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Task 2: Evaluation of the Causes & Mechanisms of IASCC in PWRs - Scope of Future Work

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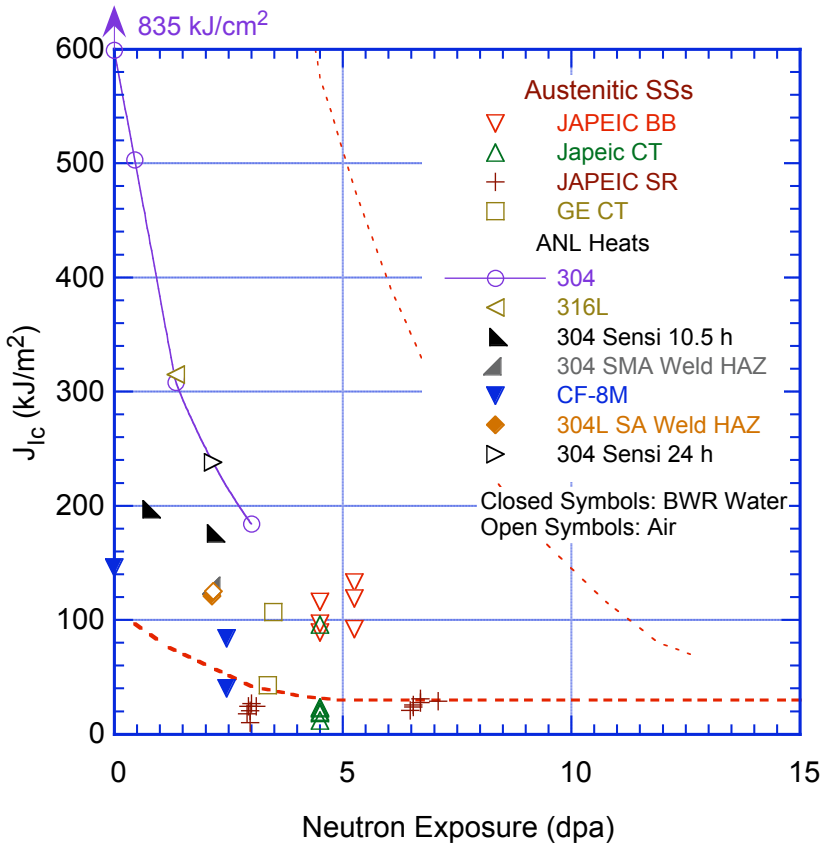
Task Objective & Source of Materials

- The program will focus on evaluating
  - IASCC susceptibility of PWR core internal materials including the effects of fluence level, material chemistry, & material condition (SA or CW)
  - void swelling behavior
  - fracture toughness & SCC behavior of wrought & cast SS at high fluence, including synergistic effects of thermal & neutron embrittlement of cast SS
  - effectiveness of mitigative measures, e.g., GBE treatment & low-S content
- Sources of irradiated materials & type of specimens include
  - SSRT (flat dog-bone) & 3-mm TEM disk specimens irradiated in BOR-60 reactor to approximately 5, 10, 20, & 40 dpa
  - four CT specimens of CIR materials (304L & CW 316 with & w/o Ti) irradiated in BOR-60 to 5-8 dpa
  - eight CT specimens of 304L & 316L from BWR control rod blade with fluence level of 3-6 dpa; some flat dog-bone tensile & TEM disk specimens will also be obtained
  - Halden-III experiment (new): CT (& some SSRT & TEM disk) specimens of 2 heats each of CF-3 & CF-8, & one heat of CF-8M cast SSs, & four compositions of 308, 308L, 316, & 316L weld metal, irradiated to 0.075 & 3.0 dpa at 315°C; additional heats of 304L, 304, 316L, & 316 SS irradiated to 3 dpa (include heats irradiated in BOR-60 reactor)

Background

- The existing data indicate that
  - IASCC susceptibility of austenitic SSs in PWR water occurs at fluence of 3-8 dpa
  - fracture toughness of these steels also decreases at 2-6 dpa
  - although SSs irradiated in fast reactors at ≥370°C to very high fluence levels exhibit stable crack extension, fracture toughness data on SSs irradiated in BWRs show no stable crack extension at 4-5 dpa
  - fracture toughness is always lower in the T-L orientation
- For cast duplex SSs, loss of fracture toughness can occur due to three processes (a) thermal embrittlement of ferrite,(b) neutron embrittlement of ferrite, & (c) neutron embrittlement of austenite
  - The extent & kinetics of thermal embrittlement of ferrite can be evaluated from the procedure in GALL report (or NUREG/CR-4513 Rev 1), & the kinetics of neutron embrittlement estimated from vessel embrittlement data
  - However, synergistic effects of concurrent exposure to high temperature & neutron fluence may lead to more rapid embrittlement of ferrite than expected from either of the two processes individually
  - For license renewal, conservative value (1×10^{17} n/cm^2) proposed for threshold fluence for significant neutron embrittlement of cast SS core components because possible synergistic effects of thermal & neutron embrittlement are not known

Change in J_{Ic} of Austenitic SSs with Neutron Dose



- JAPEIC tests on CT specimens (green open triangles) irradiated to 4.5 dpa showed no controlled crack extension

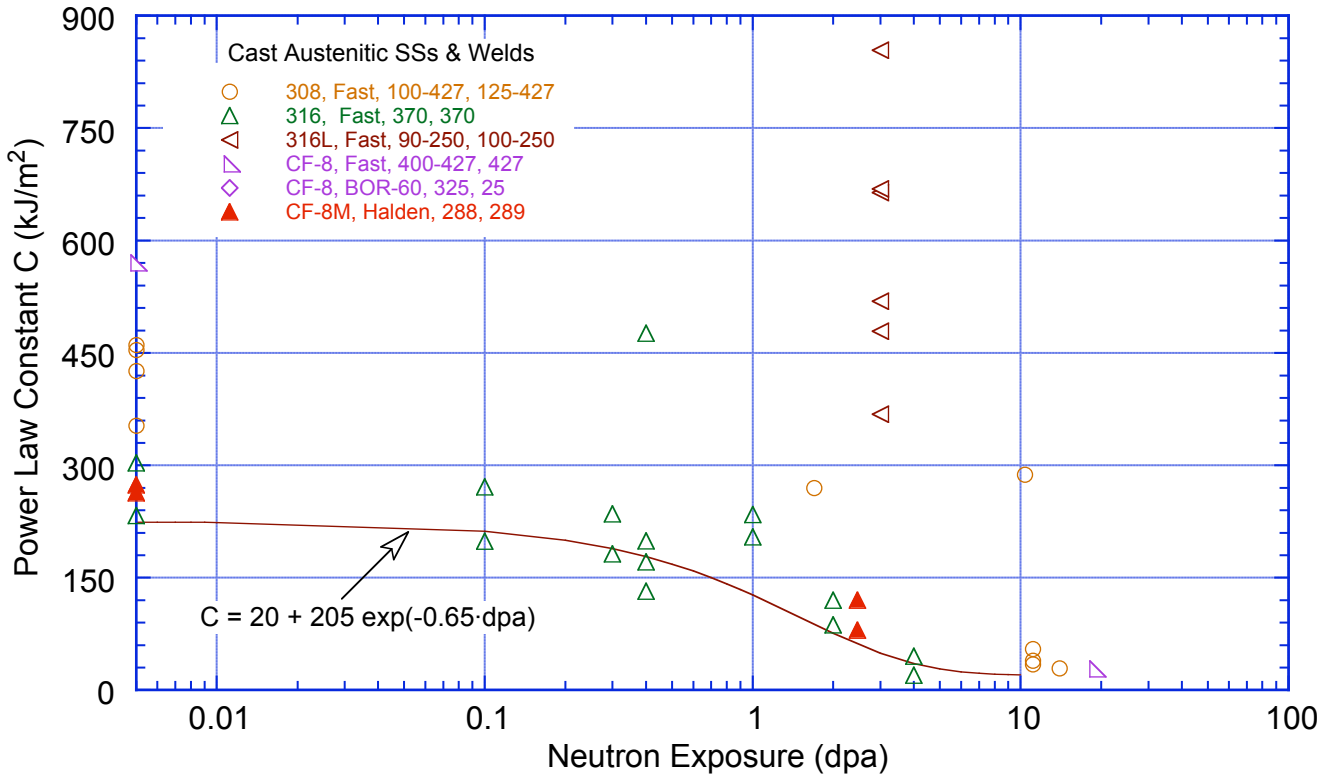
Task Scope

- The CGR & fracture toughness testing shall address the following
  - characterization of threshold fluence for IASCC susceptibility in PWR environment
  - characterization of saturation fracture toughness of irradiated wrought & cast SSs
  - synergistic effects of thermal & neutron embrittlement of cast SSs
  - CGR tests conducted at 315°C in high-purity water with <10 ppb DO (no additions), & fracture toughness J-R curve tests in low-DO water or air

- SSRT specimens used to investigate IASCC susceptibility of austenitic SSs
  - as a function of fluence, material composition, & process condition

- TEM disk specimens used
  - to characterize the microstructure & swelling behavior
  - for ball punch tests to monitor change in fracture toughness of irradiated SSs

Change in Coefficient C of Power-Law J-R Curve for Cast SSs & Weld Metals with Neutron Dose



- The synergistic effects of thermal & neutron embrittlement will be evaluated from fracture toughness data on cast SSs & weld metals irradiated to 0.075 dpa (5×10^{19} n/cm^2) & 3.0 dpa (2×10^{21} n/cm^2)

SSRT Specimens for tests in PWR Environment & TEM Disks for Microstructural Characterization & Ball-Punch Test

Material Type[a]	Material Code	SSRT Specimens Available/To be Tested[b] 5 dpa	10 dpa	40 dpa	TEM Disks Specimens Available/TEM Examination/Ball Punch Test[b] 5 dpa (Na)	10 dpa (Na)	10 dpa (He)	20 dpa (Na)	40 dpa (Na)
347 SA	D1	1/1	2/1	2/1	2/-/-	1/-/-	1/-/-	1/-/-	2/1/-
347 CW	D2	2/1	2/1	2/1	2/-/-	1/-/-	1/-/-	2/-/1	2/-/1
ABB 304 SA	B1		1/1	-	2/1/-	1/-/-	1/1/-	2/-/-	2/1/-
ABB 304 CW	B2	-	1/1	1/1	2/-/-	1/-/-	1/-/-	1/-/1	2/-/1
316LN SA	B3	1/1	2/1	-	2/-/-	1/-/-	1/-/-	1/-/1	2/1/1
316LN-Ti SA	B4	1/1	2/1	3/1	2/-/-	1/-/-	1/-/-	1/-/1	2/1/1
316 SA	B5	1/1	2/1	2/1	2/-/-	1/-/-	1/-/-	2/-/1	2/1/1
316 CW	B6	2/1	2/1	1/1	2/-/-	1/-/-	1/-/-	-	2/-/-
316 WW	B7	-	2/1	2/1	2/-/-	2/-/-	-	1/-/1	2/-/1
CF-3 cast	C1	-	2/1	-	2/-/-	1/-/-	1/-/-	1/-/1	2/1/1
CF-8 cast	C2	-	2/1	-	2/-/-	2/-/-	-	1/-/1	2/1/1
CF-3 cast	C3	-	-	2/1	2/-/-	1/-/-	-	1/-/1	2/1/1
CF-8 cast	C4	-	-	2/1	2/-/-	2/-/-	-	1/-/1	2/1/1
304 SA, low S	A1	-	2/1	-	2/-/-	1/-/-	1/-/-	2/-/-	2/1/-
304 SA, high S	A2	-	2/1	-	2/-/-	1/-/-	1/-/-	1/-/1	2/1/1
304 SA, low S	A3	-	2/1	-	2/-/-	1/-/-	1/-/-	1/-/-	2/1/-
304 CW, low S	A4	-	2/1	-	2/-/-	1/-/-	1/-/-	2/-/-	2/-/-
304 CW, low S	A5	1/-	2/1	1/1	2/-/-	1/-/-	1/-/-	2/-/-	2/-/-
304 GBE	A6	1/1	2/1	1/1	2/-/-	1/-/-	1/-/-	1/-/1	2/-/-
316 GBE	B8	1/1	2/1	1/1	2/-/-	1/-/-	1/-/-	2/-/1	2/-/1
690 GBE	E1	1/1	2/1	1/1	2/-/-	1/-/-	1/-/-	1/-/1	2/1/1
304 BASE	A7	1/1	2/1	-	2/-/-	1/-/-	1/-/-	2/-/-	2/1/-
316 BASE	B9	1/1	2/1	-	2/-/-	2/-/-	-	2/-/-	2/1/-
690 BASE	E2	1/1	2/1	-	2/-/-	2/-/-	-	1/-/-	2/1/-
HP 304L SA, high O	A8	-	2/1	1/1	2/-/-	1/-/-	1/-/-	2/-/1	2/1/1
HP 304L SA, low O	A9	-	2/1	3/1	2/-/-	2/-/-	2/-/-	2/-/-	2/1/-
304L SA	A10	-	2/1	-	-	-	-	-	-
304L CW	A11	-	2/1	1/1	2/-/-	1/-/-	1/-/-	2/-/1	2/-/1
304-like alloy	A12	-	2/-	3/-	2/-/-	1/-/-	1/-/-	2/-/-	2/-/-
Total		15/12	54/26	29/16	56/1/-	34/-/-	23/1/-	40/1/16	56/18/15

[a]SA = solution-annealed; CW = cold-worked at room temperature; WW = warm-worked at 400°C; GBE = grain-boundary-engineered; BASE = base heat for GBE modification; HP = high-purity.

[b]Doses are targeted dose. The 40-dpa specimens have not been received.

Test Matrix for SSRT & CGR/JR Curve Tests

		FY07		FY08				FY09				FY10				FY11			
		3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
IML Cell #2																			
Halden II	289°C BWR	----	----	----	----														
BWR CRB (GE)	289°C BWR					----	----	----	----	----	----	Mod							
Halden III Low	315°C BWR (HWC)												----	----	----	----	----	----	
IML Cell #1																			
SSRT BOR-60	320°C PWR	----	----	----	----	----	----	----	----	----									
CIR Material	320°C PWR										----	----	----	----					
Halden III Low	315°C PWR														----	----	----	----	
Out-of-Cell																			
Halden III Base	315°C PWR						----	----	----	----	----	----	----	----					

- BWR CRB Material: duplicate 1/4-T CT specimens of Type 304L & 316L SS irradiated to ≈3 and 6 dpa. Notch orientation same for low fluence & transverse for high fluence
  - CGR/JR tests at 289°C in NWC & HWC BWR environment
- Halden III: 1/4-T CT specimens of 5 compositions of cast SS & 4 of weld metal irradiated to 0.075 dpa (5 x 10^{19} n/cm^2)
  - JR tests at 315°C in HWC BWR water, precrack in NWC BWR water
- CIR Material: 1/2-T RCT specimens of 304L & CW316 SS irradiated to 4-7 dpa
  - CGR/JR tests at 320°C in PWR environment

Task 2 Significant Milestones

- Obtain 40-dpa SSRT & TEM disk specimens from ANL materials & four CT specimens from CIR materials irradiated in the BOR-60 reactor (03/08)
- Obtain eight CT specimens of 304L & 316L SS from BWR control rod blade with fluence level of 3-6 dpa (03/08)
- Issue topical report on IASCC susceptibility & microstructural characteristics of austenitic SS irradiated up to 45 dpa in the BOR-60 reactor (12/09)
- Obtain 0.075 dpa specimens from Halden III irradiations (04/10)
- Issue a topical report describing the results & conclusions from the testing of high fluence austenitic SSs from the CIR BOR-60 materials & BWR component materials (09/10)
- Issue a topical report describing the CGR & fracture toughness J-R curve test results & conclusions from the testing of nonirradiated & low-fluence cast SS & weld metal materials (09/11)
- Obtain 3.0 dpa specimens from Halden III irradiations