INL/MIS-23-74734-Revision-0

ASME, Section III, Division 5, Metallic

September 2023

Changing the World's Energy Future

Ting-Leung Sham

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/MIS-23-74734-Revision-0

ASME, Section III, Division 5, Metallic

Ting-Leung Sham

September 2023

Idaho National Laboratory
Idaho Falls, Idaho 83415

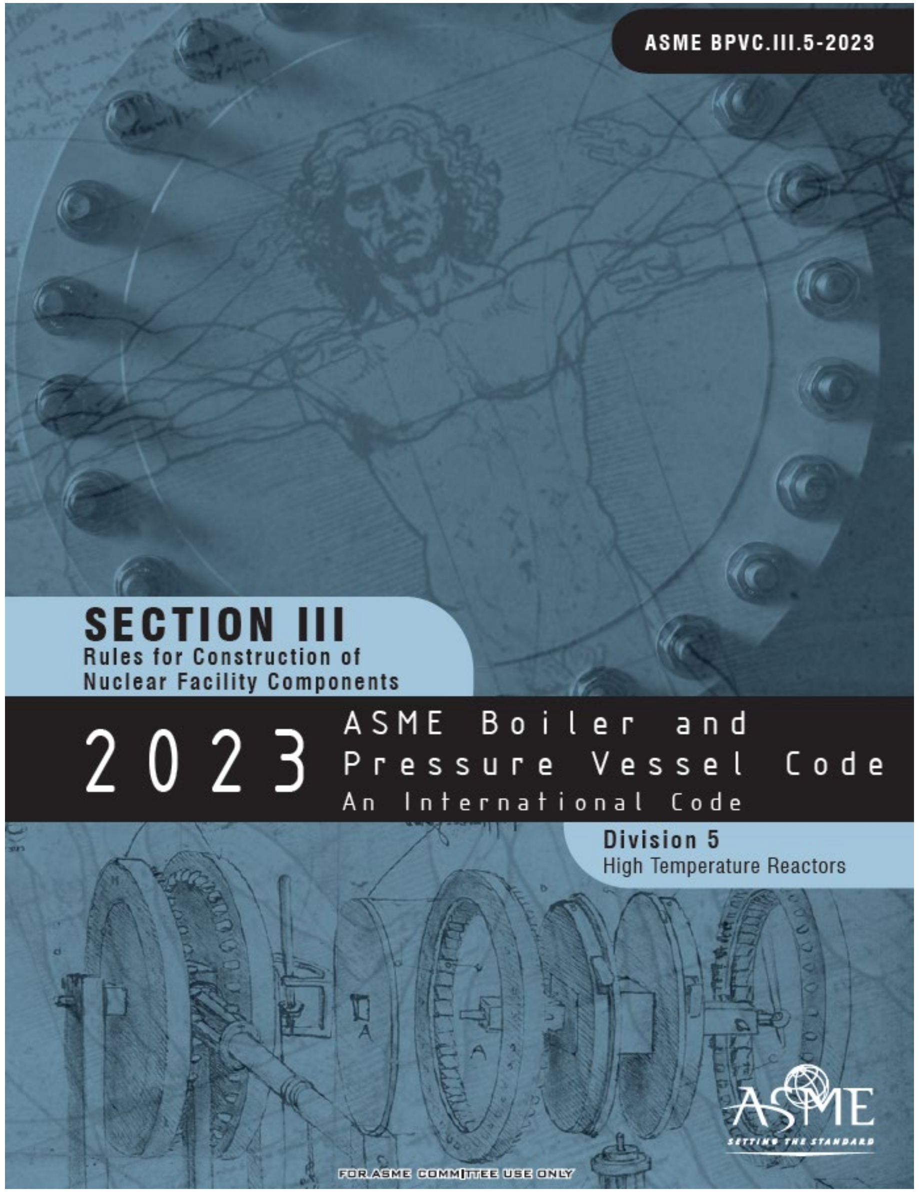
http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

ASME, Section III, Division 5, Metallic

Technical Workshop
BPV III International Meeting, Sheffield, UK
September 25-28, 2023

Ting-Leung (Sam) Sham
Chair, Subgroup High Temperature Reactors



ASME Section III, Rules for Construc 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)**

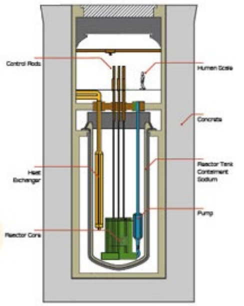
Division 5 Construction Rules for High Temperature Metallic Components – A Long History of Development

1963	Code Case 1331, design rules for nuclear components initiated.
Early 1970s	Code Cases 1592, 1593, 1594, 1595 and 1596, covering materials and design, fabrication and installation, examination, testing, and overpressure protection.
1975	NRC endorsed Code Case series 1592-1596 in RG 1.87 for HTGR, LMR, GFR.
Late 1970s	Code Case series 1592-1596 converted to Code Case N-47. Used by Clinch River Breeder Reactor project, with additional DOE requirements.
…	Continued improvements of N-47.
1995	Subsumed N-47 into a new Section III, Division 1, Subsection NH.
2011	Consolidated Subsection NH and other nuclear Code Cases, and added construction rules for graphite core components, into a new Section III, Division 5 construction rules for high temperature reactors.

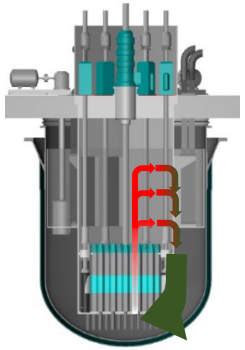
Examples of Different Advanced Reactor Designs Being Developed By Industry

Fast Reactors

Advanced Reactor Concepts, ARC-100



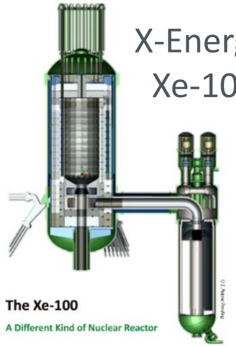
GE Hitachi PRISM



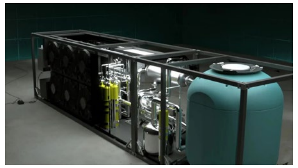
Westinghouse, LFR

TerraPower & GEH Natrium

Oklo, Aurora



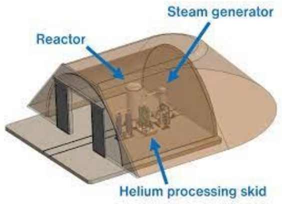
X-Energy, Xe-100



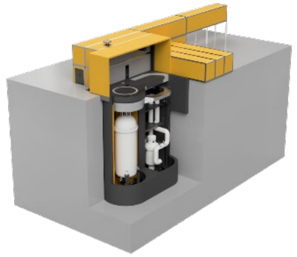
Radiant Nuclear

Gas Reactors

General Atomic, Fast Modular Reactor

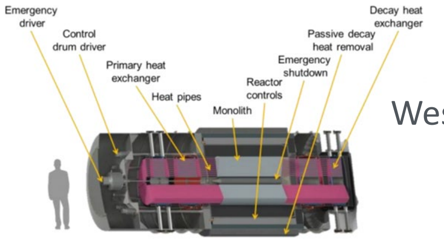


BWXT, BANR



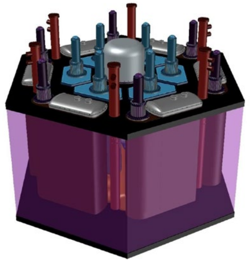
Ultra Safe Nuclear, MMR

Heat Pipe Reactor

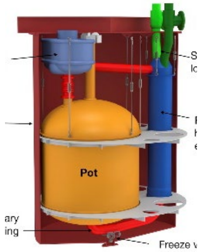


Westinghouse eVinci

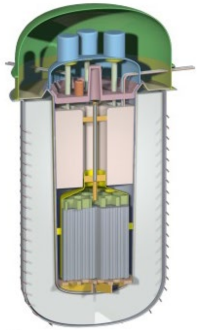
Molten Salt Reactors



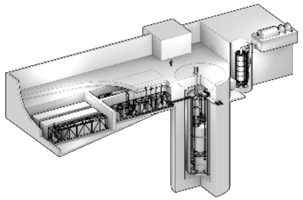
Exodys, FC-MSR



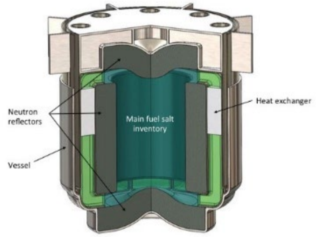
ThorCon



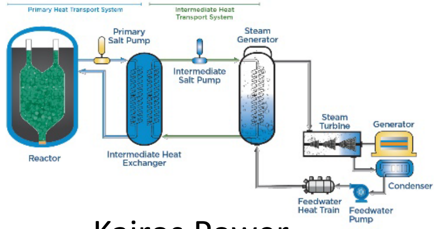
Terrestrial Energy IMSR



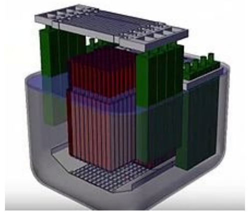
Flibe Energy LFTR (thorium)



TerraPower MCFR



Kairos Power



Moltex Energy, SSR

Section III, Division 5 Organization

Class	Subsection	Subpart	Subsection 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 Pressure Boundary Components					
Class A	HB	A	HBA	Low Temperature Service	Metallic
Class A		B	HBB	Elevated Temperature Service	Metallic
Class B Metallic Pressure 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

Section III, 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

Regulatory Guide 1.87 revision 2, Jan 2023		
Classification Method	Component Classification	
Traditional	Quality Group A	Quality Group B
Risk-informed (10 CFR 50.69)	RISC-1	RISC-1
Risk-Informed (RG 1.233)	SR	SR
	SR Qualify Design Standards	
Components		
Pressure Vessels, Piping, Pumps, Valves, Atmospheric Storage Tanks, Storage Tanks (0-15 psig)	ASME Code, Section III, Division 5, Class A	ASME Code, Section III, Division 5, Class B
Metallic Core Support Structures	ASME Code, Section III, Division 5, Subsection HG	NA
Nonmetallic Core Support Structures	ASME Code, Section III, Division 5, Subsection HH	NA

Division 5 High Temperature Materials – Environmental Effects

Effects of coolant and irradiation on structural failure modes are different from one reactor design to another even for the same structural material

Division 5 cannot cover these effects for all reactor types, and for all different design characteristics for the same reactor type, viz. molten salt reactor

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.

Essentially, 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, etc.

Conduct surrogate materials surveillance

ASME Section III, Division 5, Metallic Components

- The need for performance monitoring and surveillance programs, particularly for very long design lifetimes, e.g., 500,000 hour, has been reinforced in Division 5 recently
- A General Note has been added to Table HBB-I-14.10E-1 on the stress rupture factors for 9Cr-1Mo-V weldment (2023 Edition):
  - The values in this table are extrapolated from shorter term test data using an engineering model. For longer design lives, the designer should consider further strength reductions to account for potential in-service material degradation, per HBB-2160(a). In addition, enhanced material surveillance programs and/or heightened in-service inspection per the rules of ASME Section XI may be warranted.

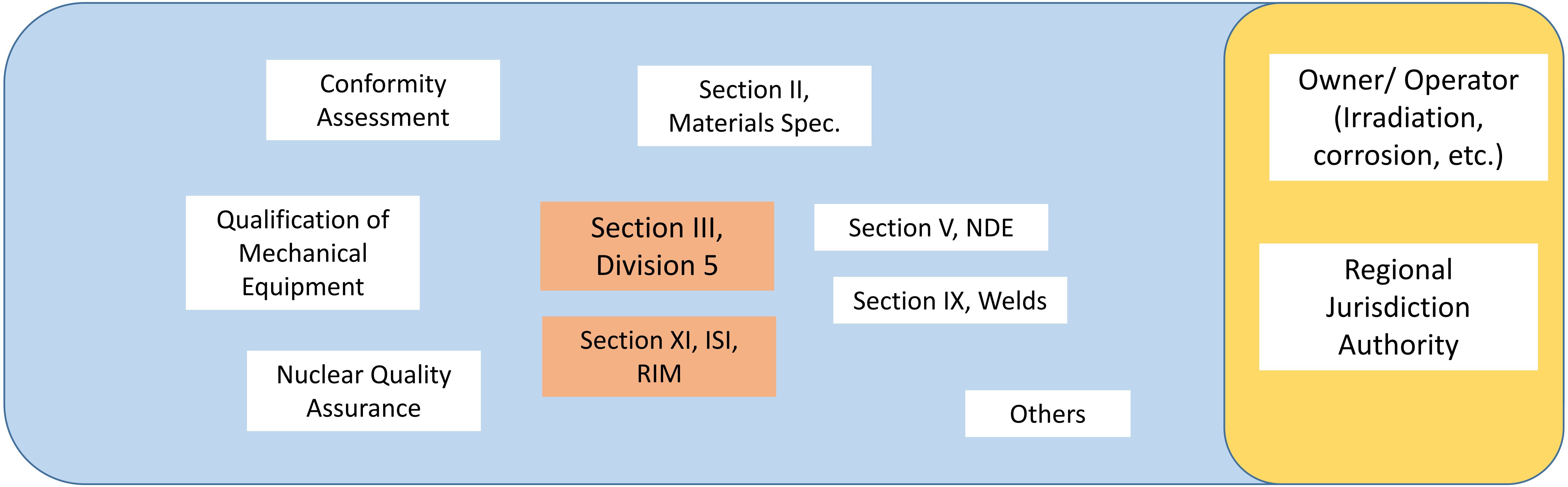
NRC Draft Interim Staff Guidance on Material Compatibility

- NRC issued a Draft Interim Staff Guidance (ISG) on Material Compatibility for non-LWRs in February 2023
  - DANU-ISG-2023-01, Accession Number ML22203A175
- The ISG identifies information the NRC staff should consider in its review related to materials qualification
- It also indicates where monitoring and surveillance may be appropriate to be relied upon to ensure component integrity

ASME SETTING THE STANDARD

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))



Section III, Division 5, Metallic Components

Component	Class	Elevated Temperature Service	Low Temperature Service (reference Section III, Division 1)
Metallic coolant boundary components	Class A	Subsection HB, Subpart B	Subsection HB, Subpart A
Metallic core support structures	Class SM	Subsection HG, Subpart B	Subsection HG, Subpart A
Metallic coolant boundary components	Class B	Subsection HC, Subpart B	Subsection HC, Subpart A
Metallic supports	Class A & Class B	N/A	Subsection HF, Subpart A

Division 5 Class A Components

- 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 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

Division 5 Class SM Components

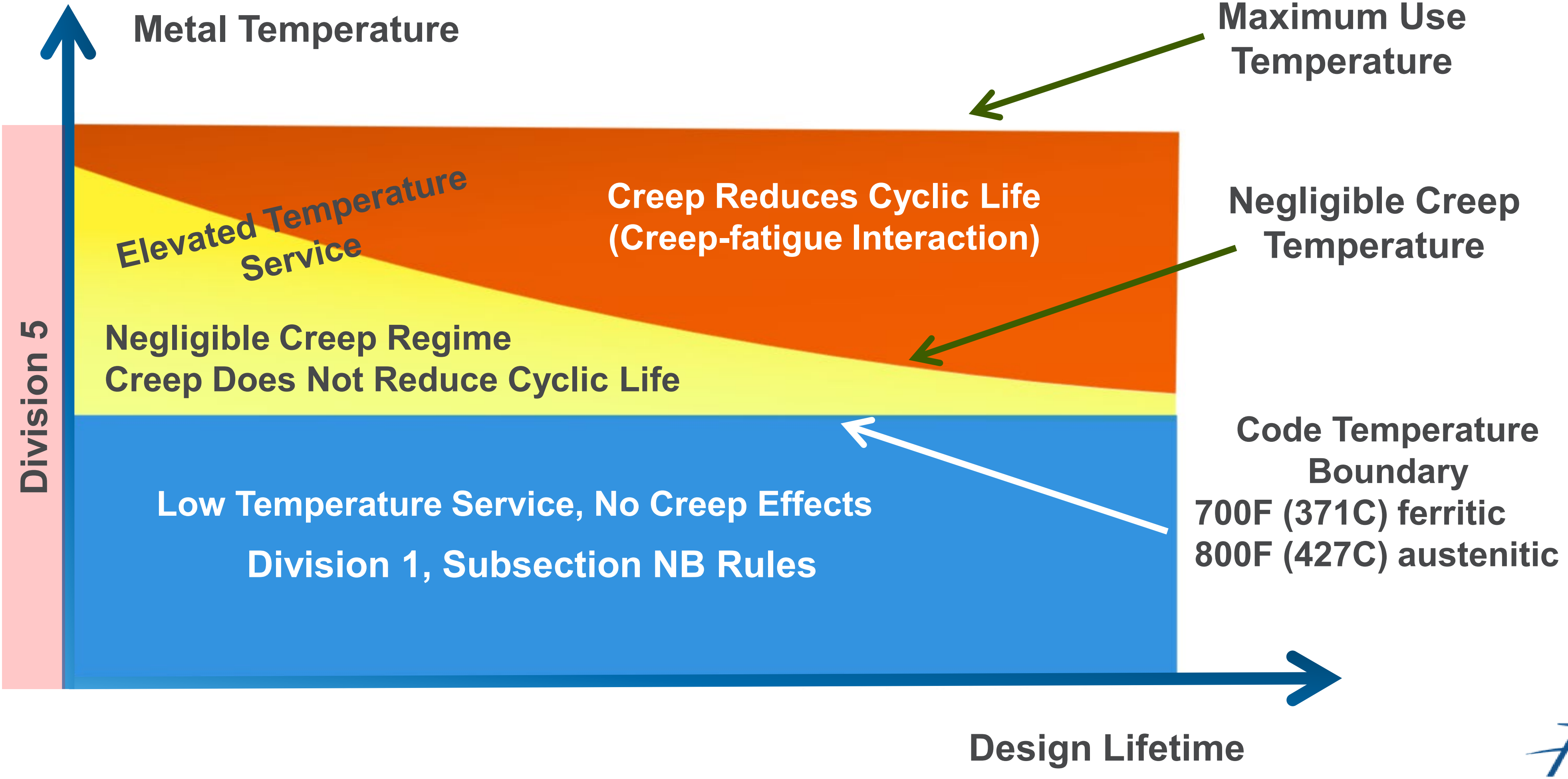
- Extension of construction rules of Division 1 Subsection NG for core support structures, internal structures, threaded structural fasteners, and temporary attachments to elevated temperature service
- Load-controlled design rules are very similar to those for Class A
  - Consistent with Division 1 Subsection NG 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 B Components

- 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 certified 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

ASME SETTING THE STANDARD

Temperature Boundaries For Class A & Class SM Components



Design Evaluation Methods For Class A Components

Design Check	Elastic Analysis	Elastic, Perfectly Plastic Analysis (EPP)	Inelastic Analysis
Primary Load	Allowed	Allowed	Not allowed
Strain Limits	Allowed	Allowed	Allowed
Creep-fatigue	Allowed	Allowed	Allowed
Buckling	Use Division 1 Subsection NB pressure charts when time-temperature limit is satisfied	TBD	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)
- EPP methods have been developed in the past 10 years to improve on screening tools
  - No stress classification and linearization, can leverage modern finite element analysis tools
- Design methods based on inelastic analysis results provide more accurate but less conservative checks on failure modes
  - Intended for checking "hot spots"

Division 5 Class A Material Code Cases

Current Class A Materials

- Type 304 and 316 stainless steels
- Alloy 800H
- Grade 91 (9Cr-1Mo-V)
- 2¼Cr-1Mo (solution annealed)
- Alloy 617
- SA 508 Grade 3 and SA 533B reactor pressure vessel steels (for short term, elevated temperature excursions)

New Material Code Cases

- Lessons-learned from Alloy 617 Code Case effort have streamlined the balloting workflow for Class A material code cases
- After requester submitted material design parameters and supporting data package to ASME, Division 5 could turn around a material code case in about three Code Week cycles (less than a year)
- Data requirements for new materials are described in Division 5, "Nonmandatory Appendix HBB-Y, Guidelines For Design Data Needs For New Materials"

Recent Development and Priorities

Division 5 High Priority Items (Metallic) - Making Progress

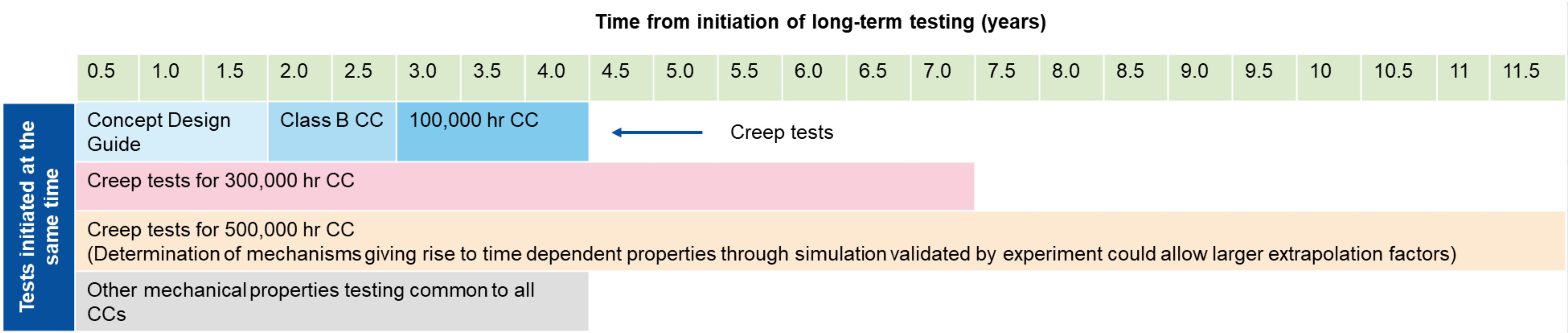
- Developed new Elastic, Perfectly Plastic (EPP) design evaluation methods (Completed)
- Extend allowable stresses and design parameters of Class A materials to support 60-year design lifetime (In progress)
- Qualify a new Class A alloy – Alloy 709, advanced austenitic stainless steel (In progress)
- Develop Division 5 code case for PM-HIP (Powder Metallurgy – Hot Isostatic Pressing) 316H stainless steel (In progress)
- Revamp Class B design rules and incorporate more materials (In progress)

ASME
SETTING THE STANDARD

Extension of Allowable Stresses and Design Parameters to Support 60-Year Design Life

Class A Material	Time Dependent Allowable Stress	Minimum Expected Stress-to-Rupture	Thermal Aging Factor	Stress Rupture Factor (Weldment)	Isochronous Stress-Strain Curves
Type 304 Stainless Steel	Completed	Completed	Ongoing	Ongoing	Ongoing
Type 316 Stainless Steel	Completed	Completed	Ongoing	Ongoing	Ongoing
Alloy 800H	Ongoing	Completed	TBD	Ongoing	Ongoing
Grade 91	Completed	Completed	Completed	Completed	Completed
2¼Cr-1Mo	TBD	TBD	TBD	TBD	TBD

“Staged” Approach for Material Code Cases to Support Advanced Reactor Projects – Alloy 709 Case Study



A three/four-year testing program, without resource constraints, would have sufficient time to generate data package to support:

- Conceptual design (first 2 years)
  - Conceptual Design Guide for 500,000-hour lifetime
- Preliminary design
  - 100,000-hour Class A code case (3 to 4 years)
  - Class B material code case (first 2 to 3 years)

Additional creep data only at 7-year mark from start:

- Final design
  - 300,000-hour Class A code case

Additional creep data only at 12-year mark from start:

- Nth-of-a-kind
  - 500,000-hour Class A code case

ASME
SETTING THE STANDARD

Advanced Manufacturing: Division 5 Code Case for Powder Metallurgy Hot Isostatic Pressing (PM-HIP) 316H Stainless Steel

- PM-HIP is a mature advanced manufacturing method that is used by many non-nuclear industries to fabricate structural components
- PM-HIP attributes are also attractive for fabricating reactor components
  - Particularly timely for microreactors
- Target Division 5, 316H PM-HIP elevated temperature code case by 2025 to support Section III Strategic Priorities
- R&D and testing are currently being conducted through INL, EPRI and UK Nuclear Advanced Manufacturing Research Centre (AMRC) collaborative effort

LWR reactor head – Courtesy EPRI

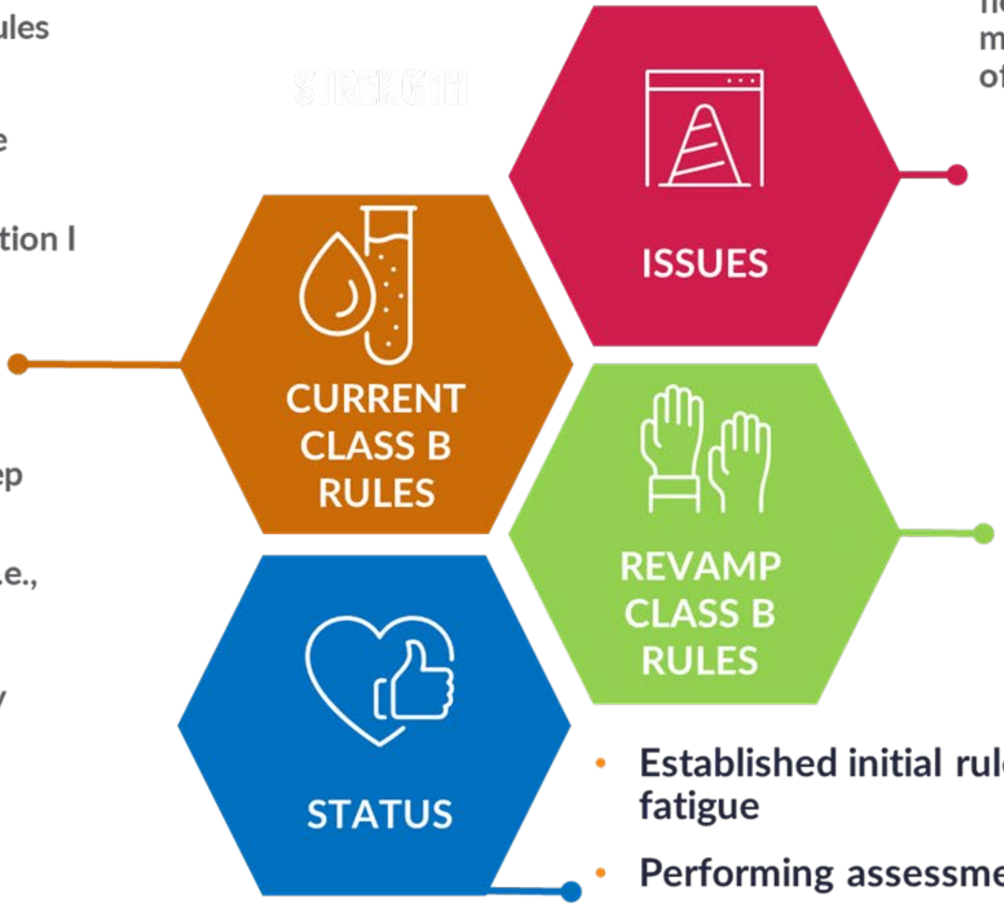
316L PM-HIP component for ASME Section III Code Case N-834

Kyffin, W., Gandy, D., Burdett, B. (2020)

ASME
SETTING THE STANDARD

Revamp Division 5 Class B Design Rules

- Are extension of construction rules of Section III, Division 1, Class 2 vessel, pump, valve and piping designs to elevated temperature service
- Similar to commercial rules (Section I and Section VIII, Division 1)
- Based on the design-by-rule approach
- Allowable stresses based on extrapolated 100,000-hour creep rupture properties
- Cyclic loading in creep regime (i.e., creep-fatigue interaction) not considered
  - Except for piping, but very conservative rules



- These rules do not provide the design flexibility and are not adequate to address many design and operational characteristics of new high temperature reactors
  - Different design lifetimes, e.g., 7, 20 or 60 years
  - Thermal cycles
  - Limited permissible Class B materials

- Incorporate time-dependent allowable stresses and design lifetime concept
- Introduce simplified design-by-analysis approach to address primary load, strain limits and creep-fatigue
- Expand the permissible Class B materials list

- **Established initial rules for primary load, strain limits and creep-fatigue**
- **Performing assessment of the new rules using sample problems**
- **Considering data requirements for Class B**

New Class B Code Case

Materials Identified for Future Incorporation into the New Class B Code Case		
Creep data in Section III, Division 5	**Creep Data in Section II (non-nuclear)**	**None of the above**
• 304H, 316H, Alloy 800H, Grade 22 (solution annealed), Grade 91, Alloy 617	• 316L, 316Ti, Ti-mod 304 (TP321), 304N, 316N • Alloy 690, Hastelloy X, Alloy 625, Hastelloy N, Haynes 230, Haynes 242, Haynes 282, Inconel 740H • Grade 92, Grade 22 (N&T)	• Alloy 709 • XM-19 (NITRONIC 50) • Haynes 244 • HT-9 • 15-15-Ti

ASME
SETTING THE STANDARD

Other Division 5 Initiatives For Metallic Components

- Constitutive models to support inelastic analysis method
  - New Appendix HBB-Z on guidance on constitutive model development added to Division 5
  - Viscoplastic models with material parameters covering the entire use temperature range have been approved for Grade 91, 316H, Alloy 617
  - R&D is being conducted through DOE program on universal viscoplastic model form for all Class A materials to simplify implementation of inelastic analysis methods by designers
- Design rules for Class A diffusion bonded compact heat exchanger
  - R&D through DOE Integrated Research Project (IRP) – led by University of Wisconsin, Madison (completed)
  - New DOE IRP on diffusion bonding process development – led by University of Michigan (ongoing)
  - Compact heat exchanger code case based on research from the Wisconsin IRP is being developed
- Design rules for Class A cladded structural components
  - R&D through DOE GAIN voucher to Kairos Power
  - Cladded Class A component code case is being developed

ASME
SETTING THE STANDARD

Concluding Remarks

- ASME, Section III, Division 5 stands ready to support near-term deployment of advanced reactors
- We are making progress:
  - Improving design rules
  - Extending design lifetimes
  - Adding more materials
  - Adding advanced component fabrication method

Thank You

Contact Info:

TingLeung.Sham@inl.gov