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Task 1: Evaluation of the Causes & Mechanisms of IASCC in BWRs - Prior Effort Overview

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Task Objective & Approach

- Investigate IASCC susceptibility, & crack growth/fracture toughness behavior of SSs as a function of fluence, material type, & water chemistry
  - IASCC susceptibility evaluated from SSRT tests & fractographic analysis
  - Crack growth & fracture toughness data from 1/4-T CT specimens
- Halden Phase I irradiations focused on investigating
  - the effects of alloying & impurity elements on IASCC susceptibility
  - fracture toughness as a function of fluence at 289°C in air
  - CGRs as a function of fluence in BWR environments (NWC & HWC)
- Halden Phase II irradiations focused on investigating
  - the effects of GBE & elements such as O, S, Mo, and Ti, on IASCC
  - CGRs & fracture toughness of wrought & cast SSs & weld HAZ materials, including the effects of PWHT & GBE treatment
  - the possible effects of fracture morphology & BWR coolant environment on fracture toughness

Task Status

- Investigated IASCC susceptibility as a function of fluence, material type, & material composition, including the effects of GBE treatment
  - Results of Halden-I irradiations published in several NUREG/CR reports
  - Topical report with results of Halden-II irradiations is being reviewed
- Obtained CGR data to provide a better understanding of
  - threshold fluence for neutron irradiation effects to be significant
  - disposition curve for cyclic & SCC growth rates of irradiated SSs
  - fluence level above which benefit of HWC is lost
- Obtained fracture toughness J-R curve data on wrought & cast SSs, including HAZ materials, under BWR irradiation conditions & temperatures

Composition of SSs from Halden Phase I Irradiations

ANL ID[a]	Source Heat ID	Elemental Composition (wt.%)										
		Ni	Si	P	S	Mn	C	N	Cr	O	B	Mo, Nb
C1	ASW-70378	8.12	0.50	0.038	0.0020	1.00	0.060	0.060	18.11	0.0102	<0.001	-
L2	BPC-4111	10.50	0.82	0.080	0.0345	1.58	0.074	0.102	17.02	0.0065	<0.001	-
C3	PNL-C1	8.91	0.46	0.019	0.0040	1.81	0.016	0.083	18.55	-	<0.001	-
L4	BPC-488	10.20	0.94	0.031	0.0100	1.75	0.110	0.002	15.80	0.0037	<0.001	-
L5	BPC-4104	9.66	0.90	0.113	0.028 3	0.47	0.006	0.033	21.00	0.0068	<0.001	-
L6	BPC-4127	10.00	1.90	0.020	0.0051	1.13	0.096	0.087	17.10	0.0058	<0.001	-
L7	BPC-4112	10.60	0.18	0.040	0.0384	1.02	0.007	0.111	15.40	0.0274	<0.001	-
L8	BPC-491	10.20	0.15	0.093	0.0100	1.85	0.041	0.001	18.30	0.0059	<0.001	-
C9	PNL-C6	8.75	0.39	0.013	0.0130	1.72	0.062	0.065	18.48	0.0102	<0.001	-
C10	ASW-23381	8.13	0.55	0.033	0.0020	1.00	0.060	0.086	18.19	0.0074	<0.001	-
L11	BPC-493	8.15	0.47	0.097	0.0094	1.02	0.014	0.004	17.40	0.0071	<0.001	-
C12	ASW-23805	8.23	0.47	0.018	0.0020	1.00	0.060	0.070	18.43	-	<0.001	-
L13	BPC-496	8.18	1.18	0.027	0.0222	0.36	0.026	0.001	17.40	0.0042	<0.001	-
L14	BPC-4129	7.93	1.49	0.080	0.0023	1.76	0.107	0.028	15.00	0.0045	<0.001	-
L15	BPC-4126	8.00	1.82	0.010	0.0129	1.07	0.020	0.085	17.80	0.0110	<0.001	-
C16	PNL-SS14	12.90	0.38	0.014	0.0020	1.66	0.020	0.011	16.92	0.0157	<0.001	Mo 2.30
L17	BPC-4128	8.00	0.66	0.090	0.0089	0.48	0.061	0.078	15.30	0.0090	<0.001	-
L18	BPC-498	8.13	0.14	0.016	0.0326	1.13	0.080	0.001	18.00	0.0055	<0.001	-
C19	ASW-74827	8.08	0.45	0.031	0.0030	0.99	0.060	0.070	18.21	0.0200	<0.001	-
L20	BPC-4101	8.91	0.017	0.010	0.0039	0.41	0.002	0.002	18.10	0.0940	<0.001	-
C21	ASW-12455	10.24	0.51	0.034	0.0010	1.19	0.060	0.020	16.28	0.0112	<0.001	Mo 2.08
L22	BPC-4100	13.30	0.024	0.015	0.0036	0.40	0.003	0.001	16.10	0.0103	<0.001	Mo 2.04
L23	BPC-4114	12.04	0.68	0.030	0.0475	0.96	0.043	0.092	17.30	0.0093	<0.001	Nb 1.06
L24	BPC-4105	12.30	0.03	0.007	0.0055	0.48	0.031	0.002	16.90	0.0129	<0.001	Nb 1.72
L25	BPC-4133	8.93	0.92	0.020	0.0082	1.54	0.019	0.095	17.20	0.0085	0.010	-
L26	BPC-4131	8.09	0.79	0.004	0.0022	0.91	0.070	0.089	17.20	0.0080	<0.001	-
L27	BPC-4132	10.30	0.96	0.040	0.0018	0.97	0.057	0.019	15.30	0.0058	0.030	Mo 2.01

Irradiation Conditions & Test Matrix for Halden Phase I Specimens

Alloy ID	SSRT Test			J-R, Crack Growth Rate Test		
	high[a]	medium[a]	low[a]	high	medium	low
C1	1	1	1			
L2	1	1		1	1	
C3	1	1	1	1	1	1
L4	1	1	1			
L5	1	1	1	1		
L6	1	1				
L7	1	1				
L8	1	1	1			
C9	1	1	1			
C10	1	1	1			
L11	1	1	1			
C12	1	1	1			
L13	1	1	1			
L14	1	1		1		
L15	1	1				
C16	1	1	1	1	1	
L17	1	1				
L18	1	1	1	1	1	
C19	9	5	1	1	1	1
L20	9	5	1	1	1	1
C21	1	1	1	1	1	1
L22	1	1	1	1	1	
L23	1	1		1		
L24	1	1		1		
L25	3					
L26	3					
L27	2					

Specimen numbers in red not tested.

Composition of SSs from Halden Phase II Irradiations

Heat ID	Composition (wt%)								
	Ni	Si	P	S	Mn	C	N	Cr	Others
GB304	8.19	0.41	0.029	0.006	1.73	0.054	0.052	18.28	Mo 0.23, Co 0.10, Cu 0.31
333	8.45	0.68	0.027	0.019	1.38	0.04	0.068	18.54	Mo 0.37
304L	8.33	0.45	0.028	0.007	1.74	0.023	0.09	18.35	Mo 0.37, Co 0.13, Cu 0.35
GB304L	8.33	0.45	0.028	0.007	1.74	0.02	0.09	18.35	Mo 0.37, Cu 0.35
327	9.54	0.01	0.001	0.002	1.12	0.006	<0.001	19.71	Mo 0.02, O 0.008
945	9.03	0.03	<0.005	0.005	1.11	0.005	0.003	19.21	Mo <0.005, O 0.047
L15	8	1.82	0.01	0.013	1.07	0.02	0.085	17.8	O 0.011
GB316	11.16	0.35	0.029	0.025	1.59	0.041	0.05	16.34	Mo 2.07, Cu 0.37, Co 0.09
623	12.2	0.7	0.007	0.002	0.97	0.019	0.103	17.23	Cu 0.21, Mo 2.38
625	12.3	0.72	0.007	0.002	0.92	0.012	0.064	17.25	Ti 0.027, Cu 0.21, Mo 2.39
690	61.49	0.05	-	0.001	0.15	0.03	-	29.24	Fe 9.02, Co 0.007, Cu 0.01
GB690	59.4	0.42	0.026	0.003	0.42	0.01	-	29.1	Fe 10.26, Al 0.22, Ti 0.29
151	23.49	0.06	0.006	0.005	1.39	0.004	0.001	24.02	Mo 0.002

Irradiation Conditions & Test Matrix for Halden Phase II Specimens

Heat ID	Material	Available Specimens	Neutron fluence E >1 MeV (x10 ^{21} n/cm ^{2})	Damage Dose (dpa)	Irr. Temp. (°C)
GB304	Grain -boundary - optimized 304 SS	3	1.31	1.96	296-305
333	ABB 304 SS	3	1.63	2.44	290-296
304L	304L SS , commercial heat	2	1.31	1.96	296-305
GB304L	Grain -boundary -optimized 304L SS	3	1.31	1.96	296-305
327	High -purity 304L SS, low O	3	1.63	2.44	290-296
945	High -purity 304L SS, high O	3	1.63	2.44	290-296
L15	304 SS, laboratory heat	1	1.63	2.44	290-296
GB316	Grain -boundary -optimized 316 SS	3	1.31	1.96	296-305
623	316LN (high N, low C)	2	1.63	2.44	290-296
625	316LN, Ti -doped	2	1.63	2.44	290-296
690	Alloy 690	2	1.31	1.96	296-305
GB690	Grain -boundary -optimized Alloy 690	3	1.31	1.96	296-305
151	Fe-Cr-Ni model alloy, Fe-20Cr-24Ni	2	1.63	2.44	290-296

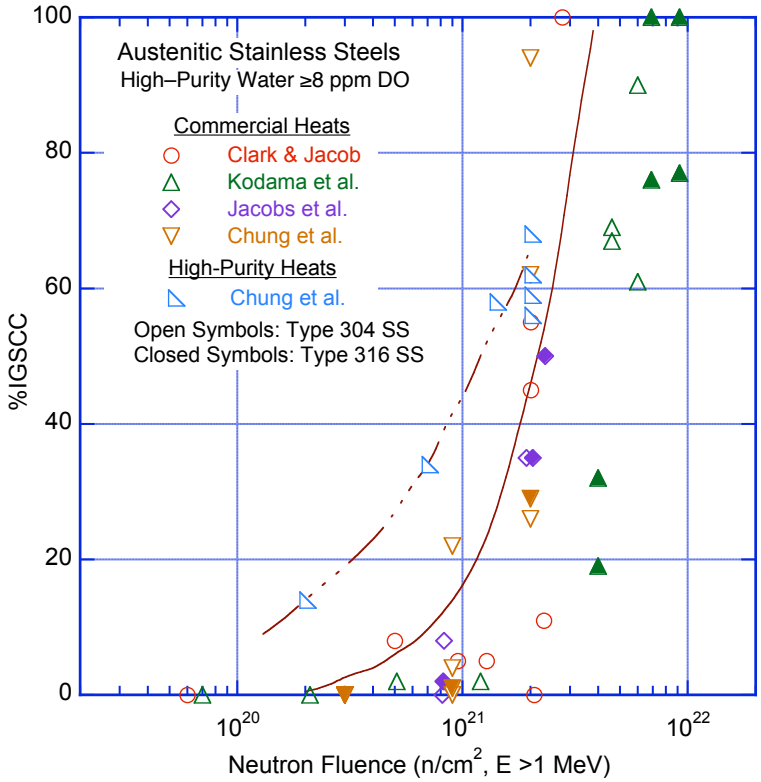
Test Matrix for CGR/J-R Tests on Halden Phase II Specimens

Material Type	Condition	Fluence x 10^{21} n/cm^2	Total Spec.	Specimen ID *	Tests Planned	Test Type
GG 304L SA Weld HAZ	As Welded	-	2	**GG5BA**, GG5BB	-	CGR
GG 304L SA Weld HAZ	As Welded	0.50	2	**GG5TA, GG5TB**	-	CGR
GG 304L SA Weld HAZ	As Welded	1.44	2	**GG6TA**, **GG6TB**	-	CGR/JR
GG 304L SA Weld HAZ	AW+24 h @ 500°C	-	2	**GG3BA-TT**, GG3BB-T T	-	CGR
GG 304L SA Weld HAZ	AW+24 h @ 500°C	1.63	2	GG3TA-TT, GG3TB-T T	1	CGR/JR
304 SS SMA Weld HAZ	As Welded	-	2	**85-YA**, 85-Y B	-	CGR
304 SS SMA Weld HAZ	As Welded	0.50	2	**85-7A**, 85-7 B	-	CGR
304 SS SMA Weld HAZ	As Welded	1.44	2	**85-XA**, **85-XB**	-	CGR/JR
304 SS SMA Weld HAZ	AW+24 h @ 500°C	-	2	**85-3ATT**, 85-3 B T T	1	CGR
304 SS SMA Weld HAZ	AW+24 h @ 500°C	0.50	2	**85-1ATT**, 85-1 B T T	-	CGR
304 SS SMA Weld HAZ	AW+24 h @ 500°C	1.44	2	85-2ATT, 85-2 B T T	-	CGR
CF-8M Cast Austenitic SS	10,000 h @ 400°C	1.63	2	**75-11TT**, **75-11TM**	-	CGR/JR
304 SS Sensitized #1	10.5 h @ 600°C	0.50	2	**85-1TT**, 85-2 T T	-	CGR/JR
304 SS Sensitized #1	10.5 h @ 600°C	1.44	2	**85-3TT**	-	CGR/JR
304 SS Sensitized #2	24 h @ 600°C	0.50	2	85-5A1TT, 85-5B1TT	1	CGR/JR
304 SS Sensitized #2	24 h @ 600°C	1.44	2	**85-5A2TT**	-	CGR/JR
304 SS	-	1.31	1	**IT304-CT01**	-	CGR/JR
304 SS	GBE Process	1.31	1	GB304-CT01	1	CGR/JR
316 SS	-	1.31	1	IT316-CT01	1	CGR/JR
316 SS	GBE Process	1.31	1	GB316-CT01	1	CGR/JR

Specimen IDs in bold letters have been tested.

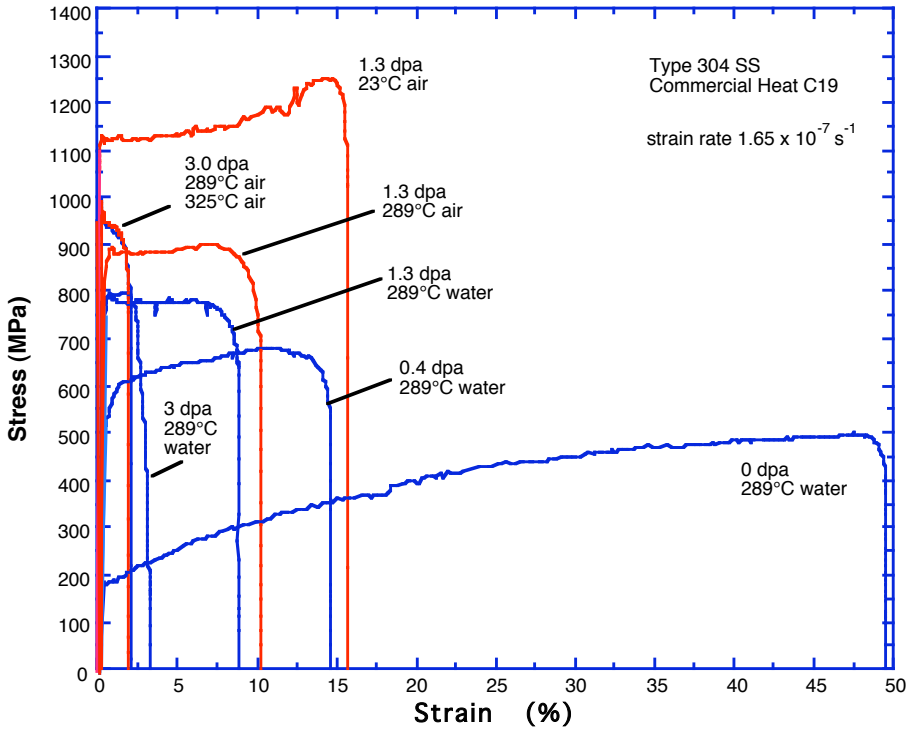
Specimen IDs in red were tested in air, the remaining tests were conducted in NWC BWR environment.

Susceptibility of Irradiated SSs to IGSCC (SSRT data)



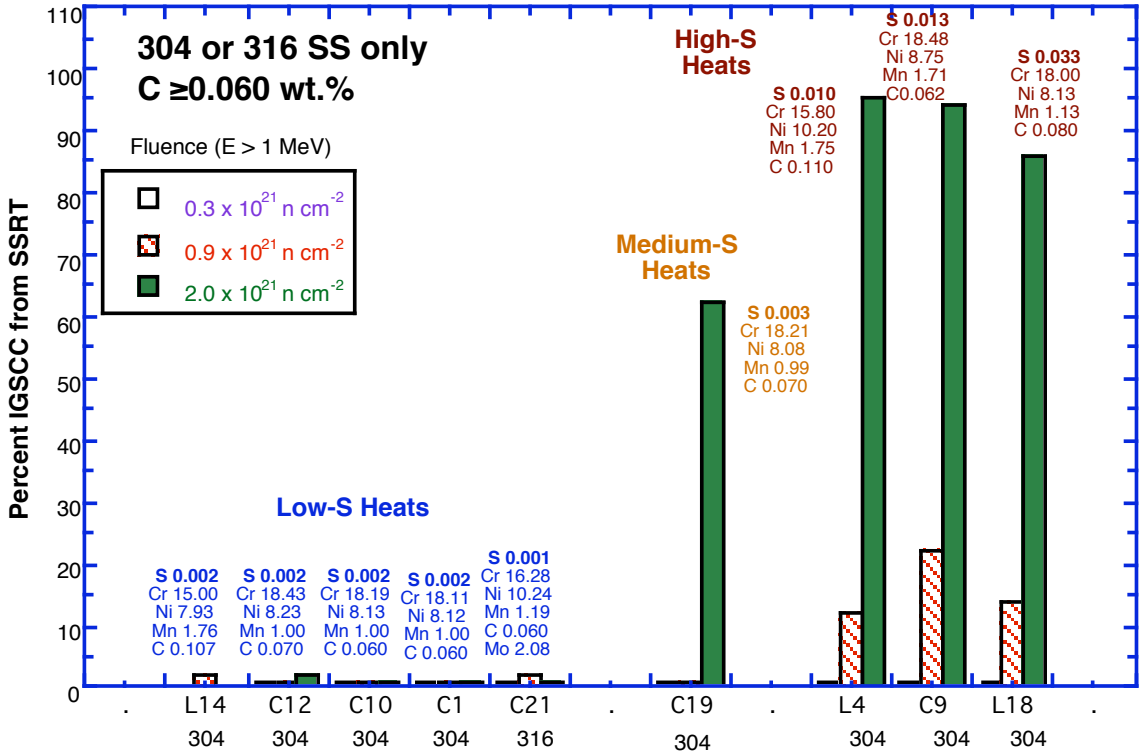
- High-purity heats are more susceptible to IASCC than commercial-purity heats
- Although role of microstructural characteristics is not clearly known, low Si & C, low grain-boundary Cr, & high O, correlate with greater vulnerability to IASCC

Irradiation Hardening of Irradiated SSs (SSRT data)



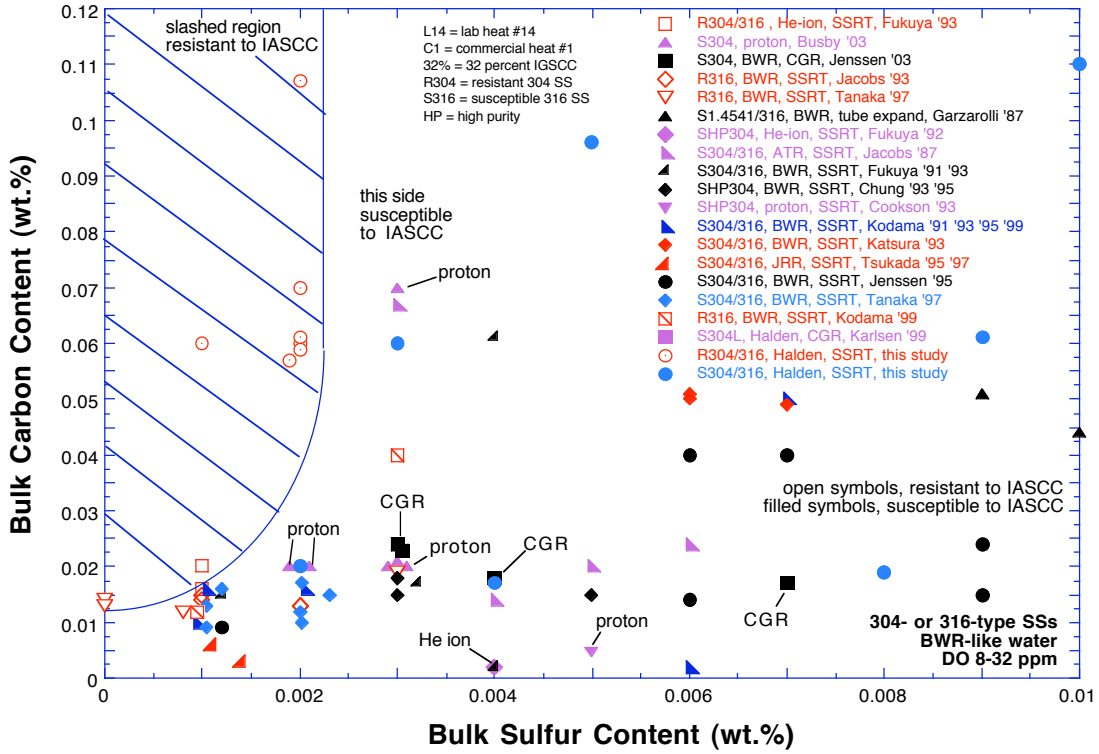
- Neutron irradiation increases the yield strength & decreases ductility
- Irradiation hardening appears to saturate at ≈3 dpa

Effect of S Content on Susceptibility to IGSCC



- Susceptibility increases significantly at higher S contents; SSs with ≤0.002 wt.% S are resistant to IGSCC

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



- Range of susceptible S levels increases somewhat with increasing C levels, trade-off may be increased susceptibility to thermally induced sensitization