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Task 2: Evaluation of the Causes & Mechanisms of IASCC in PWRs - Prior Effort Overview

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Task Objective & Approach

- Investigate modes of degradation of austenitic SS core internals in PWRs as a function of fluence, material chemistry, & cold work
  - Effects of high fluence on IASCC susceptibility
  - Neutron irradiation embrittlement, i.e., loss of fracture toughness
  - Void swelling behavior
  - Effect of cold work relative to solution annealed SSs
  - Effectiveness of mitigative measures, e.g., GBE treatment, low-S content
- Irradiations in BOR-60 reactor in Dimitrovgrad, Russia
  - SA & CW Types 304, 304L, 316, 316LN, & 347 SS
  - GBE treated Type 304 & 316 SS, & Alloy 690
  - CF-3 & CF-8 cast SSs
  - Several commercial & lab heats of SSs with low or high S or O content
- EBR-II Type 304 SS component irradiated in sodium to ≈50 dpa at 370°C
  - Tested in air, and high- & low-DO high-purity water at 289°C

Task Status

- BOR-60 SSRT specimens irradiated up to ≈10 dpa and TEM disk specimens irradiated up to ≈20 dpa are available for testing;
  arrangements are being made to obtain the SSRT & TEM disk specimens irradiated to ≈40 dpa
- Completed SSRT tests on BOR-60 specimens irradiated to 10 dpa to
  - obtain baseline data in air
  - compare results for common materials irradiated to comparable dose level in the Halden reactor
- Examined void swelling behavior & characterized microstructure of BOR-60 TEM disk specimens from several heats of austenitic SSs and Alloy 690 irradiated to ≈25 dpa.

Composition of Materials from BOR-60 Irradiations

	Material Type[a]	Heat ID	Mat. Code[b]	Ni	Si	P	S	Mn	C	N	Cr	Other Elements[c]
1	347 SA	316642	D1	10.81	0.29	0.023	0.014	1.56	0.030	0.021	18.06	Nb 0.60, Mo 0.29, Cu 0.09
2	347 CW	316642CW	D2	10.81	0.29	0.023	0.014	1.56	0.030	0.021	18.06	Nb 0.60, Mo 0.29, Cu 0.09
3	316 SA	2333	B1	8.50	0.65	0.031	0.029	1.38	0.035	0.068	18.30	Mo 0.37
4	316 CW	2333 CW	B2	8.50	0.65	0.031	0.029	1.38	0.035	0.068	18.30	Mo 0.37
5	316 LN SA	623	B3	10.33	0.70	0.007	0.002	0.97	0.019	0.103	17.23	Mo 2.38, Cu 0.21
6	316 LN-Ti SA	625	B4	10.31	0.72	0.007	0.002	0.92	0.012	0.064	17.25	Mo 2.39, Ti 0.027, Cu 0.21
7	316 SA	C21	B5	10.24	0.51	0.034	0.001	1.19	0.060	0.020	16.28	Mo 2.08, B <0.001, O 0.0112
8	316 CW	C21 CW	B6	10.24	0.51	0.034	0.001	1.19	0.060	0.020	16.28	Mo 2.08, B <0.001
9	316 WW	C21 WW	B7	10.24	0.51	0.034	0.001	1.19	0.060	0.020	16.28	Mo 2.08, B <0.001
10	CF-3 cast SS	52	C1	9.40	0.92	0.012	0.005	0.57	0.009	0.052	19.49	Mo 0.35, δ 13.5%
11	CF-8 cast SS	59	C2	9.34	1.08	0.008	0.007	0.60	0.062	0.045	20.33	Mo 0.32, δ 13.5%
12	CF-3 cast SS	69	C3	8.59	1.13	0.015	0.005	0.63	0.023	0.028	20.18	Mo 0.34, δ 23.6%
13	CF-8 cast SS	68	C4	8.08	1.07	0.021	0.014	0.64	0.063	0.062	20.64	Mo 0.31, δ 23.4%
14	304 SA	C1	A1	8.12	0.50	0.038	0.002	1.00	0.060	0.060	18.11	B 0.001, O 0.0102
15	304 SA	C9	A2	8.75	0.39	0.013	0.013	1.72	0.062	0.065	18.48	B <0.001, O 0.0101
16	304 SA	C12	A3	8.23	0.47	0.018	0.002	1.00	0.060	0.070	18.43	B <0.001
17	304 CW	C1 CW	A4	8.12	0.50	0.038	0.002	1.00	0.060	0.060	18.11	B <0.001
18	304 CW	C12 CW	A5	8.23	0.47	0.018	0.002	1.00	0.060	0.070	18.43	B <0.001
19	304 GBE	304 GBE	A6	8.43	0.46	0.014	0.003	1.54	0.065	0.088	18.38	Mo 0.51, Co 0.22
20	316 GBE	316 GBE	B8	11.12	0.57	0.011	0.022	1.85	0.070	0.056	16.57	Mo 2.27, Co 0.10
21	690 GBE	690 GBE	E1	59.40	0.30	–	0.003	0.42	0.010	–	29.10	Fe 10.26
22	304 BASE	304 BASE	A7	8.46	0.41	0.013	0.014	1.56	0.065	0.086	18.32	Mo 0.36, Co 0.12
23	316 BASE	316 BASE	B9	10.30	0.43	0.013	0.020	1.53	0.055	0.054	16.42	Mo 2.19, Co 0.10
24	690 BASE	690 BASE	E2	61.49	0.05	–	<0.01	0.15	0.030	–	29.24	Fe 9.02
25	HP 304L SA	945	A8	9.03	0.03	<0.005	0.005	1.11	0.005	0.003	19.21	O 0.047, Mo <0.005
26	HP 304L SA	1327	A9	9.54	0.01	0.001	0.002	1.12	0.006	<0.001	19.71	O 0.008, Mo 0.02
27	304L SA	C3	A10	8.91	0.46	0.019	0.004	1.81	0.016	0.083	18.55	B <0.001
28	304L CW	C3 CW	A11	8.91	0.46	0.019	0.004	1.81	0.016	0.083	18.55	B <0.001
29	304-like	L5	A12	9.66	0.90	0.113	0.028	0.47	0.006	0.033	21.00	B <0.001, δ 3%, O 0.0068

[a]SA = solution-annealed; CW = cold-worked at room temperature; WW = warm-worked at 400°C; SS = stainless steel; GBE = grain-boundary-engineered; BASE = base heat for GBE modification; HP = high-purity.
[b]A = Type 304 SS, B = Type 316 SS, C = cast SS, and D = Type 347 SS; E = Alloy 690.
[c]δ = Ferrite content.

Disk Specimens Sealed in Four Sodium & One He-Filled Capsules

	Material Type[a]	Descritpion of Material[a]	Heat ID	Mat. Code[b]	AN05 5 dpa	AN10 10 dpa	HE10 10 dpa	AN20 20 dpa	AN40 40 dpa	Disk Total
1	347 SA	commercial heat 347, SA	316642	D1	2	1	1	1	2	7
2	347 CW	commercial heat 347, CW	316642CW	D2	2	1	1	2	2	8
3	316 SA	316, Heat B, SA	2333	B1	2	1	1	2	2	8
4	316 CW	316, Heat B, CW	2333 CW	B2	2	1	1	2	2	8
5	316LN SA	316LN, SA	623	B3	2	1	1	2	2	8
6	316LN-Ti SA	316LN, Ti-doped, SA	625	B4	2	1	1	2	2	8
7	316 SA	316, SA	C21	B5	2	1	1	2	2	8
8	316 CW	316, CW	C21 CW	B6	2	1	1	1	2	8
9	316 WW	316, WW	C21 WW	B7	2	2	-	2	2	8
10	CF-3 cast	cast keel block, 13.5% ferrite	52	C1	2	1	1	2	2	8
11	CF-8 cast	cast keel block, f13.5% ferrite	59	C2	2	2	-	2	2	8
12	CF-3 cast	cast steel, 23% ferrite	69	C3	2	1	-	1	2	6
13	CF-8 cast	cast steel, f23% ferrite	68	C4	2	2	-	2	2	8
14	304 SA	commercial 304, SA, low S	C1	A1	2	1	1	2	2	8
15	304 SA	commercial 304, SA, high S	C9	A2	2	1	1	2	2	8
16	304 SA	commercial 304, SA, low S	C12	A3	2	1	1	2	2	8
17	304 CW	commercial 304, CW	C1 CW	A4	2	1	1	2	2	8
18	304 CW	commercial 304, CW	C12 CW	A5	2	1	1	2	2	8
19	304 GBE	grain-boundary-optimized 304 SS	304 GBE	A6	2	1	1	2	2	8
20	316 GBE	grain-boundary-optimized 316 SS	316 GBE	B8	2	1	1	2	2	8
21	690 GBE	grain-boundary-optimized Alloy 690	690 GBE	E1	2	1	1	2	2	8
22	304 BASE	304 SS, GBE 304 base heat	304 BASE	A7	2	1	1	2	2	8
23	316 BASE	316 SS, GBE 316 base heat	316 BASE	B9	2	2	-	2	2	8
24	690 BASE	A 690, GBE 690 base heat	690 BASE	E2	2	2	-	2	2	8
25	HP 304L SA	HP 304L, high O, SA	945	A8	2	1	1	2	2	8
26	HP 304L SA	HP 304L, low O, SA	1327	A9	2	2	2	2	2	10
27	304L SA	commercial heat 304L, SA	C3	10	-	-	-	-	-	0
28	304L CW	commercial heat 304L, CW	C3 CW	11	2	1	1	2	2	8
29	304-like alloy	lab alloy, 21wt.% Cr, ≈2% ferrite, SA	L5	12	2	1	1	2	2	8
		Total TEM Disk Specimens: 222			56	34	23	53	56	222

[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]A = Type 304, B = Type 316, C = cast, and D = Type 347 stainless steels; E = Alloy 690.

Bundle & Specimen Identification & Target Dose for SSRT Tests

Target/Actual dpa	Bundle Code	Tensile Specimen IDs	Target/Actual dpa	Bundle Code	Tensile Specimen IDs
5 / 5.5	5-1	D1-1, D2-1, D2-2, B3-1	10 / 10.2	10-1	D1-2, D1-3, D2-3, D2-4
5 / 5.5	5-2	A5-1, A6-1, B8-1, E1-1	10 / 10.2	10-2	B1-1, B1-2, B2-1, B2-2
5 / 5.5	5-3	B4-1, B5-1, B6-1, B6-2	10 / 11.8	10-3	B3-2, B3-3, B4-2, B4-3
5 / 4.8	5-4	A7-1, B9-1, E2-1, A8-1	10 / 11.8	10-4	B5-2, B5-3, B5-4, B6-3
5 / 4.8	5-5	A1-1, A2-1, A3-1, A4-1	10 / 10.4	10-5	B6-4, B6-5, B7-1, B7-2
5 / 4.8	5-6	A9-1, A10-1, A11-1, A12-1	10 / 10.4	10-6	C1-1, C1-2, C2-1, C2-2
10 / 9.1	10-7	A1-2, A1-3, A2-2, A2-3	40 / 47.5	20-1	B4-4, B4-5, C3-2, C4-2
10 / 9.1	10-8	A3-2, A3-3, A4-2, A4-3	40 / 47.5	20-2	A5-4, E1-4, A9-5, A11-4
10 / 9.1	10-9	A5-2, A5-3, A6-2, A6-3	40 / 47.5	20-3	C3-1, C4-1, A6-4, B8-4
10 / 9.6	10-10	B8-2, B8-3, E1-2, E1-3	40 / 47.5	20-4	A8-4, A9-4, A12-4, A12-5
10 / 9.6	10-11	A7-2, A7-3, B9-2, B9-3	40 / 45.0	40-1	D1-4, D1-5, D2-5, D2-6
10 / 9.6	10-12	E2-2, E2-3, A8-2, A8-3	40 / 47.2	40-2	B4-6, B5-5, B5-6, B6-6
10 / 9.6	10-13	A9-2, A9-3, A10-2, A10-3	40 / 48.1	40-3	B2-3, B7-3, B7-4, A9-6, A12-6
10 / 9.1	10-14	A11-2, A11-3, A12-2, A12-3			

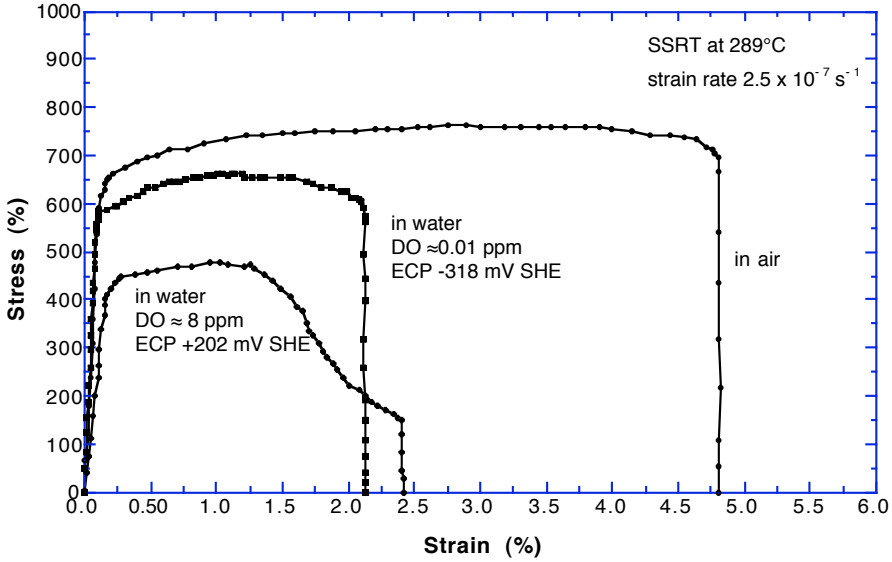
Specimens listed in red are in Russia, these specimens will be available for testing by June 2007.

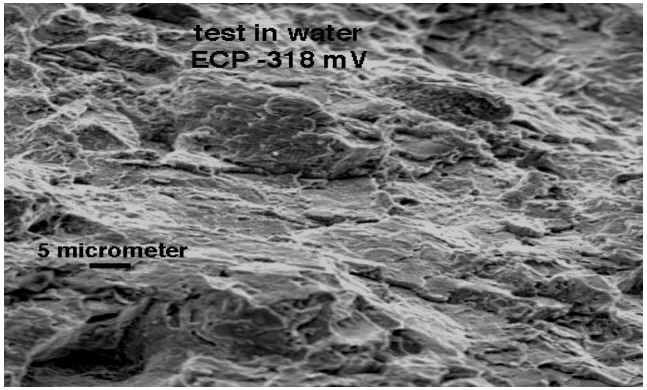
Material & Target Dose of SSRT Specimens from BOR-60 Irradiations

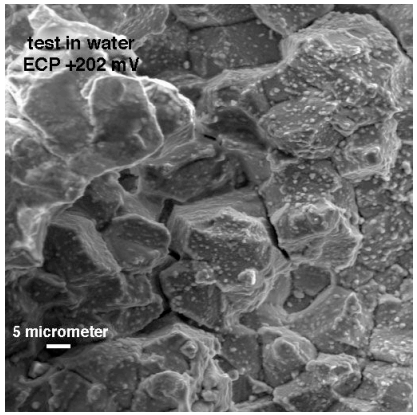
	Material Type[a]	Descritpion of Material[a]	Heat ID	Mat. Code[b]	SSRT 5 dpa	SSRT 10 dpa	SSRT 10 dpa	SSRT 40 dpa	Mat. Code[b]	SSRT Total
1	347 SA	commercial heat 347, SA	316642	D1	1	2	–	2	D1	5
2	347 CW	commercial heat 347, CW	316642CW	D2	2	2	–	2	D2	6
3	316 SA	316, Heat B, SA	2333	B1	–	2	–	–	B1	2
4	316 CW	316, Heat B, CW	2333 CW	B2	–	2	–	1	B2	3
5	316LN SA	316LN, SA	623	B3	1	2	–	–	B3	3
6	316LN-Ti SA	316LN, Ti-doped, SA	625	B4	1	2	–	3	B4	6
7	316 SA	316, SA	C21	B5	1	3	–	2	B5	6
8	316 CW	316, CW	C21 CW	B6	2	3	–	1	B6	6
9	316 WW	316, warm-worked	C21 WW	B7	–	2	–	2	B7	4
10	CF-3 cast	cast keel block, 13.5% ferrite	52	C1	–	2	–	–	C1	2
11	CF-8 cast	cast keel block, 13.5% ferrite	59	C2	–	2	–	–	C2	2
12	CF-3 cast	cast steel, 23% ferrite	69	C3	–	–	–	2	C3	2
13	CF-8 cast	cast steel, 23% ferrite	68	C4	–	–	–	2	C4	2
14	304 SA	commercial heat 304, SA, low S	C1	A1	1	–	2	–	A1	3
15	304 SA	commercial heat 304, SA, high S	C9	A2	1	–	2	–	A2	3
16	304 SA	commercial heat 304, SA, low S	C12	A3	1	–	2	–	A3	3
17	304 CW	commercial heat 304, CW	C1 CW	A4	1	–	2	–	A4	3
18	304 CW	commercial heat 304, CW	C12 CW	A5	1	–	2	1	A5	4
19	304 GBE	grain-boundary-optimized 304 SS	304 GBE	A6	1	–	2	1	A6	4
20	316 GBE	grain-boundary-optimized 316 SS	316 GBE	B8	1	–	2	1	B8	4
21	690 GBE	grain-boundary-optimized Alloy 690	690 GBE	E1	1	–	2	1	E1	4
22	304 BASE	304 SS, base heat of 304 GBE	304 BASE	A7	1	–	2	–	A7	3
23	316 BASE	316 SS, base heat of 316 GBE	316 BASE	B9	1	–	2	–	B9	3
24	690 BASE	Alloy 690, base heat of 690 GBE	690 BASE	E2	1	–	2	–	E2	3
25	HP 304L SA	HP 304L, high O, SA	945	A8	1	–	2	1	A8	4
26	HP 304L SA	HP 304L, low O, SA	1327	A9	1	–	2	3	A9	6
27	304L SA	commercial heat 304L, SA	C3	A10	1	–	2	–	A10	3
28	304L CW	commercial heat 304L, CW	C3 CW	A11	1	–	2	1	A11	4
29	304-like alloy	lab alloy, 21wt.% Cr, ≈2% ferrite, SA	L5	A12	1	–	2	3	A12	6
		Total SSRT Specimens 109			24	24	32	29		109

[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]A = Type 304 SS; B = Type 316 SS; C = cast austenitic SS; D = Type 347 SS; E = Alloy 690.

Type 304 SS from Hexagonal Fuel Assembly Can Irradiated in EBR-II to 50 dpa at ≈370°C

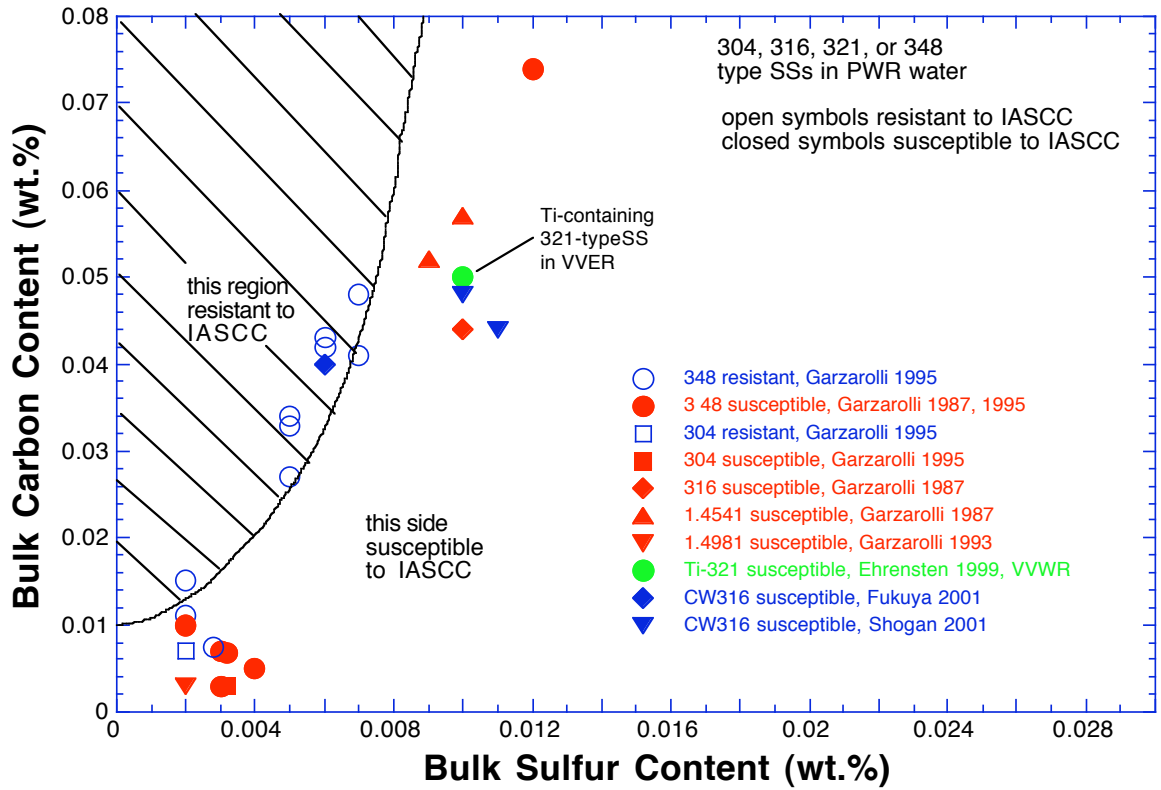






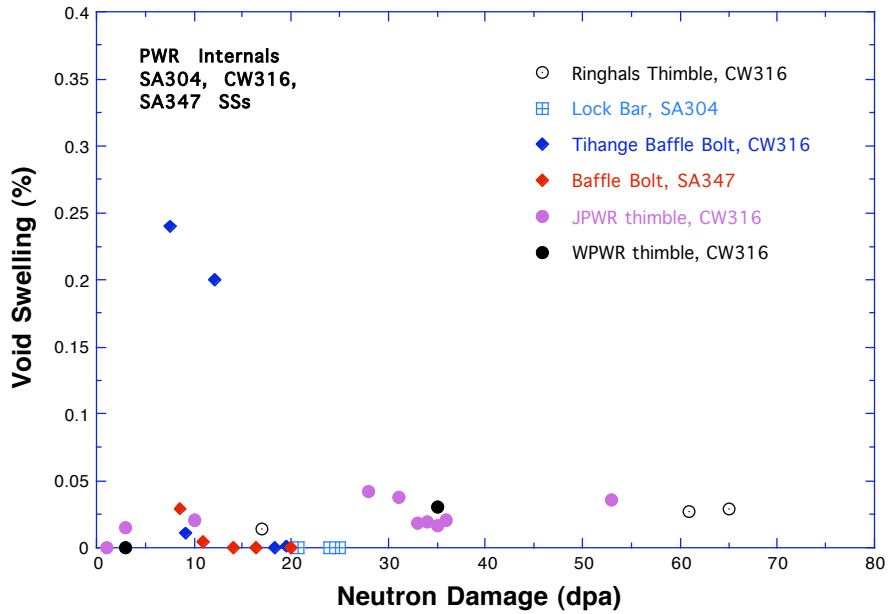
- Strength of EBR-II SS significantly lower than that of BWR components at <5 dpa
- In high-ECP water failure mode, as expected, is IG with ductility lower than in air
- Even in low-ECP water ductility is low & material failed at a lower stress

Sulfur-Carbon Map for Representation of Susceptibility or Resistance of Irradiated SSs to IASCC in PWR Environment



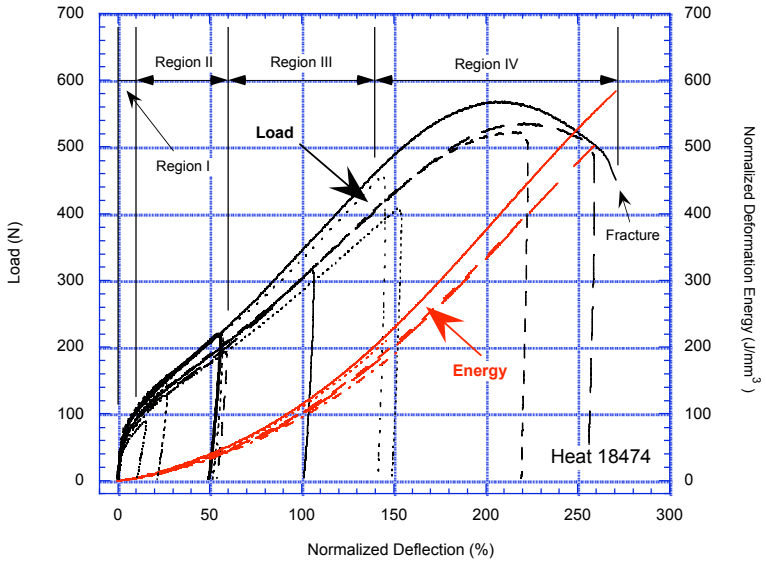
- Trends similar to those observed in S-C map for BWR environment
- For low-S steels, a high C content is beneficial to mitigate the effects of S

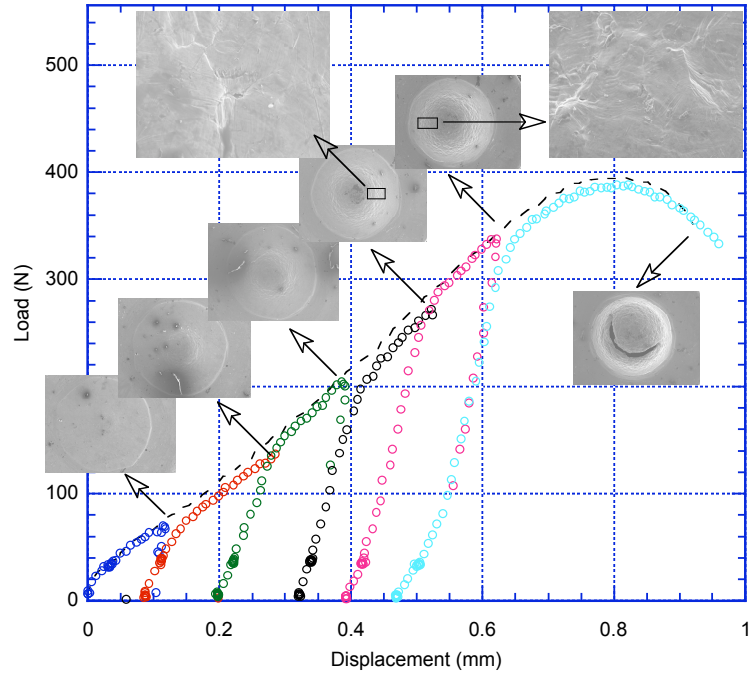
Assessment of Void Swelling in Austenitic SS Core Internals



- Based on limited data, swelling in thin-walled tubes & baffle bolts not a concern. Validity of this conclusion should be scrutinized as additional data become available
- PWR baffle reentrant corners most likely to experience high swelling rates.
  - Preliminary estimates indicate that void swelling is unlikely to exceed threshold of ≈4% for swelling rates to reach the steady state of 1%/dpa.
  - However, more accurate quantification of max temp of reentrant corners at EOL & life extension situations would be useful

Ball Punch Tests on TEM Disks





- Completed tests on several nonirradiated materials; tests on irradiated materials will be initiated in Oct. 2007
- Typical load-deflection curve shows: I - elastic bending, II - plastic bending, III - plastic membrane stretching, & VI - max. load & plastic instability with load drop due to crack propagation or through thickness thinning
- Use materials with known fracture toughness to develop correlation between ball punch fracture energy data with fracture toughness