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High Temperature Alloys Session 2

April 2021

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Changing the World's Energy Future

Idaho National Laboratory

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High Temperature Alloys II

CNSC Seminar

Outline

1. ASME Section III, Division 5 Introduction
2. Division 5 Construction Rules for Metallic Components
3. Selection of Code Classes
4. Design Evaluation Methods for Class A Components
5. Rules for Primary Loads
6. Rules for Strain Limits
7. Rules for Creep-Fatigue
8. Rules for Buckling and Instability
9. Inelastic Analysis Methods Development
10. Elastic, Perfectly Plasticity Design Evaluation Methods
11. EPP Load Controlled Code Case
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14. Design Parameters Requirements
15. High Temperature Flaw Evaluations
16. Materials Surveillance
17. Suggested Reading List

A Long Development History of Construction Rules for High Temperature Reactors Components

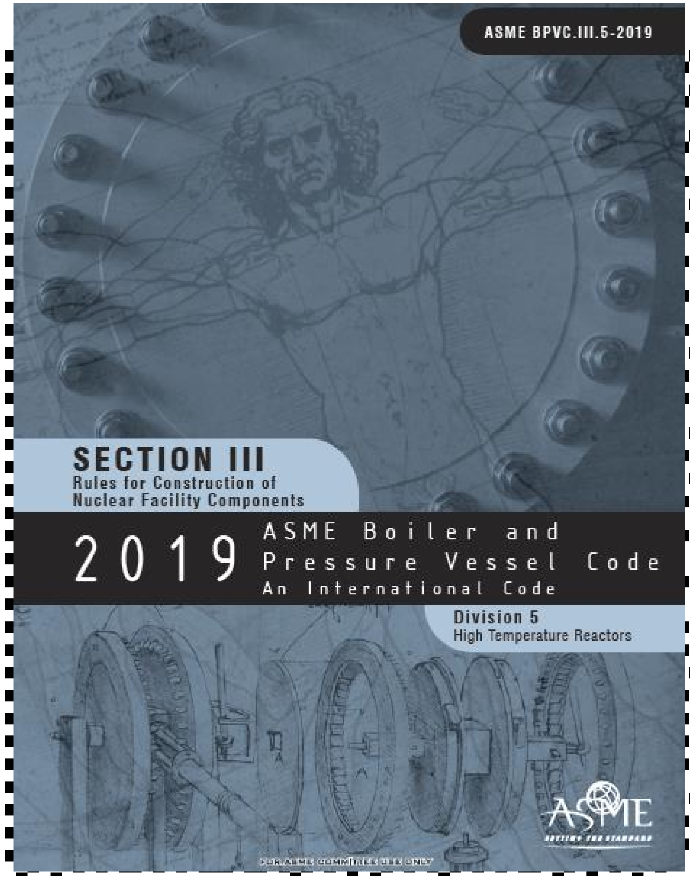
- Design rules for nuclear components initiated in 1963 - ASME Code Case 1331
- ASME published complete construction rules for elevated temperature pressure boundary metallic components under cyclic service in early 1970s
  - Code Cases 1592, 1593, 1594, 1595 and 1596, covering materials and design, fabrication and installation, examination, testing, and overpressure protection
- USNRC issued Regulatory Guide 1.87 (Rev 1, June 1975)
  - Referenced ASME Code Case series 1592-1596
  - Provided interim licensing guidelines for implementing the U.S. 10 CFR Part 50 requirements
  - Supporting licensing of ASME BPVC Class 1 components operating at elevated temperatures for HTGR, LMR, GFR
- Code Case series 1592-1596 converted to Code Case N-47
  - Code Case N-47 was used by the Clinch River Breeder Reactor (CRBR) project, with additional requirements from USDOE, for the structural design of CRBR
  - USDOE submitted license application to USNRC for a construction permit for CRBR in late 1970s
  - Review of Code Case N-47 by USNRC was in progress when the CRBR project was cancelled by the U.S. Government

From Code Case N-47 to Section III, Division 5

- Continued improvements of Code Case N-47 rules since CRBR
- ASME subsumed N-47 into a new Section III, Division 1, Subsection NH in 1995
- Extended other Section III Division 1 construction rules to elevated temperatures
  - Class CS core support structures and Class 2 components
  - Nuclear code cases N-201, N-253, N-254, N-257, and N-467
- U.S. Energy Policy Act of 2005 established the Next Generation Nuclear Plant (NGNP) Program to demonstrate the generation of electricity and/or hydrogen with a high-temperature nuclear energy source
  - Execution of NGNP Program led by the Idaho National Laboratory (INL)
  - Deemed that regulatory risks for the licensing of NGNP can be reduced by streamlining applicable Codes and Standards
  - INL requested ASME to develop a new Section III, Division 5 to consolidate Subsection NH and other nuclear Code Cases, and to add construction rules for graphite core components
  - Section III, Division 5 was published in the 2011 Addenda of the ASME BPVC
  - Continued updates and improvements of the construction rules of Section III, Division 5 have taken place since its initial publication

ASME Section III, Rules for Construction of Nuclear Facility Components - Division 5, High Temperature Reactors

- ASME Section III Division 5 Scope
  - Division 5 rules govern the construction of vessels, piping, pumps, valves, supports, core support structures and nonmetallic core components for use in high temperature reactor systems and their supporting systems
    - Construction, as used here, is an all-inclusive term that includes material, design, fabrication, installation, examination, testing, overpressure protection, inspection, stamping, and certification
- High temperature reactors include
  - Gas-cooled reactors (HTGR, VHTR, GFR)
  - Liquid metal reactors (SFR, LFR)
  - Molten salt reactors, liquid fuel (MSR) or solid fuel (FHR)



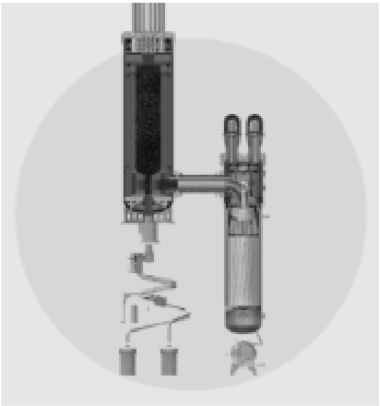
Division 5 - A Component Code

- Division 5 is organized by Code Classes:
  - Class A, Class B, Class SM for metallic components
  - Class SN for non-metallic components
- Division 5 recognizes the different levels of importance associated with the function of each component as related to the safe operation of the advanced reactor plant
- The Code Classes allow a choice of rules that provide a **reasonable assurance of structural integrity and quality** commensurate with the relative importance **assigned** to the individual components of the advanced reactor plant

Section III, Division 5 Organization

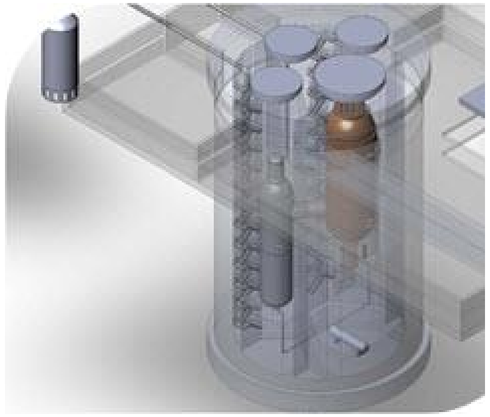
Code Class	Sub-section	Subpart	ID	Title	Scope
General Requirements					
Class A, B, & SM	HA	A	HAA	Metallic Materials	Metallic
Class SN		B	HAB	Graphite and Composite Materials	Nonmetallic
Class A Metallic Coolant Boundary Components					
Class A	HB	A	HBA	Low Temperature Service	Metallic
Class A		B	HBB	Elevated Temperature Service	Metallic
Class B Metallic Coolant Boundary Components					
Class B	HC	A	HCA	Low Temperature Service	Metallic
Class B		B	HCB	Elevated Temperature Service	Metallic
Class A and Class B Metallic Supports					
Class A & B	HF	A	HFA	Low Temperature Service	Metallic
Class SM Metallic Core Support Structures					
Class SM	HG	A	HGA	Low Temperature Service	Metallic
Class SM		B	HGB	Elevated Temperature Service	Metallic
Class SN Nonmetallic Core Components					
Class SN	HH	A	HHA	Graphite Materials	Graphite
Class SN		B	HHB	Composite Materials	Composite

Examples of High Temperature Gas-Cooled Reactor Designs

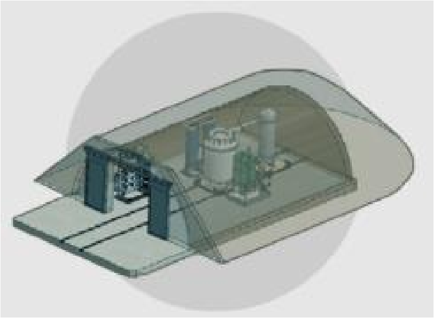


X-Energy, Xe-100

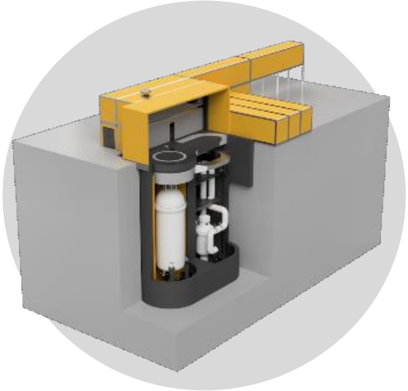
General Atomic, Fast Modular Reactor



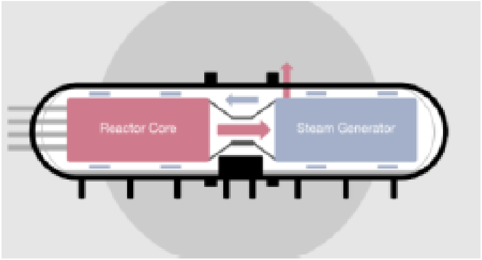
Framatome, SC-HTGR



BWXT, BANR



Ultra Safe Nuclear, MMR



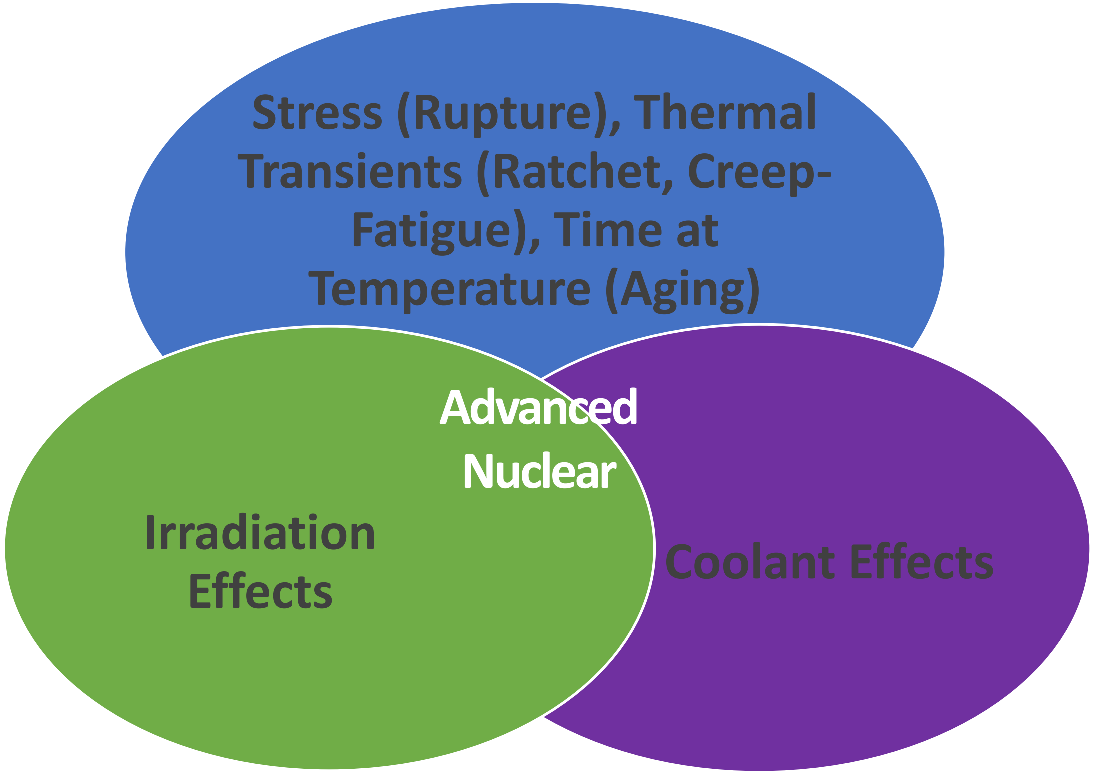
Massachusetts Institute of Technology, Horizontal Compact HTGR

Picture Source: X-Energy, General Atomic, Framatome, BWXT, Ultra Safe Nuclear, MIT

Advanced Reactors Under Development Have Drastically Different Characteristics

- Inlet/outlet temperatures
- Thermal transients
- Coolants
- Solid fuel vs liquid fuel
- Neutron spectrum and dose
- Design lifetimes
- Safety characteristics

Focus on Metallic Components

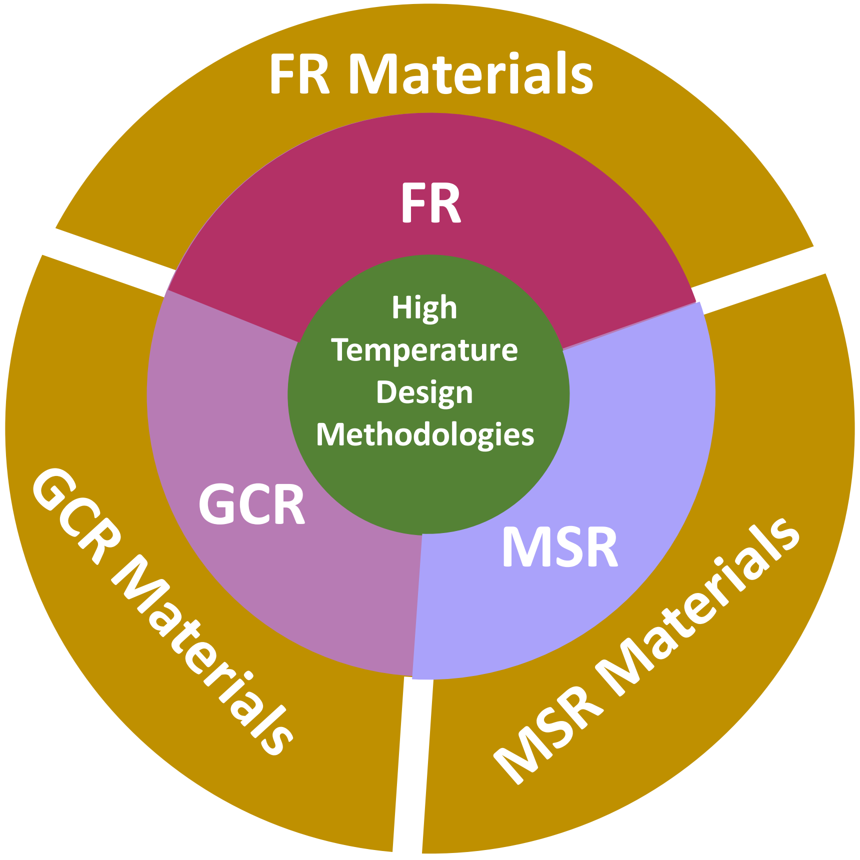


ASME Code Space: Stress (Rupture), Thermal Transients (Ratchet, Creep-Fatigue), Time at Temperature (Aging)

- Focus on structural failure modes under elevated temperature cyclic service, rather than reactor types
- Develop acceptance criteria and attendant high temperature design methodologies (HTDM) to guard against the identified structural failure modes
  - Essentially cross-cutting different reactor types

Materials Data Requirements

- Design parameters that are required by the HTDM would drive the materials data requirements
- FRs, GCRs and MSRs have different coolants, neutron irradiation environments and operating conditions (temperature, pressure, and transients)
- Different structural materials are needed to meet different requirements of FRs, GCRs and MSRs



Outside ASME Code Space (Licensing Space): Irradiation and Coolant Effects

- Effects of coolant and irradiation on structural failure modes are different from one reactor design to another even for the same structural material
- It is very challenging to cover these effects for all reactor types, and all different design characteristics for the same reactor type, viz. molten salt reactor
- The Division 5 approach is for Owner/Operator to have the responsibility to demonstrate to regional jurisdiction authority that these effects on structural failure modes are accounted for in their specific reactor design
  - Irradiation dose, dose rate, embrittlement, corrosion due to coolant, coolant chemistry and chemistry control, mass transfer leading to strength reduction or loss of ductility, etc.
- These provisos are specifically called out in the General Requirements subsection of Division 5
- In essence, these materials degradation effects are outside the scope of Section III, Division 5, and have to be addressed by Owner/Operator for their specific reactor design
  - Generate data for specific coolant and irradiation environment in test reactors, demonstration reactors
  - Conduct surrogate materials surveillance

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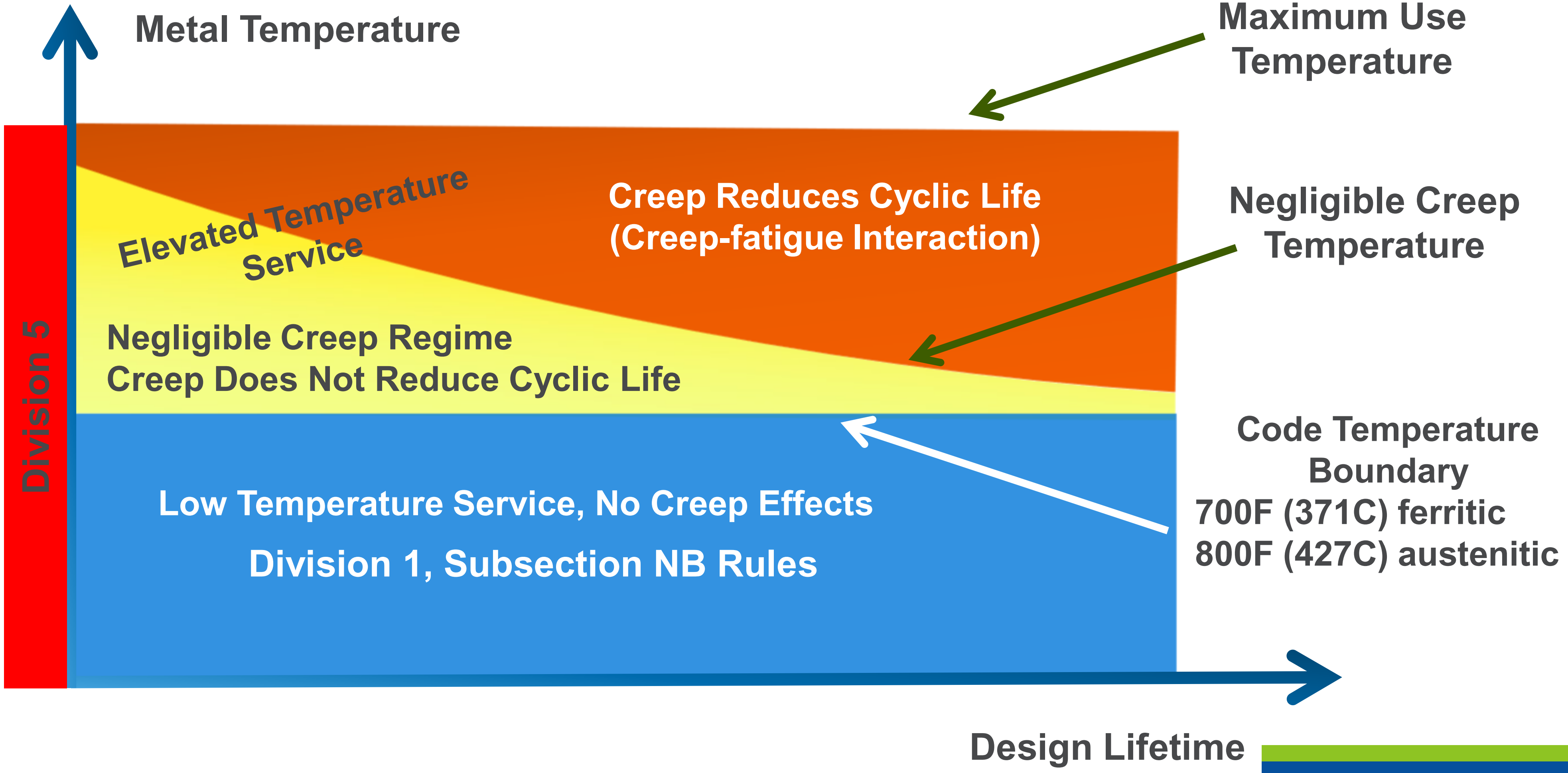
How to Select Code Classes

- Selection of appropriate Code Classes for structural components of high temperature reactor systems
  - Starts with the safety classification per safety criteria from applicable standards, and based on a system approach

Metallic	Classification	Construction Rules
Coolant boundary components and supports	Safety related	Section III, Division 5, Class A
	Non-safety related with special treatment	Section III, Division 5, Class B
	Non-safety related	Appropriate non-nuclear codes and standards
Core support structures	Safety related	Section III, Division 5, Class SM

Temperature Boundaries For Class A & Class SM Components



Class B Construction

- Extension of construction rules of Division 1 Class 2 vessel, pump, valve and piping designs to elevated temperature service
- Based on the design-by-rule approach, "Design Lifetime" concept is not used
- Allowable stresses based on extrapolated 100,000-hour creep rupture properties
- Fatigue damage resulting from cyclic service not addressed
  - Vessel, pump and valve
  - Piping in negligible creep regime
- Rules provided to address fatigue damage from cyclic service (different from Class A rules)
  - Piping with creep effect
- Alternative rules for Class B
  - Component designated as Class B may use the Class A rules for construction, but all the applicable Class A requirements shall be used; still stamped as Class B component
- **Essentially allows a component that is classified as Class B for safety consideration but constructed using Class A rules to address structural integrity issues under cyclic service**

Class SM Construction

- Extension of construction rules of Division 1 Subsection NF for core support structures, internal structures, threaded structural fasteners, and temporary attachments to elevated temperature service
- Load-controlled design rules are very similar to those for Class A
  - Consistent with Division 1 Subsection NF low temperature rules:
    - Design Loading is not used
    - Pressure difference, instead of pressure, is considered
- For deformation-controlled limits, the Class A rules in Appendix HBB-T are referenced directly
  - Applications that are appropriate for Class A components but not for Class SM supports are identified

Division 5 Class A Construction

- Class A design rules are based on design-by-analysis approach
  - Sought to provide a reasonable assurance of adequate protection of structural integrity
  - Based on design against structural failure modes; four (4) design evaluation checks

Time Independent Failure Mode	Category	Design Evaluation Procedure	Time Dependent Failure Mode	Category	Design Evaluation Procedure
Ductile rupture from short-term loading	Load-controlled	Primary load check	Creep rupture from long-term loading	Load-controlled	Primary load check
Gross distortion due to incremental collapse and ratcheting (low temperatures)	Deformation-controlled	Strain limits check	Creep ratcheting due to cyclic service	Deformation-controlled	Strain limits check
Loss of function due to excessive deformation	Deformation-controlled	Strain limits check	Creep-fatigue failure due to cyclic service	Deformation-controlled	Creep-fatigue check
Buckling due to short-term loading	Deformation-controlled	Buckling Check	Creep-buckling due to long-term loading	Deformation-controlled	Buckling Check

- Class A design rules are based on design-by-analysis approach
  - Sought to provide a reasonable assurance of adequate protection of structural integrity
  - Based on design against structural failure modes; four (4) design evaluation checks

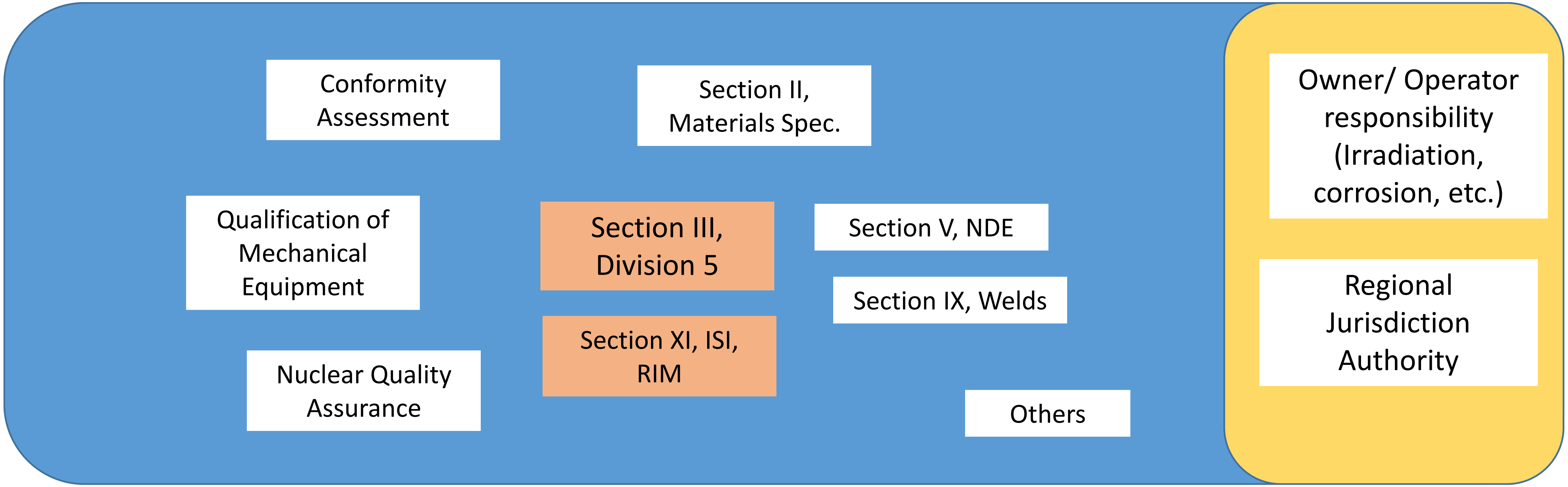
Design Evaluation Methods For Class A Components

Design Check	Using Elastic Analysis Results	Using Inelastic Analysis Results
Primary Load	Allowed	Not allowed
Strain Limits	Allowed	Allowed
Creep-fatigue	Allowed	Allowed
Buckling	Use Division 1 Subsection NB pressure charts when time-temperature limit is satisfied	Allowed

- Design methods based on elastic analysis results provide conservative bounds (sometimes very conservative) to guard against failure modes
  - Intended as “screening” tools
  - Rely on stress classification, linearization, etc. (not easily integrated with finite element methods)
  - Based on deformation models where creep and plasticity do not interact (not valid at high temp)
- Design methods based on inelastic analysis results provide more accurate but less conservative checks on failure modes
  - Intended to check “hot spots”

Reasonable Assurance of Structural Integrity

- Division 5 is not just on "design analysis," it is a Construction Code
- All Subsections (except General Requirements) have, in addition to Design, sections on:
  - Material, Fabrication, Installation, Examination, Testing, Overpressure Protection, Inspection, Stamping, And Certification (heavily referencing appropriate Division 1 Subsection(s))



Loading Categories

- Loading information is provided in the Design Specification by the Owner
  - Consists of the expected history of pressures, temperatures and mechanical load forces as a function of time, and a list of events that occur under each loading category
  - Used by the designer to conduct the four design evaluation checks
    - Primary load, strain limits, creep-fatigue, buckling
- Challenging to prescribe with some certainty the exact sequence of events for 30 to 60 years of operation
  - Encumbered on the Owner and regional jurisdictional authority to agree on a specified sequence of events that will provide a reasonable expectation of safe operation
- Loading categories: Design Loading, Service Loadings, and Test Loadings
  - Design Loading category shall equal or exceed those of the most severe combination of coincident pressure, temperature, and load forces specified under events which cause Service Level A Loadings
  - Service Loadings consist of Levels A, B, C, and D
  - Test Loadings are pressure loadings that occur during hydrostatic tests, pneumatic tests, and leak tests

Service Loadings

Service Level	Description
A	Planned operations (Normal)
B	Expected but unplanned events that does not require shutdown for inspection or repair (Upset)
C	Unusual possible events that require shutdown for inspection and potential repair (Emergency)
D	Postulated events that the integrity and functionality of the nuclear energy system may be impaired to the extent that only considerations of public health and safety are involved (Faulted)

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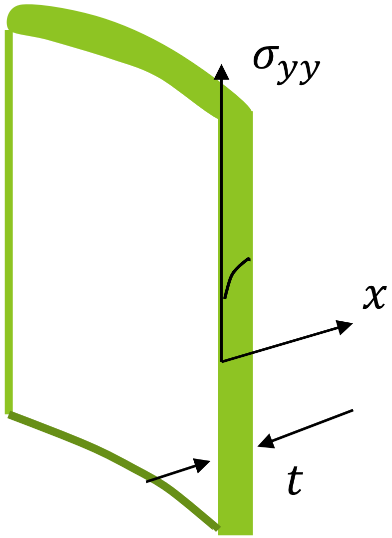
Primary Load Check – From Elastic Analysis of Structure Subject to Self-equilibrating External Loads

- Stress linearization
  - Stresses across a particular cross-section through the wall thickness of the structure are subject to a stress linearization procedure to determine
    - Primary membrane stresses, $\sigma_{ij,m} = \frac{1}{t}\int_0^t \sigma_{ij}(x)dx$;   *i,j = 1,2,3,*
    - Primary bending stresses, $\sigma_{ij,b} = \frac{6}{t^2}\int_0^t \sigma_{ij}(x) \times \left(\frac{t}{2} - x\right) dx$ *i,j = 1,2,3*
    - σ_{ij} are the stress components, and t is the wall thickness
- Stress intensity
  - Scalar stress measure defined as twice the maximum shear stress and calculated from the three-dimensional linearized stresses

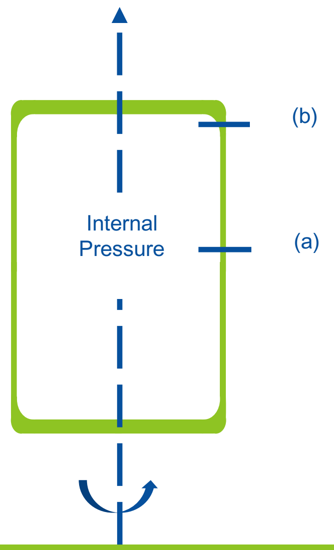


Stress Classification

- Stress intensities determined from the primary membrane stresses and the primary bending stresses are assigned to different categories
- This process is called stress classification
- Dependent on
  - Geometry of the structure
  - Location of the cross-section where the linearization procedure is performed
  - Type of applied load
  - Type of stress
- Engineering judgment is often required
- Categories
  - P_m = Primary membrane stress components
  - P_L = Local primary membrane stress components
  - P_b = Primary bending stress components at a surface
  - Q = Secondary stress components

An example of the stress classification of a flat head vessel

	Location	Origin of Stress	Type of Stress	Classification
Flat head	Center region (a)	Internal pressure	Membrane	P_m
			Bending	P_b
	Junction to shell (b)	Internal pressure	Local Membrane	P_L
			Bending	Q



Stress Classification (More Details)

- Primary stress (P_m and P_b)
  - Developed by imposed loading necessary to satisfy equilibrium of external and internal forces and moments
  - Basic characteristic - not self limiting
    - General primary membrane stress not changed by yielding
    - Membrane stress in a shell due to internal pressure
- Secondary Stress (Q)
  - Developed by constraint of adjacent material or self constraint
  - Basic characteristic - self limiting
    - Local yielding and minor distortions can satisfy constraints
    - Discontinuity stress due to the temperature difference between a cylinder and attached head
- Local Primary Membrane Stress (P_L)
  - Produced by pressure or mechanical load that can result in excessive distortion in transfer of load to other portions of the structure
  - Has some characteristics of secondary stress
    - Can result in excessive distortion
    - Membrane stress in a shell due to nozzle load
- Peak stress (F)
  - Additive to primary plus secondary stress due to stress concentration or local thermal stress
  - Basic characteristic - localized effect with no noticeable distortion
    - Concern is cyclic failure or brittle fracture
    - Stress at a local structural discontinuity, stress at a small hot spot in a vessel wall

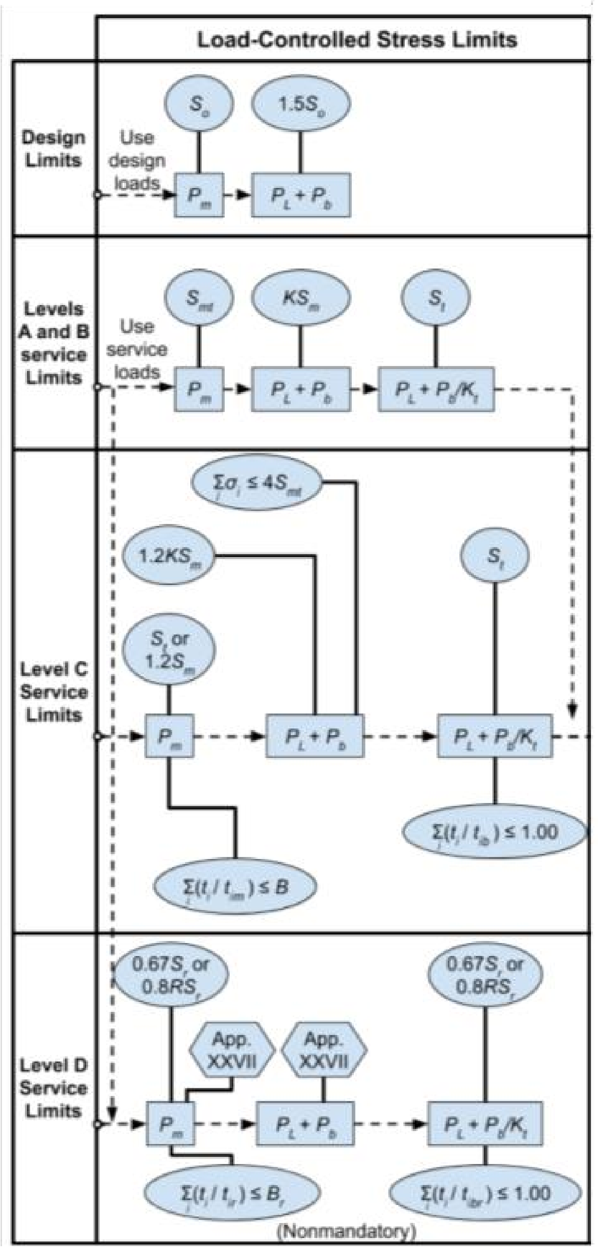
Limits for load-controlled stresses

- Allowable stresses for base metal are defined in terms of tensile strengths and creep rupture strength for use as limits to guard against the load-controlled failure modes
  - S_m = lesser of:
    - one-third of the specified minimum tensile strength at room temperature
    - one-third of the tensile strength at temperature
    - two-thirds of the specified minimum yield strength at room temperature
    - two-thirds of the yield strength at temperature
  - S_t = lesser of:
    - 100% of the average stress required to obtain a total (elastic, plastic, primary, and secondary creep) strain of 1%;
    - 80% of the minimum stress to cause the onset of tertiary creep; and
    - 67% of the minimum stress to cause rupture
  - S_{mt} = lesser of (S_m, S_t)
  - S_0 = lesser of $(S, S_{mt}@300{,}000h)$
    - S is the tabulated allowable stress in Section II, Part D Table 1A (ferrous materials) or Table 1B (nonferrous materials

Load-controlled Acceptance Criteria

- Stress intensities are determined from elastic stress analysis results
- But are used in the primary load check to address inelastic structural failure modes
- Thus require a rather complicated set of acceptance criteria to provide a reasonable assurance to guard against these load-controlled failure modes

Stress intensity	Linearized stresses used to compute stress intensity *
P_m	$\sigma_{ij,m}$
$P_L + P_b$	$\sigma_{ij,m} + \sigma_{ij,b}$
$P_L + P_b/K_t$	$\sigma_{ij,m} + \sigma_{ij,b}/K_t$
* Stress intensity = 2 × max shear stress calculated from 3D linearized stresses	



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Strain Limits

- Maximum accumulated **inelastic strain** over any cross-section of the wall thickness of the structure shall not exceed
  - Strains averaged through the thickness, 1%
  - Strains at the surface, due to an equivalent linear distribution of strain through the thickness, 2%
  - Local strains at any point, 5%
- Applied to computed inelastic strains accumulated over the expected operating lifetime of the element under consideration
- Computed for some steady-state period at the end of this time during which significant transients are not occurring
- For welds, limits reduced by a factor of two (2)

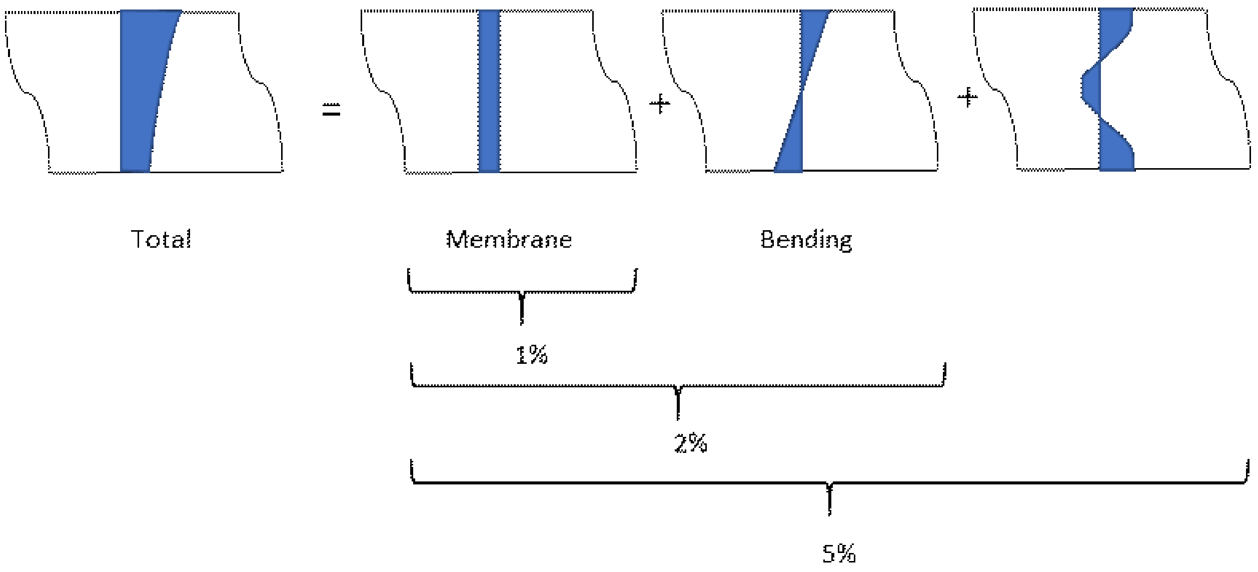
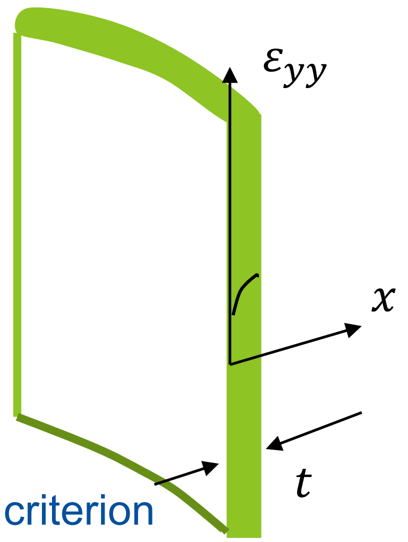


Illustration of the linearization procedure for the strain criteria in 1D

Strain Limits Evaluation - Inelastic Analysis Result

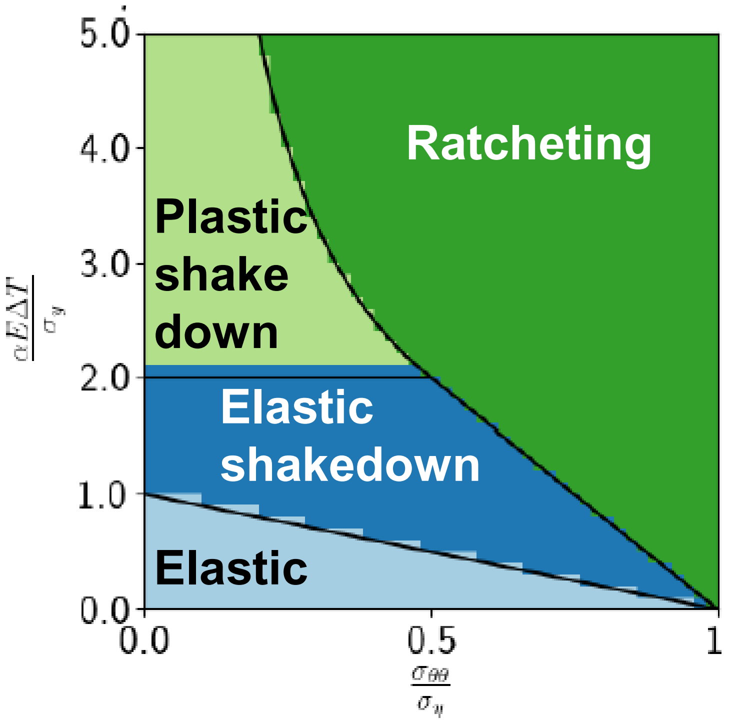
- Accumulated inelastic strains across a cross-section through the wall thickness of the structure are subject to a linearization procedure, similar to that for the stresses
  - Accumulated membrane inelastic strains, $\varepsilon_{ij,m} = \frac{1}{t}\int_0^t \varepsilon_{ij}(x)dx$; *i,j = 1,2,3,*
  - Accumulated bending inelastic strain, $\varepsilon_{ij,b} = \frac{6}{t^2}\int_0^t \varepsilon_{ij}(x) \times \left(\frac{t}{2} - x\right) dx$ *i,j = 1,2,3*
  - ε_{ij} are the accumulated inelastic strain components, and t is the wall thickness



- 1% strain limit:
  - Compute principal strains from $\varepsilon_{ij,m}$
  - Criterion is satisfied if all principal strains are either negative or zero
  - Otherwise, compare the maximum positive value of the three principal strains to the 1% strain criterion
- 2% strain limit:
  - Compute principal strains from $\varepsilon_{ij,mb}$, where $\varepsilon_{ij,mb} = \varepsilon_{ij,m} + \varepsilon_{ij,b}$
  - Criterion is satisfied if all principal strains are either negative or zero
  - Otherwise, compare the maximum positive value of the three principal strains to the 2% strain criterion
- 5% strain limit:
  - For each point x, compute principal strains from $\varepsilon_{ij}(x)$
  - Local criterion at x is satisfied if all principal strains are either negative or zero
  - Otherwise, compare the maximum positive value of the three principal strains at x to the 5% strain criterion

Strain Limits Evaluation - Elastic Analysis Result

- A number of options available for the strain limits check when the elastic analysis result is used
  - A-1, A-2, A-3, B-1, B-2, B-3 tests
  - All tests require stress linearization and stress classification
- All are based on the extension of the so-called Bree analysis which is captured by the Bree diagram
  - Classical analytic analysis of the Bree cylinder
  - Bounds biaxial pressure vessel loads
  - Four regions:
    - Elastic: all deformation elastic
    - Elastic shakedown: deformation shakes down to elasticity
    - Plastic shakedown: deformation shakes down, but steady cycle includes plasticity
    - Ratcheting: strains continue to increase

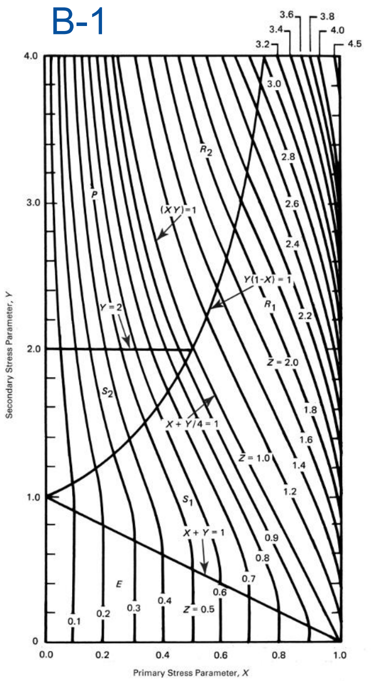


A-Tests (Using Elastic Analysis Result)

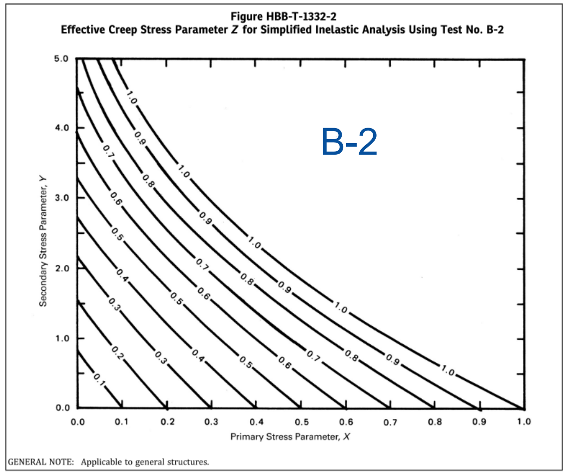
- Use of tests A-1 and A-2 is restricted within the elastic regime of the Bree diagram
  - Checks the strain limits compliance by comparing the primary stress intensity and the secondary stress intensity range against certain prescribed limits
  - Do not evaluate the accumulated inelastic strains explicitly
- A3 test imposes restrictions on the creep deformation, essentially limiting it to be negligible
  - In fact, the A-3 test provides the criteria for the negligible creep regime where the small amount of creep deformation does not reduce the fatigue life at temperatures above the Code temperature boundary of 700°F for ferritic materials and 800°F for austenitic materials

B-Tests (Using Elastic Analysis Result)

- Basic concept:
  - If the structure does not ratcheting there is a characteristic, average reference stress, or core stress, associated with the cycle that can be found from simple, analytic elastic-plastic analysis
  - Find this core stress and use it to compute deformation over the design life using the isochronous stress-strain relations
  - Accumulated inelastic strains are evaluated, but using simplified bounding methods
  - Passing the 1% strain criterion is adequate as the methods are very conservative
- B-1 and B-2 tests operate within the elastic shakedown and plastic shakedown regimes of the Bree-diagram
  - Design charts are provided in the code for the evaluations
- B-3 test can additionally operate in the ratcheting regime
  - It starts with the strain values from Test B-1 and then corrects them for ratcheting and the extra creep during relaxation above the core stress
  - This test has been removed from the 2021 edition of Division 5 because of its complexity



Design charts in ASME Section III, Division 5



Strain Limits Evaluations Using Elastic Analysis Result – A Summary

Test No.	Geometry/loading restrictions?	Cycle temperature restrictions?	Strain calculation?	Cycle definition
A-3	None	Entirely below creep range	None	Same as Division 1, Subsection NB
A-1	None	None	None	Whole life
A-2	None	Cold end below creep range	None	Whole life
B-2	None	Cold end below creep range	Core stress	Block
B-1	Either discontinuity or nonlinear temperature	Cold end below creep range	Core stress	Block
B-3	Either discontinuity or nonlinear temperature	None	Incremental summation	Individual

Outline of Topics in This Presentation

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9. Inelastic Analysis Methods Development
10. Elastic, Perfectly Plasticity Design Evaluation Methods
11. EPP Load Controlled Code Case
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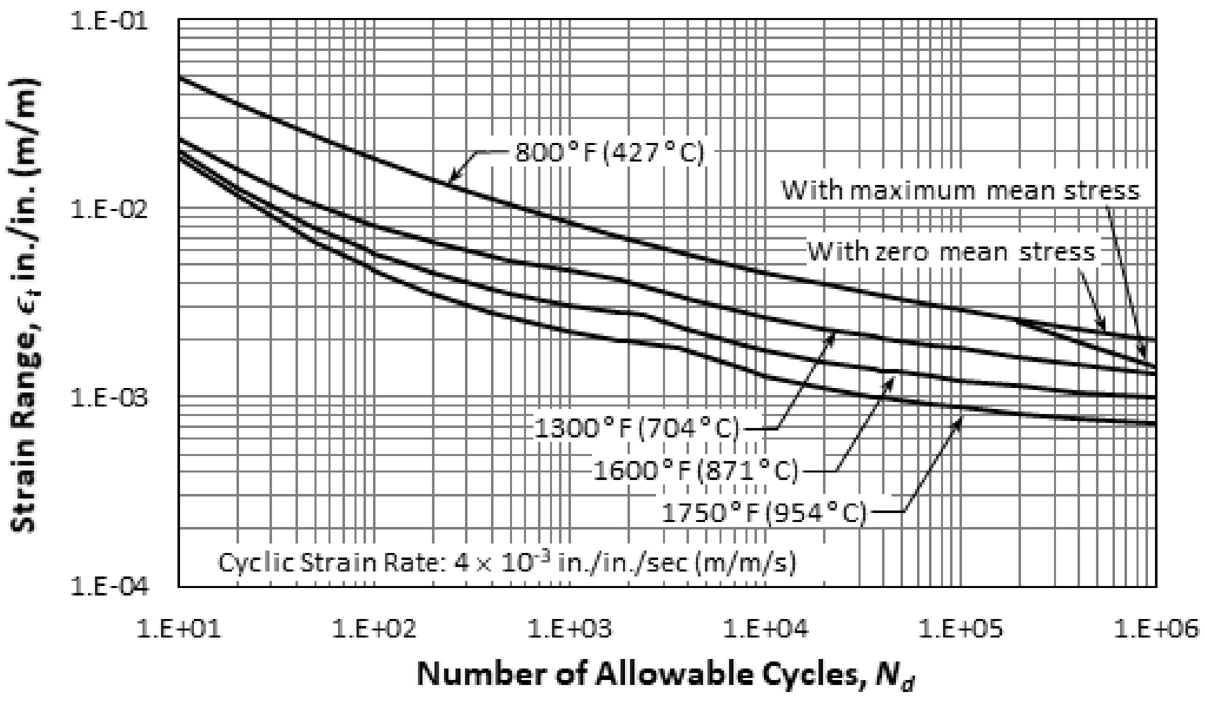
16. Materials Surveillance
17. Suggested Reading List

Fatigue Damage

- Fatigue curves are strain-based, require a strain range to determine allowable life
- Sum fatigue damage: $D_f = \sum_{i=1}^{n_{types}} \frac{N_i}{N_{d,i}}$
- Database: strain-controlled fatigue tests
- Welds: reduction by a factor of two (2) on design cycles

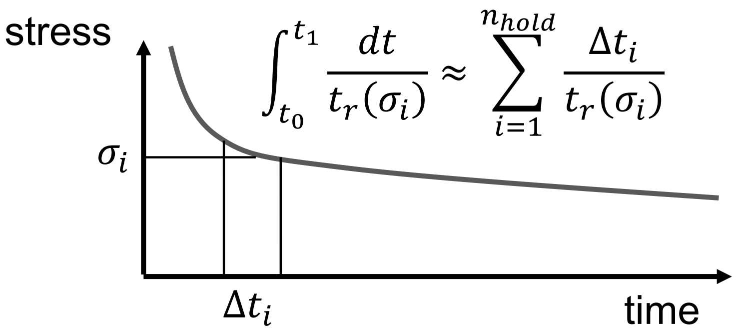


Design fatigue curves for Alloy 617

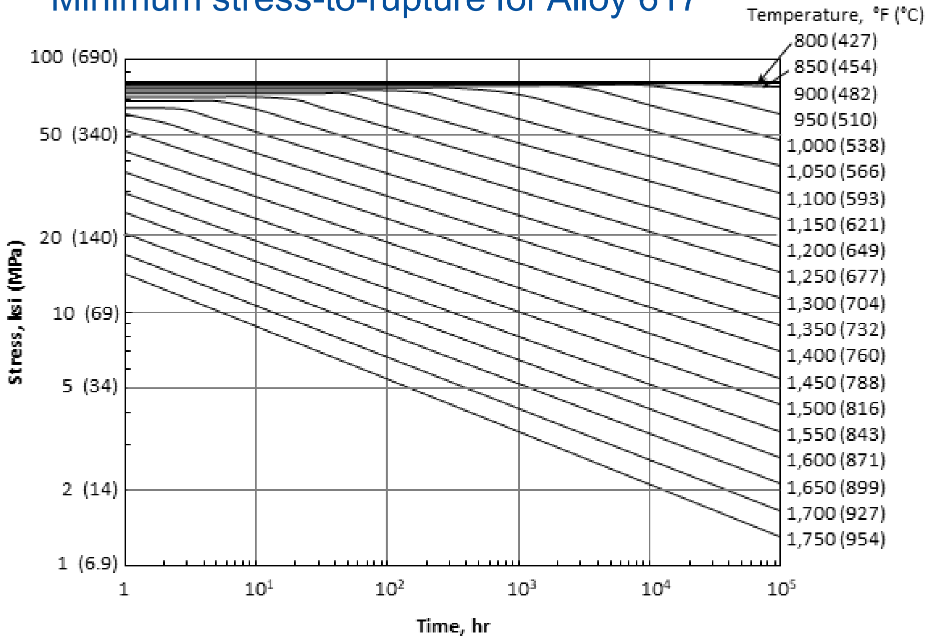
Creep Damage

- Require to construct a stress relaxation curve for each hold in each cycle type
- Determine creep damage with a time fraction rule for each time interval $\sum_{i=1}^{n_{hold}} \frac{\Delta t_i}{t_r(\sigma_i)}$
- Sum creep damage for all time intervals needed to represent the specified elevated temperature service life $D_c = \sum_{k=1}^{q} (\Delta t / T_d)_k$
- Database: creep rupture tests
- Welds: use stress rupture factor to reduce the creep rupture strength of the base metal

Stress relaxation profile

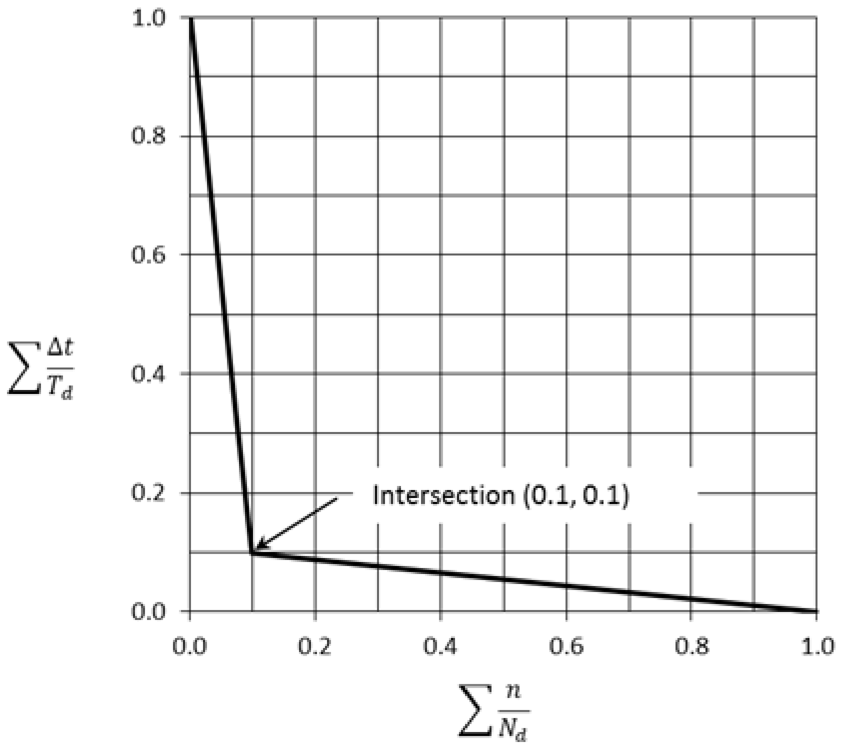


Minimum stress-to-rupture for Alloy 617



Creep-Fatigue Interaction

- Plot (D_f, D_c) points on a creep-fatigue damage envelope
  - If point falls under the envelope the structure is acceptable
- Database: creep-fatigue tests
  - Strain controlled, at constant temperature, with strain holds



Creep-Fatigue Damage Envelope for Alloy 617

Elastic Rules for Determining Fatigue Damage

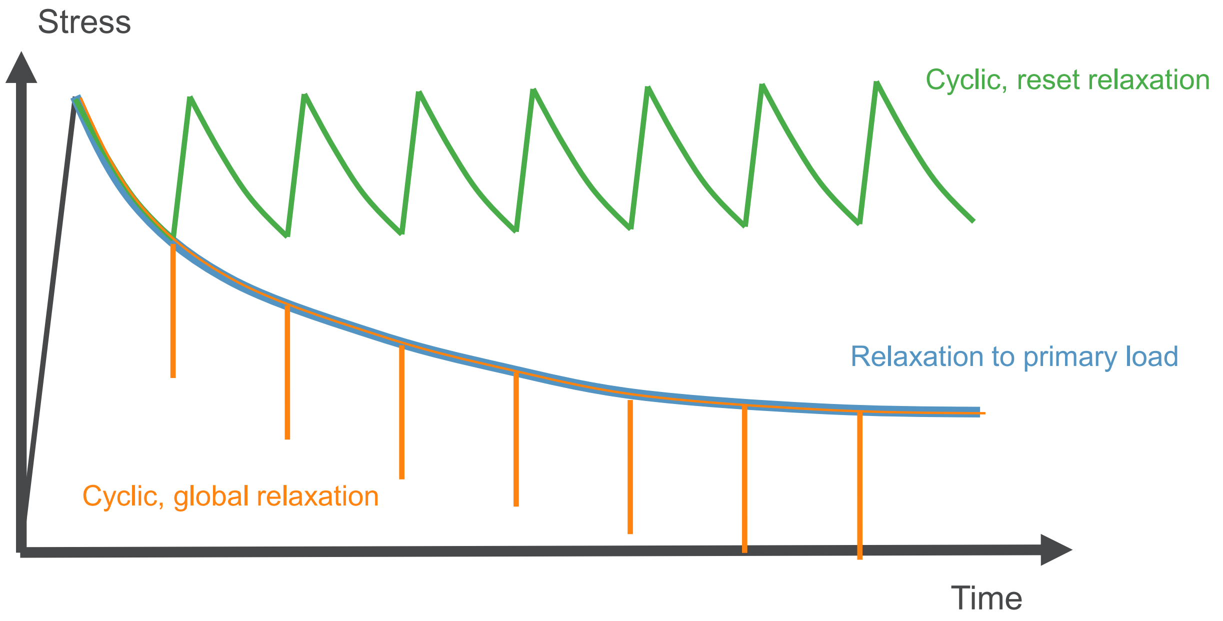
- Basic process
  - Calculate elastic effective strain range from elastic stresses and strains
  - Correct the elastic strain range to account for local plasticity, triaxiality and creep
- Notes:
  - This procedure uses primary + secondary stress range but without peak stress (peak stresses included via stress concentration factors)
  - This procedure references the B-1 ratcheting check – this check needs to be passed first in order to prohibit ratcheting
    - But the temperature anchor requirement is not required as unlike the strain limits check, the creep-fatigue rules remove this condition

Strain Range Determination

- Follow HBB-T-1413 to determine maximum equivalent elastic strain range, $\Delta\varepsilon_{max}$, using the elastic strain history (3D) within a cycle (do not include the peak strains arising from geometric discontinuities)
  - Divide the cycle period into time points
  - Select any time point as a reference time point, labeled as point o
  - For a time point i in the cycle, subtract the strains at time point o from the strains at time point i
  - Use these strain differences to determine an equivalent strain range $\Delta\varepsilon_{equiv,i}$ using
  - $\Delta\varepsilon_{equiv,i} = \frac{\sqrt{2}}{2.6}\left(\left(\Delta\varepsilon_{xi} - \Delta\varepsilon_{yi}\right)^2 + \left(\Delta\varepsilon_{yi} - \Delta\varepsilon_{zi}\right)^2 + (\Delta\varepsilon_{zi} - \Delta\varepsilon_{xi})^2 + \frac{3}{2}(\Delta\gamma_{xyi}^2 + \Delta\gamma_{yzi}^2 + \Delta\gamma_{zxi}^2)\right)^{1/2}$
  - Define $\Delta\varepsilon_{max}$ as the maximum value of the above calculated equivalent strain ranges for all time points associated with a reference point o, and for all possible reference time point within the cycle
- Follow HBB-T-1432
  - Determine $\Delta\varepsilon_{mod}$, which provides the plasticity correction to the elastically calculated strain range
    - $\Delta\varepsilon_{mod} = \varphi\Delta\varepsilon_{max}$ where φ can be determined from three different options
  - Determine the local geometric concentration factor K and the multiaxiality/Poisson ratio adjustment factor, K_v.
  - Determine the creep strain increment $\Delta\varepsilon_c$ for the cycle due to load-controlled stresses
  - Compute the total strain range, ε_t, for design fatigue curves
    - $\boldsymbol{\varepsilon_t = K_v\Delta\varepsilon_{mod} + K\Delta\varepsilon_c}$

Elastic Rules for Determining Creep Damage

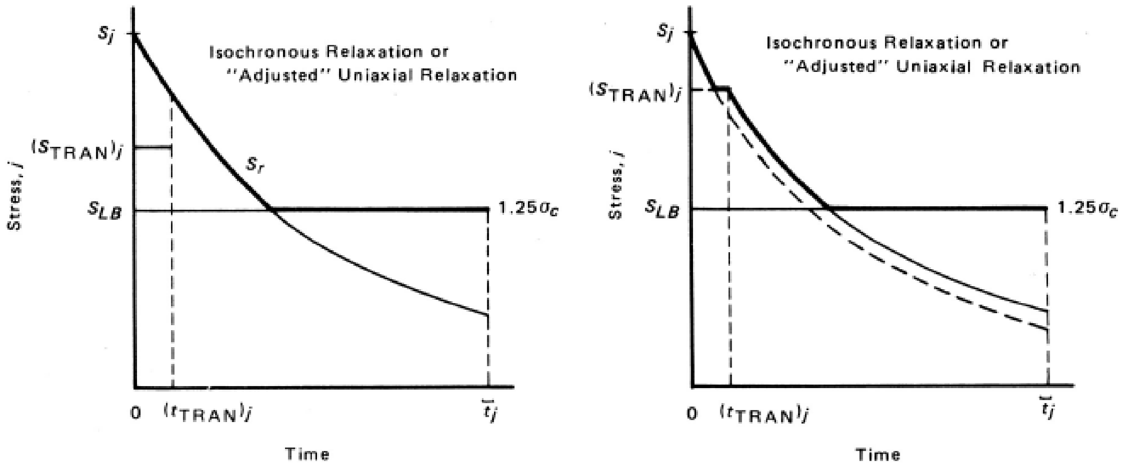
- A stress relaxation profile is required to determine the creep damage through time-fraction calculation, $D_c = \int \frac{dt}{t_r(\sigma)}$
- Two general approaches in the Code:
  - Piece together individual relaxation histories from individual cycles, assuming “full reset” behavior
  - Work with one global relaxation history – first must determine if your structure will undergo reverse plasticity
- For individual cycles, two approaches
  - Method of isochronous curves (conservative)
  - Relaxation analysis



Single Cycle Methods: Common features

- Only need to account for time above the elevated temperature cutoffs (700/800°F)
- May use the local temperature during sustained normal operation, T_{HT}, rather than the maximum metal temperature
- But need to correct this single-cycle relaxation history for the transients:
  - S_{TRAN} the maximum primary stress intensity for the cycle
  - T_{TRAN} the maximum metal temperature for the cycle
- Important: Divide the final stress/time history by a safety factor K' is required before calculating damage

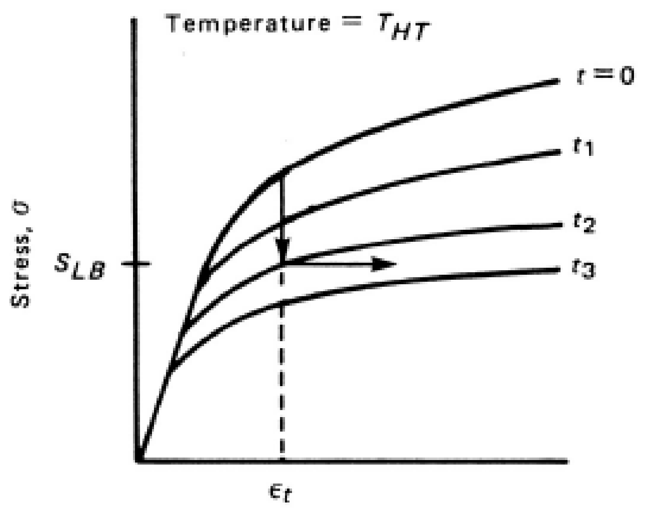
Figure HBB-T-1433-3
Stress-Relaxation Limits for Creep Damage



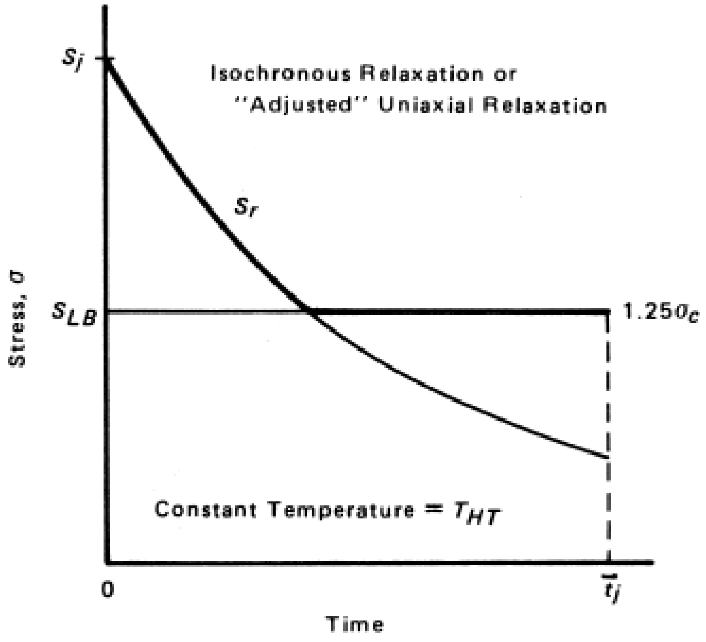
Material	K' for Elastic Analysis
Type 304/316 SS	0.9
A800H	0.9
2.25Cr-1Mo	0.9
9Cr-1Mo-V	1.0
A617	0.9

Stress Relaxation Profile from ISSCs

- Start at the stress given by the hot tensile curve for a strain of ε_t and a temperature of T_{HT}
- Use the isochronous curves for the subsequent relaxation times to generate a stress/time profile
- Do not allow this stress/time profile to fall below $1.25\sigma_c$ from the B-1 test



(a) Stress Relaxation From Isochronous Stress–Strain Curves



Stress Relaxation Profile from Relaxation Calculation

- Use creep rate equation to relax from an initial stress at temperature T_{HT}
  - Fundamental formula: $\dot{\sigma} = E\left(\dot{\varepsilon} - \dot{\varepsilon}_{creep}(\sigma)\right) \rightarrow -E\dot{\varepsilon}_{creep}(\sigma)$
  - Initial condition S_j : hot tensile stress at ε_t
  - Requires solving differential equation
- Produce a stress history, $\bar{S}_r(t)$, correct for stress multiaxiality from the formula:
  - $S_r = S_j - 0.8G\left(S_j - \bar{S}_r(t)\right)$
  - Where $G = \frac{\sigma_1 - 0.5(\sigma_2 + \sigma_3)}{\sigma_1 - 0.3(\sigma_2 + \sigma_3)}$ (use the smallest G value from the two extremums of the cycle)
- Require creep rate model in using the procedure
  - Designer or Design Specification provides model
  - 2021 Edition of Division 5: revised HBB-T has the equations for ISSCs that can be used as the creep rate models

Outline of Topics in This Presentation

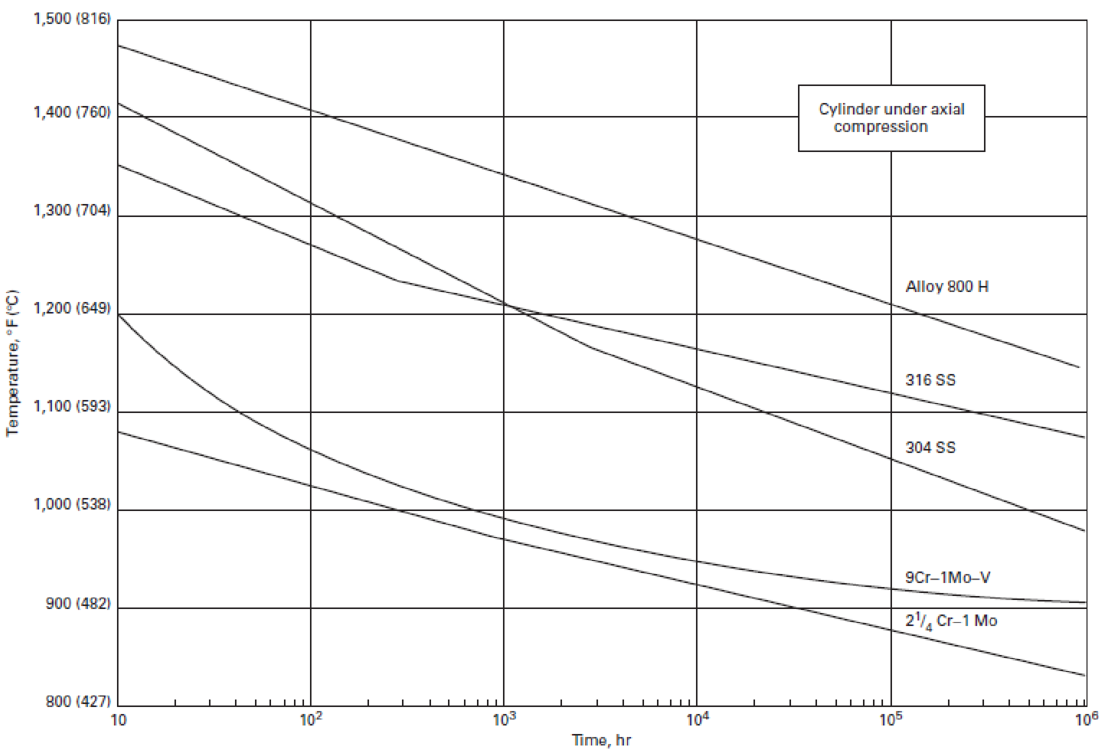
Buckling and Instability

- The buckling rules in Division 1, Subsection NB and Sections I and VIII do not address the effects of creep and address limited geometries
- General Requirements
  - The HBB-T-1500 rules are applicable to general geometries, address time-independent and time-dependent behavior and consider both load controlled and strain controlled buckling and instability
  - If strain controlled and load controlled interact or if there is significant elastic follow-up, the load controlled buckling factors apply
  - For load controlled buckling, the initial imperfections and tolerances shall be considered but need not be considered for pure strain controlled buckling
  - Calculations are based on expected minimum stress-strain curves
    - Yield values of re-solution annealed stainless steels are reduced by 17% unless demonstrated by test that the material meets specified room temperature yield strength
  - The limits apply to both Design and Service Loadings

Buckling Limits

- Load factors provided in HBB-T-1520 for time-independent and time-dependent load and strain controlled buckling
- Time-independent load and strain factors are 3.0 and 1.67 respectively for Design and Service Levels A and B Loading
  - Less for Service Levels C and D
- Time-dependent load factor for Design and Service Levels A, B and C is 1.5 and is 1.25 for Service Level D
- Alternatively, the limits of Division 1, Subsection NB may be applied if time/temperature limits are satisfied

Figure HBB-T-1522-1
Time–Temperature Limits for Application of Section II External Pressure Charts



New Development on Inelastic Analysis Methods

- Currently the Code does not provide reference inelastic models for any of the Class A materials
  - Specification of the material model left to owner's Design Specification or designers
  - Limits application of the inelastic rules
- Historical experience on the Clinch River Breeder Reactor Project shows that inelastic analysis is:
  - The least over-conservative of the Division 5 options
  - Necessary in critical locations where design by elastic analysis is too conservative to produce a reasonable design
- Current status
  - Unified viscoplastic constitutive models for Type 316 stainless steel and Grade 91 steel have been developed by DOE program
  - Guidance on inelastic material models development drafted
  - Appendix HBB-Z: Grade 91 model + Guidance being balloted by ASME (C&S Record 19-317)
  - Action will be followed by, in priority order, Type 316 SS, Alloy 617, Alloy 800H material models

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Elastic, Perfectly Plastic (EPP) Design Analysis Methods

- Use different allowable stresses as pseudo yield stress in EPP finite element analysis to determine different bounding characteristics for different failure modes
- Intended as simplified “screening” tools in place of elastic analysis methods
- No stress classification
- Applicable for any geometry or loading
- Applicable over full temperature range
- Resolves restriction on applicability at very high temperatures
  - The 1991 draft Code Case for Alloy 617 by Corum et al. restricted current elastic methods to 1200F and below
- Accounts for redundant load paths
- Simpler to implement
- Based on finite element results at integration points, no linearization

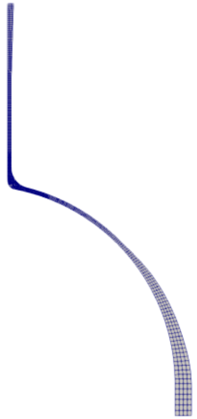
EPP Design Check	EPP Code Case	Materials Currently Covered
Primary Load	Being balloted	All Class A materials
Strain Limits	N-861	304H, 316H, Grade 91, Alloy 617
Creep-fatigue	N-862	304H, 316H, Grade 91, Alloy 617

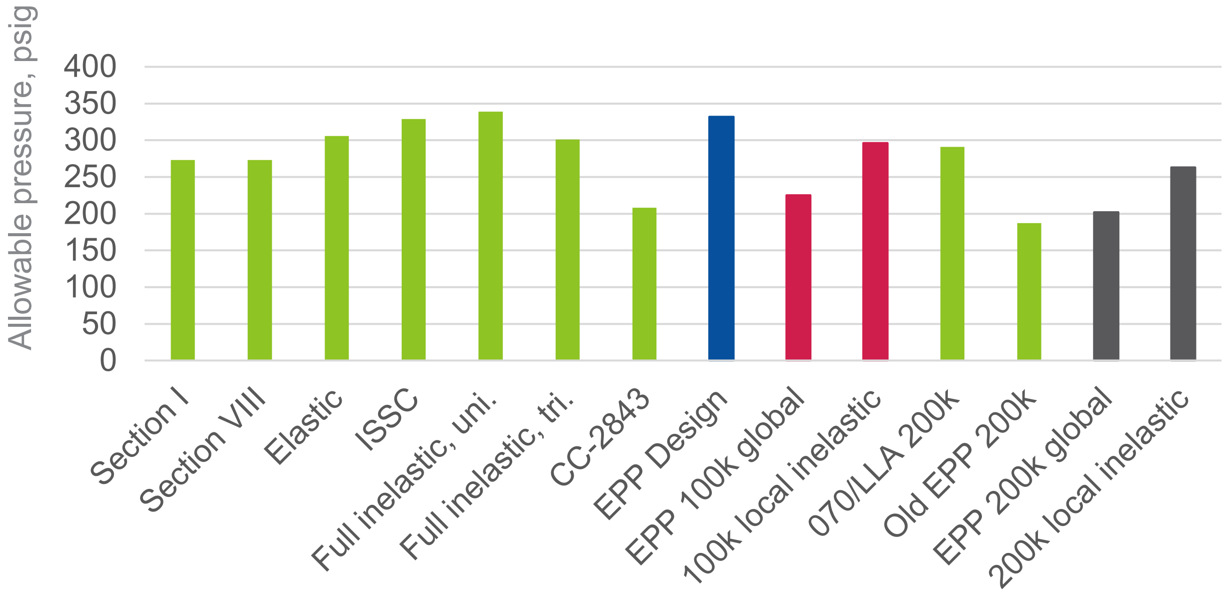
EPP Load-controlled Code Case (C&S R13-252)

- EPP finite element analysis based on von Mises yield condition
  - Introduce $\sqrt{(3/4)}$ on pseudo yield stress to address von Mises versus Tresca yield criteria
- EPP "global" design and service check based on reference stress/limit load concept
  - Basically: use allowable stress a yield stress, see if actual loads are below limits loads
  - Use fraction: find some set of times t_{trial} so that:
    - Actual loads are less than limit loads for yield stress equal to allowable stress for that time
    - $\sum \frac{t}{t_{trial}} \leq 1$
  - Process guides user towards "best possible" set of t_{trial}
- "Simplified inelastic local service check"
  - Minimum creep rate description for each Class A material
  - Calculate damage based on time-fraction from Code S_r, minimum rupture stress
  - Introduce a new scale stress measure to more effectively address stress triaxiality
    - $\sigma_e = \alpha\sigma_1 + (1-\alpha)\sigma_v$
    - σ_1 maximum principal stress, σ_v von Mises stress
  - "Screening check" to rule out bad design details (high stress concentrations)

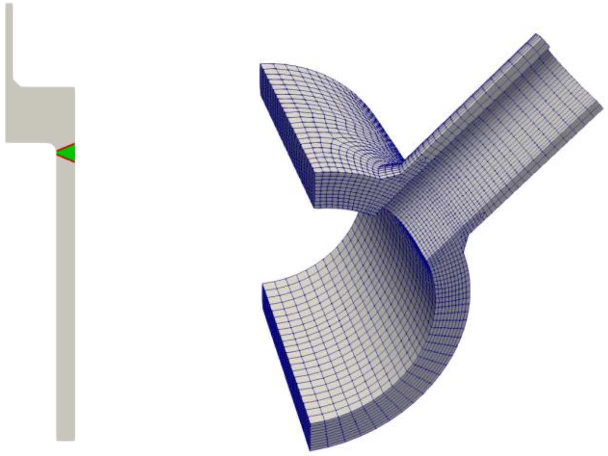
Sample Problems to Assess Effectiveness

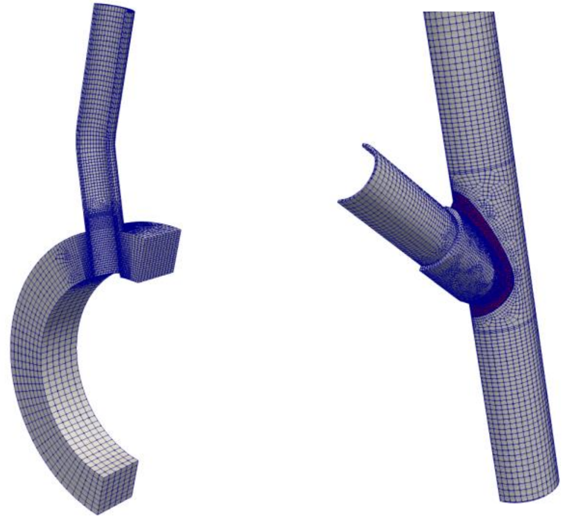
- Sections I and VIII reference problems





Example results for Type 304 stainless steel nozzle-to-sphere geometry



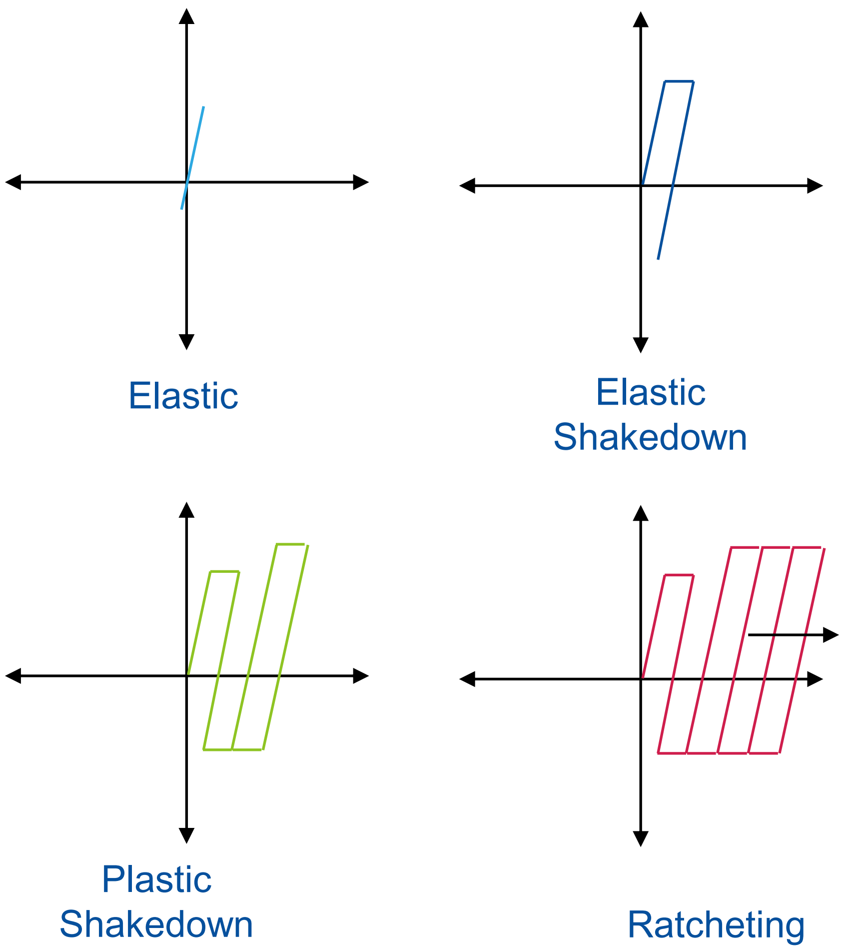


EPP Strain Limits Code Case (N-861)

- Creep bounding theorems are used to motivate the method
  - It's possible, in some situations, to bound the a) creep dissipation, b) external work, c) deformation in a creeping structure with an elastic-perfectly plastic analysis
  - For detailed theorems see early work by Frederick & Armstrong, Ponter, and Ainsworth
  - Generally assume a non-unified material:
    - $\dot{\varepsilon} = \dot{\varepsilon}_e + \dot{\varepsilon}_p + \dot{\varepsilon}_{cr} + \dot{\varepsilon}_{th}$
  - Extended by others to various plastic hardening rules
  - Extended by Carter to some kinds of unified models
    - $\dot{\varepsilon} = \dot{\varepsilon}_e + \dot{\varepsilon}_{vp} + \dot{\varepsilon}_{th}$
- The concept of a "composite cycle" is used to bound the operating cycles
- Softening factors are introduced for 9Cr-1Mo-V due to cyclic softening behavior

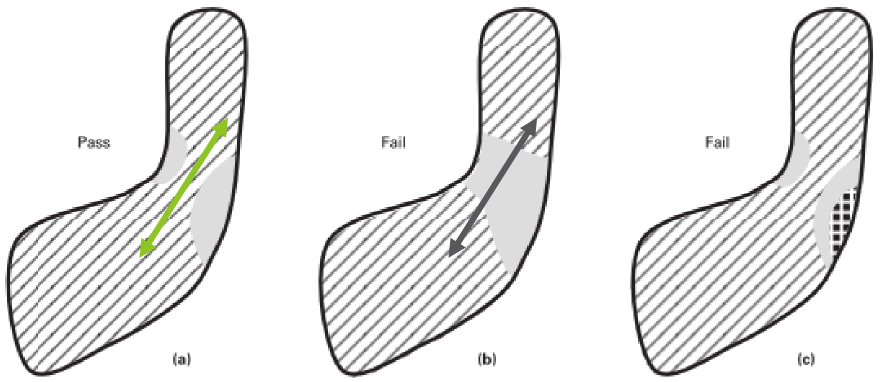
Shakedown

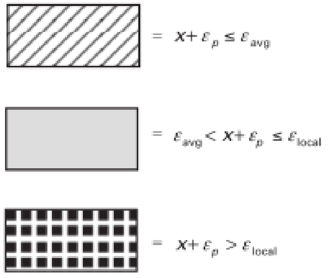
- Under cyclic loading with simple material models eventually the stresses and strain rate will become periodic
  - Elastic regime: the model never deforms plastically
  - Elastic shakedown: in the steady state the deformation is elastic
  - Plastic shakedown: in the steady state the strains are periodic
  - Ratcheting: the structure does not collapse but in the steady state the deformation increases without bound



Basic EPP Strain Limits Procedure

- Define an appropriate composite cycle, run thermal analysis to get temperature history
- Find your material properties: $E(T)$, v, and $\alpha(T)$
- Select a target strain X, and iterate on X as follows:
  - Find the pseudo-yield stress $\sigma_{py}^{X}(T)$
  - Run an EPP analysis loading the component with the composite cycle and repeating for enough cycle to establish steady cyclic behavior
  - If the model does not shakedown the design check has failed
  - Calculate the scalar plastic strain
  - $\varepsilon_p = \sqrt{\frac{2}{3}\left\{\left(\varepsilon_{xx}^{p}\right)^2 + \left(\varepsilon_{yy}^{p}\right)^2 + \left(\varepsilon_{zz}^{p}\right)^2 + 2\left(\varepsilon_{xy}^{p}\right)^2 + 2\left(\varepsilon_{xz}^{p}\right)^2 + 2\left(\varepsilon_{yz}^{p}\right)^2\right\}}$
  - For each point check (base material) $\varepsilon_p + X \leq 5\%$ (weld material) $\varepsilon_p + X \leq 2.5\%$
  - Check for a core of (base material) $\varepsilon_p + X \leq 1\%$ (weld material) $\varepsilon_p + X \leq 0.5\%$





Strain limits pass/fail criteria illustrated

EPP Creep-Fatigue Code Case (N-862)

- Similar to the EPP Strain limits procedure
  - Use “composite cycle”
    - The code case permits multiple composite cycles so that Level C loading cases do not have to stack up on Levels A and B load cases
    - For this option, must combine the fatigue damage of the multiple composite cycles using Miner’s rule
  - Use a different pseudo-yield stress
  - Require elastic shakedown instead of plastic shakedown
- Based on the rapid cycle concept (i.e., stresses do not relax) to provide a conservative bound (sometime very conservative) on creep damage

Basic EPP Creep-Fatigue Procedure

- Define an appropriate composite cycle, run thermal analysis to get temperature history
- Find material properties: $E(T)$, v, and $\alpha(T)$
- Select a trial time duration T'_d and iterate on T'_d as follows:
  - Find the pseudo-yield stress $\sigma_{py}^{T'_d}(T)$
  - Run an elastic perfectly-plastic analysis loading the component with the composite cycle and repeating for enough cycles to establish steady cyclic behavior
  - If the model does not shake down elastically the design check has failed
  - Calculate the creep damage: $D_c = \frac{t_{life}}{T'_d}$
  - Calculate the fatigue damage D_f
  - For each material point:
    - Compute the equivalent strain range $\Delta\varepsilon_{equiv}$ (with $\nu^* = 0.3$)
    - Lookup N_d
    - Compute the material point fatigue damage for the combined design cycles
  - The overall fatigue damage is the maximum damage at any material point
  - Lookup the (D_f, D_c) point in the creep-fatigue diagram to determine if the analysis passes or fails the design check

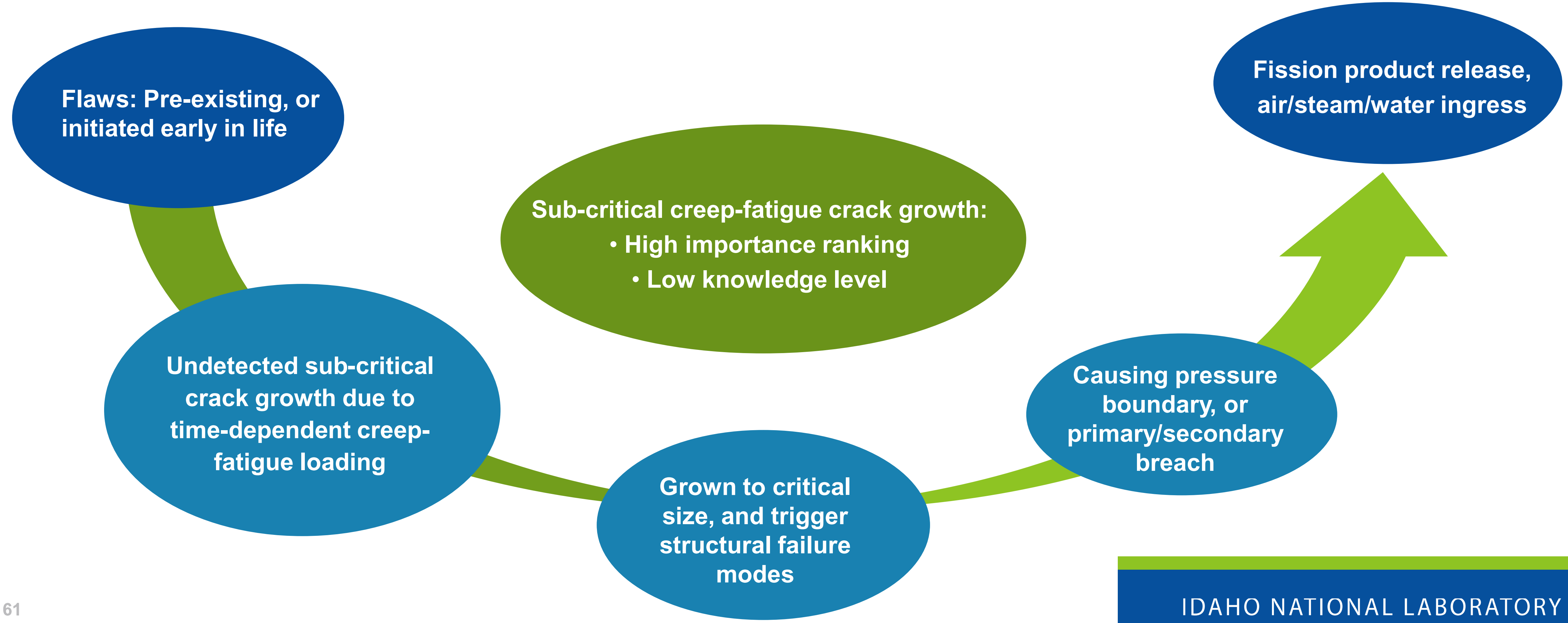
Design Parameters Required

- Allowable stresses
  - S_m: based on yield and ultimate strengths from tensile tests at temperature
  - S_t: based on data from creep rupture tests
    - Time to 1% total strain, time to onset of tertiary creep, time to rupture
  - S_r: based on data from creep rupture tests
  - S_{mt}: lesser of (S_m, S_t)
  - S_0: lesser of $(S, S_{mt}@300{,}000h)$
  - R: stress rupture factor (for welds) based on creep rupture tests of weld metal or weldment
- Thermal aging effects on yield and ultimate strengths
  - Based on yield and ultimate strengths of based metal thermally aged at constant temperature
- Isochronous stress-strain curves
  - Constructed as stress versus strain curves at constant time and temperature
  - Based on data from creep curves
- Fatigue curves
  - Based on data from strain-controlled continuous cycling tests at relative high strain rate, e.g., 10^{-3} per second
- Creep-fatigue interaction diagram
  - Based on data from strain-controlled cyclic tests with hold times at maximum and/or minimum strain level

Outline of Topics in This Presentation

High Temperature Flaw Evaluations

- Breach to secondary system due to creep or C-F crack growth may occur in intermediate heat-exchanger/steam generator (IHX/SG), cross vessel (CV), or reactor vessel (RPV), that could develop pathway for fission products release and/or air/steam/water ingress



Data Needs

Scoping Data

Scoping crack growth (CG) & mechanical data in air to validate and verify time-dependent flaw evaluation methodologies

Scoping CG data in HTGR helium and steam to determine if there is environmental effects on CG

Scoping CG & mechanical data in air on thermally-aged samples to determine if there is thermal aging effects on CG

Design Data (Multiple Heats)

CG & mechanical data

- In air, when methods validated & verified
- In NGNP helium, if needed
- In steam, if needed
- Thermally aged samples in air, if needed

ASME Section XI CCG Code Case (C&S R20-144)

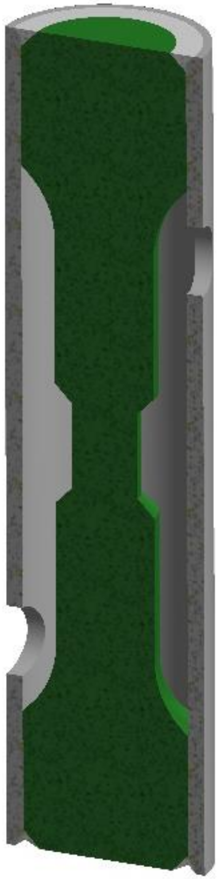
- Evaluation Procedure and Acceptance Criteria for Flaws where Crack Growth from Creep May Occur at Elevated Temperatures, Section XI, Division 2
- Inquiry:
  - What evaluation procedure and acceptance criteria may be used to assess flaws in components at elevated temperatures where creep crack growth may occur?
- Reply:
  - It is the opinion of the Committee that the evaluation procedure and acceptance criteria of this Case may be used to assess flaws in components at elevated temperatures where creep crack growth may occur.
- Scope
  - This Case describes procedures for the assessment of flaws in components operating in the high temperature creep regime which may be subjected to long periods of steady loadings. Crack extension due to creep is addressed. Guidance from other high temperature flaw evaluation codes, as discussed in the Technical Basis Document (R5 [1, 2], API579/ASME-FFS1 [3], and RCC-MRx [4, 5]) is made for the relevant methods to determine the crack growth under applicable loads. Relevant material properties are available in the ASME/DOE materials database, in the DOE Task 8 report documents [6, 7], and the above codes. These are applicable to components that are constructed to Section III, Division 5 rules. The main body of the Case presents general rules applicable to all components. Appendices A implements these general criteria for certain types of components.

Materials Surveillance

- Information on material degradations due to irradiation, corrosion, elevated temperature exposure and creep-fatigue loading is important for advanced reactor licensing and long term operations
- The establishment of an in-situ, passive surrogate materials surveillance program that would allow the collection of information on these material degradations would be an important pathway in support of timely licensing of advanced reactors
- Can “trade-off” upfront data requirements and provide assurance on integrity performance during operation
- Will be a key tool to support license review, and for materials degradation management of advanced reactor systems
- ASTM E531 - Standard Practice for Surveillance Testing of High-Temperature Nuclear Component Materials
  - Originally approved in 1975
  - 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
  - Being updated by ASTM

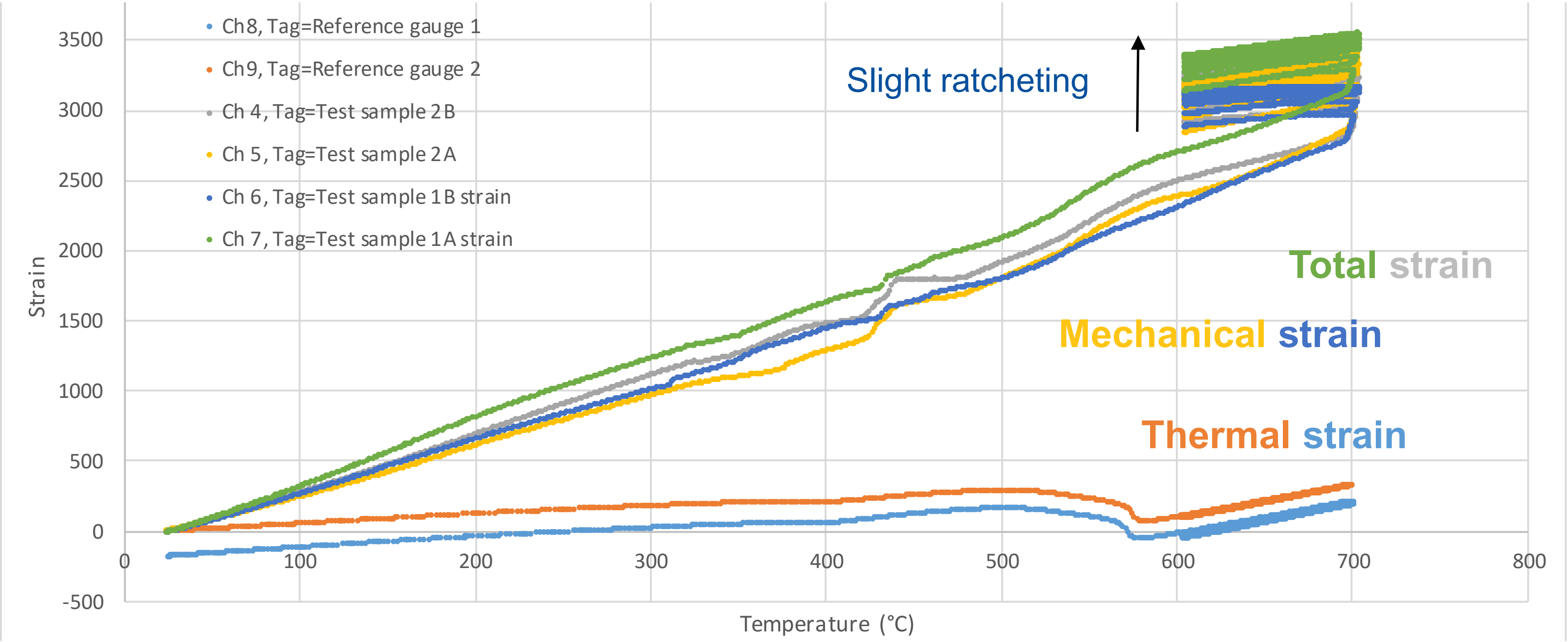
Applications for In-situ, Passive Surveillance

- Surveillance specimens in a test or demonstration reactor could be used to evaluate the performance and validate the design basis of existing or new materials to support their near-to-mid-term deployment in advanced high temperature reactors
- Surveillance specimens could be placed in an operating plant at different key locations to accumulate damage either under prototypical reactor operating conditions or under some accelerated loading conditions
- These specimens could serve as canaries, to ensure the structural materials maintain their expected design strength in service
- Data collected from the monitoring program could also be used to justify future plant life extensions



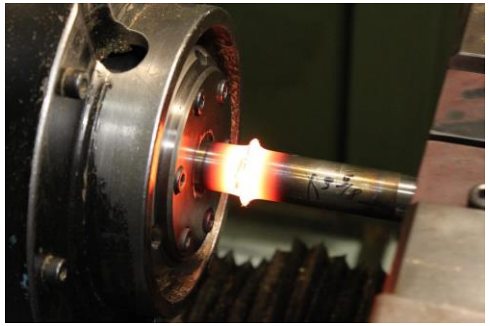
In-situ, passive test article capturing structural response

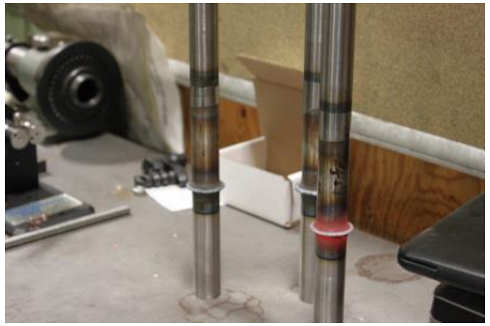
Proof of Concept Testing: Thermal Cycling



- 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

Surveillance Test Articles: Fabrication and Test





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- A. Rovinelli, M.C. Messner, T.-L. Sham, "Investigating the Correlation between Different Effective Stress Measures and the Service Life of Actual High-Temperature Structural Components," Proceedings of the ASME 2020 Pressure Vessels and Piping Division Conference, Minneapolis, July 2020, PVP2020-21471, American Society of Mechanical Engineers, New York, NY (2020)
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Questions?

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