U.S. DEPARTMENT OF ENERGY | Nuclear Energy

ART High Temperature Alloys Overview

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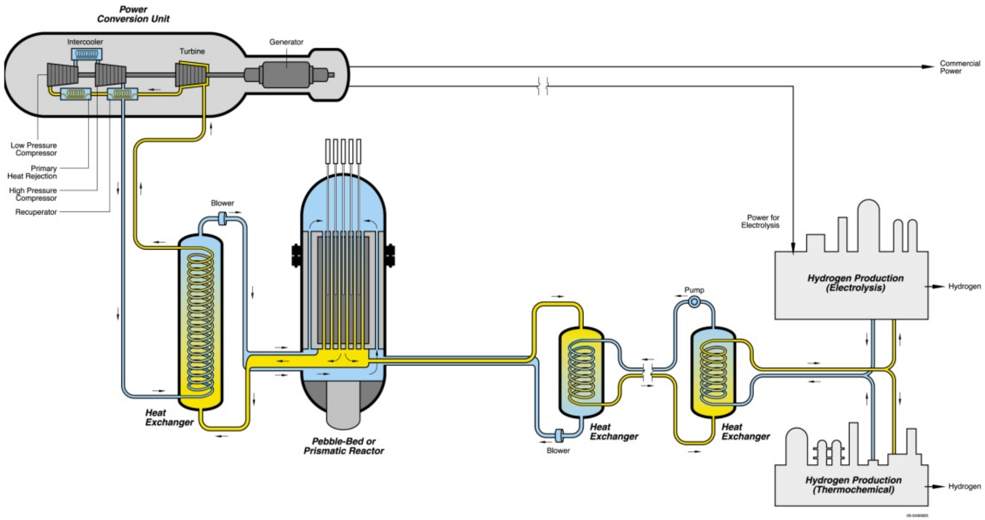
High Temperature Materials of Potential Concern

- **Pressure vessel steels**
- **Alloys for heat exchangers**
- **Control rod sleeves and other core internals**
- **Design methods for very high temperature components**



ART High Temperature Alloys Activities

- ***Development of new methods for design of high temperature reactor components***
- ***ASME Boiler and Pressure Vessel Code qualification of an additional material capable of service to higher temperature***
- ***Addressing issues that might affect licensing of high temperature reactors***
- ***These activities are being carried out by Argonne, Idaho and Oak Ridge National Laboratories.***

Design Methods Based on EPP+SMT Address NRC Concerns on Strain Accumulation and Creep-Fatigue Damage at Critical Locations

- **Critical locations are stress risers:**
  - **Notches; Thermal gradient; Thickness changes**
- **Creep enhances local deformation and shortens life due to microstructural damage**

bottom of tubesheet weld*

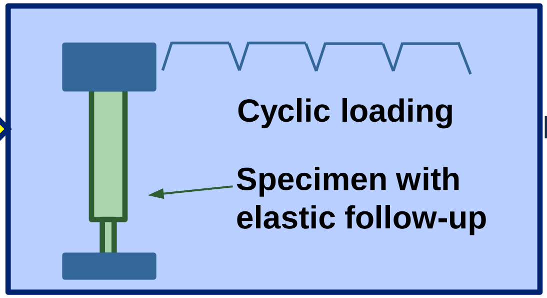
(*P. Di Lillo, et. al., Proc. of Elevated Temperature Application of Materials for Fossil, Nuclear, and Petrochemical Industries)

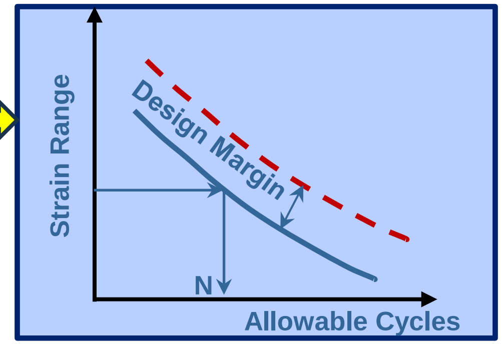
- **Goal is to address NRC concerns on stress risers and multi-axial stress effects at discontinuities and welds;**
- **New design methods based on EPP+SMT are proposed to address these NRC concerns;**
- **There are additional advantages of the proposed methodologies that make the design process more robust and simpler .**

Overview of EPP+SMT Integrated Approach

Strain range from EPP strain limit evaluation

Strain redistribution and slower creep relaxation bounded by suitably sized specimen with elastic follow up representative of real component





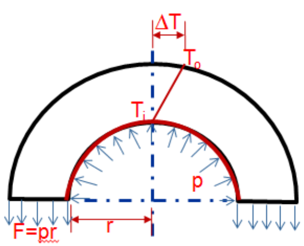
SYNERGISTIC APPROACH MAXIMIZES ADVATAGES

- EPP methodology provides better representation of strain range at stress risers/discontinuities
  - Current Div. 5 elastic methods require stress classification and complex adjustments
- SMT methodology provides more accurate representation of combined effects of creep and fatigue at local stress risers/discontinuities with multiaxiality
  - Based directly on test data – not theoretical separation of creep and fatigue and their interaction
- Use of Strain Limit Code Case also ensures strain limit compliance

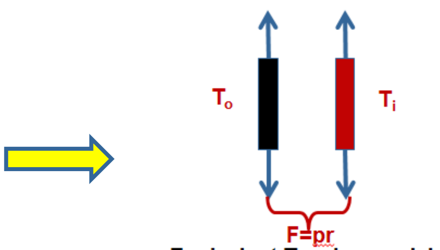
Additional Advantages of Integrated EPP+SMT Approach

EPP based design methods have already been qualified for Div. 5 applications via approved code cases

- Strain limit code case qualified with inelastic analysis
  - Inelastic analysis baselined by Two-bar data

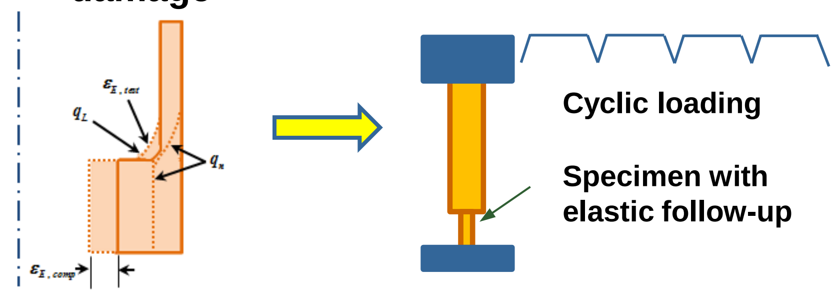


Pressurized cylinder with radial thermal gradient



Equivalent Two-bar model

- Creep fatigue damage code case qualified with SMT data
  - Still requires use of “D” diagram-separate evaluation of creep damage and fatigue damage



New design methods based on EPP+SMT have additional advantages

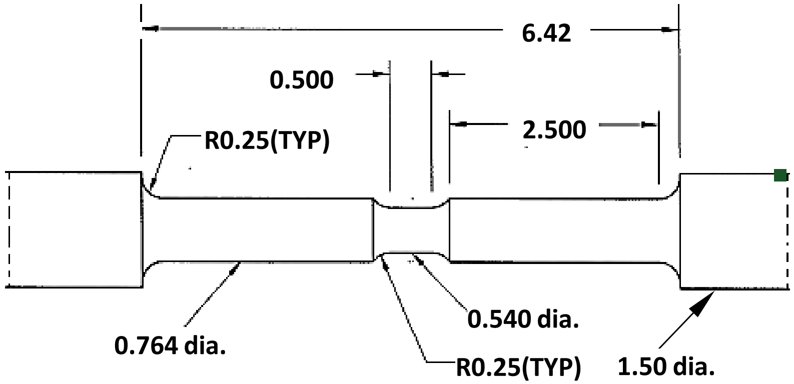
EPP strain limit code case + SMT creep fatigue evaluation → EPP+SMT integrated approach → “All temperature code” Design method

- EPP strain limits and creep-fatigue evaluation are approved for SS304 and SS316
  - Integrated into alloy 617 code case
  - Overcomes restrictions on design methods above 1200°F
- Integrated approach combines advantages of EPP and SMT methodologies.
  - No stress classification with EPP
  - No separation of creep and fatigue evaluation with SMT
- “All temperature code” based on EPP provides smooth transition between low (no creep) and high (creep) temperature design
- Compatible with SG-HTR goals and BNCS oversights

Different Types of SMT Specimens

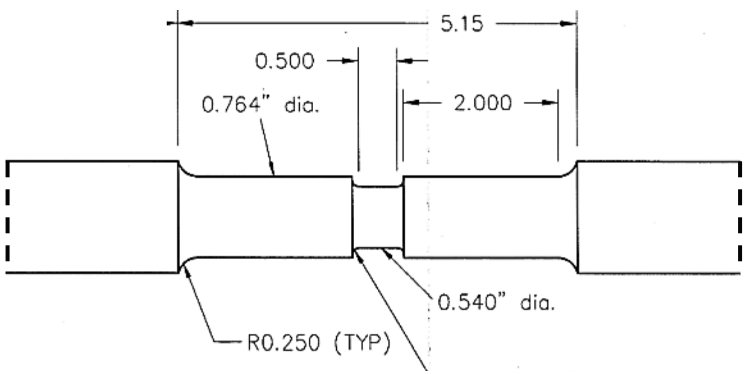
$$K \le \frac{q_n}{q_n - 1}$$

Type 1
Q=3.5; K=1.37



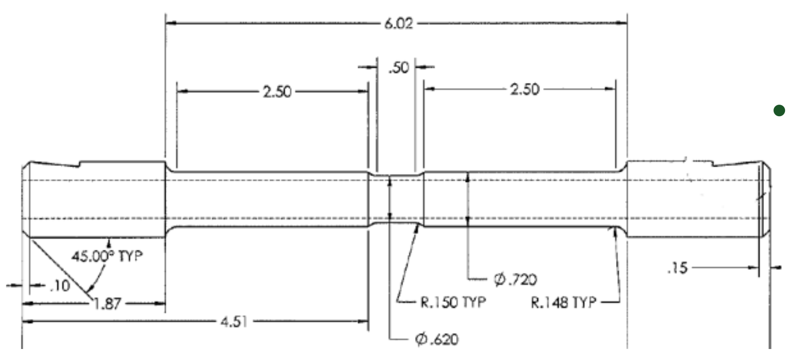
- **Type 1: to develop bounding design curve**
  - **Elastic follow-up**

Type 2
Q=2.5; K=1.7



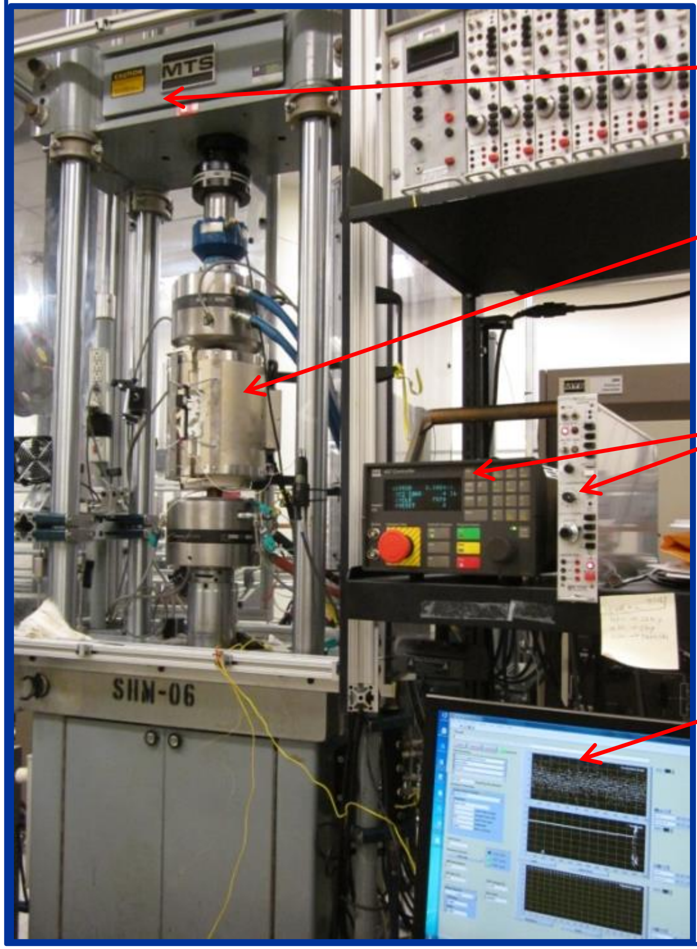
- **Type 2 with stress concentration:**
  - **Elastic follow-up;**
  - **Localized stress redistribution.**

Tubular
Q=3.8; K=1.45



- **Tubular specimen: internal pressurization with axial loading:**
  - **Elastic follow-up,**
  - **Stress riser;**
  - **Multi-axial stress state.**

SMT Test Setup



MTS servo-hydraulic machine

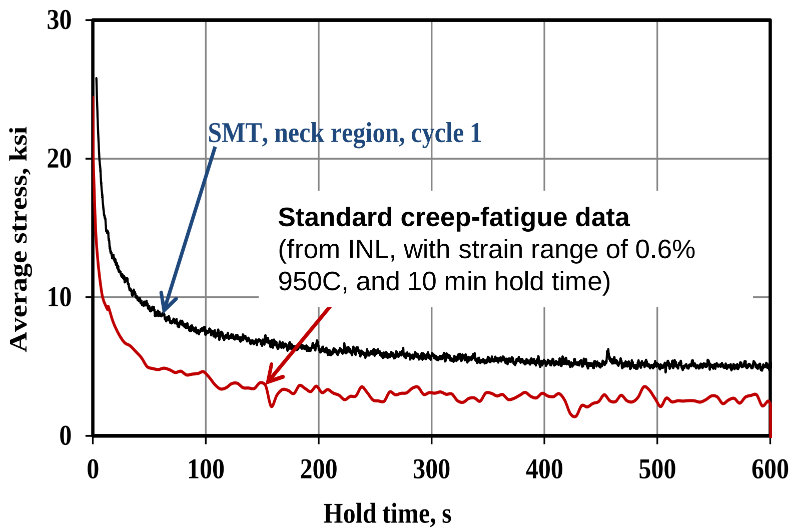
Three zone resistance furnace

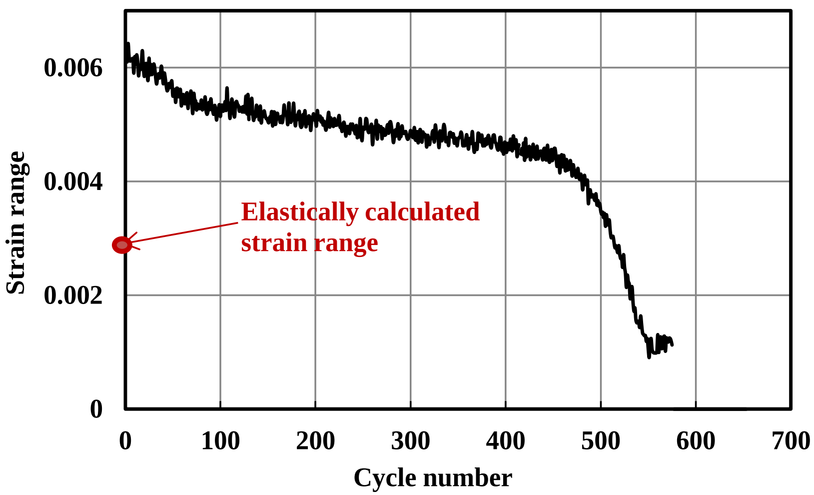
Control & measurement system

Labview program control and data acquisition

- Loading profile defined to provide cross-check against INL creep-fatigue test data from standard specimens; loading profile is automated through Labview program.
- Accuracy in displacement/strain control and strain measurements are critical.
- Measurement and control system established.
- Stable thermal environment verified.

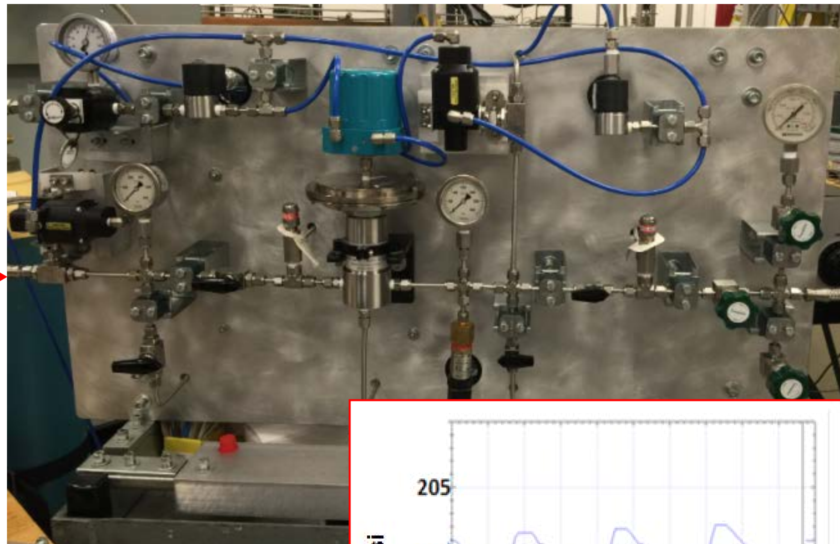
Type 1 Alloy 617 SMT Creep-Fatigue Test Results at 950ºC

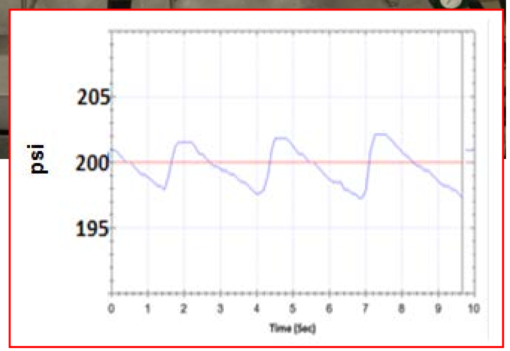


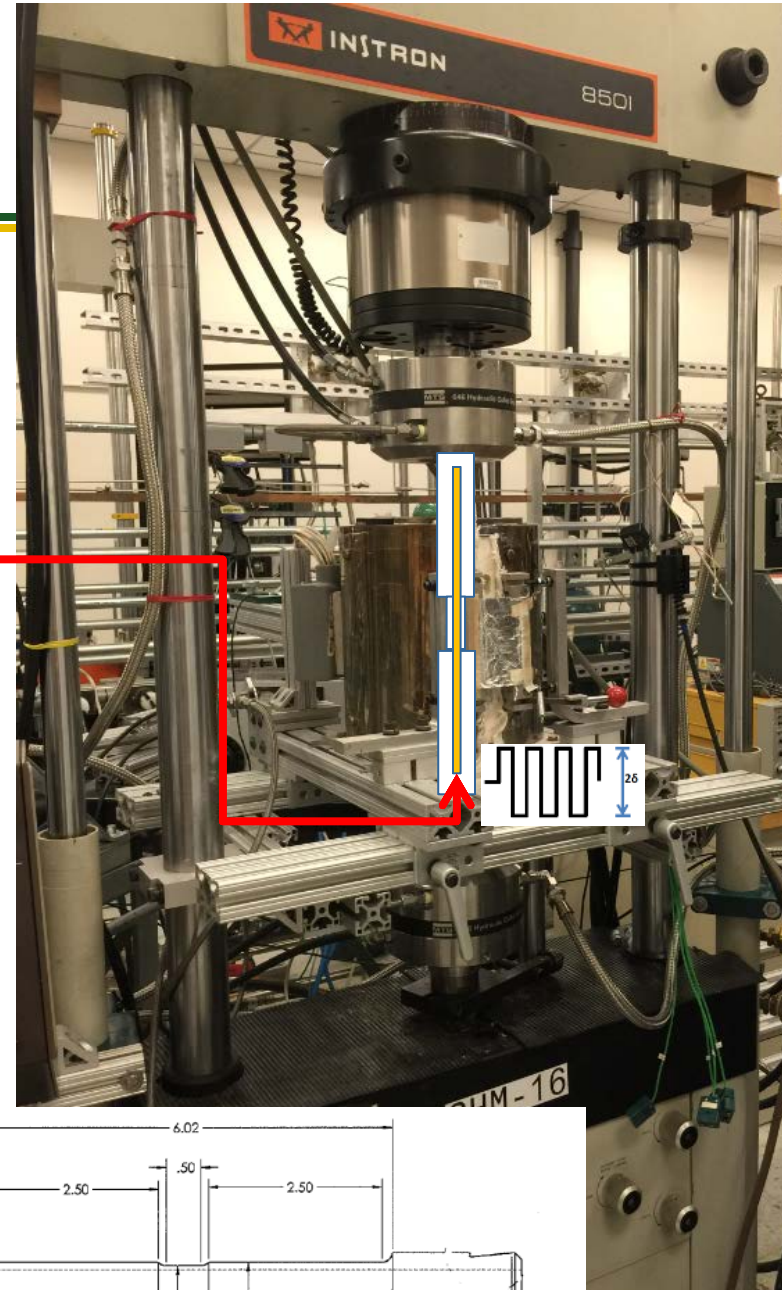


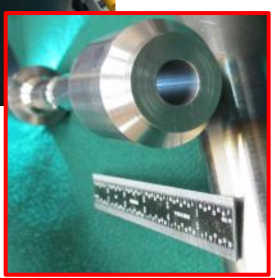
- **Stress relaxes more slowly due to elastic follow-up;**
- **Elastic follow-up increased strain range about a factor of two;**
  - **Function of follow-up magnitude**
- **Elastic Follow-up in SMT specimen decrease cyclic life of Alloy 617 at 950ºC.**

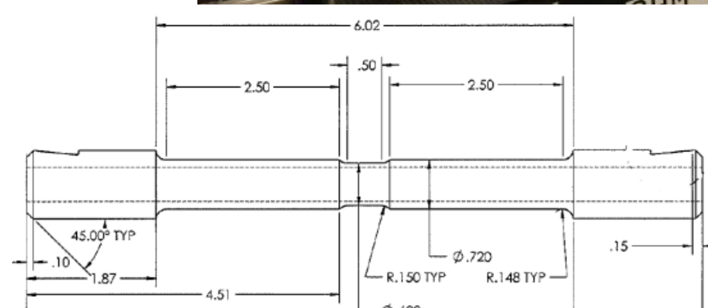
Pressurization SMT on Alloy 617









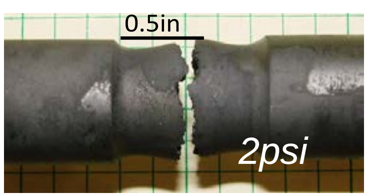


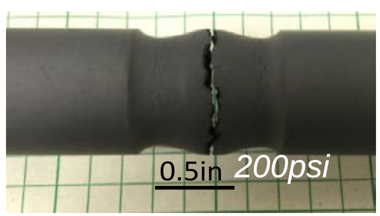
Pressurization Test Results on Alloy 617

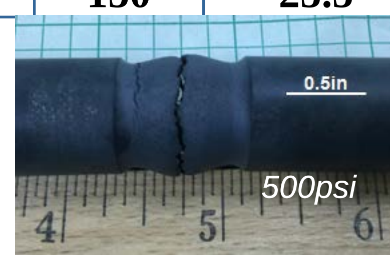
- Cylindrical SMT tests to further validate EPP creep-fatigue methodology
  - Pressure induced discontinuity stress
    - Do not relax at elevated temperature like typical discontinuity stresses
    - Combined with displacement induced stresses to represent real component loading.
  - Significant through-wall stress risers
    - Current type 2 specimen represents localized stress risers constrained by surrounding material
    - More general case where stress riser influences through wall stress/strain redistribution

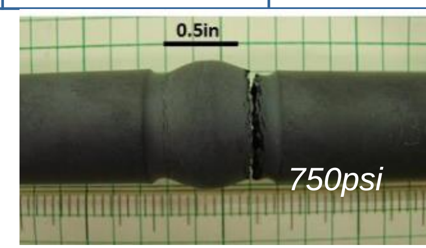
950 ^{o}C, tensile hold 600s, with elastic cal. Strain range of 0.3%. Initial strain range, 0.8%

Specimen ID	Internal pressure	Original OD	Max OD after testing	Wall thickness at failure location	Cycle to failure	Life time, h	Failure location	Elastic follow up
P01	2 psi	0.62in	~0.68in	~68mil	220	37.4	Center	~3.8
P02	200 psi		~0.72in	~62mil	220	37.4	Center	~3.8
P04	500 psi		~0.75in	~54mil	200	34	center	~4.0
P03	750 psi		~0.81in	~41mil	150	25.5	Transition radius	~4.1





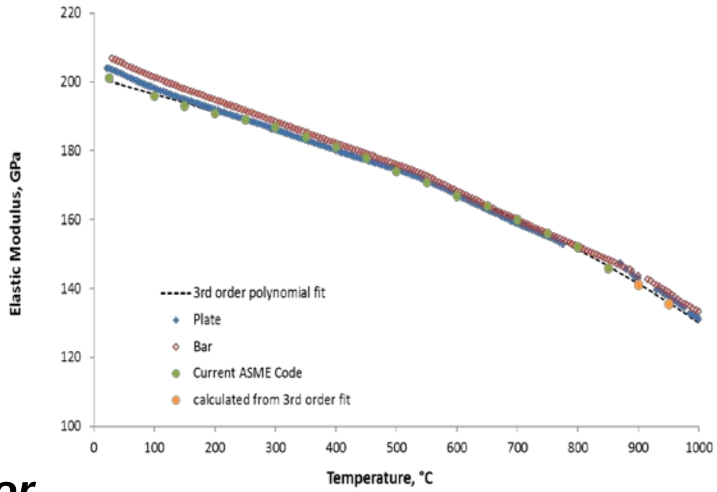




Internal pressurization and axial C-F loading – SMT key feature test article

High Temperature Alloy Qualification

- ***The Ni-Cr-Co-Mo material Alloy 617 will be qualified under the High Temperature Reactor section of the ASME Boiler and Pressure Vessel Code to allow construction of nuclear components for gas cooled reactors***
- ***A draft Code Case to allow use up to 425ºC, where time dependent deformation is not significant, is in the ASME approval process***
- ***The draft Code Case allowing use up to 950ºC for 100,000 hour design life is complete and under review; sections of the draft have been distributed for review and comment***



- ***Developed design evaluation methodology for strain limits and creep-fatigue damage based on Elastic, Perfectly Plastic (EPP) methodology***
  - *Section III, Division 5, EPP Code Cases have been fully approved by ASME.*
  - *The first major change to the rules for elevated temperature design in approximately three decades and is a major step forward in the implementation of modern computer technology and failure mode analysis.*

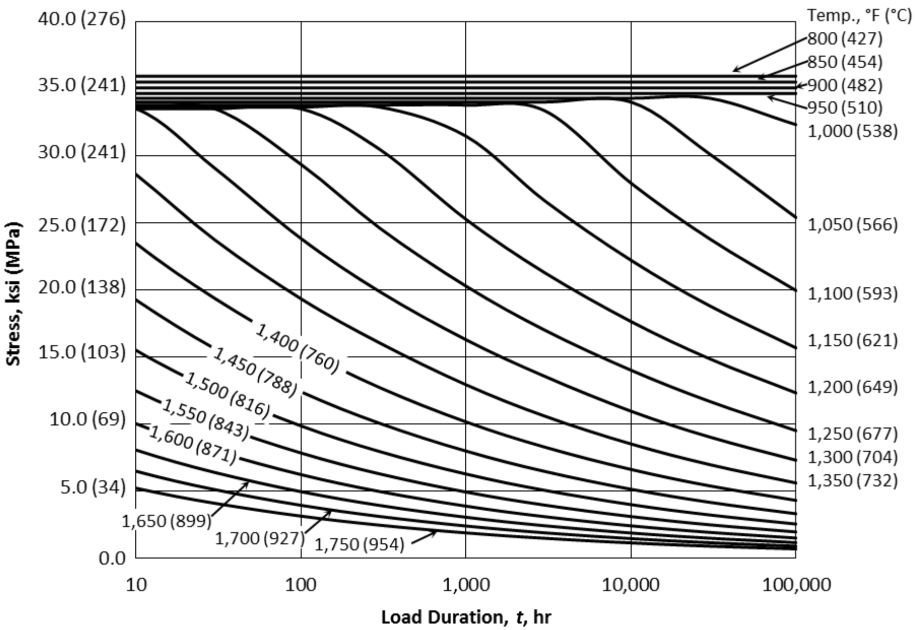
Flow Sheet for Approval of the Alloy 617 Code Case for 950ºC and 100,000 hours

Item no.	Record	Project Manager	Alloy 617 Code Case Topics	Section III, for approval (balloting order indicated by numbers)	Section II, for approval (balloting order indicated by numbers)
1 D	RC-16-994	R. Wright	Permissible base materials	1.WG-ASC	4. (SG-NFA, SG-StrengthWeld)
2 D			Permissible weld materials	2.SG-ETD	5. BPV II
3 D			Yield and ultimate (S_y, S_u)	3.(SG-HTR, SG-MF&E)	
4 D			Allowable stresses (S_o, S_m, S_r, S_t, S_{mt})		
5 D			Stress rupture factor		
6 D			Relaxation cracking		
7 D			Aging factor		
8 D			Cold work and annealing		
9 D	RC-16-995	R. Wright	Extend modulus values to higher temperatures	1.WG-ASC	4. (SG-PhyProp, SG-NFA)
10 D			Thermophysical properties (CTE, diffusivity, conductivity)	2.SG-ETD 3.(SG-HTR, SG-MF&E)	5. BPV II
11	RC-16-996	Jetter	Temp/time limits for buckling charts	1.WG-AM 2. SG-ETD 3.(SG-HTR, SG-MF&E)	4. (SG-ExtPress, SG-NFA) 5. BPV II
12	RC-16-997	Jetter	Huddleston parameters	1.WG-ASC 2.SG-ETD	
13			Isochronous stress-strain curves	3.(SG-HTR, SC-D)	
14 D	RC-16-998	Jetter	Negligible creep	1.WG-CFNC	
15 D			Creep-fatigue D-diagram	2.SG-ETD	
16 D			EPP creep-fatigue damage evaluations	3.(SG-HTR, SC-D)	
17 D	RC-16-999	Jetter	EPP strain limits evaluations	1.WG-AM 2. SG-ETD 3.(SG-HTR, SC-D)	
18 D	RC-16-1000	Jetter	Fatigue curves	1.(WG-FS, WG-CFNC) 2.SG-ETD 3.(SG-HTR, SG-MF&E, SC-D)	
19	RC-16-1001	Jetter	Overall Alloy 617 Code Case	1. BPV III	

S_t, Time-Dependent Allowable Stress for Service

S_t is defined as the lesser of three quantities:

- 100% of the average total stress required to obtain a total strain of 1% (elastic, plastic, primary and secondary creep)
- 67% of the minimum stress to cause rupture
- 80% of the minimum stress to cause the initiation of tertiary creep



T (°F)	Time (h) 1	3	10	30	100	300	1000	3000	10000	30000	100000
800	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
850	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5
900	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1	35.1
950	34.7	34.7	34.7	34.7	34.7	34.7	34.7	34.7	34.7	34.7	34.7
1000	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	34.3	32.3
1050	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	34.0	30.1	25.4
1100	33.8	33.8	33.8	33.8	33.8	33.8	33.8	33.4	28.0	23.8	20.0
1150	33.6	33.6	33.6	33.6	33.6	33.6	31.5	26.7	22.2	18.8	15.7
1200	33.5	33.5	33.5	33.5	33.5	30.5	25.3	21.3	17.6	14.9	12.3
1250	33.5	33.5	33.5	33.5	29.4	24.6	20.3	17.0	14.0	11.7	9.5
1300	33.5	33.5	33.5	29.1	23.8	19.9	16.3	13.6	11.0	9.0	7.3
1350	33.5	33.5	28.6	23.7	19.3	16.0	12.9	10.6	8.5	7.0	5.6
1400	33.5	29.0	23.5	19.4	15.6	12.7	10.2	8.3	6.6	5.4	4.3
1450	29.1	23.9	19.3	15.6	12.4	10.0	8.0	6.5	5.1	4.2	3.3
1500	24.2	19.7	15.5	12.5	9.9	7.9	6.3	5.0	4.0	3.2	2.5
1550	19.8	15.9	12.5	10.0	7.8	6.3	4.9	3.9	3.1	2.5	1.9
1600	16.1	12.9	10.0	8.0	6.2	5.0	3.9	3.1	2.4	1.9	1.5
1650	13.1	10.4	8.1	6.4	4.9	3.9	3.0	2.4	1.9	1.5	1.1
1700	10.7	8.4	6.5	5.1	3.9	3.1	2.4	1.9	1.4	1.1	0.9
1750	8.7	6.8	5.2	4.1	3.1	2.4	1.9	1.5	1.1	0.9	0.7

1% Strain	Tertiary Creep	Rupture

The ASME D-diagram

$$\underbrace{\sum_j \left(\frac{n}{N_d}\right)_j}_{\text{Cyclic Damage}} + \underbrace{\sum_k \left(\frac{\Delta t}{T_d}\right)_k}_{\text{Creep Damage}} \leq D$$

Fatigue damage

$$D_F = \left(\frac{N_d}{N_f}\right)$$

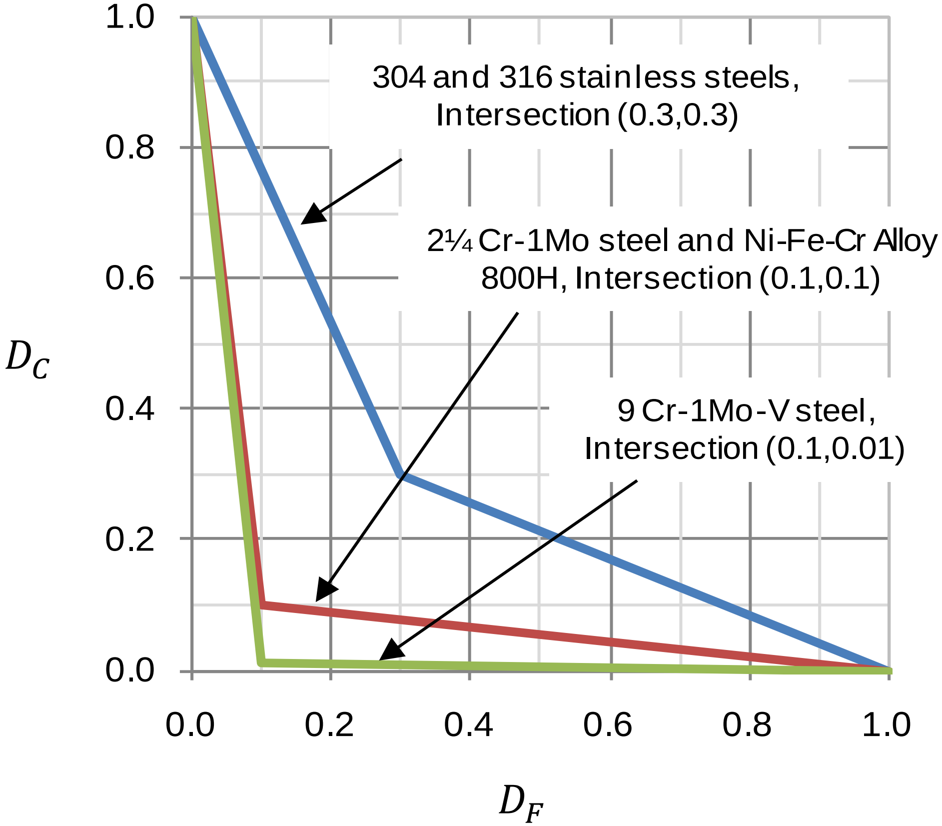
N_d: c-f cycles to failure
N_f: fatigue cycles to failure

Creep damage
$D_C = D_k^c * N_d$

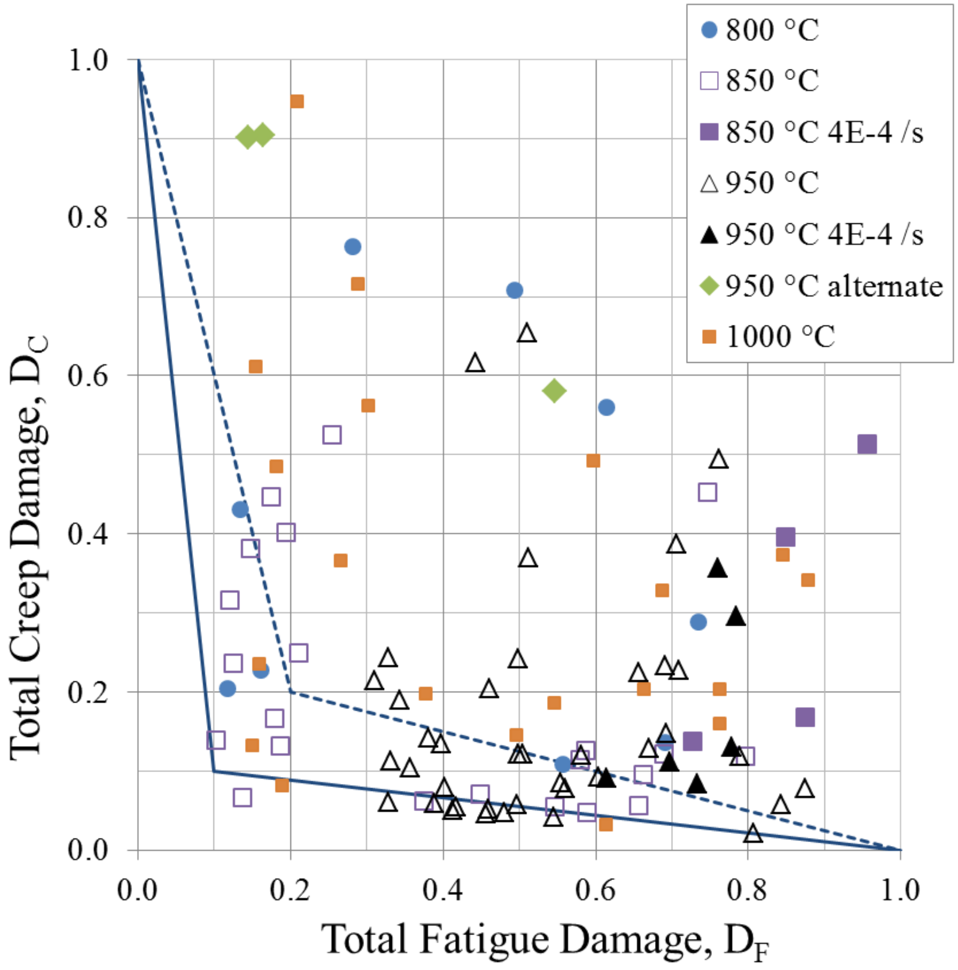
D_k^c: creep damage for mid cycle

$$D_k^c = \frac{{b_0}^{-m}}{A(1-b_1 m)}\left((t_h + t_0)^{1-b_1 m} - (t_0)^{1-b_1 m}\right)$$

where t_h is the stress relaxation hold time in seconds



D-diagram for Alloy 617



Further Review of High Temperature Reactor Regulator Requirements

- **Mid 2000's, NRC updated the licensing needs for next generation power plants**
  - General issues related to high temperature stability
  - Ability to withstand service conditions
  - Long-term thermal aging
  - Environmental degradation (impure helium)
  - Issues associated with fabrication and heavy-section properties
  - Further development of Section III of the ASME code needed (for higher temperatures – up to at least 900 ^{o}C), including Alloy 617 and Hastelloy X
  - Creep behavior models and constitutive relations are needed for cyclic creep loading
  - Models must account for the interaction between the time independent and time dependent material response

Regulatory issues and ASME code

- **Current versions of the Code (Section III, Division 5) address to some degree the prior regulatory concerns**
  - Uniaxial creep behavior is addressed
  - Creep-fatigue for wrought products
  - Environmental effects
  - Rules for the design of welded joints
- **Some concerns still not addressed by the code**
  - Detailed material properties needed for cyclic finite element creep design analysis
  - More work needed to adequately cover cyclic loads in creep regime and creep fatigue-creep rupture interaction effects
  - Creep-fatigue of weldments is not well understood
  - Need to expand high temperature design work to handle additional materials, higher temperatures and creep damage mechanisms anticipated for the new reactors.

Resolution of Regulatory Issues for VHTR Materials

- **R&D topics to address regulatory and licensing concerns include**
  - Crack growth and fracture mechanics under prototypical VHTR heat exchanger and steam generator environments.
  - Develop an understanding of the relationship between complex multi-axial component loading and metallurgical behavior observed in uniaxial testing under laboratory conditions.
  - Simplified strain limits and creep-fatigue bounding rules at geometric and metallurgical discontinuities.
  - Long-term integrity of welded construction, and development of validated weldment design rules and analysis methods.

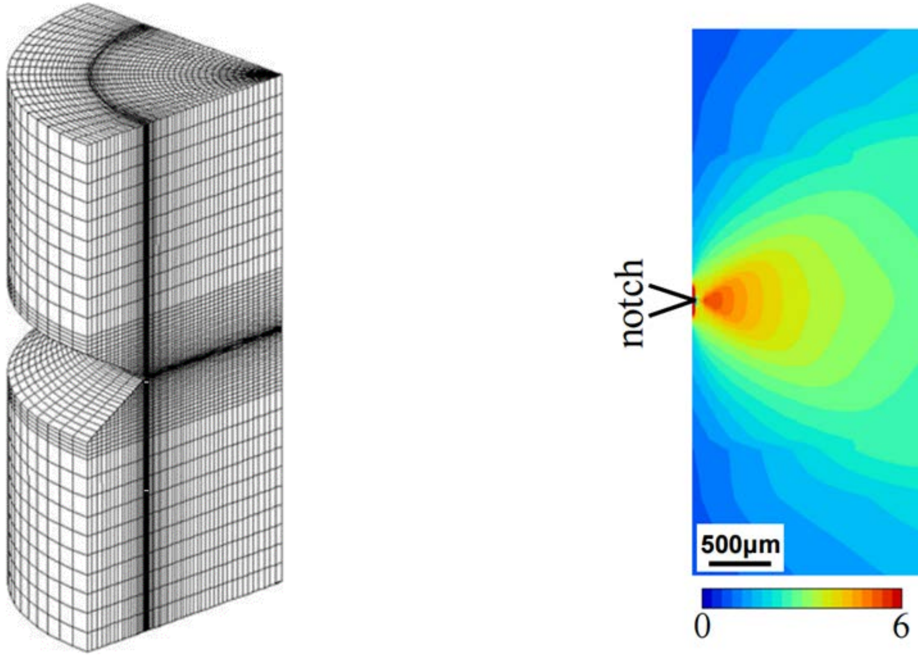
Fundamental understanding of the regulatory issues developed in this project using Alloy 617 will be applicable to austenitic materials in any high temperature reactor system

Near Term Activities Associated with Potential Structural Integrity Issues

- **Initiate multi-axial creep-rupture testing of notched specimens and creep-crack growth tests of base metal and welds for validation of maps. Characterize evolution of damage using quantitative metallography.**
  - Address concerns that creep failures often initiate at sites of stress concentration, in the presence of multi-axial stress states.
- **Characterize fatigue behavior of Alloy 617 welds; develop understanding of damage and fracture mechanisms.**
- **Develop fracture-mechanism map using normalized stress and temperature axes that can be generalized to austenitic family of alloys.**

Creep Rupture Testing

- **V-notch test specimens**
  - The circumferential notch is used to induce a multi-axial stress state
  - A means to characterize the notch strengthening or notch weakening behavior

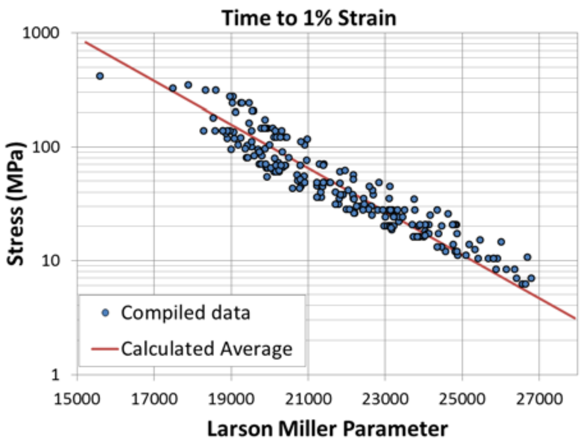


Finite element model showing the tri-axiality parameter (used as an evaluation parameter for stress multi-axiality)

Shigeyama, et al, ASME PVP Conference 2013

High Temperature Alloy Qualification

- ***The Ni-Cr-Co-Mo material Alloy 617 will be qualified under the High Temperature Reactor section of the ASME Boiler and Pressure Vessel Code to allow construction of nuclear components for gas cooled reactors***
- ***A draft Code Case to allow use up to 427ºC, where time dependent deformation is not significant, is in the ASME approval process***
- ***The draft Code Case allowing use up to 950ºC for 100,000 hour design life is nearing completion and portions are and under review***



Representation of one aspect of creep behavior of Alloy 617; data are from US ART program as well and from KAERI and CEA through GIF VHTR collaboration

- ***Developed design evaluation methodology for strain limits and creep-fatigue damage based on Elastic, Perfectly Plastic (EPP) methodology***
  - *Section III, Division 5, EPP Code Cases have been fully approved by ASME.*
  - *The first major change to the rules for elevated temperature design in approximately three decades and is a major step forward in the implementation of modern computer technology and failure mode analysis.*