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NRC Work on Thermal Aging (TA) Embrittlement of Austenitic Stainless Steel Weld (ASSW) and Cast Austentic Stainless Steel (CASS)

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Overview

- This work is part of KM activities within RES to review the tech basis for LTO aging management based on best available data and is not related to OE.
- NRC is investigating TA of duplex steels, ASSWs covered by recently issued technical letter report, TLR-RES/DE-2023-14-Rev. 0, “Assessment of Thermal Aging Embrittlement of Austenitic Stainless Steel Weld Metals” (ML24180A123)
- CASS covered by separate TLR that is in review.
- The NRC work focused on TA effects on fracture toughness but also looked at TA effects on tensile properties.
- These efforts include an assessment of the Section XI, Appendix C flaw evaluation procedures with respect to TA.

Definition: Thermal Aging Embrittlement

- **Location:** Occurs only in the ferritic phase within the dual phase structure.
- **The Mechanism:** This ***diffusion-controlled*** phenomenon is often referred to as "475°C embrittlement" because the decomposition kinetics are highest there.
- **Microstructural Change:** It is characterized by the ***spinodal decomposition*** of the ferritic phase into two separate BCC phases: one that is chromium-rich and a separate iron-rich one.
- **Secondary Phase Precipitation:** Further, G-phase precipitation—a complex silicide containing Ni, Mo, and Si—can occur in the ferrite, adding to the hardening effect.

Mechanical Property Data

- NUREG/CR-6428, Rev. 1 (2018) (NUREG) contains the most comprehensive compilation of TA effects on ASSW FT data.
- NUREG/CR-4513, Rev. 2 w/ errata issued on 3/15/21 (2018) covers TA of CASS.
- Tensile and J-R curves for TA materials were supplemented by more recent results and data from MHI (Hojo, 2014) and recent results from the literature.
- The results are mainly from testing in air.

NUREG-2191, Rev. 1, Vol. 2, XI.M12 for CASS in PWRs

- Uses a screening process to determine those heats that are potentially susceptible to TE.
- Potentially susceptible heats require augmented inspections. Alternatively, a flaw tolerance evaluation, using specific geometry, stress information, material properties, and ASME Code, Section XI can be used to demonstrate adequate toughness.
- NUREG/CR–4513, Rev. 2 with errata provides methods for predicting the FT of aged CASS materials with delta ferrite content up to 40%.

Screening Process in XI.M12 from NUREG/CR-4513 Rev. 2

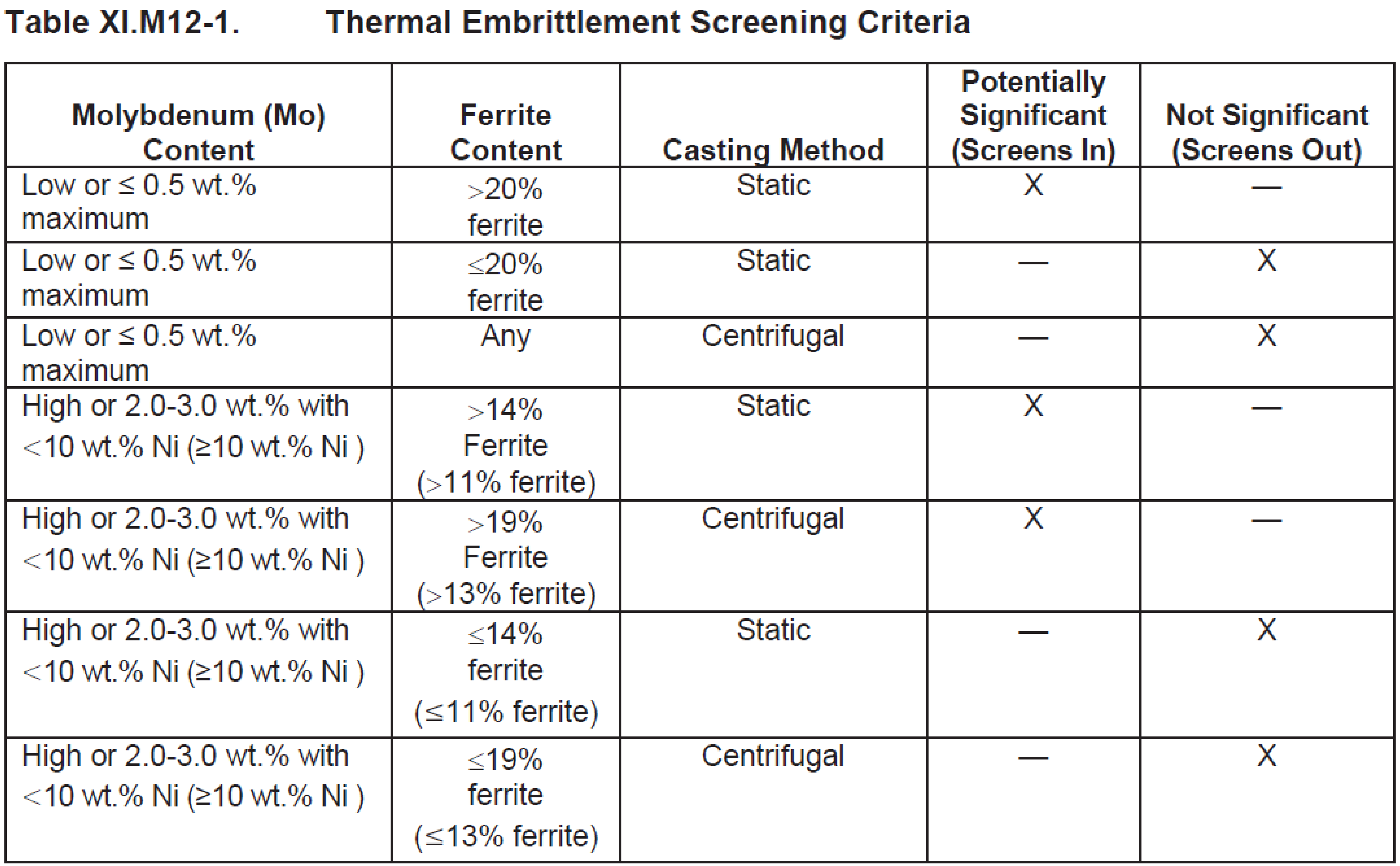
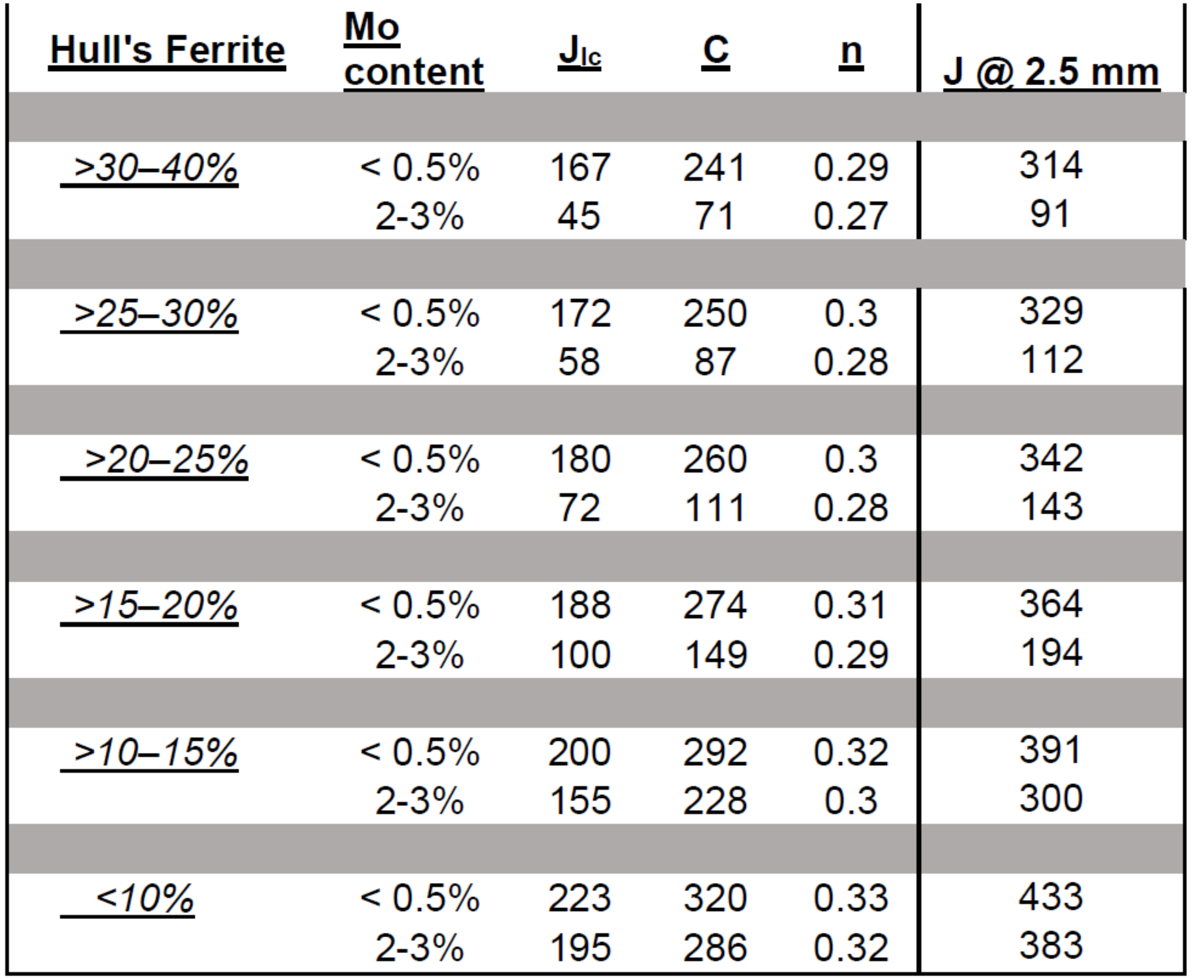


Table XI.M12-1. Thermal Embrittlement Screening Criteria

Molybdenum (Mo) Content	Ferrite Content	Casting Method	Potentially Significant (Screens In)	Not Significant (Screens Out)
Low or ≤ 0.5 wt.% maximum	>20% ferrite	Static	X	—
Low or ≤ 0.5 wt.% maximum	≤20% ferrite	Static	—	X
Low or ≤ 0.5 wt.% maximum	Any	Centrifugal	—	X
High or 2.0-3.0 wt.% with <10 wt.% Ni (≥10 wt.% Ni)	>14% Ferrite (>11% ferrite)	Static	X	—
High or 2.0-3.0 wt.% with <10 wt.% Ni (≥10 wt.% Ni)	>19% Ferrite (>13% ferrite)	Centrifugal	X	—
High or 2.0-3.0 wt.% with <10 wt.% Ni (≥10 wt.% Ni)	≤14% ferrite (≤11% ferrite)	Static	—	X
High or 2.0-3.0 wt.% with <10 wt.% Ni (≥10 wt.% Ni)	≤19% ferrite (≤13% ferrite)	Centrifugal	—	X

Screens in if J @ 2.5 mm < 255 kJ/m^2

Estimated L-B FT based on NUREG/CR-4513 Rev. 2 at operating temperatures



Hull's Ferrite	Mo content	J_{Ic}	C	n	J @ 2.5 mm
>30–40%	< 0.5%	167	241	0.29	314
	2-3%	45	71	0.27	91
>25–30%	< 0.5%	172	250	0.3	329
	2-3%	58	87	0.28	112
>20–25%	< 0.5%	180	260	0.3	342
	2-3%	72	111	0.28	143
>15–20%	< 0.5%	188	274	0.31	364
	2-3%	100	149	0.29	194
>10–15%	< 0.5%	200	292	0.32	391
	2-3%	155	228	0.3	300
<10%	< 0.5%	223	320	0.33	433
	2-3%	195	286	0.32	383

Low Moly < 40% ferrite
J @ 2.5 > 255 kJ/m^2

J_{ic} based on nominal flow stress

Effect of Aging Time and Temperature

- Aging parameter “P” establishes equivalency of different aging times/temperatures:

$$P = \log(t) - \frac{1000Q}{19.143}\left(\frac{1}{T_s+273} - \frac{1}{673}\right)$$

$$t = time\ (hours)$$

$$Q = activation\ energy\ \left(\frac{kJ}{mol}\right)$$

$$T_s\ = aging\ temperature\ (°C)$$

- Most accelerated laboratory aging is at 400 °C for 10k hours, P=4.
- This is equivalent to 54 EFPY at 290 °C (assuming Q of 113 kJ/mol)
- Aging representative of 54 or 72 EFPY at PWR hot leg or pressurizer temperatures requires longer aging, higher P.

Methodology presented in NUREG/CR-4513, Rev. 2 is applicable to service times that are equivalent to 10,000 h at 400°C (P=4) . This corresponds to:

- ≤* 125 EFPY at 290°C for CF-8/CF-3 materials, and

- ≤ 30 EFPY at 320°C for CF-8/CF-3 and ≤15 EFPY for CF-8M materials used within primary pressure boundary components, and

- ≤ 15 EFPY at 350°C for CF-8/CF-3 materials used in the reactor core internals.

The methodology is not applicable for 2 of 3 cases shown above.

*NUREG/CR-4513, Rev. 2 before errata has these ≤ signs as ≥; corrected by errata

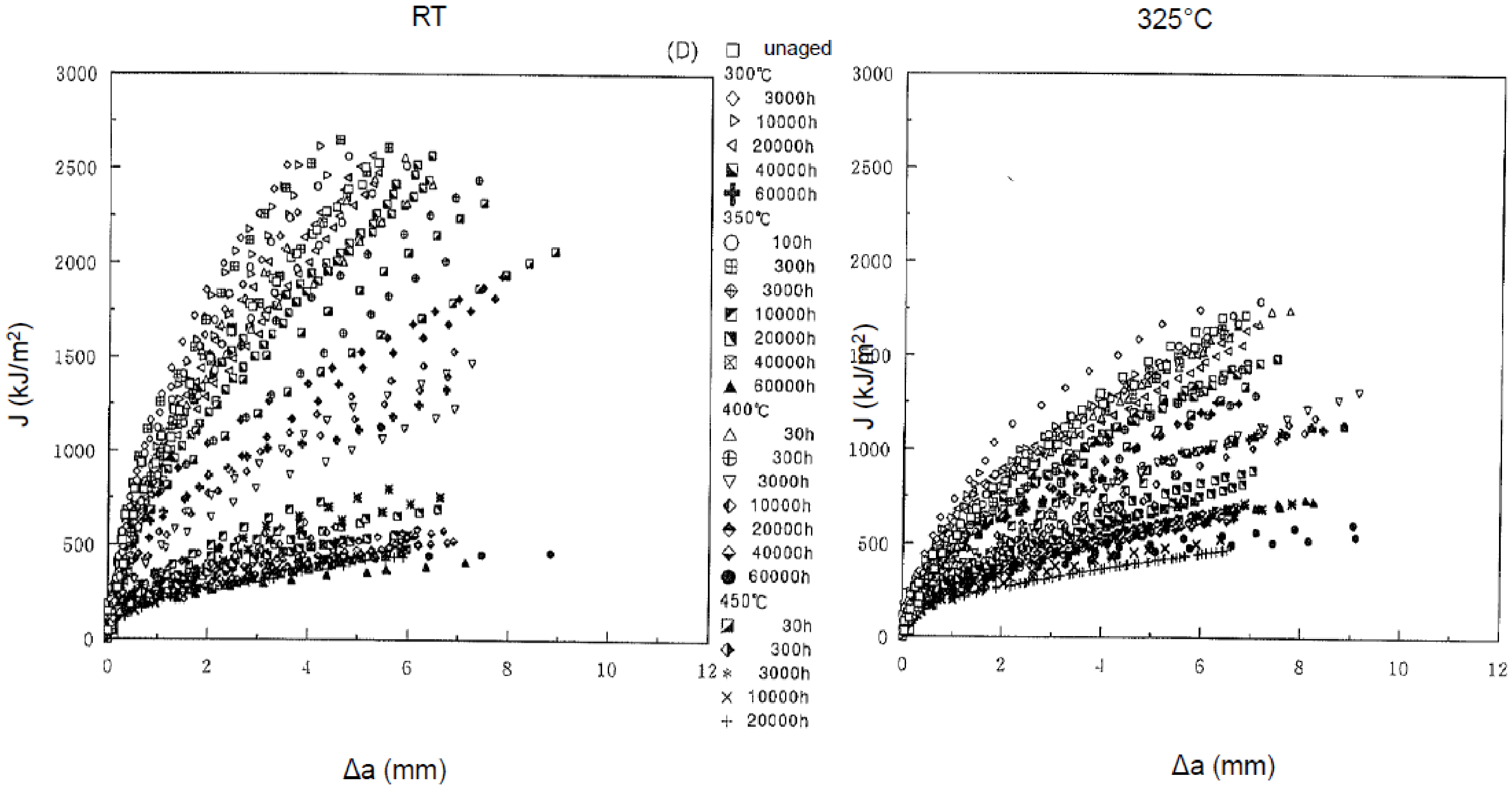
Equivalent Accelerated Aging Times at 400 °C for Various Service Temperatures and EFPY
Activation Energy = 113 kJ/mol

Service Temp.	Piping Type	EFPY	Service Time (hr)	P	Accelerated Aging Time (hr)
290	BWR, PWR CL	54	473040	3.96	9145
320	PWR HL	54	473040	4.49	31018
343	PWR PZR	54	473040	4.86	72994
290	BWR, PWR CL	72	630720	4.09	12193
320	PWR HL	72	630720	4.62	41357
343	PWR PZR	72	630720	4.99	97325

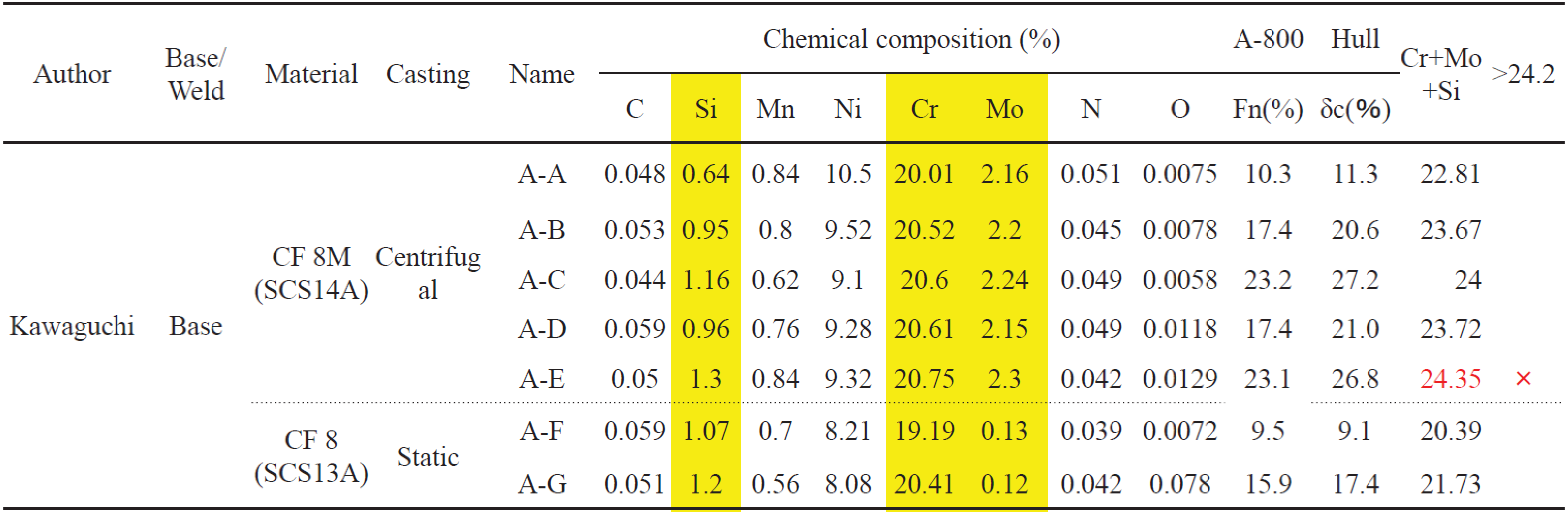
The Japanese methodology assumes Q = 100 kJ/mol.

Supplement data in the NUREGs with results from Japanese PWROG.

Data was presented to ASME WG on pipe flaw evaluation, Aug. 18, 2014 by Kiminobu Hojo. Tensile and full J-R curves at RT & 325°C, 4 aging temperatures, 5 to 7 aging times (P max of 4.9), duplicate tests.



From Hojo November 2014 presentation; CASS data from Kawaguchi plus 3 welds



Author	Base/ Weld	Material	Casting	Name	Chemical composition (%)								A-800	Hull	Cr+Mo +Si	>24.2
					C	Si	Mn	Ni	Cr	Mo	N	O	Fn(%)	δc(%)		
Kawaguchi	Base	CF 8M (SCS14A)	Centrifugal	A-A	0.048	0.64	0.84	10.5	20.01	2.16	0.051	0.0075	10.3	11.3	22.81	
				A-B	0.053	0.95	0.8	9.52	20.52	2.2	0.045	0.0078	17.4	20.6	23.67	
				A-C	0.044	1.16	0.62	9.1	20.6	2.24	0.049	0.0058	23.2	27.2	24	
				A-D	0.059	0.96	0.76	9.28	20.61	2.15	0.049	0.0118	17.4	21.0	23.72	
				A-E	0.05	1.3	0.84	9.32	20.75	2.3	0.042	0.0129	23.1	26.8	24.35	×
		CF 8 (SCS13A)	Static	A-F	0.059	1.07	0.7	8.21	19.19	0.13	0.039	0.0072	9.5	9.1	20.39	
				A-G	0.051	1.2	0.56	8.08	20.41	0.12	0.042	0.078	15.9	17.4	21.73	

Focus on A-C and A-E, Both centrifugal cast, CF-8M with ~25% ferrite

Large database of mechanical properties available to assess the effects of TA

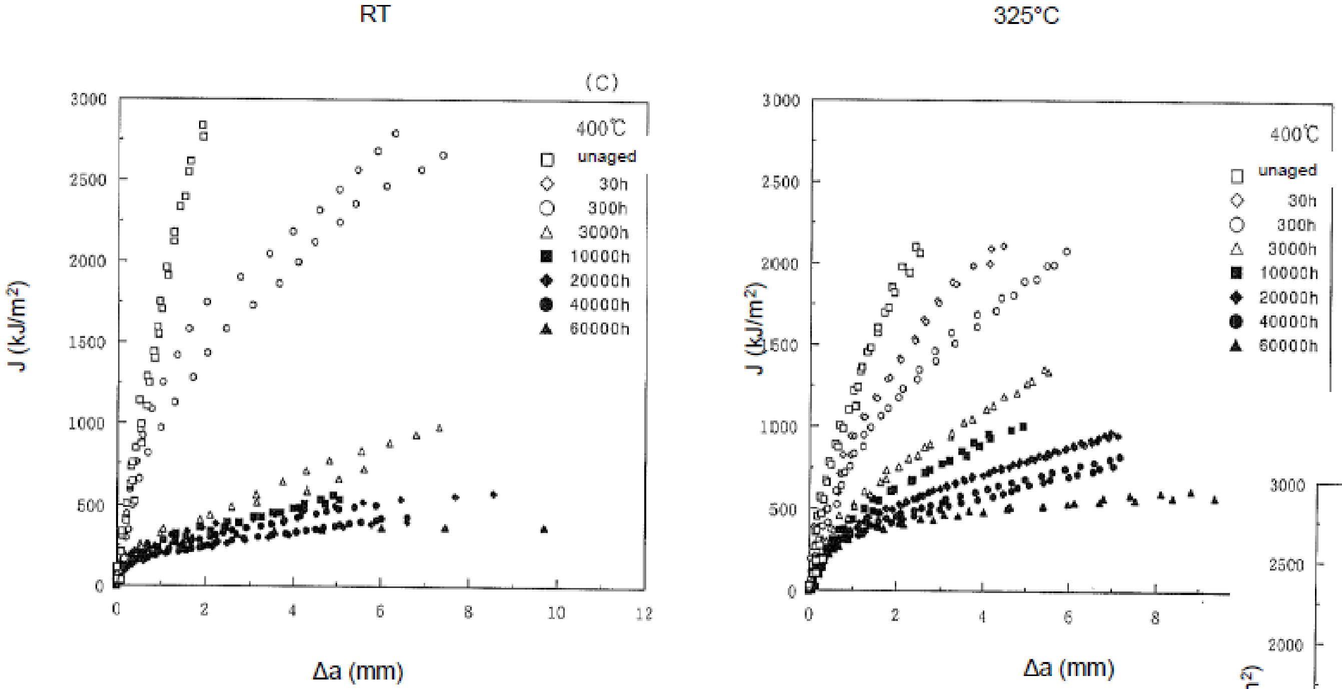


Fig. 2.21 J-Δa (Aging temp. 400°C, CF8M, EF+AOD, δ_c=23.1%)

A-C

A-E

Aging for 60,000 hrs @ 400 deg C
Is equivalent to P of 4.8

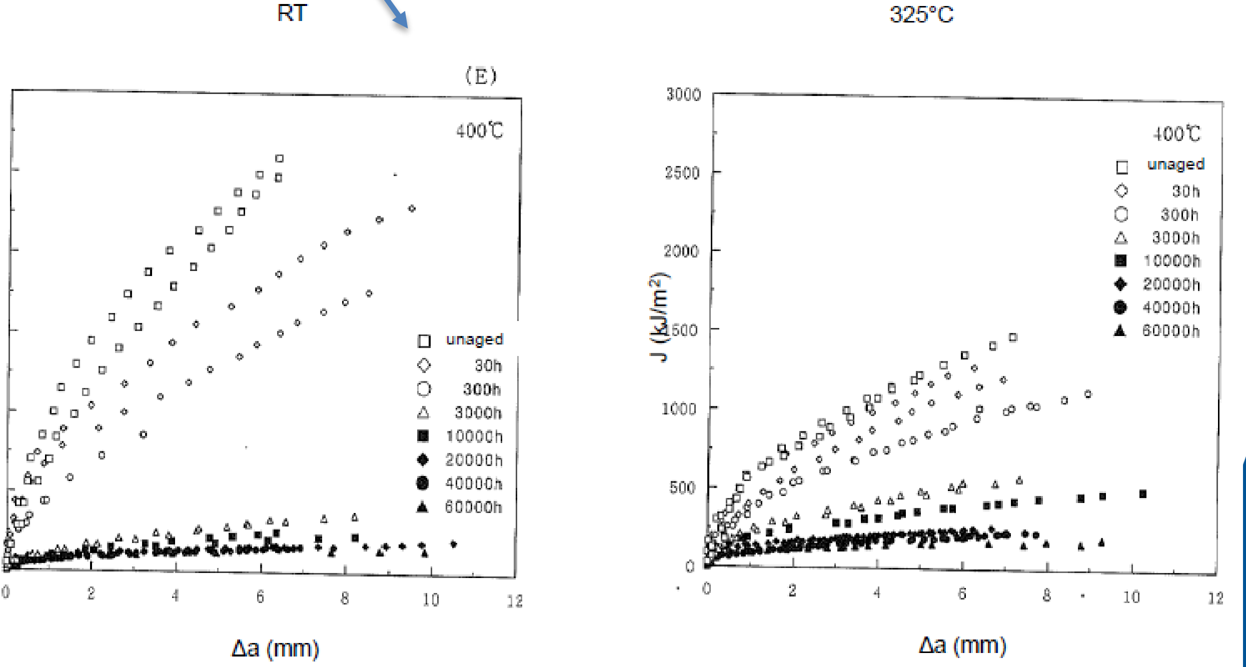
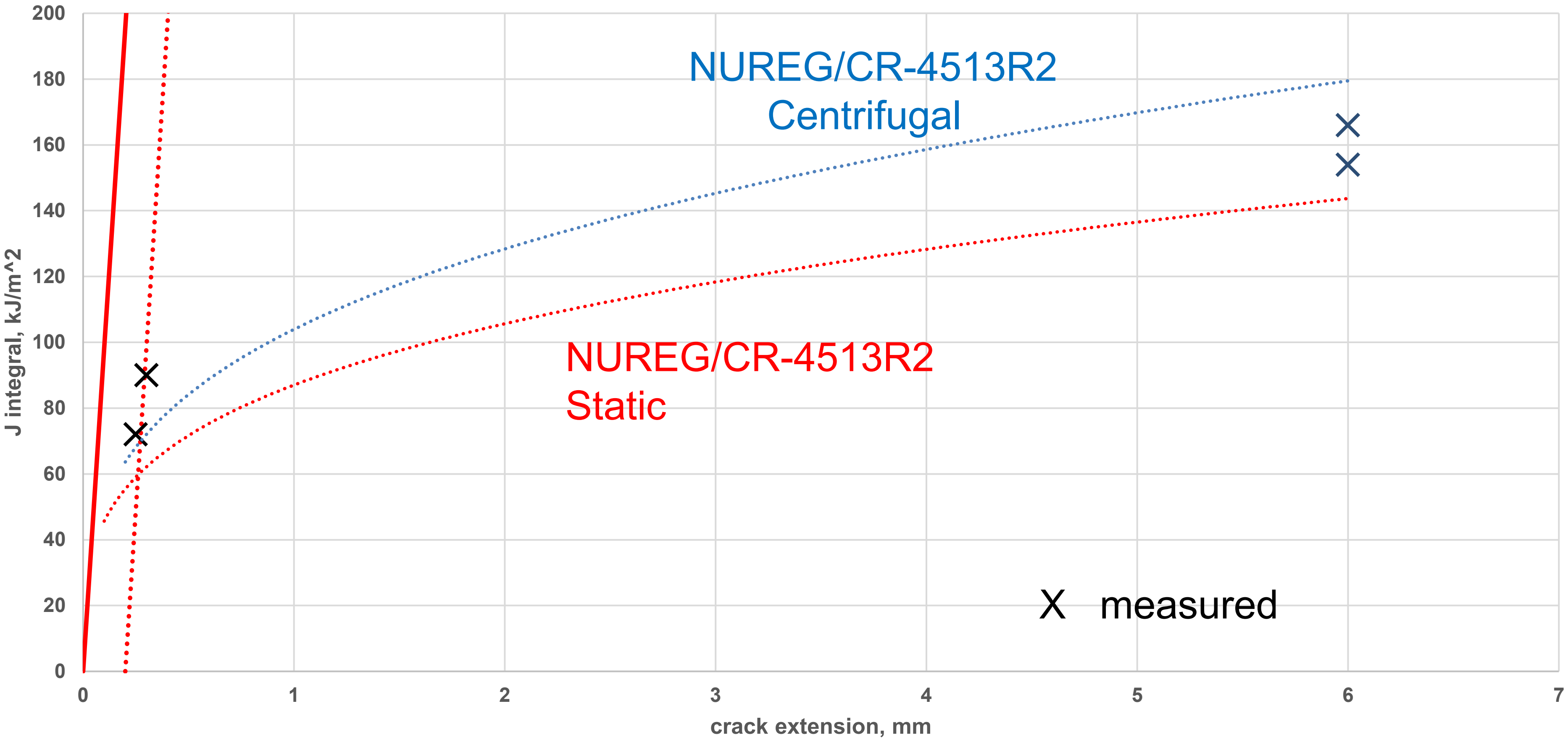


Fig. 2.29 J-Δa (Aging temp. 400°C, CF8M, EF, δ_c=23.0%)

Hojo alloy A-E CF-8M 25-30% ferrite Hull's method



tests at 325 deg C
P=4.8

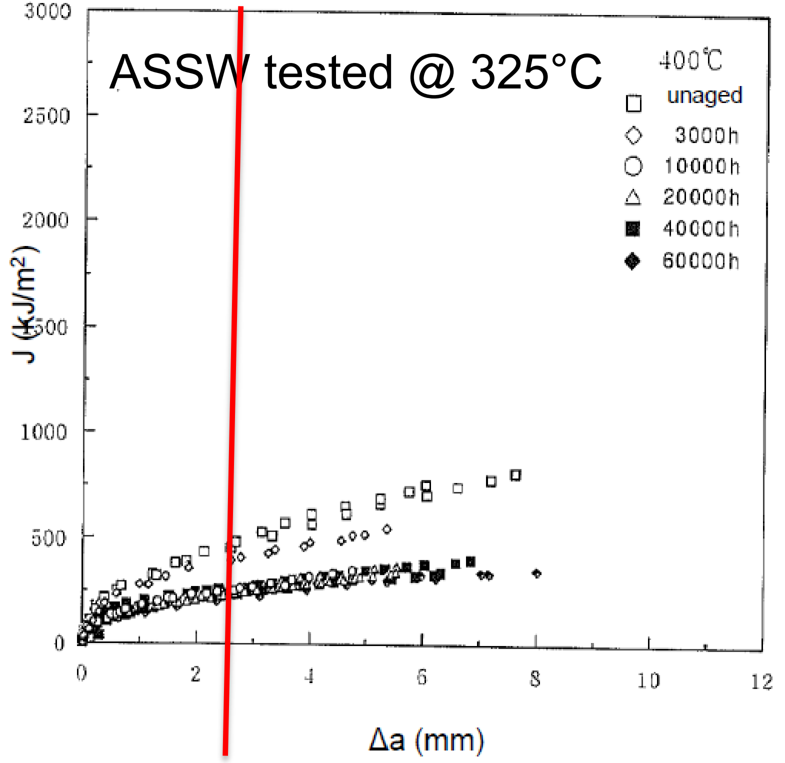


Fig. 2.45 J-Δa (Aging temp. 400°C, 308L, SMAW, δc=9%)

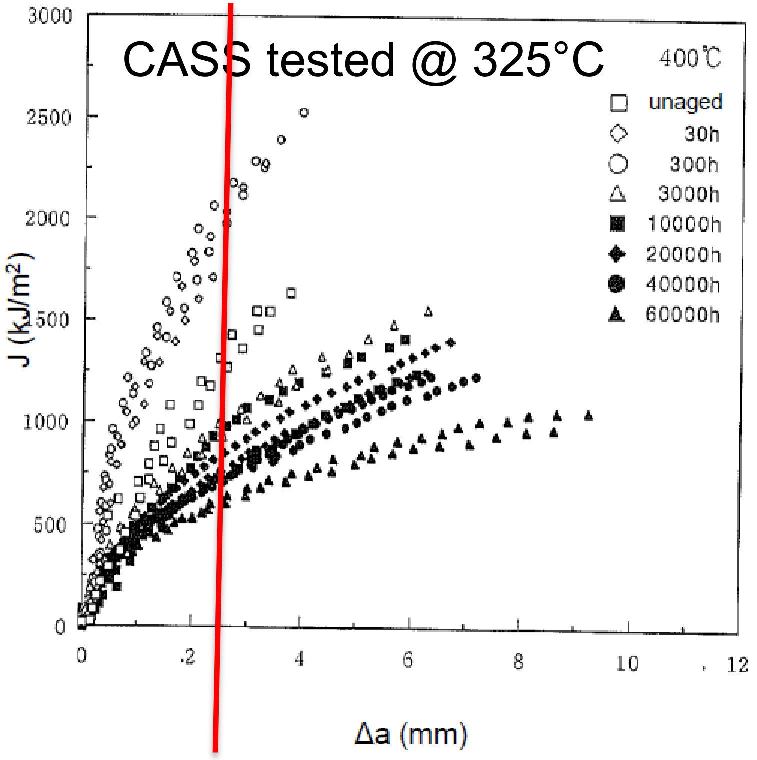


Fig. 2.13 J-Δa (Aging temp. 400°C, CF8M, EF+AOD, δc=10.3%)

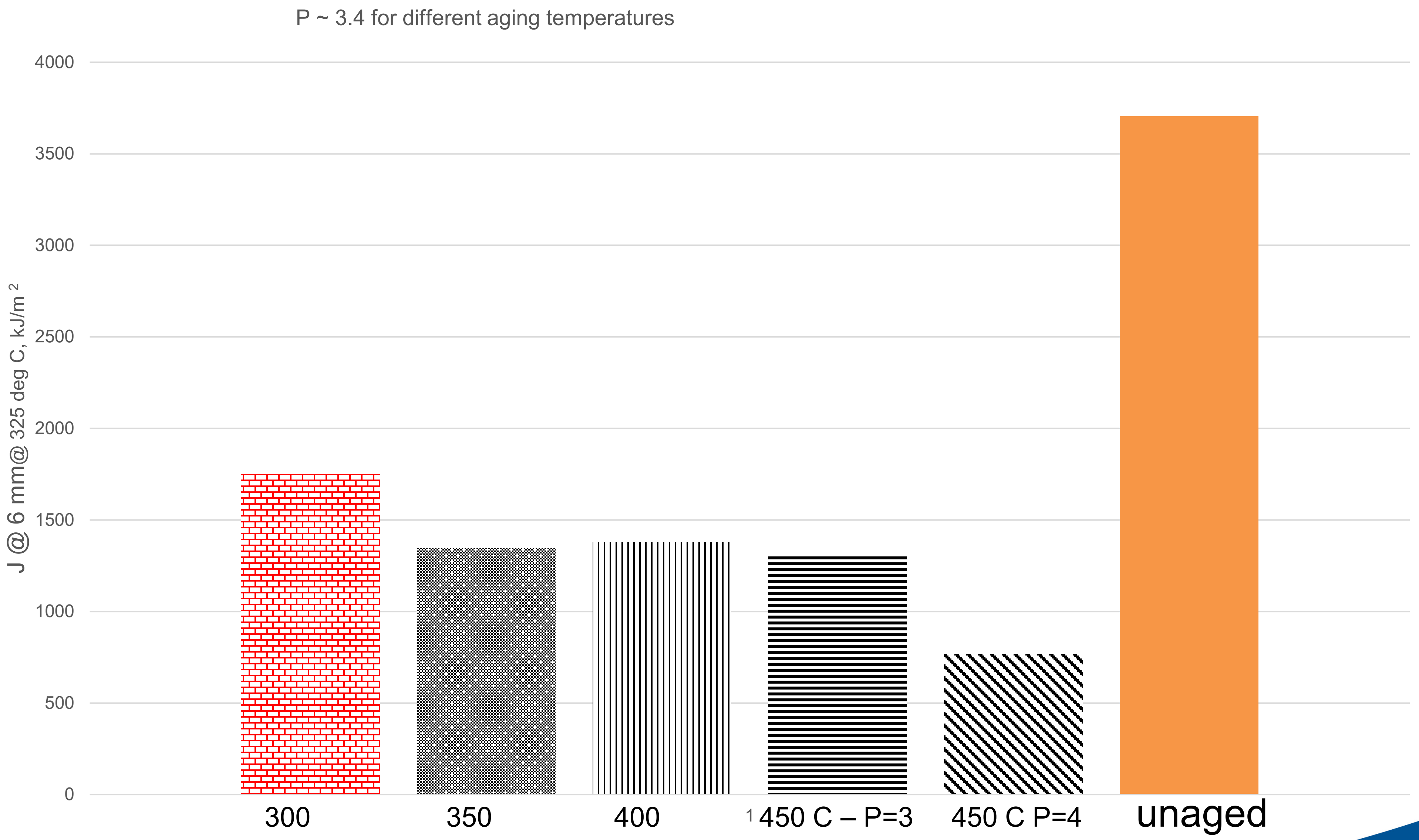
Unaged: YS ~ 350 Mpa
UTS ~ 480
J_{Ic} = 235 kJ/m^2
J@6 = 720

P of 4.8: YS = 368 MPa
UTS = 505
J_{Ic} = 105 kJ/m^2
J@6 = 316

Unaged: YS = 160 MPa
UTS = 450
J_{Ic} = 1200 kJ/m^2
J@6 > 2400

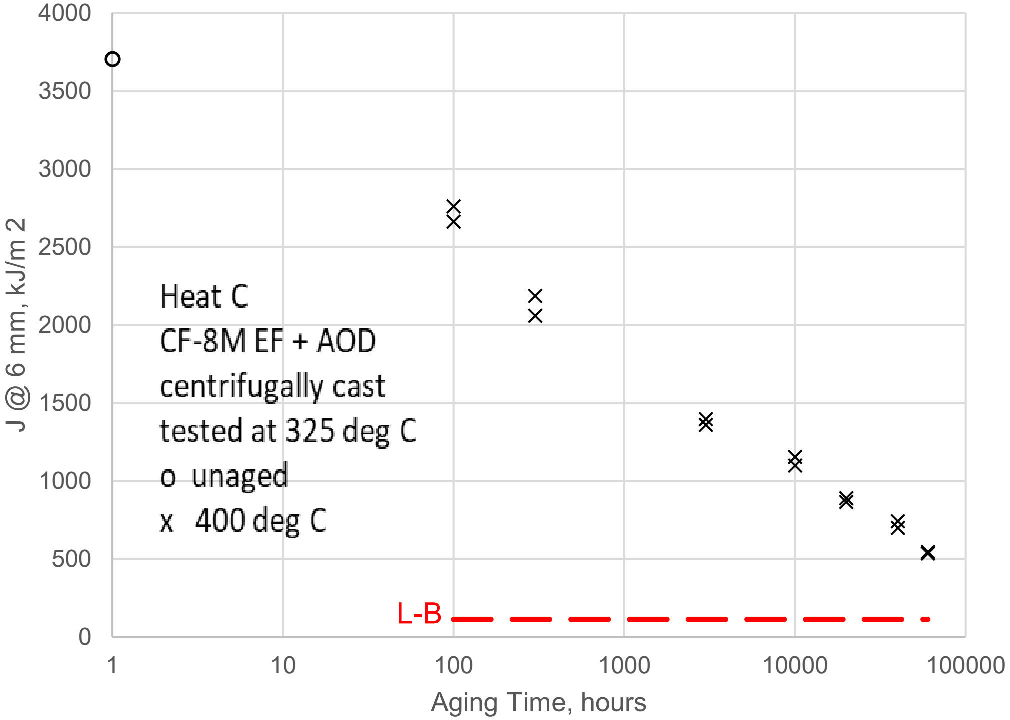
P of 4.8: YS = 151 MPa
UTS = 497
J_{Ic} = 366 kJ/m^2
J@6 = 890

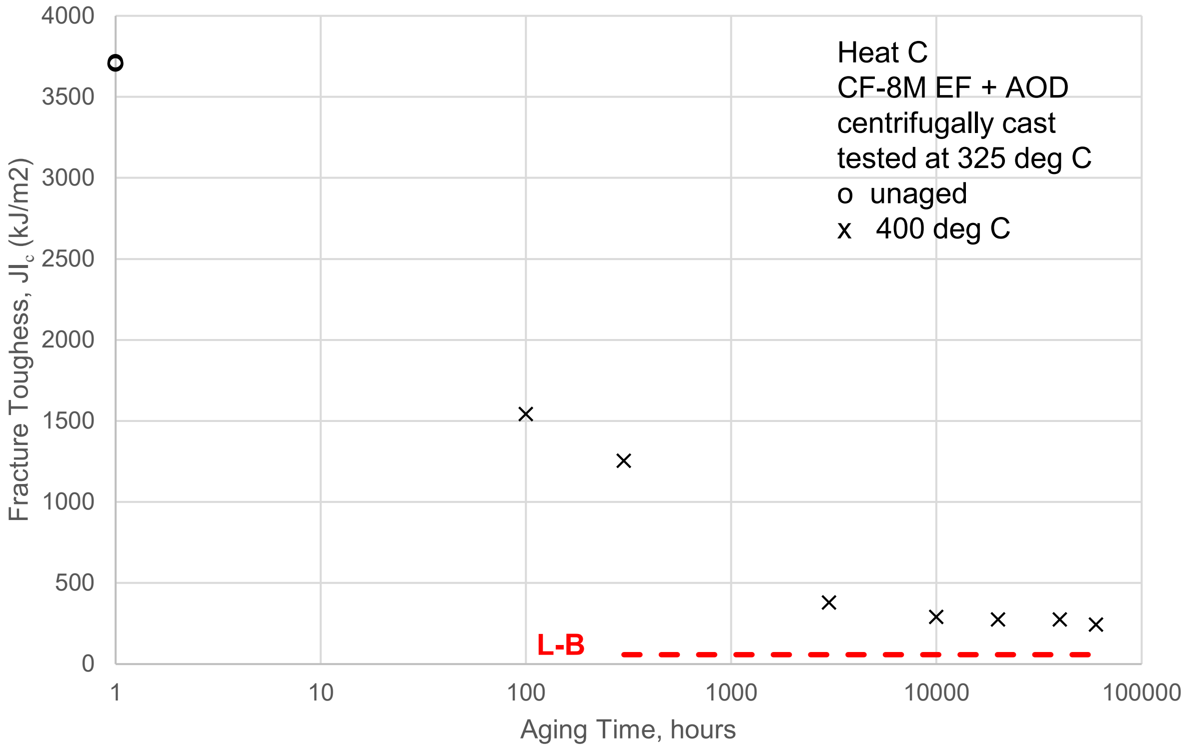
J_{Ic} & J @ 1 usually saturated @ P of 4 (aging for 10k hrs @ 400°C),
J-R curve does not usually saturate @ P of 4, for the weld it does.



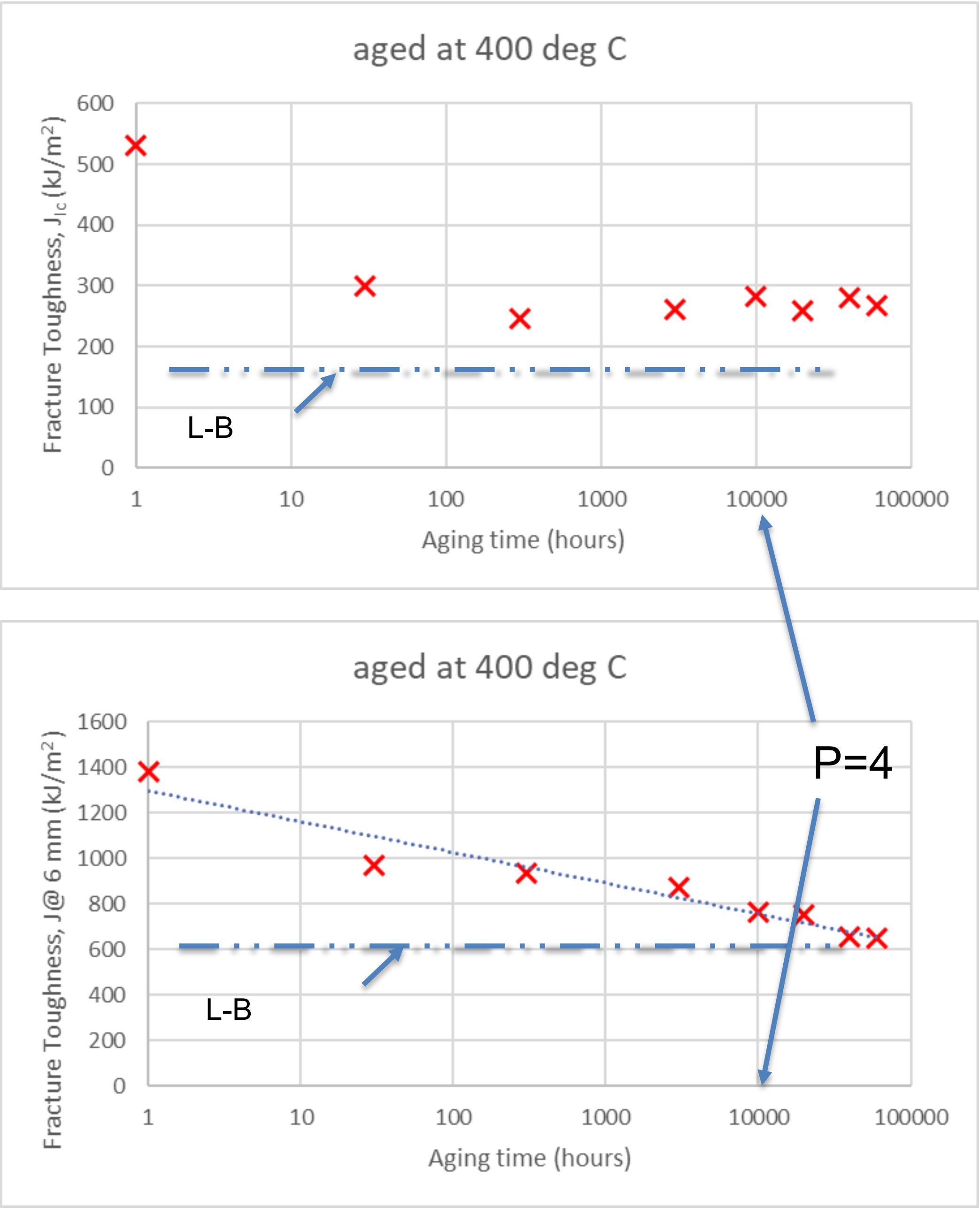
P value based on Q=100 kJ/mole provides conservative estimate for accelerated thermal aging up to 400°C.

- J_{IC} tends to saturate earlier than J-R curve.
- For TE screening, $J_{2.5}$ has been historically used, e.g. in CASS AMP, but J-value at $J_{2.5}$ may not be fully saturated at P=4.





Fracture toughness of Type 316L GTAW Weld Material with 8% ferrite as a function of aging time, from Hojo, 2014.

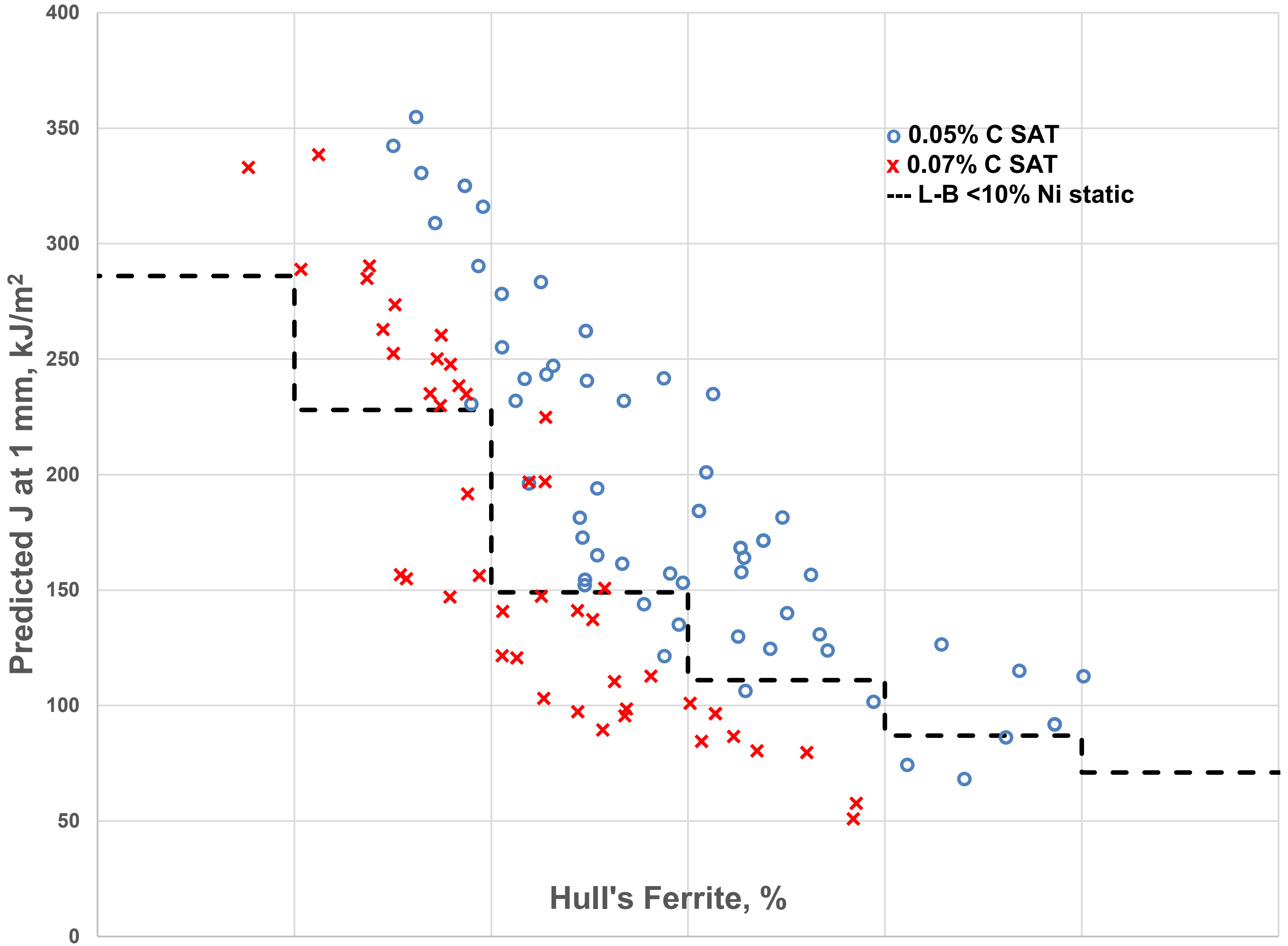


Upper. J_{Ic}

Lower. J_{6mm}

Different approaches to estimate toughness of CASS

- ANL method from NUREG/CR-4513, Rev. 2
- H3T method from Japan
- EDF method from France
- Code Case N-906



For CF-8M
Compare SAT to L-B predictions as a function of carbon content

Similar trends with using the SAT predictions for CF-8 RVIs in the 2015 PWROG-15032

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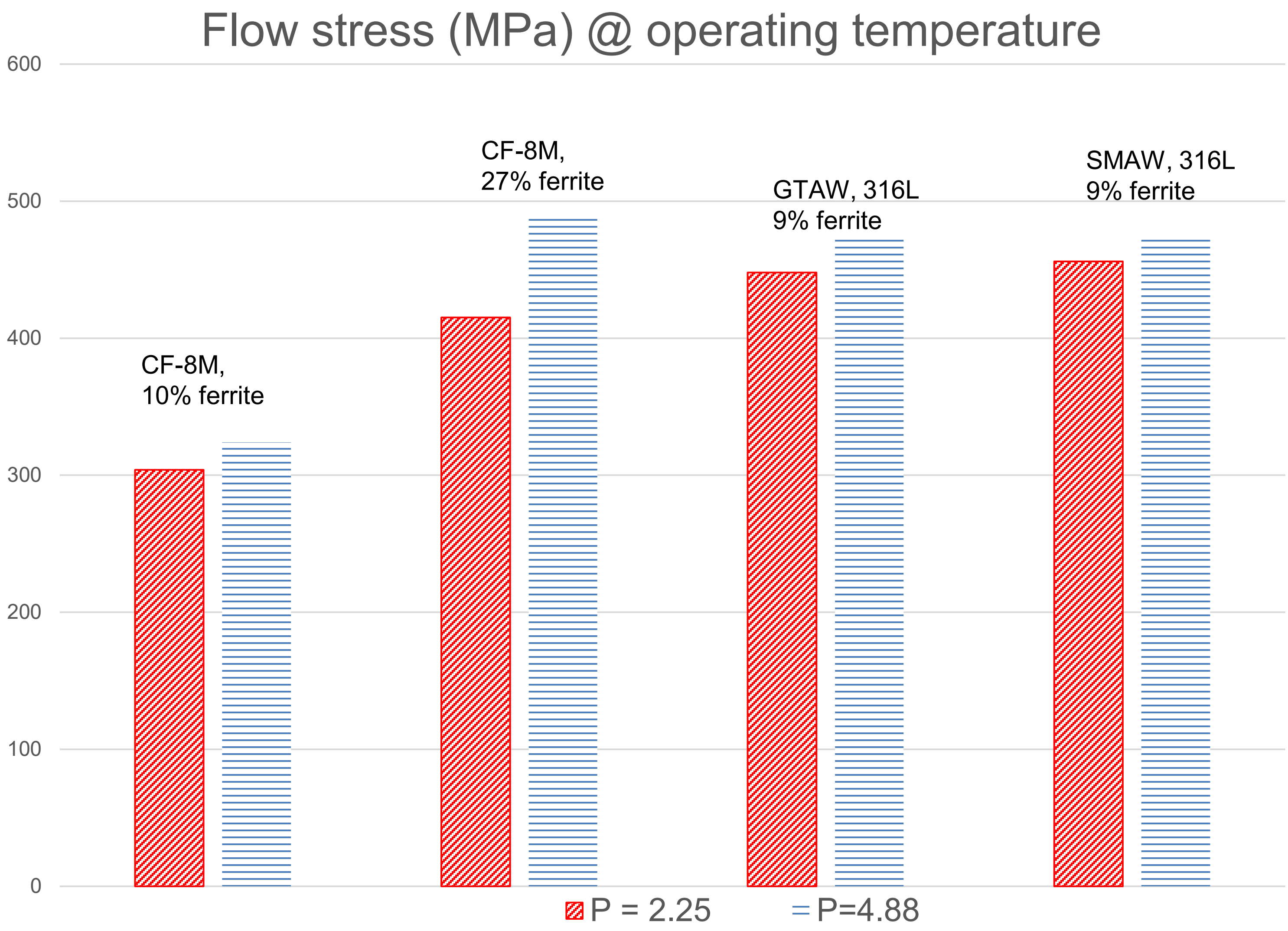


Flow stress is a weak function of TA

Summary of Tensile & Toughess

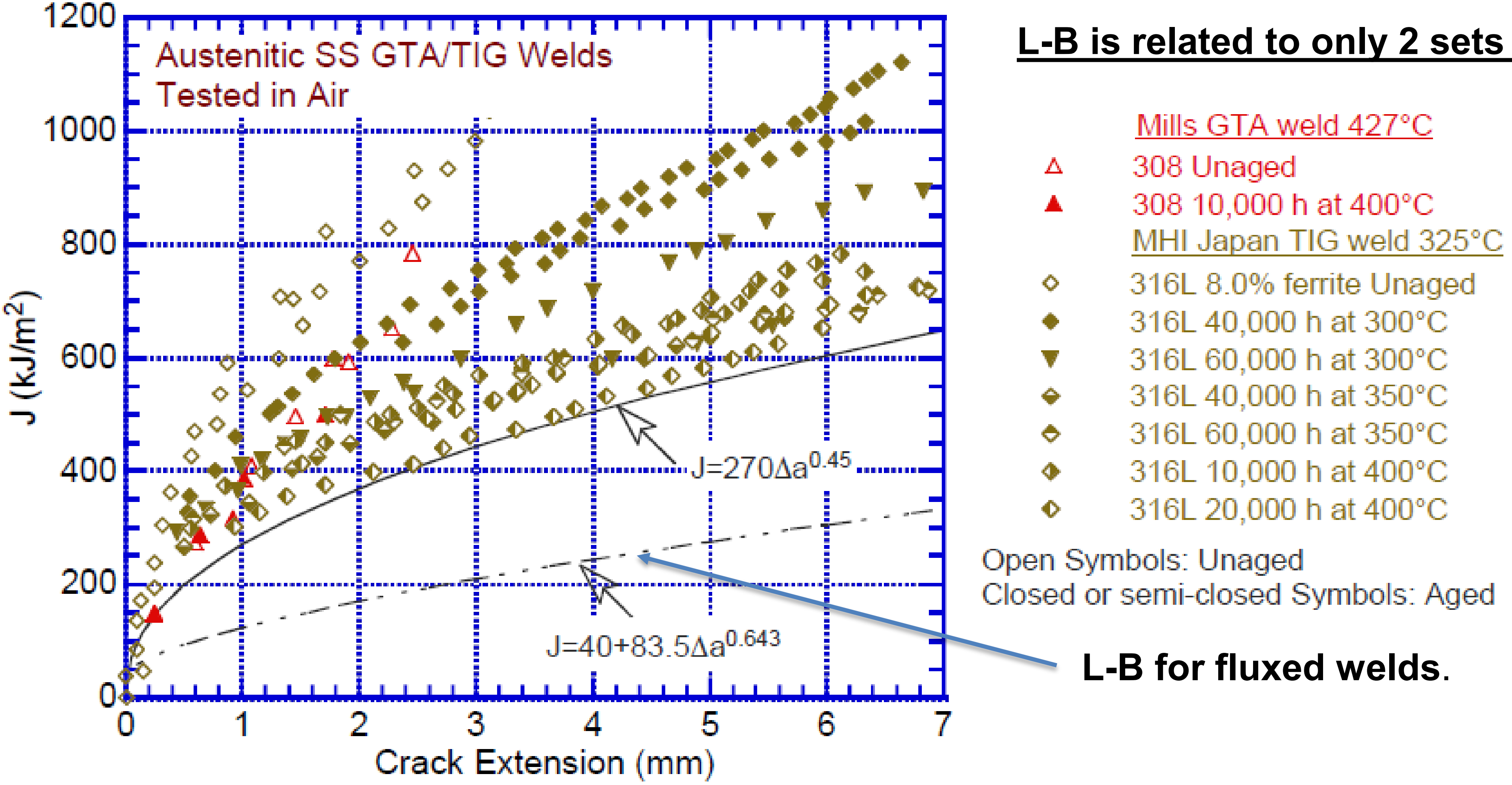
- For CASS, L-B FT curves provided in NUREG are adequate for SLR. FT is function of ferrite and Mo content.   Tensile properties are function of ferrite content.
- For ASSW, weld process is most significant factor controlling ASSW mechanical properties.
- Data not included in NUREGs is mostly bounded by the proposed lower bound J-R curves, including archival BWR weld material; exceptions for GTAW & 1 centrifugal cast pipe.
- For CASS, ANL L-B FT provide simple & more consistent FT estimates compared to the ANL SAT predictions.
- For ASSW, the welding process is the main factor for predicting L-B FT properties.

ASME Flaw Evaluations

- Currently, GTAW welds are treated as wrought material, therefore limit load analysis (C-5000) is used with no Z factor.
- For SMAW welds, EPFM is used (C-6000)
- Z-factors are provided in C-6330 applicable to flux welds and CASS. The same Z-factor is used for SAW/SMAW welds and CASS (Type CF3, CF8, or CF8M) with ferrite content > 14%, except for CF8M with ferrite > 25%.

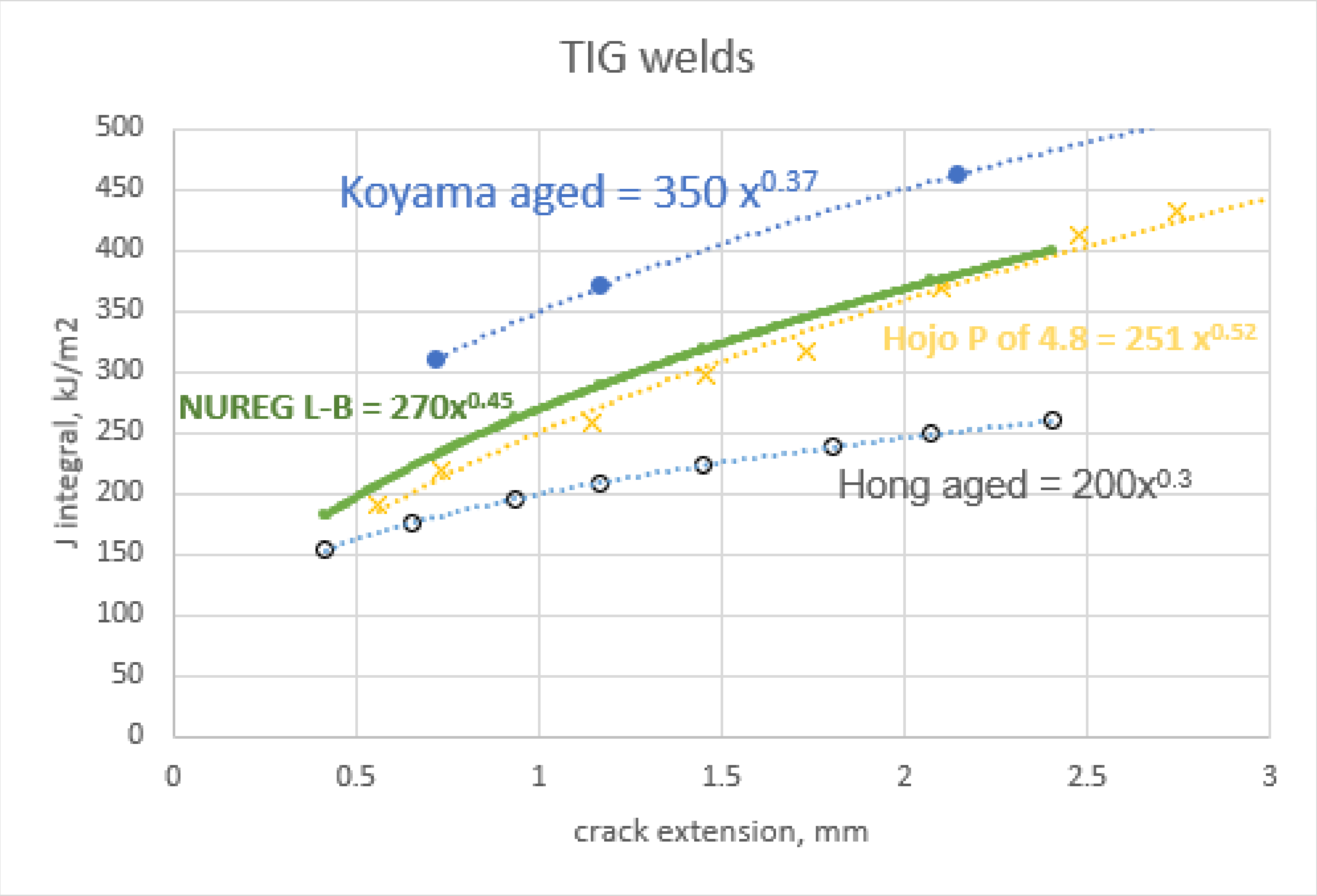
Definition: The Z-factor is a dimensionless multiplier on the applied load used in EPFM flaw evaluations for circumferential cracks in pressurized components, such as welds in pressurized water reactor (PWR) piping.

NUREG/CR-6428, Rev. 1 Lower Bound GTAW Curve



<u>L-B is related to only 2 sets of data</u>.

L-B for fluxed welds.



Comparison of Other GTAW J-R Curves to NUREG/CR-6428 Lower Bound

NRC Presentation to ASME WGPFE
August 2024

- Summarized results of NRC’s TLR on Thermal Aging of ASSW
- Concluded that TE of ASSW can cause significant reduction in the J-R toughness.
- Recommended changes to Z-factors for aged ASSW for both SAW/SMAW and GTAW.
- Recommended ASME open a record to re-evaluate the Sec. XI flaw evaluation procedures for ASSW.
- Recommended clarification of the origin of the minimum SMAW J-R value of 350 kJ/m^2

ASME Code Activity Related to ASSW

- EPRI Presentation, ASME Sec. XI WGPFE February 2025
  - Clarified the J-R curve basis for the Sec. XI Appendix C Z-factors. $J_{2.5}$ of 285 kJ/m^2 (not 350 kJ/m^2).
  - Concluded no need to revise Z-factor for unaged SAW/SMAW in Appendix C due to existing conservatisms
- May 2026 Presentation at WGPFE (Yun-Jae Kim, Jun-Won Park, Young Ha Lee – Korea University, D.J. Shim, EPRI-MRP)
  - Built on presentation at May 2025 WGPFE.
  - Describes EPRI project to develop a simplified model to predict the thermal aging effect on ASSW piping flaw evaluation, including parameters related to the thermal aging effect on mechanical properties and weld mismatch effect on fracture.
  - Describes plan to validate the proposed model using systematic FE analysis for ASSW piping using both unaged and aged material properties.
  - Effort to be completed by April, 2027.
- No current proposal for changes to Section XI to address ASSW toughness.

Conclusions & Recommendations

Aging management for TA should account for TA effects on both tensile and fracture properties.

The measured J_{Ic} saturates after thermal aging for 10k hrs @ 400 deg C; the J-R curve does not.

Using CMTR to predict ferrite content allows for a reasonable, conservative estimate of L-B toughness for BWR and most PWR systems operated beyond 72 EFPY (SLR conditions).

<u>For CASS:</u>

Our current knowledge base does not allow one to predict the SAT FT of CASS materials consistently based solely on chemical composition and casting method.

Based on the NUREG/CR-4513, Rev. 2 L-B J-R curves, simplified screening for CASS materials is possible; for example, CASS materials with < 0.5% Mo and < 40% ferrite would not be susceptible to TE.

This effort would indicate that the NUREG/CR-4513, Rev. 2 model with the L-B values for CF-8M and < 10% Ni for all CF-8M materials is appropriate as the basis for any flaw evaluations associated with CF-8M materials in the US domestic fleet of reactors for up to 72 EFPY.

<u>For ASSW</u>:

Additional GTAW samples would provide a better L-B estimate of FT.