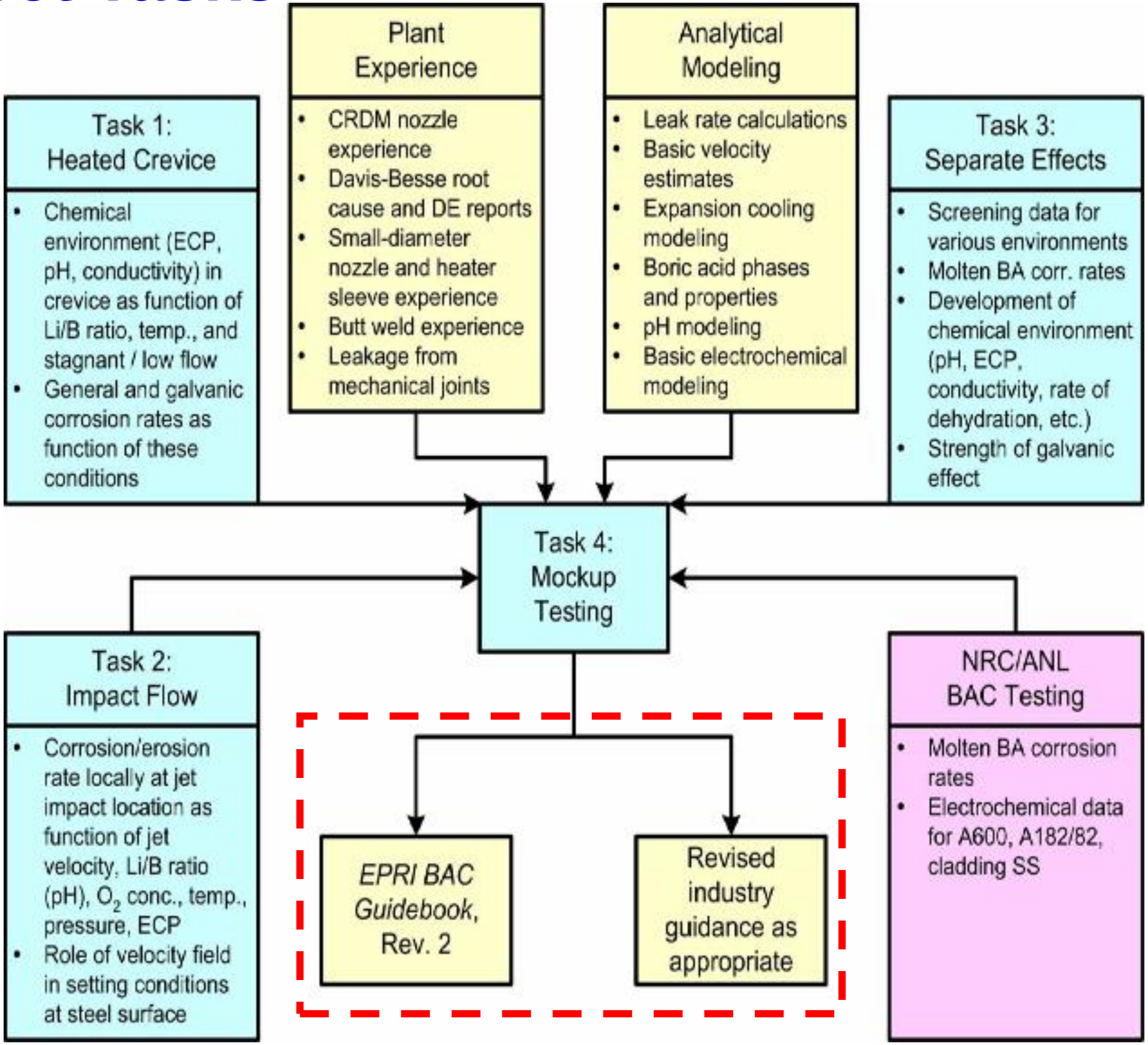
Boric Acid Corrosion Testing Program Overview

NRC/EPRI MRP Meeting
Rockville, MD
February 29, 2012

Rick Reid
EPRI

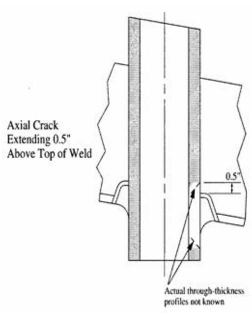
Project Tasks



ELECTRIC POWER RESEARCH INSTITUTE

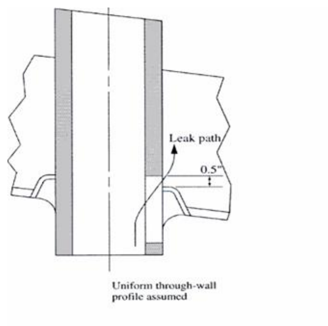
Implications Assessment of BAC Testing

Overview of BAC Test Programs



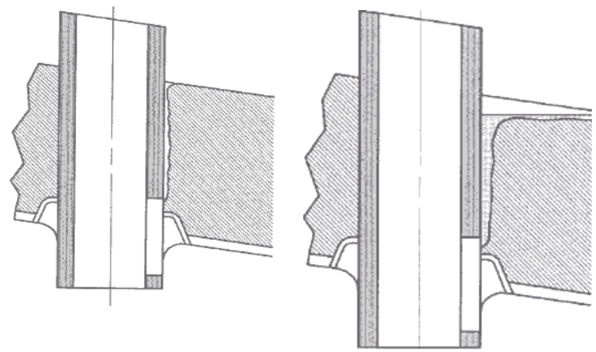
Task1

Stagnant/Low Flow Corrosion



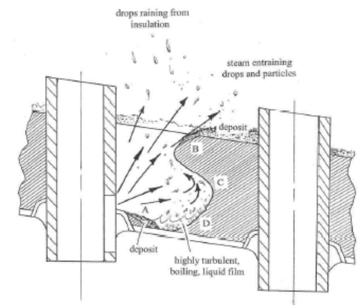
Task 2

Flowing/Impingement Corrosion



Task 3

Separate Effects:
Immersion Tests
Electrochemical Tests
Chemical Concentration Tests



Task 4

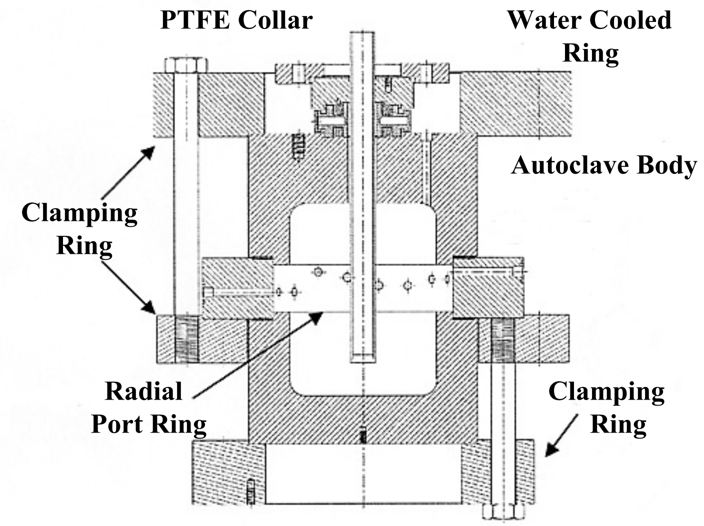
Full-Scale Mockup Testing

- Task 1: Rockwell Scientific performed corrosion tests in stagnant and low flowing (<0.005gpm) primary water simulating early stages of degradation
- Task 2: University of New Brunswick performed primary water impingement corrosion tests
- Task 3: Dominion Engineering, Inc. measured corrosion rates in immersion corrosion environments including concentrated boric acid and wetted molten boric acid, among other tests
- Task 4: DEI and SwRI designed and conducted tests with full-scale mockups of leaking CRDM nozzles and BMNs that simulated a range of operating conditions

ELECTRIC POWER RESEARCH INSTITUTE

Task 1: Heated Crevice Tests (1/2)

- Objectives:
  - Quantify corrosion rates likely to occur in the early stages of a CRDM nozzle leak
- Methodology:
  - Simulated annulus between Alloy 600 and LAS RPV Head
    - Crevice device to simulate the corrosion of (1) low alloy steel and (2) high chromium steel exposed to stagnant or low flow primary coolant
  - Volumetric flow rate: 2 liters/hr
  - Water chemistry: 3.5 ppm Li - 2000 ppm B, 0.5 ppm Li – 200 ppm B
  - Temperatures: 200°C, 250°C, and 280°C

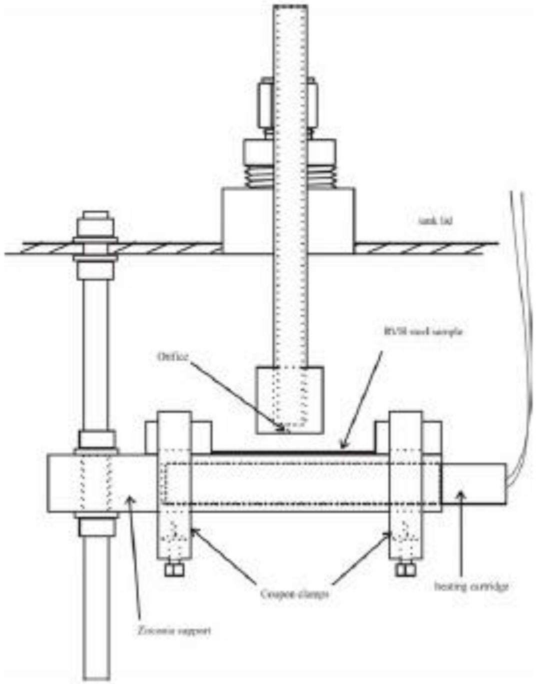


Task 1: Heated Crevice Tests (2/2)

- Results and Findings:
  - Rapid corrosion does not occur at test conditions
  - Beginning of cycle chemistry slightly more aggressive (~0.10 mm/yr (4 mpy) versus ~0.03 mm/yr (1 mpy))
  - Corrosion rate is insensitive to test temperature changes
  - Most pronounced corrosion rate change occurred when 25 cc/kg H2 change to air at 200°C (near zero to 0.13 mm/yr (5 mpy) in RPV steel and 0.08 mm/yr (3 mpy) in 5% Cr steel).
  - Galvanic coupling the LAS to Alloy 600 does not result in significant increases to the corrosion rate for the conditions tested
- Report: Reactor Vessel Head Boric Acid Corrosion Testing (MRP-163) *Task 1: Stagnant and Low Flow Primary Water Tests (2005)*

Task 2: Jet Impingement Tests (1/2)

- Objectives:
  - Investigate corrosion of low-alloy steel by primary water jet impingement
- Methodology:
  - Impinge water jet onto a RPV low-alloy steel heated plate
  - Temperature: 325°C; Pressure: 2200 psig
  - Test parameters investigated:
    - Test duration
    - Flow characteristics
    - Purge gas
    - Jet length
    - Initial chemistry
    - Heating
    - Jet orientation
  - Electrical resistance and electrochemical potential measured.
  - Scanning electron microscopy and surface profilometry measurements for calculated wastage rates



Impingement Test Assembly

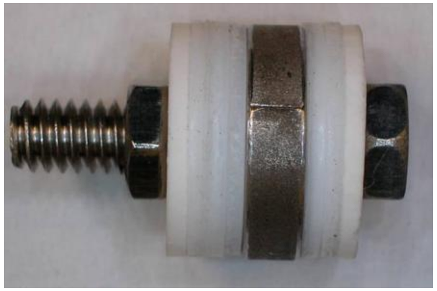
EPRI ELECTRIC POWER RESEARCH INSTITUTE

Task 2: Jet Impingement Tests (2/2)

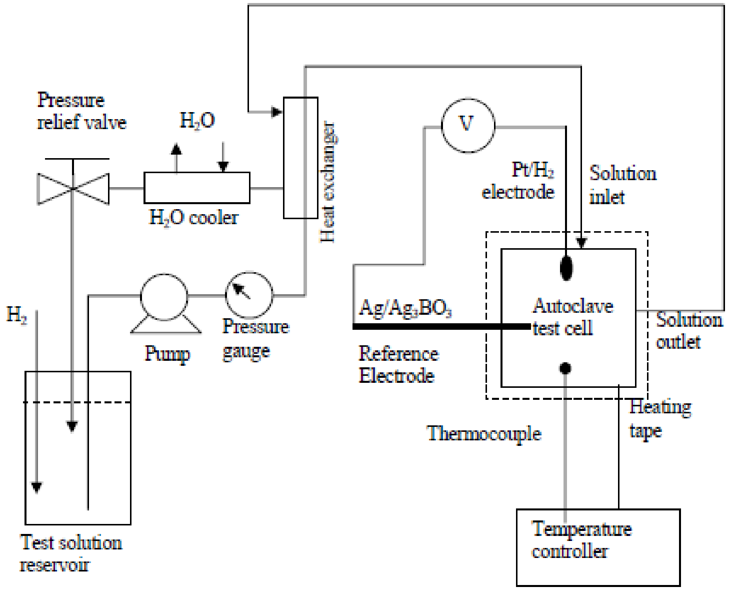
- Results and Findings:
  - Heat flux, water chemistry, flow rate, jet velocity and oxygen are all important parameters affecting LAS corrosion
  - Damage at jet impingement is minimal
  - Corrosion rates are markedly higher at higher coolant boron to lithium ratios (lower pH) and higher levels of dissolved oxygen.
  - Corrosion rates – 0.002 to 0.2 in^3/yr
- Report: Reactor Vessel Head Boric Acid Corrosion Testing (MRP-164) *Task 2: Jet Impingement Studies (2006)*

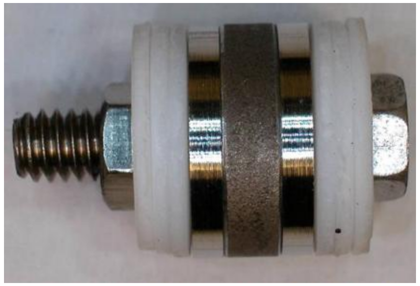
Task 3: Separate Effects Tests (1/3)

- Objective
  - Investigate the separate effects of chemistry, temperature, and sample configuration on corrosion rates
- Methodology
  - Immersion tests using low alloy steel corrosion coupon in an autoclave with a liquid/slurry phase and a gas phase



Crevice Specimen





Galvanic Specimen

Task 3: Separate Effects Tests (2/3)

- Methodology (continued)
  - Test conditions tested included the following parameters:
    - Temperature: 100°C, 200°C, or 315°C
    - Boron concentration: 2000 ppm as boron, 1000 g boric acid per 1 kg of water, or 9000 g of boric acid per 1 kg of water
    - Lithium to boron ratio: no lithium, Li/B = 0.002, or Li/B = 0.05
    - Gas composition: oxygen or a mix of hydrogen (10%) and nitrogen (90%)
    - Sample configuration: uncoupled (free), creviced (with PTFE), or galvanically coupled (to Alloy 600)
  - Corrosion rates determined by the mass and the test duration using the initial dimensions to determine the surface area.

Plant Chemistry: B – 500 to 2000 ppm; Li/B – 0.002 to 0.007

Task 3: Separate Effects Tests (3/3)

- Results and Findings:
  - pH is the most significant parameter – temperature, galvanic coupling, crevice geometry, and oxygen are secondary effects to pH.
  - Slurries of hydrated molten boric acid can corrode LAS at up to 5 in/yr
  - Dynamic concentration tests indicated that molten boric acid mixtures are unlikely to retain the moisture necessary for high corrosion rates
  - Lithium concentration could lower corrosion rates by 10X or greater
- Report: Reactor Vessel Head Boric Acid Corrosion Testing (MRP-165) *Task 3: Separate Effects Testing (2005)*

ANL Test Program (1/3)

- Objective
  - Determine the electrochemical potentials (ECPs) and corrosion rates of RPV head and CRDM nozzle materials in boric acid solutions at varying temperatures and environmental conditions.
- Methodology
  - Three different environments designed to simulate the postulated stages of corrosion attack were investigated:
    - High pressure/high temperature aqueous solutions
    - High temperature/atmospheric pressure hydrogen-boron-oxygen environments (Hydrated and Dry)
    - Low temperature saturated boric acid solutions

ANL Test Program (2/3)

- Results
  - No corrosion detected for Alloy 600 and Type 308 stainless steel
  - No corrosion detected for reactor vessel steel in dehydrated molten boric acid at 150, 260, and 300°C.
    - High corrosion rates (0.6-6.0 in/yr) were measured for reactor vessel steel in molten boric acid with water additions at 140-170°C. However, it may be very difficult under plant conditions to keep molten boric acid hydrated.
    - Maintaining heads clean eliminates potential for development of hydrated molten boric acid conditions

ANL Test Program (3/3)

- Results (continued)
  - Corrosion significantly slowed by the presence of lithium, with effect most apparent at high temperatures. Increased boric acid volatility at higher temperatures limits ability to concentrate, increasing Li/B ratio and lowering corrosion rate
  - Corrosion rates under deoxygenated conditions were about half to two-thirds of the rate under the corresponding oxygenated conditions
  - No significant acceleration due to galvanic coupling or crevices

Full-scale CRDM Mock-up BAC Tests

- Objectives:

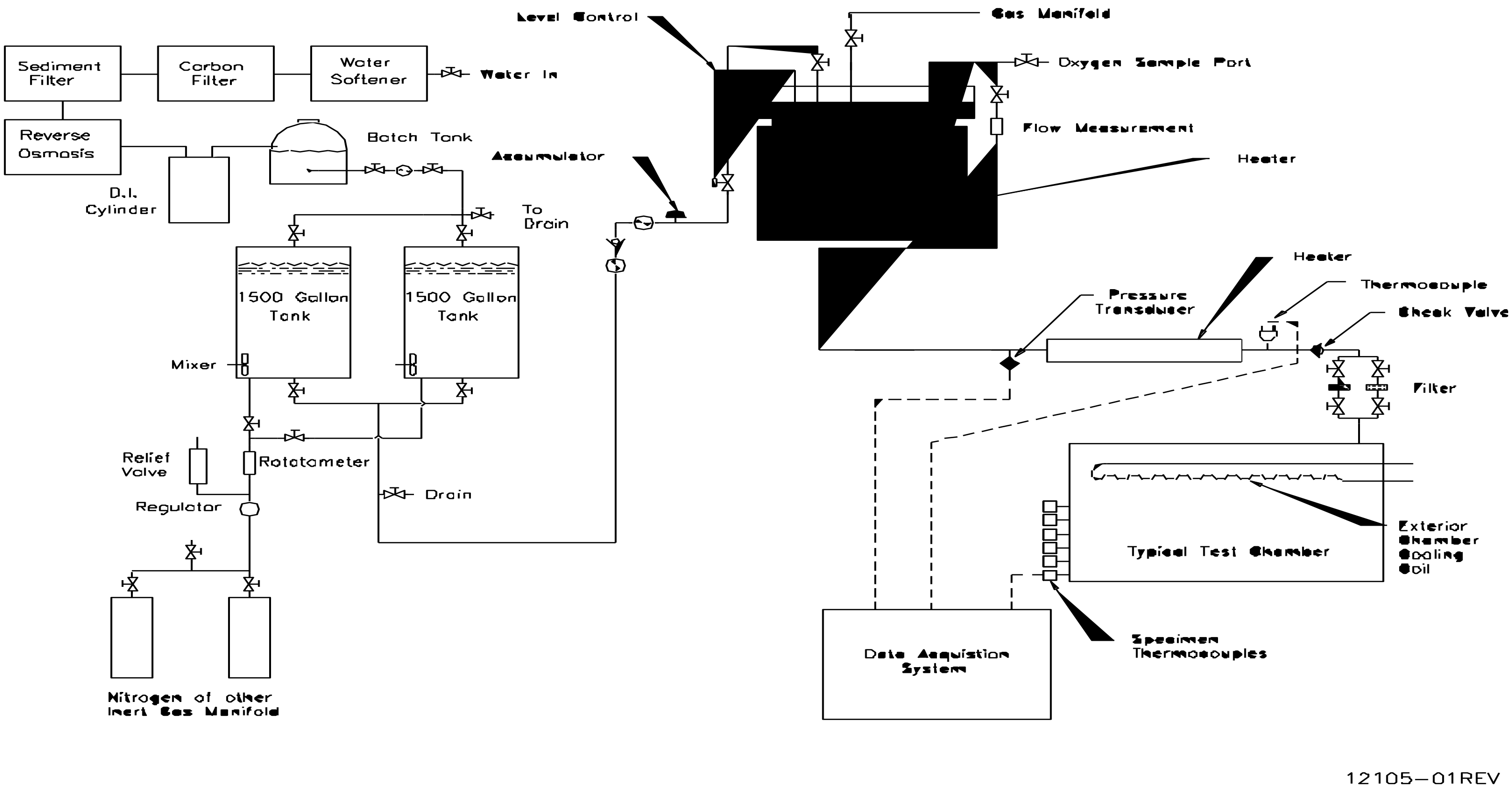
  Perform full-scale CRDM BAC tests with prototypic geometries, materials, thermal-hydraulic conditions and primary coolant chemistries

- Approach:

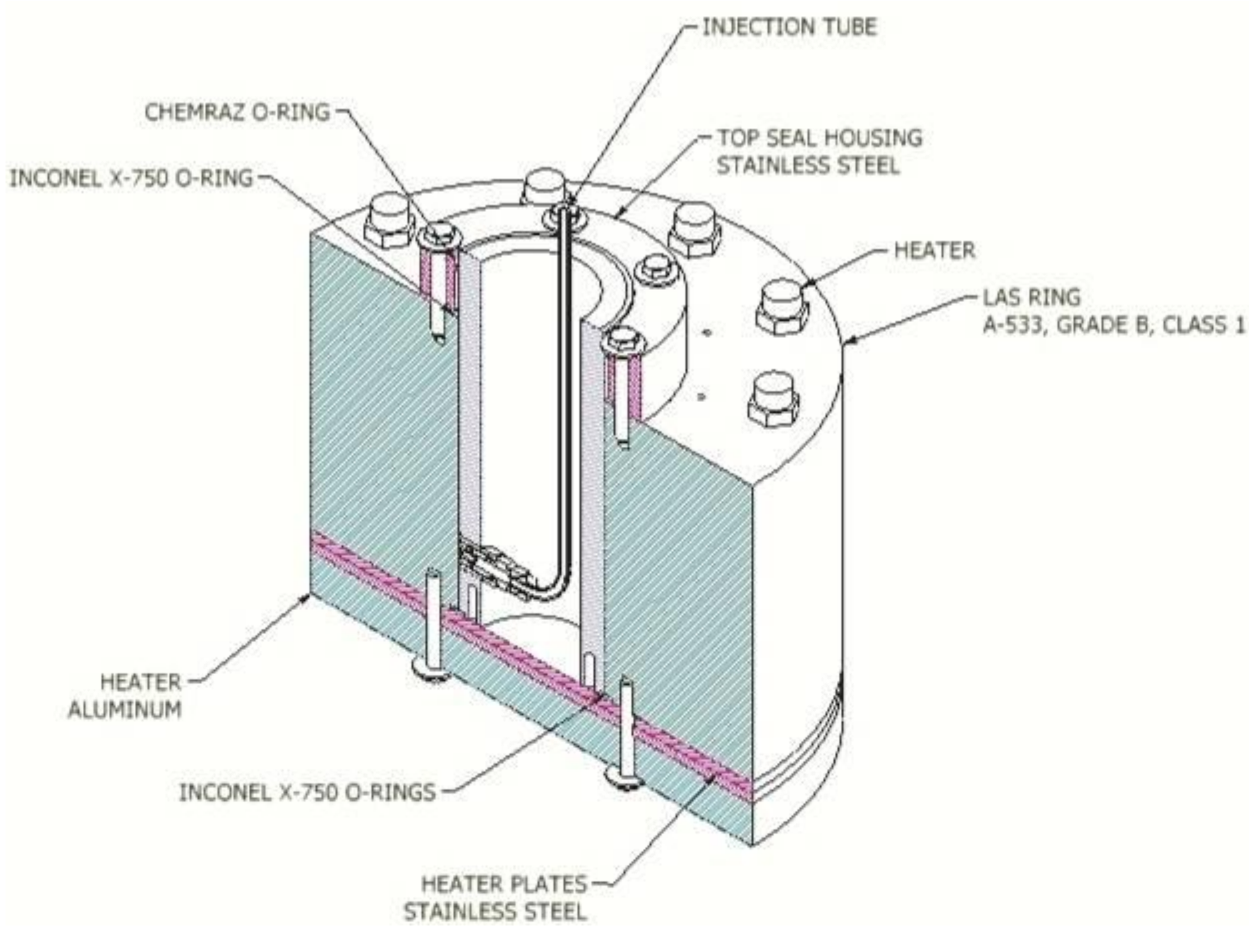
  - A modular CRDM mockup fabricated from low-alloy steel and alloy 600 materials. With capability to vary:
    - Flow rate, Temperature, Pressure, Chemistry
    - LAS-Nozzle annulus gap width and geometry

- Testing Completed and Report Issued December 2009
  - EPRI 1019085 (MRP-266): Full-Scale CRDM Mockup Boric Acid Corrosion Testing

Test Assembly Schematic



CRDM Mock-Up


INJECTION TUBE
CHEMRAZ O-RING
TOP SEAL HOUSING
STAINLESS STEEL
INCONEL X-750 O-RING
HEATER
LAS RING
A-533, GRADE B, CLASS 1
HEATER
ALUMINUM
INCONEL X-750 O-RINGS
HEATER PLATES
STAINLESS STEEL

CRDM Test Results Summary (1/4)

Test No.	Ave. Flow Rate [gpm]	Gap [mil]	Total Material Wastage [in^3/yr]	Area-Avg Wastage Rate [in/yr]	General Observations	Photo of Post-Test Annulus
01	0.0114	1	0.10	0.015	(-) Localized impingment with no wastage (-) Tenacious deposits around injection site (-) Single flow channel to top of annulus (-) Localized (irregular) wastage at top of annuuls	
02	0.0015	10	0.00	0.002	(-) LAS annulus was still clean (-) Insignificant wastage observed (-) Small pit directly beneath injection site (-) Small amount of loose white deposits located at injection site and top of annulus	
03	0.0110	10	0.24	0.034	(-) Annular flow path was originally upward (evidence of pitting) (-) Tenacious deposits formed around the entire injection site (-) No wastage at local injection site (-) Wastage was observed around injection site and within deposit ring (-) Effluent passed through restrictive passage along bottom of annulus	
04	0.0920	10	4.10	0.214	(-) Few deposit were formed in the annulus (-) Flow fanned out vertically above injection site (-) Coloration of deposits on top of LAS indicated corrosion products (-) Minimal wastage at local injection site (-) Significant wastage observed around and below injection site	

ELECTRIC POWER RESEARCH INSTITUTE

CRDM Test Results Summary (2/4)

Test No.	Ave. Flow Rate [gpm]	Gap [mil]	Total Material Wastage [in^3/yr]	Area-Avg Wastage Rate [in/yr]	General Observations	Photo of Post-Test Annulus
06a	0.0100	10	0.93	0.189	(-) Minimal wastage at injection site (-) Measurable wastage around and below injection site (-) Defined horizontal boundary - Top 2" of LAS appear to have not been exposed to effluent	
07a	0.1000	10	16.30	0.290	(-) No evidence of injection site on the cavity surface (-) Few deposits formed in annulus (-) Wastage was around and below cavity (-) Wastage was observed at the top of the annulus at both 90° locations from the injection site (-) Evidence of possible leakage at lower o-ring	
08a	0.0100	10	0.90	0.183	(-) Minimal wastage at injection site (-) Measurable wastage around and below injection site (-) Defined horizontal boundary - Top 2" of LAS appear to have not been exposed to effluent	

CRDM Test Results Summary (3/4)

Test No.	Ave. Flow Rate [gpm]	Gap [mil]	Total Material Wastage [in^3/yr]	Area-Avg Wastage Rate [in/yr]	General Observations	Photo of Post-Test Annulus	Back of Annulus or Exit Plane Photo (if needed)
09a	0.1000	10	17.70	0.242	(-) Rust-colored deposits evident on mockup and in test box (-) Evidence of wastage-induced leak at bottom weld seal (90° from injection site) (-) Minimal wastage at injection site (-) Measurable wastage around injection site		
10a	0.0010	1	0.00	0.024	(-) LAS annulus was still clean (-) Insignificant wastage observed (-) Small pit directly beneath injection site (-) Small amount of loose white deposits located at injection site and top of annulus		—
11a	0.0100	10	2.10	0.070	(-) Rust colored deposits on outside of deposit (-) Localized impingment with no wastage (-) Tenacious deposits around injection site (-) Deposits form flow path to top of annulus		—

CRDM Test Results Summary (4/4)

Test No.	Ave. Flow Rate [gpm]	Gap [mil]	Total Material Wastage [in^3/yr]	Area-Avg Wastage Rate [in/yr]	General Observations	Photo of Post-Test Annulus	Back of Annulus or Exit Plane Photo (if needed)
12a	0.1000	10	16.83	0.346	(-) No evidence of injection site on the cavity surface (-) Few deposits formed in annulus (-) Deep channel wastage around and below cavity and engineered channel (-) Wastage was observed at the top of the annulus at both 90° locations from the injection		
Inverted 01	0.0136	10	1.90	0.158	(-) Localized impingment with no wastage plateau (-) Wastage around plateau region (-) Two flow channels formed by deposits guided flow to top of annulus (-) Localized (irregular) wastage at top of annuuls		—
Inverted 02	0.1000	10	10.60	0.357	(-) Notable impingment damage with no wastage plateau (-) Deep attack around a 3-inch x 2-inch oval about the injection location, especially close to top hot plate area. (-) Diffus attack fanning out toward the bottom exit of the annulus		

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Deposit Formation

0.01gpm

0.1gpm

0.1gpm

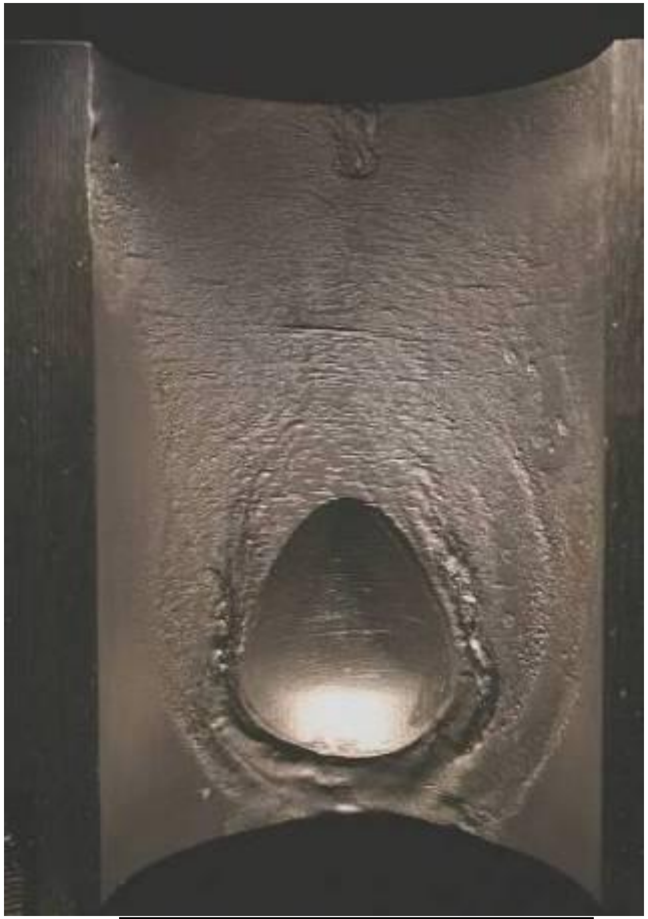
Pre-machined Cavity Effect

#4

0.1 gpm, 10 mil

Wastage – 4.1 in^3/yr

#7a



0.1 gpm, 10 mil

Wastage – 14.86 in^3/yr

Pre-machined Cavity Effect

#8a

0.01 gpm, 10 mil

Wastage – 0.90 in^3/yr

#6a

0.01 gpm, 10 mil

Wastage – 0.93 in^3/yr

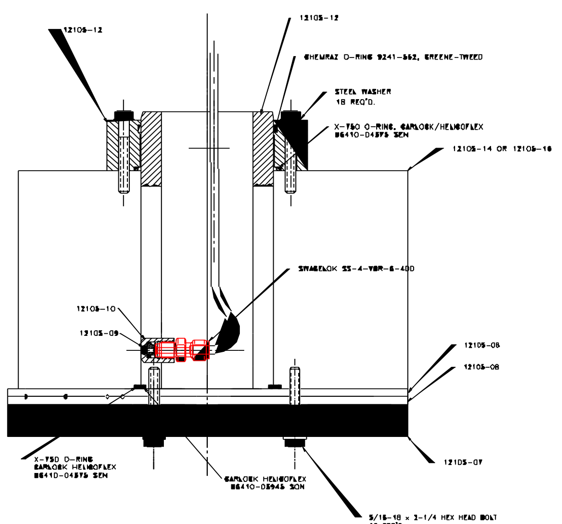
Bottom Mounted Instrument Nozzle

Mock-Up Testing

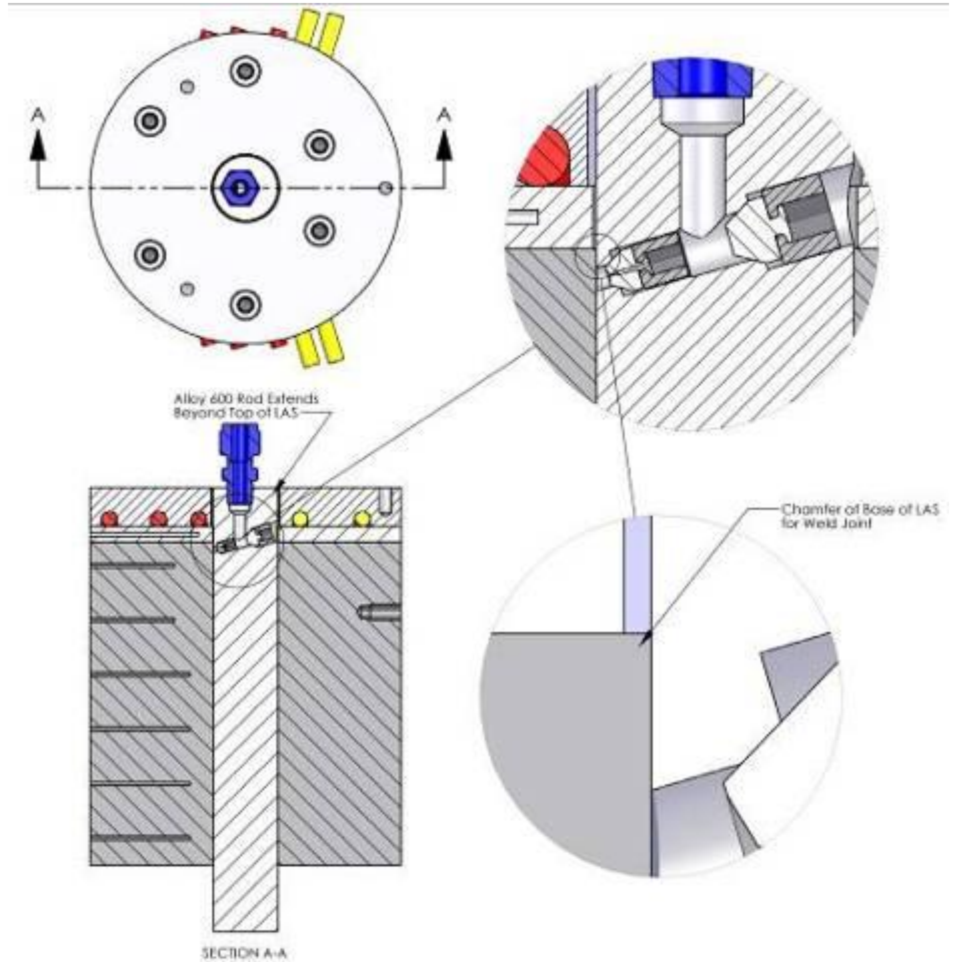
Full-Scale BMI Nozzle BAC Testing

Injection Design

- Design uses a replaceable orifice
- Allows extended duration tests
- Possibility of running tests with increasing leak rates



CRDM Mock-Up Design

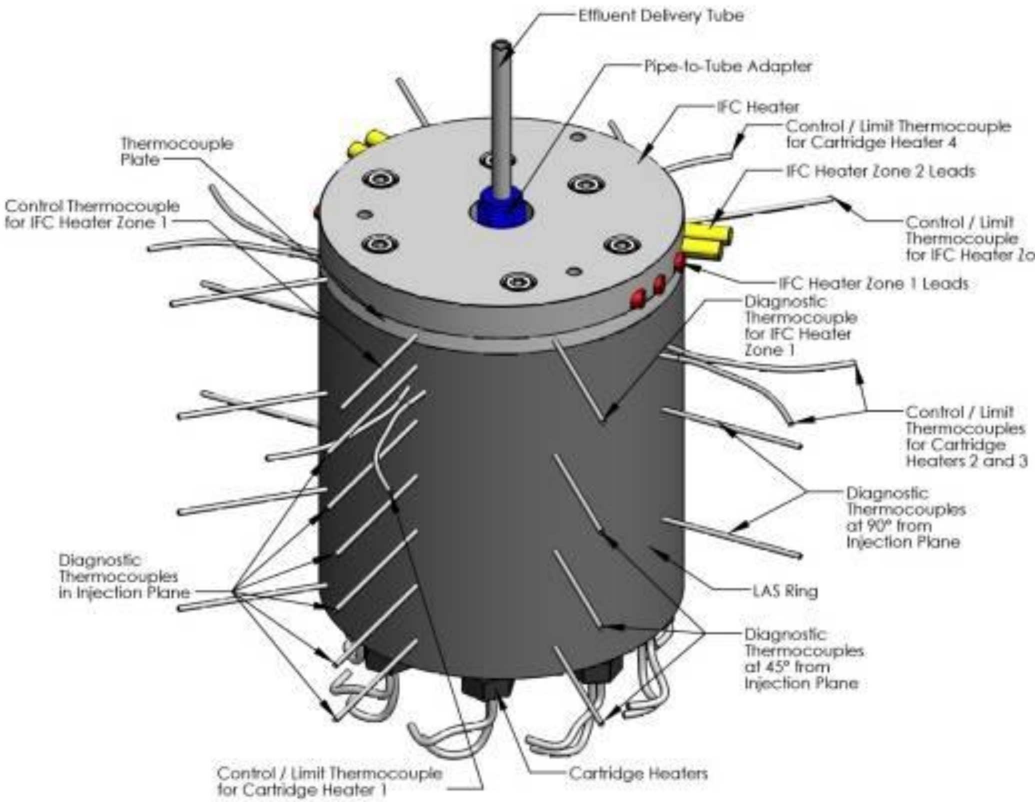


BMN Mock-Up Design

ELECTRIC POWER RESEARCH INSTITUTE

Full-Scale BMI Nozzle BAC Testing

Mockup Assembly – Thermocouples, Bottom Insulation and Support Installed

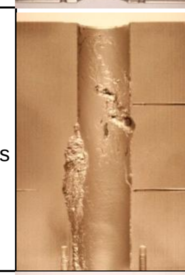
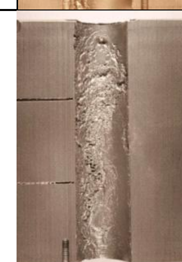
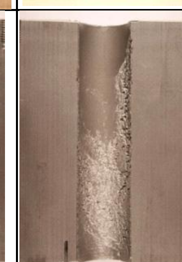


Mockup Symmetric About Vertical Plane Aligned with Injection Location

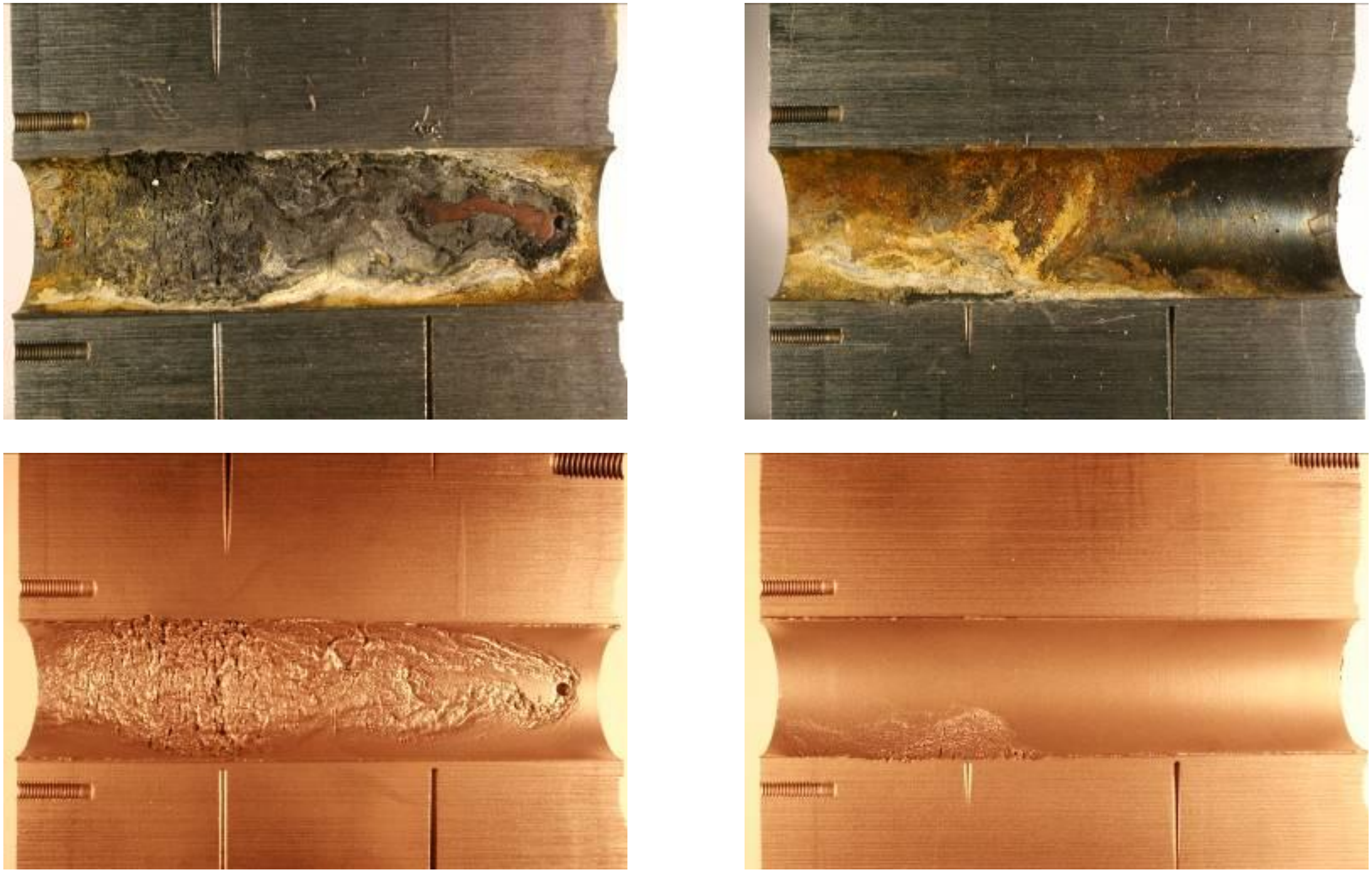
BMN Test Results Summary (1/2)

Test No.	Ave. Flow Rate [gpm]	Gap [mil]	Total Material Wastage [in^3/yr]	Area-Avg Wastage Rate [in/yr]	General Observations	Photo of Post-Test Annulus	Back of Annulus or Exit Plane Photo (if needed)
1	0.0099	10	2.26	0.383	(-) Notable impingment damage with small plaeau (-) Flow path restricted to front of annulus (-) Wastage is distributed axially with increased wastage closer to annulus exit		—
2	0.0060	10	1.69	0.693	(-) Minimal impingment damage (-) Minimal damage around inject or upper half of annulus (-) Limited flow arc twists around annulus to 90° (-) All damage located on lower half of annulus		
3	0.0055	10	4.84	0.744	(-) Notable impingement damage at injection (-) Minimal damage around injection location (-) Flow restricted to front of annulus (-) Damage in lower two-thirds of annulus		—

BMN Test Results Summary (2/2)

Test No.	Ave. Flow Rate [gpm]	Gap [mil]	Total Material Wastage [in^3/yr]	Area-Avg Wastage Rate [in/yr]	General Observations	Photo of Post-Test Annulus	Back of Annulus or Exit Plane Photo (if needed)
4	0.0010	10	0.26	0.085	(-) No damage at impingment or upper part of annulus (-) Flow path restrcited to 1/2-inch front half of annulus (-) Damage is very localized near exit of annulus.		—
5a	0.0058	1	2.42	0.235	(-) Minimal impingment damage with no wastage plateau (-) Minimal wastage in upper one-third of annulus (-) Flow twisted around annulus and most damage is on backside lower two-thirds of annulus (-) Flow area restricted to ~1/2 annulus arc		
7a	0.0280	10	3.43	0.313	(-) Notable impingement damage at injection (-) Some Plateau (-) Extensive damage over entire length of annulus (-) Flow are restricted to ~1/2 annulus arc (-) Flow twisted to exit at 90° (-) Damage on exit plan of LAS		

BMN Test 1 Cross Section



BMN Test Results: Test 1 (10-mil gap; 0.01 gpm leak rate)

Low Alloy Steel

(“reactor vessel”)

Inconel Tube

Deposits clearly visible after two days

Very heavy deposits after ~one month

BMN Test 5

- Long-term test (164 days)
  - 0.006 gpm leakage rate; 1-mil annulus gap
  - Boric acid deposits visible after just one day

Together…Shaping the Future of Electricity