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Overview of Advanced High-Temperature Materials, ASME Qualification, and US DOE R&D Program

June 2021

Changing the World's Energy Future

Ting-Leung Sham

Idaho National Laboratory

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40th CNS Annual Conference
SMR Symposium W1B: High Temperature Gas-Cooled Reactors Training

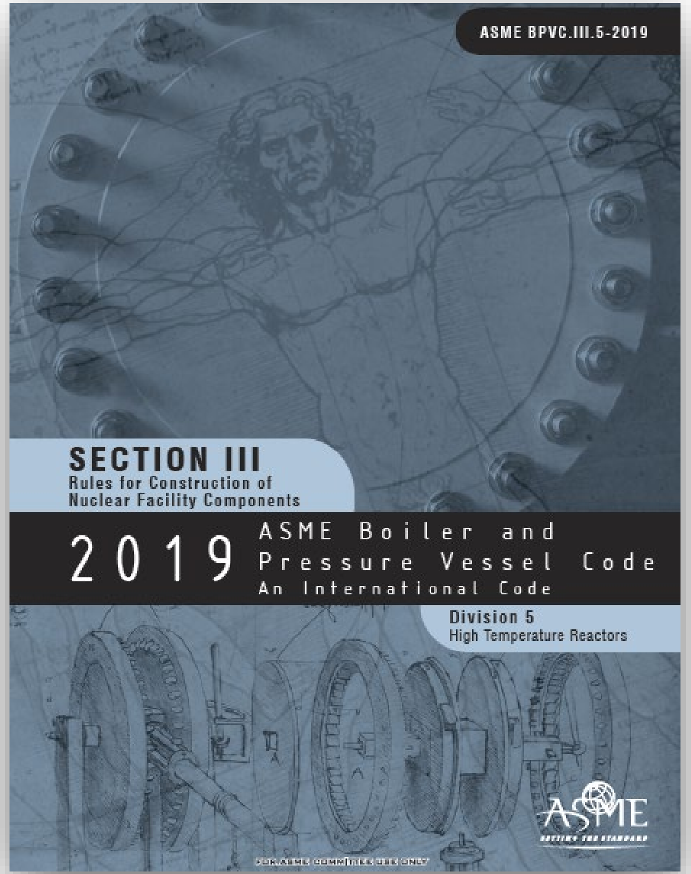
Idaho National Laboratory

Outline

1. ASME Section III, Division 5 Introduction
2. High Temperature Alloys, Weld Materials and Bolting
3. Design Parameters Required for Design Evaluations
4. Data Requirements for New Materials
5. US DOE High Temperature Materials R&D Program

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)



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

- Design rules for metallic 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
- 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
- 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
- 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

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

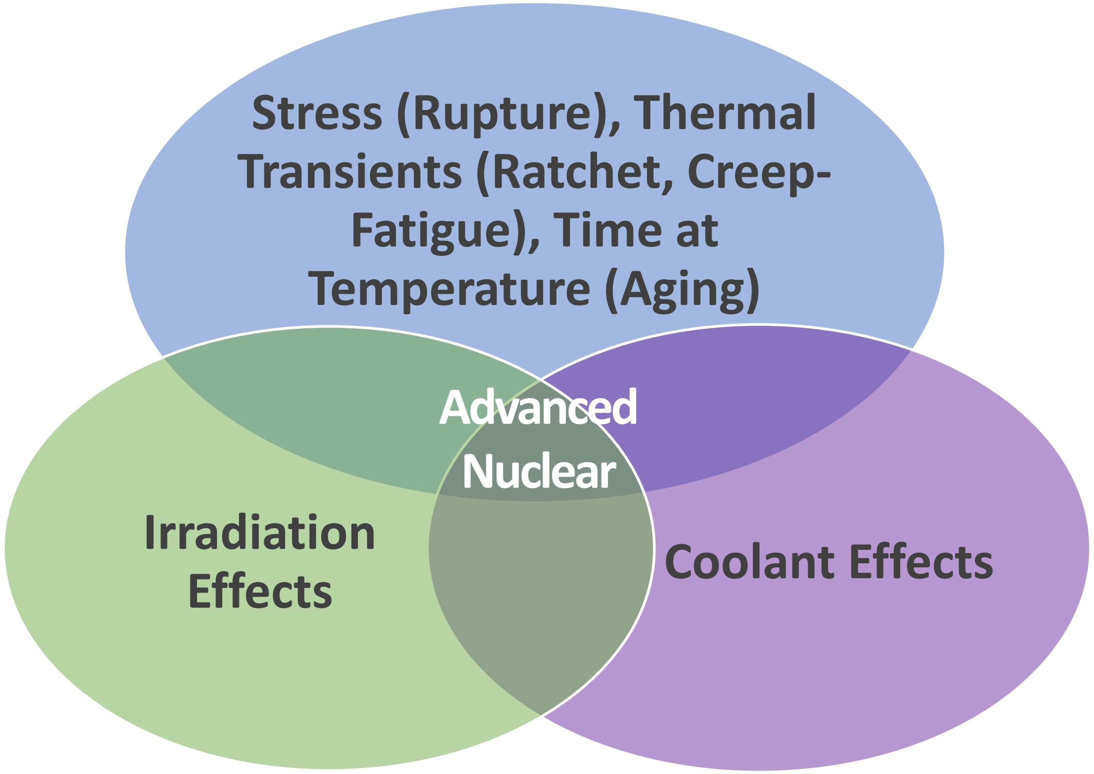
Section III, Division 5 Organization

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

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

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 materials degradation 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.

Section III, Division 5 Endorsement

- US Nuclear Regulatory Commission (NRC) is currently assessing Section III, Division 5 (2017 Edition) for endorsement
- Draft Regulatory Guide (DG-1380) and draft technical basis draft NUREG are scheduled to be issued for public comment by June 30, 2021, per NRC plan
- The DG is likely to include a number of conditions, in the areas of general requirements, mechanical design, metallic materials allowable stresses, and graphite materials/design
- DG-1380 is a revision to RG 1.87, Revision 1, 1975 (which endorsed the 159X series code cases with conditions)

Division 5 High Temperature Base Materials

Alloy	Temperature not exceeding, F (C)	Lifetime for Allowable Stresses, hr
Type 304 stainless steel	1500 (816)	300,000
Type 316 stainless steel	1500 (816)	300,000
Fe-Ni-Cr (Alloy 800H)	1400 (760)	300,000
2.25Cr-1Mo (Grade 22, Class 1, annealed)	1100 (593)	300,000
9Cr-1Mo-V (Grade 91)	1200 (650)	300,000
Ni-Cr-Co-Mo (Alloy 617)	1750 (954)	100,000
SA-533 Type B, Class 1 plate and SA-508 Grade 3, Class 1 forgings	700 to 800 (371 to 427) Exceeding 800 to 1000 (427 to 537)	3,000 1,000

Division 5 Weld Materials

Alloy	Permission Weld Materials (Specification Number; Class)
Type 304 and 316 stainless steel	SFA-5.4; E 308, E 308L, E 316, E 316L, E 16-8-2 SFA-5.9; ER 308, ER 308L, ER 316, ER 316L, ER 16-8-2 SFA-5.22; E 308, E 308T, E 308LT, E 316T, E316LT-1 EXXXT-G (16-8-2 chemistry)
Fe-Ni-Cr (Alloy 800H)	SFA-5.11; ENiCrFe-2 SFA-5.14; ERNiCr-3
2.25Cr-1Mo (Grade 22, Class 1, annealed)	SFA-5.5; E 90XX-B3 (>0.05% Carbon) SFA-5.23; EB 3, ECB 3 SFA-5.28; E 90C-B3 (>0.05% Carbon), ER 90S-B3 SFA-5.29; E 90T-B3 (>0.05% Carbon)
9Cr-1Mo-V (Grade 91)	SFA-5.5; E90XX-B9 SFA-5.23; EB9 SFA-5.28; ER90S-B9
Ni-Cr-Co-Mo (Alloy 617)	SFA-5.14; ERNiCrCoMo-1
SA-533 Type B, Class 1 plate and SA-508 Grade 3, Class 1 forgings	Associated weld metals

Division 5 Bolting Materials

Bolting	Specification; Class
Type 304 stainless steel	SA-193; B8 Class 1, B8A Class 1A
Type 316 stainless steel	SA-193; B8M Class 1, B8MA Class 1A
Ni-Cr-Fe-Mo-Cb (Alloy 718)	SB-637; NO 7718

Design Parameters Required for Design Evaluations

- 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

Section III, Division 5 Code Qualification of New Materials

Required testing to introduce a new structural material into Section III, Division 5, or a Division 5 Code Case (information from Division 5, Appendix HBB-Y)

- HBB-Y-2100 Requirement For Time-independent Data
- HBB-Y-2110 Data Requirement for Tensile Reduction Factors for Aging
- HBB-Y-2200 Requirement for Time-Dependent Data
- HBB-Y-2300 Data Requirement for Weldments
- HBB-Y-3100 Data Requirement for Isochronous Stress-Strain Curves
- HBB-Y-3200 Data Requirement for Relaxation Strength
- HBB-Y-3300 Data Requirement for Creep-Fatigue
- HBB-Y-3400 Data Requirement for Creep-Fatigue of Weldments
- HBB-Y-3500 Data Requirement for Cyclic Stress-Strain Curves
- HBB-Y-3600 Data Requirement for Inelastic Constitutive Model
- HBB-Y-3700 Data requirement for Huddleston multiaxial failure criterion
- HBB-Y-3800 Data Requirement for Time-Temperature Limits for External Pressure Charts
- HBB-Y-4100 Data Requirement for Cold Forming Limits
- Validation of Elastic-Perfectly Plastic (EPP) Simplified Design Methods for the new alloy

US DOE High Temperature Materials R&D

- Development of viscoplastic constitutive models for inelastic design analysis
  - Completed Grade 91, Type 316 stainless steel, Alloy 617
- Modernization of design evaluation methods more suitable for finite element methods
  - Elastic Perfectly Plastic (EPP) Code Cases for primary load, strain limits and creep-fatigue design evaluations
- Experiments to support long-term plant operations
  - Notch strengthening/weakening testing for Alloy 617 base metal and weldment
  - Crack growth testing for Alloy 617
- Qualifying Alloy 800H weld metal (21-31MnNb, matching filler metal) for enhanced creep rupture strength
- Qualifying high temperature 316H nuclear components fabricated by Powder Metallurgy, Hot-Isostatic Pressing
- Qualifying Alloy 709, an advanced austenitic alloy with higher creep strength than Type 316 stainless steel

Suggested Reading List - 1

- ASME Section III, Rules for Construction of Nuclear Facility Components - Division 5, High Temperature Reactors, American Society of Mechanical Engineers, New York, NY
- Next Generation Nuclear Plant Reactor Pressure Vessel Materials Research and Development Plan INL Document PLN-2803, Rev. 1, 2010
- Next Generation Nuclear Plant Steam Generator and Intermediate Heat Exchanger Materials Research and Development Plan INL Document PLN-2804, Rev. 1, 2010
- NGNP High Temperature Materials White Paper INL/EXT-09-17187, Rev. 1, 2012
- R.I. Jetter and D.K. Morton, "Chapter 17, Division 5, High Temperature Reactors," in Companion Guide to the ASME Boiler and Pressure Vessel and Piping Codes, Fifth Edition, Volume 1, American Society of Mechanical Engineers, New York, NY (2018)
- Robert I. Jetter, Mark C. Messner, James Nestell, T.-L. Sham, and Yanli Wang, “Background Information for Addressing Adequacy or Optimization of ASME BPVC Section III, Division 5 Rules for Metallic Components,” ASME NTB-2-2019, American Society of Mechanical Engineers, New York, NY (2019)
- R.I. Jetter, M. Messner, J. Nestell, T.-L. Sham, Y. Wang, Gap Analysis for Addressing Adequacy or Optimization of ASME Section III Division 5 Rules for Metallic Components, Nuclear Technical Book, NTB-3-2020, American Society of Mechanical Engineers, New York, NY, ISBN No. 978-0-7918-7377-9, July (2020)
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- D.R. Eno, G.A. Young, and T.-L. Sham," A Unified View of Engineering Creep Parameters," Proceedings of the ASME 2008 Pressure Vessels and Piping Division Conference, Chicago, Illinois, July 2008, Paper No. PVP2008-61129, American Society of Mechanical Engineers, New York, NY (2008)
- T.-L. Sham, K. Natesan, "Code Qualification Plan for an Advanced Austenitic Stainless Steel, Alloy 709, for Sodium Fast Reactor Structural Applications," International Conference on Fast Reactors and Related Fuel Cycles: Next Generation Nuclear for Sustainable Development (FR17), 26-29 June 2017, Yekaterinburg, Russia, IAEA-CN-245-74 (2017)
- R.N. Wright, T.-L. Sham, "Status of Metallic Structural Materials for Molten Salt Reactors," INL/EXT-18-45171, Idaho National Laboratory, Idaho Falls, ID, May (2018)
  - https://www.osti.gov/biblio/1467482-status-metallic-structural-materials-molten-salt-reactors