nearly indistinguishable from the unirradiated specimen. Such a material would be expected to meet the leak-before-break criterion applied to a pipe or a vessel, but once the material is loaded to its yield strength, the absence of work hardening would result in immediate failure. Although further work is necessary, especially at higher temperatures, ASTAR-811C appears to be superior to the other tantalum alloys presented in this paper in its tensile properties, especially in its resistance to plastic instability.

The effect of oxygen doping of T-111 before irradiation was to further embrittle the material in postirradiation tensile tests. These results may indicate that control of oxygen takeup rates during reactor service of tantalum alloy components is required.

SUMMARY AND CONCLUSIONS

1. Only unalloyed tantalum showed measurable swelling in the temperature range of 660 to 920 K and at fluences of 0.56 to 1.7 × 10^{26} neutrons/m^2 (E > 0.1 MeV): 0.36% at a fluence of 1.7 × 10^{26} neutrons/m^2 (E > 0.1 MeV).

2. Upon irradiation, T-111 strengthens, by a factor of 2.3, with partial recovery observed at 925 K.

3. ASTAR-811C strengthens upon irradiation to about the same level as T-111.

4. Unalloyed tantalum is about one-third as strong as T-111 in both irradiated and unirradiated conditions.

5. Ta–10 W is about 40% weaker than T-111 following irradiation.

6. T-111 and Ta–10 W show severe plastic instability following irradiation, limiting uniform elongation to about 0.2%.

7. ASTAR-811C and tantalum did not exhibit plastic instability, but unalloyed tantalum is too weak for SP-100 structural application.

8. T-111 doped with 400 wt ppm (4500 at. ppm) oxygen and irradiated at 753 K to a fluence of 1.7 × 10^{26} neutrons/m^2 (E > 0.1 MeV) was severely embrittled as shown in a tensile test at the irradiation temperature.

For temperatures in the range of 650 to 950 K, swelling does not appear to be a problem for the goal fluence of present SP-100 reactor system concepts. If tantalum alloys are used as cladding and structural materials, plastic instability is a concern that might be minimized by using ASTAR-811C. Further examination at higher temperatures is required before firm conclusions can be drawn. As is typical of refractory metals, oxygen presents a potentially severe embrittlement hazard. Use of the alloys with lithium coolant might be a satisfactory combination of structural material and coolant because of the affinity of lithium for oxygen.

This investigation might be generalized to make some comments on other refractory metal systems. The alloy, Nb-1 Zr, has been irradiated and observed to exhibit channel deformation and associated plastic instability by Wiffen (1984). However, when significant swelling is present, uniform elongation increases. Wiffen (1984) reasons that voids cannot be swept from channels as can dislocation loops so that softening in channels does not occur. This is further substantiated by experiments where specimens of Nb-1 Zr have been doped with ^{10}B to produce helium upon irradiation in a reactor with a thermal neutron spectrum. Here again, channel deformation is not observed. Wiffen (1984) proposes that helium bubbles or voids promoted by the insoluble gas prevent channeling.

Buckman and Goodspeed (1971) have observed precipitation of Ta_2C in ASTAR-811C. After 1 h at 2272 K, a fine conerent precipitate of Ta_2C was observed by transmission electron microscopy (TEM). Further investigation of irradiated ASTAR-811C by TEM might reveal carbides formed during irradiation. Such carbides could possibly account for the better performance of ASTAR-811C compared with the other tantalum alloys studied. If this is the case, carbides or other precipitates might be used to alleviate the plastic instability problem in other refractory metal alloys.

ACKNOWLEDGMENTS

The authors wish to thank M. J. Kania for doing the thermal analyses of the irradiation vehicles. The assistance of E. L. Ryan, L. T. Gibson, and L. K. Egner for performing physical tests and preparing specimens is gratefully acknowledged. The irradiation vehicle was designed by D. A. Dyslin and fabricated under the supervision of J. W. Woods. The suggestions of J. A. Horak, R. L. Klueh, A. F. Rowcliffe, and R. H. Cooper, who reviewed the manuscript, were most valuable. The assistance of Frances Scarboro for editing and typing was invaluable and most appreciated.

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Fig. 11. Percent void volume as a function of irradiation temperature for EBR-II-irradiated tantalum [from Wiffen, F. W. (1973) "The Tensile Properties of Fast Reactor Neutron Irradiated BCC Metals and Alloys," in Defects and Defect Clusters in B.C.C. Metals and Their Alloys, National Bureau of Standards, Gaithersburg, Maryland, 1973, pp. 176–96].

Fig. 12. Tensile stress-strain curves for unirradiated and irradiated (specimen numbers are KT39 and KT58, respectively) T-111 demonstrating plastic instability in the irradiated material.

Fig. 13. Fracture surface of T-111 irradiated and tested at 873 K showing ductile rupture associated with plastic instability. Fluence ($E > 0.1$ MeV) = 1.6×10^{26} neutrons/m^2.

Table 1. Irradiation Temperatures

Specimen Holder	Temperature (K; ±10%)		Specimen Holder	Temperature (K; ±10%)	
	Maximum[a]	Mean		Maximum[a]	Mean
	Capsule 0-12			Capsule 0-13	
2G	720	720	3F		700
2H	770	760	3G		720
2I		800	3H	770	760
2J	960	920	3I		800
2K		870	3J	910	870
2L		820	3K		870
2M		760	3L		820
2N		680	3M		760
2O		750	3N	910	870
2P	770	750	3O	880	850
2Q		700	3P	770	750
2R	670	600	3Q		700
			3R	670	660
			3S		660

[a]Calculated for reactor cycle with highest nuclear heating.

Table 2. Neutron Fluence and Displacements Per Atom for Subassembly X185

Position	Height[a] (cm)	Fluence, × 10^{26} neutrons/m^2 Total	Fast (E > 0.1 MeV)	dpa in Tantalum
F	37.15	0.924	0.624	0.57
G	31.43	1.16	0.785	0.78
H	25.72	1.43	0.970	1.0
I	20.00	1.75	1.18	1.4
J	14.29	2.09	1.41	1.8
K	8.57	2.34	1.58	2.1
L	2.86	2.48	1.67	2.2
M	−2.86	2.48	1.67	2.2
N	−8.57	2.34	1.58	2.1
O	−14.29	2.08	1.41	1.7
P	−20.00	1.71	1.15	1.3
Q	−25.72	1.37	0.927	0.96
R	−31.43	1.08	0.727	0.70
S	−37.15	0.829	0.560	0.50

[a]Positions above the core midplane are positive; positions below the midplane are negative.

Table 3. Chemical Compositions of Alloys Investigated (wt ppm Unless Specified wt %)

	T-111	ASTAR-811C	Ta	Ta–10 W
Co	<5	<5		
Cr	<10			
Cu	<40			
Fe	<20	45	<15	<40
Hf	2.0 wt %	0.9 wt %		
Mo	<10	10		<20
Nb	470	930	210	370
Ni	<10	<10	<10	<20
Re		1.39 wt %		
Si			<10	
Ta	Bal	Bal	Bal	Bal
Ti			15	
V	<10	<10		
W	8.5 wt %	8.2 wt %	250	10.2 wt %
Zr	620			

Table 4. Annealing Treatment, Hardness, and Grain Size for the Four Alloys Irradiated

Alloy	Heat Treatment[a]		Hardness		Grain Size	
	Temperature (K)	Time	DPH 500g[b]	BHN[a]	ASTM[b] No.	ASTM[a] No.
Ta	1360	1	89	64	7	6.5
Ta—10 W	1810	1	216	197	7	7.5
T-111	1920	1	237	218	8	8.5
ASTAR-811C	1920[c]	0.5[c]	—	274[c]	8[c]	—

[a]Information from vendor, Wah Chang Albany Corporation.

[b]Measured by Westinghouse Hanford Company.

[c]Processing by ORNL.

Table 5. Interstitial Impurities (wt ppm)

	T-111	ASTAR-811C	Ta	Ta-10 W
C	22	235	<10	<10
H	2.0	2.8	1.7	2.4
N	<5	13	16	10
O	25	50	44	27

Table 6. Length Change Measurements and Derived Swelling for Unalloyed Tantalum Irradiated in EBR-II

Irradiation Temperature (K)	Fluence (E > 0.1 MeV) ($\times 10^{26}$ neutrons/m^2)	$\frac{\Delta L}{L}$ (%)	$\frac{\Delta V}{V}$[a] (%)
700	0.927	0.09	0.27
700	0.927	0.12	0.36
750	1.15	0.15	0.45
750	1.15	0.10	0.30
850	1.41	0.10	0.30
850	1.41	0.15	0.45

[a] $\frac{\Delta V}{V} = 3 \frac{\Delta L}{L}$.

Table 7. Swelling Measurements for Each Alloy Averaged Over All Temperatures and Fluences

Alloy	Average Length Change ΔL(μm)	Standard Deviation in ΔL (μm)	$\frac{\Delta L}{L}$ (%)	$\frac{\Delta V}{V}$ (%)	Standard Deviation of Swelling $\frac{3\sigma}{L}$ (%)	Number of Specimens
T-111	0.94	11	0.0020	0.0060	0.072	27
T-111(CW)[a]	−1.3	15	−0.0027	−0.0081	0.093	8
T-111(O_2)[b]	−20	23	−0.042	−0.13	0.15	4
ASTAR 811C	−19	11	−0.040	−0.12	0.069	9
Ta	56	11	0.12	0.36	0.072	6
Ta–10 W	−4.8	3.6	−0.010	−0.030	0.069	20
Ta–10 W(CW)[a]	−5.1	11	−0.011	−0.033	0.024	4

[a]26% cold worked.

[b]360 to 450 wt ppm oxygen.

Table 8. Irradiation Parameters and Tensile Data

Specimen	Fluence (10^{26} neutrons/m^2) (E > 0.1 MeV)	Temperature (K) ($T_{Irrad} = T_{Test}$)	Strength (MPa) Yield	Strength (MPa) Ultimate Tensile	Elongation (%) Uniform	Elongation (%) Total
			T-111			
KT15	0	663	601	667	14.8	26.3
KT9	0.73	663	1530	1540	0.13	4.6
KT10	1.6	683	1650	1650	0.22	5.0
KT56	0	723	575	634	13.6	27.5
KT65	0	723	563	623	14.3	31.1
KT51	0.79	723	1350	1350	0.26	6.1
KT50	0.79	723	1390	1390	0.27	6.2
KT18	0	803	493	561	14.1	25.5
KT27	1.2	803	1370	1370	0.15	5.6
KT14	0	823	493	561	14.1	27.7
KT21	1.7	823	1590	1590	0.25	4.3
KT[illegible]	0	873	472	536	15.3	27.5
KT57	1.6	873	1440	1440	0.18	5.1
KT58	1.6	873	1400	1400	0.19	5.1
KT53	0	923	427	517	16.7	26.8
KT61	1.4	923	1050	1070	0.44	7.2
			ASTAR-811C			
CT19	0	763	710	855	10.1	19.0
CT11	1.0	763	1390	1430	0.98	6.4
CT12	1.0	763	1380	1420	1.1	6.5
CT4	0	873	586	745	10.4	18.0
CT7	1.4	873	1230	1260	0.78	6.5
CT9	1.4	873	1230	1280	0.92	6.7
			T-111 (26% Cold Worked)			
MT17	0	663	952	965	0.52	8.8
MT3	0.56	663	1670	1670	0.21	4.9
MT4	0.56	663	1610	1610	0.27	5.8
MT15	0	723	910	924	0.44	8.6
MT7	0.79	723	1410	1410	0.58	6.2
MT8	0.79	723	1420	1430	0.53	6.1
			T-111 + 380 to 450 wt ppm O_2			
KT84	0	753	617	710	7.1	14.8
KT88	1.2	753		903	0	0
KT91	0	853	578	703	16.3	24.7
KT86	1.4	853		1200	0	0

Table 8 (Continued)

Specimen	Fluence (10^{26} neutrons/m^2) (E > 0.1 MeV)	Temperature (K) ($T_{Irrad} = T_{Test}$)	Strength (MPa)		Elongation (%)	
			Yield	Ultimate Tensile	Uniform	Total
			Ta—10 W			
ET45	0	663	456	585	15.0	27.8
ET37	0.73	663	1030	1030	0.19	8.1
ET38	0.73	663	1010	1010	0.12	8.4
ET20	0	703	497	579	14.5	29.2
ET15	0.93	703	1020	1030	0.59	9.1
ET3	0	753	475	549	14.9	29.2
ET11	1.2	753	986	986	0.14	9.0
ET12	1.2	753	993	993	0.11	9.0
ET21	0	803	447	521	15.7	26.1
ET23	1.2	803	952	952	0.11	8.9
ET24	1.2	803	958	958	0.11	8.9
			Ta—10 W (Cold Worked)			
HT9	0	703	889	889	0.37	7.6
HT2	0.62	703	1230	1230	0.18	6.4
HT3	0.62	703	1230	1230	0.18	6.5
			Tantalum			
AT20	0	703	91.7	254	24.6	40.1
AT2	0.93	703	465	536	6.1	16.2
AT14	0	753	64.8	239	28.3	35.6
AT5	1.2	753	620	689	6.1	14.1
AT15	0	853	61.8	214	22.4	39.4
AT7	1.4	853	514	551	4.4	13.1

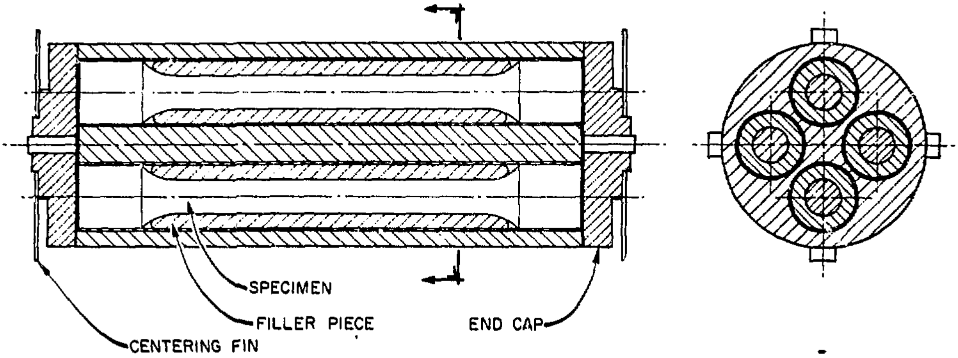


Fig. 1

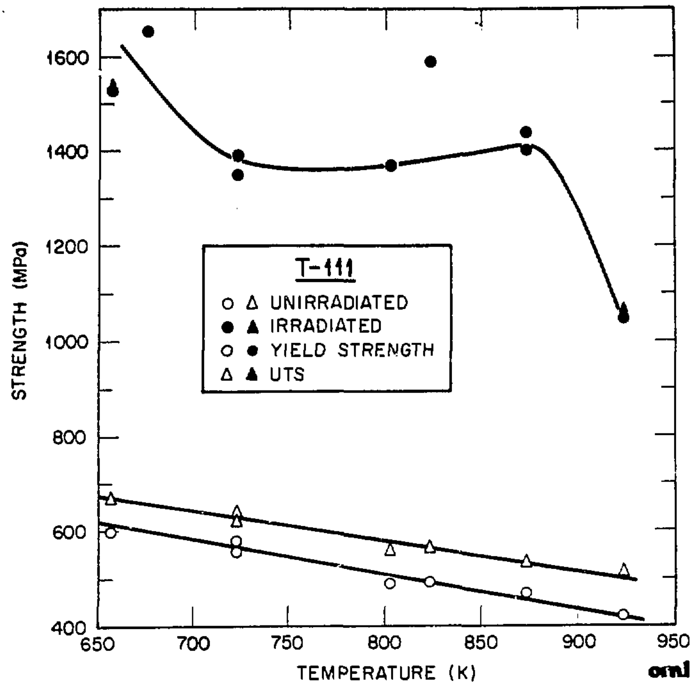

T-111
UNIRRADIATED
IRRADIATED
YIELD STRENGTH
UTS
STRENGTH (MPa)
TEMPERATURE (K)
400
600
800
1000
1200
1400
1600
650
700
750
800
850
900
950
ornl

Fig. 2

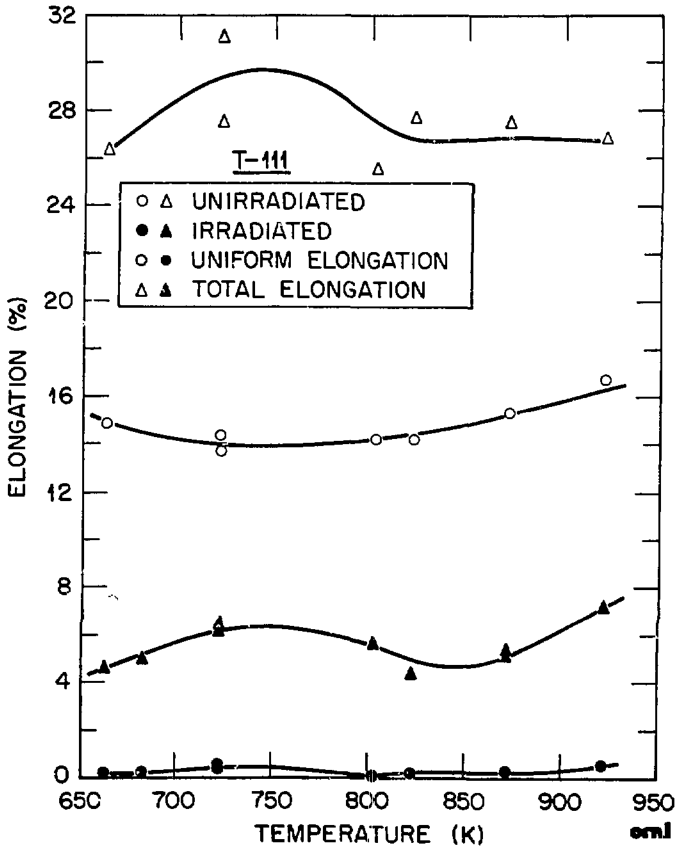

T-111
UNIRRADIATED
IRRADIATED
UNIFORM ELONGATION
TOTAL ELONGATION
ELONGATION (%)
TEMPERATURE (K)
0
4
8
12
16
20
24
28
32
650
700
750
800
850
900
950
ornl

Fig. 3

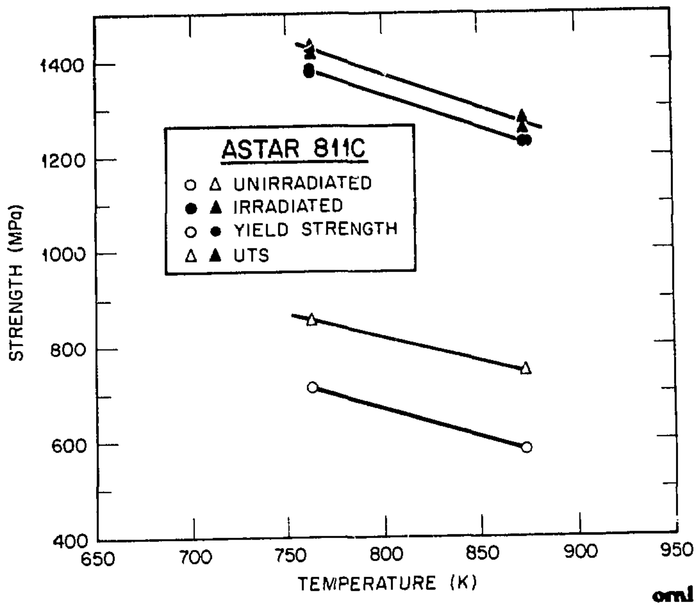

ASTAR 811C
○ △ UNIRRADIATED
● ▲ IRRADIATED
○ ● YIELD STRENGTH
△ ▲ UTS
STRENGTH (MPa)
1400
1200
1000
800
600
400
650
700
750
800
850
900
950
TEMPERATURE (K)
ornl

Fig. 4

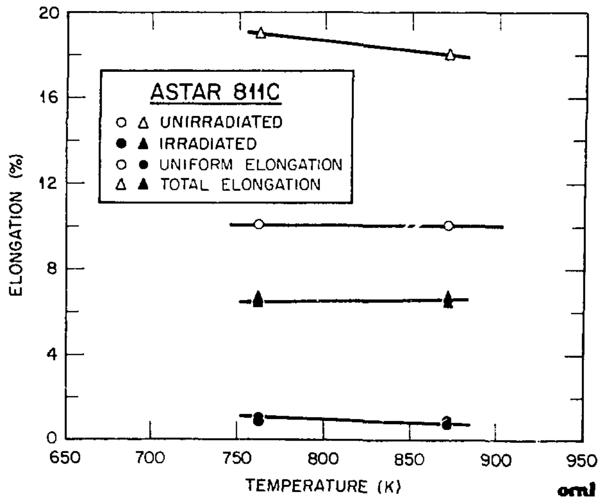

ASTAR 811C
○ △ UNIRRADIATED
● ▲ IRRADIATED
○ ● UNIFORM ELONGATION
△ ▲ TOTAL ELONGATION
ELONGATION (%)
20
16
12
8
4
0
650
700
750
800
850
900
950
TEMPERATURE (K)
ornl

Fig. 5

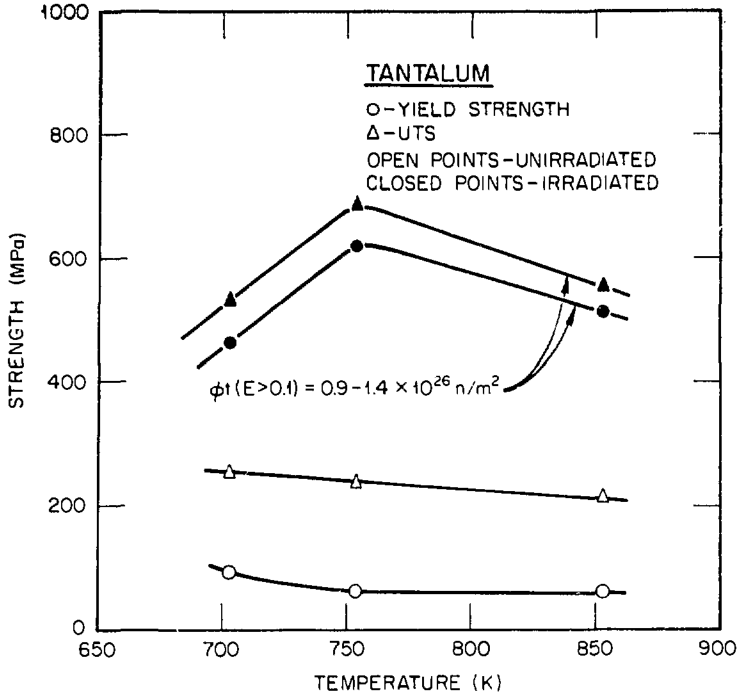

TANTALUM
O-YIELD STRENGTH
Δ-UTS
OPEN POINTS-UNIRRADIATED
CLOSED POINTS-IRRADIATED
ϕt (E>0.1) = 0.9-1.4 × 10^26 n/m^2
STRENGTH (MPa)
TEMPERATURE (K)
0
200
400
600
800
1000
650
700
750
800
850
900

Fig. 6

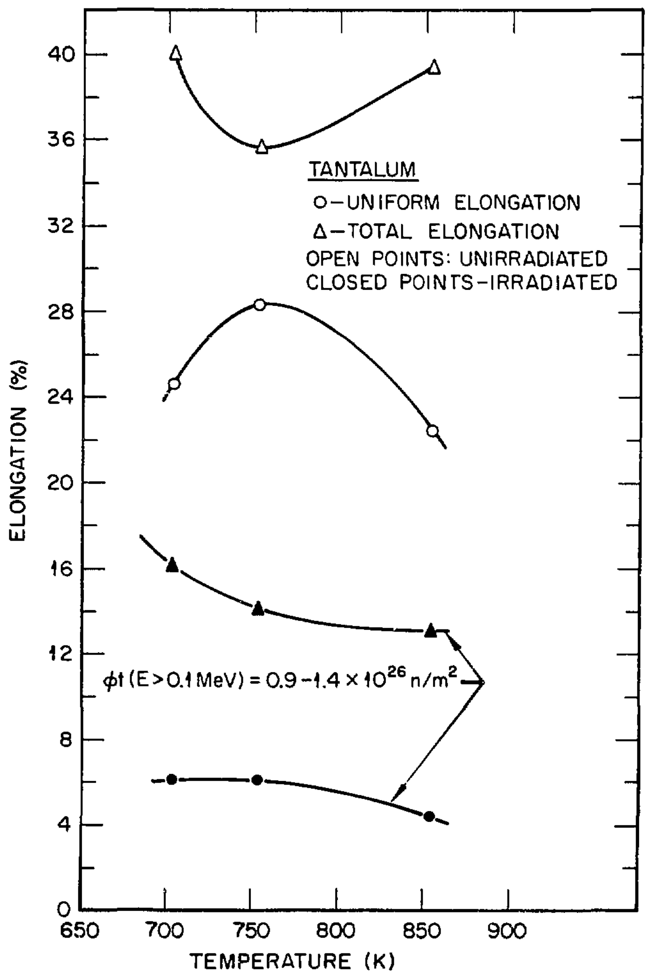
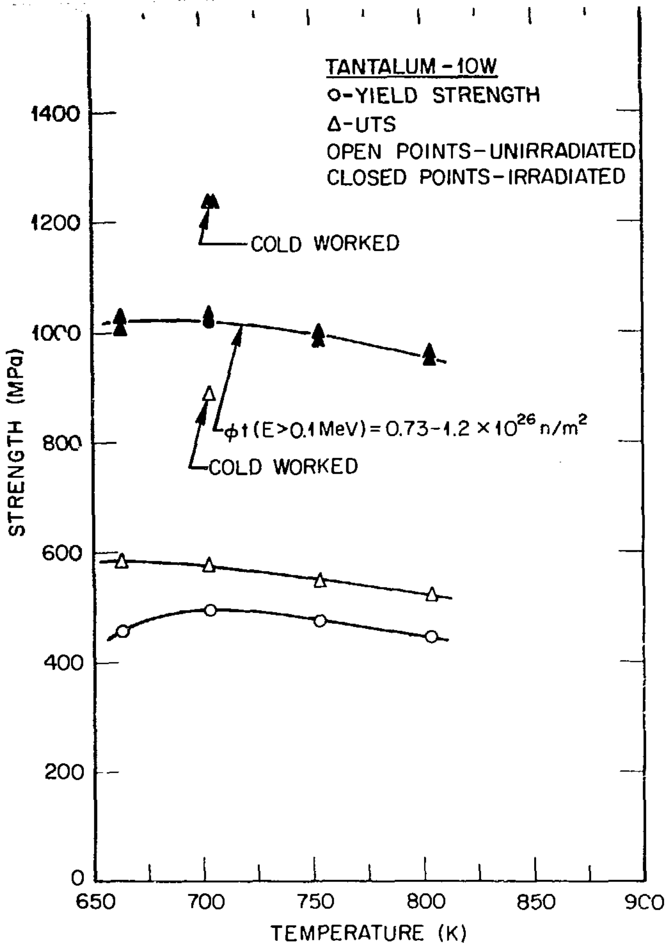
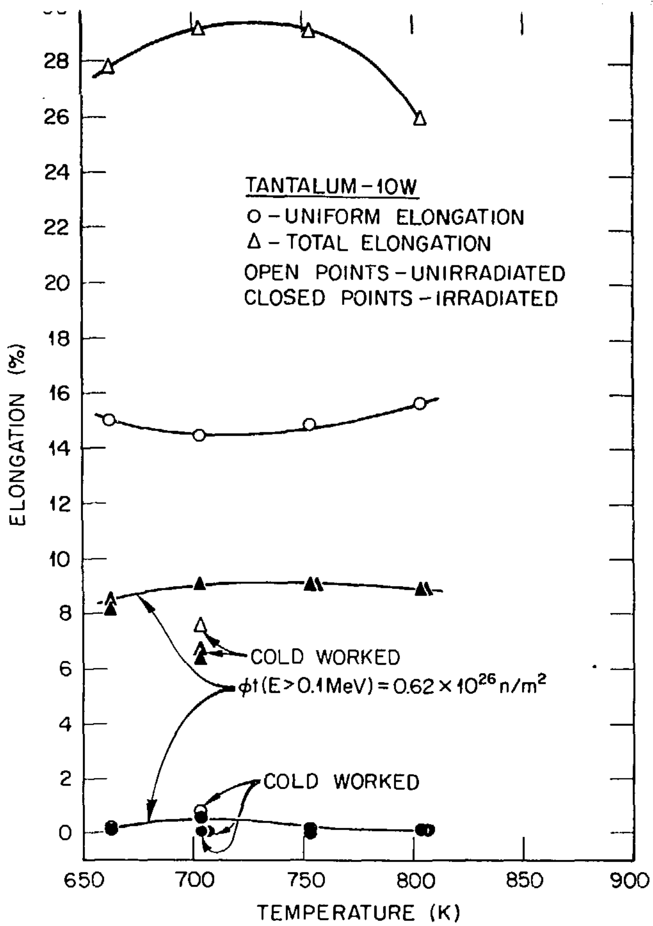

TANTALUM
O-UNIFORM ELONGATION
Δ-TOTAL ELONGATION
OPEN POINTS: UNIRRADIATED
CLOSED POINTS-IRRADIATED
ϕt (E>0.1 MeV) = 0.9-1.4 × 10^26 n/m^2
ELONGATION (%)
TEMPERATURE (K)
0
4
8
12
16
20
24
28
32
36
40
650
700
750
800
850
900

Fig. 7



TANTALUM - 10W
O-YIELD STRENGTH
Δ-UTS
OPEN POINTS-UNIRRADIATED
CLOSED POINTS-IRRADIATED
COLD WORKED
φt (E>0.1 MeV) = 0.73-1.2 × 10^26 n/m^2
COLD WORKED
STRENGTH (MPa)
TEMPERATURE (K)

Fig. 8



TANTALUM - 10W
O - UNIFORM ELONGATION
Δ - TOTAL ELONGATION
OPEN POINTS - UNIRRADIATED
CLOSED POINTS - IRRADIATED
COLD WORKED
φt (E>0.1 MeV) = 0.62 × 10^26 n/m^2
COLD WORKED
ELONGATION (%)
TEMPERATURE (K)

Fig. 9

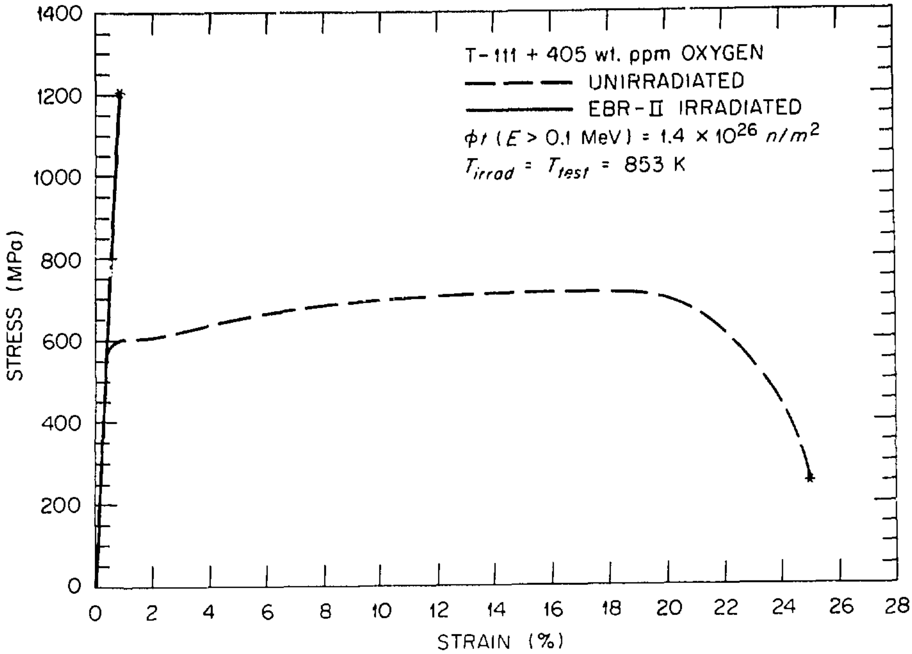

T-111 + 405 wt. ppm OXYGEN
UNIRRADIATED
EBR-II IRRADIATED
φt (E > 0.1 MeV) = 1.4 × 10^26 n/m^2
T_irrad = T_test = 853 K
STRESS (MPa)
STRAIN (%)
0
200
400
600
800
1000
1200
1400
2
4
6
8
10
12
14
16
18
20
22
24
26
28

Fig. 10

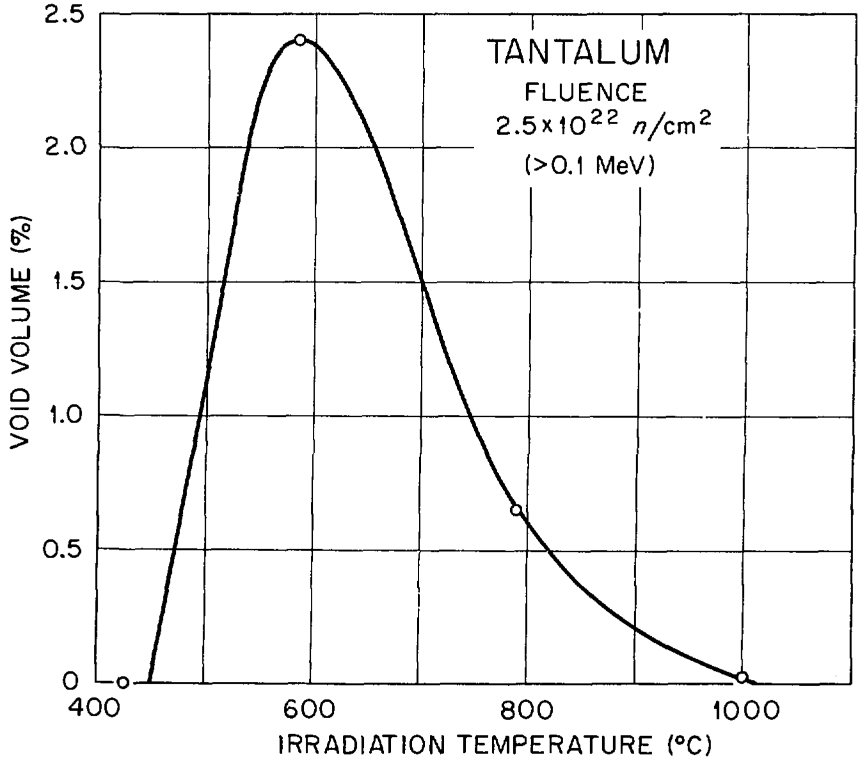

TANTALUM
FLUENCE
2.5×10^22 n/cm^2
(>0.1 MeV)
VOID VOLUME (%)
IRRADIATION TEMPERATURE (°C)
0
0.5
1.0
1.5
2.0
2.5
400
600
800
1000

Fig. 11

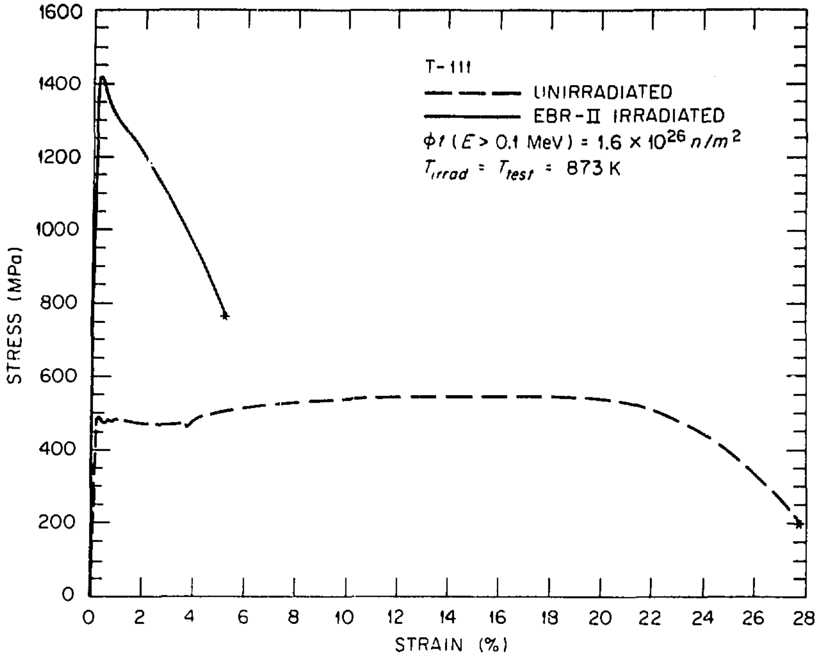

T-111
UNIRRADIATED
EBR-II IRRADIATED
ϕt (E > 0.1 MeV) = 1.6 × 10^{26} n/m^2
T_{irrad} = T_{test} = 873 K
STRESS (MPa)
STRAIN (%)
0
200
400
600
800
1000
1200
1400
1600
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28

Fig. 12

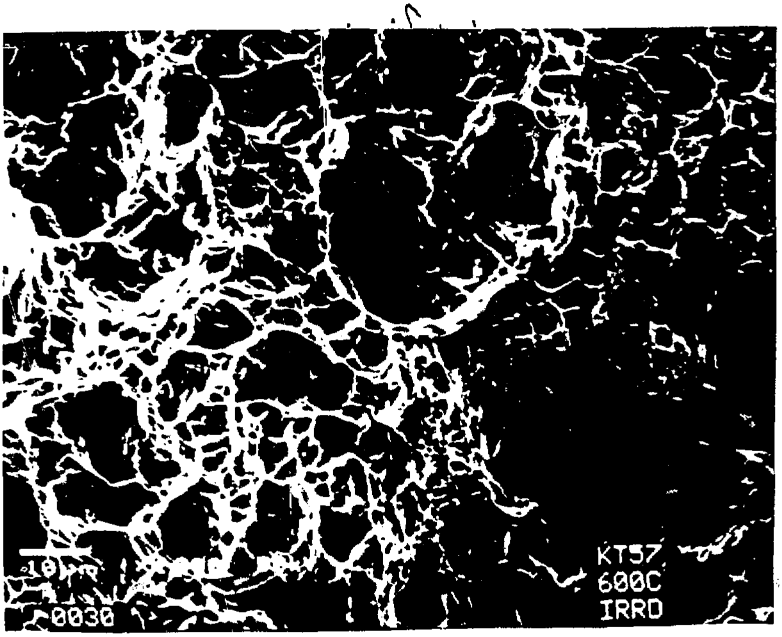

KT57
600C
IRRD
0030

Fig. 13