

July 22nd, 2025

Fitness for Service Assessment of a Corroded Heat Exchanger

Alex Humenik

Thermal-Fluids Engineer – Fermi National Accelerator Laboratory

Erik Voirin

Mechanical Engineer – Fermi National Accelerator Laboratory

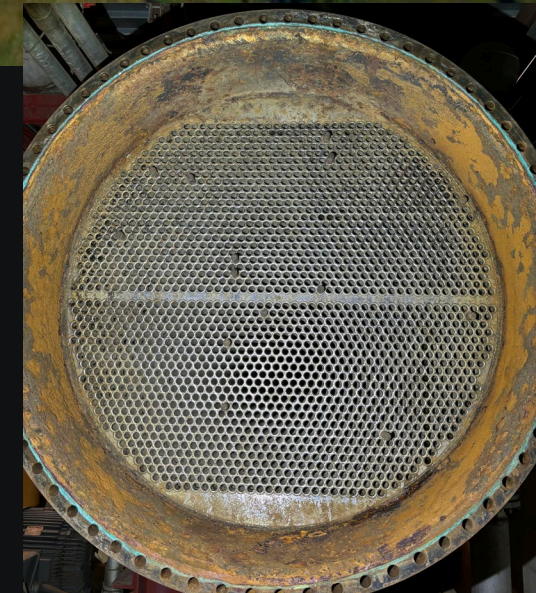


U.S. DEPARTMENT
of **ENERGY** Fermi National Accelerator Laboratory is managed by
FermiForward for the U.S. Department of Energy Office of Science

This manuscript has been authored by FermiForward Discovery Group, LLC under Contract No. 89243024CSC000002 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Background & Corrosion Issue

- The Main Injector Accelerator utilizes nine water-water shell & tube heat exchangers to cool accelerator equipment
- Each unit utilizes untreated pond water to cool the highly purified Low Conductivity Water (LCW) System
- All units in operation since late 1990s
- No documented inspection history
- No cathodic protection or corrosion mitigation
- Corrosion deposits & characteristics indicative of MIC and galvanic
- API 579 (ASME FFS-1) was used to determine integrity of corroded heat exchanger channels



Design & Operation

- Construction Code: ASME BPVC Sec. VIII Div 1 – 1992-A2
- 304 Stainless Steel Shell, Tube Sheet, & Tubes
- SA 516 Carbon Steel Channel Material
- 40” OD X 20’ Long
- All units in operation since late 1990s
- Hydrolancing occurred every other year. Some units had not been cleaned in 3 years
- FFS assessment completed for a period of 2.5 years

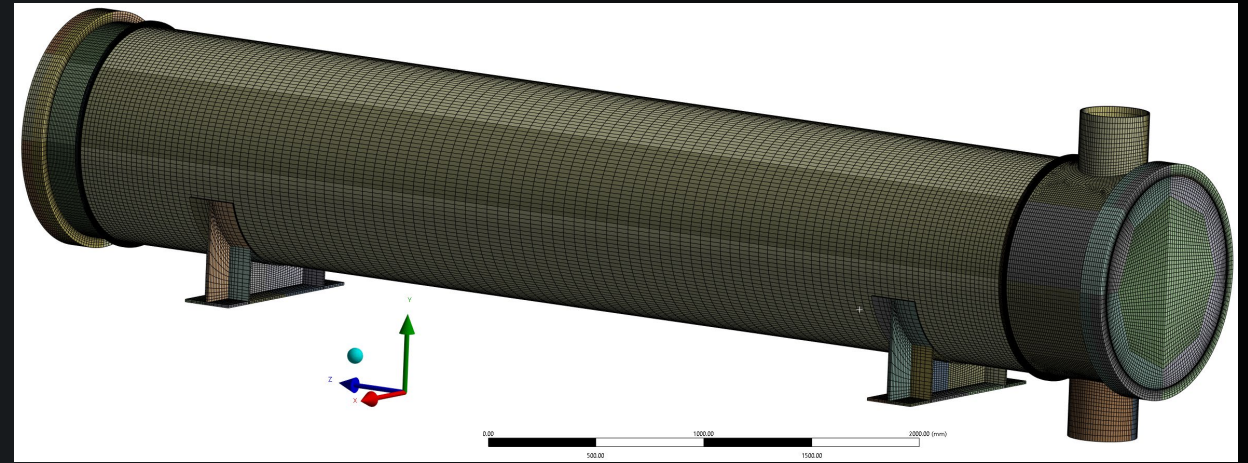
TEMA NEN TYPE-C SHELL & TUBE HEAT EXCHANGER

Design Condition (Actual):	Shell	Tube
Pressure (Max Operating)	150 psi (50 psi)	75 psi (35 psi)
Temperature (Max Operating)	200°F (110°F)	150°F (85°F)
# of Passes	1	2
Corrosion All.	0”	0.0625”
Nominal Thickness	0.25”	0.375”
Fluid	Low Conductivity Water	Untreated Pond Water
Flowrate (Max Operating)	1500 GPM (1500 GPM)	2250 GPM (1750 GPM)



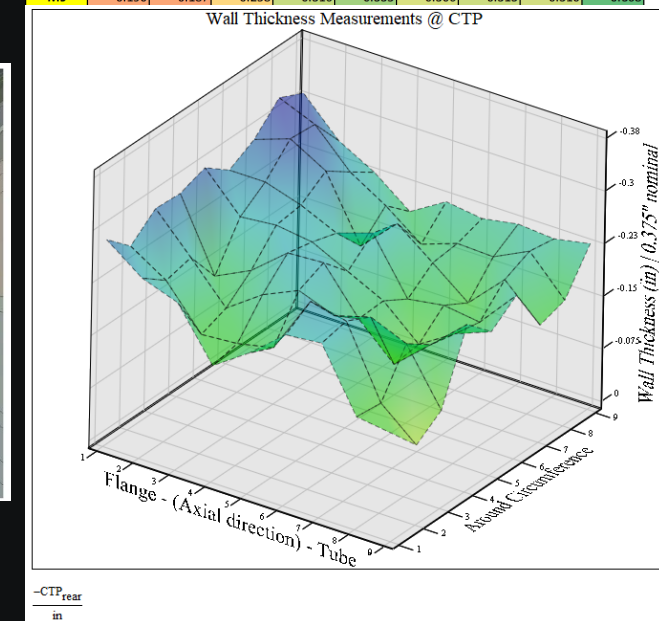
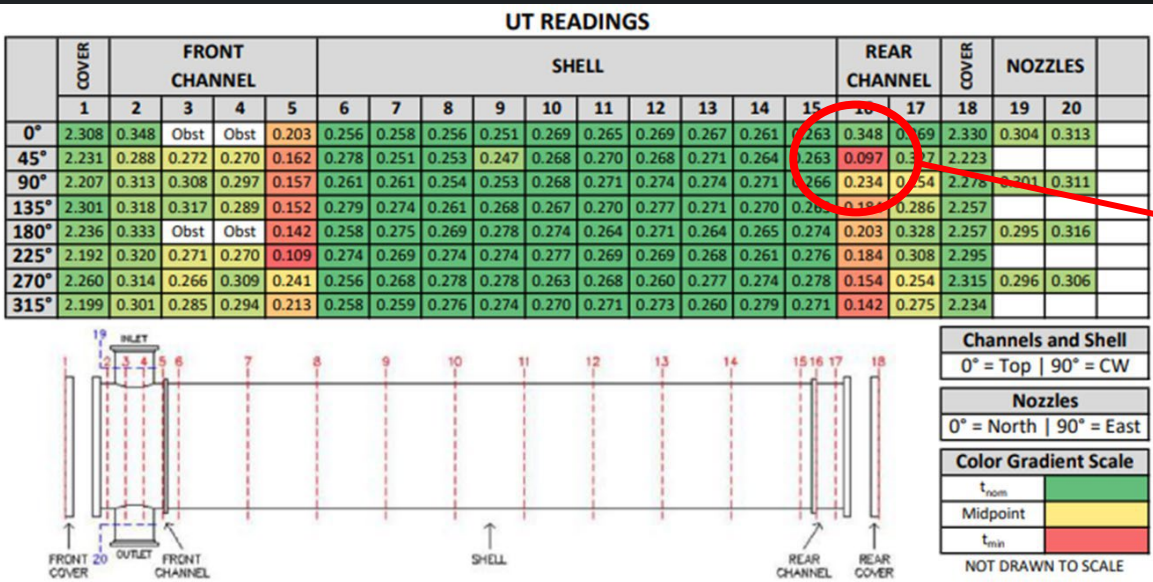
Geometry

- The heat exchanger wall thickness readings were mapped out on a 2D grid shown below. Inspection data points were used to generate a 3D model.
- A more precise CTP of the thinnest section was constructed by taking measurements in a 4"x4" box along the 16th circumferential inspection plane @ 45°.
- CTP used due to thickness readings varying >10%
- Additional measurements of worst wall thickness reading
- Fillet Weld on OD not considered for conservatism



REAR CHANNEL @ 45° - INSPECTION PLANE 16

	C1	C2	C3	C4	C5	C6	C7	C8	C9
M1	0.192	0.282	0.298	0.336	0.277	0.338	0.336	0.258	0.277
M2	0.185	0.240	0.290	0.323	0.312	0.237	0.282	0.338	0.330
M3	0.210	0.225	0.274	0.276	0.308	0.281	0.251	0.284	0.317
M4	0.189	0.249	0.261	0.280	0.300	0.287	0.296	0.316	0.326
M5	0.165	0.248	0.252	0.314	0.300	0.306	0.318	0.354	0.312
M6	0.178	0.295	0.331	0.339	0.300	0.245	0.164	0.234	0.292
M7	0.097	0.286	0.332	0.280	0.234	0.258	0.275	0.291	0.305
M8	0.144	0.161	0.253	0.345	0.303	0.285	0.295	0.276	0.326
M9	0.190	0.187	0.258	0.316	0.306	0.313	0.310	0.310	0.368



Level 1, 2, & 3 Assessment Applicability

- Part 4: General Metal Loss – Level 3 Required
- Part 5: Local Metal Loss – Level 3 Required

Must be thicker than:

- (a) 0.100 in. - FALSE ← $t_{mm} = 0.097''$ & $t_{mm} \leq t_{am}$
- (b) $20\%t_{nom} = 0.075$ - TRUE
- (c) $50\%t_{min} = 0.060$ in - TRUE

e) The Level 1 and Level 2 Assessment procedures include a limitation on the minimum measured thickness, t_{mm} . The limitation on t_{mm} is to guard against potential inadequacy in inspection method capabilities to accurately characterize excessively thinned areas. If the limitation on t_{mm} is not satisfied, a Level 3 Assessment may be performed. Future inspection frequency shall be established based on a detailed investigation of all applicable damage mechanisms and inspection results shall be appropriately validated (see [Part 4, paragraph 4.3.4.6](#)).

- Part 9: Crack-Like Flaw – Level 3 Required

$$1.8\sqrt{Dt} = 6.88 \text{ in} \rightarrow \text{FALSE}$$

iv) The crack-like flaw geometry can be of the surface or through-thickness type, specific limitations for the crack-like flaw depth are included in the Level 1 Assessment procedure (see [paragraph 9.4.2](#)). The maximum permitted crack length is 200 mm (8 inches).

v) For cylindrical and spherical shell components, the crack-like flaw is oriented in the axial or circumferential direction (i.e., perpendicular to a principal stress direction) and is located at a distance greater than or equal to $1.8\sqrt{Dt}$ from any major structural discontinuity where D is the

*Crack found to be longer than 8"

*Tube sheet joint = major structural discontinuity

Part 4 & 5: General and Local Metal Loss

- Utilized ASME BPVC Sec. VIII Div. 2 – Part 5: Design By Analysis Methods for level 3 assessments
- Elastic-Plastic Stress Analysis Method was used in accordance with BPVC DBA Methods in sections 5.2.4 and 5.3.3

Assessment Types (2D.1.4)

Protection Against Plastic Collapse	Applicable
Protection Against Local Failure	Applicable
Protection Against Collapse From Buckling	Not Applicable
Protection from Creep or Creep Damage	Not Applicable
Protection Against Fatigue Damage	Not Applicable

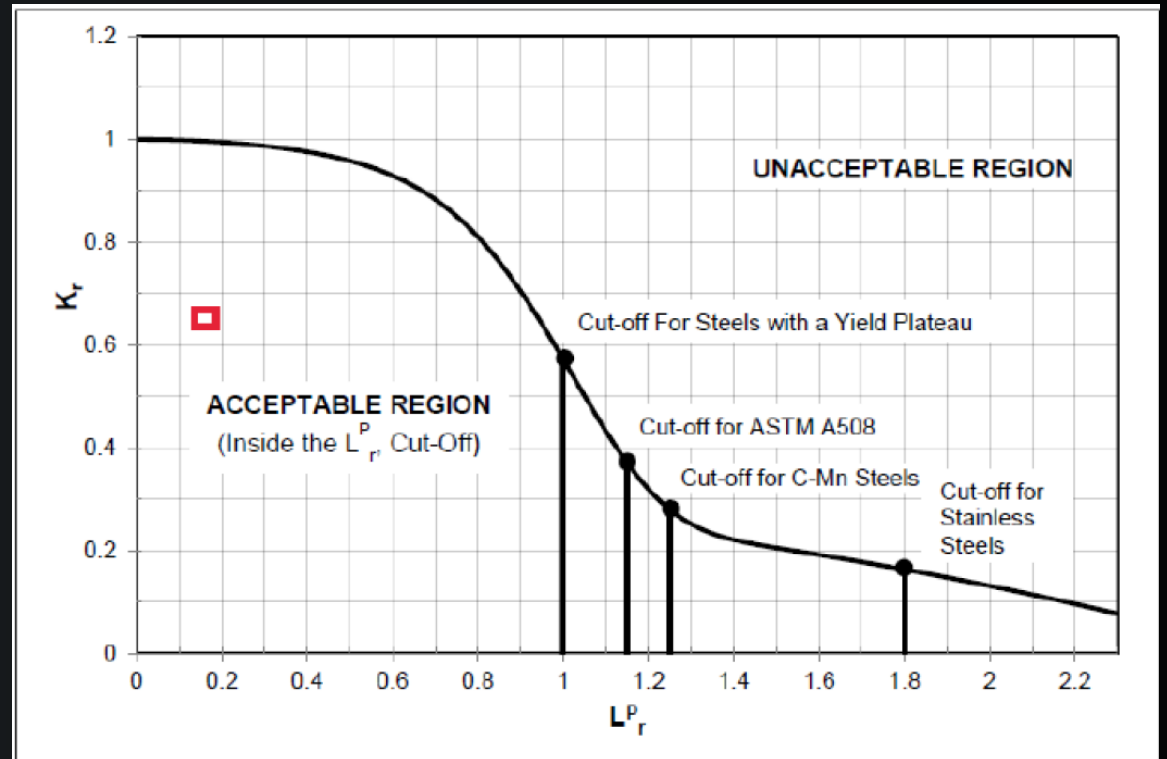
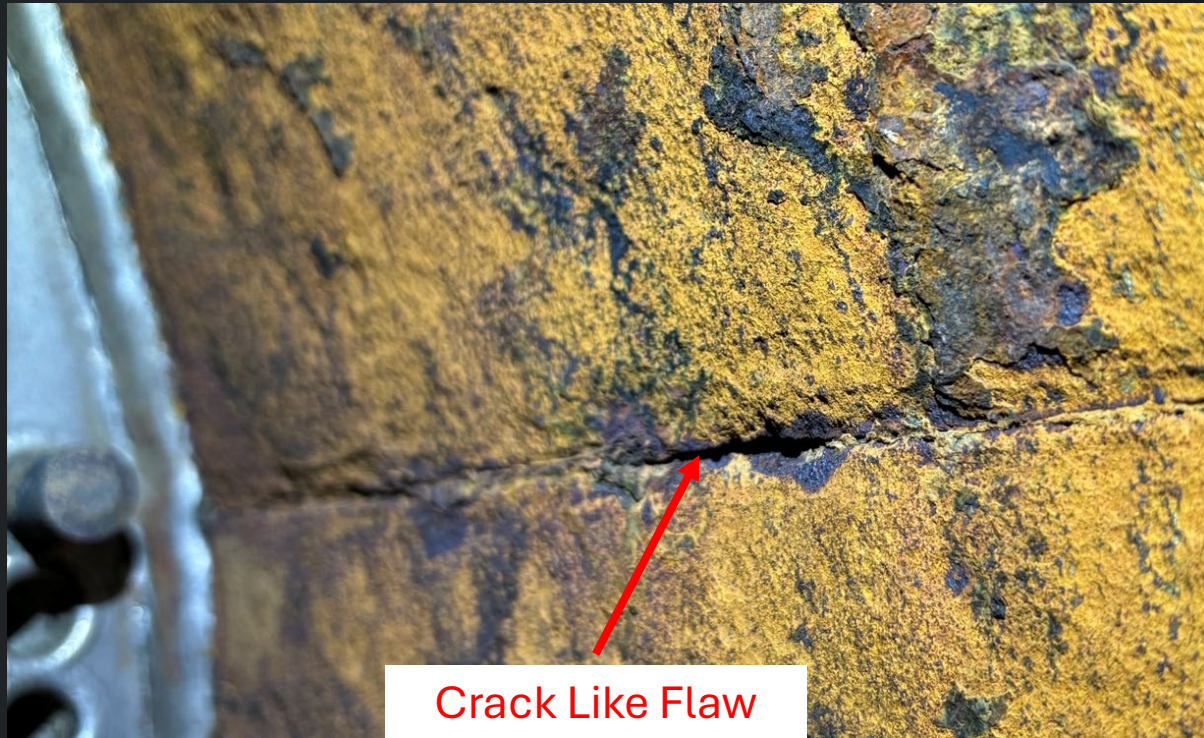


Protection From Failure Type	ASME Section VIII Div. 2 Part 5 Elastic-Plastic Method	Material Model	Geometric Behavior	Code Requirements or Required Load Factor	Results vs Original 75 psi Design Pressure	Results / Requirements (Must be at least 1.0 to PASS FFS)	FFS Assessment Results (PASS/FAIL)
Plastic Failure	5.2.4	True SS Curve	Non-linear effects included	6.000	14.25	2.375	PASS
Local Failure	5.3.3	True SS Curve	Non-linear effects included	2.550	5.19	2.035	PASS
Buckling Failure	5.4.3	True SS Curve	Non-linear effects included	2.083	14.25	6.840	PASS
Failure from Cyclic Loading	5.5.7	Elastic-Perfectly-Plastic	Non-linear effects included	No Accumulation of Plastic Strain	Zero Plastic Strain	N/A (Meets Requirements)	PASS

Results of Numerical Analyses		Comment
Plastic Failure Occurs @ LF:	14.250	= 1068.75 psi Internal Pressure
Required Plastic Design Factor:	3.6	(4.0 * 0.9)
MAWP Limit for Plastic Failure:	296.88	(psi)
Rear Channel Local Failure Occurs @ LF:	8.7589	Bottom @ Tubesheet Connection Notch
Front Channel Local Failure Occurs @ LF:	5.1902	Bottom @ Tubesheet Connection Notch
Required Local Design Factor	1.53	(1.7 * 0.9)
Minimum MAWP Limit for Local Failure:	254.42	(psi)
Weld Efficiency Factor (WEF) (Using Global Method A)	0.6	Lowest Joint efficiency listed in ASME Sect. VIII Div. 1 Table UW-12 for corner joints or butt joints with zero radiography (lower than Original manufacturer value of 0.70)
MAWP Limit for Plastic Failure * WEF:	178	psi
MAWP Limit for Local Failure * WEF:	153	psi
FFS Limit for Channel MAWP	153	psi (Above Original 75 psi MAWP)

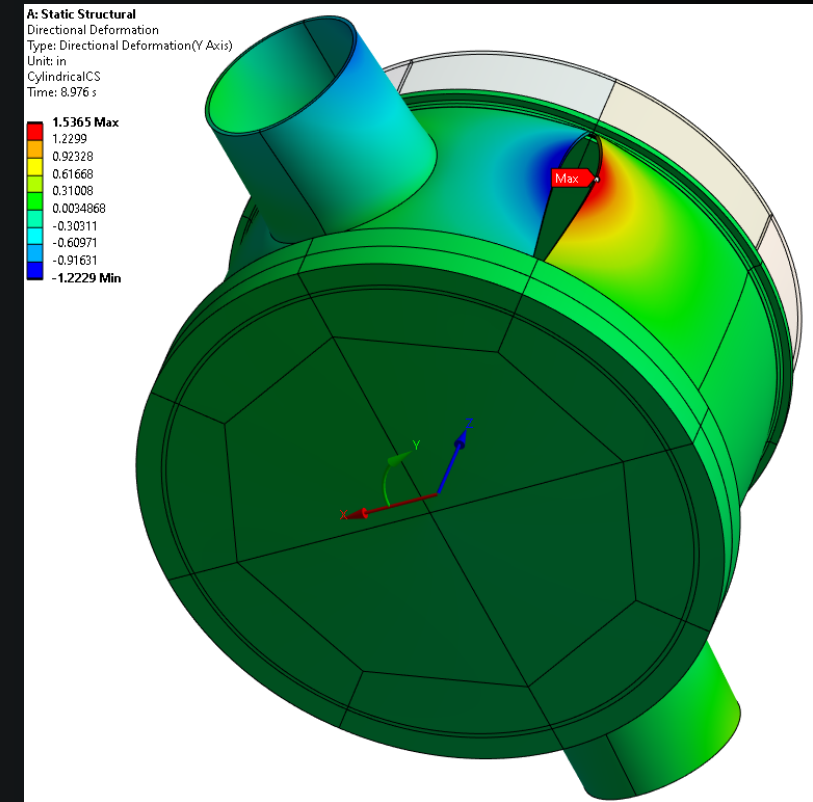
Part 9: Crack Like Flaw

- Level 3 assessment applied on longitudinal seam welds of end channels experiencing weld metal loss and sharp grooves
- Method B: Utilizing K_r (stress intensity ratio) and L_r^P (load ratio), were found to be within the “acceptable region” on the Failure Assessment Diagram (FAD) for assumed crack length
- Since the permitted crack length a Leak Before Break Analysis was completed



Leak-Before-Break Analysis

- A theoretical through wall crack was assumed to be present for this analysis, which is a “worst-case” scenario
- All analyses resulted in a rupture pressure of above 400 psi, far surpassing the achievable system pressure
- At 75 psi (MAWP) a theoretical crack is arrested at the tube-sheet and will not propagate through the length of the heat exchanger.
- A leak of this size and type is not likely due to the crack being within the acceptable region on the FAD.
- Deformation of the crack is used to determine potential leak rates at various operating pressures. Typical operating pressure ranges from 5-30psi resulting in readily detectable leaks.



Pressure (psi)	Leak Rate (gpm)
0	0.0
5	1.9
10	5.3
15	9.8
20	15.3
25	21.5
30	28.5
35	36.3

Calculated Leak Rates vs Pressure

Results of FFS Assessment

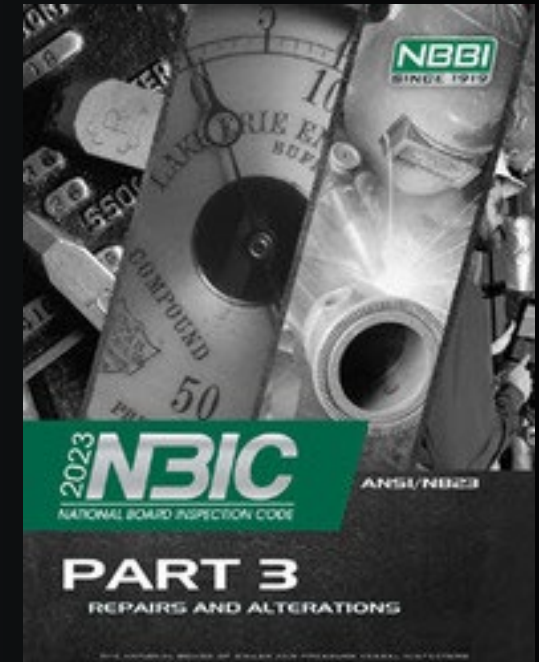
- Heat Exchanger is fit for service at original design conditions and can operate safely
- Fit for a period of 2.5 years with inspection at a 1.25 year interval

Leak Mitigation Plan:

- ASME Code Case N-705-14 allows the operation of a system in a nuclear facility with a known leak if operation parameters are below 275psi and 200°F. There are **NO** current through-wall defects on any heat exchanger and development of one is very unlikely.
- Daily inspections of the heat exchangers tracked in an electronic logbook by technicians and operators
- Preventative measures in the event of a leak including response plan from machine personnel
- End channels covered to protect electrical equipment in the event of a failure

Remediation:

- Repairs of the heat exchanger via end channel replacements
- Replacement work will follow NBIC – Part 3: Repairs and Alterations
- Stainless Steel tube sheet & tubes will remain untouched



Current Status

- Two heat exchangers that underwent FFS assessments have started repair work
- All end channel assemblies will be fitted with cathodic protection using a sacrificial anode
- Water analyses and corrosion testing & characterization will be used to determine exact cause of corrosion





Fermilab

Fermi *FORWARD*



U.S. DEPARTMENT
of ENERGY