EPRI-NRC Cooperative Research Project: PWSCC Crack Initiation Characterization of Alloys 600/182 and Alloys 690/52/152

- 2021 Status Update

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Alloy 690/52/152 PWSCC Research Collaboration Meeting
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Pacific Northwest NATIONAL LABORATORY

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Outline

- Objectives
- Approach
- Material Selection
- Test Systems
- Program Plan & Schedule
- Testing Status
- Data Insights
- Next Steps

Objectives

- Obtain primary water stress corrosion cracking (PWSCC) initiation data for Alloy 182 to support the xLPR Code development project.
  - Validate xLPR model fitting parameters for temperature, stress, and yield strength.
  - Understand uncertainties and accuracy of PWSCC initiation models.

- Obtain PWSCC initiation data for Alloy 690/52/152 to develop inspection requirements for components made from these alloys.
  - Support reviews of potential submittals requesting credit for the use of more resistant materials.

Approach

- The NRC and EPRI have entered into a memorandum of understanding (MOU) to conduct cooperative research on PWSCC initiation testing at PNNL.

- Perform initiation testing on multiple heats/welds:
  - Alloy 182, to investigate the effects of stress, temperature, cold work, and possibly other factors for use in xLPR and to use as a benchmark for an Alloy 52/152 factor of improvement (FOI),
  - Alloy 600, to serve as a benchmark for an Alloy 690 FOI and a benchmark for Alloy 182 results,
  - Alloy 690/52/152, to obtain FOIs compared Alloy 600/182,
  - Accelerated conditions: 360°C, hydrogen potential on/near the Ni/NiO stability boundary.

Material Selection

Overview

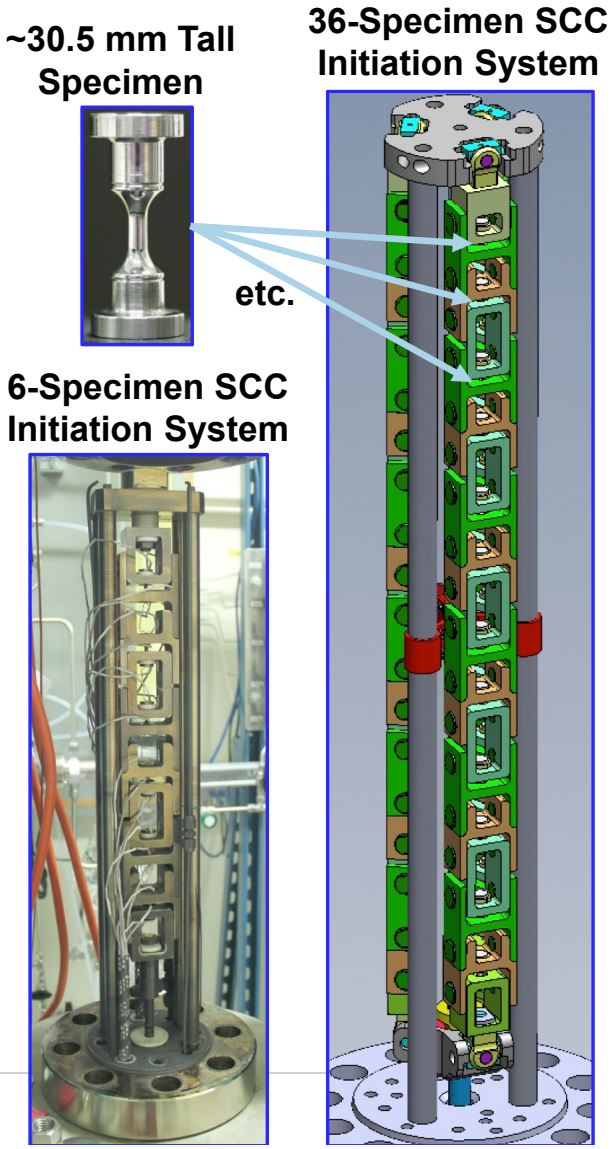
- Four heats / welds of each Alloy 182, 600, 690, and 52/152 were originally selected.
  - Additional EWI heat evaluated recently for use to meet material testing needs (YS at 360 °C: 510-537 MPa)
- SCC crack growth rate (CGR) data were obtained for many of the materials in their as-produced condition.
- PNNL applied 7.5% and 15% cold work (CW) by cold forging (CF) for relevance to service components (i.e., surface layer conditions) and to serve as a test accelerant:
  - SCC CGR testing has revealed a strong effect of CW on Alloy 600 CGRs,
  - Strong increase in CGR is consistent with strong reduction in SCC initiation time for CW Alloy 600,
  - Alloy 182 might exhibit the same correlation.
- Yield strength and hardness characterizations were performed on the CF materials.

Materials, YS and Hardness for 15% CF Condition

Material	ID	YS@360°C (MPa)	Hardness (kg/mm^2)
Alloy 182 Build-up	Studsvik 8001231	550	240-345
Alloy 182 DMW	Flawtech 844305	515, 525	225-345
Alloy 182 DMW	Phase 2B	460, 500	225-330
Alloy 182 U-Groove	KAPL 823030	580, 590	250-350
Alloy 600 Plate	NX6106XK-11	575	270
Alloy 600 Plate	522068	450	240
Alloy 600 Plate	33375-2B	540	265
Alloy 600 CRDM	WNP5	520	240
Alloy 152 U-groove	MHI 307380	500	225-345
Alloy 52 U-groove	MHI NX2686JK	470	225-315
Alloy 52M Butter	ENSA DPM Butter	430	240-300
Alloy 152M U-groove	IHI 444537/WC83F8	550, 560	255-345
Alloy 690 CRDM	RE243	415, 420	240
Alloy 690 CRDM	WP142	445, 455	247
Alloy 690 Plate	114092	460	260
Alloy 690 Plate	B25K-2	515	270

Test Systems

- PNNL Systems:
  - Two 36-specimen testing systems (built for NRC/EPRI program)
  - Three 12-specimen testing systems (built for NRC peening program)
  - Two 6-specimen testing systems (modified/shared with LWRS program)
  - Two 3-specimen testing systems (owned by DOE/BES)
  - Five 3-specimen testing systems (built for NRC CGR)
- Measurements of servo load, tare load, and autoclave temperature are performed every ~60 seconds.
  - These key environmental variables are stable to within ≤0.5%.
- Direct current potential drop (DCPD) is used to detect crack initiation in-situ; DCPD voltage across specimen increases strongly at the point of initiation due to crack extension.
- DCPD data acquisition software was rewritten for the NRC/EPRI program to optimize the interaction between hardware and measurement parameters for multiple specimen initiations.
- All specimens within a single system are at the same load; applied stress is controlled by adjusting gauge diameter.
- Load train carries the load of a failed specimen through a catch mechanism (6, 12, and 36-specimen systems).



Project Plan and Schedule

Test Item	2021	2022	2023
Alloy 600/52/152			
Stress Effects			
As-Welded A182			
7.5% CF A182 at YS			
7.5% CF A182 at 0.9YS			
15% TS A182			
25% TS A182			
Temperature Effects			
15% CF A182 at 330 °C			
15% CF A182 at 300 °C			
Dissolved H2 Effects			
15% CF A181 at High H2			
15% CF A181 at Low H2			
Other			
15% CF A182 vs Surface Cond.			
15% CF A52/152 – Defects			
15% CF A52/152 – Dilution			
15% CF A690 – HAZ			

Testing Status (no new info)

Alloy 600/182 – 15% Cold Forged Results (tested at YS)

Alloy 600 (15% CF) Heat ID	Material	Total Specimens	# Tested	# Cracked	Median Initiation Time (hrs)
NX6106XK-11	Alloy 600 Plate	9	9	9	1433
33375-2B	Alloy 600 Plate	9	9	9	413
WNP5	Alloy 600 CRDM	9	9	9	457
522068	Alloy 600 Plate	9	9	9	550
COMBINED	---	*36*	*36*	*36*	*480*

Alloy 182 (15% CF) Heat ID	Material	Total Specimens	# Tested	# Cracked	Median Initiation Time (hrs)
Studsvik 8001231	Alloy 182 Build-up	9	9	8	83
Flawtech 844305	Alloy 182 DMW	9	9	9	106
Phase 2B	Alloy 182 DMW	9	9	7	2238
KAPL 823030	Alloy 182 U-Groove	9	9	6	1635
COMBINED	---	*36*	*36*	*30*	*736*

Testing Status (no new info)

Alloy 600/182 – 15% Cold Forged Results (tested at YS) (cont.)

Alloy 182 (15% CF) Heat ID	Material	Total Specimens	# Tested	# Cracked	Median Initiation Time (hrs)
EWI	Alloy 182 U-Groove	12	12	12	30

Testing Status (new info in purple)

Alloy 600 – 15% Cold Forged Results (tested at Sub-YS)

90% YS					
Alloy 600 (15% CF) Heat ID	Material	Total Specimens	# Tested	# Cracked	Median Initiation Time (hrs)
33375-2B	Alloy 600 Plate	6	6	6	843
WNP5	Alloy 600 CRDM	12	12	11	590 1 @ > 913
COMBINED	---	*18*	*18*	*17*	717
80% YS					
Alloy 600 (15% CF) Heat ID	Material	Total Specimens	# Tested	# Cracked	Median Initiation Time (hrs)
33375-2B	Alloy 600 Plate	6	6	6	1323
WNP5	Alloy 600 CRDM	6	6	**6**	**1071**
COMBINED	---	*12*	*12*	***12***	**1244**

Testing Status

Alloy 182 – 15% Cold Forged Results at *90%* YS

- 15% CF Alloy 182 is exhibiting much longer initiation times when tested at 90% yield stress (compared to tests at 100% YS).
  - Median initiation time is ~13x longer than testing at 100% YS.

Alloy 182 (15% CF) Heat ID	Material	Total Specimens	# Tested	# Cracked	Median Initiation Time (hrs)
Studsvik 8001231	Alloy 182 Build-up	6	6	5	10437
KAPL 823030	Alloy 182 U-Groove	6	6	6	9245
COMBINED	---	*12*	*12*	*11*	9788

Testing Status (new info in purple)

Alloy 182 – 7.5% Cold Forged and As-Welded Results (tested at YS)

- 7.5% CF Alloy 182 is exhibiting longer initiation times than 15% CF material.
- As-welded Alloy 182 also exhibiting longer initiation times (no initiations to date).

Alloy 182 (7.5% CF) Heat ID	Material	Total Specimens	# in Test	# Cracked	Median Initiation Time (hrs)
Studsvik 8001231	Alloy 182 Build-up	6	6	**0**	**3 @ >7734 (overloaded) 3 @ >23,154**
KAPL 823030	Alloy 182 U-Groove	6	6	3	**3 @ >23,697 >12,361 (all KAPL)**
COMBINED		*12*	*12*	*3*	***15,444***

Alloy 182 (As-welded) Heat ID	Material	Total Specimens	# in Test	# Cracked	Median Initiation Time (hrs)
Studsvik 8001231	Alloy 182 Build-up	3	3	**0**	**>44,480 (5.07 yrs)**
Flawtech 844305	Alloy 182 DMW	3	3	**0**	**>44,480**
Phase 2B	Alloy 182 DMW	3	3	**0**	**>44,480**
KAPL 823030	Alloy 182 U-Groove	3	3	**0**	**>44,480**
COMBINED		*12*	*12*	***0***	**>44,480**

Testing Status (new info in purple)

Alloy 182 – 15% Cold Forged Results at 330 °C and 300 °C (tested at YS)

- Testing Studsvik and **Phase 2B** welds to determine temperature effects (activation energy).

Alloy 182 (15% CF) Heat ID & Material	Test Temp.	Total Specimens	# Tested	# Cracked	Median Initiation Time (hrs)
Studsvik 8001231 Alloy 182 Build-up	360 °C	9	9	8	83
	330 °C	12	12	12	333
	300 °C	**12**	**12**	**12**	**302**

Testing Status

Alloy 182 – 15% Cold Forged *Dissolved Hydrogen Effects*

- 15% CF Alloy 182 tested at ±7.5 mV about the Ni/NiO stability ECP.
- Evaluating PWSCC initiation sensitivity to potential undetected ΔECP variations.
  - ΔECP is monitored and precisely controlled for the test temperature via [H] control

Alloy 182 (15% CF) Heat ID	ECP [mV]	Total Specimens	# Tested	# Cracked	Median Initiation Time (hrs)
Studsvik 8001231	-7.5 mV	6	6	3	3 initiated in ~30 hrs 3 @ >7613 hrs no initiation
Studsvik 8001231	+7.5 mV	5	5	5	30
KAPL 823030	-7.5 mV	6	6	5	30 1 @ >7613 hrs no initiation
KAPL 823030	+7.5 mV	6	6	5	30 1 @ >88 hrs no initiation

Testing Status (new info in purple)

Alloy 690/52/152 – 15% Cold Forged Results (tested at YS)

- Currently on track to reach >5 years exposure by the end of the program.

Alloy 690 (15% CF) Heat ID	Material	Total Specimens	# in Test	# Cracked	Median Initiation Time (hrs)
RE243	Alloy 690 CRDM	3	3	**0**	**>50,163 (5.73 yrs)**
WP142	Alloy 690 CRDM	3	3	**0**	**>50,163**
114092	Alloy 690 Plate	3	3	**0**	**>50,163**
B25K-2	Alloy 690 Plate	3	3	**0**	**>50,163**
COMBINED		*12*	*12*	***0***	**>50,163**

Alloy 52/152 (15% CF) Heat ID	Material	Total Specimens	# in Test	# Cracked	Median Initiation Time (hrs)
MHI 307380	Alloy 152 U-groove	6	6	**0**	**>50,163 (5.73 yrs)**
IHI 444537/WC83F8	Alloy 152M U-groove	6	6	**0**	**>50,163**
MHI NX2686JK	Alloy 52 U-groove	6	6	**0**	**>50,163**
ENSA DPM Butter	Alloy 52M Butter	6	6	**0**	**>50,163**
COMBINED	*Alloy 152, Alloy 52*	*12, 12*	*12, 12*	***0, 0***	**>50,163, >50,163**

Testing Status - Summary (new info in purple)

Temperature-Adjusted Medians with Q = 185 kJ/mol

Material	Condition	σ/σ_{YS}	Median Testing Time [hrs]	
			Test Temp.	Reference Temp.
			360 °C	325 °C
A182	15% CF	1	736	5,760 (0.66 yrs)
A182	7.5% CF	1	>15,444	120,860 (13.7 yrs)
A182	15% CF	0.9	9,788	76,598 (8.7 yrs)
A182	0% CF	1	>44,480	>348,088 (39.7 yrs)
A600	15% CF	1	480	3,756 (0.43 yrs)
A690/52/152	15% CF	1	>50,163	>392,562 (44.8 yrs)

Data Insights

- Alloy 182
  - 15% CF materials tested at YS exhibit a wide range of initiation times; 45% are at very low times.
    - Data scatter is complicating application of the data to predictions for plant components.
    - Wide range of initiation times suggests potential microstructural variability effects on Alloy 182 initiation.
    - Initiation times of 15% CF material are consistent with publicly available data (e.g., EdF).
  - Substantially longer initiation times for lower strength conditions (7.5% CF and as-welded).
  - Much longer initiation times for 15% CF material tested at 90% YS; initiations at ~1.1 years.
  - The Alloy 182 stress exponent for the heats being tested in this project appears to be substantially different than historical Alloy 600 values.
- Alloy 600
  - Results thus far are consistent with values from PNNL LWRS program and other publicly available data.
  - Sub-YS data shows that initiation of Alloy 600 is possible at 80% of the YS
    - Combined median initiation time was is 260% longer than Alloy 600 tested at the YS (heats WNP5 & 33375-2B)
- Alloy 690/152/52
  - No initiations after 5.7 years.
  - Current estimated FOIs based on median initiation times after 5.7 years: Alloy 690 = 105x, Alloy 152/52 = 68x.
    - Instrumented specimens showed no indication of initiation via DCPD.
    - Un-instrumented specimens showed no indication of initiation via system response (e.g., actuator movement).
    - Specimen surface examinations for cracks are underway.

Next Steps

- Alloy 182
  - Temperature effects: test Studsvik specimens at 300 °C. Begin tests on Phase 2B specimens at 330 °C.
  - Applied stress effects: continue 7.5% YS and as-welded specimen tests.
  - Finish tests on tensile strained specimens.
  - Finish tests investigating dissolved hydrogen effects.
  - Bend bar tests for short-crack initiation/growth tests.
- Alloy 600
  - Applied stress effects: complete ongoing tests at 80% YS.
- Alloy 690/52/152 and variants
  - Testing goal of 5 years reached. Specimen evaluations starting soon.
    - Current plan is to continue testing while mutually agreeable.
  - Begin testing weldment interfaces looking at dilution zones, HAZ and defects.
    - Material selection underway and a subject of discussion at this meeting

The End