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Technical Basis of Surrogate Materials Surveillance for Advanced Reactors

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Collaborators

- Argonne
  – Mark Messner, Yoichi Momozaki, Ed Boron
- Subject Matter Expert
  – Bob Jetter

Background

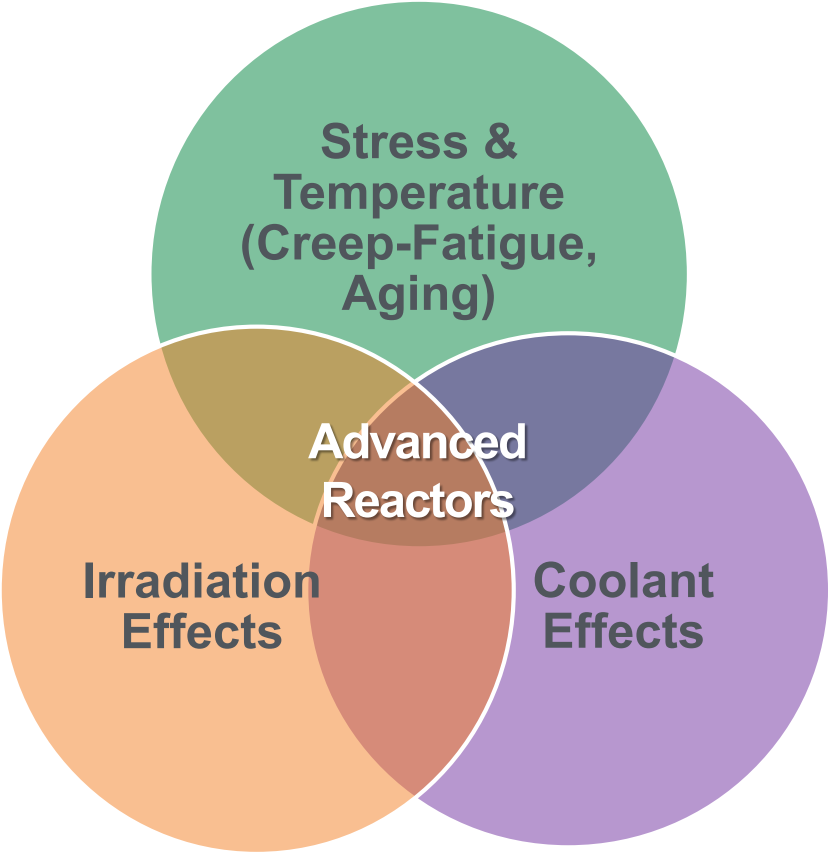
- Information on materials degradations during advanced reactor operations is limited
- The establishment of surrogate materials surveillance program that would allow the collection of information on the materials degradations would be an important pathway in support of the timely licensing of advanced reactors

Current Practice on Surrogate Materials Surveillance

- ASTM E531 - Standard Practice for Surveillance Testing of High-Temperature Nuclear Component Materials
  - Originally approved in 1975 and based on LWR technologies
  - Practice is used when nuclear reactor component materials are monitored by specimen testing
  - Covers procedures for periodic specimen testing performed through the service life of the components to assess changes in selected metallic material properties that are caused by neutron irradiation and thermal effects
  - Provides guidance on how to place surveillance samples to obtain the desired irradiation conditions
  - Test specimens removed from reactor per surveillance program schedule for mechanical properties testing
  - Acceptance criteria are not provided
  - ASTM is currently updating E531 so that it would be more applicable to the new advanced reactors being developed

Materials Degradations During Operations

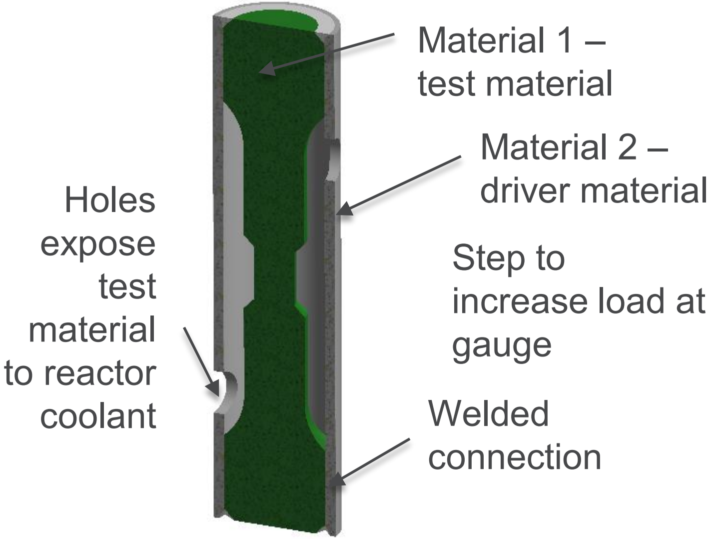
- Effects of materials degradations during reactor operations are synergistic
  - Irradiation, corrosion, elevated temperature exposure and stress (creep-fatigue loading)
- Advantageous to have additional test specimens/articles to capture these synergistic effects to complement the current test specimens selection in ASTM E531

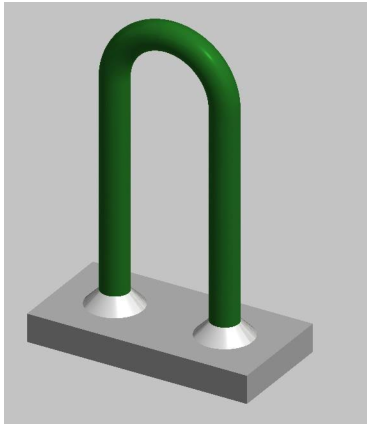


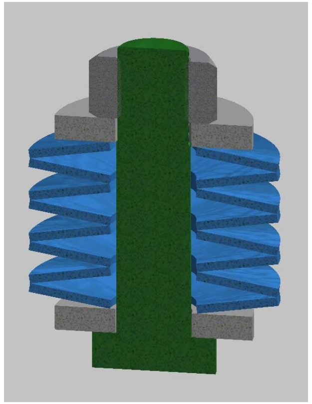
Specimen Design Downselection

- **Key criteria:**
  - Passive load
  - Fabricability
  - Specimen size
  - Measurement possibilities
- **Selected a variant of this specimen**
  - Creep-fatigue specimen with elastic follow up
  - Welded inside a tube
  - Strain driven by CTE difference

Potential Specimen Designs

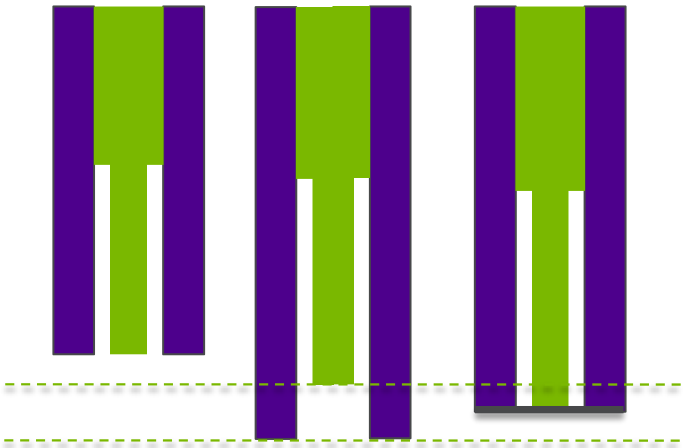






Specimen Designs

Basic design | Temp. increase | Temp. increase, constrained

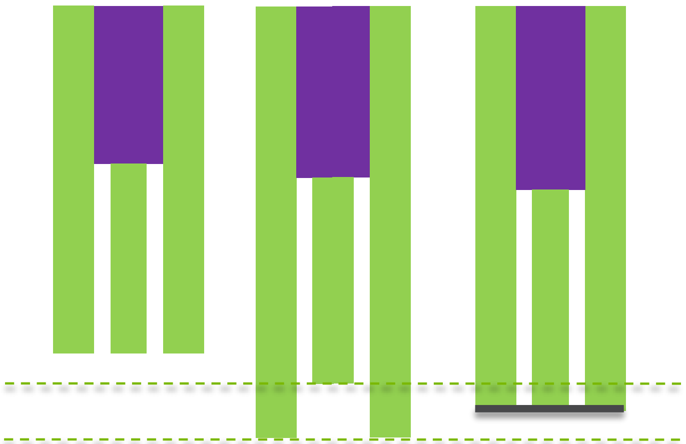


Driver (hollow cylinder) Test specimen

Driver induces tension in test specimen if $CTE_{driver} > CTE_{test}$

Challenge: CTE of stainless steel is higher than basically any other high temperature structural material

Modified design | Temp. increase | Temp. increase, constrained

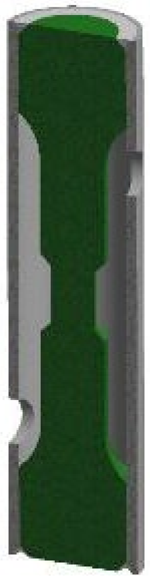


Driver (hollow cylinder) Test specimen

Driver induces tension in test specimen if $CTE_{driver} < CTE_{test}$

Use Differential Thermal Expansion To Drive Test Article During Reactor Operations

Cross section of axi-symmetric test article



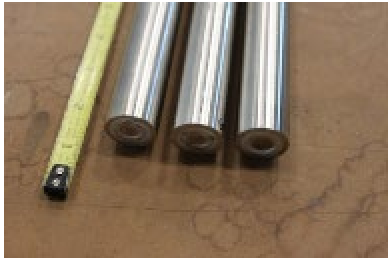
Fabricated a proof-of-concept test article using 316H (test material) and A617 (driver)

1) Stir-friction weld inner bars together

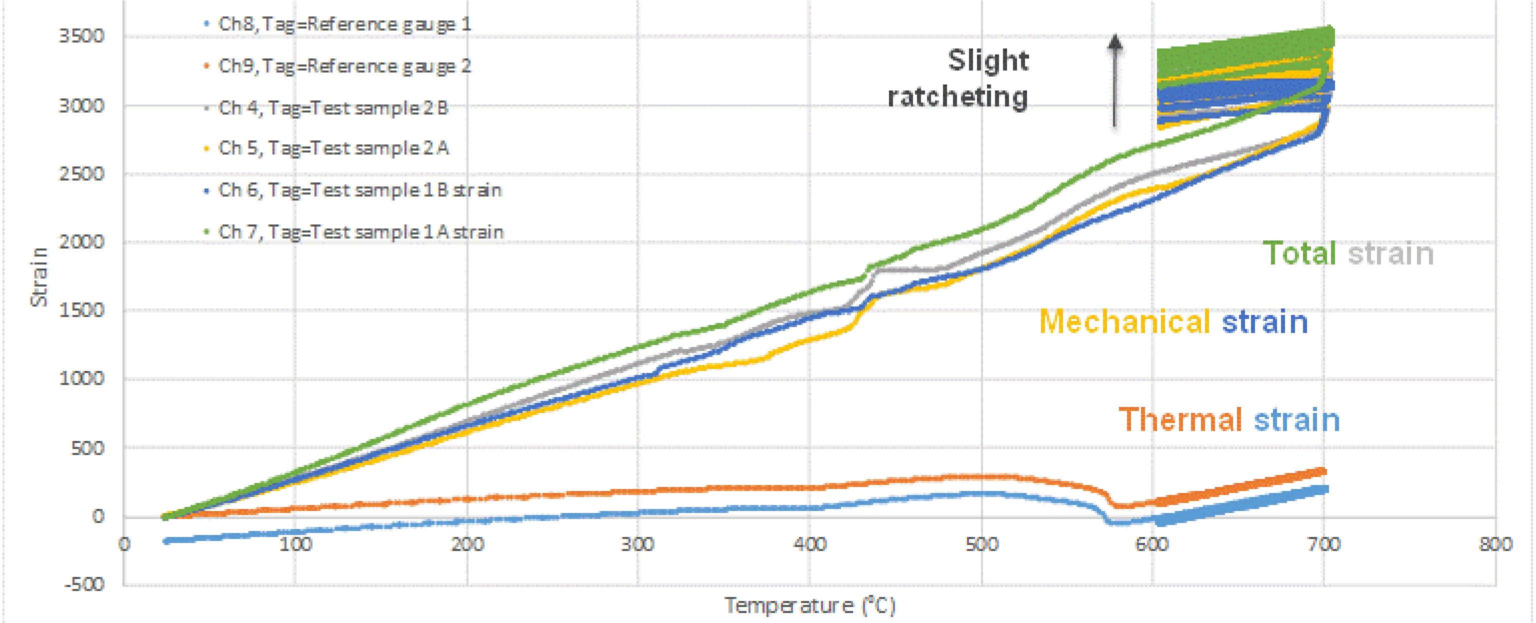
3) Fabricate outer casing

2) Machine inner bars

4) E-beam weld outer casing to inner bars



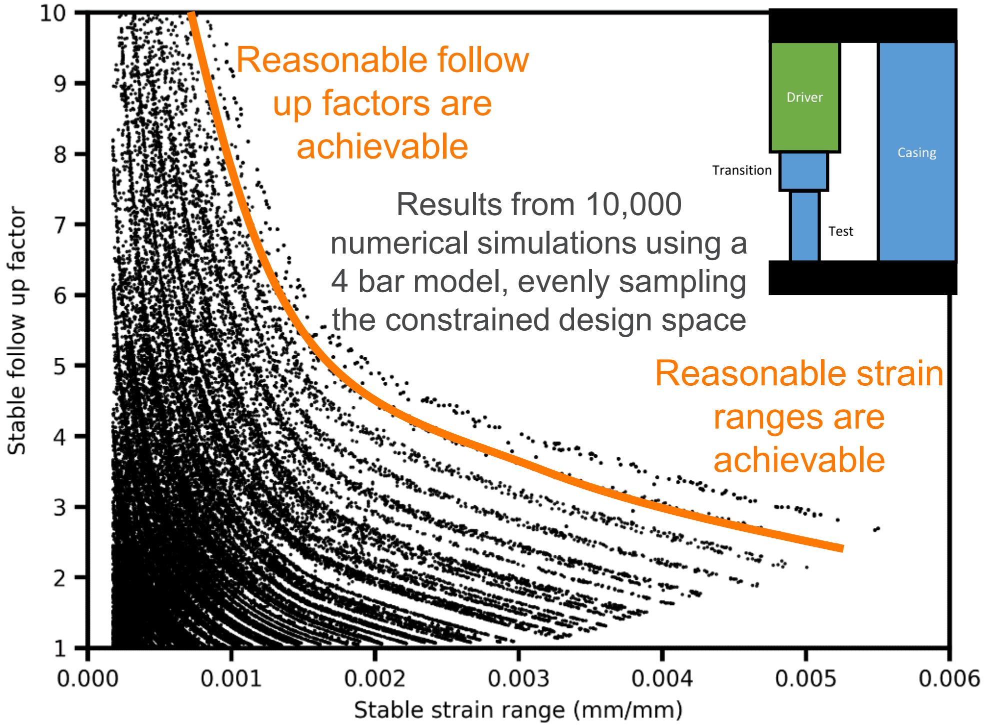
Proof-of-Concept Testing: Thermal Cycling



- 100ºC temperature change during steady-cycle
- Test article only has thermocouple and strain gauge – cannot measure stress
- Two measurements of strain (two strain gauges on reference bar, two strain gauges on sample)

Designing a Family of Specimens to Hit Target Strain Ranges and Stresses During Hold

- The first samples were a "proof of concept"
  - Made with material on hand
  - Dimensions selected to minimize machining, not based on detailed design
- Now apply modeling and simulation to:
  - Design specimen dimensions (given temperature change) to hit target:
    - Strain ranges
    - Stress during hold
    - Elastic follow up factor
  - Assess limitations of the basic design

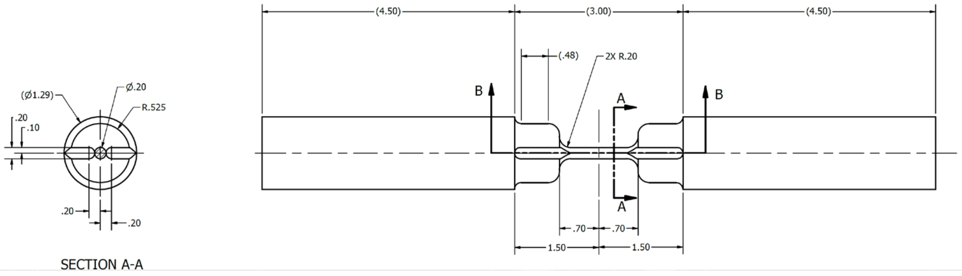


Pareto front: possible combinations of elastic follow up factor and stable strain range for a family of specimen designs

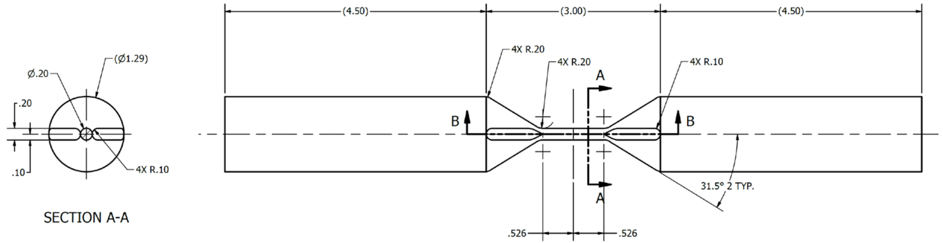
Challenges with In-situ Monitoring of Realistically-sized Specimens

- The original proof of concept had a strain gauge affixed to the inner test region to monitor strain versus time
- **Challenges with strain gauges:**
  - Accuracy/drift (particularly at high temperature)
  - Ensuring long-term adhesion with test article
  - Sensor leads
  - *Required gauge size!*
- **Decision to design and fabricate two types of specimens (and two different detailing "styles"):**
  - **Small specimen: (3" length, ⌀1")**
    - Realistically-sized for operating reactor
    - Demonstrate machining/fabrication techniques
    - Cycle to failure in furnace
    - Cannot affix standard strain gauge!
  - **Large specimen: (12" length, ⌀2")**
    - Too large for operating reactor
    - Can instrument to validate models

Large, detail 1



Large, detail 2



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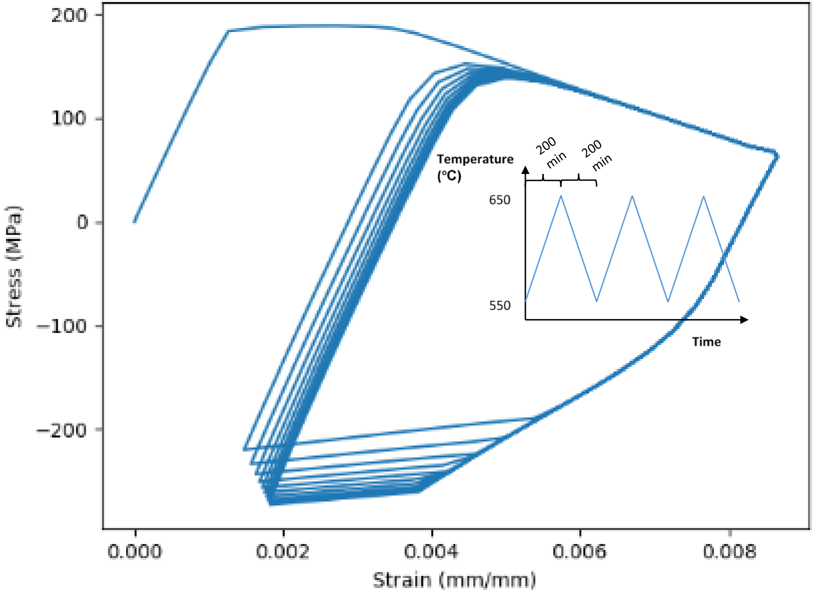
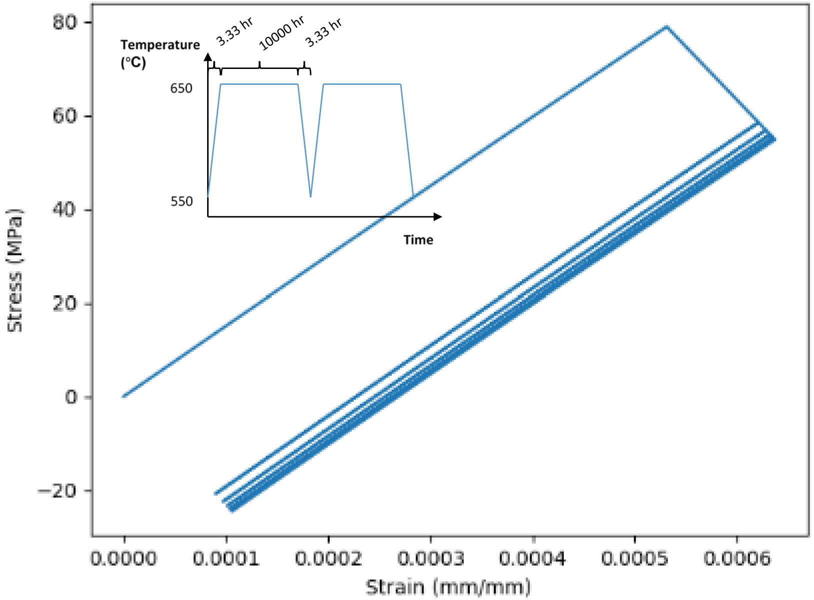
Large and Small Specimen Geometry Determine Through High Throughput Simulations + Design Optimization

Large specimen predicted stress-strain history



Sized to fail in 10,000 h. Will test in furnace to failure

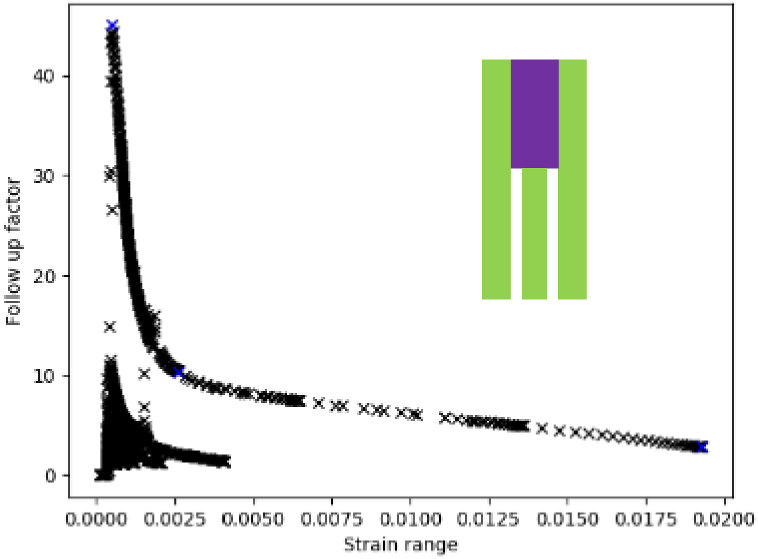
Small specimen predicted stress-strain history



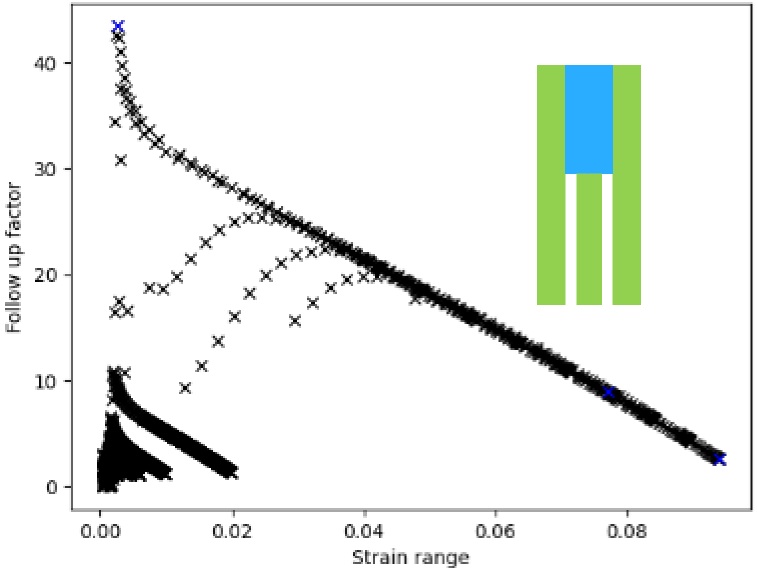
Sized to fail in 50,000 h to test specimen fabricability for representative in-reactor condition

Mean Thermal Expansion Coefficient ($\times 10^{-6}/C$)		Temperature, °C						
		400	500	600	700	800	900	1000
ASME Section III, Division 5, Class A materials	Type 304, 316 SS	18.0	18.4	18.8	19.2	19.4		
	Alloy 800H	16.5	16.8	17.2	17.5	17.9		
	9Cr-1Mo-V	12.0	12.3	12.7	13.0	13.6		
	2.25Cr-1Mo	13.8	14.4	14.8	15.1	15.4		
	Alloy 617	13.8	14.2	14.6	15.1	15.6	16.1	
	Alloy 718 (bolting)	14.2	14.5	14.9	15.5			
Nickel alloys	A740H	13.9	14.3	14.6	15.0	15.7		
	Haynes 230	13.6	14.0	14.4	14.7			
	Haynes 282	13.1	13.5	13.7	14.2	14.9	15.9	16.9
	Alloy 600	14.5	14.9	15.3	15.8	16.1	16.4	
	Alloy 690	14.8	15.2	15.7	16.2	16.6		
	Haynes 242	11.9	12.2	12.3	13.0	14.0	14.5	15.0
	Hastelloy N	13.0		13.4	13.8	14.5	14.9	
Cr-Mo steels	5Cr-1Mo	13.1	13.4	13.6	13.9	14.1		
	12Cr-HT9	11.6	12.0	12.3	12.6	12.8	12.9	13.0
	Grade 92	11.6	12.0	12.2	13.1	13.1	10.6	8.6
Stainless steels	Alloy 709	17.0	17.2	17.5	17.8	18.1		
	310 SS	16.5	16.8	18.1				
	347 SS	17.7	18.3	18.9	19.3	19.7	20.1	20.5
FeCrAl alloys	Kanthal APMT	12.8	13.1	13.3	13.5	13.8	14.3	14.7
	PM2000		14.7					15.4
	MA956	12.3	12.7	13.0	13.4	13.9	14.4	14.9
	MA957	11.7	11.5	11.3	11.1	10.9	10.6	10.4
Refractories	TZM	5.47	5.54	5.61	5.68	5.74	5.81	5.88
	Mo	4.40	4.58	4.76	4.94	5.12	5.30	5.48
	W	4.29	4.33	4.37	4.40	4.44	4.48	4.52
	V	9.68	9.84	9.99	10.15	10.31	10.47	10.62
	Nb	7.65	7.82	8.0	8.21	8.42	8.63	8.83
	Nb-1Zr	6.99	7.07	7.15	7.23	7.33	7.43	7.53
	V-4Cr-4Ti	10.1	11.2	11.6	12.1	12.6	13.2	13.8
	Mo-41Re	5.63	5.69	5.76	5.81	5.88	5.94	6.00
	Mo-47.5Re		5.72	5.87	6.01	6.16	6.30	6.45
	W-25Re		4.48	4.59	4.70	4.82	4.93	5.04

Further Explore Design Space



316H + Alloy 617



316H + Mo:
Much larger design space in follow up factor and strain range

Summary

- Completed initial development on surveillance test articles
- Successfully demonstrated that the use of thermal expansion coefficient mismatch can provide creep-fatigue loading on surveilled material passively through temperature cycling
- Found sufficient design envelope for surveillance test article geometries to accommodate different desired strain ranges for in-reactor use
- Designed a large specimen (12”) for thermal cycling test and a small specimen (3”) to demonstrate fabricability
- These specimens are being fabricated
- Expect to starting the thermal cycling test on the large specimen in early 2021

Questions?