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Primary Water Stress Corrosion Cracking Tests and Metallurgical Analyses of Davis-Besse Control Rod Drive Mechanism Nozzle #4

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Outline

- Background
- Test materials
- Crack growth rate testing
- Metallurgical analyses
- Summary

Background

- 2002 PWSCC indication
  - Through wall PWSCC in Nozzle #3
  - Significant corrosion of the low alloy steel reactor pressure vessel head (RPVH)
  - Replaced with RPVH from the cancelled Midland, MI PWR
  - Operation resumed in 2004
- 2010 PWSCC indication
  - Observed after 5.5 effective full power years of operation
  - Bare metal visual: 13 potential leaking nozzles, Nozzle #4 confirmed leaker
  - Volumetric: 11 axial indications, 1 small circumferential indications, and 2 leak paths Nozzles #4 & #67
  - Surface: 12 indications; 6 were potential leakers

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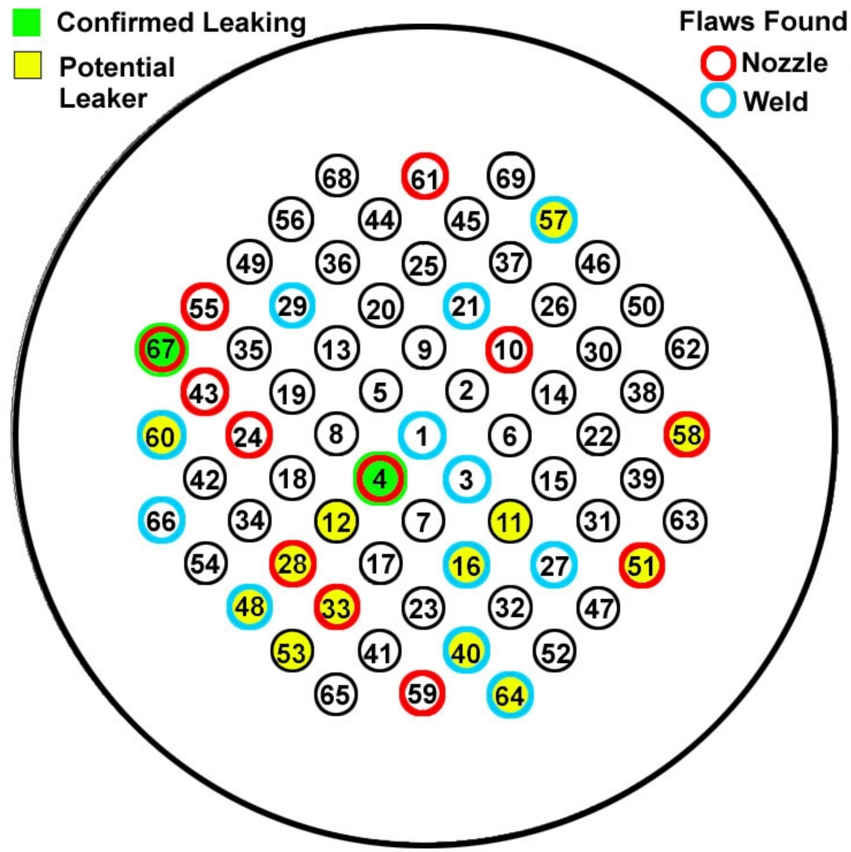
2010 Inspection Results



Continued Operation

- Licensee performed ½ nozzle repairs on 24 nozzles
- Sample of Nozzle #4 provided to the NRC for testing and analyses
- On June 18, 2010, the licensee informed NRC that Davis-Besse would shut down on October 1, 2011 to replace the head

Test Materials

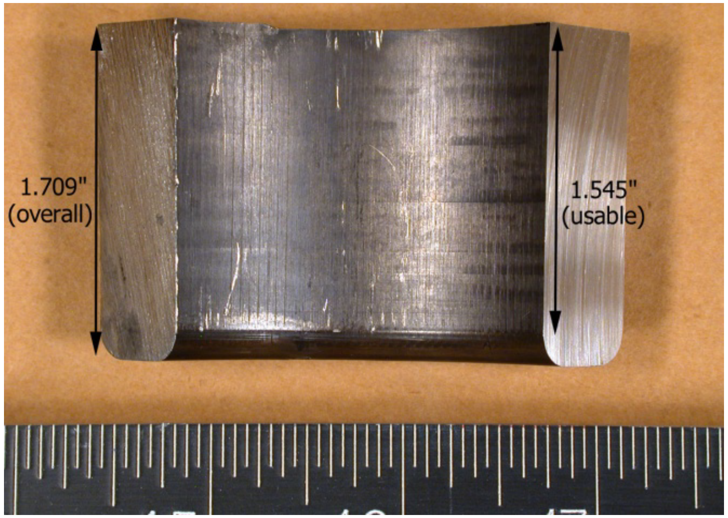
Alloy 600 heat	Ni	Cr	Fe	Mn	C	P	Cu	Co	Si	S	B* (appm)
SB-167 Specification	72.0 min	14.0-17.0	6.0-10.0	1.0 max	0.15 max	N/A	0.5 max	N/A	0.5 max	0.015 max	N/A
M3935	77.89	15.58	6.25	0.27	0.028	0.004	0.01	0.01	0.37	0.0022	69
M7929	75.28	16.12	7.24	0.26	0.03	N/A	0.01	0.05	0.45	0.003	77

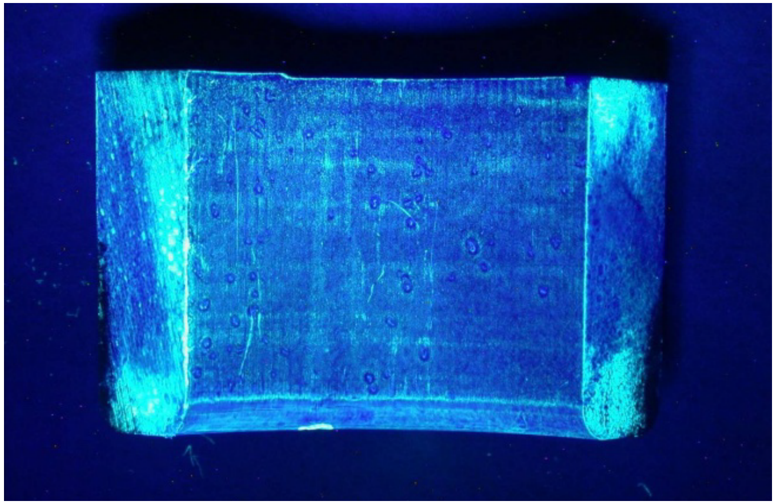
*Boron concentration measured by PNNL

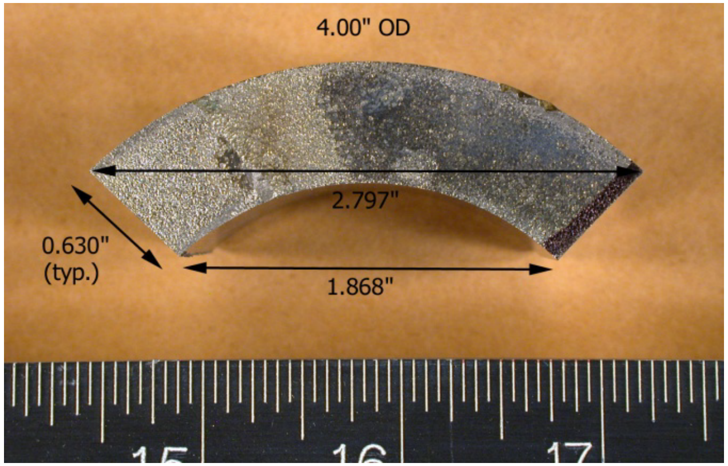
Alloy 600 heat	Yield Strength, MPa	Tensile Strength, MPa	Elongation, percent	Hardness, Vickers*		
				Min	Max	Ave ± SDEV
SB-167 Specification	205 min	550 min	35 min	N/A	N/A	N/A
M3935	334	590	60	146.6	190.7	160.2 ± 6.5
M7929	296	668	53	166.6	209.5	186.5 ± 9.6

*Hardness in the crack growth plane for M3935-RPVH #1-CRDM #1 and M7929-RPVH #2-CRDM #4 measured by PNNL

Nozzle #4 Section

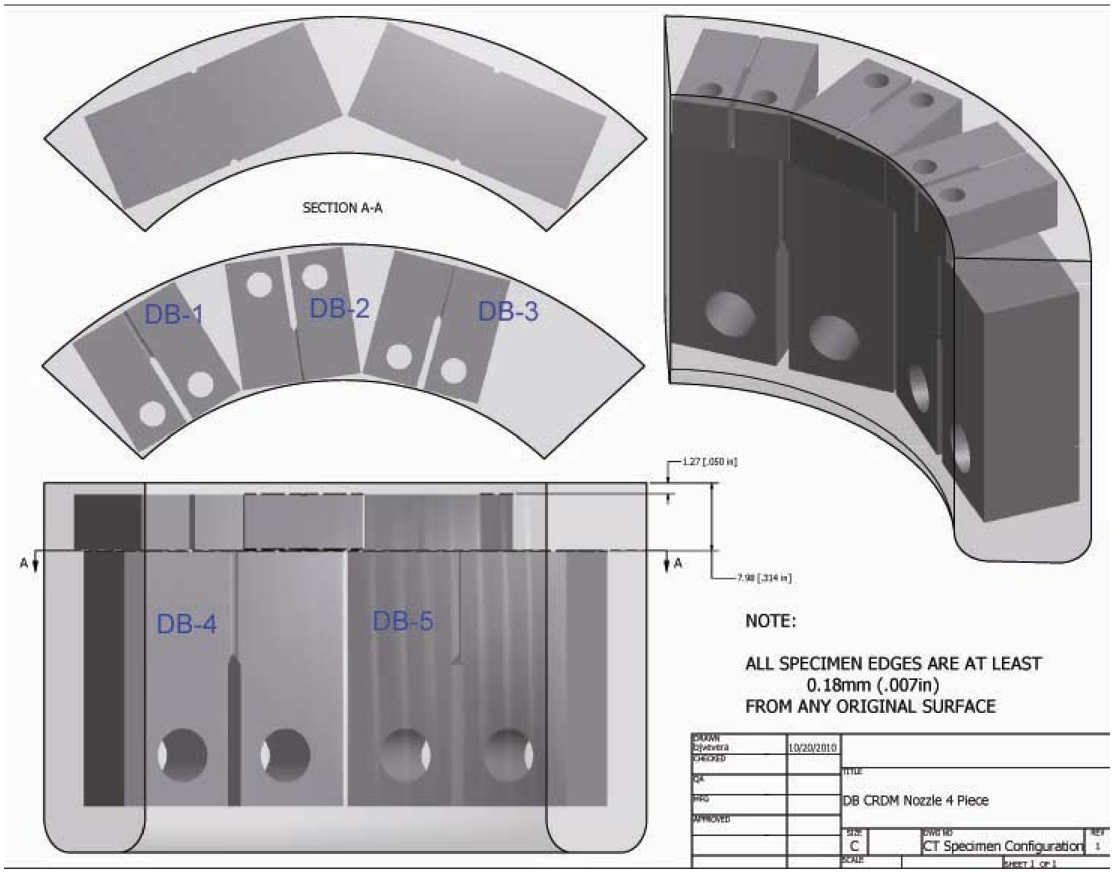






- 90° section of Nozzle #4 cut from below the J-groove weld
- Penetrant test revealed no surface cracking indications
- 5 compact tension (CT) test specimens machined from this section

Test Specimen Machining



- Layout for compact tension specimens
- Sample for metallurgical analyses (next to Specimen DB-3)
- All specimens were free releasable after machining

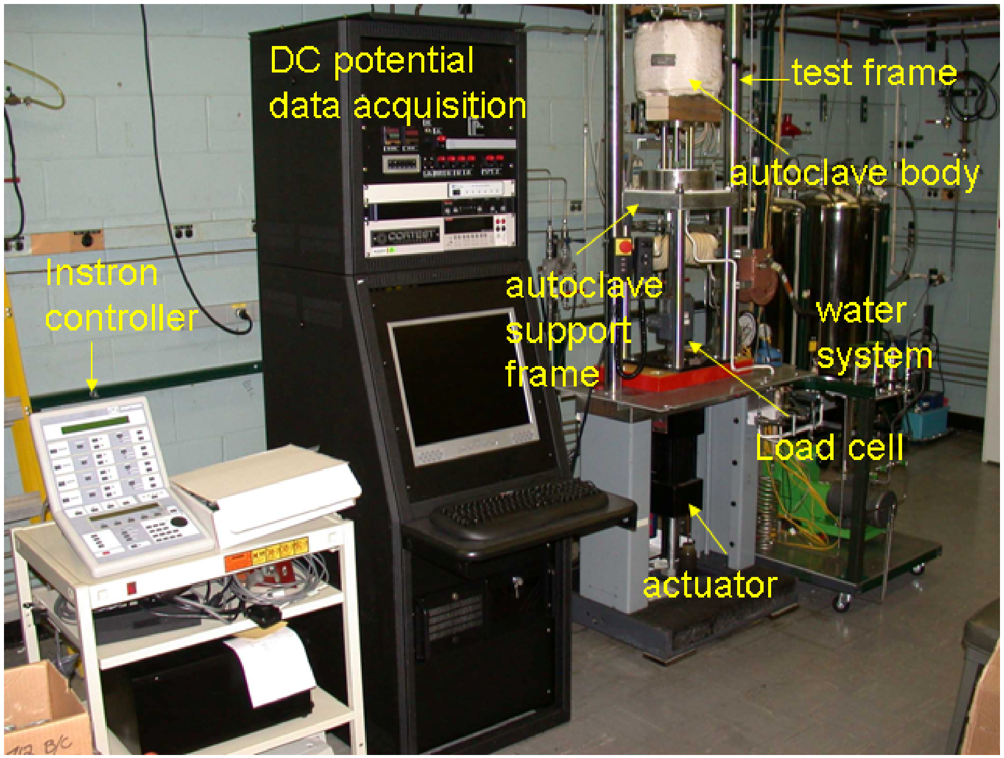
Test Specimens

- 2 - ½ thickness (T)- compact tension (CT) specimens
  - Tested at Argonne National Laboratory (ANL)
- 3 - ¼ T-CT specimens
  - 1 tested at ANL
  - 2 tested at Pacific Northwest National Laboratory (PNNL)

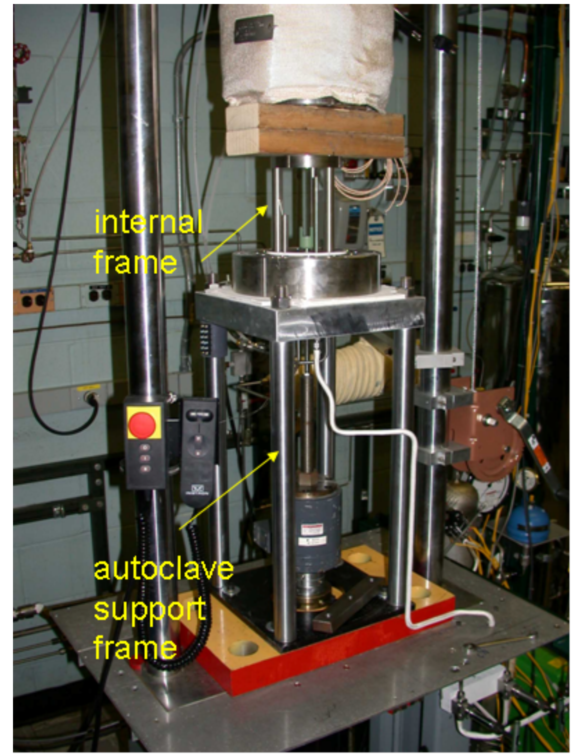
Testing and Analyses

- Machined compact tension test specimens supplied to Argonne National Laboratory (ANL) and Pacific Northwest National Laboratory (PNNL)
- Primary objective was to obtain crack growth rates for the replacement RPVH alloy 600 nozzle material (heat M7929).
- Secondary objective was to characterize Alloy 600 material microstructure and correlate microstructure to crack growth rates

Crack Growth Rate Testing

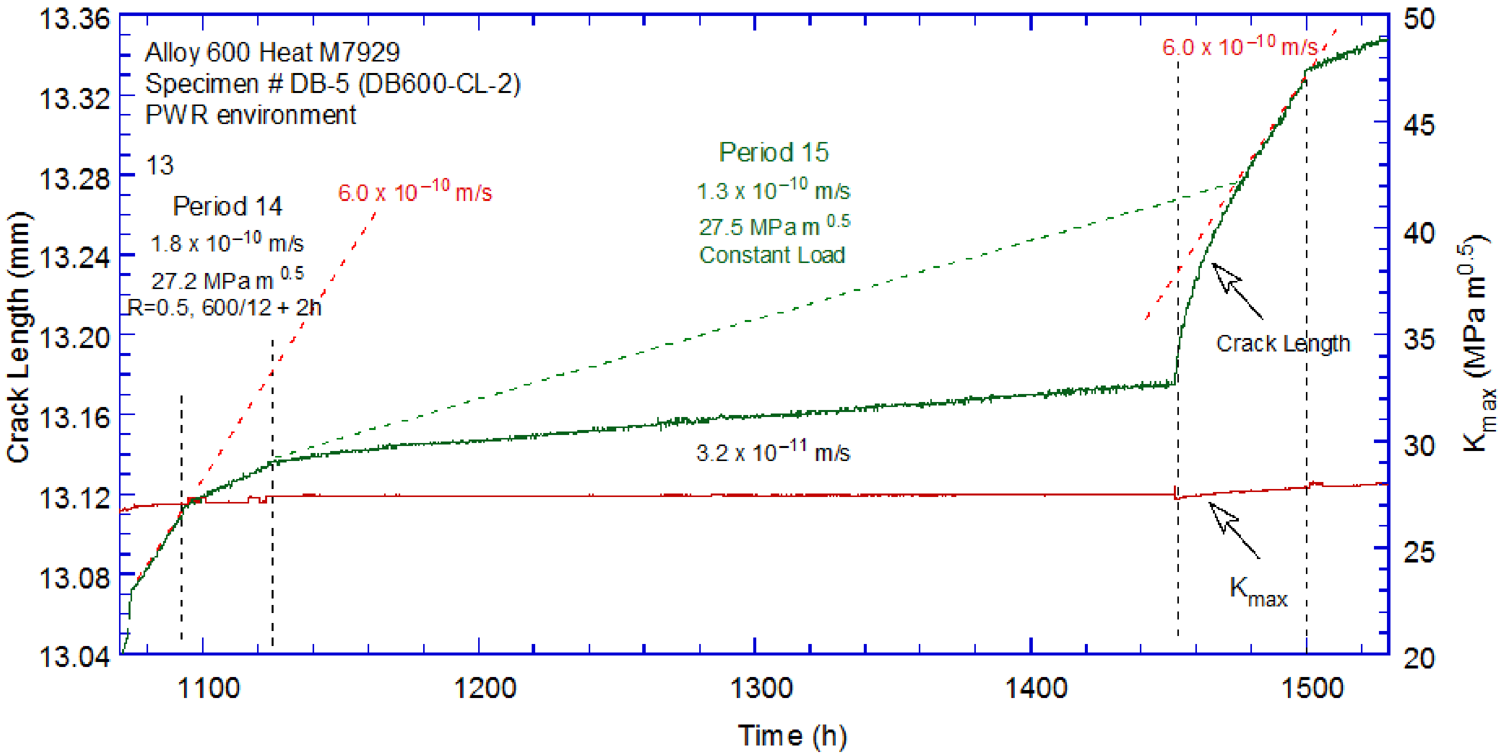


Crack growth rate test systems located at ANL used to obtain accurate crack growth rates



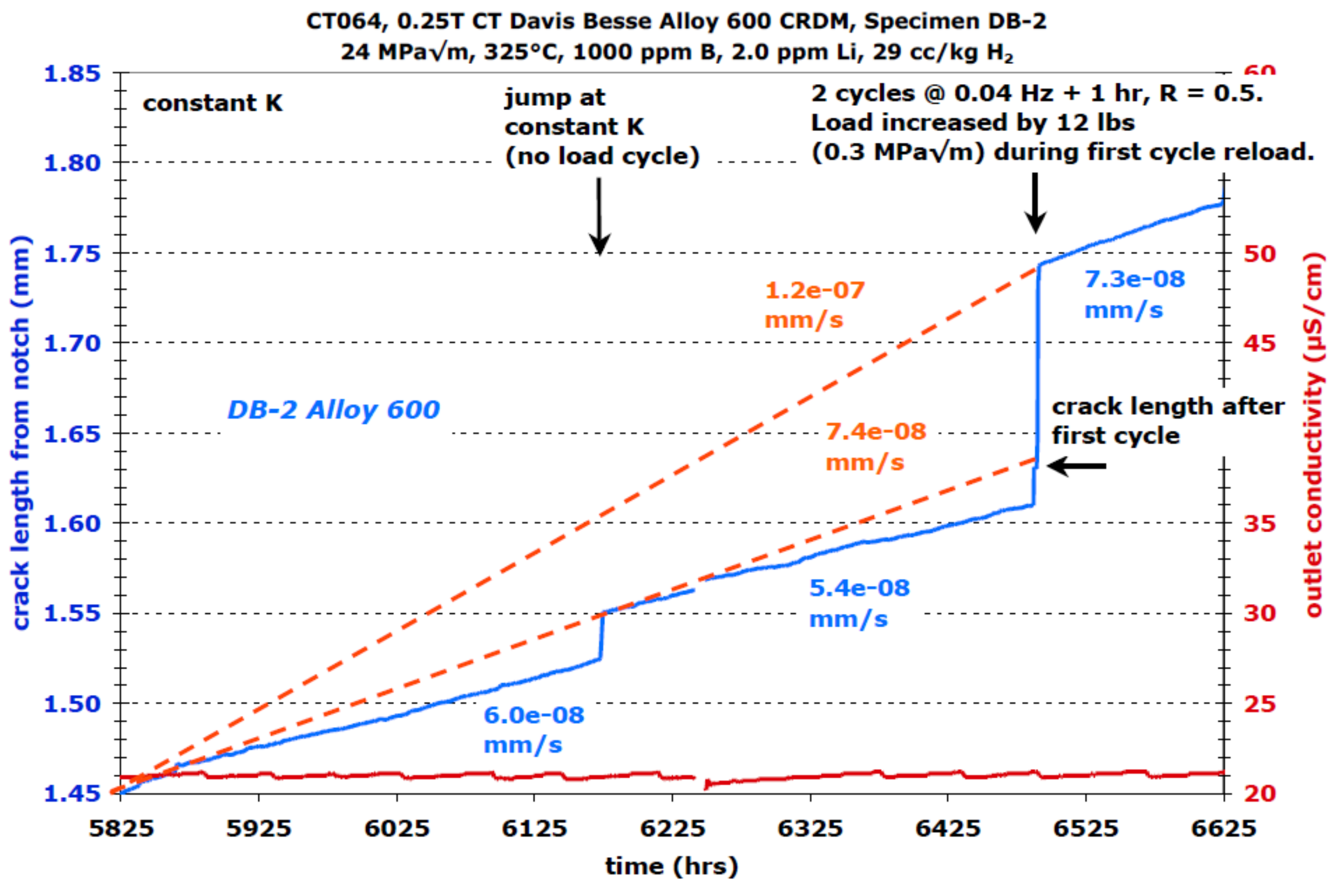
Testing in autoclaves under simulated PWR conditions

Crack Growth Rate Testing



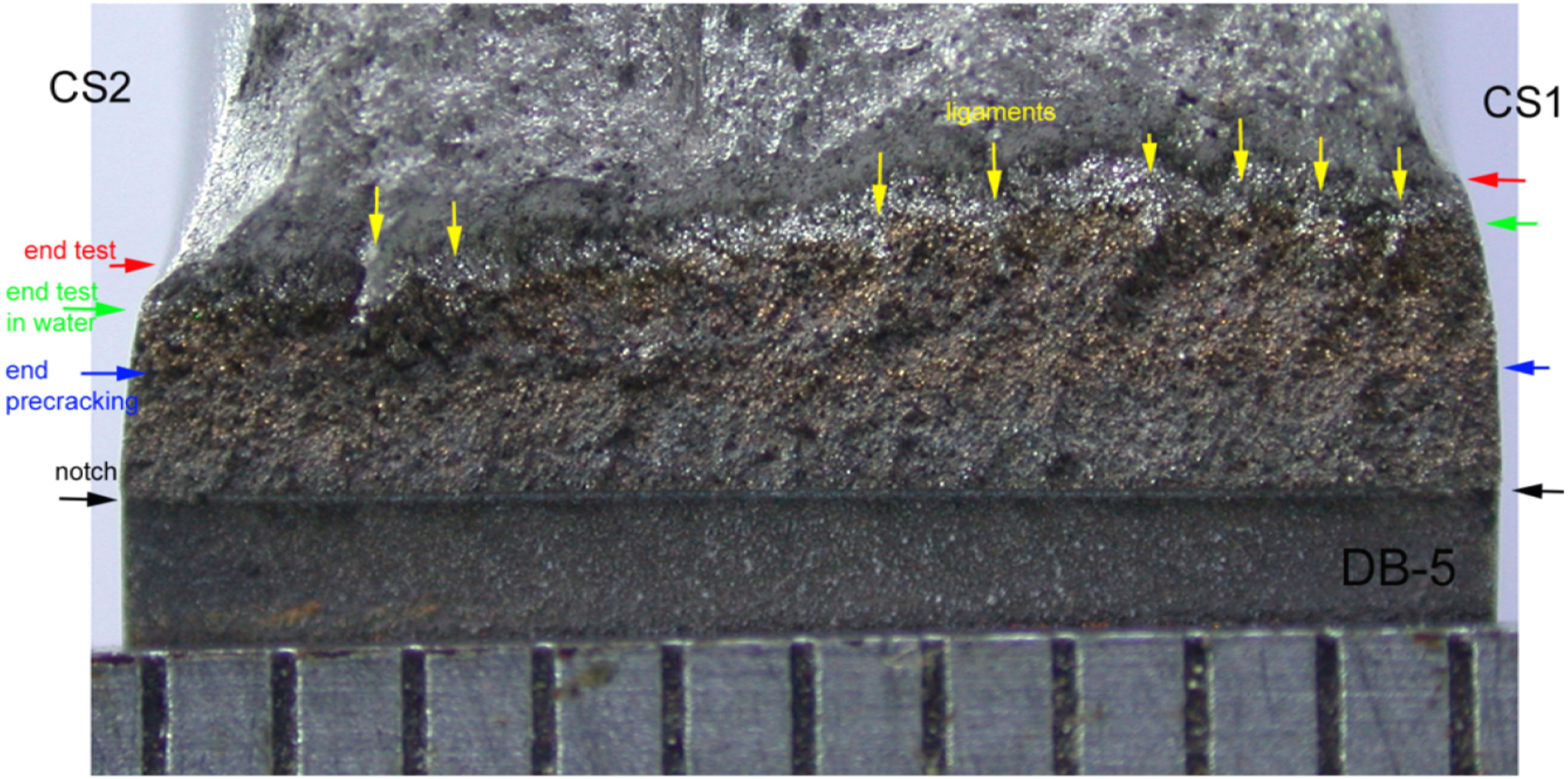
- Corrections applied to measured CGR to account for the formation of ligaments

Crack Growth Rate Testing



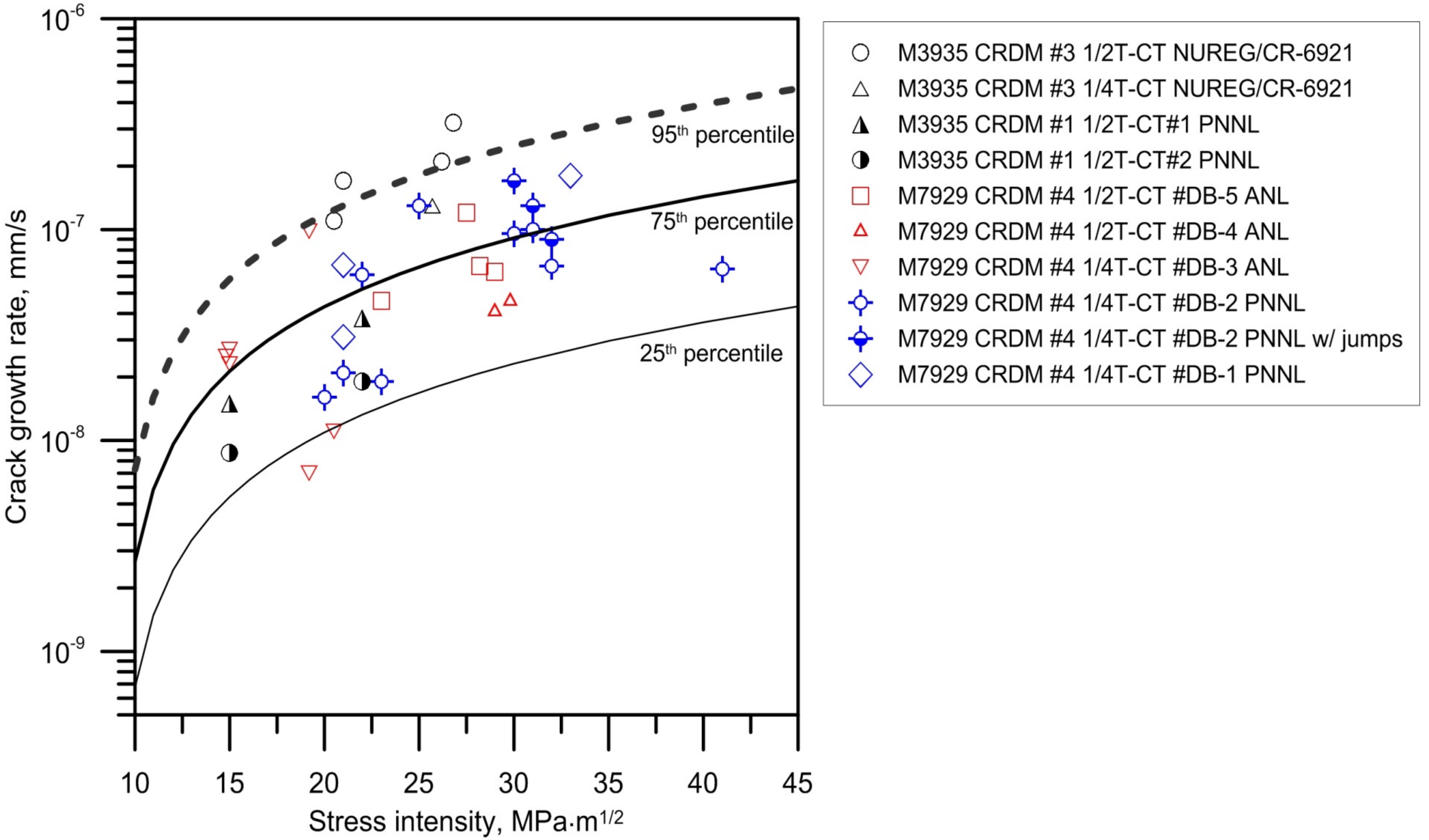
- Formation and breaking of ligaments that affected CGR measurements was also observed at constant K

Crack Growth Rate Testing

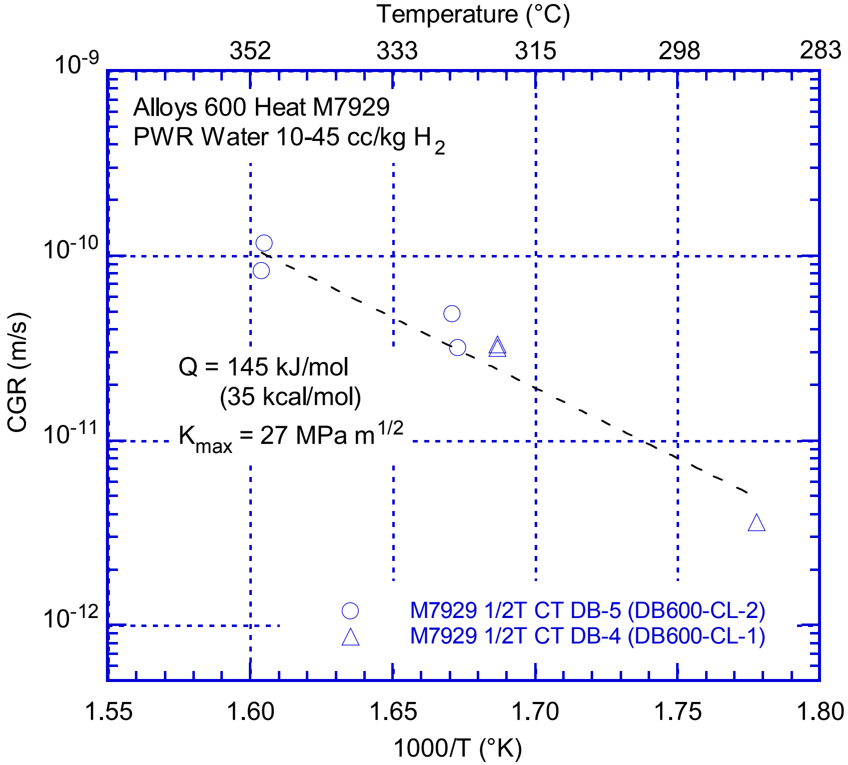


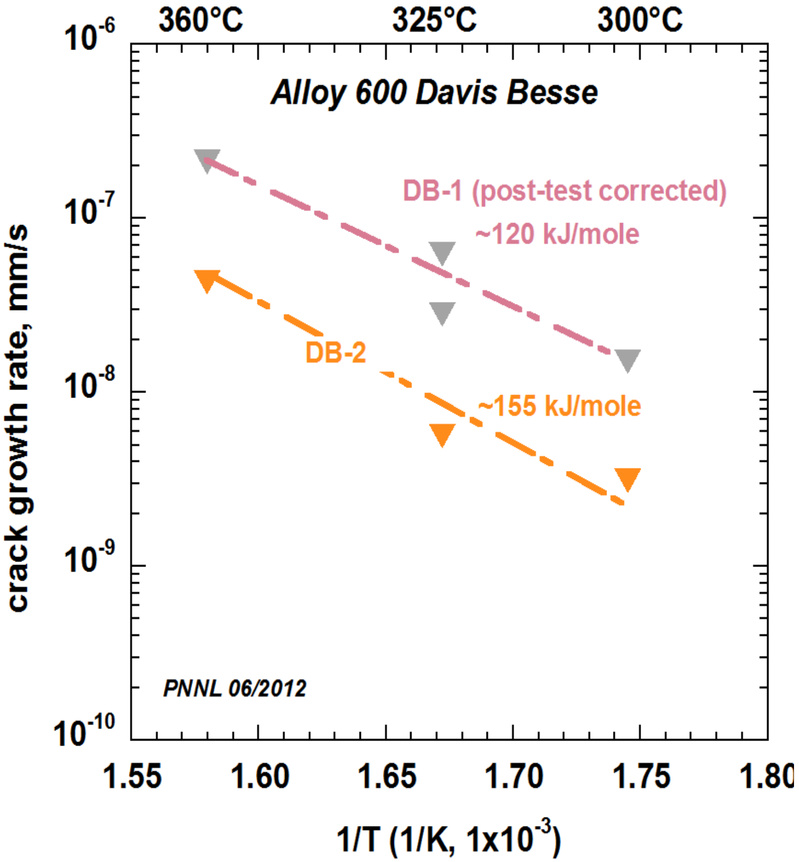
- Formation of ligaments that affected CGR measurements was confirmed by examination of the fracture surfaces

Crack Growth Rates



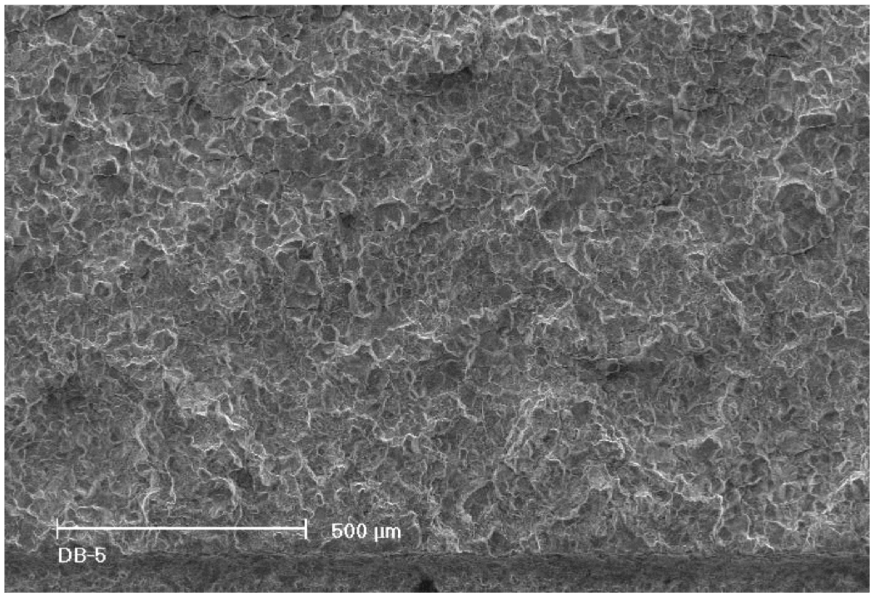
Temperature Sensitivity

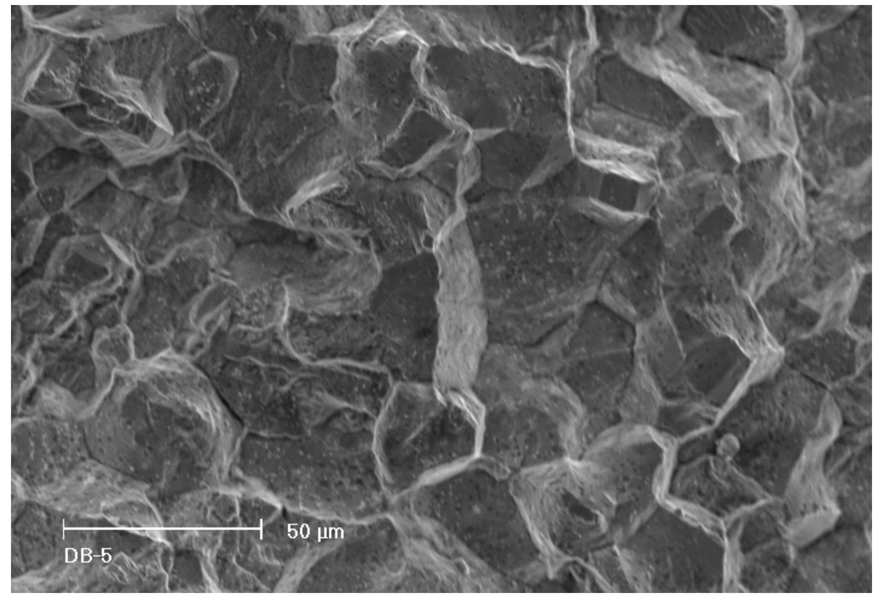




- Activation energy typical of alloy 600

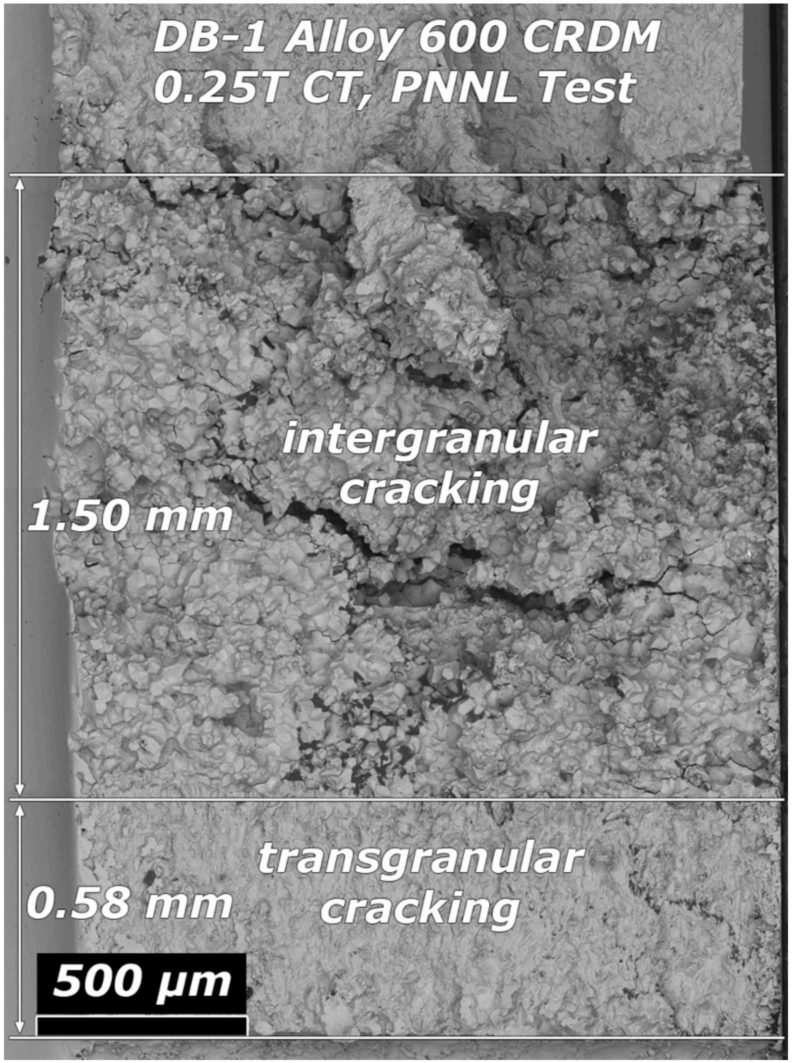
Fracture Surfaces





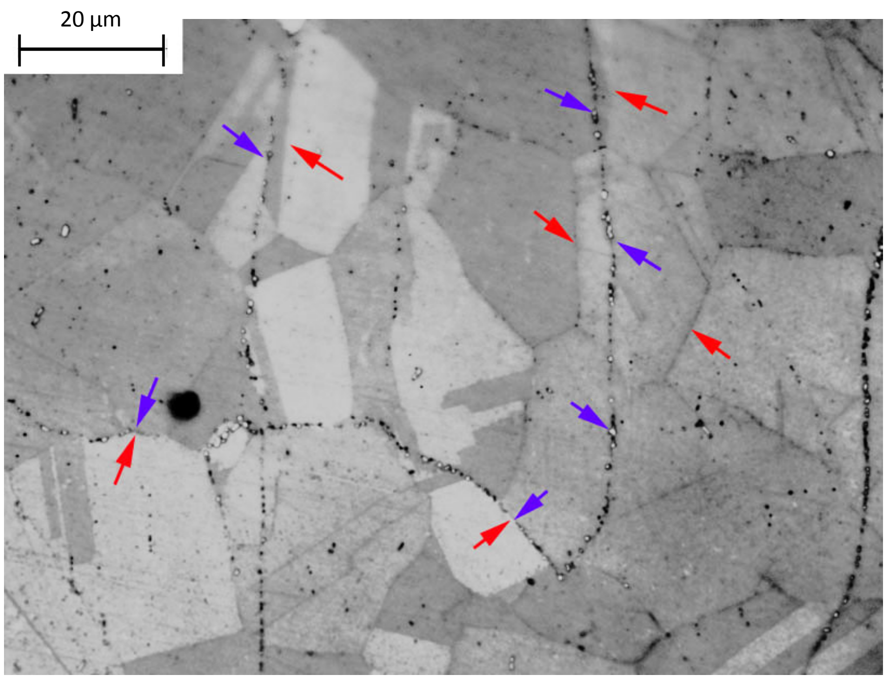
- Predominately intergranular cracking on fracture surface of the CT specimens

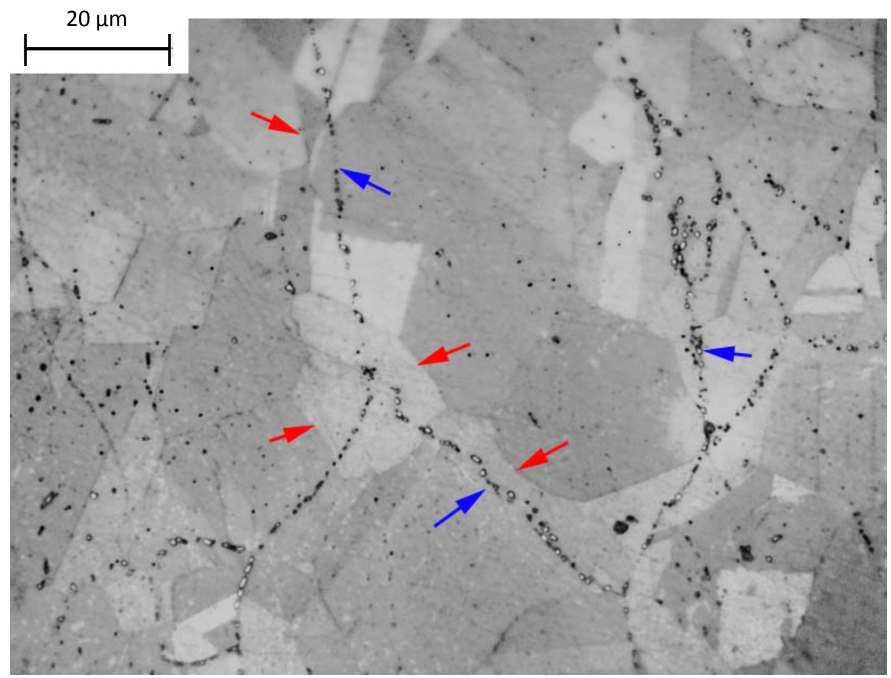
Fracture Surfaces



- Transgranular extension during air precracking at room temperature.
- Rapid intergranular engagement
- High degree of crack branching

Metallurgical Analyses

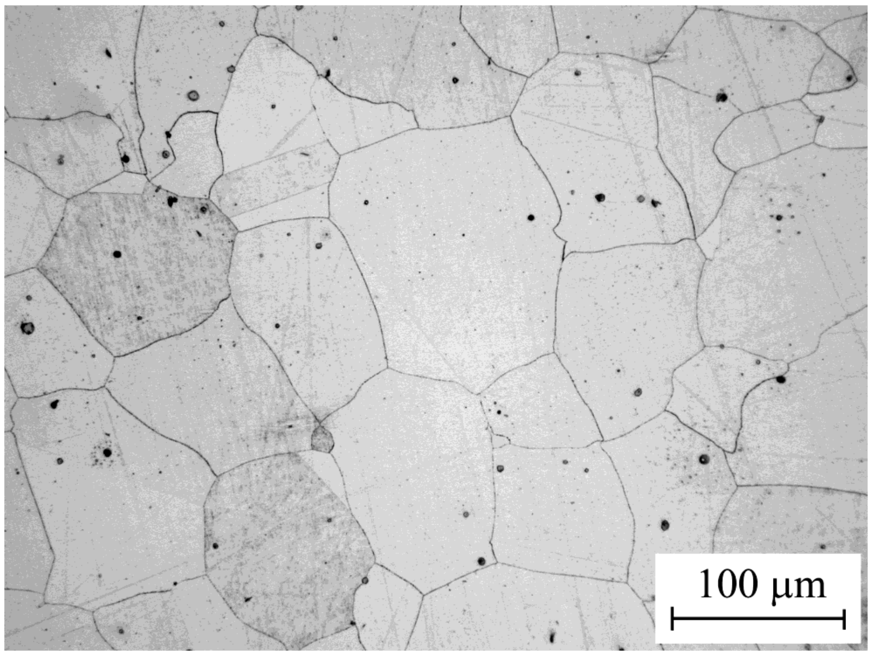


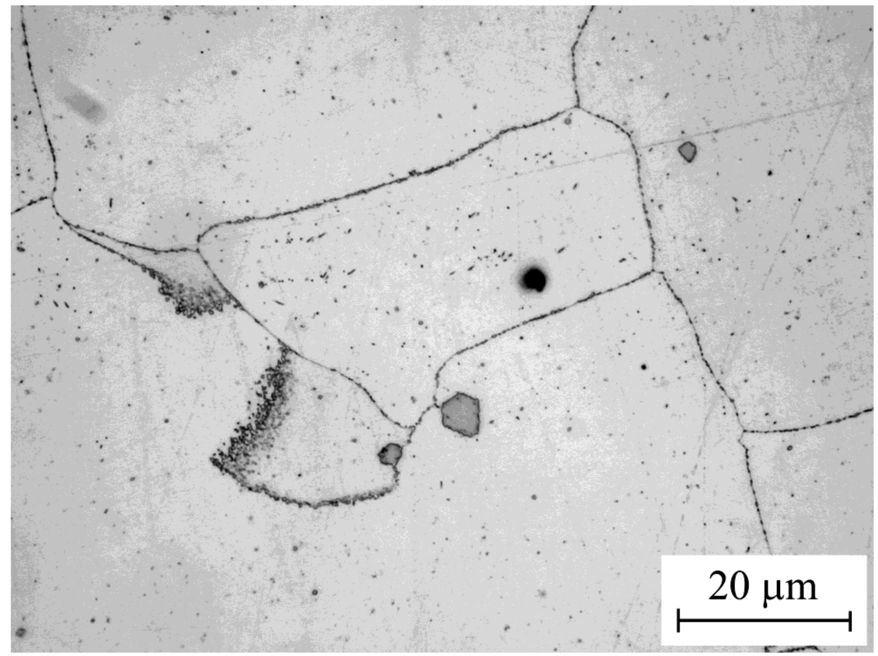


Replacement Davis-Besse RPVH CRDM Nozzle #4 – Alloy 600 Heat M7929

- Red arrows: grain boundaries
- Blue Arrows: carbides
- Conclusion: carbides located on prior grain boundaries; not an ideal microstructure for PWSCC resistance

Metallurgical Analyses

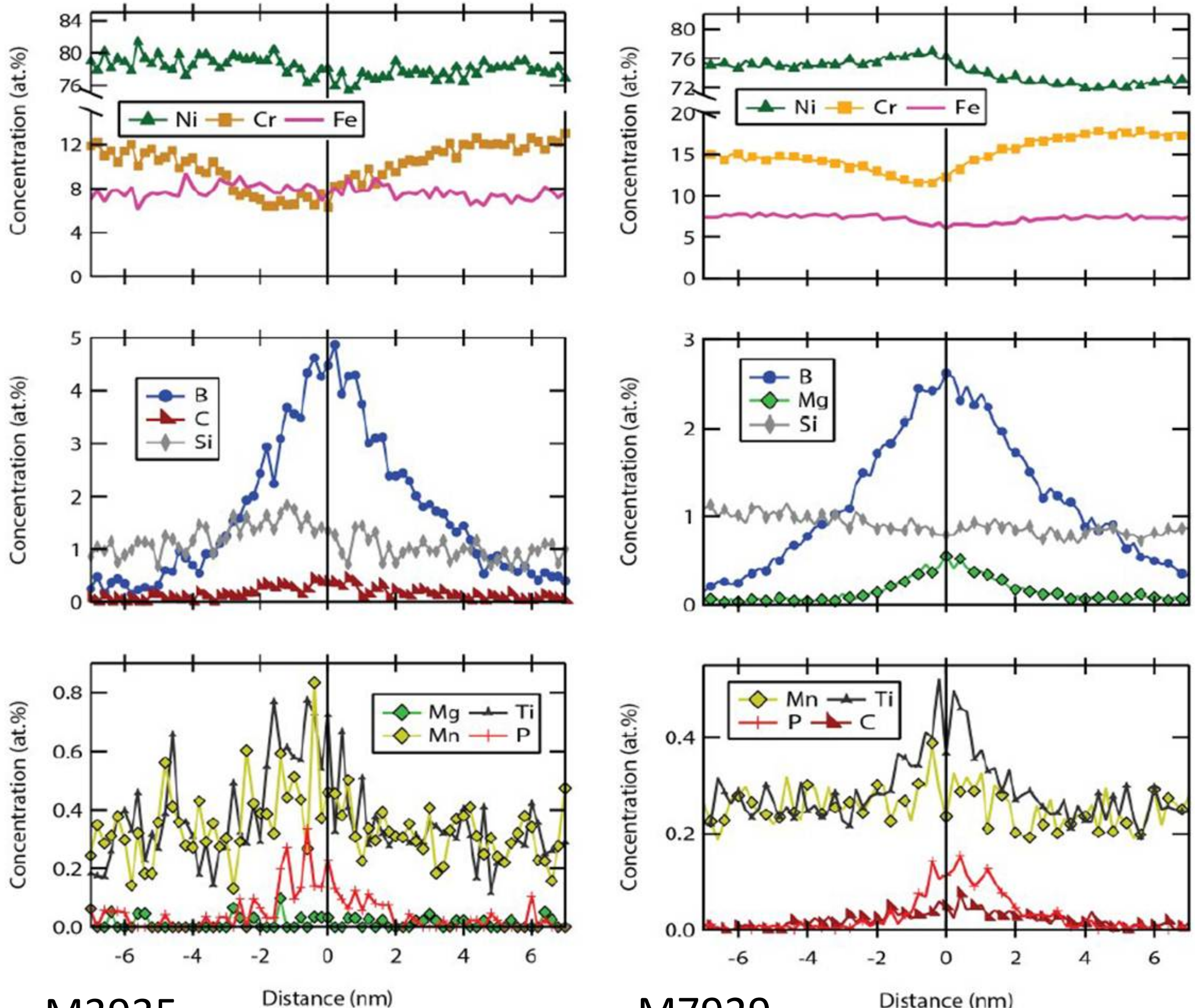




Original Davis-Besse RPVH CRDM Nozzle #3 – Alloy 600 Heat M3935

- Carbides present at grain boundaries
- Material was susceptible to PWSCC (NUREG/CR-6921, November 2005)

Atomic Probe Tomography



M3935

M7929

Davis-Besse Alloy 600

Original RPVH

- 15.78 EFPY
- PWSCC of CRDM nozzles and boric acid corrosion of the low alloy steel RPVH
- Alloy 600 heat M3935
  - Grain boundary carbides with 500 – 700 nm spacing
  - 200 – 400 micron grain size
  - 160.2 ± 6.5 Hv
  - 6 atomic percent boron at grain boundaries with significant chromium depletion

Replacement RPVH

- 5.5 EFPY
- PWSCC of CRDM nozzles
- Alloy 600 heat M7929
  - Transgranular carbides on prior grain boundaries
  - 15 – 30 micron grain size
  - 186.5 ± 9.6 Hv
  - 2.5 atomic percent boron at grain boundaries

Summary

- Laboratory crack growth rates in the replacement Davis-Besse RPVH were typically between the 25% and 95% of the MRP-55 disposition curves
- Fracture surface examinations show a high degree of intergranular engagement consistent with materials susceptible to PWSCC
- Alloy 600 heat M3935 from the original RPVH were found to have significant enrichment of boron on grain boundaries that were depleted in chromium
- Microstructure of the alloy 600 M7929 heat from the replacement RPVH likely contributed to the increased PWSCC susceptibility

Acknowledgements

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