IDENTIFYING LIMITATIONS OF ASME SECTION III DIVISION 5 FOR ADVANCED SMR DESIGNS

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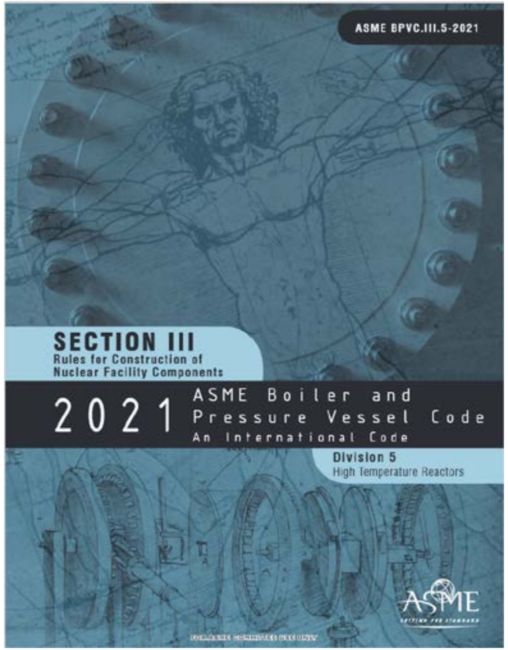

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U.S. DEPARTMENT OF ENERGY
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TWO PARTS

1. What is ASME Section III, Division 5?
2. What are the potential limitations of the Code when designing/constructing microreactor components?

Part 2 summarizes a publicly-available Argonne National Laboratory technical report:

Messner, Sham, and Barua. "Identifying Limitations of ASME Section III Division 5 For Advanced SMR Designs." Argonne National Laboratory Technical Report ANL-21/27, 2021.

https://www.osti.gov/biblio/1804300-identifying-limitations-asme-section-iii-division-advanced-smr-designs

PART 1: WHAT IS ASME SECTION III, DIVISION 5?

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, storage tanks, 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)

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

Construction Rules and Inservice Inspection – Metallic Components

<table>
<tr><th colspan="2">ASME Construction Rules for Nuclear Facility Components (Section III)</th><th>ASME Inservice Inspection of Nuclear Power Plant Components (Section XI)</th></tr>
<tr><td>Material Qualification – Within Division 5 Scope</td><td>Outside Division 5 Scope
• Corrosion
• Mass transfer phenomena
• Radiation
• Fission product</td><td>High temperature flaw evaluation methodology
• Support inservice inspection and disposition of detected flaw/UT indication</td></tr>
<tr><td>Approved by ASME Section III for incorporation into Division 5
• Testing performed in air and at elevated temperatures</td><td>Approved by Jurisdictional Regulatory Body
• Support construction license application</td><td>Approved by ASME Section XI
• Methodology required upfront, at construction license application</td></tr>
<tr><td colspan="3">Availability of elevated temperature material surveillance program (in-situ stress, temperature, corrosion, neutron irradiation) will be helpful for new materials insertion</td></tr>
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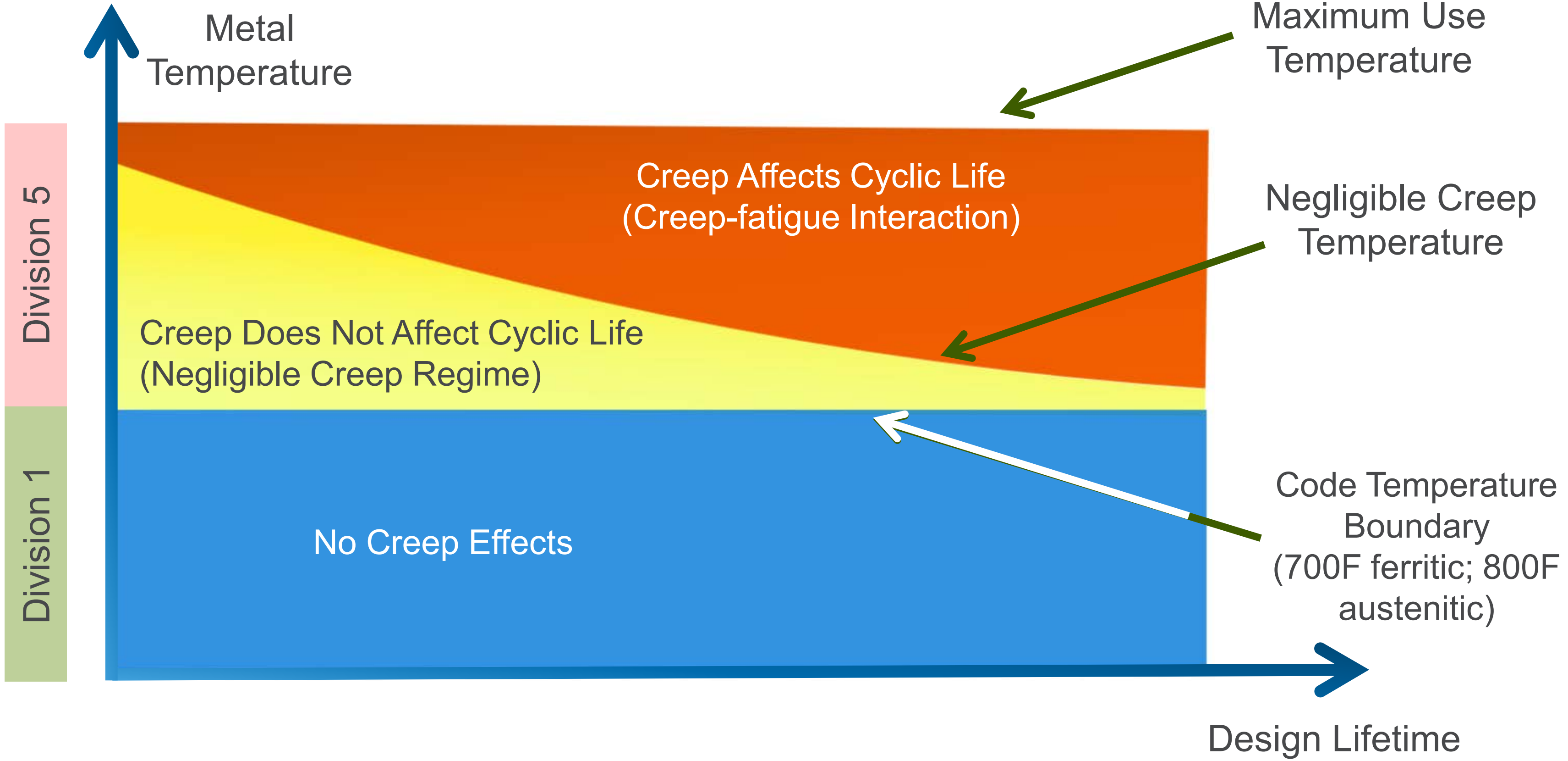
Temperature Boundaries For Class A Components



Design Rules For Class A Components – Structural Failure Modes

Time Independent Failure Mode	Design Method	Time Dependent Failure Mode	Design Method
Ductile rupture from short-term loading	Primary Load Check	Creep rupture from long-term loading	Primary Load Check
Gross distortion due to incremental collapse and ratcheting	Strain Limits Check	Creep-fatigue failure	Creep-Fatigue Check
Loss of function due to excessive deformation	Strain Limits Check	Creep-buckling due to long-term loading	Buckling Check
Buckling due to short-term loading	Buckling Check		

PART 2: LIMITATIONS FOR MICROREACTOR APPLICATIONS

BASE MATERIALS

CLASS A MATERIALS, TEMPERATURES, AND TIMES

Material	Temperature limit	Time limit
304H	815° C	300,000 hours
316H	815° C	300,000 hours
800H	760° C	300,000 hours
2¼Cr-1Mo (Gr. 22)	650° C	300,000 hours*
9Cr-1Mo-V (Gr. 91)	650° C	500,000 hours**
Alloy 617	950° C	100,000 hours

* Limited service life allowed above 593° C
** Life extension not fully complete, ASME targeting 2023 edition

MISSING MATERIALS (?)

- Low Cr Ni-base alloy for molten salt reactors (i.e. Hastelloy N)
- Very high temperature inert materials (refractory alloys)
- FeCrAl alloys – improved corrosion/temperature resistance without Ni

Optimal materials for other concepts/vendors may be missing – but it's difficult to qualify *every* potential material

RECENT NRC REVIEW OF THE 2017 EDITION (REGULATORY GUIDE DG-1380)

- Lots of call outs on construction and certification
- Base metal temperature restrictions
  - SS 304: 700° C
  - SS 316: 700° C
  - 2-1/4Cr-1Mo: 510° C
  - 9Cr-1Mo-V: None, but see welds
- Grade 91 material properties
  - Use 2019 edition instead of 2017 for most of the allowable stresses
- Design by inelastic analysis: you must validate the models in the design report
- Very specific comment on buckling load factors

KEY GAPS: BASE METALS

1. Time-temperature gaps for Class A materials
2. Some caveats and exceptions carved out by our regulator (USNRC)
3. Reduced accuracy of the simplified (design by elastic analysis) rules above critical temperatures
4. Lack of information (constitutive models) for design by inelastic analysis
5. Some microreactor materials may not be Code qualified

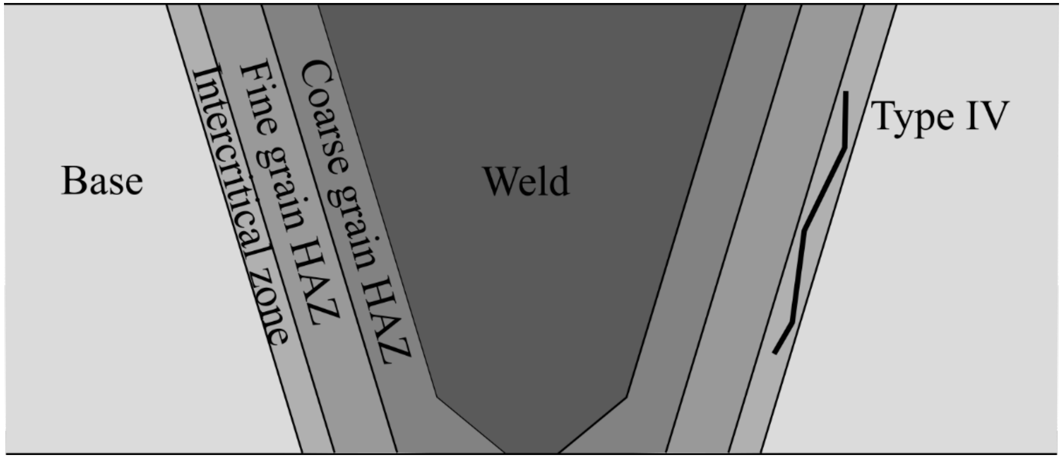
MITIGATION

1. Effort at ASME to extend qualified properties for current materials to 500,000 hours (60 years)
2. Be aware of key issues identified by NRC
3. Recommendations on temperature limits available from ANL technical reports and papers
4. ASME is in the process of addressing: Grade 91 models included in 2023 edition, likely will include A617 and 316H as well
5. Vendor data may be required

WELDMENTS

WELD BEHAVIOR AT HIGH TEMPERATURES

- Overmatched welds for low-temperature service are often undermatched when at high temperatures
- At least two causes:
  - "Metallurgical notch effect" – weld and HAZ material deforms differently than base metal
  - The weld heat reduces the strength of the HAZ

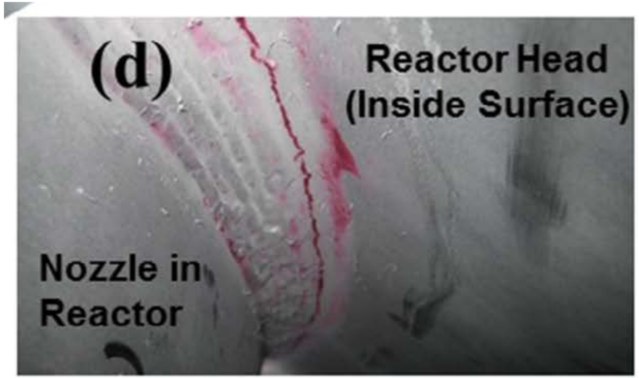


Typical schematic of a weldment

Mitigation:

- Good weld practice
- Select good weld type/weld material combinations
- Post-weld heat treatment

MATERIAL-SPECIFIC HIGH TEMPERATURE FAILURE MECHANISMS



Yoon, Yu, and Nguyen. *Engineering Failure Analysis*, 2015.

- We are aware of two specific mechanisms for the Class A materials:
  - Type IV cracking for the ferritics and particularly Grade 91
    - Reduction of ductility in the intercritical zone, leading to cracking
    - Mechanism disputed (over coarsening of strengthening precipitates?)
  - Stress relaxation cracking for the austenitics
    - Cracking caused by deformation during the relaxation of initial weld residual stress
    - Associated with thick sections in austenitic stainless (304 and 316)
- These mechanisms can be addressed through the Division 5 stress rupture factors, but the Code Committees continue to evaluate new data as it becomes available

KEY WELDMENT GAPS IDENTIFIED IN THE REPORT

1. Grade 91 stress rupture factors
2. Time-temperature gaps in Class A welded construction
3. Expanding the allowable Class A weld types
4. Limited welds/materials for Class B in the non-negligible creep regime
5. Additional consideration of stress relaxation cracking for the austenitics

MITIGATION

1. ASME is in the process of addressing the Grade 91 stress rupture factors
2. Test data – perhaps from vendors – will be required to address time/temperature gaps
3. Similarly, vendors may need to test weldments types not included in the Code if they plan to use them in their designs
4. ASME will likely address the Class B rules in the near future – but vendors should be aware these rules are currently limited
5. “Best-practice” mitigations, taking examples from UK AGR experience and/or non-nuclear commercial practice

ENVIRONMENTAL EFFECTS

DIFFERENT ADVANCED SMRs CONCEPTS WILL OPERATE IN DIFFERENT CONDITIONS

Category	Neutron Spectrum	Coolant	Core outlet Temperature, T (°C)
Liquid metal cooled SMRs	Fast	Sodium, Lead, Lead-Bismuth	400<T<565
Molten salt SMRs	Thermal, Fast	Molten salt	565<T<720
High temperature gas cooled SMRs	Thermal, Fast	Helium	T>720

IRRADIATION AND COOLANT INTERACTIONS ARE KEY ENVIRONMENTAL EFFECTS

Irradiation

- Hardening and loss of ductility
- Irradiation creep
- Void swelling
- Helium embrittlement
- Effects on creep-rupture, fatigue, and creep-fatigue failure

Coolants

- Liquid metal (Sodium, Lead, Lead-bismuth)
- Molten salts
- High temperature helium

KEY GAP

System environmental effects are explicitly outside the scope of Section III, Division 5 of the ASME Code

There are too many potential combinations of reactor operating temperature, operating dose, and coolant type to provide complete design rules at this time

However, the designer must account for these effects to satisfy the regulator

GAPS IN ASME SECTION III, DIVISION 5 RULES

- Only explicit mention of irradiation effects is in HBB-3124
  - Cautions the designer about the increase of brittle transition temperature and deterioration of fracture resistance due to irradiation
  - Suggests not to place any structural discontinuities in high radiation areas
- Only explicit consideration of corrosion is in HBB-3121
  - Requires a corrosion allowance in design thickness to account for the expected gross loss of material
- In HBB-Y-4200 (guidance on materials)
  - Explicitly places the environmental degradation issues (except the effect of thermal aging on yield and ultimate tensile strength) outside the ASME code
  - Requires the Owner/Operator to account for these issues in some way and justify their decisions to the regulator
  - Refers to Nonmandatory Appendix W in Section III for general design and construction guidance to mitigate the environmental effects

POTENTIAL MITIGATION ACTIONS TO FILL GAPS IN SECTION III, DIVISION 5 RULES

- Altering design data to account for environmental effects relevant to advanced SMRs while keeping the overall design method the same (similar to RCC-MRx)
  - A method could be developed for specifying what experimental data is required for different combination of radiation dose and coolant exposure
  - Some tests can be avoided by introducing adequately conservative design factors (e.g. RCC-MRx code applies a factor of 10 to the creep-damage for 316 SS)
- Use of cladded components
  - Class A base material will carry the structural load while a thin clad will serve to protect the base
  - Near term solution, long term testing can be avoided by selecting certain categories of clad material
  - A Code Case is currently under development for 316H SS components cladded with Nickel or Tungsten
- Development of in-situ materials surveillance program
  - Insert surveillance specimens as “canaries” at the critical locations inside the reactor
  - Failure of specimens before a predetermined length of time will indicate a problem in the design
  - A method can be developed to predict the remaining life via some out-of-reactor tests
  - Most likely to be passive (e.g. bimetallic specimen) to avoid complication in the design of components

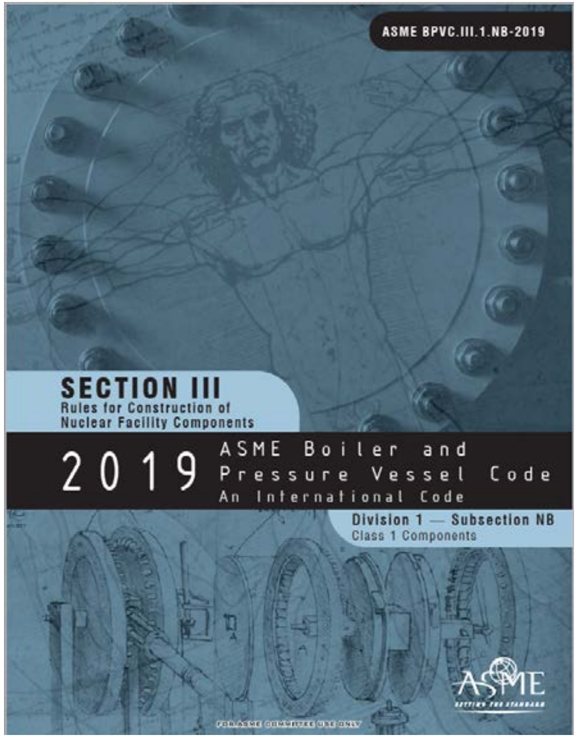
ACKNOWLEDGEMENTS

The original work was completed under a contract with the Canadian Nuclear Safety Commission

Report co-authors: Sam Sham (now at INL) and Bipul Barua

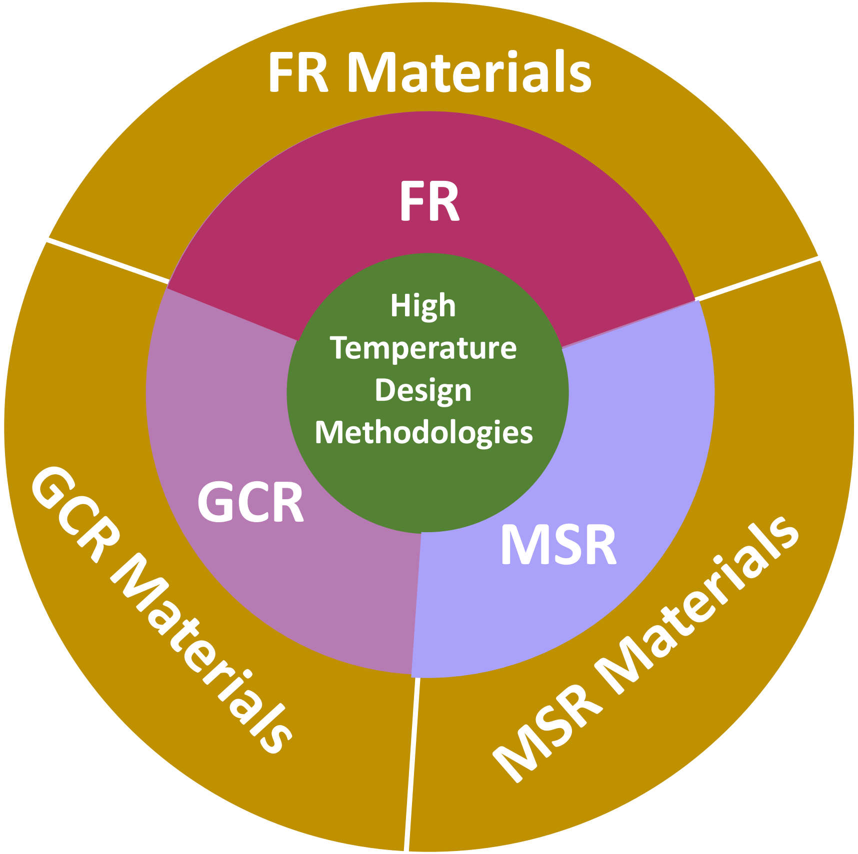
QUESTIONS?

SECTION III, DIVISION 1 WELD CONSTRUCTION RULES



- The base of the Section III, Division 5 weld construction rules are the Section III, Division 1 (LWR) rules
- These ensure that the welds meet nuclear quality standards in construction, initial inspection, and ongoing, in-service inspections
  - Welds are overmatched for time independent strength for Class A (Class I) construction
- The Section III, Division 5 construction and inspection rules supplement the LWR rules with criteria specific to high temperature construction – *including reductions in the allowable stress for weldments*

Design Rules and Material Code Cases



- High temperature design methodologies are the technical basis of the ASME Code rules
- Based on structural failure modes under elevated temperature cyclic service
- Establish what types of material data are required to support Code rules
- Rules cross-cut FRs, GCRs and MSRs
- 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