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Materials surveillance technology development

Molten Salt Reactor Program – Annual Review

April 21-24, 2026

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Argonne National Laboratory

Overview of MSR materials surveillance

- **MSR materials experience both mechanical and environmental degradation**
  - Mechanical: creep-fatigue
  - Environmental: salt corrosion, irradiation
- **There are very limited data on combined effects to quantify/bound this degradation for component design**
- **A material surveillance program would monitor material degradation in service to mitigate the risk posed by the limited up-front test data**
- **Surveillance data may enable extension of component service life beyond conservative ASME design limits**
  - Life extension through surveillance is well established in LWRS

This work aims to develop the technology required to implement a surveillance program in an operating plant

Size test articles

- Sizing procedures to mimic component loading
- Passively actuated test articles

Insert into reactor

- Decide on locations/quantity
- Design test articles to minimize impact on component operation

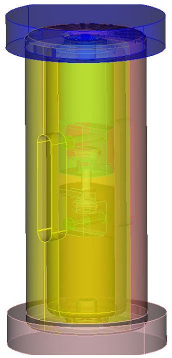
Periodically remove and test ex-situ

- How often to remove and how many?
- Robust article design
- Instrumented out of reactor testing – strain measurement

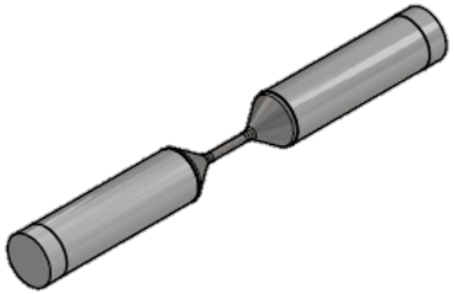
Acceptance criteria

- Damage inference based on out of reactor testing
- Acceptance criteria: what is the component remaining life?

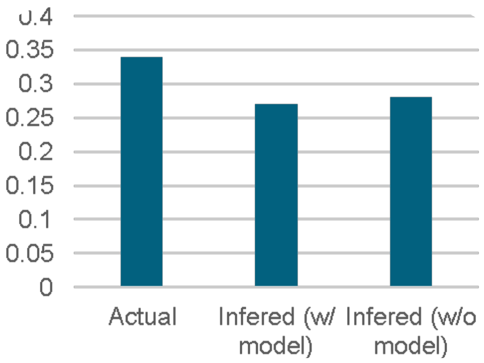
Four pillars of an MSR surveillance program



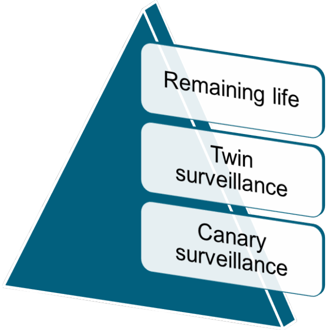
Robust test articles (Design, fabrication feasibility, and experimental validation)



Sizing procedures



Damage inference



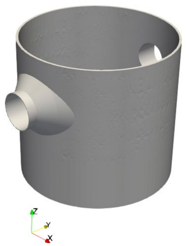
Acceptance procedures

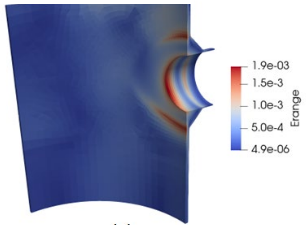
INL

ANL

ANL's main focus for FY26

- Develop material surveillance sample problem book, including completing worked examples starting from the ASME design calculations.



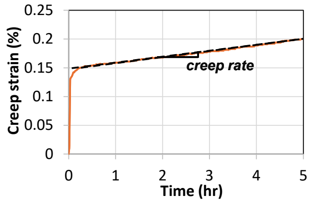


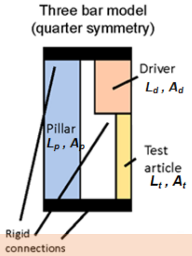
Spreadsheet tool input

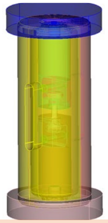
Objectives		
Total Strain Range:	3.13E-03	
Elestic Followup Factor:	1.25	
Thermal transient		
Temperature_low T1	500	degC
Temperature_high T2	650	degC
Ramping up rate	15	degC/hr
Ramping down rate	15	degC/hr
Holding time	980	hour
Material properties		
SS316H		
E at T1	1.60E+11	Pa
E at T2	1.46E+11	Pa
Secont CTE, T1 to T2:	2.09E-05	1/degC
Sy at T1	1.17E+08	Pa
Sy at T2	1.10E+08	Pa
A617		
E at T1	1.74E+11	Pa
E at T2	1.63E+11	Pa
Secont CTE, T1 to T2:	1.70E-05	1/degC
Sy at T1	1.62E+08	Pa
Sy at T2	1.64E+08	Pa

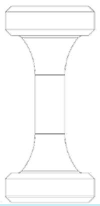
Spreadsheet tool output

Get W1/W2 and L2/L1		
Δε	3.1341E-03	
α (W1/W2)	0.0015	**ok**
β (L2/L1)	3.8988E+00	
Geometry		
L1	5.000	mm
W1	2.500	mm
L2	19.494	mm
W2	1718.744	mm
L3	24.494	mm
W3	50.000	mm
Geometry check		
Does buckling occur?	No	









Remaining life calculation		
Total cycles operated	10	
Total creep damage	1.26E-02	
Creep remaining life	7.67E+05	hours

Determine critical mechanical strain range from component analysis → Size surveillance specimen using spread-sheet tool → Use spead-sheet results to determine feasible specimen design → Measure creep rate from short term testing of out-of-reactor specimen → Estimate remaining life using spreadsheet tool and measured creep rate

Specimen sizing

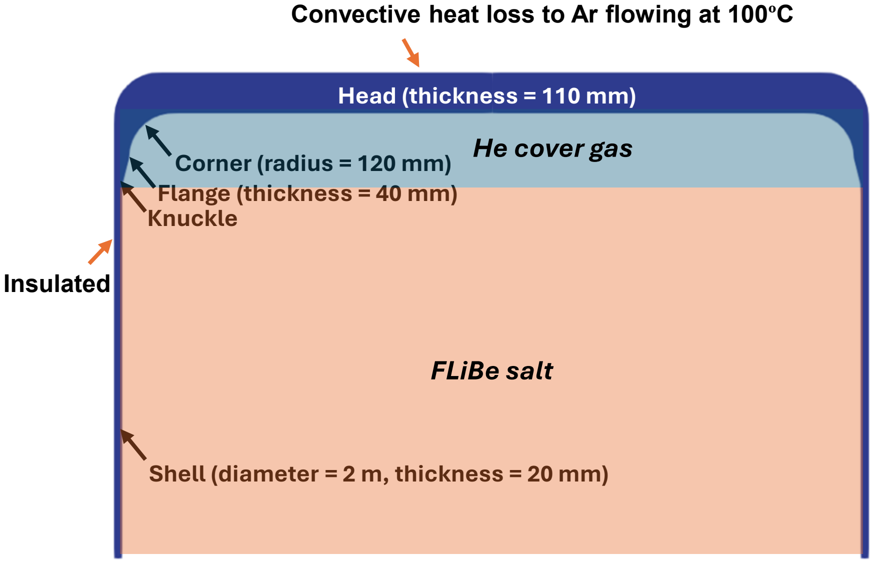
Remaining life estimation

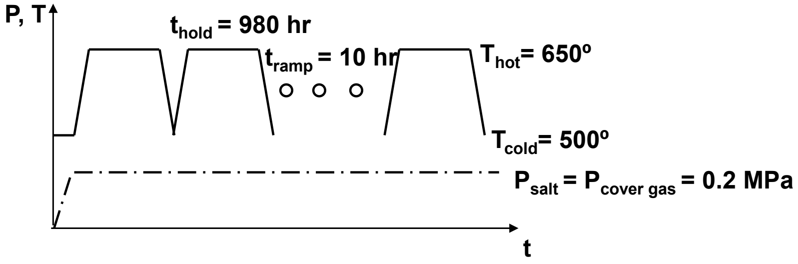
Sample problem

- A flat head vessel
- Material: 316H
- ASME design life: 66 cycles
- Mechanical strain range: 0.115%
- Critical location: knuckle

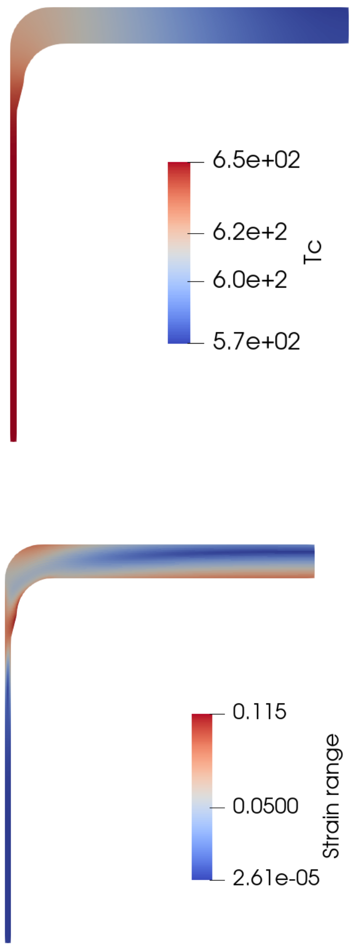
ASME Section III, Division 5 design evaluation

Mechanical strain range	0.115 %
Total creep damage accumulation	0.99
Total fatigue damage accumulation	1.4×10^{-4}
Creep-fatigue evaluation	PASS





Geometry and loading conditions

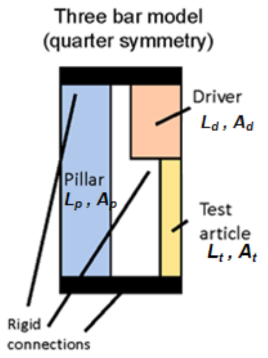


FE results

Specimen sizing

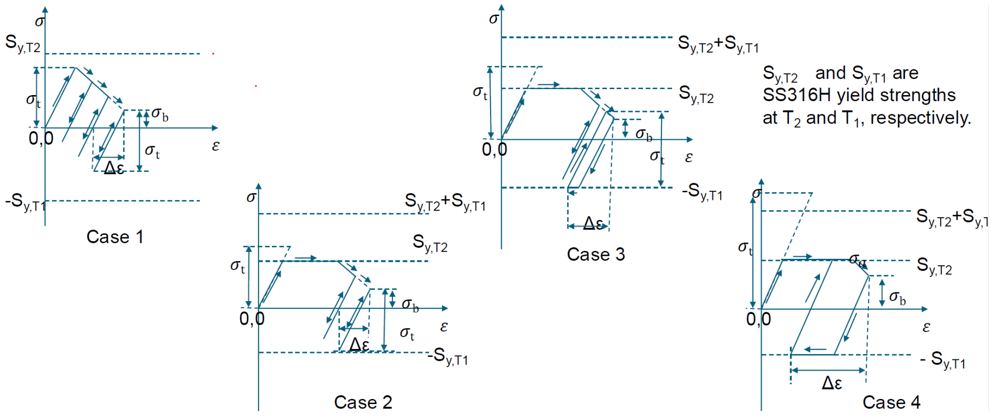
Simplified sizing method

- **Simplified approach:**
  - Uses closed-form relationships based on strain range and elastic follow-up
  - Eliminates numerical optimization and complex material modeling
  - Implementable in Excel workbook (next slide)
- **Assumptions:**
  - Creep occurs primarily during high-temperature hold periods
  - Test section modeled as elastic–perfectly plastic and power-law creep
  - The driver and pillar remain elastic and experience negligible creep



Three-bar model representation of surveillance article

- **Optimization variables:**
  - $l1$, $l2$, $A1$, $A2$, $A3$
- **Objective function:**
  - Simulated specimen response under thermal history best matches component response
- **Constraints:**
  - Specimen sizes obey constraints



Guosheng, et al., 2025, ANL-AMMT--021

Stress-strain response categories (in the test section)

Excel spread-sheet sizing tool

- **Key inputs:**
  - Target strain range Δε
  - Elastic follow-up factor q
  - Thermal cycle parameters
  - Material parameters (E, CTE, minimum creep rate)
  - Test section geometry constraints
- **Key outputs:**
  - Specimen geometry ratios
  - Buckling assessment
  - Assumption checks
    - No yielding in the driver and pillar
    - Negligible creep in the driver and pillar

Objectives		
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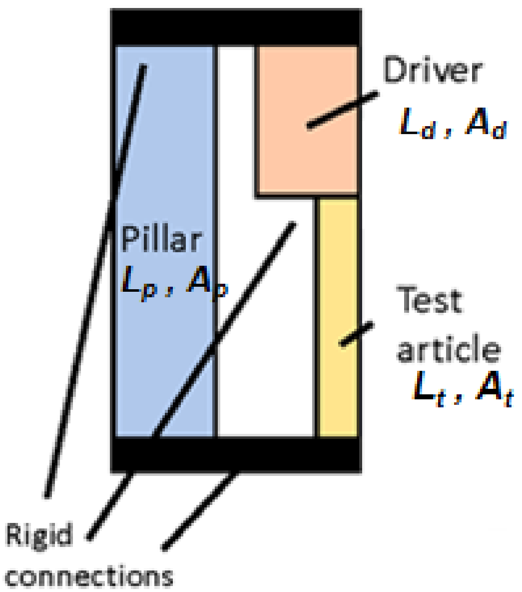
Spreadsheet tool output

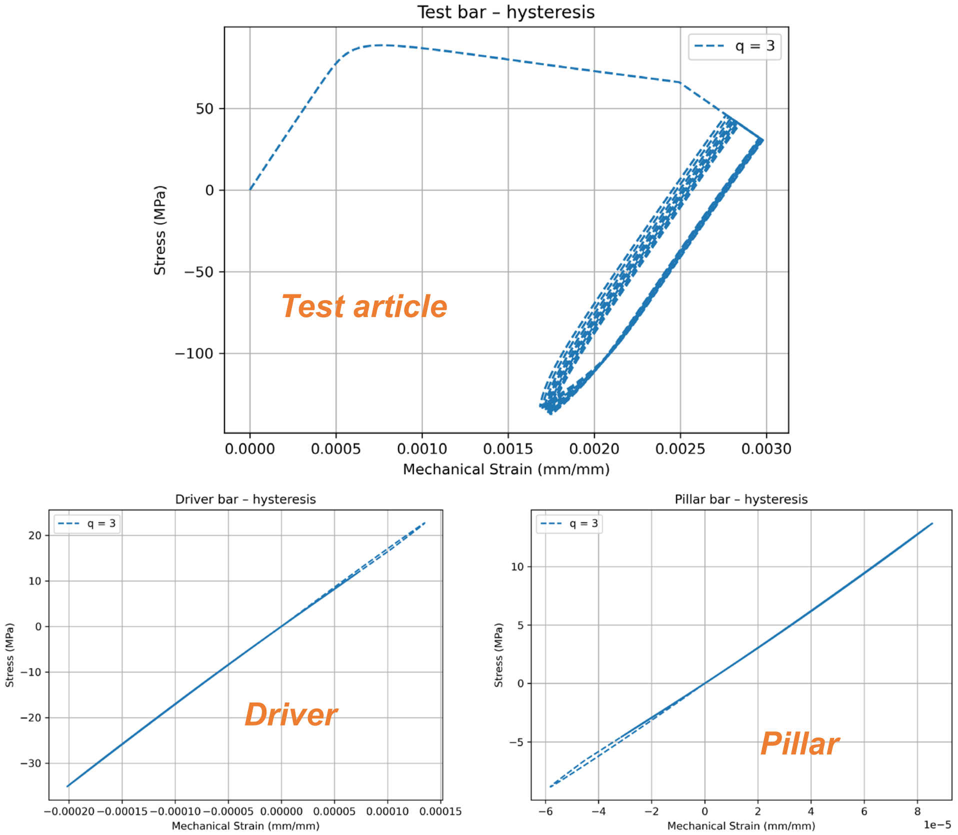
Surveillance specimen sizing using the spreadsheet tool

Three bar model
(quarter symmetry)



<u>Materials</u>
Test article: 316H (same as the vessel)
Driver: A617
Pillar: 316H

Spreadsheet inputs	Target mechanical strain range	0.115%
	T_{cold}	500 ºC
	T_{hot}	650 ºC
	t_{hold}	980 hr
	A_t/A_p	0.1
	Elastic follow up factor, q	3
Spreadsheet outputs	A_t/A_d	0.256
	L_d/L_t	5.781



Analytical model simulation results (using inelastic models)
Nominal life (w/o design margin): 4685 cycles

Feasible specimen design based on spreadsheet results

Spreadsheet output

$A_t/A_p = 0.1$

$A_t/A_d = 0.256$

$L_d/L_t = 5.781$

Actual article design

For given dimensions of test section:

Length, $L_t = 17.60$ mm

Diameter, $d_t = 3.60$ mm

Actual article design

Evaluate dimensions of driver, pillar, and end cap:

Driver length, $L_d = 101.74$ mm

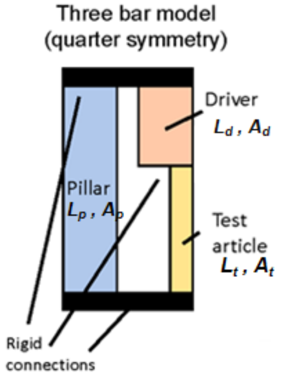
Driver outer diameter, $d_{d\_o} = 9.60$ mm

Driver inner diameter, $d_{d\_i} = 6.44$ mm

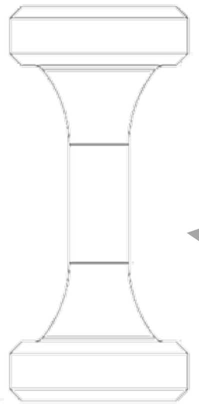
Pillar length, $L_p = 119.34$

Pillar outer diameter, $d_{p\_o} = 28.02$ mm

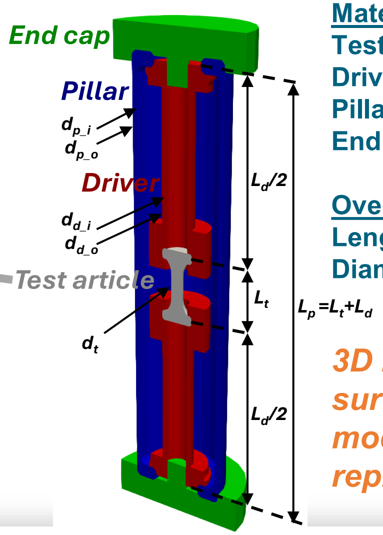
Pillar inner diameter, $d_{p\_i} = 24.60$ mm



Three-bar model (1D analytical representation)



Actual test article geometry



Materials

Test article: 316H (same as the vessel)

Driver: A617

Pillar: 316H

End cap: A617

Overall size

Length: 5.4 inch

Diameter: 1.6 inch

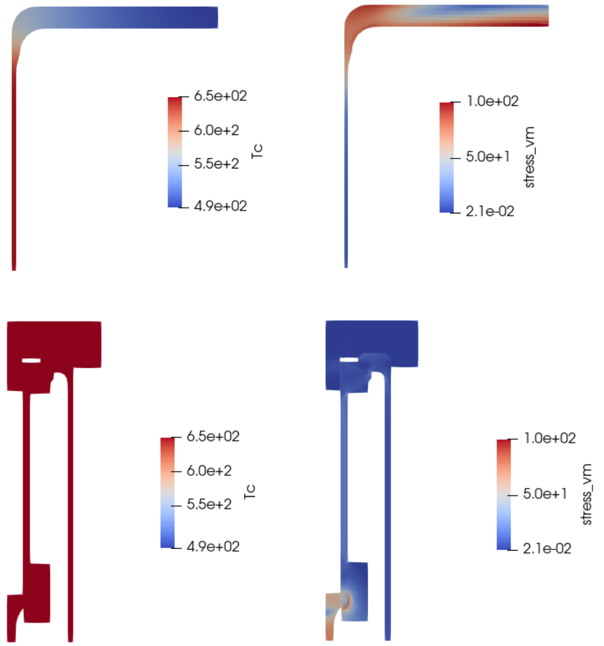
3D model of the surveillance article (half model and simplified representation)

Verification of specimen sizing

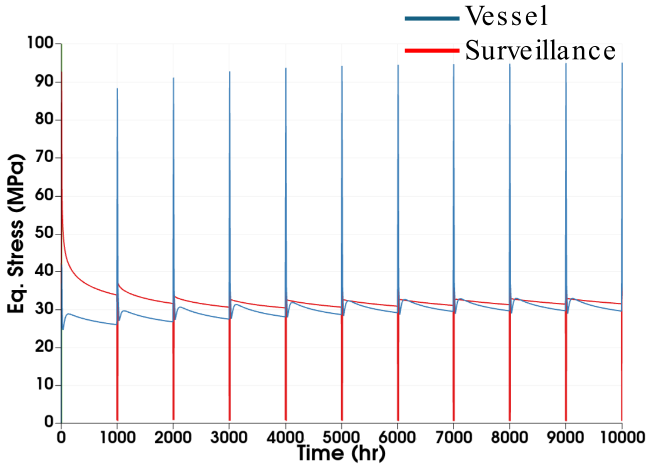
- **Average nominal life comparison: Sample Problem vs. Surveillance Specimen**
  - Assesses whether the specimen experiences comparable damage to the component under identical conditions
  - Not intended to establish margins for surveillance article
    - Should come from targeting higher strain range
- **Simulations:**
  - full inelastic model
- **Life estimation:**
  - ASME creep–fatigue method (no safety margins applied)

Nominal life (cycle) comparison:

Vessel	6469
Three-bar analytical model	4685
Surveillance specimen	6338



Temperature and stress after first heat-up cycle: vessel (top) vs. specimen (bottom)

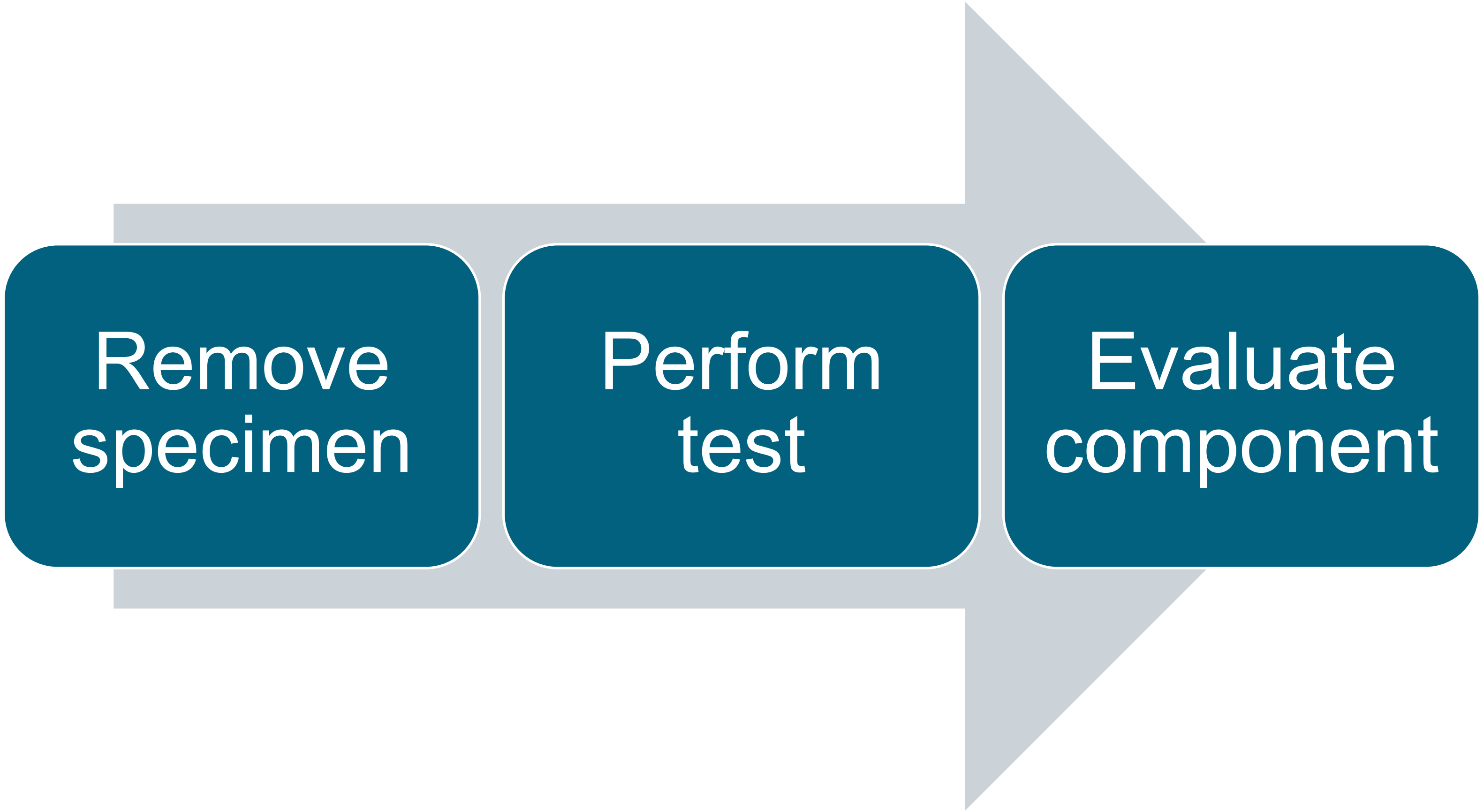


Equivalent stress: vessel critical location vs surveillance test section

The specimen reproduces the component damage state with good fidelity

Remaining Life Estimation

Conceptual illustration of surveillance-based life assessment



Will the component survive until the next inspection?

Assumptions and methodology

- **Based on MPC-Omega method (API 579)**
- **Damage per cycle is repeatable once stabilized behavior is achieved**
- **Remaining life is extrapolated assuming future operation follows the same cycle**

Inputs

Stress history, $\sigma(t)$

Temperature history, $T(t)$

Baseline material (MPC-Omega parameters)

Surveillance update

Remove surveillance specimen

Measure creep response from short-term test of test article

Update creep-rate correlation using surveillance data

Damage evaluation

Use $\sigma(t), T(t)$ and updated creep-rate correlation

Compute $\dot{D}_c(t)$

Integrate damage over cycle:

$$D_{c,\,cycle} = \int \dot{D}_c \; dt$$

Life estimation

Failure criterion: $D_c = D_{c,\,limit}$

Remaining life:

$$N_{remain} = \frac{D_{c,\,limit} - D_c}{D_{c,\,\mathrm{cycle}}}$$

Example remaining life calculations of the vessel

Remaining life after 10 operating cycles

	Creep rate (1/hr)	Creep damage per cycle	Remaining life (cycles)
Baseline (w/o environmental effect)	$5.67 * 10^{-9}$	0.0002	4988
Assumed to be measured from surveillance test article (with environmental effect)	$1.13 * 10^{-8}$	0.0004	2489
	$1.70 * 10^{-8}$	0.0006	1656

- **These calculations used the three-bar analytical model to calculate stress history**
- **Baseline creep rate is based on the stress at the beginning of hold during 10th cycle**
- **Since the fatigue damage is negligible, $D_{c,\,limit}$ = 1 is considered.**

Conclusions/next steps

Conclusions/next steps

- **Extended prior methods to a representative MSR sample problem, demonstrating that the surveillance specimen reproduces component creep–fatigue behavior.**
- **Next steps:**
  - Develop additional sample problems across a range of strain range conditions to generalize the approach.
  - Refine the translation from analytical sizing to a feasible 3D specimen design, supported by inelastic FE simulations.
  - Establish a practical workflow linking spreadsheet sizing → FE validation → deployable specimen design, with a path toward standardization through ASTM International.

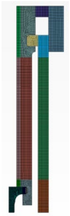
An automated workflow for throughput FE simulations of surveillance specimen

Inputs
1. Thermal cycle
2. Target strain range
3. Follow up factor

→ Simplified spreadsheet method in python →

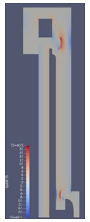
Surveillance article dimensions
1. Test section
2. Driver
3. Pillar

→ Cubit-python interface →



Axisymmetric mesh generation of actual geometry

→ MOOSE-python interface →



MOOSE contact simulation

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