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MRP: Design Rules for Refractory Metals

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Changing the World's Energy Future

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MRP: Design Rules for Refractory Metals

Joint ART Materials/AMMT Program Review

DOE Headquarters, Germantown, MD

June 5-8, 2023

Sam Sham

Idaho National Laboratory

Microreactor Program Work Package

- **AT-23IN080409**
  - Structural Materials – INL
    - Task 2: Gap analysis on refractory metals for ASME Section III, Division 5

Technology Maturation Program to De-Risk Microreactor Designs

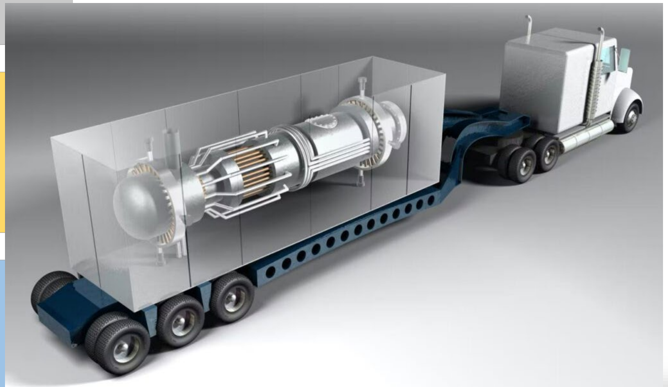
Due to the compact reactor configurations, microreactor designs tend to have higher temperatures than larger reactors

In some designs, the temperature capability of the structural materials, and not the fuel, sets the upper temperature limit of the reactor

In some other designs, structural materials with low neutron absorption cross-sections are needed

While others require structural materials with higher corrosion resistance

Refractory metals meet many of these requirements



Refractory Metals

PROS

- High melting point
- High creep strength
- Low thermal expansion coefficient
- High thermal conductivity
- Prior space reactor applications
- Good corrosion resistance
- Low neutron absorption cross-sections

CONS

- Low oxidation resistance
- Low fracture toughness
- Difficult to fabricate
- Difficult to weld
- Etc..

Codes and Standards

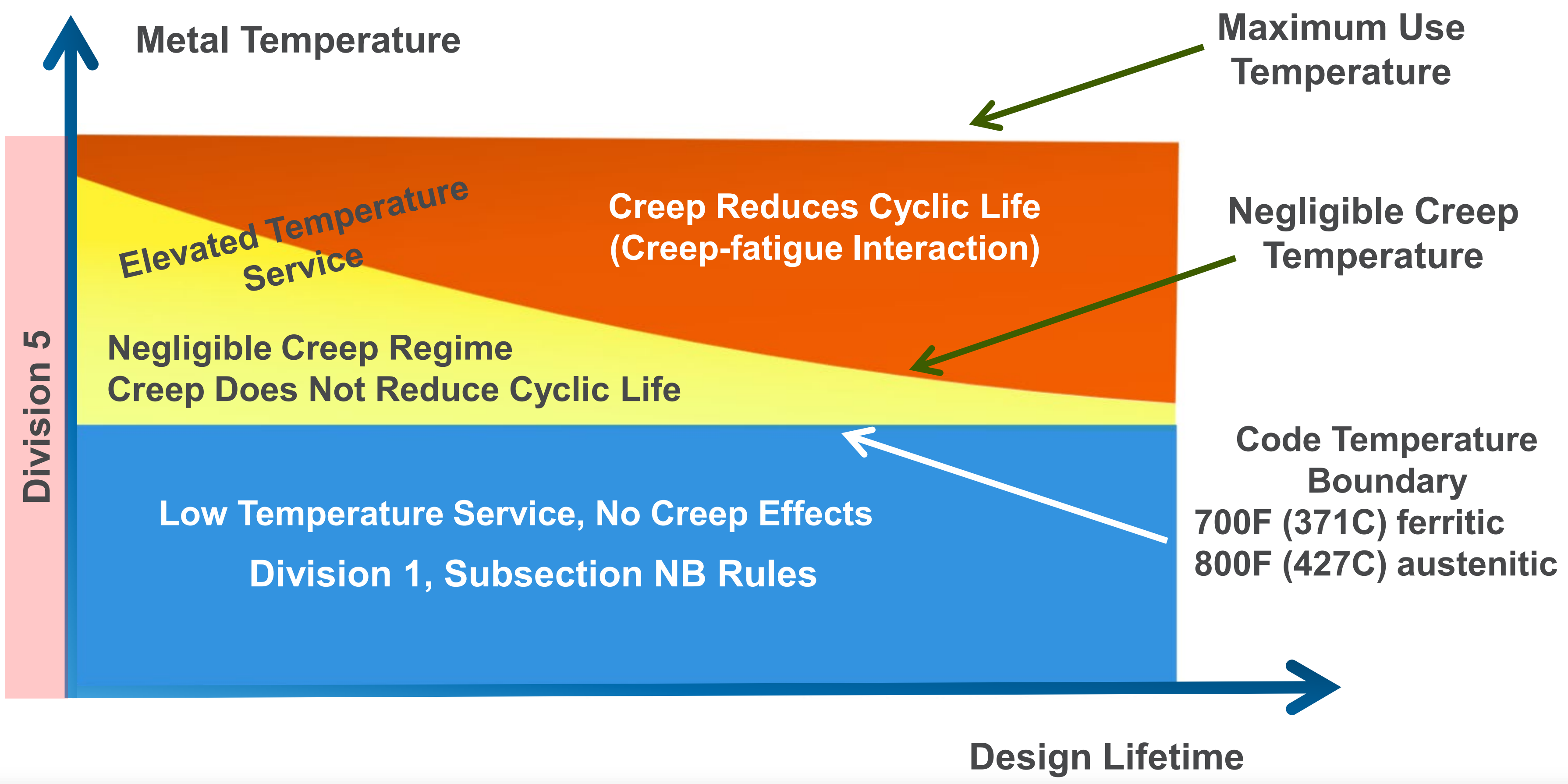
Task Scope

- Determine gaps in design rules for refractory metals for Section III, Division 5 Class A construction
- Develop plan to establish a Division 5 refractory metal code case as a prototype to enable the use of refractory metals by advanced reactor developers to meet their design requirements

Scope of ASME Section III, Division 5 for Metallic Components

- **Division 5 specifies the mechanical properties and allowable stresses to be used for design of metallic components in high-temperature reactors**
- **HAA-1130 and HBB-1110(g) state that Division 5 rules do not provide methods to evaluate deterioration that may occur in service as a result of corrosion, mass transfer phenomena, radiation effects, or other material instabilities**
  - These effects shall be taken into account with a view to realizing the design or the specified life of the components and supports
  - The changes in properties of materials subjected to neutron radiation may be checked periodically by means of material surveillance programs

Temperature Boundaries for Section III Division 5 Class A Components



Structural Failure Modes for Class A Components

- **Class A elevated temperature 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

Structural Failure Modes for Section III Division 1 Class 1 Components (Low Temperature)

Structural Failure Modes	Remarks
• Excessive plastic deformation • Plastic instability – incremental collapse • High strain – low cycle fatigue	• Addressed by design-by-analysis rules
• Excessive elastic deformation including elastic instability	• Functional requirements or potential for buckling
• Brittle fracture	• Material toughness • Nonmandatory Appendix G, brittle fracture evaluation

Design Rules Gaps for Refractory Metals

Design Methods	Material Properties

• Rules to prevent brittle fracture (low temperatures)
• Rules to prevent ductile tearing stability (elevated temperatures)
	• Creep-fatigue behavior
	• Data gaps
	  • Fracture toughness
	  • Fatigue
	  • Creep-fatigue
	  • Creep
	  • Thermal aging
	  • Welds

Division 5 on Brittle Fracture

- Division 5, Paragraph HBB-3241, Nonductile Fracture
  - (a) A portion of the Design Report (NCA-3211.40) shall justify the ability of the component to withstand the expected service conditions without undergoing nonductile fracture
  - For loading times, stresses, and temperatures where creep effects are not significant (HBB-3211), an acceptable procedure for nonductile failure prevention is given in Section III Appendices, Nonmandatory Appendix G for ferritic materials
  - When Section III Appendices, Nonmandatory Appendix G is not applicable, the fracture analysis shall consider the anticipated stress level and flaw size, and compare these conditions with the fracture toughness of the material in the flaw region and at the appropriate temperature

Section III Nonmandatory Appendix G for Brittle Fracture

- Procedure recommended for shell and head regions of RPV for Service Levels A and B
- A lower bound fracture toughness curve indexed to RT_{NDT} is provided for ferritic steels (SA-533B, SA-508 Gr. 1 to 3)
- Acceptance - No brittle fracture of a postulated design flaw at ID and OD under Levels A and B loadings
  - Aspect ratio of surface flaw is 1 to 6 and flaw depth is

	Thickness, *T*, less than 4”	*T* from 4 to 12”	*T* greater than 12”
Flaw depth	1”	*T*/4	3”

Section VIII Division 2, Paragraph 3.11.2.8 – Establish MDMT by Fracture Mechanics

- MDMT – Minimum Design Metal Temperature
- Fracture toughness determined per ASTM E399 (not recommended) or E1820 (J-integral based)
- Acceptance - No brittle fracture at the MDMT for a postulated surface flaw at ID and OD
  - Aspect ratio of surface flaw is 1 to 6
  - Flaw depth = min (T/4, 1”)

API 579-1/ASME FFS-1, Part 9, Level 2 or Level 3 - Fracture Mechanics

- Minimum Allowable Temperature (MAT) in API 579-1/ASME FFS-1 is the same as MDMT of Section VIII Division 2
- Use Annex 9J to determine MAT (or MDMT) for a component for the construction material, stress state and postulated flaw size, based on the brittle fracture resistance using the Failure Assessment Diagram (FAD) approach
  - Primary stress, and secondary + residual stresses are used to determine the stress intensity factors

API 579-1/ASME FFS-1, Part 9, Level 2 or Level 3 - Fracture Mechanics

- Minimum Allowable Temperat… 9-1/ASME FFS-1 is the same as M… n 2
- Use Annex … a co… , stress state and po… the brittle fracture res… ailure Assessment Diagram (FAD) app…
  - Primary stress, and secondary + residual stresses are used to determine the stress intensity factors

- Section VIII, Division 2 plus API 579-1/ASME FFS-1 could serve as a better basis to develop a more flexible brittle fracture procedure for refractory metals

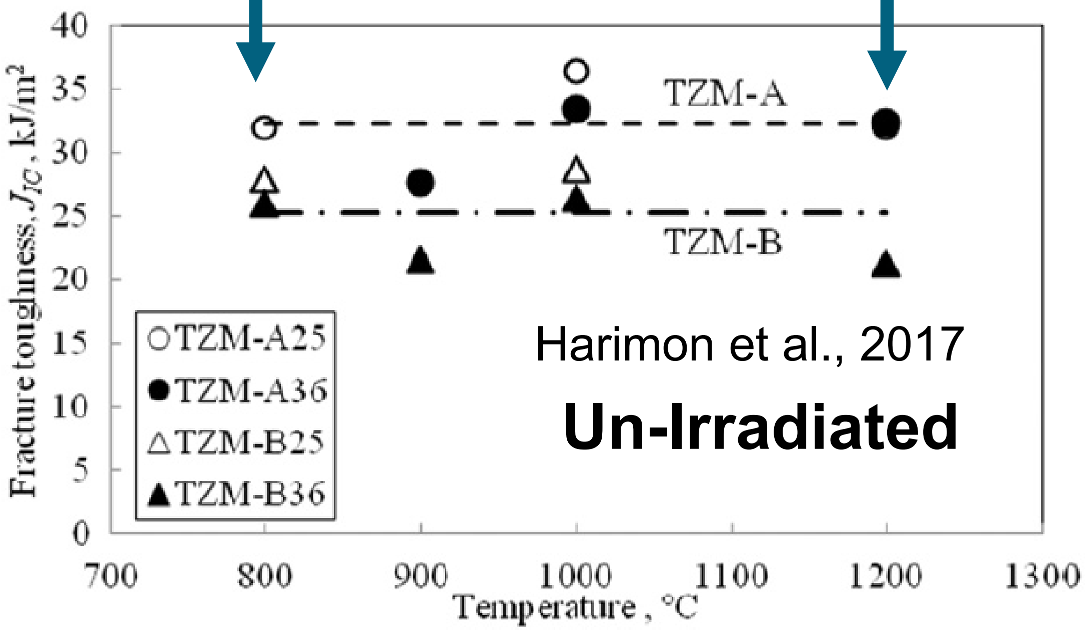
FY24-26, Plan for Division 5 Refractory Metal Code Case

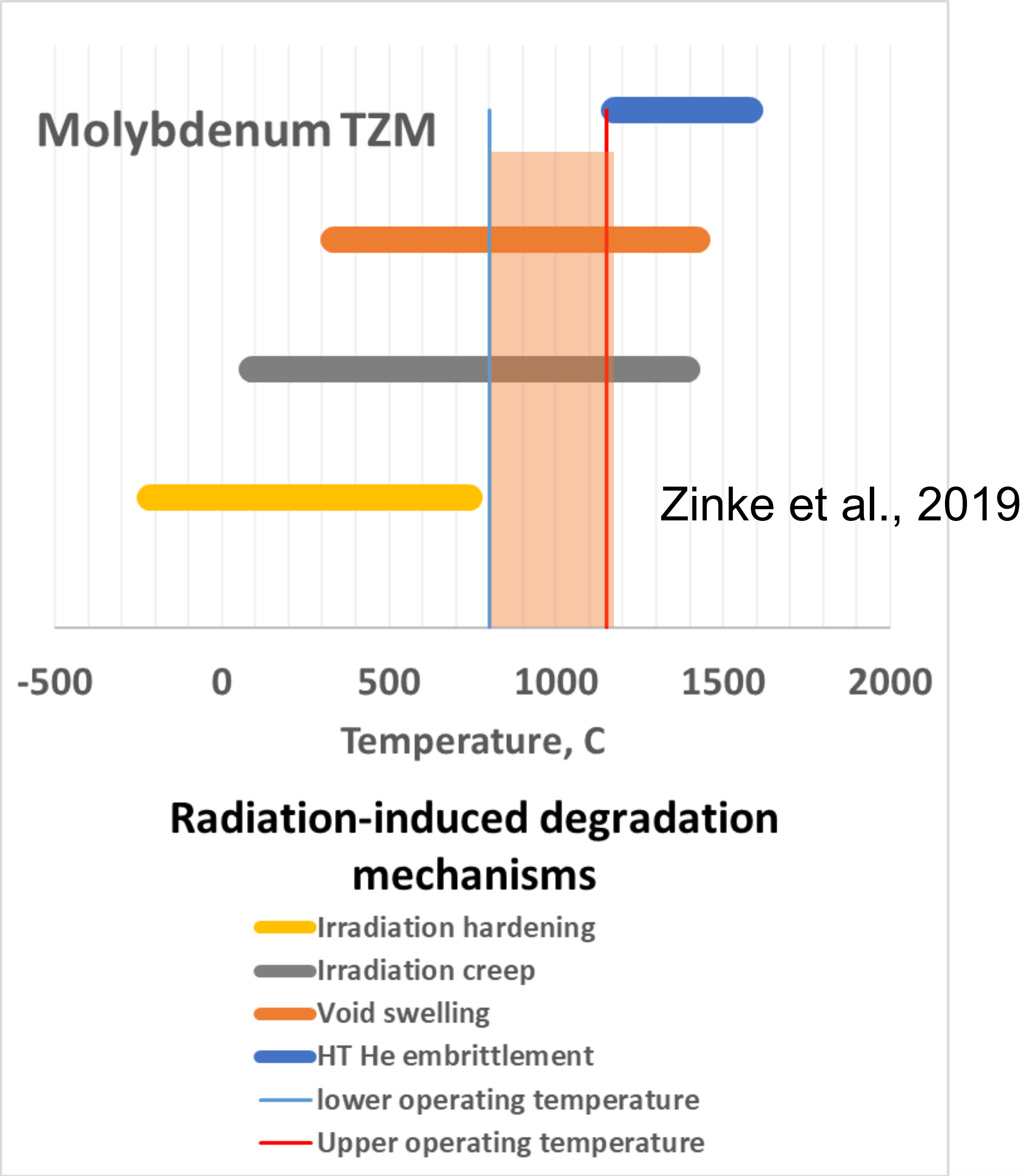
- **Material - Molybdenum TZM or Nb-1Zr**
- **Design analysis methods**
  - Elevated temperatures
    - EPP primary load, strain limits, creep-fatigue
  - Low temperatures
    - Extend EPP primary load, strain limits, fatigue to low temperature
  - Brittle fracture
  - Ductile tearing
- **Data requirements (testing in inert environment)**
  - Fracture toughness
  - Tensile, creep, fatigue, creep-fatigue

Molybdenum TZM

$K_{JC} \sim 12\ MPa\sqrt{m}, at\ 20C$

$K_{JC} = 90\ MPa\sqrt{m}$ $K_{JC} = 75\ MPa\sqrt{m}$





Thank you

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