Attachment 5

Westinghouse WCAP-17651-NP
Revision 0

Palisades Nuclear Power Plant Reactor Vessel Equivalent Margins Analysis

44 pages follow

WCAP-17651-NP
Revision 0

February 2013

Palisades Nuclear Power Plant Reactor Vessel Equivalent Margins Analysis

Westinghouse

WCAP-17651-NP
Revision 0

Palisades Nuclear Power Plant Reactor Vessel Equivalent Margins Analysis

Elliot J. Long*
Materials Center of Excellence I

February 2013

Reviewer: Gordon Z. Hall*
Major Reactor Component Design & Analysis I

J. Brian Hall*
Materials Center of Excellence I

Approved: Frank C. Gift*, Manager
Materials Center of Excellence I

*Electronically approved records are authenticated in the electronic document management system.

Westinghouse Electric Company LLC
1000 Westinghouse Drive
Cranberry Township, PA 16066, USA

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

ASME	American Society of Mechanical Engineers
B&PV	Boiler and Pressure Vessel
CD	cooldown
CE	Combustion Engineering
CEOG	Combustion Engineering Owners Group
CFR	Code of Federal Regulations
CVN	Charpy V-notch
EFPY	effective full-power years
EMA	equivalent margins analysis
EOLE	end-of-license extension
FSAR	Final Safety Analysis Report
HU	heatup
IS	intermediate shell
J-R	fracture toughness resistance
LS	lower shell
L-T	lateral-transverse
MnS	manganese-sulfide
NRC	U.S. Nuclear Regulatory Commission
RG	Regulatory Guide
RRVCH	replacement reactor vessel closure head
SF	structural factor
SIF	stress intensity factor
T-L	transverse-lateral
US	upper shell
USE	upper-shelf energy

EXECUTIVE SUMMARY

This report presents the methodology and results of the upper-shelf equivalent margins analysis (EMA) for the three Palisades Nuclear Power Plant reactor vessel materials with end-of-license-extension (EOLE) upper-shelf energy (USE) levels below the 50 ft-lb limit of 10 CFR 50, Appendix G. Materials with EOLE USE levels below 50 ft-lb are required to be evaluated, per paragraph IV.A.1.a of 10 CFR 50, Appendix G, for equivalent margins of safety specified in ASME Code Section XI, Appendix K.

The two Palisades reactor vessel beltline materials and one extended beltline material that drop below the 50 ft-lb limit were identified in WCAP-17341-NP, Revision 0 and WCAP-17403-NP, Revision 1, respectively. These reports concluded that upper shell plate D-3802-3 in the extended beltline, and lower shell plate D-3804-1 and intermediate to lower shell circumferential weld 9-112 (Heat #27204) in the traditional beltline, are predicted to drop below the 50 ft-lb limit required per 10 CFR 50, Appendix G at EOLE, which corresponds to 42.1 effective full-power years (EFPY). In WCAP-17403-NP, Revision 1, a methodology was proposed that could demonstrate acceptance to the 10 CFR 50, Appendix G 50 ft-lb limit for upper shell plate D-3802-3. However, Palisades has elected to perform the EMA on this material due to the risk that it may fall below the 50 ft-lb limit if future operation includes higher flux levels.

All three Palisades reactor vessel beltline and extended beltline regions with predicted Charpy upper-shelf energy levels falling below 50 ft-lb at EOLE were found to be acceptable for equivalent margins of safety per the ASME Code Section XI.

Service Level A and B Transients

- Intermediate to lower shell circumferential weld 9-112 (Heat #27204) is governing for EOLE USE margin at the 1/4-thickness location for normal Level A and B load conditions, based on the Regulatory Guide 1.161 fracture toughness methodology.
- This limiting material passed the flaw extension and stability criteria of ASME Section XI Appendix K.
- The equivalent margins analysis for the plate materials are acceptable and bounded by the conservative test data reported in NUREG/CR-5265 in all cases for Service Level A and B transients.

Service Level C Condition

- Intermediate to lower shell circumferential weld 9-112 (Heat #27204) is governing for EOLE USE margin at the 1/10-thickness location for the service Level C load condition, based on the Regulatory Guide 1.161 fracture toughness methodology.
- This limiting material passed the flaw extension and stability criteria of ASME Section XI Appendix K.
- The equivalent margins analysis for the plate materials are acceptable and bounded by the conservative test data reported in NUREG/CR-5265 in all cases for the Service Level C transient.

Service Level D Condition

- Intermediate to lower shell circumferential weld 9-112 (Heat #27204) is governing for EOLE USE margin at the 1/10-thickness location for the service Level D load condition, based on the Regulatory Guide 1.161 fracture toughness methodology.

- This limiting material passed the flaw extension and stability criterion of ASME Section XI, Appendix K.

- The equivalent margins analysis for the plate materials is acceptable and bounded by the conservative test data reported in NUREG/CR-5265 in all cases for the Service Level D transient.

1 INTRODUCTION

An upper-shelf energy (USE) evaluation was performed for the Palisades reactor vessel (RV) beltline materials in WCAP-17341-NP, Revision 0 (Reference 1) and for the extended beltline materials in WCAP-17403-NP, Revision 1 (Reference 2). These reports concluded that materials in three locations – upper shell plate D-3802-3 in the extended beltline, and lower shell plate D-3804-1 and intermediate to lower shell circumferential weld 9-112 (Heat #27204) in the traditional beltline – are predicted to drop below the 50 ft-lb limit required per 10 CFR 50, Appendix G (Reference 3) at end-of-license extension (EOLE), which corresponds to 42.1 effective full-power years (EFPY). In WCAP-17403-NP, Revision 1, a methodology was proposed that could demonstrate acceptance to the 10 CFR 50, Appendix G 50 ft-lb limit for upper shell plate D-3802-3. However, Palisades has elected to perform the equivalent margins analysis (EMA) on this material due to the risk that it may fall below the 50 ft-lb limit if future operation includes higher flux levels.

Reactor vessel materials with USE levels below 50 ft-lb are required to be evaluated, per paragraph IV.A.1.a of 10 CFR 50, Appendix G (References 3 and 4), for equivalent margins of safety specified in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code Section XI, Appendix K (Reference 5). This summary report provides the methodology and results of the upper-shelf EMA of the Palisades reactor vessel limiting materials for 42.1 EFPY. Figure 1-1 shows the locations of interest for this analysis in the Palisades reactor vessel.

Section 2 of this report discusses the methodologies used to complete the Palisades EMA. Section 3 identifies the acceptance criteria for the EMA with consideration of the various service loadings including Levels A, B, C, and D. Section 4 provides the inputs necessary to complete the EMA, while Section 5 documents the EMA evaluations. The conclusions of this report are documented in Section 6.

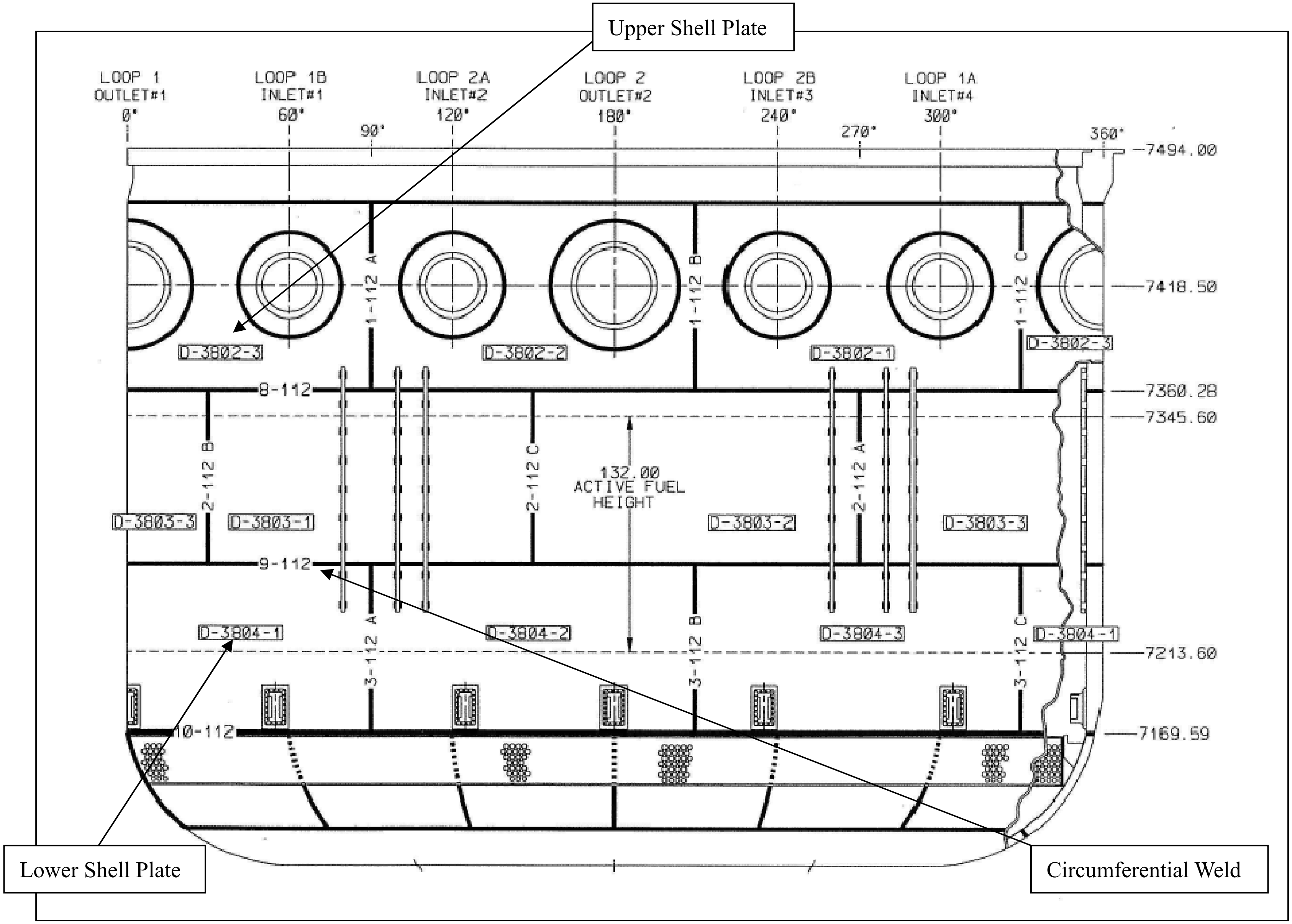

Figure 1-1 Palisades Reactor Vessel with Locations for EMA

2 METHOD DISCUSSION

2.1 ASME SECTION XI, APPENDIX K METHODOLOGY

ASME Section XI, Appendix K (Reference 5) specifies the methodology to be used to evaluate the equivalent margins for low upper-shelf materials. Reference 5 contains different postulated flaw depths, locations, and orientations, as well as the applied J-integral and stability criteria. These are briefly described here.

Applied SIF Calculation for Axial and Circumferential Flaws with Pressure Loading

For an axial flaw of depth a, the stress intensity factor (SIF) due to internal pressure is calculated with a structural factor (SF) on pressure using procedure in Article K-4000 in Reference 5.

Applied SIF for Axial and Circumferential Flaws with Thermal Loading

For an axial or circumferential flaw of depth a, the SIFs due to radial thermal gradients for cooldown rates up to 100°F/hr are calculated using procedure in Article K-4000 in Reference 5.

The SIFs for all other thermal design transients are computed using the stress distributions from the actual design transients analyzed in this EMA. The procedure from ASME Section XI, Appendix A (Reference 6) employing the cubic polynomial coefficients are also used.

Effective Flaw Depth and Applied J-Integrals

The effective flaw depth for small-scale yielding (a_e) is used and the applied J-integrals are calculated again using the procedure in Reference 5.

The calculation of a J-integral due to applied loads accounts for the material's elastic-plastic behavior of a stress-strain curve.

Postulated Flaws for Level A and B Service Loadings

The postulated flaw is an interior semi-elliptical surface with a depth of one-quarter of the vessel wall thickness and an aspect ratio (length over depth) of 6:1. Orientation of the flaw is assumed to be as follows:

$$a_0 = \frac{t_{base}}{4}$$

where,

a_0 = postulated initial flaw depth, inches
t_{base} = thickness of the base or weld material, inches

For weld materials, the major axis of the flaw is to be oriented along the weld line.

For base materials, both axial and circumferential orientations are to be considered.

All the postulated flaws are oriented in the radial direction.

Postulated Flaws for Levels C and D Service Loadings

The postulated flaw is an interior semi-elliptical surface with a depth of 1/10 of the base metal wall thickness plus the cladding thickness (with a total depth not exceeding 1 inch), a surface length of six times the depth, and the flaw plane oriented in the radial direction.

$$a_0 = \frac{t_{base}}{10} + t_{clad}$$

where,

t_{clad} = thickness of the cladding, inches

For weld materials, the adequacy of the upper-shelf toughness with a flaw’s major axis oriented along the weld of concern is evaluated.

For the base materials, the adequacy of the upper-shelf toughness with a flaw’s major axis oriented along axial and circumferential directions is evaluated. The toughness properties for the corresponding orientations are used.

Flaws of various depths, ranging up to the maximum postulated depth, shall be analyzed to determine the most limiting flaw depth.

2.2 REGULATORY GUIDE 1.161 METHODOLOGY

Material Fracture Toughness Property

The material J-integral resistance property as a function of flaw extension is a conservative representation for the RV material beltline region. As the actual beltline J-integral fracture resistance material properties for the Palisades RV are not available, U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide (RG) 1.161 (Reference 7, Section 3) is used. Regulatory Guide 1.161 has been developed to provide comprehensive guidance acceptable to the NRC staff for evaluating reactor pressure vessels when the Charpy USE falls below the 50 ft-lb limit of Appendix G to 10 CFR Part 50. The analysis methods in the regulatory position are based on methods developed for the ASME Code, Section XI, Appendix K (Reference 5). The NRC staff has reviewed the analysis methods in Appendix K and finds that they are technically acceptable but are not complete, because Appendix K does not provide information on the selection of transients and gives very little detail on the selection of material properties. In RG 1.161, specific guidance is provided on selecting transients for consideration and on appropriate material properties to be used in the analyses. The material fracture toughness J-resistance is provided in Reference 7 and is expressed as:

$$J_R = (MF)C_1(\Delta a)^{C_2}\, exp[C_3(\Delta a)^{C_4}]$$

where,

J_R = J-integral fracture resistance for the material, in-lb/in^2

MF = margin factor (see Table 4-4)

Δa = amount of ductile flaw extension, inches

C_1, C_2, C_3, C_4, = material constants used to describe the power-law fit to the J-integral resistance curve for the material

<u>Base Metal</u>

$$C_1 = exp[-2.44 + 1.13 * \ln CVN - 0.00277 * T]$$

$$C_2 = 0.077 + 0.116 * \ln C_1$$

$$C_3 = -0.0812 - 0.0092 * \ln C_1$$

$$C_4 = -0.409$$

<u>Weld Metal</u>

$$C_1 = exp[-4.12 + 1.49 * \ln CVN - 0.00249 * T]$$

$$C_2 = 0.077 + 0.116 * \ln C_1$$

$$C_3 = -0.0812 - 0.0092 * \ln C_1$$

$$C_4 = -0.5$$

Per RG 1.161, the Charpy v-notch upper-shelf energy (CVN) value should be matched to the proper orientation of the plate material (see Figure 2-1). Therefore, for axial flaws, the CVN value for the lateral-transverse (L-T) “strong” orientation in the vessel wall should be used. Similarly, for circumferential flaws, the CVN value for the transverse-lateral (T-L) “weak” orientation should be used. See Section 5.1 for additional details.

Also, with consideration of plate materials, the J-R model described in this section is developed for materials with high fracture toughness. For plate material with sulfur content less than 0.018 wt. %, the J-R model may be used. For plate material with sulfur content greater than 0.018 wt. %, the model may be used if it can be justified as conservative or a material-specific justification can be made based on other data. See Section 5.2 for additional details.

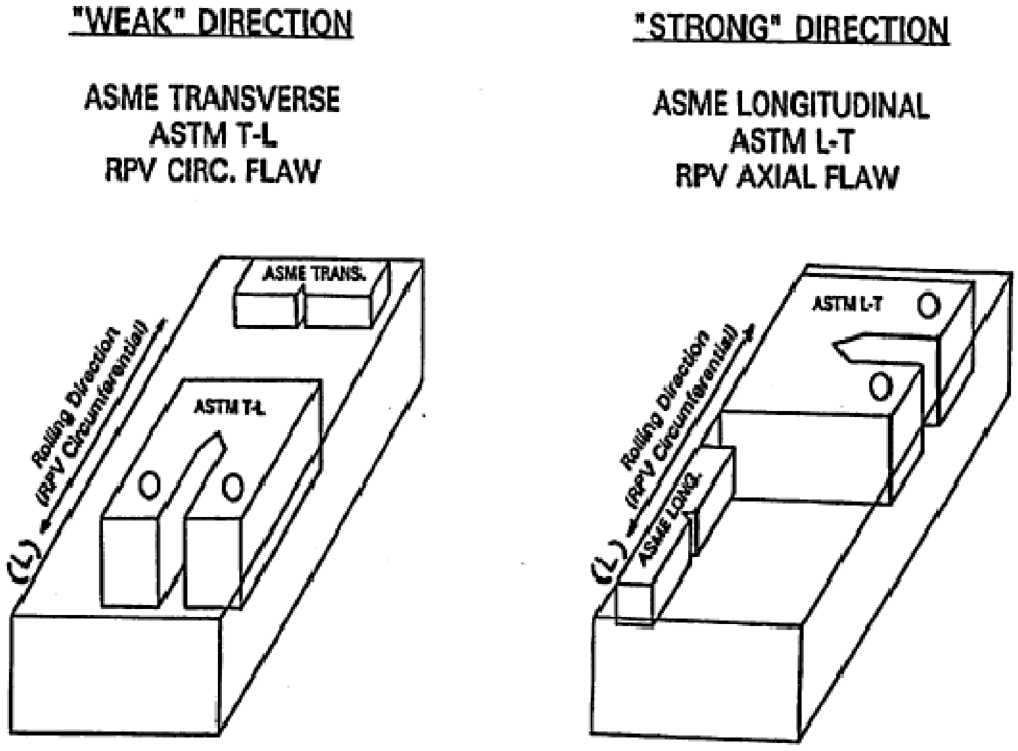

Figure 2-1 Definition of ASME Orientations

3 ACCEPTANCE CRITERIA

The ASME Code forms the basis for the requirements of Appendix G to 10 CFR Part 50. The acceptance criteria for the low-USE locations in the RV beltline materials are established in the ASME Code Section XI, Appendix K, Article K-2000 (Reference 5) and are summarized here.

3.1 LEVEL A AND B SERVICE LOADINGS

Flaw Extension Criterion

The applied J-integral evaluated at a pressure 1.15 times the accumulation pressure (as defined in the plant-specific overpressure protection report), with a structural factor of 1 on thermal loading for the plant-specific heatup (HU) and cooldown (CD) conditions, shall be less than the J-integral of the material at a ductile flaw extension of 0.1 inch.

$$J_1(a_1, 1.15P_a, CD\ or\ HU) < J_{0.1}$$

where J_1 is the applied J-integral with:

$$a_1 = \frac{t}{4} + 0.1\ in$$

where,

P_a = accumulation pressure as defined in the plant-specific overpressure protection report, but not exceeding 1.1 times the design pressure, ksi

HU = heatup

CD = cooldown

$J_{0.1}$ = the J-integral resistance at a ductile flaw extension of 0.1 inch, in-lb/in^2

Flaw Stability Criterion

Flaw extensions at pressures up to 1.25 times the accumulation pressure shall be ductile and stable, using a structural factor of 1 on thermal loading for the plant-specific HU and CD conditions.

$$J(1.25\ P_a, CD\ or\ HU)\ should\ be\ in\ ductile\ tearing\ mode\ and\ stable$$

The flaw stability criterion is evaluated using:

- The J-integral due to applied loads for the postulated flaw in the vessel should satisfy the equilibrium equation for the stable flaw extension:

$$J = J_R$$

In the preceding equation:

J = J-integral due to applied loads
J_R = J-integral resistance to ductile tearing for the material

- The applied J-integral should satisfy the stability criterion for the following ductile tearing equation. Under increasing load, stable flaw extension will continue as long as $\frac{\partial J}{\partial a}$ remains less than $\frac{\partial J_R}{\partial a}$.

$$\frac{\partial J}{\partial a} \leq \frac{\partial J_R}{\partial a}$$

In the preceding equation:

$\frac{\partial J}{\partial a}$ = partial derivative of applied J-integral with respect to flaw depth, a, with constant load

$\frac{\partial J_R}{\partial a}$ = slope of the J-resistance curve

The above requirements for flaw extension and stability for Level A and B service loadings are satisfied as discussed in Section 5 of this report.

3.2 LEVEL C SERVICE LOADINGS

Flaw Extension Criterion

The applied J-integral, with a structural factor of 1 on loading, shall be less than the J-integral of the material at a ductile flaw extension of 0.1 inch.

$$J_1(a_1, P_a, CD\ or\ HU) < J_{0.1}$$

where J_1 is the applied J-integral with:

$$a_1 = a_0 + 0.1\ in$$

Flaw Stability Criterion

Flaw extensions shall be ductile and stable, similar to Level A and B service loadings, with a structural factor of 1 on loading.

The preceding requirements for flaw extension and stability for Level C service loadings are satisfied as discussed in Section 5 of this report.

3.3 LEVEL D SERVICE LOADINGS

Flaw Stability Criterion

The total flaw depth after stable flaw extension shall be less than or equal to 25 percent of the vessel wall thickness and the remaining ligament shall not be subject to tensile instability.

This requirement for flaw stability for Level D service loadings is satisfied as discussed in Section 5 of this report.

Tensile instability occurs only when the applied J-integral slope exceeds that of the material curve and the flaw continually grows per RG 1.161 and Appendix K of the ASME B&PV Code. As shown in Section 5 of this report for the Palisades EMA, flaws are stable with adequate margins. Therefore, crack growth or stability is not an issue.

4 EQUIVALENT MARGINS ANALYSIS INPUTS

The following material property inputs, vessel design data, and transient data were used in the EMA of the three Palisades reactor vessel materials with predicted EOLE USE values below 50 ft-lb. The two materials in the traditional beltline region, lower shell plate D-3804-1 and intermediate to lower shell circumferential weld 9-112 (Heat #27204) have EOLE USE values below 50 ft-lb. Though it can be shown by the methodology documented in WCAP-17403-NP that the extended beltline region material, upper shell plate D-3802-3, remains above 50 ft-lb at EOLE, Palisades has elected to perform the EMA on this material with consideration of the possibility of future operation at higher flux levels. Table 4-1 documents the Palisades reactor vessel geometry. Table 4-2 contains the unirradiated, EOLE 1/10T, and EOLE 1/4T USE for the three Palisades reactor vessel materials. Unit pressure load through-wall stress profiles for axial and hoop stresses were used in all the pressure SIF calculations. Design transients for all Level A and B transients were considered in addition to the 100°F/hr CD transient specified in Reference 5; see Table 4-3. ASME Code Section D material properties for yield strength and modulus of elasticity are from Reference 8.

Level A and B transients with a 100°F/hr cooldown rate, Level C transients with a 400°F/hr cooldown rate, and Level D transients with a 600°F/hr cooldown rate were used in the EMA. These transient definition points are also listed in Tables 4-5 through 4-7. Finally, cladding effects for the Levels C and D load levels were conservatively ignored because the temperatures at evaluation points are above the cladding stress free temperature of 400°F (Reference 9).

The Palisades Final Safety Analysis Report (FSAR) subsection 4.2.2 lists and describes RV design basis transients; however, further information is needed to conduct a transient stress analysis. Therefore, to accommodate this need, the Design Specification for the Replacement Reactor Vessel Closure Head (RRVCH) for Palisades Nuclear Generation Station, DS-ME-04-10, Revision 3 (Reference 10) was used to obtain temperature vs. time and pressure vs. time RV design basis transient data. Design Specification DS-ME-04-10 contains one additional transient (steam line rupture) that was not included in the original design basis transients for the reactor vessel. The steam line rupture transient is conservatively included in the EMA. Additional transients from RG 1.161 are also evaluated.

Table 4-1 Palisades RV Beltline Geometry and Design

Parameter	Value$^{(1)}$
Base Metal Inside Diameter (Di)	172.7 in
Base Metal Inner Radius	86.35 in
Base Metal Wall Thickness (t)	8.79 in
Cladding Thickness	0.25 in$^{(2)}$
Material Specification	SA-302 Gr. B Modified Plate
Accumulation Pressure (p_{acc})	2.750 ksi

Notes:

1. Reactor vessel beltline geometry values were obtained from WCAP-15353 – Supplement 2 – NP (Reference 11).
2. Cladding and cladding effects were conservatively ignored in the various stress analyses performed for Palisades as part of the EMA.

Table 4-2 Palisades RV Beltline Predicted Upper-Shelf Energy at 42.1 EFPY

Reactor Vessel Material(1)			Unirradiated USE(1) (ft-lb)	Projected EOLE USE(2)	
Location		**Heat Number**		**At 1/10t (ft-lb)**	**At 1/4t (ft-lb)**
LS Plate D-3804-1		C-1308-1(3)	72	46.1	48.2
US Plate D-3802-3(4)	Using CVGraph Refitted Initial USE	C-1281	62.2	47.5	50.1
	Using 95% Shear Initial USE	C-1281	59	46.6	47.5
IS to LS Circumferential Weld 9-112		27204	84	47.9	49.6

Notes:

1. Reactor vessel material information, heat numbers, and unirradiated initial USE values were taken from WCAP-17341-NP (Reference 1) for LS plate D-3804-1 and IS to LS circumferential weld 9-112 and from WCAP-17403-NP (Reference 2) for US plate D-3802-3. This information is consistent with P-PENG-ER-006 (Reference 12).
2. The projected EOLE USE values at 1/4t were taken from WCAP-17341-NP for LS Plate D-3804-1 and IS to LS circumferential weld 9-112 and from WCAP-17403-NP for US plate D-3802-3. The projected EOLE USE values at 1/10t were calculated for the EMA using the methodology described in RG 1.99, Revision 2 (Reference 13), which is equivalent to the methodology used in the previous reports.
3. The heat number for LS plate D-3804-1 has also been reported as C-1308A.
4. Using the methodology proposed in WCAP-17403-NP, it can be demonstrated that US Plate D-3802-3 meets the 50 ft-lb limit of 10 CFR 50, Appendix G. However, Palisades has elected to perform the EMA on this material due to the risk that it may fall below the 50 ft-lb limit if future operation includes higher flux levels.

Table 4-3 List of Transients Evaluated in the EMA

Number	Transient Description	Load Level
1	Plant HU at 100°F/hr	A
2	Plant CD at 100°F/hr	A
3	Plant Loading Change, 5% Full Load/Minimum	A
4	Plant Unloading Change, 5% Full Load/Minimum	A
5	Plant Load Change, 10% Full Load Step, Step Increase, T_{cold}	A
6	Plant Load Change, 10% Full Load Step, Step Decrease, T_{cold}	A
7	Plant Load Change, 10% Full Load Step, Step Increase, T_{hot}	A
8	Plant Load Change, 10% Full Load Step, Step Decrease, T_{hot}	A
9	Plant Loading Change, 15% Full Load/Min	A
10	Plant Unloading Change, 15% Full Load/Min	A
11	Loss of Primary Coolant Flow, T_{cold}	B
12	Loss of Primary Coolant Flow, T_{hot}	B
13	Reactor Trip or Loss of Load, T_{cold}	B
14	Reactor Trip or Loss of Load, T_{hot}	B

Table 4-3 List of Transients Evaluated in the EMA (cont.)

Number	Transient Description	Load Level
15	Reactor Trip, Loss of Load, or Loss of Primary Coolant Flow, $T_{surgeflow}$	B
16	Safety Valve Operation, T_{inlet}	B
17	Safety Valve Operation, T_{outlet}	B
18	Steam Line Rupture$^{(1)}$	D
19	RG 1.161 Cooldown at 100°F/hr	B
20	RG 1.161 Cooldown at 400°F/hr	C
21	RG 1.161 Cooldown at 600°F/hr	D

Notes:

1. This design transient is conservatively bounded by the Regulatory Guide (Reference 7) transient for Level D loads.

Table 4-4 Fracture Toughness Margin Factors from Reference 7

Metal	Levels A, B, and C	Level D
Base	0.749	1
Welds	0.629	1

Table 4-5 Level A and B 100°F/hr Cooldown Transient

Time (sec)	Pressure (ksi)	Fluid T_{fluid} (°F)
0	2.75	533
2,800	2.75	456
3,600	2.75	433
5,400	2.75	383
7,200	2.75	333
9,000	2.75	283
10,800	2.75	233

Table 4-6 Level C 400°F/hr Cooldown Transient

Time (sec)	Pressure (ksi)	Fluid T_{fluid} (°F)
0	2.25	533
1,197	1.3	400

Table 4-7 Level D 600°F/hr Cooldown Transient

Time (sec)	Pressure (ksi)	Fluid T_{fluid} (°F)
0	2.25	533
798	1.3	400

5 EQUIVALENT MARGINS ANALYSIS EVALUATIONS

5.1 APPLIED J-INTEGRAL CALCULATIONS

For the Level A and B service load conditions, the Palisades EMA has considered a total of 17 design transients from the Palisades FSAR, along with the 100°F/hr, 400°F/hr and 600°F/hr cooldown rate transients provided in Reference 7. The typical through-wall thermal stress, shown in Figure 5-1, was computed analytically at inside surface, mid-wall, and outside surface locations. Typical axial through-wall stress distributions for the vessel during a heatup transient, shown in Figure 5-2, were used in this EMA. The associated vessel wall metal temperatures, required for the applied J-integral evaluation and the material fracture toughness resistance (J-R), were also used.

The applied J-integral values for the circumferential flaws for all Level A and B service level conditions are shown in Figure 5-1. These figures show the peak J-integral values during each transient as a function of crack extension starting from the 1/4-thickness flaw. These calculations used a structural margin of 1.25 for pressure loading and 1 for thermal loading, as required by Reference 5.

Figure 5-2 shows the applied J-integral values at 1/10-thickness flaws, with a structural margin of 1 for pressure and thermal loadings, for circumferential flaws under Level C and D conditions.

All applied J-integral values shown in Figure 5-1 and Figure 5-2 are applicable for both the weld and base metals because flaws are considered circumferential. Only circumferential base metal flaws are considered in this analysis, because only the “weak” orientation USE is projected to drop below 50 ft-lbs as described below.

The measured initial USE value for the Palisades Nuclear Power Plant LS plate D3804-1 is 110 ft-lb in the longitudinal direction. Similarly, US plate D3802-3 has an initial USE value of 91 ft-lb in the longitudinal direction per P-PENG-ER-006 (Reference 12). The estimated transverse values for the LS and US plates are 72 and 59 ft-lb, respectively, which were reduced by 35 percent to approximate the transverse direction per NUREG-0800, Revision 2 Branch Technical Position MTEB 5-3 (Reference 14). Table 5-1 documents the calculation of the end-of-license-extension (EOLE) USE with consideration of the Charpy testing direction for Palisades. Data were obtained from WCAP-17341-NP and WCAP-17403-NP for the LS and US plates, respectively.

The table shows that for the longitudinal “strong” direction, both plates exhibit an EOLE USE value per 10 CFR 50, Appendix G above 50 ft-lb. When the initial longitudinal USE value is reduced to 65 percent per MTEB 5-3 to approximate the transverse “weak” direction, both plates drop below the 50 ft-lb limit. Therefore, only circumferential flaws are postulated in the two plates, because the EOLE USE in the longitudinal “strong” direction is above the 10 CFR 50, Appendix G limit. As stated previously in Section 2.2, the CVN value should be matched to the proper orientation of the plate material. Therefore, for axial flaws, the CVN value for the lateral transverse (L-T) “strong” orientation in the vessel wall will be used. Similarly, for circumferential flaws, the CVN value for the transverse-lateral (T-L) “weak” orientation will be used. Therefore, only circumferential base metal flaws are considered in this analysis.

The applied J-integral values shown in Figure 5-1 and Figure 5-2 are used in the flaw evaluations. Table 5-2 summarizes the maximum circumferential applied J-integrals for all design, 100°F/hr, 400°F/hr, and 600°F/hr transients.

5.2 MATERIAL FRACTURE TOUGHNESS PROPERTIES

The estimated base material fracture toughness properties for the 1/4- and 1/10-thickness locations are shown in Figure 5-3 and Figure 5-4, respectively using the high-toughness / low-sulfur model from RG 1.161. The corresponding material toughness values for the weld material are shown in Figures 5-6 and 5-7, also using the model from RG 1.161. These figures show the toughness values at different metal temperatures ranging from 300°F to 600°F, over which the vessel wall metal temperatures vary during the transients. These include the USE levels considered for the materials at the flaw location and a flaw extension of up to 1 inch.

Per P-PENG-ER-006, the sulfur content of US plate D-3802-3 is 0.029 wt. %. Similarly, for LS plate D-3804-1, the sulfur content is 0.024 wt. %. The Palisades plates have a sulfur content greater than the high-toughness model limit of 0.018 wt. % specified in RG 1.161. The J-R model in RG 1.161 has an upper limit in sulfur because J-R data for plates with high sulfur content are scarce and the available data showed low toughness, flat J-R curves, and a size effect. The most data available for a high-sulfur A-302 B plate are for the V-50 plate in NUREG/CR-5265 (Reference 15). This plate has a reported sulfur content of 0.021 and 0.025 wt. % with USE values of 44 to 51 ft-lb, averaging around 48 ft-lb at the 1/4T locations in the T-L (weak) orientation. This USE is comparable to the EOLE projection for the Palisades high-sulfur plates.

The V-50 plate was unusual in that it had a test specimen size effect that has not been observed in other RV material J-R curves and is unique to the V-50 plate. A high content of manganese-sulfide (MnS) inclusions and banded regions of microstructure, are believed to be the causes of the unusual specimen size effect observed. Conservatively, the lowest J-R curve test data from this testing program is plotted in Figure 5-5, which is from a 6T size specimen and is considerably lower than test data for the 1T J-R, which is the standard size specimen typically used. In addition, the manufacturing practices used to produce this extremely low-toughness V-50 plate are not representative of those used in the Palisades RV. The V-50 plate is A-302 B plate with a nickel content of 0.23 wt. % while the Palisades plates are SA-302B Modified, which means that they have at least 0.4 wt. % nickel. Nickel was added to increase toughness. Therefore, the J-R curve test data from the V-50 plate data can be conservatively viewed as the worst possible case and can be compared to the J-applied values from this evaluation. Adjusting the 180°F 6T plate V-50 J-R curve data to 600°F using the ratio of the RG 1.161 correlation, the 600°F data can be approximated as shown in Figure 5-5.

High-sulfur A-302 B Modified plate J-R data are available in NUREG/CR-6426 (Reference 16). However, the weak-direction Charpy USE value is 64 ft-lb, which is above the 10 CFR 50, Appendix G limit of 50 ft-lb. This further validates that the V-50 plate was an anomaly and can be considered a very conservative lower bound of the available high-sulfur A-302 B plate J-R data. The J-applied in the Palisades SA-302 B Modified plate remains below the measured very conservative lower-bound V-50 A-302 B plate J-R data.

5.3 FLAW EVALUATION RESULTS

The flaw stabilities for various material, flaw location, and service load levels are shown in Figure 5-8 through Figure 5-13. Figure 5-8 shows the applied J-integral and material J-resistance for circumferential flaws in base metal at the 1/4-thickness location for Level A and B design transients. The corresponding results for the NRC Regulatory Guide 100°F/hr cooldown transient are shown in Figure 5-9. The J-applied remains below even the conservative temperature-adjusted V-50 plate J-R data. Figure 5-8 compares the J-R data using the high-toughness, low-sulfur model of RG 1.161, along with the measured V-50 plate J-R data, to the J-applied calculated in this analysis.

For the weld metal, Figure 5-10 and Figure 5-11 show the applied J-integral and material J-resistance results for the Level A and B transients for the circumferential flaws, and the corresponding NRC Regulatory Guide 100°F/hr cooldown transient.

For Level C and D loads, circumferential flaw versus crack extension results are shown Figure 5-12 for base metal and in Figure 5-13 for the weld metal. The J-applied curves for Levels C and D are essentially flat, indicating very small flaw extension. The J-applied curves are also well below the J_R curves, indicating stable flaw extension.

Table 5-2 lists the minimum material fracture toughness J-resistance as calculated per RG 1.161 at a peak metal temperature of 610°F, which is observed at the 1/4-thickness locations. All transients that have applied J-integral values with the crack tip at significantly lower temperatures than 610°F are well below the J-resistance listed, indicating that the EMA criteria are met.

Maximum available equivalent margins were computed for the Level A and B governing transient with 100°F/hr cooldown rate at accumulation pressure levels by iteration. The maximum structural margin factors that result in the J-applied values equal to the material J-resistance at 0.1-inch crack extension as calculated per RG 1.161 are listed in Table 5-3. This evaluation indicates that the minimum structural margin available for the base material is 2.874 (with circumferential flaws). For the weld material with the circumferential flaws, the minimum structural margin available is 2.490. All these cases have their structural factors well above the minimum requirement of 1.15 (Reference 5).

The flaw extension figures demonstrate that:

- The NRC Regulatory Guide 100°F/hr cooldown transient with the accumulation pressure levels governs the Level A and B transients.
- All cases considered are acceptable with the applied J-integral values at 0.1-inch crack extensions below the material J-resistance ($J_{0.1}$) required by Reference 5.

Table 5-1 Palisades US and LS Plate EOLE USE Calculation with Consideration of Charpy Test Specimen Orientation

Charpy Orientation	**Reactor Vessel Material**	**Wt.% Cu**	**1/4T EOLE Fluence (x 10^{19} n/cm^2, E > 1.0 MeV)**	**Unirradiated USE (ft-lb)**	**Projected USE Decrease (%)**	**Projected EOLE USE (ft-lb)**
Longitudinal(1)	US Plate D-3802-3	0.25	0.0902	91(1)	19.5	73
	LS Plate D-3804-1	0.19	2.024	110(1)	33	74
Transverse(2)	US Plate D-3802-3	0.25	0.0902	59	19.5	47.5
	LS Plate D-3804-1	0.19	2.024	72	33	48.2

Notes:

1. Measured longitudinal-direction initial USE values from P-PENG-ER-006. All other data are taken from WCAP-17341-NP and WCAP-17403-NP for the LS and US plates, respectively.
2. Data are taken from WCAP-17341-NP and WCAP-17403-NP for the LS and US plates, respectively, and summarized in Table 4-2.

Table 5-2 Applied J-Integral and Material J-Resistance at 0.1-Inch Crack Extension for All Transients

Number	Transient Description	Load Level	a/t	Circumferential $J_{applied}$ (in-lb/in^2)	Base J_R (in-lb/in^2)	Weld J_R (in-lb/in^2)
1	Plant HU at 100°F/hr	A	1/4	49.1	601	462
2	Plant CD at 100°F/hr	A		106.4		
3	Plant Loading Change, 5% Full Load/Minimum	A		47.9		
4	Plant Unloading Change, 5% Full Load/Minimum	A		104.7		
5	Plant Load Change, 10% Full Load Step, Step Increase, T_{cold}	A		55.2		
6	Plant Load Change, 10% Full Load Step, Step Decrease, T_{cold}	A		49.5		
7	Plant Load Change, 10% Full Load Step, Step Increase, T_{hot}	A		53.3		
8	Plant Load Change, 10% Full Load Step, Step Decrease, T_{hot}	A		52.5		
9	Plant Loading Change, 15% Full Load/Min	A		48.2		
10	Plant Unloading Change, 15% Full Load/Min	A		68.1		
11	Loss of Primary Coolant Flow, T_{cold}	B		53.5		
12	Loss of Primary Coolant Flow, T_{hot}	B		90.3		
13	Reactor Trip or Loss of Load, T_{cold}	B		48.1		
14	Reactor Trip or Loss of Load, T_{hot}	B		90.1		
15	Reactor Trip, Loss of Load, or Loss of Primary Coolant Flow, $T_{surgeflow}$	B		86.5		
16	Safety Valve Operation, T_{inlet}	B		69.7		
17	Safety Valve Operation, T_{outlet}	B		96.6		
19	RG 1.161 Cooldown at 100°F/hr	B		181.5		
20	RG 1.161 Cooldown at 400°F/hr	C	1/10	163.8	783	708
21	RG 1.161 Cooldown at 600°F/hr	D		304.8		

Table 5-3 Available Margins on Pressure Load for Level A and B 100°F/hr Cooldown Transient

Time (sec)	Base Material			Weld Material		
	Circumferential Flaw		$J_{0.1}$ Material (in-lb/in^2)	Circumferential Flaw		$J_{0.1}$ Material (in-lb/in^2)
	SF	J-applied (in-lb/in^2)		SF	J-applied (in-lb/in^2)	
0	3.106	699	699	2.760	527	528
2,800	2.874	776	776	2.490	578	580
3,600	2.882	807	807	2.490	600	601
5,400	2.963	885	885	2.549	653	653
7,200	3.102	975	975	2.659	711	711
9,000	3.272	1,076	1,076	2.797	776	777
10,800	31.69	1,188	1,188	27.05	847	848
Minimum SF	2.874			2.490		

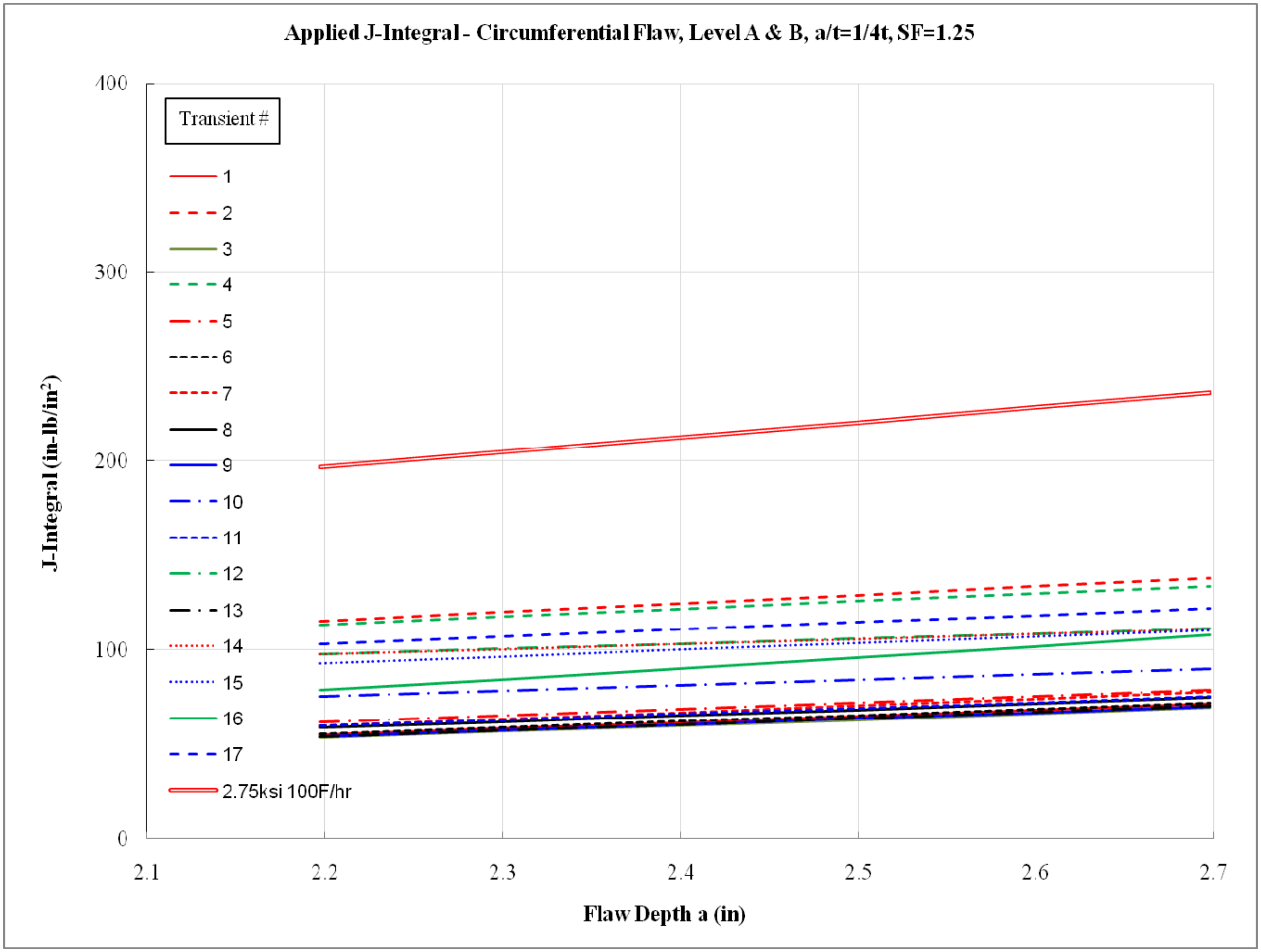

Figure 5-1 Applied J-Integral versus Crack Extension for Circumferential Flaw – 1/4t, Level A and B

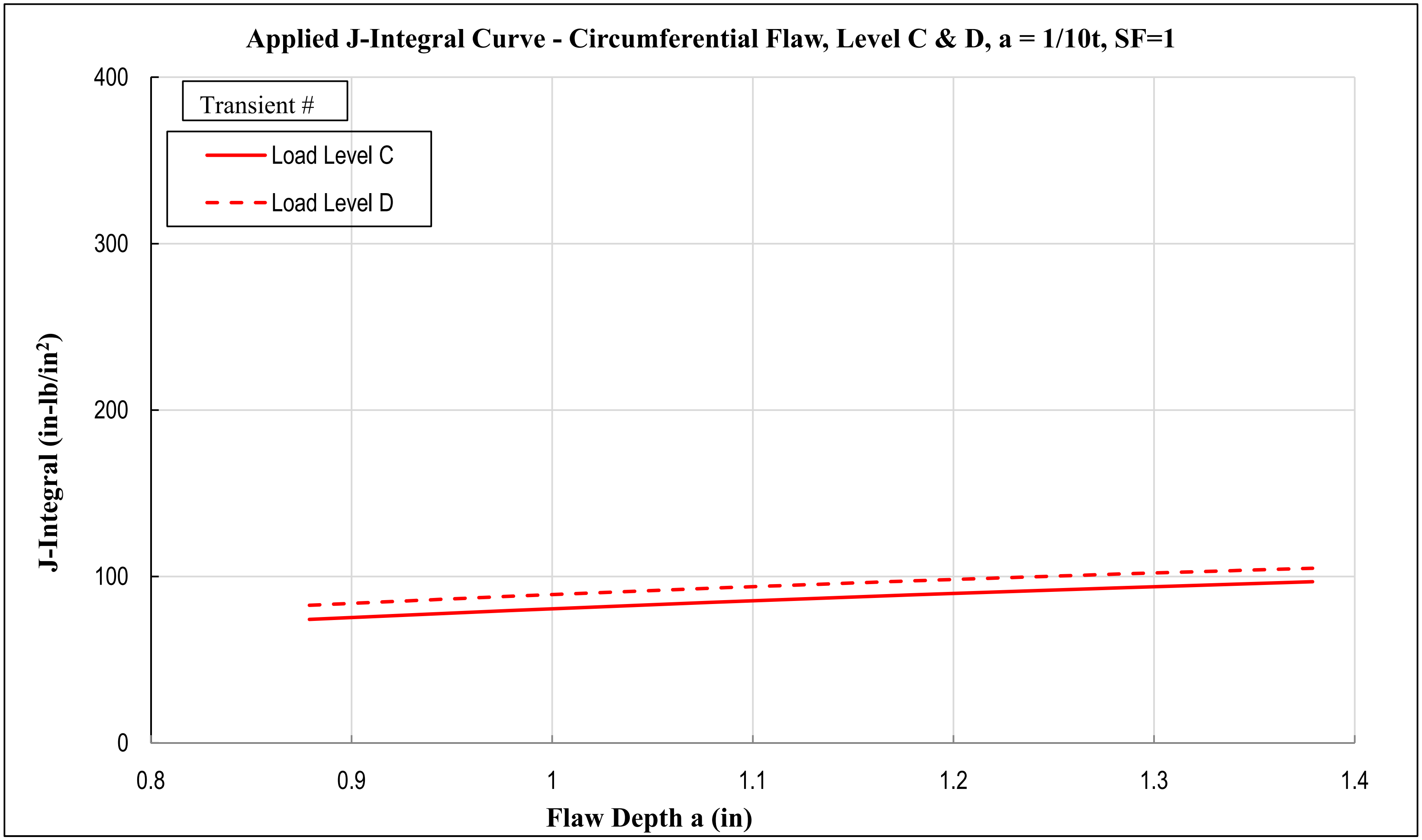

Figure 5-2 Applied J-Integral versus Crack Extension for Circumferential 1/10t Flaw, Levels C and D

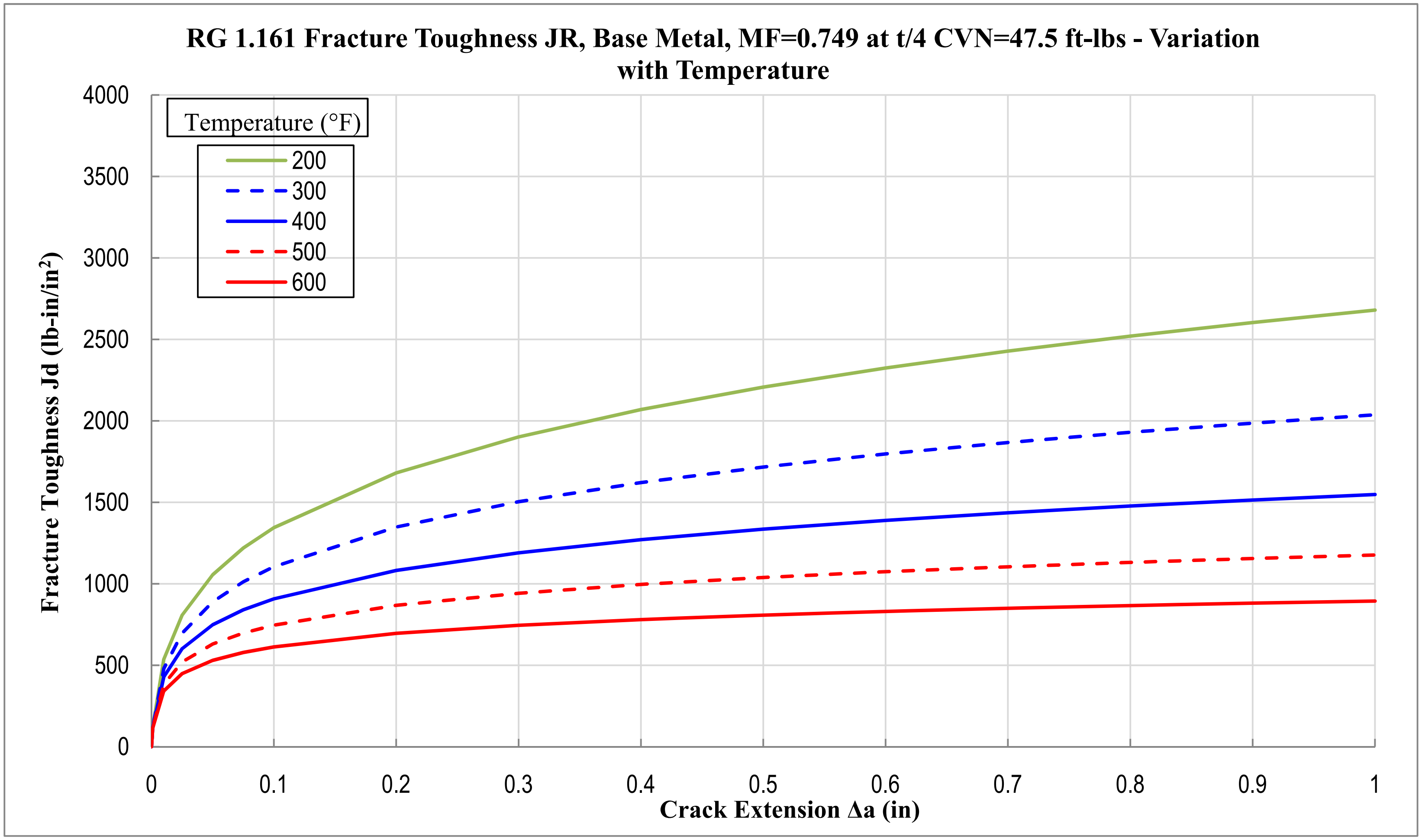

Figure 5-3 Base Metal Fracture Toughness at t/4 CVN = 47.5 ft-lb – Variation with Temperature

Note: JR = J-resistance, CVN = Charpy V-notch

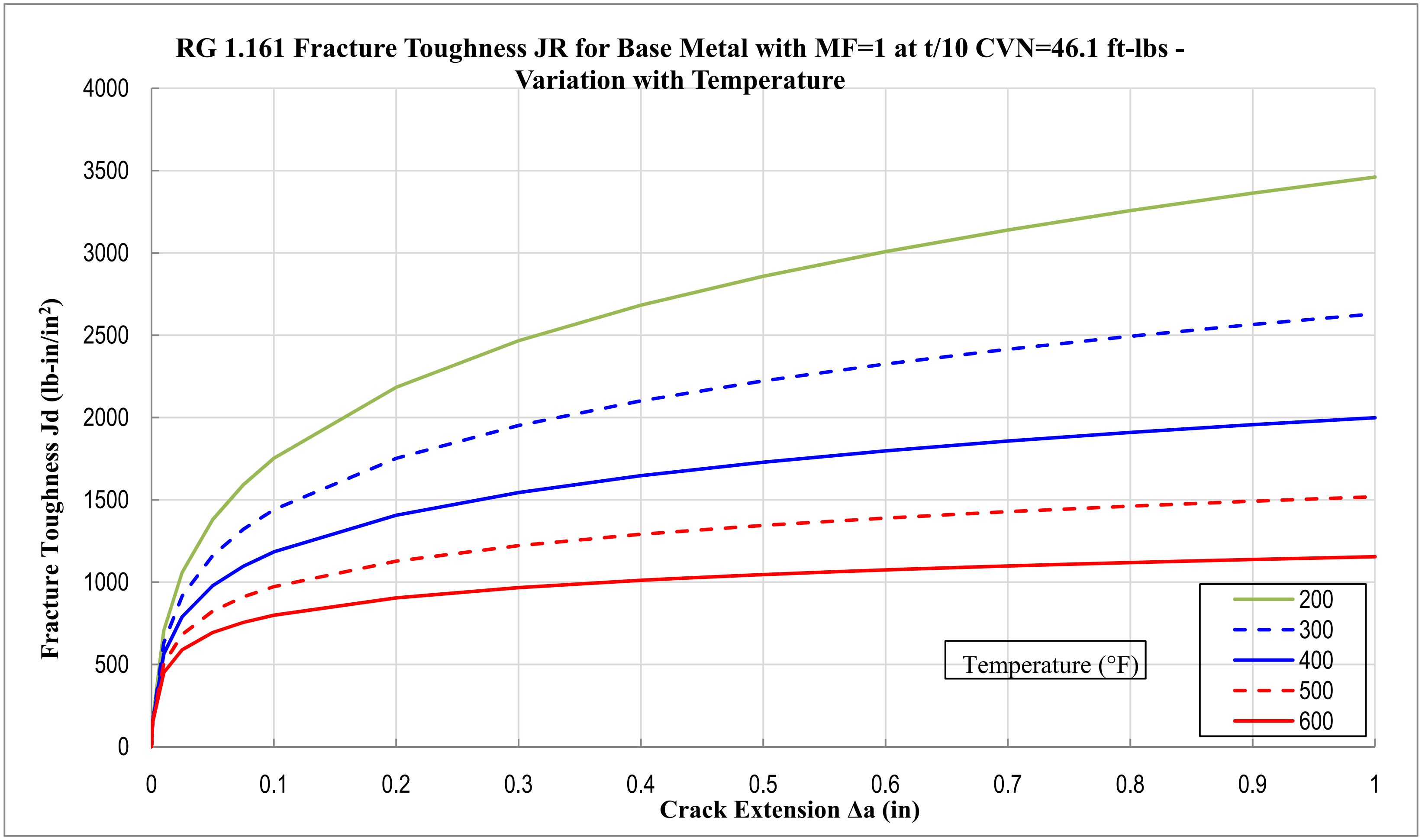

Figure 5-4 Base Metal Fracture Toughness at t/10 CVN = 46.1 ft-lb – Variation with Temperature

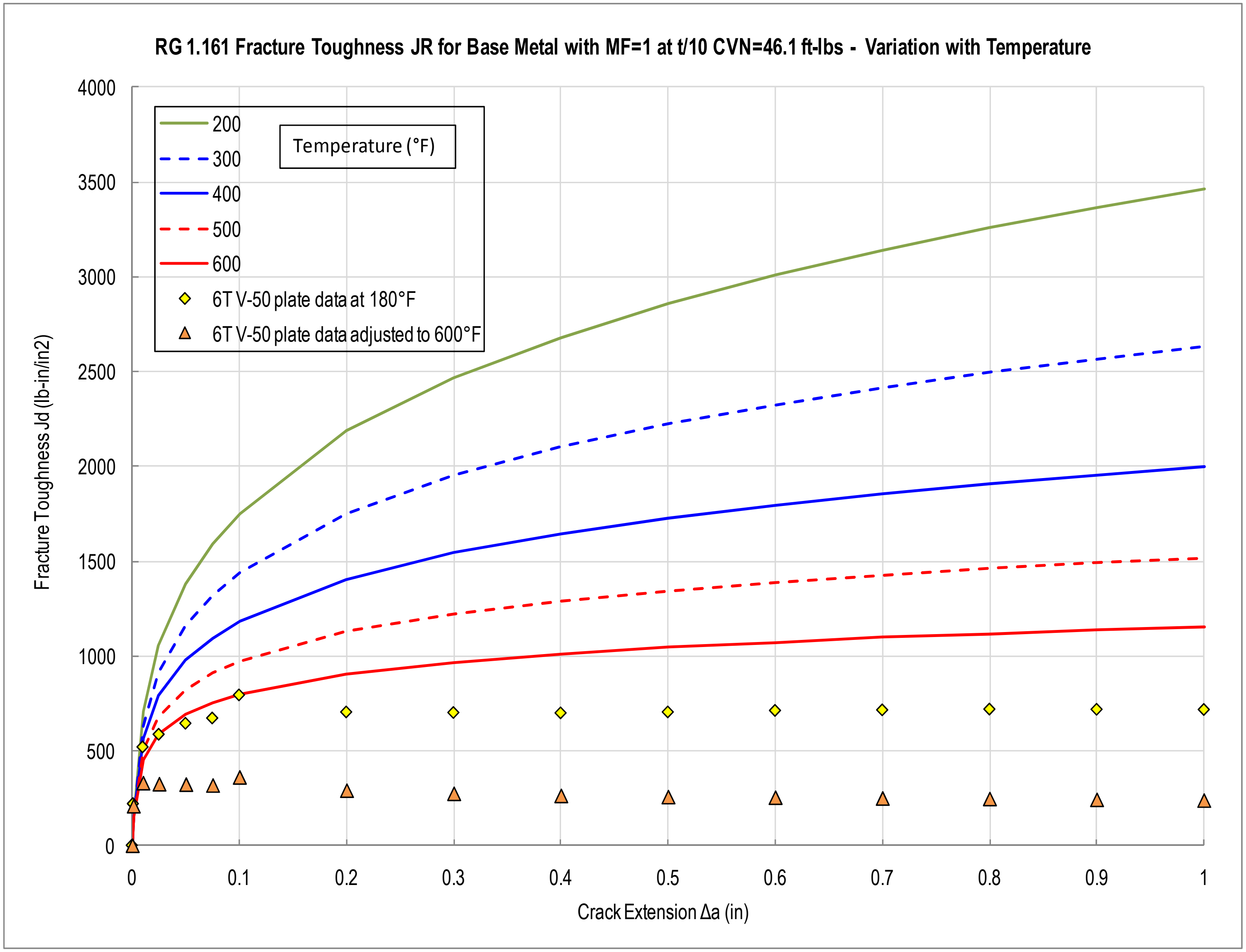

Figure 5-5 Base Metal Fracture Toughness at t/10 CVN = 46.1 ft-lb vs. Measured High-Sulfur V-50 Plate Data – Variation with Temperature

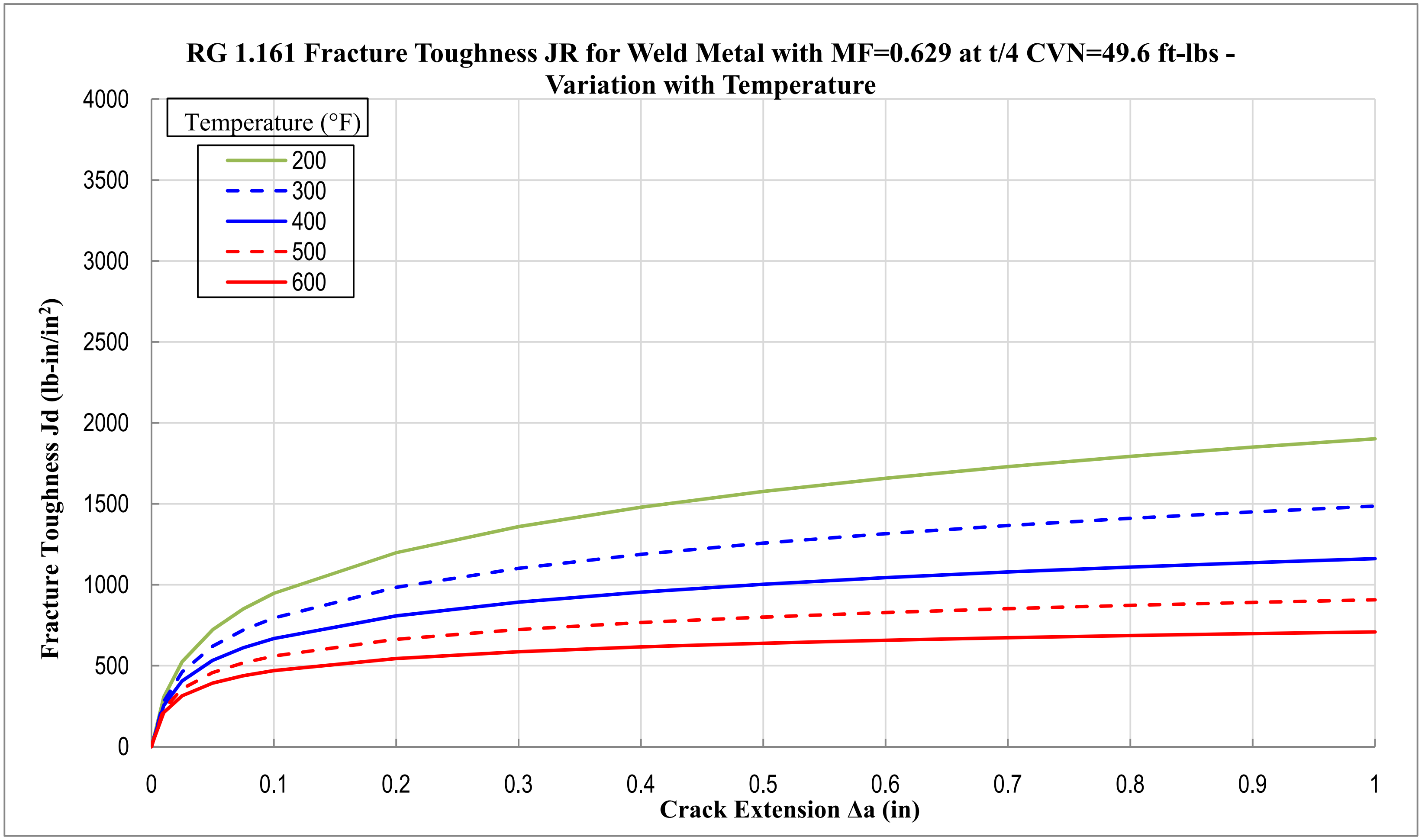

Figure 5-6 Weld Metal Fracture Toughness at t/4 CVN = 49.6 ft-lb – Variation with Temperature

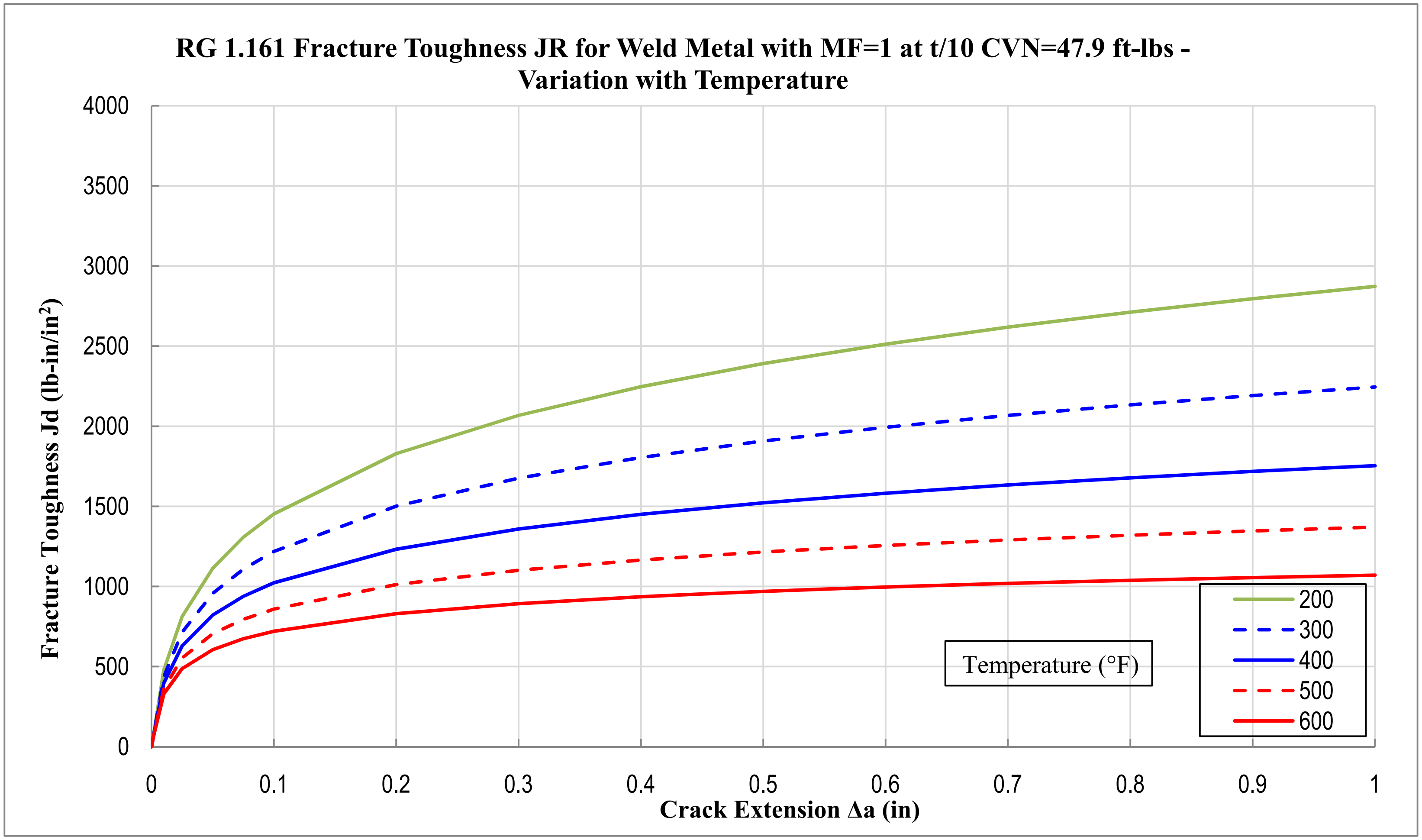

Figure 5-7 Weld Metal Fracture Toughness at t/10 CVN = 47.9 ft-lb – Variation with Temperature

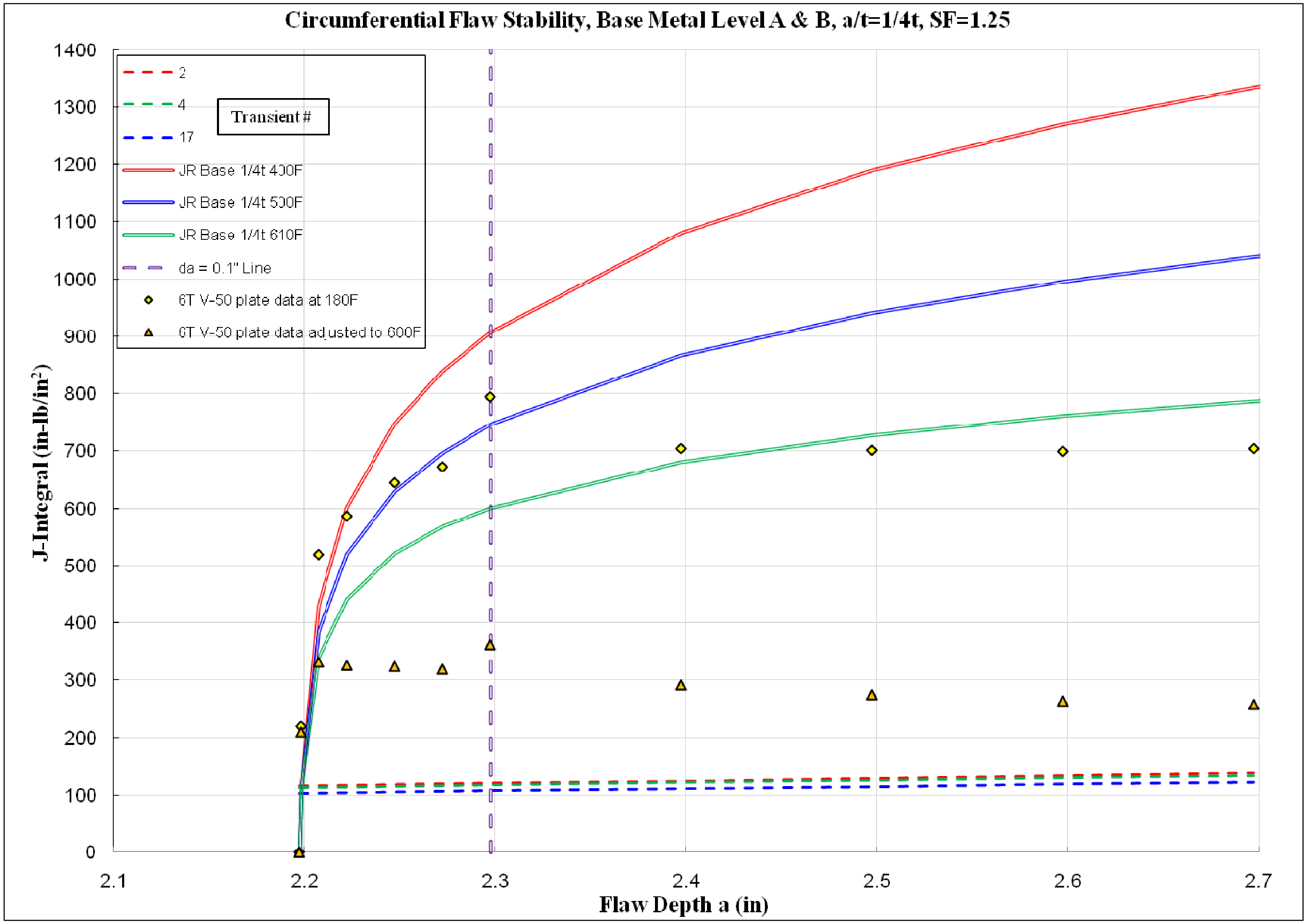

Figure 5-8 **Circumferential Flaw J-Integral versus Crack Extension – t/4, Level A and B, Base Material with Comparison of the Measured High-Sulfur V-50 Plate Data**

Note: The limiting transients 2, 4, and 17 are shown.

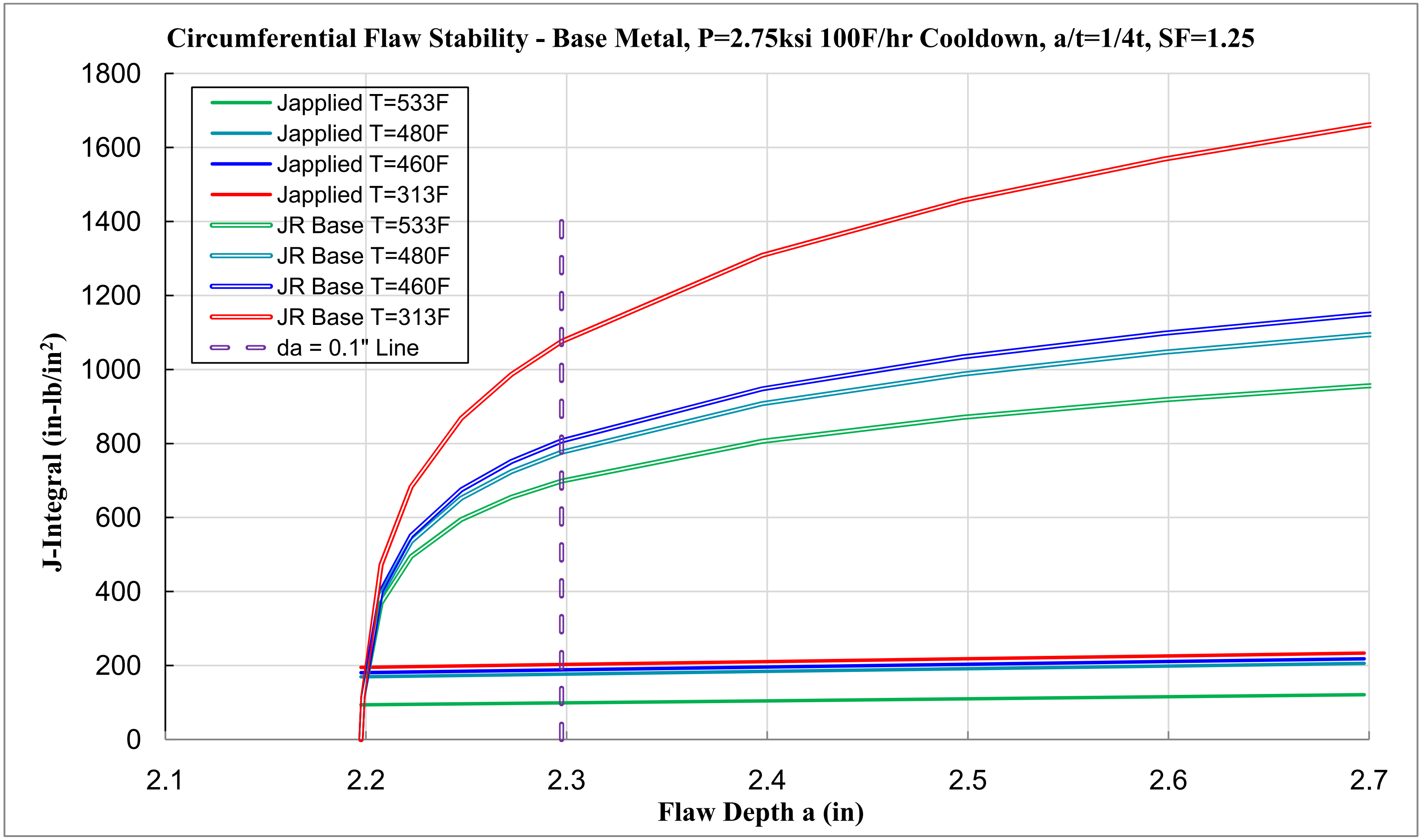

Figure 5-9 Circumferential Flaw J-Integral versus Crack Extension – t/4, P=2.75 ksi 100°F/hr Cooldown, Base Metal

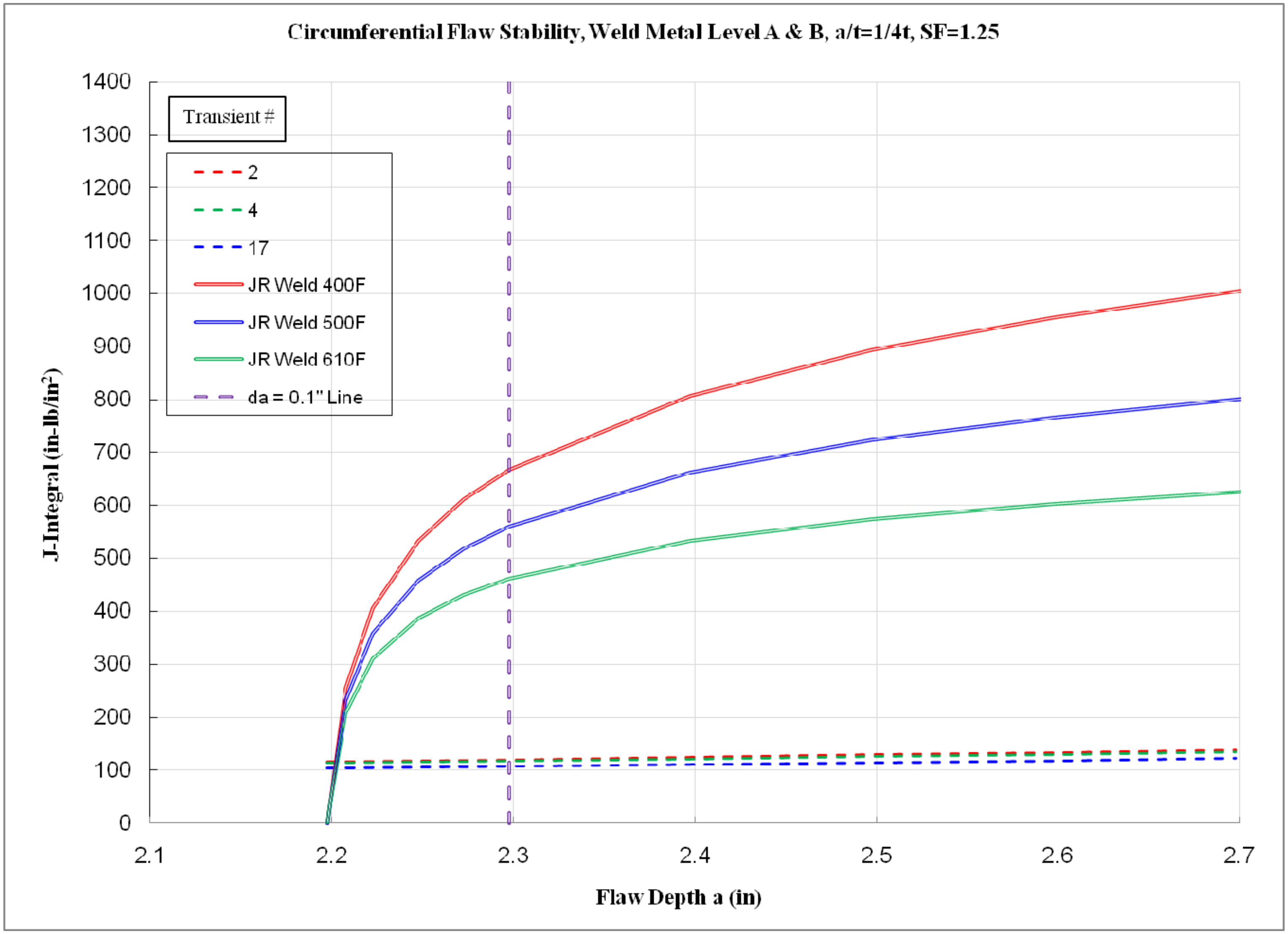

Figure 5-10 Circumferential Flaw J-Integral versus Crack Extension – t/4, Level A and B, Weld Material

Note: The limiting transients 2, 4, and 17 are shown.

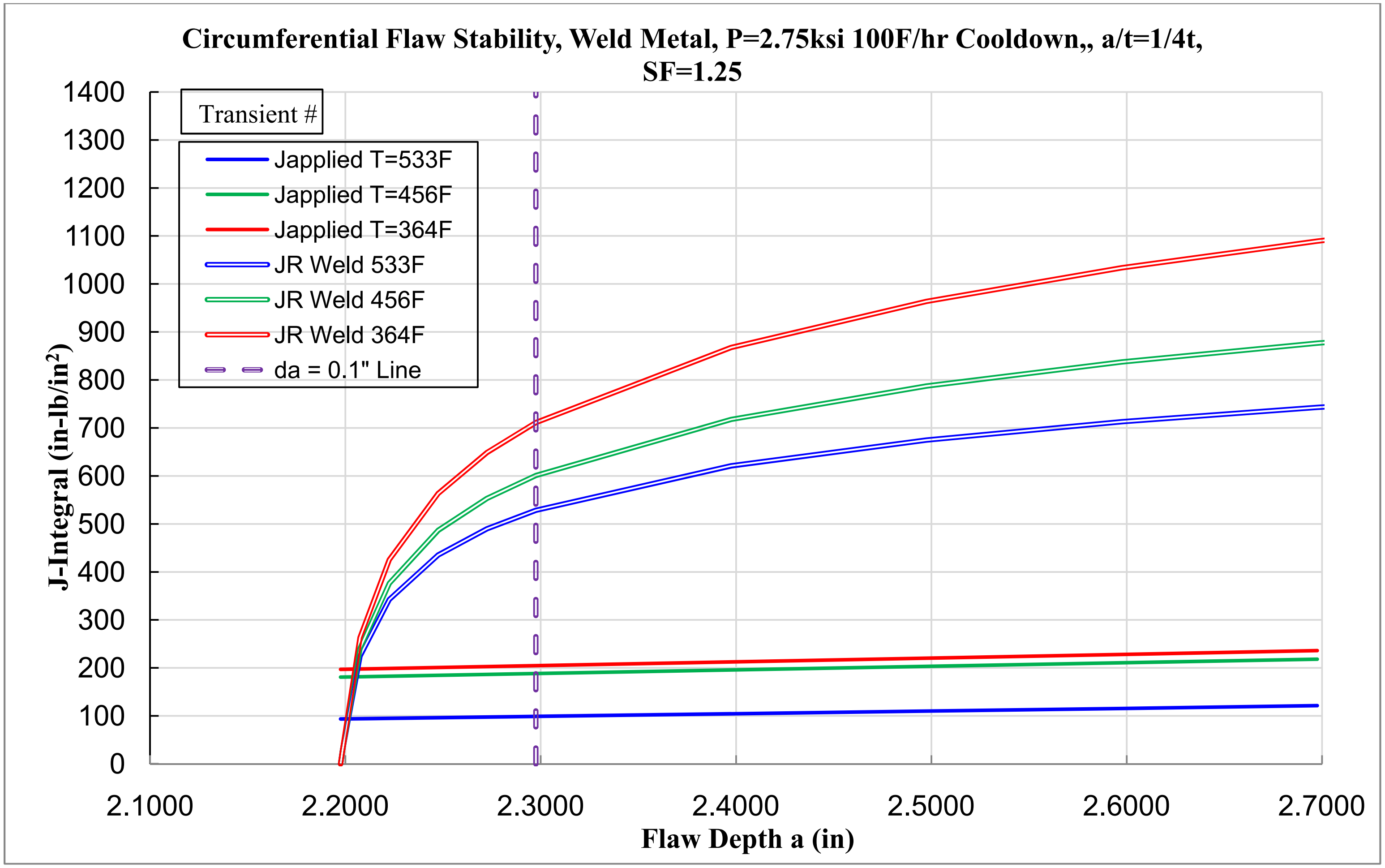

Figure 5-11 Circumferential Flaw J-Integral versus Crack Extension – t/4, P=2.75 ksi 100°F/hr Cooldown, Weld Metal

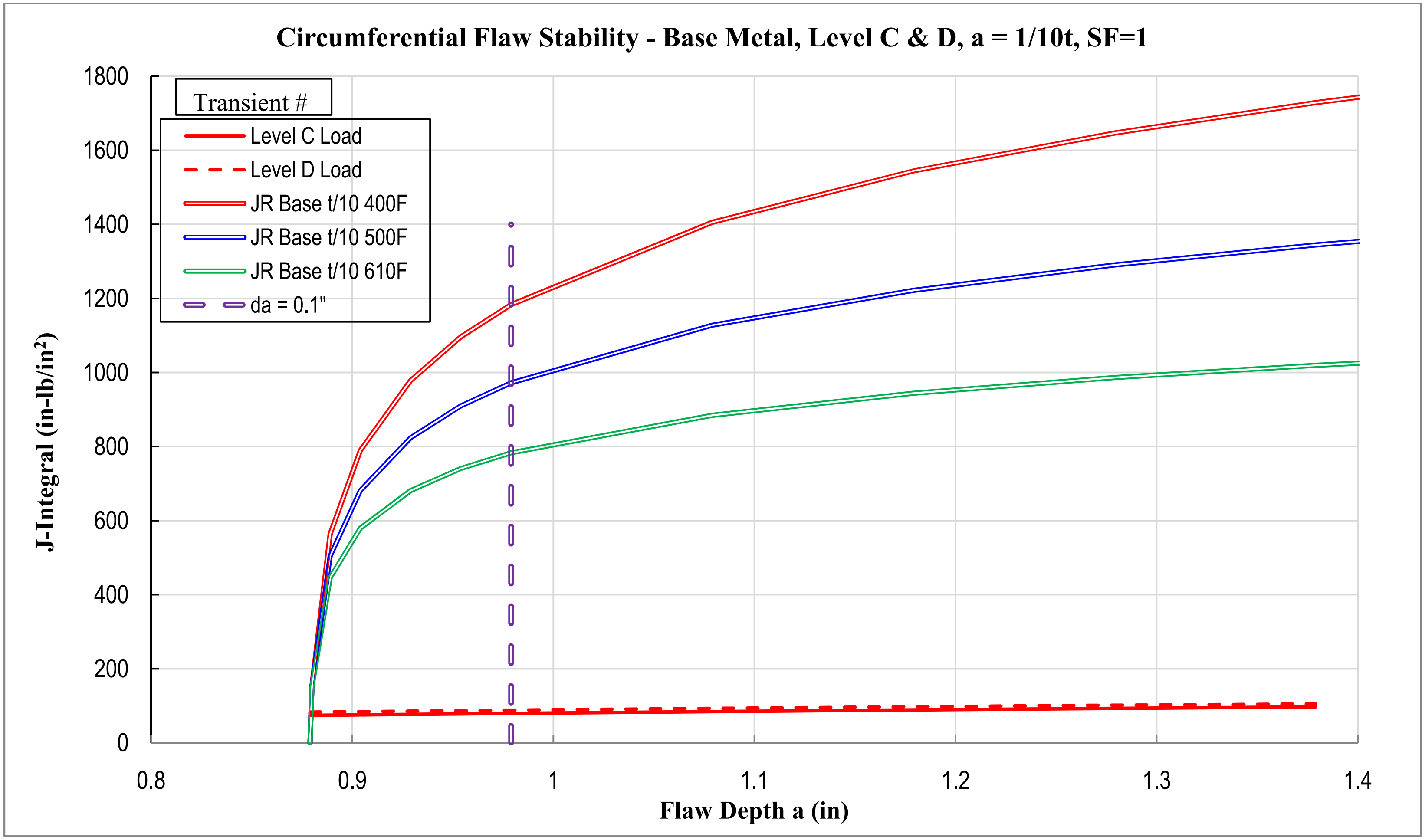

Figure 5-12 Circumferential Flaw J-Integral versus Crack Extension – t/10, Levels C and D, Base Metal

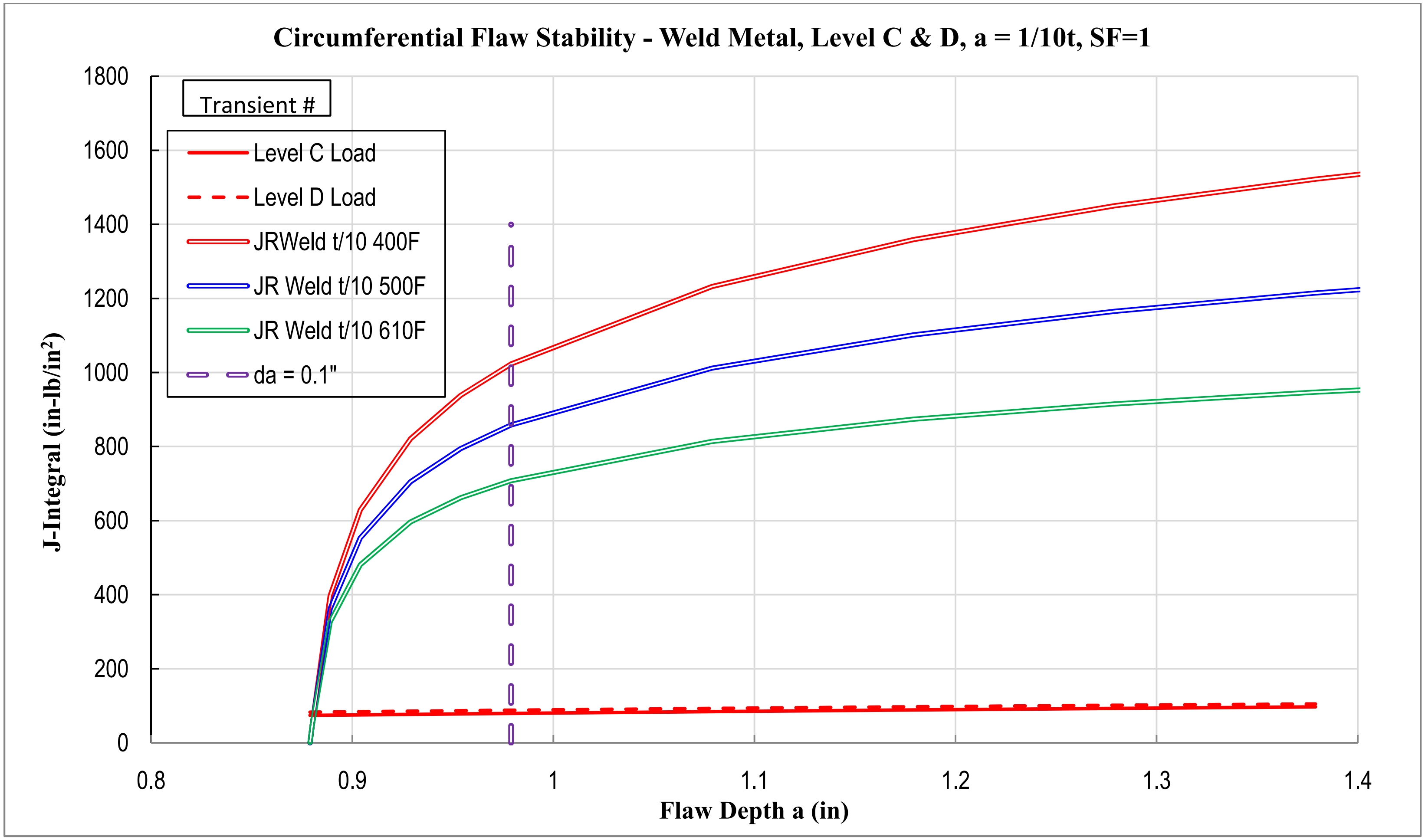

Figure 5-13 Circumferential Flaw J-Integral versus Crack Extension – t/10, Levels C and D Loads, Weld Metal

6 CONCLUSIONS

The Palisades reactor vessel beltline and extended beltline regions with predicted Charpy upper-shelf energy levels falling below 50 ft-lb at the EOLE period were evaluated for equivalent margins of safety per the ASME Code Section XI (References 5, 6, and 18) and found to be acceptable. The minimum structural margin available for the limiting reactor vessel material (intermediate to lower shell circumferential weld 9-112 [Heat #27204]) of 2.490 (circumferential flaws) occurs during a Service Level A and B transient using the toughness model of RG 1.161. The equivalent margins analyses for the plate materials, lower shell plate D-3804-1 and upper shell plate D-3802-3, are bounded by the conservative test data reported in NUREG/CR-5265. Use of the conservative V-50 plate data from NUREG/CR-5265 for the Palisades plate materials with sulfur content greater than the 0.018 wt. % limit specified in Regulatory Guide 1.161 shows that the applied J-integral values are acceptable.

Palisades Plant-Specific EMA Comparison to CE-NPSD-993

CE-NPSD-993, Revision 0 (Reference 17) is a generic Combustion Engineering (CE) EMA that was completed in May 1995 for the Combustion Engineering Owners Group (CEOG). This report summarized that all CE reactor vessel materials with end-of-life USE values below 50 ft-lb would satisfy equivalent margins of safety to ASME Code Section III, Appendix G with consideration of the generic design transients and reactor vessel geometries assumed in that report. Therefore, based on the results of this plant-specific EMA, the results of the CEOG report with consideration of the design transients and vessel geometries for Palisades are confirmed.

Per CE-NPSD-993, the minimum acceptable USE value for plate materials in the longitudinal direction was 30 ft-lb for Level A and B transients. Likewise, for the transverse direction, a value of 19.5 ft-lb was concluded to be the acceptable value for plate materials. On a generic basis, weld materials need to exhibit at least 34 ft-lb for longitudinal welds and 19.5 ft-lb for circumferential welds to provide equivalent margins of safety for Level A and B transients. The minimum acceptable USE values for Level C and D transients were generically determined to be 30 and 19.5 ft-lb for plate materials in the longitudinal and transverse directions, respectively. Weld materials need to exhibit at least 30 ft-lb for longitudinal and circumferential welds to provide equivalent margins of safety for Level C and D transients. For Palisades, the predicted USE in the transverse "weak" direction at EOLE was 47.5 ft-lb for US Plate D-3802-3. The predicted USE does not drop below 50 ft-lb for the longitudinal "strong" direction plate data at EOLE. The predicted USE for intermediate to lower shell circumferential weld 9-112 (Heat #27204) material at EOLE was 49.6 ft-lb.

Service Level A and B Transients

- Intermediate to lower shell circumferential weld 9-112 (Heat #27204) is governing for EOLE USE margin at the 1/4-thickness location for normal Level A and B load conditions, based on the Regulatory Guide 1.161 fracture toughness methodology.

- The applied J-integral values for the assumed 1/4-thickness inside-surface circumferential flaws in the base metal and circumferential flaws in the weld metal with a safety margin of 1.15 on pressure loading are within the material fracture toughness J-resistance at 0.1-inch crack extension.

- The assumed flaw is ductile and stable with crack extension with a safety margin of 1.25 on pressure loading.

- The equivalent margins analyses for the plate materials are acceptable and bounded by the conservative test data reported in NUREG/CR-5265 in all cases for Service Level A and B transients.

Service Level C Condition with 400°F/hr Cooldown Transient

- Intermediate to lower shell circumferential weld 9-112 (Heat #27204) is governing for EOLE USE margin at the 1/10-thickness location for the Service Level C load condition, based on the Regulatory Guide 1.161 fracture toughness methodology.

- The applied J-integral values for the assumed 1/10 base metal thickness inside-surface circumferential flaws in the base metal and circumferential flaws in the weld metal with a safety margin of 1.00 on loading are within the material fracture toughness J-resistance at 0.1-inch crack extension.

- The assumed flaw is ductile and stable with crack extension with a safety margin of 1 on pressure loading.

- The equivalent margins analyses for the plate materials are acceptable and bounded by the conservative test data reported in NUREG/CR-5265 in all cases for the Service Level C transient.

Service Level D Condition with 600°F/hr Cooldown Transient

- Intermediate to lower shell circumferential weld 9-112 (Heat #27204) is governing for EOLE USE margin at the 1/10-thickness location for the Service Level D load condition, based on the Regulatory Guide 1.161 fracture toughness methodology.

- The applied J-integral values for the assumed 1/10 base metal thickness inside-surface circumferential flaws in the base metal and circumferential flaws in the weld metal with a safety margin of 1.00 on loading are within the material fracture toughness J-resistance at 0.1-inch crack extension.

- The total flaw depth after a stable flaw extension is well within 75 percent of the vessel wall thickness, with the remaining ligament stable for crack propagation.

- The equivalent margins analyses for the plate materials are acceptable and bounded by the conservative test data reported in NUREG/CR-5265 in all cases for the Service Level D transient.

7 REFERENCES

1. Westinghouse Report WCAP-17341-NP, Revision 0, "Palisades Nuclear Power Plant Heatup and Cooldown Limit Curves for Normal Operation and Upper-Shelf Energy Evaluation," February 2011.

2. Westinghouse Report WCAP-17403-NP, Revision 1, "Palisades Nuclear Power Plant Extended Beltline Reactor Vessel Integrity Evaluation," January 2013.

3. Code of Federal Regulations, 10 CFR Part 50, Appendix G, "Fracture Toughness Requirements," U.S. Nuclear Regulatory Commission, Washington D.C., Federal Register, Volume 77, No. 14, January 23, 2012.

4. Code of Federal Regulations, 10 CFR Part 50.55a, "Codes and Standards," U.S. Nuclear Regulatory Commission, Washington D.C., Federal Register, Volume 77, No. 14, January 23, 2012.

5. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code, Section XI, Division 1, Appendix K, "Assessment of Reactor Vessels with Low Upper Shelf Charpy Impact Energy Levels," 2007 Edition Up to and Including 2008 Addenda.

6. ASME B&PV Code, Section XI, Division 1, Appendix A, "Analysis of Flaws," 2012 Edition.

7. Regulatory Guide 1.161, "Evaluation of Reactor Pressure Vessels with Charpy Upper-Shelf Energy Less than 50 Ft-Lb," U.S. Nuclear Regulatory Commission, June 1995.

8. ASME B&PV Code, Section II, Part D, "Materials," 2012 Edition.

9. B. R. Ganta, D. J. Ayres, and P. J. Hijeck, "Cladding Stresses in a Pressurized Water Reactor Vessel Following Application of the Stainless Steel Cladding, Heat Treatment and Initial Service," presented at ASME Pressure Vessel and Piping Conference, San Diego, California, June 1991.

10. Westinghouse Design Specification DS-ME-04-10, Revision 3, "Design Specification for a Replacement Reactor Vessel Closure Head (RRVCH) for Palisades Nuclear Generating Station," August 2006.

11. Westinghouse Report WCAP-15353 – Supplement 2 – NP, Revision 0, "Palisades Reactor Pressure Vessel Fluence Evaluation," July 2011.

12. Combustion Engineering Report P-PENG-ER-006, Revision 0, "The Reactor Vessel Group Records Evaluation Program Phase II Final Report for the Palisades Reactor Pressure Vessel Plates, Forgings, Welds and Cladding," Combustion Engineering, Inc., October 1995.

13. Regulatory Guide 1.99, Revision 2, "Radiation Embrittlement of Reactor Vessel Materials," U.S. Nuclear Regulatory Commission, May 1988.

14. "Fracture Toughness Requirements," Branch Technical Position 5-3, Revision 2, Contained in Chapter 5 of Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition, NUREG-0800, March 2007.

15. NUREG/CR-5265, "Size Effects on J-R Curves for A 302-B Plate," U.S. Nuclear Regulatory Commission, January 1989.

16. NUREG/CR-6426, Volumes 1 and 2, "Ductile Fracture Toughness of Modified A 302 Grade B Plate Materials, Data Analysis," U.S. Nuclear Regulatory Commission, January and February 1997.

17. Combustion Engineering Report CE-NPSD-993, Revision 0, "Evaluation of Low Upper Shelf Energy for Reactor Vessel Beltline Weld and Base Metal Materials for Combustion Engineering Nuclear Steam Supply Systems Reactor Pressure Vessels," CEOG Task 821, C-E Owners Group, May 1995.

18. ASME B&PV Code, Section XI, Division 1, Appendix G, "Fracture Toughness Criteria for Protection Against Failure," 1998 Edition Up to and Including 2000 Addenda.