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Fracture Toughness Characterization of Reactor Pressure Alloys from the ATR-2 Experiment

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Light Water Reactor Sustainability Program

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EXECUTIVE SUMMARY

The UCSB ATR-2 irradiation experiment is designed to generate a new database on a wide variety of irradiated reactor pressure vessel (RPV) steels to fill a critical gap in predicting high fluence embrittlement for extended plant operation up to 80 years. A major focus in this experiment is to characterize the effects of irradiation temperature, neutron flux and fluence, and alloy chemistry on MNSP evolution, and model how these features impact hardening and embrittlement, manifested as shifts in ductile-to-brittle transition temperature. As part of these efforts, disk compact tension (DCT) specimens of three representative materials were included in the ATR-2 experiment to have direct measurement of transition fracture toughness shift and, thus, to have some benchmark data to compare outcoming predictive models with actual fracture toughness shifts. In addition, the attempts would be made to use these fracture toughness data to address the potential effect of high dose irradiation on the shape of the Master Curve for highly embrittled RPV material.

This report provides data for the first phase on this program – fracture toughness characterization of these materials in the unirradiared condition to establish baseline properties to measure fracture toughness shifts after irradiation.

1. INTRODUCTION

The UCSB ATR-2 irradiation experiment is designed to generate a new database on a wide variety of irradiated reactor pressure vessel (RPV) steels to fill a critical gap in predicting high fluence embrittlement for extended plant operation up to 80 years [1-5]. A major focus in this experiment is to characterize the effects of irradiation temperature, neutron flux and fluence, and alloy chemistry on MNSP evolution, and model how these features impact hardening and embrittlement, manifested as shifts in ductile-to-brittle transition temperature. As part of these efforts, disk compact tension (DCT) specimens of three representative materials were included in the ATR-2 experiment to have direct measurement of transition fracture toughness shift and, thus, to have some benchmark data to compare outcoming predictive models with actual fracture toughness shifts. In addition, the attempts would be made to use these fracture toughness data to address the potential effect of high dose irradiation on the shape of the Master Curve for highly embrittled RPV material. The fracture toughness and tensile specimens were tested over the range of temperatures where fracture toughness tests have been performed to provide crucial information for validity verification of fracture toughness data. The report is prepared in satisfaction of Milestone M2LW-17OR040201– "Complete report that documents fracture toughness characterization of reactor pressure alloys from the ATR-2 experiment."

2. MATERIAL DESCRIPTION

Three materials were selected for fracture toughness evaluation as part of ATR-2 experiment. Two materials, CM17 and LP, are from the UCSB split-melt steels matrix and third material, PBR, is a weld material from Palisades Nuclear Power Plant (NPP) steam generator. The chemical composition of all three materials is presented in Table 1.

Table 1. Chemical composition of CM17, LP, and PBR materials

	Composition, wt. %									
	Cu	Ni	Mn	Cr	Mo	P	C	S	Si	Fe
CM17	0.22	1.59	1.54	0.00	0.5	0.004	0.16	0.000	0.25	balance
LP	0.41	0.86	1.44	0.06	0.55	0.005	0.14	0.008	0.23	balance
PBR	0.2	1.2	1.3	0.04	0.54	0.01	0.11	0.017	0.18	balance

All three materials have very high cooper content, CM17 and Palisades weld also have very high nickel content. The Palisades weld, designated weldment "B" from weld heat 34B009, was provided to UCSB and ORNL by Palisades NNP for research purposes. This weld came from steam generator and it was produced with the same weld wire and heat-treated in the same fashion as beltline weld of Palisades NNP. The UCSB split-melt steels were processed and have microstructures and properties that are typical of A-533B steels used for RPVs.

3. TENSILE PROPERTIES

Uniaxial tensile tests have been performed using a MTS servo-hydraulic frame with 89-kN capacity on SS-J2 type miniature tensile specimens made from unirradiated CM17, LP, and Palisades weld materials. The SS-J2 specimen has a 1.2 x 0.5mm cross-section along the 5mm gauge length. Tests were performed according to the ASTM E8 Standard Test Methods for Tension Testing of Metallic Materials using a nominal strain rate of 10-3 s-1. The test temperature range for each material covers the test temperature range of the Master Curve fracture toughness testing as well as the room temperature and the average

irradiation temperature for that material. The engineering strains were determined from the machine stroke measurements. Table 2 summarizes tensile data of three materials from this study. These data are being used to validate fracture toughness data as described in section below.

Table 2. Tensile properties of three materials in this study

Material	Temperature, °C	Elongation, %		Strength, MPa	
		Uniform	Total	Yield	Ultimate
CM17	-130	18.22	27.33	625.4	735.7
	-60	17.22	27.28	555.0	698.1
	22	10.82	23.23	394.7	493.0
	293	9.71	15.86	404.0	456.4
LP	-50	16.94	29.28	524.0	715.0
	-30	17.59	26.47	582.6	730.8
	-10	20.00	28.35	551.6	670.5
	22	19.14	25.06	518.5	696.4
	264	14.71	20.43	527.4	665.3
Palisades B weld	-130	15.84	24.05	608.8	706.7
	-115	17.81	26.86	579.2	693.6
	22	17.75	28.18	515.7	617.1
	285	12.00	19.79	451.6	568.1

4. FRACTURE TOUGHNESS CHARACTERIZATION

4.1 Testing and analysis procedure

The disk compact tension DCT specimens were selected for this experiment. The diametr of this specimens was 20 mm and it was determined by the diameter of the ATR-2 capsule. Te thickness of the specimens was 6.6 mm. The fracture toughness tests were conducted in accordance with the ASTM E 1921 [6] Standard Test Method for Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range, with a computer-controlled test and data acquisition system. The specimens were fatigue precracked to a ratio of the crack length to specimen width (a/W) of about 0.5. The unloading compliance method used for measuring the J-integral. Specimens were tested a 98-kN (22-kip) capacity servohydraulic machine. All tests were conducted in strain control, with an outboard clip gage having a central flexural beam that was instrumented with four strain gages in a full-bridge configuration. The broken specimens were examined with a calibrated measuring optical microscope to determine the initial and final crack lengths.

Values of J-integral at cleavage instability, J_c, were converted to their equivalent values in terms of stress intensity K_{Jc} by the following equation [6]:

$$K_{Jc} = \sqrt{J_c \frac{E}{1-\nu^2}} \tag{1}$$

where E is Young's modulus and ν is Poisson's ratio.

A K_{Jc} datum was considered invalid if this value exceeded the $K_{Jc(limit)}$ requirement of the ASTM Standard E 1921 [6]:

$$K_{Jc(\lim it)} = \sqrt{\frac{b_o \sigma_{YS}}{30} \cdot \frac{E}{1-\nu^2}} \tag{2}$$

where b_o is the remaining ligament and σ_{YS} was the yield strength of the material at the test temperature. All invalid data were censored and substituted by the $K_{Jc\ (limit)}$ values for calculation of the transition fracture toughness temperature, T_o. After that, all K_{Jc} data (valid and substituted) were converted to 1T equivalence, $K_{Jc(1T)}$, using the size adjustment procedure of ASTM Standard E1921 [6]:

$$K_{Jc(1T)} = 20 + \left[K_{Jc(x)} - 20\right] \cdot \left(\frac{B_x}{B_{1T}}\right)^{1/4} \tag{3}$$

where $K_{Jc(x)}$ = measured K_{Jc} value,
B_x = gross thickness of test specimen,
B_{1T} = gross thickness of 1T C(T) specimen.

The reference fracture toughness transition temperature, T_o, was determined using the multi-temperature equation from E1921 [6]:

$$\sum_{i=1}^{N} \delta_i \frac{\exp\left[0.019\left(T_i - T_o\right)\right]}{11 + 77\exp\left[0.019\left(T_i - T_o\right)\right]} - \sum_{i=1}^{N} \frac{\left(K_{Jc(i)} - 20\right)^4 \exp\left[0.019\left(T_i - T_o\right)\right]}{\left\{11 + 77\exp\left[0.019\left(T_i - T_o\right)\right]\right\}^5} = 0 \tag{4}$$

where δ_i= 1.0 if the datum is valid or zero if datum is invalid,
T_i= test temperature corresponding to $K_{Jc(i)}$.

4.2 CM17 FRACTURE TOUGHNESS RESULTS

Fracture toughness data of CM17 are summarized in Table 3. The first trail reveal preliminary value of T_o=-34°C. All specimens were included in this trial. This calculation put specimens C17-17 and C17-31 outside T_o-50°C range, thus final T_o calculation was performed without these two specimens and it yield final T_o value of -35°C. Figure 1 illustrates fracture toughness and relevant master curve of CM17 material.

Table 3. Fracture toughness data of CM17 material

Specimen ID	Temperature, °C	Measured K_{Jc}, MPa√m	1T-adjusted K_{Jc}, MPa√m	1T K_{Jc} limit, MPa√m	Validity	Remarks
C17-10	-60	118.1	90.0	134.4	Valid	
C17-16	-60	112.4	86.0	132.6	Valid	
C17-17	-90	64.4	51.7	139.9	Valid	
C17-23	-60	96.4	74.5	134.1	Valid	
C17-28	-40	114.5	87.5	125.3	Valid	
C17-31	-130	38.8	33.4	151.5	Valid	
C17-34	-60	102.8	79.1	135.5	Valid	
C17-35	-60	98.5	76.0	133.9	Valid	
C17-27	-40	91.2	70.8	127.0	Valid	
C17-9	-40	118.8	90.5	129.4	Valid	
C17-12	-20	182.0	135.7	126.4	Invalid	

C17-15	-40	115.4	88.1	129.7	Valid	
C17-4	-20	203.9	151.3	129.7	Invalid	
C17-2	-20	261.5	192.4	130.8	Invalid	
C17-6	-40	105.0	80.7	132.3	Valid	
C17-7	-40	119.6	91.1	129.2	Valid	

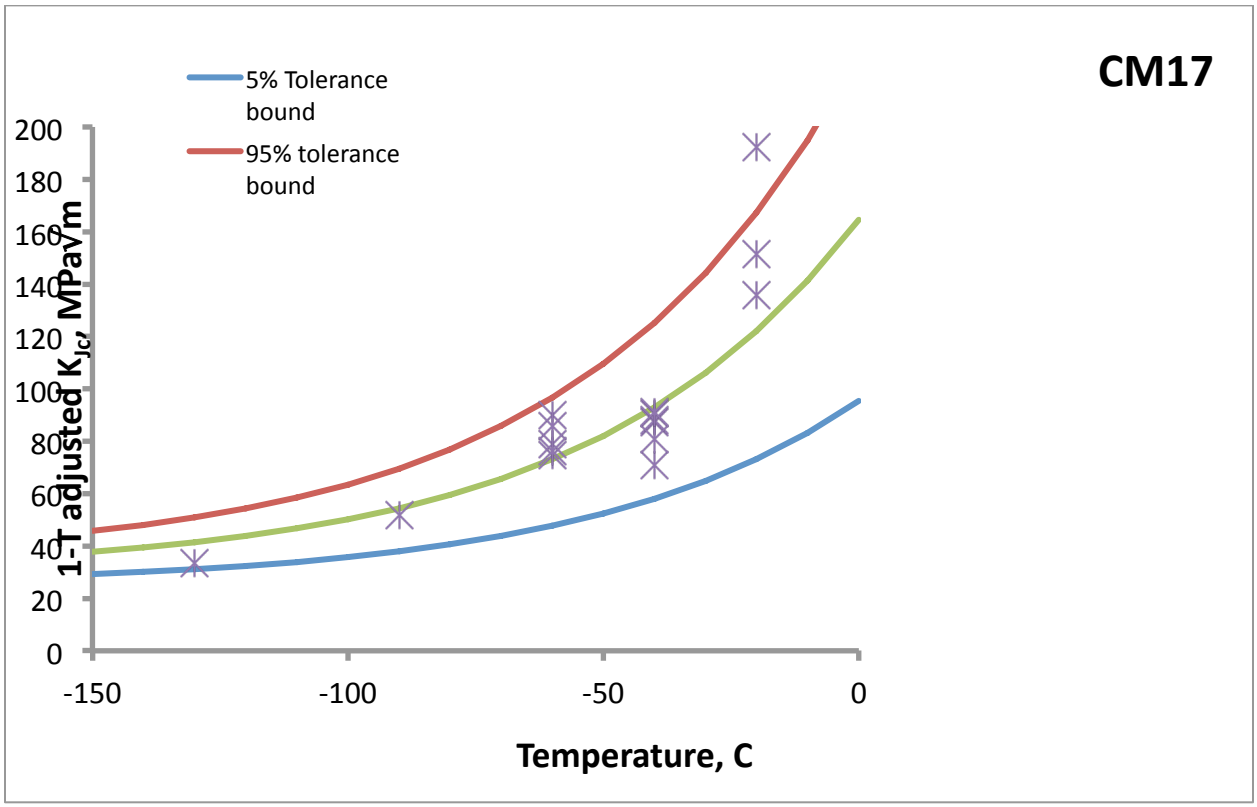

Figure 1. Fracture toughness data and the master curve of CM17 material

4.3 LP FRACTURE TOUGHNESS RESULTS

Fracture toughness data of LP are summarized in Table 4. All specimens produced valid K_{Jc} data, but four specimen exhibited pop-in event. Final T_o value for LP alloy is -18°C. Figure 2 illustrates fracture toughness and relevant master curve of LP material.

Table 4. Fracture toughness of LP material

Specimen ID	Temperature, °C	Measured K_{Jc}, MPa√m	1T-adjusted K_{Jc}, MPa√m	1T K_{Jc} limit, MPa√m	Validity	Remarks
LP-20	-50	96.6	74.7	129.5	Valid	
LP-24	-50	57.6	46.8	129.9	Valid	Pop-in
LP-29	-30	88.0	68.5	125.9	Valid	
LP-31	-50	70.4	55.9	130.5	Valid	Pop-in
LP-39	-50	70.7	56.1	130.9	Valid	Pop-in
LP-40	-50	93.8	72.7	131.2	Valid	

LP-48	-50	58.9	47.8	127.8	Valid	Pop-in
LP-23	-30	76.1	60.1	126.9	Valid	
LP-41	-30	79.1	62.2	126.2	Valid	
LP-25	-10	172.7	129.0	138.5	Valid	
LP-38	-30	179.0	133.5	138.5	Valid	
LP-44	-10	158	119.1	125.7	Valid	

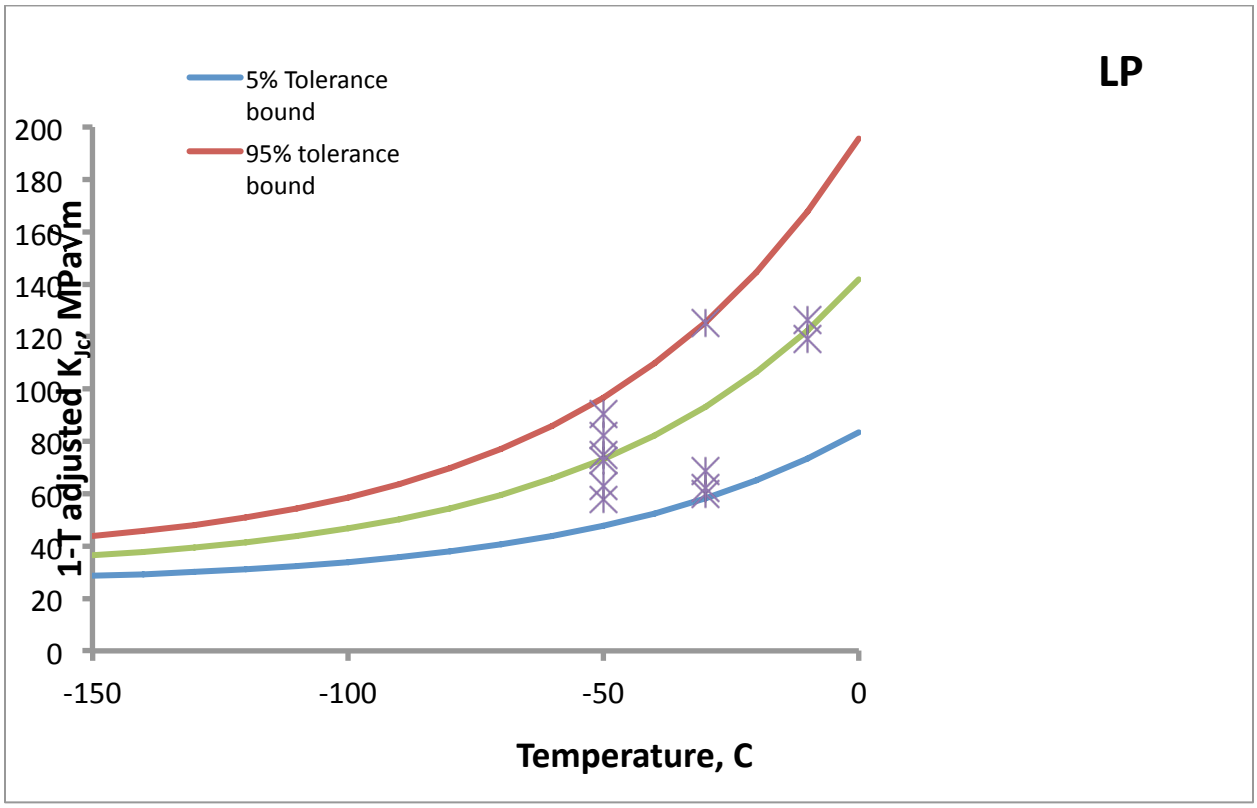

Figure 2. Fracture toughness and the master curve of LP material

4.4 PALISADES WELD B FRACTURE TOUGHNESS RESULTS

Fracture toughness data of Palisades Weld B are summarized in Table 5. All specimens but one produced valid K_{Jc} data, but four specimen exhibited pop-in event. Final T_o value for LP alloy is -102°C. Figure 3 illustrates fracture toughness and relevant master curve of Palisades weld B material.

Table 5. Fracture toughness of Palisades weld B

Specimen ID	Temperature, °C	Measured K_{Jc}, MPa√m	1T-adjusted K_{Jc}, MPa√m	1T K_{Jc} limit, MPa√m	Validity	Remarks
PBR-1	-130	80.9	63.5	147.1	Valid	
PBR-2	-130	78.3	61.6	149.2	Valid	
PBR-3	-115	101.8	78.4	145.7	Valid	
PBR-5	-115	100.8	77.7	142.3	Valid	
PBR-6	-115	87.8	68.4	142.0	Valid	
PBR-8	-115	45.4	38.1	143.2	Valid	
PBR-11	-115	99.8	76.9	144.9	Valid	
PBR-12	-130	97.2	75.1	151.7	Valid	

PBR-21	-130	131.5	99.6	158.9	Valid	
PBR-22	-130	110.7	84.7	155.24	Valid	
PBR-23	-115	128.8	97.7	150.2	Valid	
PBR-24	-130	65.5	52.5	159.9	Valid	
PBR-25	-130	122.5	93.2	155.7	Valid	
PBR-26	-115	116	88.5	140.9	Valid	
PBR-30	-115	138.1	104.3	152.4	Invalid	
PBR-31	-115	224	165,6	141.8	Valid	

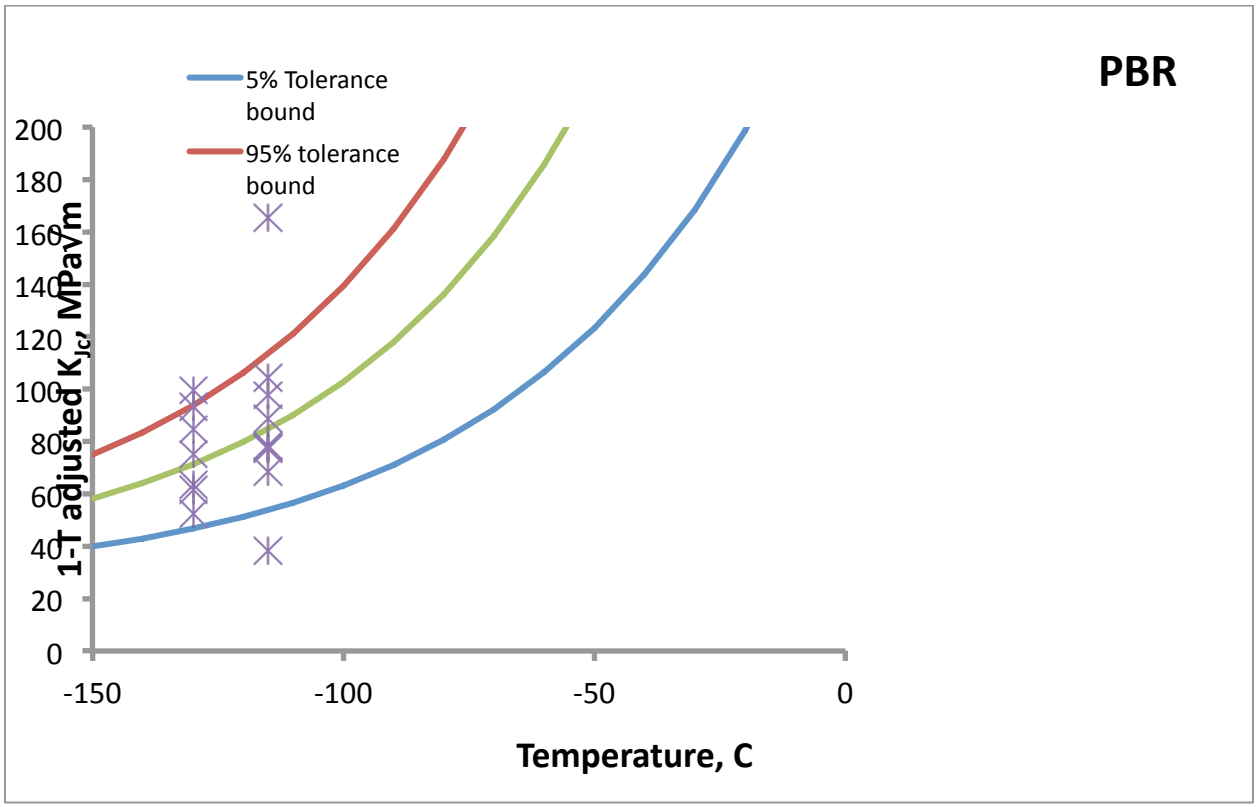

Figure 3. Fracture toughness of Palisades weld B

SUMMARY

Fracture toughness characterization of three materials has been performed in the unirradiated condition using DCT specimens. The same specimen type has been irradiated in ATR-2 experiment. These data will be used as reference point for measuring shift of fracture toughness transition temperature, T_o, after irradiation to very high fluence in ATR-2 experiment.

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