

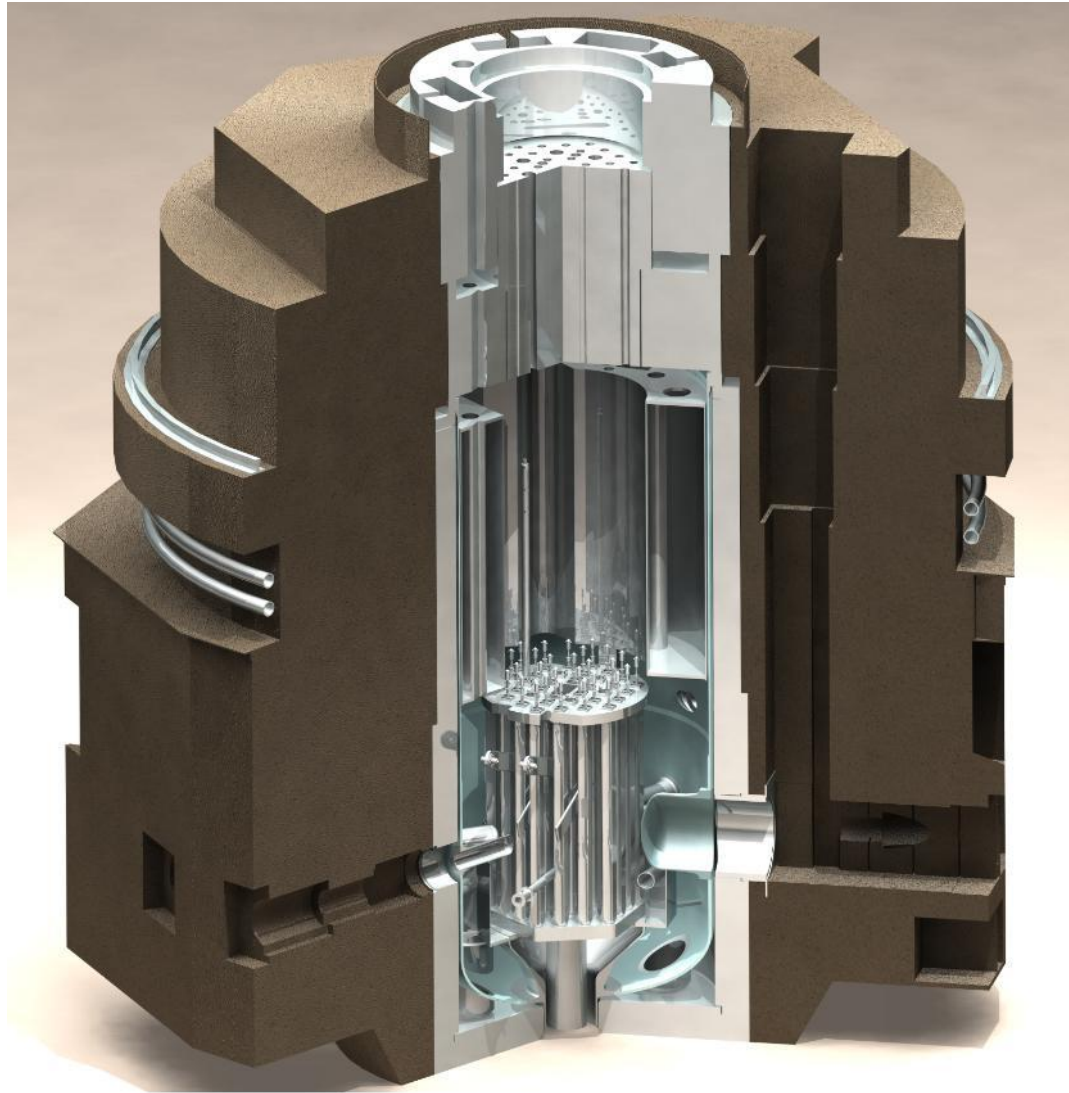
# Failure, Evidence, Redesign

Resolving Retaining-Ring Fractures in the NBSR Refueling Plug

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September XX<sup>th</sup>, 2026

- NBSR and RP Description
- Failure History
- Failure Hypotheses
- Investigation Plan
- Key Findings
- Corrective Redesign
- Conclusions

# NBSR Design Overview



- HEU fuel (93%  $^{235}\text{U}$ ) –  $\text{U}_3\text{O}_8 + \text{Al}$ 
  - 350 g  $^{235}\text{U}$ /fuel element
  - 34 plates: 11"  $\times$  2.5"  $\times$  0.02"
  - Heavy water coolant ( $\text{D}_2\text{O}$ )
- 30 Fuel Elements
  - ~38-day fuel cycle at 20 MW
  - 4 fresh elements per cycle (usually) with a management scheme to shuffle other elements in the core
  - ~960 g of  $^{235}\text{U}$  consumed per cycle
  - 7 or 8 cycles per element depending on where it is loaded initially
- Axially split-core
  - BTs and CNS(s) are at the thermal neutron flux trap elevation
  - BT fluxes  $\sim 1.5 \times 10^{14}$  n/cm<sup>2</sup>-s

# The Story in One Slide

**A very lightly loaded component failed more than once  
So, the question was not “how much load?” but “what mechanism is active?”**

## Failure

B5 transfer arm ring fractured, was replaced, and fractured again; L5 ring was also found fractured.



## Evidence

Stress analysis, load testing, galvanic assessment, XRF, hardness testing, and chloride exposure test converged on SCC.



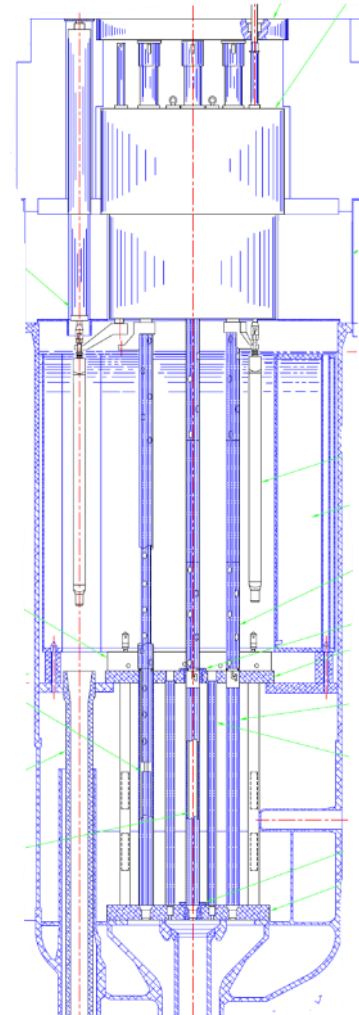
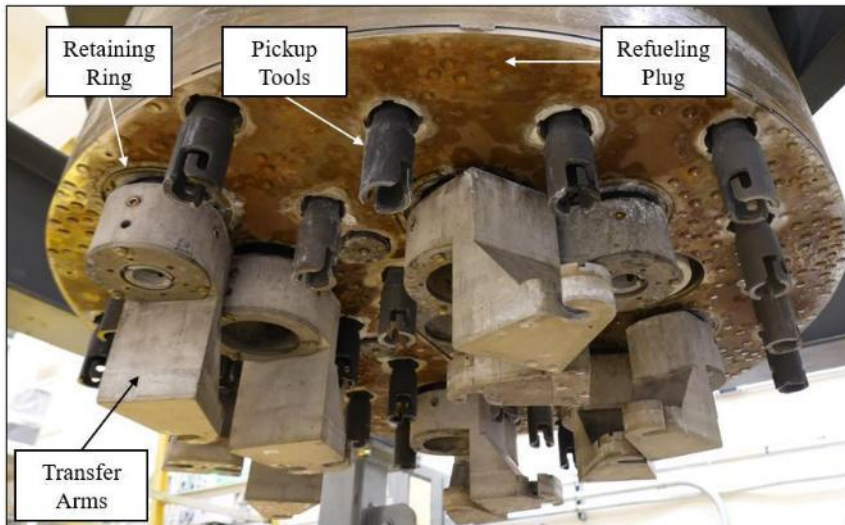
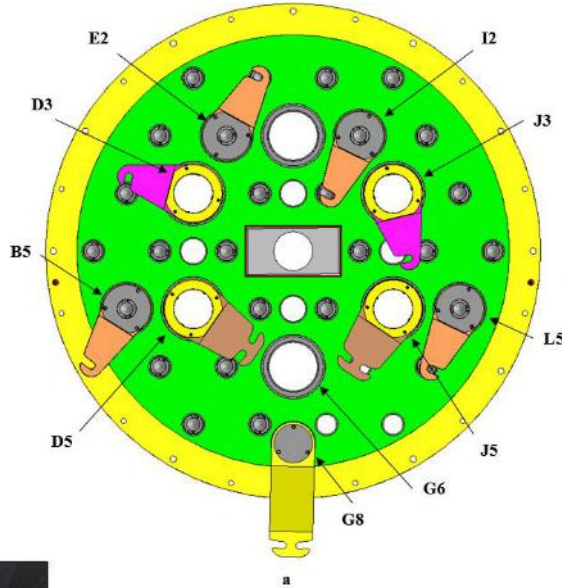
## Redesign

The bearing assembly was converted to a mechanically retained Nitronic 60 system, eliminating the underlying conditions that enabled the failures.

# Refueling Plug

## Where the failed rings live

- The Refueling Plug sits above the core and contains the fuel-handling system of transfer arms and pick-up tools.
- Each lower transfer-arm bearing is retained inside an RP bore/opening.
- Failures occurred at small transfer arms bearing locations B5 and L5.

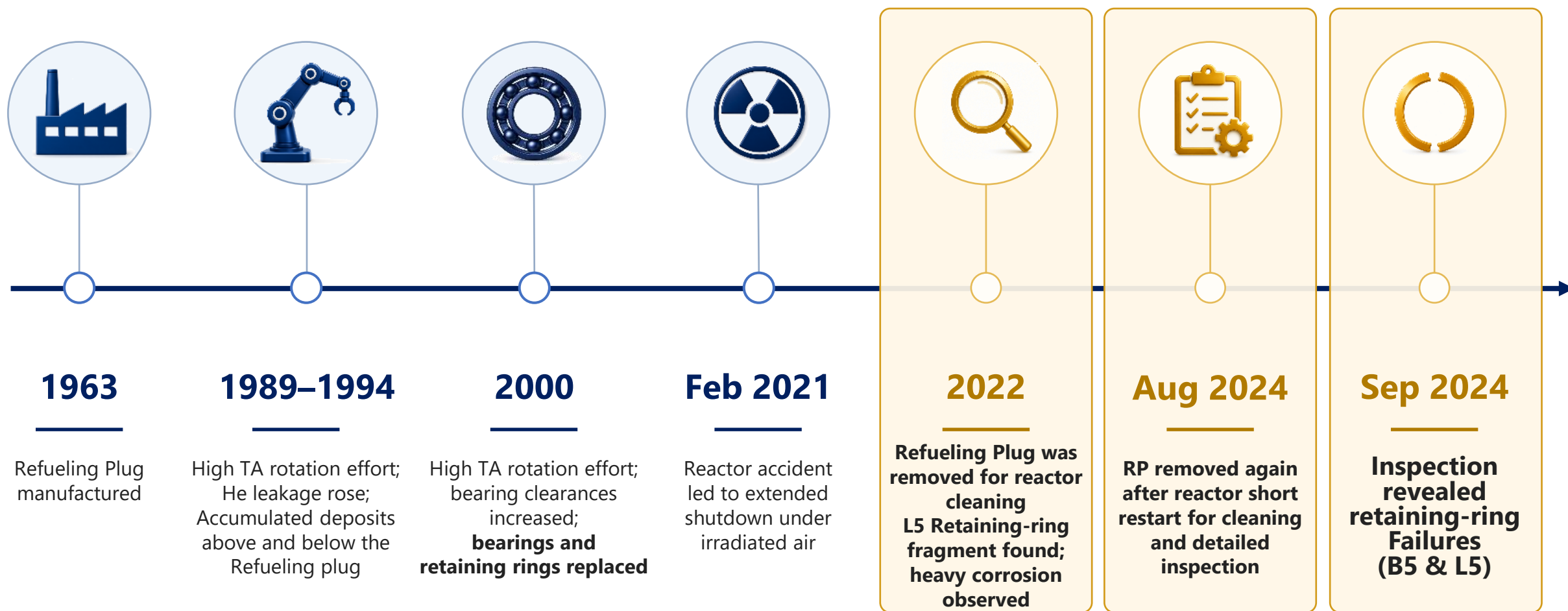


# Existing bearing assembly



**The failed part was not isolated: it sat inside a coupled material, geometry, and environment problem.**

# Failure history: recurrence was the clue



# Working Hypotheses



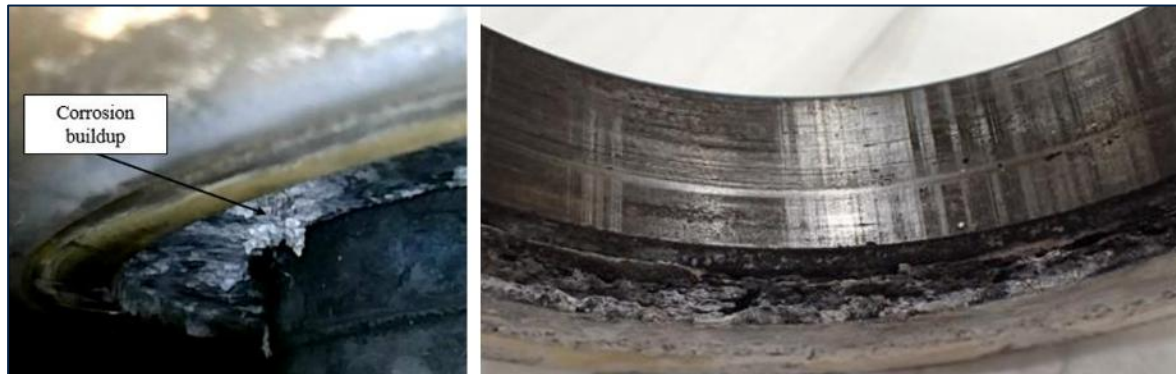
## Sustained tensile stress

Ring seating stress + possible CRUD-driven groove contact load

| Element         | 17-7 PH (%) | 15-7 PH (%) |
|-----------------|-------------|-------------|
| Chromium (Cr)   | 16.0-18.0   | 14.0-16.0   |
| Molybdenum (Mo) | None        | 2.00-3.00   |

## Susceptible material

PH stainless alloy, later shown to be Mo-free 17-7 PH  
*"Reserve the right to substitute PH 17-7 SS for PH 15-7 Mo on larger rings."*



## Aggressive local environment

Moisture-retaining deposits, suspected chlorides, galvanic Al/Graphitar corrosion

# Investigation Layout

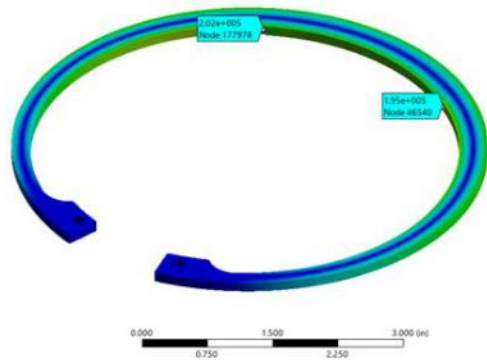
## Each evidence stream answered one narrow question

*The mechanism was determined from the combined pattern of results — not from any single test.*

|   |                          |                                  |                                                              |
|---|--------------------------|----------------------------------|--------------------------------------------------------------|
| 1 | <b>Stress state</b>      | FEA + load testing               | <i>Where are the highest stresses? Is load alone enough?</i> |
| 2 | <b>Environment</b>       | Inspection + galvanic assessment | <i>What produced deposits and localized attack?</i>          |
| 3 | <b>Material</b>          | XRF + Rockwell C hardness        | <i>Was the ring the specified alloy and condition?</i>       |
| 4 | <b>SCC reproduction</b>  | Heated chloride exposure         | <i>Does stress + chloride reproduce fracture?</i>            |
| 5 | <b>Corrective design</b> | Nitronic 60 bearings             | <i>Can the enabling conditions be removed?</i>               |

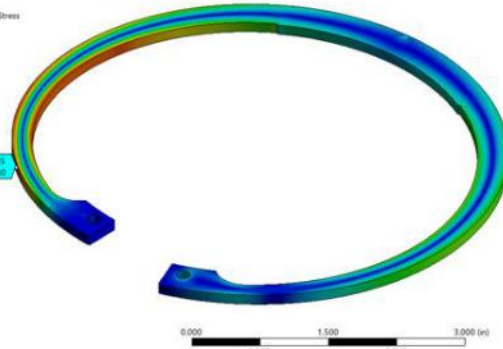
**Investigation Logic: Stress + Environment + Material + Reproduction → Mechanism → Corrective Design**

# Evidence Stream 1: Stress State



a

D: Static Structural  
Equivalent Stress  
Type: Equivalent (von-Mises) Stress  
Unit: psi  
Time: 2 s  
Custom Obsolete  
1/14/2025 2:30 PM



b

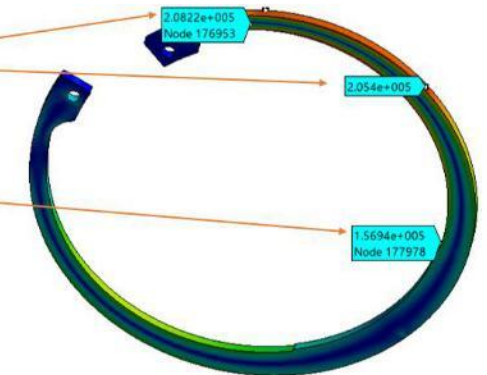


a

b



c



## What The Stress/Load Tests Showed

- Seating in the groove creates sustained tensile stress in the ring.
- Bounding groove-contact loading raised local OD stress at the observed fracture location.
- Mechanical loading produced localized plastic deformation, but no fracture.

**Interpretation: Mechanical Load Was A Contributor To Stress State, Not A Standalone Failure Mechanism.**

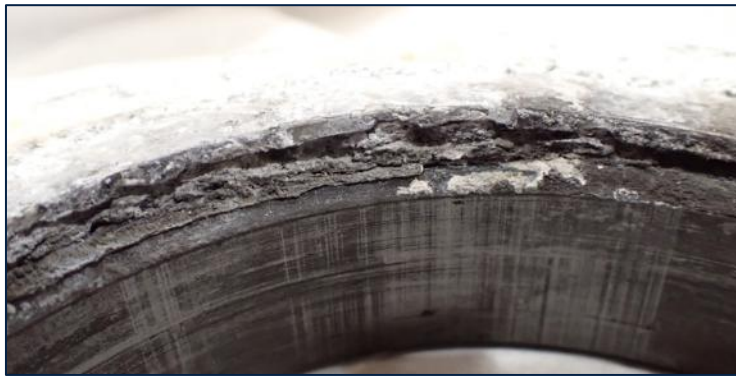
# Evidence Stream 2: Environment

**Deposits + galvanic coupling created a local corrosion environment at the bearing groove.**



## **Deposit retention**

White/gray deposits built up around the bearing and retaining-ring groove.



## **Localized attack**

Aluminum degradation concentrated at the aluminum–Graphitar interface.



## **Constrained groove**

Corrosion bands and fracture geometry suggest repeated buildup and possible incremental ring displacement.

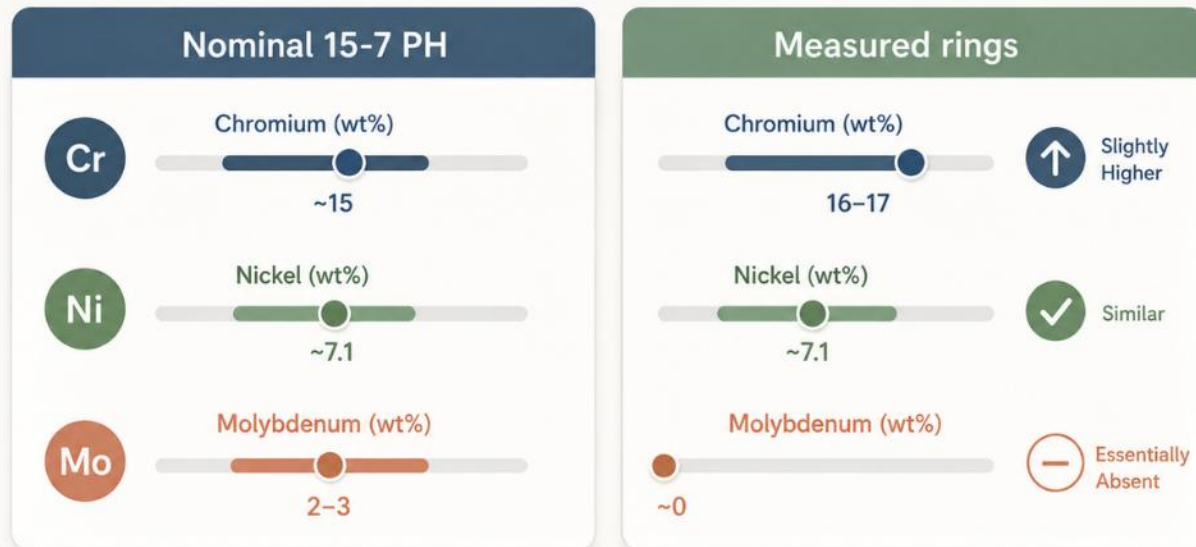
**Environment was not just background noise - it provided the local chemistry and constraints needed for SCC.**

# Evidence Stream 3 – Material

## Key material finding

Medium rings were compositionally consistent with **17-7 PH**, not the nominal **15-7 PH**.

### Nominal 15-7 PH vs Measured Rings



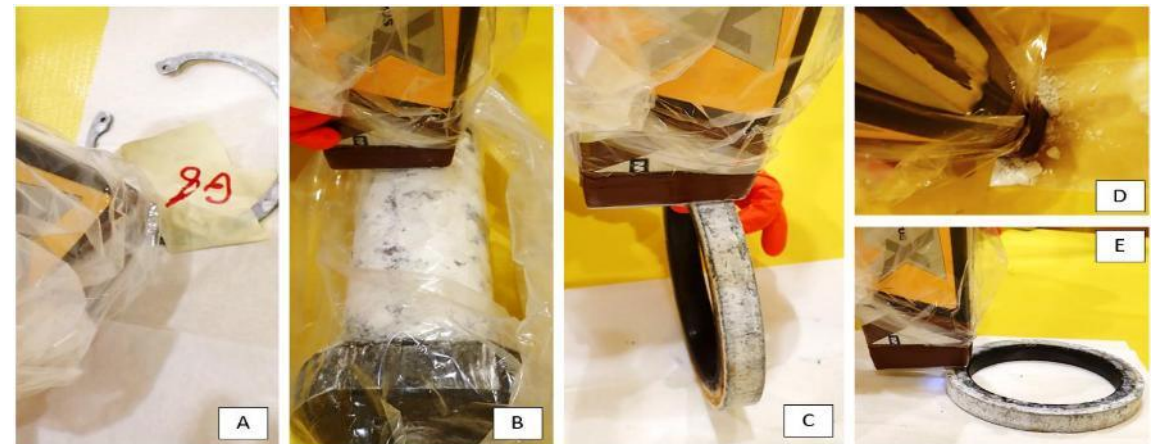
Measured rings are inconsistent with nominal 15-7 PH and are more consistent with **17-7 PH**.



Mo is effectively absent in the measured larger rings.

### Why it matters?

- Molybdenum strengthens the passive film and improves resistance to localized corrosion.
- Its absence increases susceptibility to pitting and crevice-corrosion initiation in chloride-bearing environments.



# Evidence Stream 4: Corrosion Test



## Only the stressed rings fractured in heated chloride exposure.

The test reproduced the critical combined condition of susceptible material + stress + chloride.

### EXPERIMENTAL STORY

1. Compressed (as-installed)



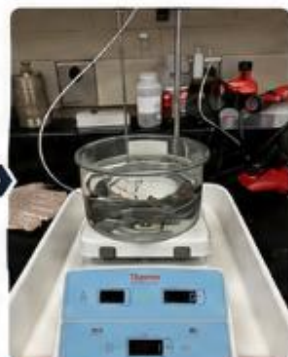
↓  
↑  
3 rings compressed to as-installed diameter

2. Control (uncompressed)



↻  
2 rings left uncompressed as controls

3. Exposure 10% NaCl, Heated



🧪  
Heated 10% NaCl exposure for 14.5 hours

4. After 14.5 h Post-test



🔍  
Two of three compressed rings fractured

5. Fracture Detail



📷  
Fracture surface consistent with SCC morphology

### RESULTS AT A GLANCE

#### STRESSED (Compressed)

**2 / 3**

RINGS FRACTURED



#### CONTROLS (Uncompressed)

**0 / 2**

RINGS FRACTURED



The result reproduced the essential stress + chloride condition.

### INTERPRETATION



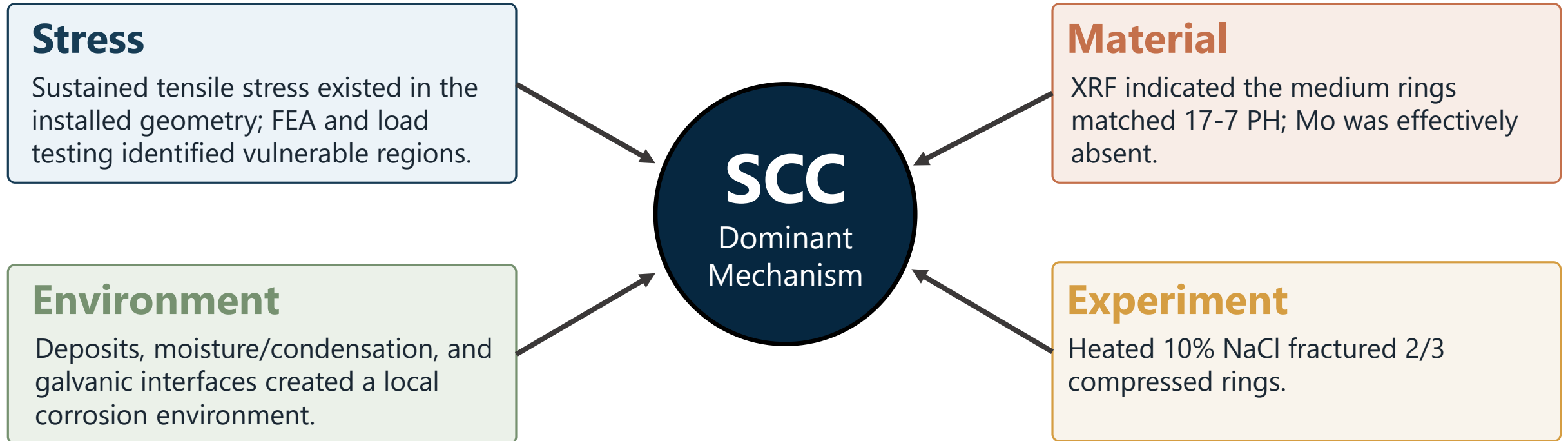
#### Sustained tensile stress made the difference.

Only when rings were stressed did chloride exposure lead to cracking—consistent with a stress corrosion cracking (SCC) mechanism.



The accelerated test supplied the combined-condition evidence: **susceptible material + stress + chloride exposure.**

# Integrated Conclusion - SCC



**The failure mechanism was not assumed; it was assembled from converging evidence.**

# Corrective Redesign

The redesign translated root-cause evidence into hardware changes

## LEGACY ARCHITECTURE: COUPLED RISKS



### Galvanic couple

Graphitar + aluminum + stainless



### Hidden groove retention

thin PH ring in stressed groove



### Crevice environment

deposits + condensation

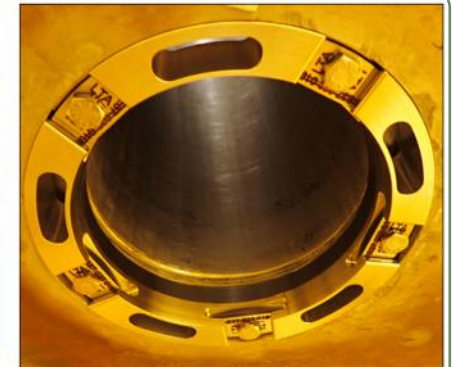
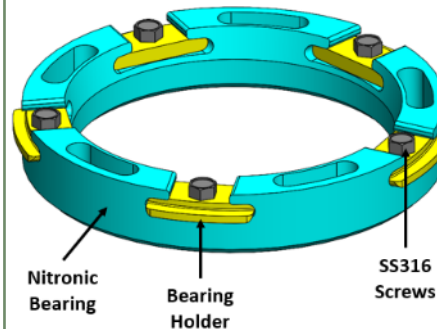


### Material uncertainty

larger rings substituted to 17-7 PH



## NEW SYSTEM: CORROSION-RESISTANT, BOLTED, VALIDATED



### Nitronic 60

Corrosion + galling resistance



### Bolted Retention

Mechanically locked



### As-built Compatibility

Legacy clearances and TA motion preserved



### Validated Installation

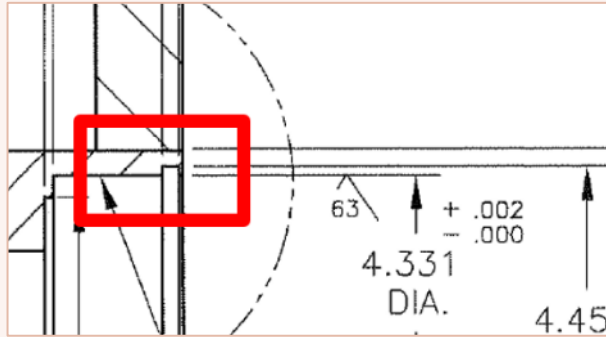
Locking Helicoils, TA tests

Design move: remove the coupled stress/corrosion/material vulnerability

# Corrective Redesign

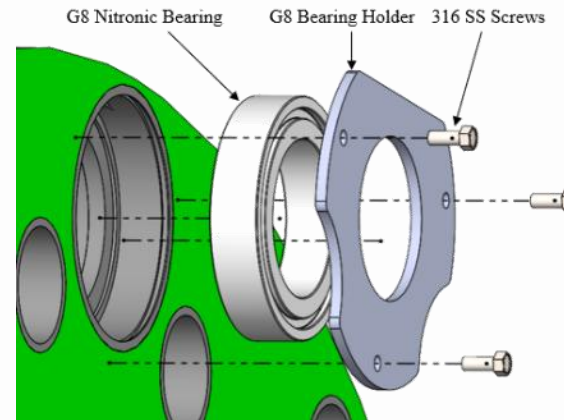
As-built geometry overruled the standard design - G8 Required a dedicated solution

Why would the standard design not work?

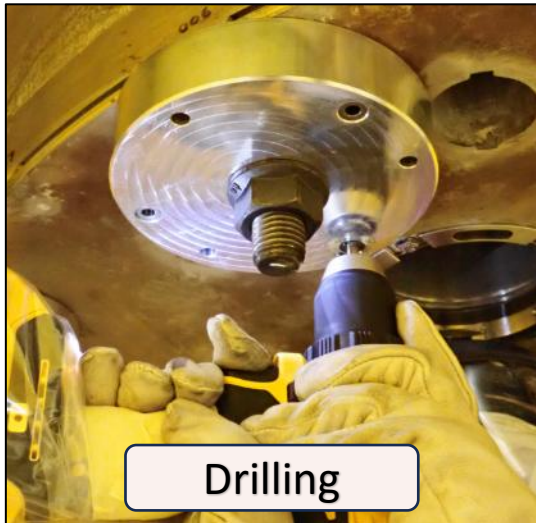


**Shallow groove with small worn support shoulder**

G8 Bearing Concept



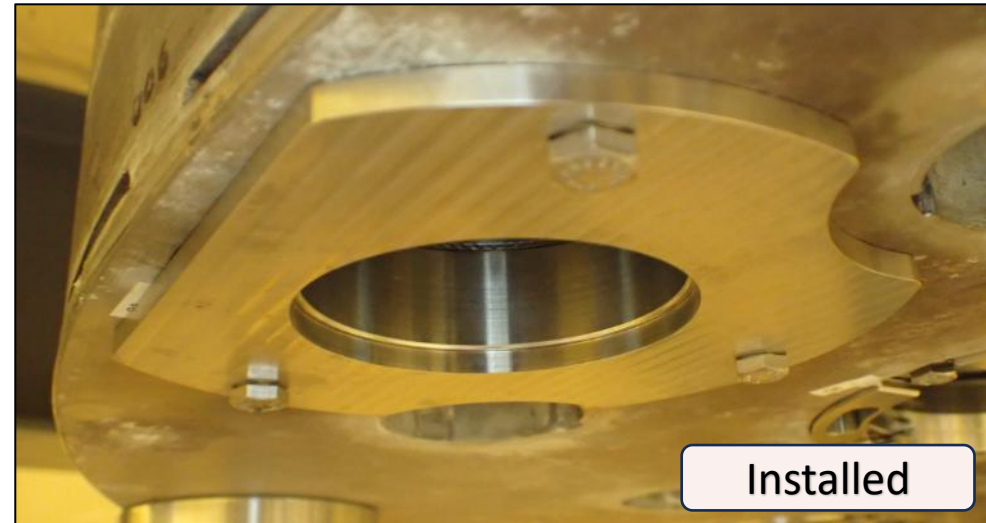
A custom external holder replaced the groove-retaining concept



Drilling

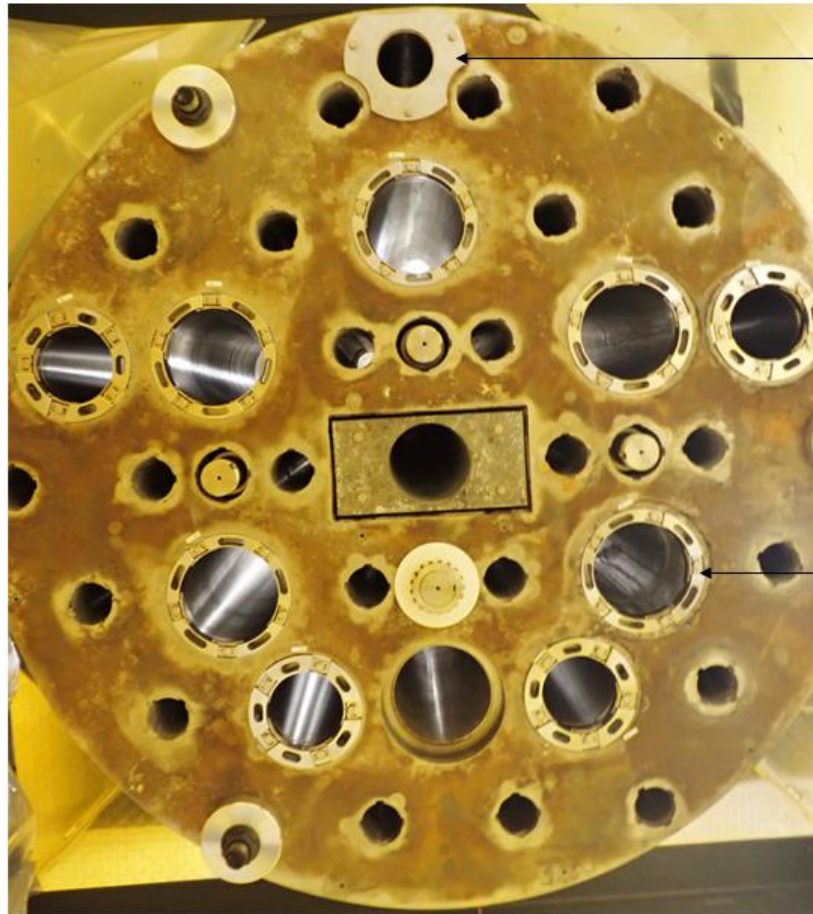


Tap, Install Helicoils and Screw



Installed

# From evidence to installed hardware



G8 Bearing

Small TA  
Bearing

Large TA  
Bearing

**The investigation did not stop at explaining failure.**

**It produced a validated replacement system.**

1

**Evidence-based root cause**

SCC was supported by stress, environment, material, and experiment.

2

**Redesign tied to failure drivers**

The new architecture removed the vulnerable retaining-ring path.

3

**Installed and checked**

Prototype validation and post-installation testing closed the loop.

**Failure → convergent evidence → corrective redesign → installed system**