CONF-920673--19

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

THE EFFECT OF IRRADIATION ON THE MECHANICAL PROPERTIES OF 6061-T651 ALUMINUM*

David J. Alexander

Metals and Ceramics Division
OAK RIDGE NATIONAL LABORATORY
P.O. BOX 2008
Oak Ridge, TN 37831-6151

---

*Research sponsored by the Division of Energy Research, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-84OR21400. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

[illegible]

MASTER

David J. Alexander[1]

THE EFFECT OF IRRADIATION ON THE MECHANICAL PROPERTIES OF 6061-T651 ALUMINUM

REFERENCE: Alexander, D. J., "The Effect of Irradiation on the Mechanical Properties of 6061-T651 Aluminum," *Effects of Radiation on Materials: 16th International Symposium, ASTM STP 1175*, Arvind S. Kumar, David S. Gelles, Randy K. Nanstad, and Edward A. Little, Eds., American Society for Testing and Materials, Philadelphia, 1993.

ABSTRACT: Critical components of the Advanced Neutron Source (ANS) reactor, to be built at Oak Ridge National Laboratory (ORNL), will be fabricated from 6061-T651 aluminum alloy. This alloy has been selected for its favorable neutronic, thermal, and mechanical properties. The effect of irradiation on the tensile properties and fracture toughness has been studied to allow the lifetime of these components to be estimated. Irradiations were carried out in the High Flux Isotope Reactor at ORNL at a temperature of approximately 95°C to a fluence of approximately 10^{26} m^{-2} (thermal). Testing was conducted from room temperature to 150°C. The yield and ultimate tensile strengths were increased by irradiation, and the total elongation decreased, but the fracture toughness at 26 and 95°C was not degraded by irradiation, and decreased only slightly at 150°C.

KEYWORDS: aluminum, 6061-T651, irradiation effects, fracture toughness, yield strength, ductility, mechanical properties

The Advanced Neutron Source (ANS), to be built at Oak Ridge National Laboratory (ORNL), will be a user-oriented neutron research laboratory centered around the most intense, continuous beams of neutrons available in the world. These beams will be at least five times more intense than those available elsewhere. About 48 neutron beam stations will be set up in beam rooms and the neutron guide hall for neutron scattering and for fundamental nuclear physics research. In addition, extensive facilities will be provided for materials irradiation, isotope production, and analytical chemistry. The goal of the project is to produce a peak thermal neutron flux (<0.625 eV) in the reflector of greater than 5×10^{19} $m^{-2} \cdot s^{-1}$.

A key to the successful attainment of this goal is allowing the neutrons produced in the reactor core to escape through the vessel that controls the flow of cooling water over the fuel elements. An aluminum alloy, 6061-T651, has been selected for this structure, called the Core Pressure Boundary Tube (CPBT). This alloy [nominal composition Al-1.0Mg-0.6Si-0.3Cu-0.2Cr (weight percent)] offers acceptable

---

[1] Development Staff Member, Metals and Ceramics Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge TN 37831-6151.

mechanical properties in the unirradiated condition, a low neutron cross section that will limit neutron absorption, and high thermal conductivity for heat removal. As the CPBT provides the primary pressure boundary for the reactor, its integrity is a vital issue for the safe operation of the ANS. The intense neutron flux that the CPBT will be exposed to will result in a significant increase in the silicon content of the alloy, due to transmutation of aluminum by thermal neutrons. This can be expected to embrittle the aluminum, and reduce its fracture toughness. Therefore, a critical step in the design of the reactor systems is to generate data for the effects of irradiation on the mechanical properties of the 6061-T651 material, in particular the effect on fracture toughness. This will permit the safe operating life of the CPBT to be estimated.

An irradiation program is under way at ORNL to provide these data. Irradiations are planned to two levels of thermal fluence: 10^{26} and 8×10^{26} m^{-2}. This maximum value corresponds to the expected fluence at the CPBT after approximately 6 months of operation of the ANS reactor. Irradiations are being carried out in the target region of the High Flux Isotope Reactor (HFIR) at ORNL. This reactor offers a neutron spectrum with a ratio of thermal to fast neutrons (approximately 2:1) that is similar to that calculated for the CPBT. The high flux in the HFIR target region allows irradiations to the necessary high fluences to be completed in reasonable time periods. The first irradiation capsule, called HANSAL-T1, has been irradiated to the lower fluence level of 10^{26} m^{-2} (thermal). This paper presents results from some of the specimens contained in HANSAL T-1.

CAPSULE DESIGN

The HANSAL-T1 capsule was designed to be inserted in the HFIR target region so that it would be exposed to the highest possible flux, to reduce the irradiation time. The standard capsule for insertion in the target region is cylindrical, with a diameter of approximately 12 mm. In order to allow larger specimens to be irradiated, a new capsule was designed that occupied a cluster of four standard positions (see Fig. 1). This permitted 16 compact fracture toughness specimens 28.6 × 27.4 × 11.4 mm thick (1.125 × 1.080 × 0.45 in.) [designated 0.45 T C(T)] to be stacked end-to-end in a column inside the capsule. Narrow channels controlled the flow of reactor cooling water over the specimen faces to achieve the desired irradiation temperature (Fig. 1). Because of the flux gradient along the length of the HFIR core there was a corresponding gradient in fluence and temperature along the length of the specimen column, as shown in Fig. 2. The target temperature for the irradiation was 95°C, the expected peak temperature of the CPBT under normal operating conditions.

The 0.45 T C(T) specimens are slightly smaller (see Fig. 3) than the more common compact specimens that are 31.75 × 30.48 × 12.7 mm thick (1.25 × 1.20 × 0.50 in.) [designated 0.5 T C(T)]. The 0.5 T specimens contain a notch cutout that allows a clip gage to be inserted to the load line for measuring displacement during the test. The clip gage is mounted on knife edges attached to the sides of the notch cutout, as Fig. 3 shows. Remotely attaching knife edges to aluminum specimens in the hot cell would be difficult, so the 0.45 T specimens were designed with 60° grooves 0.5 mm deep (0.020 in.) with a 0.05-mm (0.002-in.) root radius machined on the top and bottom of the specimen along the load line. An outboard clip gage (Fig. 4) was seated in these grooves and used to measure the load line displacement. The specimens contained a thin slot rather than a notch cutout. During irradiation the slot and the loading holes were filled with removable inserts fabricated from 6061-T651 (Fig. 5) to reduce disruptions to the water flow and thus improve the accuracy of the heat transfer calculations.

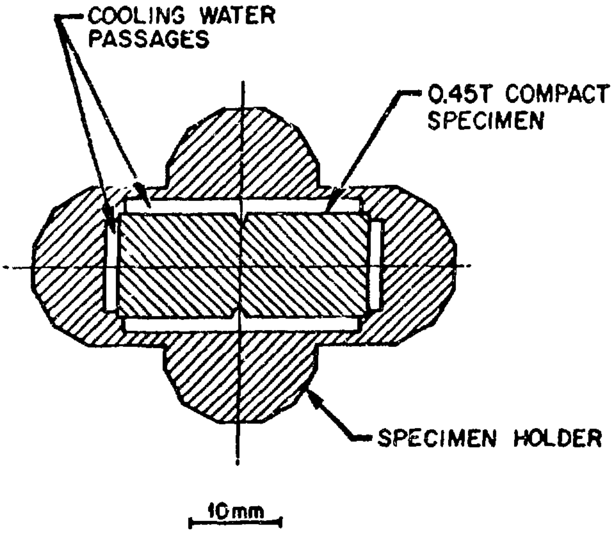

FIG. 1--Cross section through the HANSAL-T1 capsule, showing the outer shroud holding the stack of specimens, the specimen cross section, and the channels for cooling water on all sides of the specimen stack.

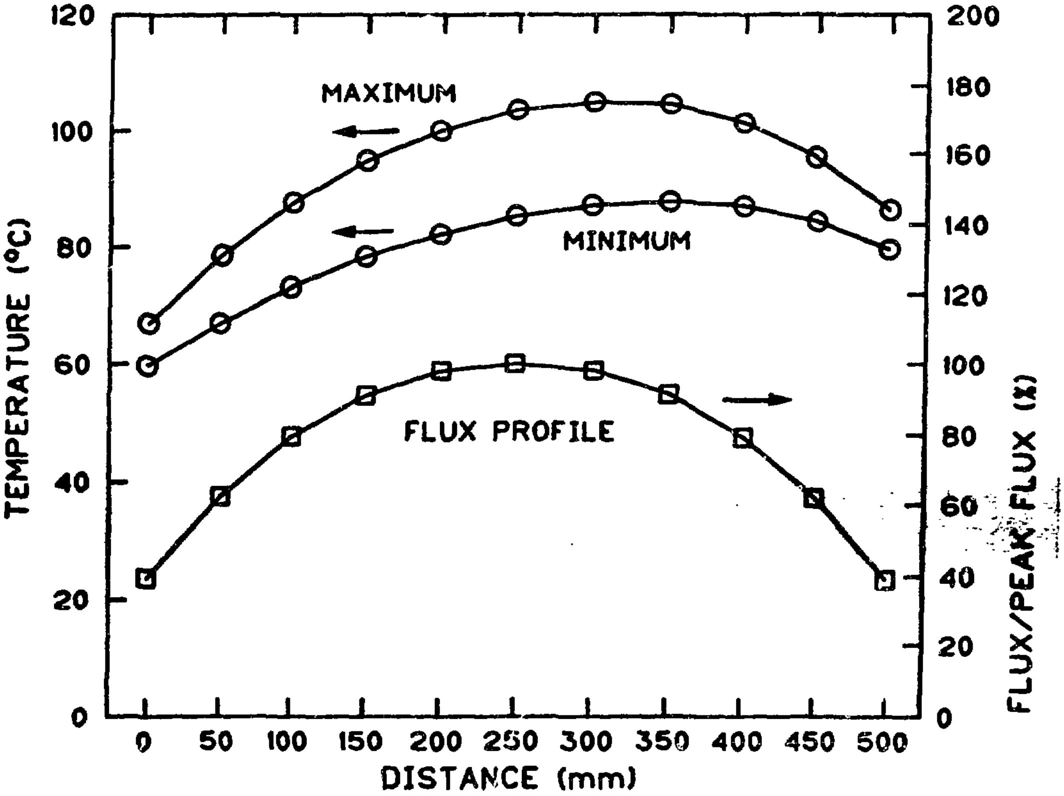

FIG. 2--Calculated temperature and flux profiles along the length of the HANSAL-T1 capsule. Cooling water flows from left to right and is warmed as it passes over the specimens, so less cooling occurs on the right side. The flux profile, expressed as a percent of the peak flux, is symmetric about the capsule centerline.

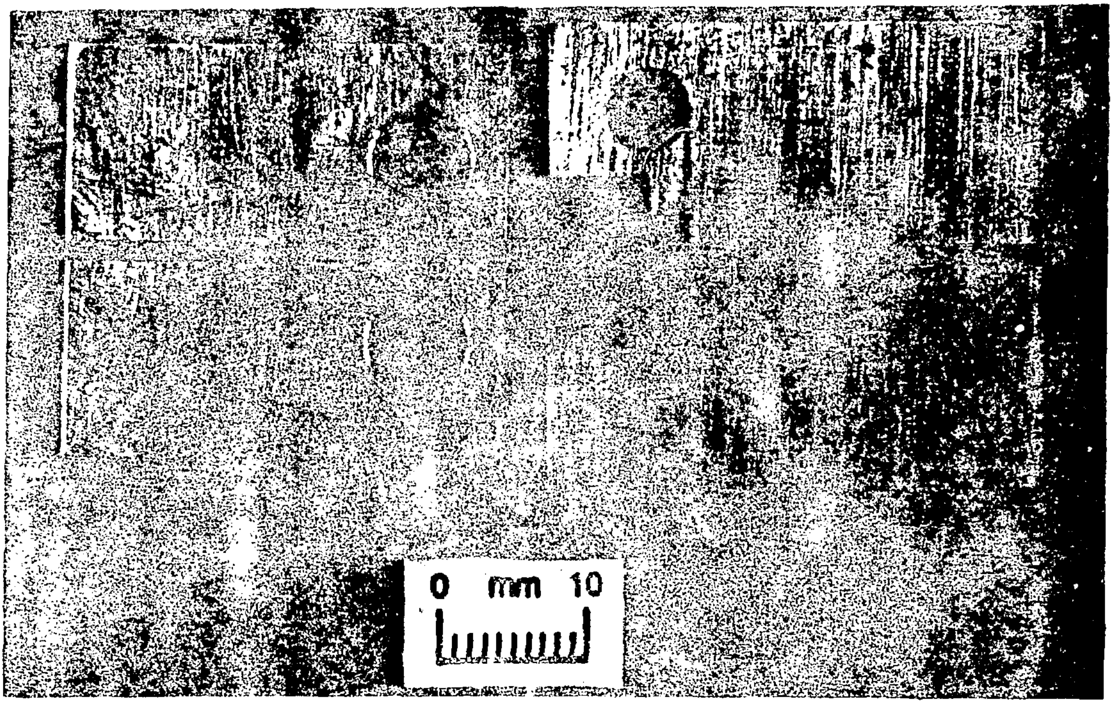

FIG. 3--A comparison of the 0.45 T compact specimen used for irradiation (left) and the conventional 0.5 T compact specimen (right). Note the notch cutout that allows the clip gage to be inserted to the load line for the 0.5 T specimen, compared to the slot and outboard grooves for the 0.45 T specimen.

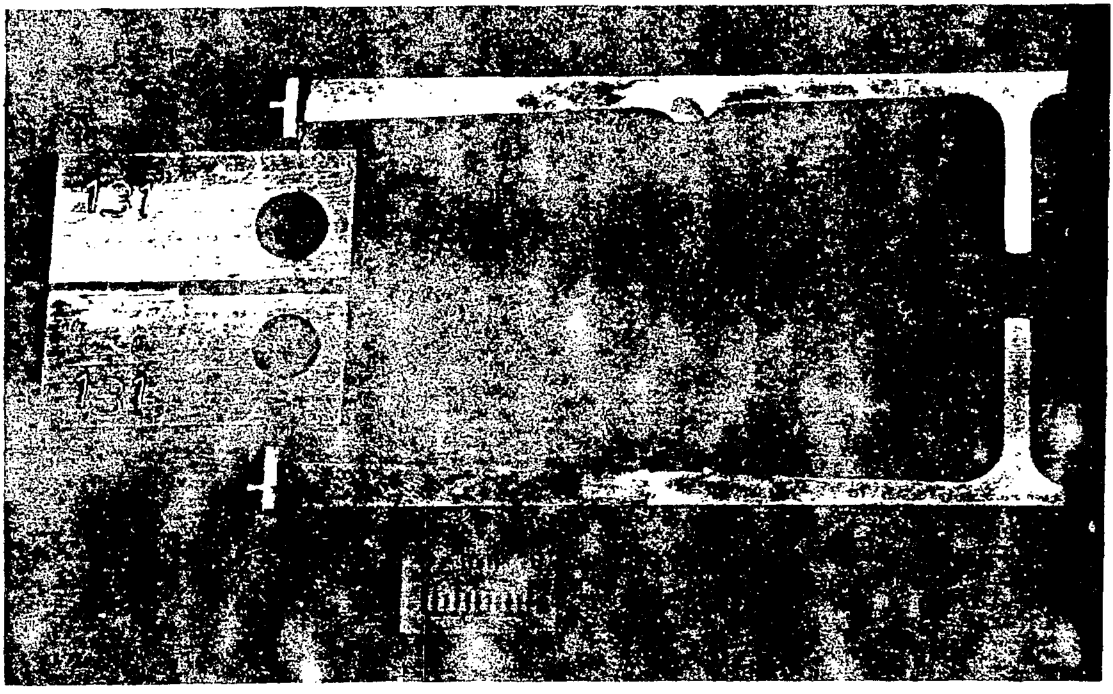

FIG. 4--The outboard clip gage used for measuring load line displacements during the fracture toughness testing. The central flexural beam has four strain gages in a full-bridge configuration. Knife edges are attached to the ends of the arms, and seat in the grooves on the specimen.

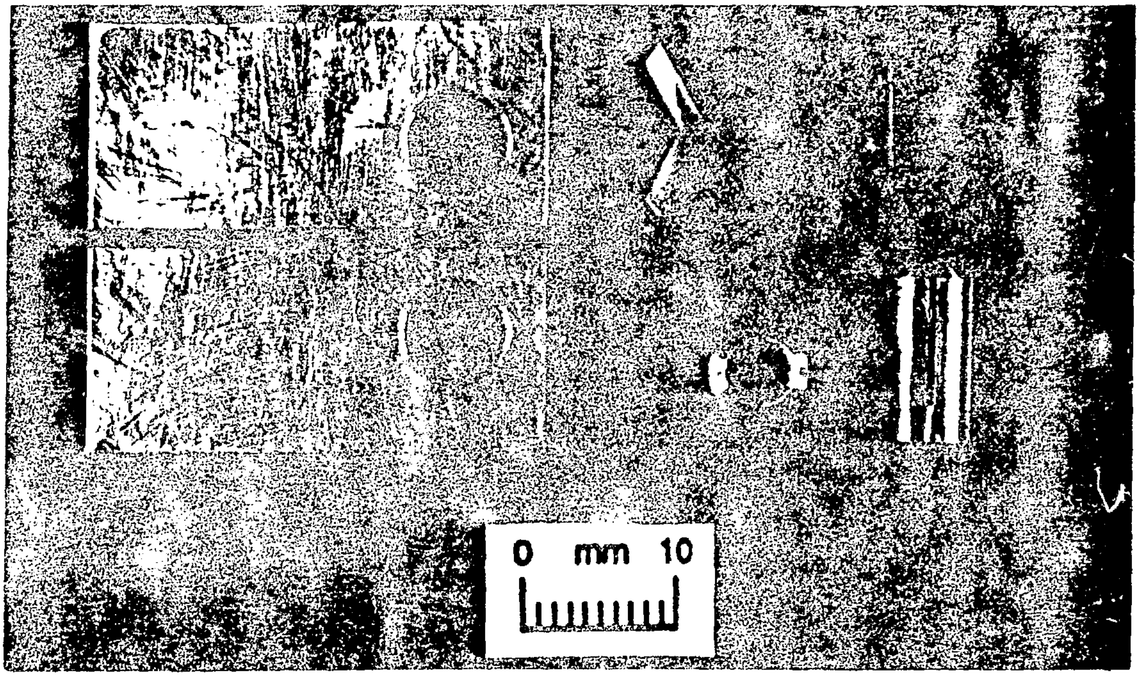

FIG. 5--Notch and loading hole inserts for the irradiation compact specimens. These inserts reduced disruptions in the flow of cooling water, to improve the correlation of the specimen with the heat transfer calculations. Note the tabs on the slot filler for insertion in the specimen packet holder, and the slots in the loading hole plugs to assist removal after irradiation.

Sealed canisters of 6061-T651 aluminum containing granules of a bismuth-lead-tin alloy with a melting point of 97°C were placed in the loading holes of eight of the compact specimens. No active instrumentation was employed to monitor the temperature during irradiation.

Inserted between each compact specimen was a specimen packet assembly (Fig. 6) that contained a flat tensile specimen with a gage section 7.6 mm long, 2.5 mm wide, and 1.9 mm thick (0.300 × 0.100 × 0.075 in.), two transmission electron microscopy (TEM) disks, and two field ion microscope/atom probe needles (APN). Five of the 15 packets contained flux monitors for postirradiation analysis. The packet holder contained two cutouts that interlocked with tabs in the slot inserts (Fig. 5). This allowed the packets to be stacked between the compact specimens (Fig. 7), so that all of the compact specimens and packets were fixed in place inside the capsule during irradiation.

EXPERIMENTAL PROCEDURE

All of the specimens were fabricated from the middle of the thickness of a commercially produced 19-mm-thick (0.75-in.) plate. The compact specimens were fatigue precracked at room temperature prior to irradiation to a crack length to width (a/W) value of about 0.5, and then side grooved 10% of their thickness on each side. A chevron notch was used to facilitate crack initiation during precracking, and to help maintain crack front straightness. The compact specimens were machined in the T-L orientation, so that the crack would extend in the rolling

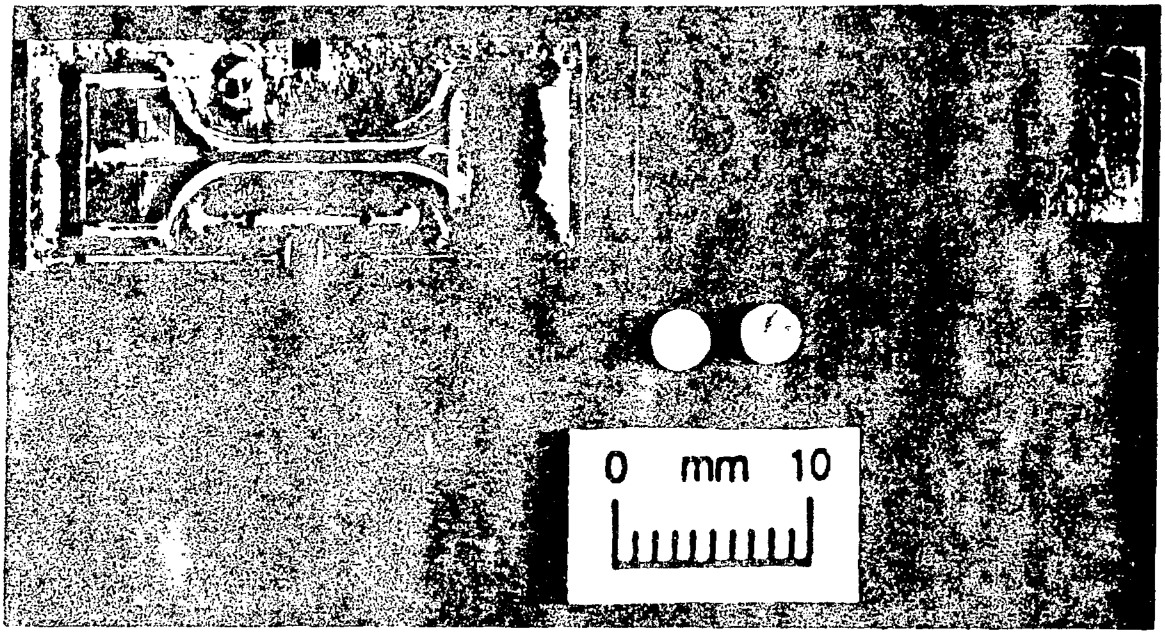

FIG. 6--The specimen packet assembly, showing the holder with machined recesses for the flat tensile specimen, two TEM disks, two APNs, and one flux monitor. The tensile specimen, TEM disks, and APNs are shown also. Note the cutout in the holder for the slot filler from the compact specimen.

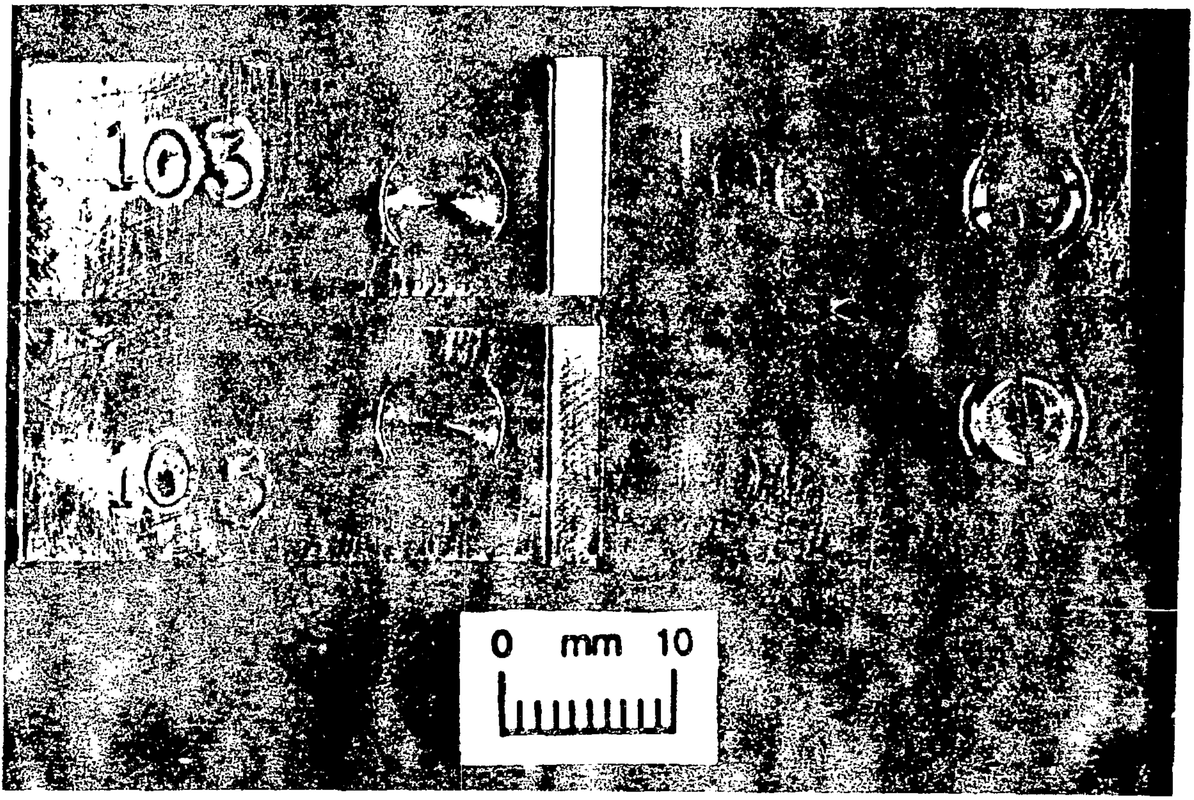

FIG. 7--The stack of specimens, showing alternating compact specimens and specimen packet assemblies.

direction. This was intended to simulate the probable direction of crack growth in the extruded cylindrical structure of the CPBT, where the hoop stresses would be the maximum stresses in the structure. Also, the toughness in the T-L orientation would be expected to be lower than in the L-T orientation, as the crack growth would be parallel to the extrusion direction. The tensile specimens were oriented perpendicular to the rolling direction, in the T orientation.

The J-integral-resistance (J-R) curve toughness tests were conducted in general accordance with ASTM E 813-89, Standard Test Method for J_{Ic}, A Measure of Fracture Toughness, and ASTM E 1152-87, Standard Test Method for Determining J-R Curves, with a computer-controlled test and data acquisition system [1]. Tests were conducted at room temperature, 95, and 150°C. The latter temperatures represent the peak operating temperature and the maximum anticipated off-normal overtemperature expected for the CPBT, respectively. A clip-on thermocouple was mounted on each specimen throughout the test to monitor the temperature. The specimen and load train were enclosed in a split-box furnace and heated to the desired temperature. The temperature was maintained within ±2°C during the test.

Unirradiated specimens (both 0.45 T and 0.5 T specimens as shown in Fig. 3) were tested in the laboratory on a 98-kN (22-kip) servohydraulic machine, and irradiated specimens were tested in a hot cell with a 490-kN (110-kip) servohydraulic machine with an ultraprecision 22-Kn (5-kip) load cell. All tests were conducted in strain control, with an outboard clip gage with a central flexural beam (Fig. 4) that was instrumented with four strain gages in a full-bridge configuration. This gage was rugged yet accurate, and could be readily handled with manipulators in the hot cell. After testing, the crack front was marked by cyclically loading the specimens at room temperature. The specimens were then broken open. The unirradiated specimens were examined with a measuring microscope to determine the initial and final crack lengths. The irradiated specimens were photographed, and enlarged prints of the fracture surfaces were fastened to a digitizing tablet to allow the crack lengths to be measured.

The flat subsize tensile specimens were also tested at room temperature, 95, and 150°C. The same servohydraulic testing machines were used as for the fracture toughness testing, operating in stroke control at a constant velocity of 2.1×10^{-3} mm/s (0.005 in./min) for an initial strain rate of 3×10^{-4} s^{-1}. Unirradiated cylindrical specimens with a gage section 31 mm long by 6.35 mm in diameter (1.22 by 0.25 in.) were tested over a range of temperatures for comparison with the flat tensile specimens. These specimens were tested on a screw-driven machine at a constant crosshead speed of 8.5×10^{-3} mm/s (0.02 in./min) for an initial strain rate of 3×10^{-4} s^{-1}. Yield and ultimate tensile strengths and uniform and total elongations were calculated for all tests from the load vs time chart records by drawing offset lines parallel to the initial elastic loading portion of the test.

The HANSAL-T1 capsule was irradiated for three cycles in HFIR, for a total exposure equivalent of 62.5 days. Assuming thermal (<0.4 eV) and fast (>0.1 MeV) fluxes of 2.04×10^{19} and 1.02×10^{19} $m^{-2} \cdot s^{-1}$, respectively, at the current operating level of 85 MW, the total maximum fluences are 1.1×10^{26} (thermal) and 5.5×10^{25} (fast) m^{-2}.

RESULTS

The tensile properties are given in Table 1 and shown in Figs. 8 through 10 [2,3]. As expected, irradiation increased the yield and ultimate tensile strengths, while both the uniform and total elongations were reduced (Fig. 8). In addition, the ratio of the ultimate tensile to the yield strength was reduced by irradiation (Table 1).

TABLE 1--Tensile data.

Specimen number	Temperature (°C)	Yield strength		Ultimate strength		Elongation (%)		σ_u/σ_y
		(MPa)	(ksi)	(MPa)	(ksi)	Uniform	Total	
				Unirradiated				
235	21	270	39.1	301	43.7	7.4	19.5	1.12
272		255	37.0	297	43.1	7.7	17.1	1.16
208	26	261	37.8	300	43.5	8.3	20.7	1.15
255		267	38.7	302	43.8	6.4	17.3	1.13
264	95	247	35.8	284	41.2	6.3	21.2	1.15
241	150	231	33.5	255	37.0	4.1	24.4	1.10
				Irradiated				
204	26	311	45.1	339	49.1	6.5	20.3	1.09
252		312	45.3	345	50.0	6.4	18.3	1.10
207		301	43.7	334	48.4	5.7	18.0	1.11
233		316	45.9[a]	344	49.9	6.1	16.8	1.09
215		305	44.3	332	48.1	5.9	19.3	1.09
273	95	290	42.1	314	45.6	4.3	17.5	1.08
244		287	41.6	313	45.4	4.9	19.8	1.09
256		285	41.4	307	44.5	5.1	18.1	1.07
226	100	289	41.9	309	44.8	2.9	17.7	1.07
222	120	284	41.2	308	44.6	4.0	19.5	1.09
237	150	281	40.8	296	42.9	2.8	17.2	1.05
261		284	41.2	303	43.9	3.3	19.3	1.07
211		275	39.9	285	41.4	2.1	15.4	1.04
265		265	38.4	297	43.1	4.4	23.8	1.12

[a]Estimated value, gap in X-Y record.

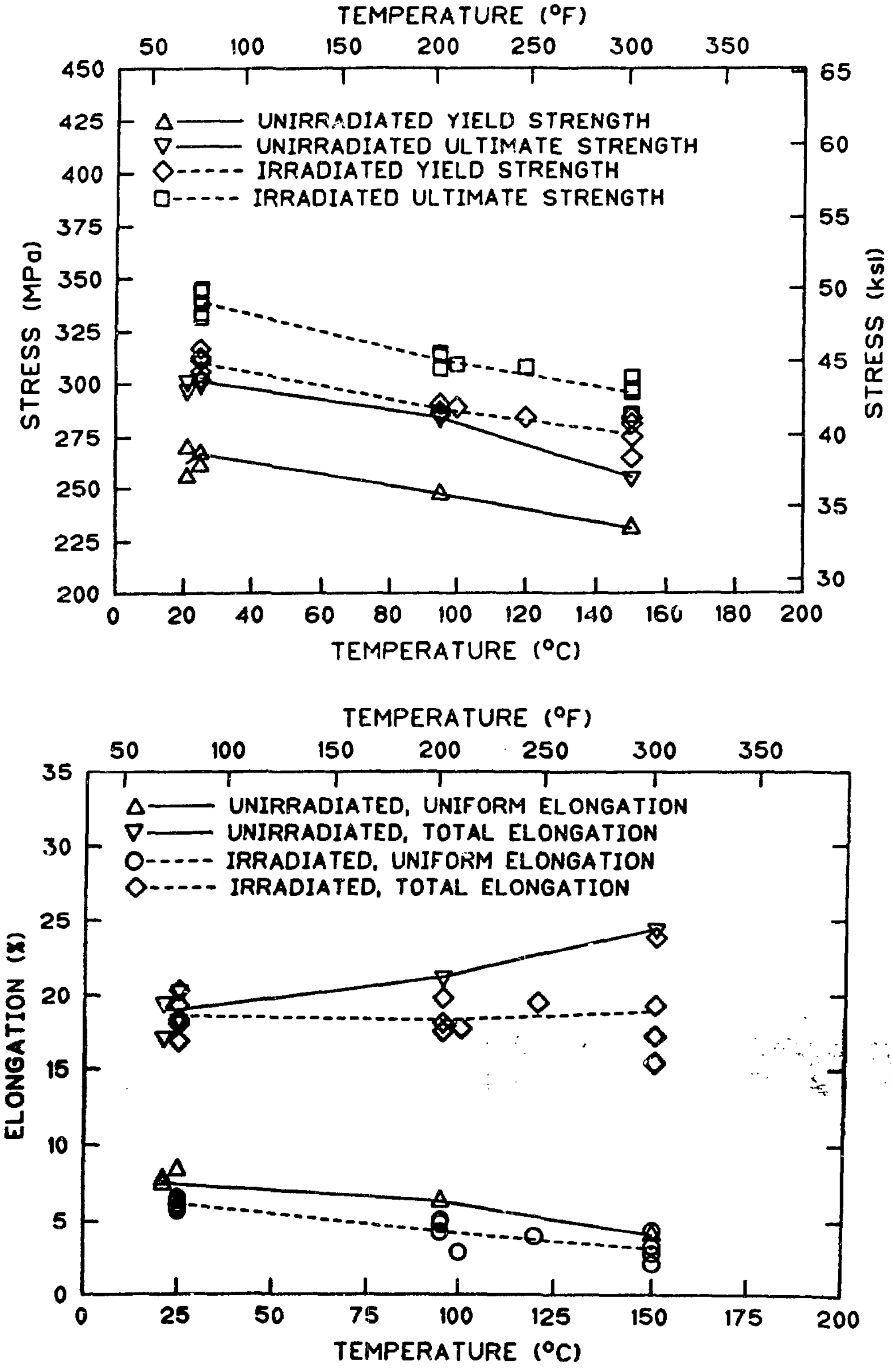

FIG. 8--The effects of test temperature and irradiation on the tensile properties of 6061-T651 aluminum. Top: yield and ultimate tensile strength. Bottom: uniform and total elongation. The strength is increased and the ductility is decreased by irradiation.

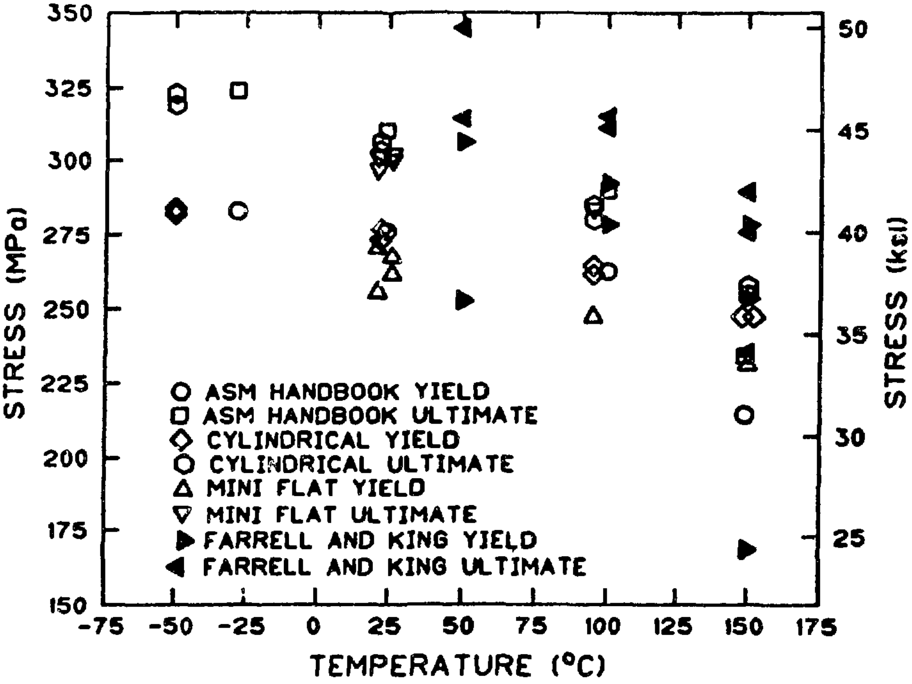

FIG. 9--Yield and ultimate tensile strength data for unirradiated 6061-T651 aluminum. The data from Farrell and King, shown in filled symbols, tend to show greater yield and ultimate tensile strengths than the other data.

Only seven of the sixteen fracture toughness specimens have been tested due to difficulties encountered in removing the temperature monitor canisters. It is believed that an oxide film has been formed on the surfaces of the specimens and the temperature canisters, due to the cooling water that was in contact with the specimens. The wedging of this oxide between the specimen and the temperature monitor canisters has prevented them from being removed. New fixtures are being designed to assist in the removal of the canisters.

The results of the fracture toughness tests are shown in Table 2 and Fig. 11. These show that there is no degradation of the fracture toughness at 26 or 95°C, and only a slight decrease at 150°C. In fact, the toughness values of the irradiated material at 26 and 95°C are slightly higher than for the unirradiated condition, although this is believed to be simply scatter in the data.

All of the tests showed sudden rapid crack extension, as evidenced by large drops in the load and simultaneous large increases in crack extension. Examples of the J-R curves are shown in Fig. 12. The number of crack jumps for each specimen is noted in Table 2. More crack jumps were noted in the irradiated specimens. Some of the tests show apparent decreases in J following such crack jumps. This decrease is an artifact of the mathematical formulation employed in ASTM E 1152, which assumes small incremental crack advances. The decreasing J values result in some of the tests having J-R curves that are concave-upwards. This is an artifact of the curve fitting procedure used to fit the data to a power law equation. In these cases, the tearing modulus has a negative value, which is physically meaningless. This does emphasize how little resistance the material has to crack extension.

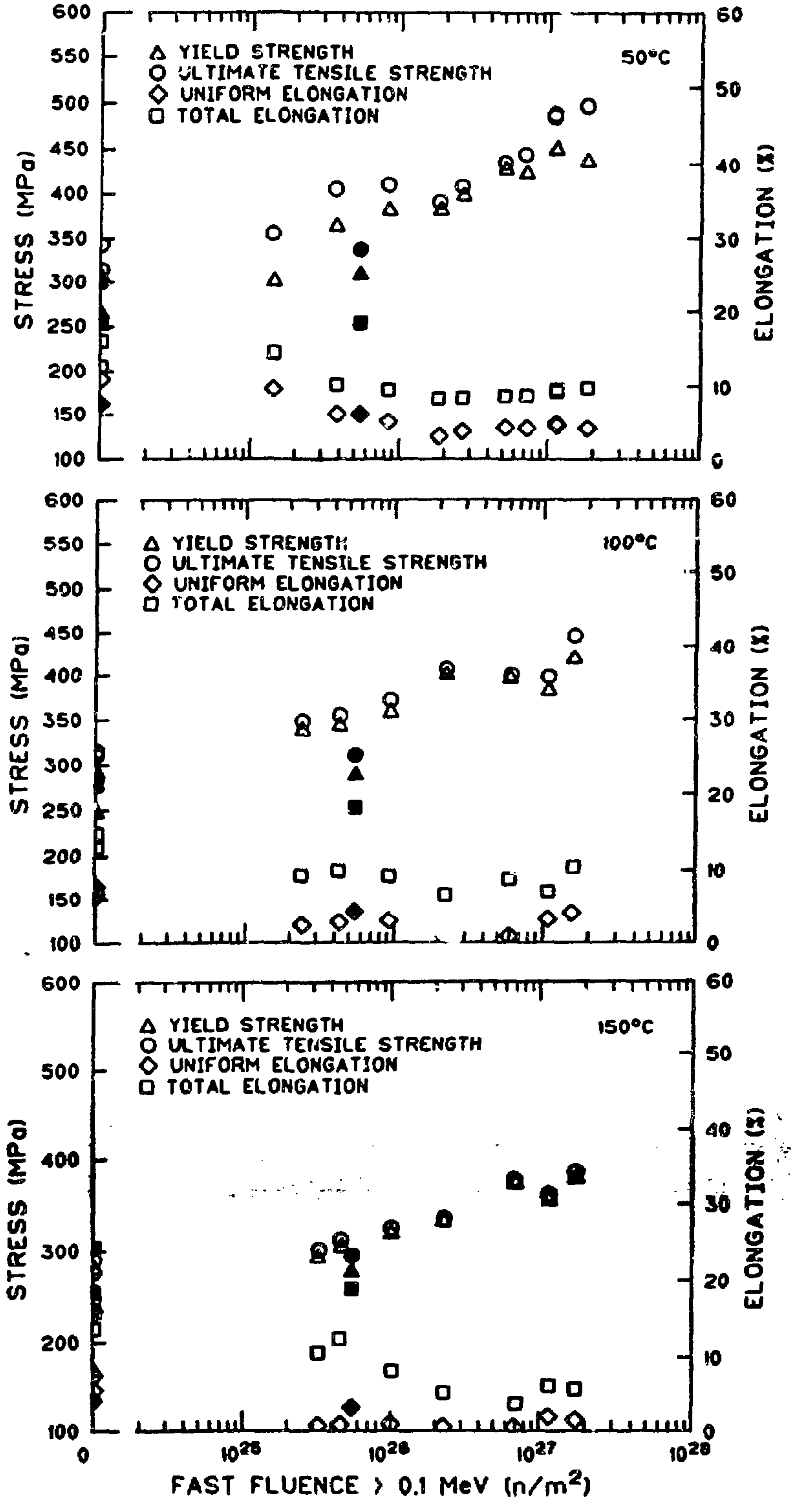

FIG. 10--A comparison of the average present data (shown in filled symbols) with the results of Farrell and King. Top: 50°C test temperature. Middle: 100°C test temperature. Bottom: 150°C test temperature. The present data show slightly lower initial strengths and smaller increases in strength after irradiation than the previous data.

TABLE 2--Fracture toughness data.

Specimen	Temperature (°C)	K_J[a]		Tearing modulus	Crack length agreement (%)	Number of crack jumps
		MPa√m	ksi√in.			
			Unirradiated			
102	21	33.0	30.1	0.02	-36	2
131[b]		33.8	30.8	--	-30	2
142	26	33.6	30.6	0.53	-33	2
134[c]		32.1	29.3	0.82	-22	3
107[d]	95	29.9	27.2	-0.43	-31	3
144		30.8	28.0	0.94	-25	4
103		30.2	27.5	0.43	-31	2
156	150	32.3	29.4	3.12	-33	2
101		31.3	28.5	1.83	-32	2
133		32.6	29.6	3.16	-25	3
			Irradiated			
104	26	33.9	30.9	0.24	-32	7
118		34.8	31.7	0.97	-24	4
122[b]		35.6	32.3	--	-85	2
105	95	31.7	28.9	0.02	-29	5
127		32.2	29.3	0.02	-27	3
111[b]	150	30.5	27.7	--	-36	5
114[d]		27.3	24.9	-0.86	-23	6

[a] Based on J-integral formulation from ASTM E 1152-87 with conversion to K by $K^2 = JE$ (E = elastic modulus).

[b] Estimated - too few points.

[c] Improperly side grooved - one side too deep.

[d] Concave upwards.

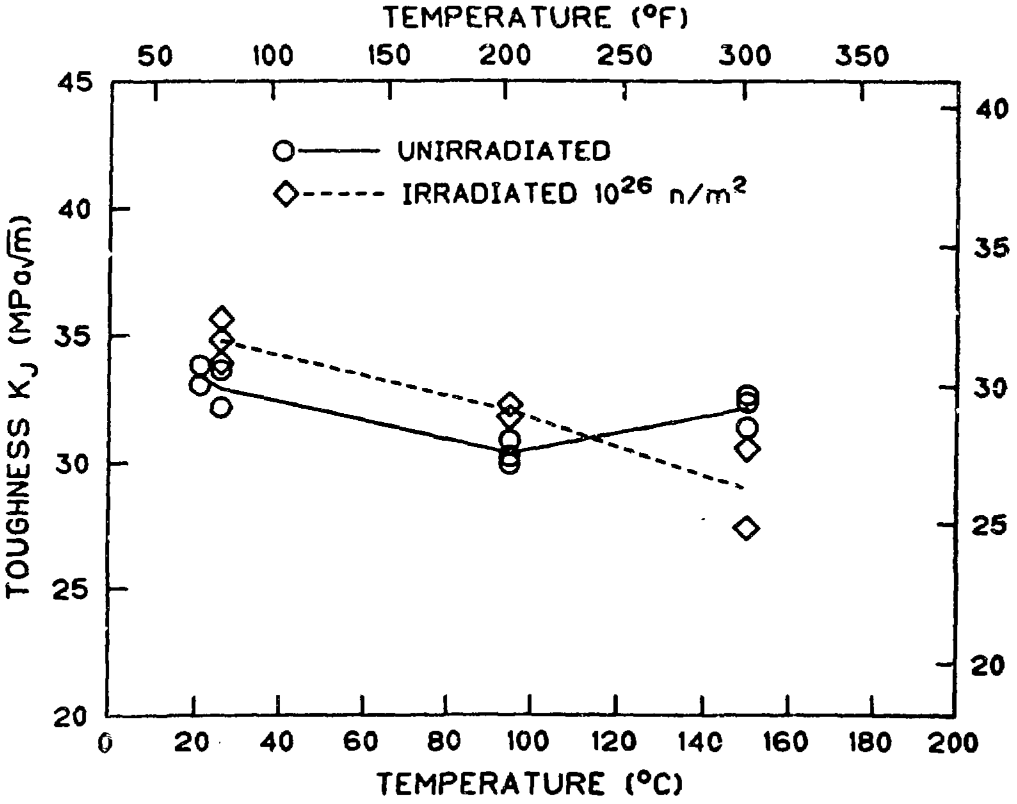

FIG. 11--The critical fracture toughness values. The toughness at 26 or 95°C does not decrease after irradiation, and drops only slightly at 150°C.

These tests were not able to meet the necessary requirements for accurately predicting the final measured crack length, with the error exceeding the allowable 15% (see Table 2). In all cases, the predicted final crack length was less than the actual measured crack length. It is believed that the rapid crack growth was at least partially responsible for this poor agreement. However, because the J-R curves are so flat, the possible effect on the critical J values is limited, and these should still be accurate estimates of the material's toughness. Additional investigations are under way to try and determine the reasons for the poor agreement between measured and predicted final crack length.

DISCUSSION

The tensile tests show that, as expected, irradiation increases the yield and ultimate tensile stresses and decreases the ductility (Fig. 8). These results can be compared to previous data for 6061-T6 from the literature shown in Figs. 9 and 10. Farrell and King [2] irradiated 6061 specimens in HFIR target positions, so the ratio of thermal to fast neutrons should be essentially identical to the present work. However, their irradiations were carried out at the lower temperature of 55°C. In addition, they performed their own "T6" heat treatment rather than using commercially treated material. The unirradiated yield and ultimate tensile strengths that their treatment produced are slightly greater than typical commercial properties as

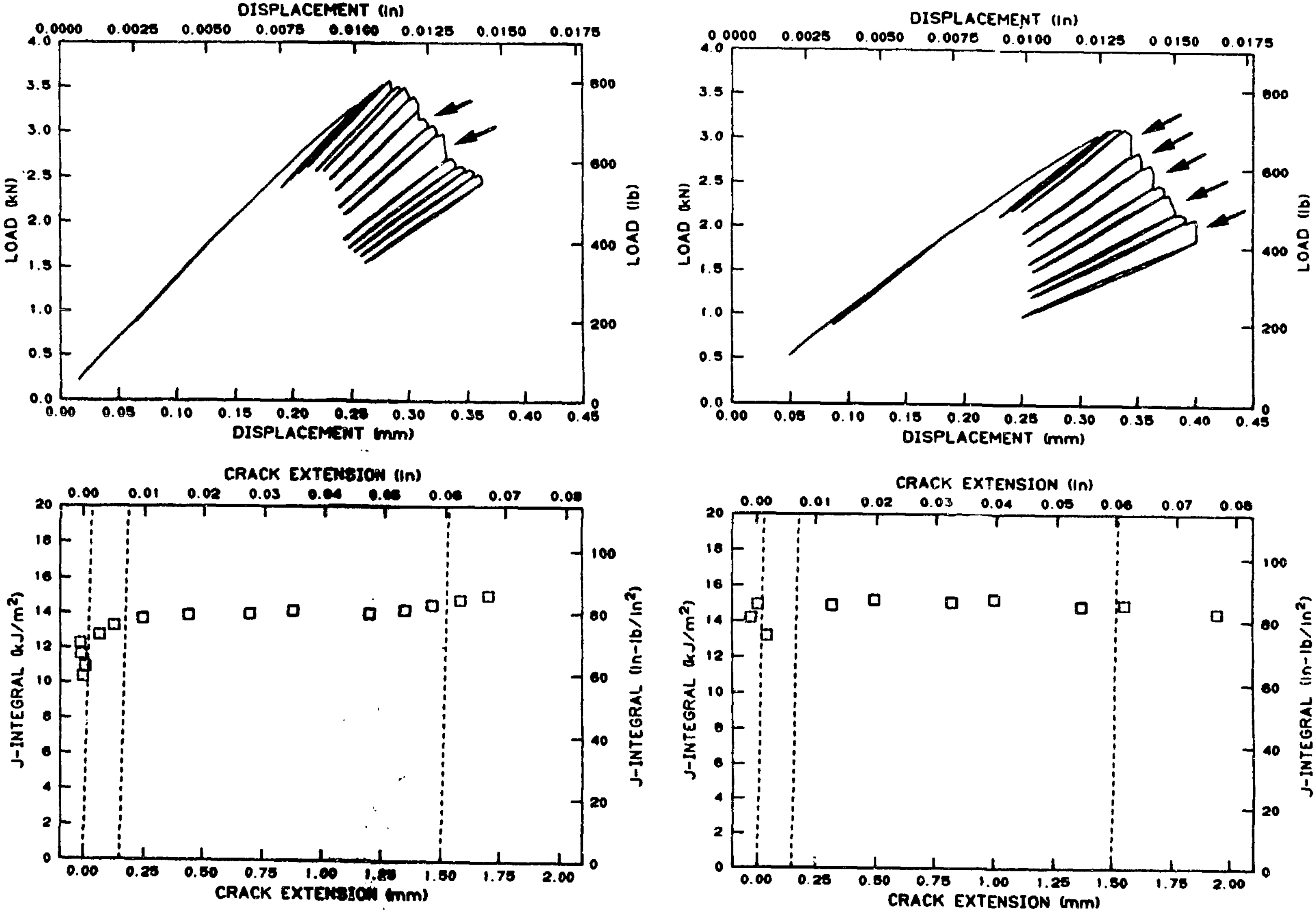

FIG. 12--Load-displacement and J-R curves. Left: specimen 103, unirradiated, tested at 95°C. Right: specimen 105, irradiated, tested at 95°C. Note sudden crack extensions indicated by arrows.

given in handbooks, as Fig. 9 shows [3]. The unirradiated specimens tested in this work gave results very similar to the handbook values (see Fig. 9). The higher values observed by Farrell and King are believed to be the result of more rapid quenching of their thin specimens during their "T6" heat treatment than would be observed in thicker commercial material.[1]

In addition to the slightly higher strengths observed by Farrell and King, the increase in yield and ultimate tensile strengths due to irradiation observed in the present experiments is slightly smaller than that observed previously. The average values from the present results (filled symbols) are plotted with the previous data [2] in Fig. 10. The present data for room temperature have been plotted with the previous 50°C results, and the present 95°C data with the previous 100°C results. The present results have been plotted at a fast neutron fluence of 5.5×10^{25} m^{-2} to correspond to the Farrell and King results, as their data are given in terms of fast fluence [note that Farrell and King have used a different definition of thermal fluence (<0.025 eV)]. In the present work, the variation in fluence due to the flux gradient along the length of the capsule has been ignored. When the flux monitors have been analyzed, and an accurate flux profile is known, the fluences of the individual specimens will be available. At present a typical value for all specimens is a reasonable way to represent the data.

The uniform and total elongations are also plotted in Fig. 10. In general, the present tests show similar uniform elongations, but much greater total elongations than the previous data. This greater total elongation may be due to the different specimen design, or the different heat treatments. Both sets of data show a similar trend with the ductility decreasing after irradiation, the uniform ductility in particular. This suggests that the material has lost some of its capacity for uniform deformation, and that the deformation is localizing in the specimen.

The reason for the different response to irradiation in the two experiments is not clear. There are slight differences in the initial mechanical properties that are apparently due to the differences between the heat treatments. The present irradiations were conducted at about 95°C, as opposed to 55°C for Farrell's and King's work. Even this small different is significant, as there is little effect of irradiation above ~130°C on the mechanical properties of aluminum alloys.[1] There is also the possibility that the present irradiations occurred at a higher temperature than calculated. Irradiation at a temperature significantly higher than the expected 95°C would result in a smaller increase in strength due to irradiation, since the diffusivity of the transmuted silicon would be increased. This should result in increased coarsening of the silicon particles, and hence a smaller strength increase, as is observed. Examination of the TEM specimens and the temperature monitors should provide additional information about this possibility.

The fracture toughness results are somewhat surprising, as it was expected that the irradiation would result in a decrease in the fracture toughness. This does not appear to be the case at 26 or 95°C, and even at 150°C the decrease in toughness is slight. Nine specimens remain to be tested, and these additional data should provide further support for this response. These results are apparently the first data available for the effect of such high levels of irradiation on the fracture toughness of 6061-T651 aluminum, so there are no direct comparisons that

---

[1] Memorandum, K. Farrell, Oak Ridge National Laboratory, to D. J. Alexander, Oak Ridge National Laboratory, November 10, 1992.

can be made. However, there is some existing information about fracture of notched 6061-T6 specimens for comparison.

Weeks, Czajkowski, and Farrell [4] have reported the results of notched tensile tests and impact tests of notched nonstandard Charpy specimens 55 × 10 × 3 mm (2.165 × 0.394 × 0.118 in.) with a 45° notch 0.61 mm (0.024 in.) deep, for a notch to depth ratio of 0.2. These specimens had been cut from components of the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory. The aluminum material had been heat treated after fabrication to a "T6" condition. The estimated thermal and fast (>0.1 MeV) neutron fluences were 4.2×10^{27} and 2.0×10^{26} m^{-2}, respectively, for a thermal to fast ratio of 21, very different from the ratio of about 2 for the HFIR. The temperature of the components during irradiation was believed to be about 60°C. The impact energy of these specimens decreased from about 2 J at either 23 or 99°C for unirradiated material to about 0.3 J at either temperature, after irradiation. This large decrease in the impact energy was used to derive an apparent decrease in the fracture toughness from about 22 $MPa\sqrt{m}$ before irradiation to about 8 $MPa\sqrt{m}$ after irradiation. A similar value was determined from the notched tensile tests. This is a very different response from that shown by the present experiment.

There are several possible reasons for the different response of the present material. The most obvious difference is the much higher thermal fluence received by the HFBR component, approximately 40 times greater. This higher level of fluence would result in much greater levels of transmuted silicon in the HFBR-irradiated materials, and thus a much greater decrease in toughness. In addition, the ratio of the thermal to fast neutrons is very different for the HFIR and the HFBR. The higher ratio of thermal neutrons for the HFBR may be particularly damaging for aluminum alloys. Weeks et al. [4] have suggested that the effects of irradiation will increase as the thermal to fast ratio of the flux increases. For a lower ratio of thermal to fast neutrons, as in the HFIR, more point defects will be produced than in the high thermal to fast spectrum of the HFBR. This should increase the rate of diffusion of the silicon in the aluminum matrix, and should result in a coarser distribution of silicon precipitates for material irradiated in the HFIR. This will result in less increase in the flow properties, and presumably less degradation of the fracture toughness. The TEM and APN specimens irradiated in this experiment will provide additional information about the effects of the irradiation on the microstructure of the 6061 alloy.

The most disturbing features of the fracture toughness results are the extremely low tearing modulus values and the increased tendency for sudden rapid crack extension after irradiation. The tearing modulus values are given in Table 2. The unirradiated material has a low tearing modulus, but after irradiation the J-R curves are essentially horizontal, with extremely low tearing moduli. The low values of the tearing modulus indicate that the material has very little resistance to crack extension, once it has begun. In addition, the tendency to sudden rapid crack growth is increased. Thus, after irradiation crack extension may begin suddenly, and once initiated, may continue with very little resistance. The low tearing moduli are reflected by the decrease in the uniform elongation seen in the tensile tests. These tests indicate that the material is prone to localized deformation after irradiation. Similarly, the deformation is localized in the fracture toughness test, and the result is very little resistance to crack extension, as Fig. 12 shows.

The low tearing modulus values and the tendency for sudden crack extension in 6061-T651 indicate that the design of the CPBT must be approached with great caution. Although the toughness of this aluminum alloy is apparently not degraded by irradiation, at least at

10^{26} m^{-2}, the implications of the inherently low resistance to crack extension must be considered very carefully.

CONCLUSIONS

Specimens of the aluminum alloy 6061-T651 have been irradiated to a peak thermal fluence of 1.1×10^{26} m^{-2} (<0.4 eV) in HFIR, at an approximate temperature of 95°C, and tested at 26, 95, and 150°C. This resulted in increases in the yield and tensile strengths, and a drop in the ductility. The fracture toughness was not degraded at 26 or 95°C, and decreased only slightly at 150°C. The tearing modulus values are low for unirradiated 6061-T651, and decrease to very low values after irradiation. An increased tendency to sudden crack extension after irradiation was noted. Further testing of the remaining specimens and examination of the temperature monitors and TEM specimens should provide confirmation of these results.

ACKNOWLEDGMENTS

This work was funded by the Advanced Neutron Source Project at Oak Ridge National Laboratory, managed by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy under contract DE-AC05-84OR21400. The HANSAL-T1 capsule was designed by J. E. Corum, A. W. Longest, and D. E. Heatherly. D. E. Heatherly and J. W. Wolfe assembled the capsule. A. W. Longest performed the heat transfer calculations. R. W. Reed, Jr., welded the temperature monitor canisters. The mechanical testing of the unirradiated material was performed by R. L. Swain, J. J. Henry, Jr., and E. T. Manneschmidt. The irradiated specimens were tested by R. L. Swain and J. E. Gilley. The outboard clip gage was designed and fabricated by John A. Shepic, Lakewood, CO 80228. We would like to thank K. Farrell, G. M. Goodwin, D. L. Selby, and C. D. West for helpful reviews of the manuscript, which was prepared by J. L. Bishop.

REFERENCES

[1] Nanstad, R. K., Alexander, D. J., Swain, R. L., Hutton, J. T., and Thomas, D. L., "A Computer Controlled Automated Test System for Fatigue and Fracture Testing," *Applications of Automation Technology to Fatigue and Fracture Testing, ASTM STP 1092*, A. A. Braun, N. E. Ashbaugh, and F. M. Smith, Eds., American Society for Testing and Materials, Philadelphia, 1990, pp. 7-20.

[2] Farrell, K. and King, R. T., "Tensile Properties of Neutron-Irradiated 6061 Aluminum Alloy in Annealed and Precipitation-Hardened Conditions," *Effects of Radiation on Structural Materials, ASTM STP 683*, J. A. Sprague and D. Kramer, Eds., American Society for Testing and Materials, Philadelphia, 1979, pp. 440-49.

[3] *Metals Handbook, Tenth Edition*, ASM International, Metals Park, Ohio, 1990, p. 103.

[4] Weeks, J. R., Czajkowski, C. K., and Farrell, K., "Effects of High Thermal Neutron Fluences on Type 6061 Aluminum", *Effects of Radiation on Materials: 16th International Symposium, ASTM STP 1175*, A. S. Kumar, D. S. Gelles, R. K. Nanstad, and E. A. Little, Eds., American Society for Testing and Materials, Philadelphia, 1993, this volume.