HTGR Technology Course for the Nuclear Regulatory Commission

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Module 11

High Temperature Materials Performance

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Outline

- Design and material issues for components
- High-temperature design methodology
- High-temperature design codes and testing standards
- High-temperature material performance modeling
- Nonmetallic components
- Summary

Design and Material Issues for Components

- **Material application**
  - Reactor pressure boundary, load bearing, reactor internal structural components
- **Operating environment**
  - Reactor coolant (Helium with impurities)
  - High temperatures, pressure, and fluence
- **Material technology choice**
  - Metallics, Ceramics and Composites
  - Commercially availability
- **Material qualification and codification**
  - ASME Boiler & Pressure Vessel Code
  - International Codes & Standards – RCC-M, KTA, others
- **Factors affecting material selection**
  - Component performance requirements
  - Material performance and qualification
  - Nuclear regulatory review and acceptance

Design and Material Issues for Components

- **Regulatory bases for existing materials are primarily focused on LWR technology and safety case**
  - 10 CFR 50.55a requires reactor coolant pressure boundary components be designed, fabricated, erected, and tested in accordance with the requirements of Class I components of Section III of ASME B&PV Code or equivalent standard

- **HTGR material qualification and acceptance requires reviews against HTGR technology and safety case**

- **Goal is to select acceptable materials that are**
  - Commercially available
  - Has an established near term codification path
  - If not; develop plans for codification or qualification by testing and analysis

Design and Material Issues for Components

- **HTGR technology issues that play a role in selection and qualification of materials**
  - Passive heat removal,
  - Slow accident progression,
  - No core melt conditions, and
  - Fission product retention capability of coated particle fuel

- **Material selection process is driven by**
  - Material properties
  - Component design and performance requirements
  - Component assembly - manufacturability
  - Effects of operating environment on material properties and component performance

- **Codification and regulatory acceptance is driven by**
  - Identification of failure mechanisms
  - Performance limit
  - Design margin
  - Safety margin

Design and Material Issues for Components

- **Basis for qualification plan**
  - Establish component design requirements
  - Match requirements to existing candidate materials
    - Existing design and fabrication experience
    - Fabrication assessment and review
    - Technical maturity
    - Performance assessment
    - Testing and inspection
    - Environmental compatibility
    - Availability, cost and schedule
- **Select qualification path (material meets the design requirements)**
  - Already in ASME Code, and accepted by the NRC
  - Already in ASME Code, but not reviewed by the NRC
  - Not in ASME Code

Design and Material Issues for Components

- **Material properties that influence material choice and Code requirements are**
  - Mechanical properties - strength, creep, fatigue and other performance properties (at higher temperatures)
  - Thermal properties (capacity, emissivity, conductance)

- **Environmental degradation mechanisms that impact material properties and component performance**
  - Helium gas chemistry (coolant impurities) – oxidation, carburization, and decarburization
  - Thermal and radiation impact on material properties
  - Material aging effects

- **NRC material PIRT identified important phenomenon as**
  - High temperature materials stability and component's ability to withstand service conditions
  - Long term thermal ageing and environmental degradation,
  - Fabrication of heavy-section components and properties of reactor pressure vessel
  - Irradiation effects on material properties
  - Consistency of quality and performance over the service life

Classes of High Temperature Materials

• Ferritic steels	T < 450 °C
• Ferritic/martensitic steels	T < 650 °C
• Austenitic stainless steels	T < 800 °C
• Nickel-base superalloys	T < 1050 °C
• Oxide Dispersion Strengthed alloys/nanoprecipitates	T < 1100 °C
• Inter-metallics	T < 1250 °C
• Refractory alloys	T < 1400 °C
• Ceramics / Composites	T < 1600 °C

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High Temperature Design Methodology

- **Availability of materials**
  - Commercially availability
  - Current application in nuclear or non-nuclear industries
- **Suitability of material**
  - Material properties at applicable temperatures
  - Helium gas service conditions
- **Have these materials been characterized to the extent necessary for the specific HTGR component application**
- **Is material codified and/or standardized**
  - Codes (ASME, RCC-M), Standards (ASTM, KTA)
- **Is material suitable/qualified for nuclear application**
  - ASME Section III
  - NRC review and acceptance RG 1.84
  - Qualification by analysis and/or testing
- **The manufacturability issues**
  - Forging size
  - Thick section welding issues and performance
  - Inspection requirements

High Temperature Design Methodology

- **Material selection process must consider**
  - Required properties at normal and accident reactor conditions
  - Operating environment – e.g., helium
  - Size, form, availability, cost and manufacturability
- **For operations at higher temperatures**
  - Material strength becomes an important factor
  - Creep becomes an issue
  - Operating environment; Helium with impurities becomes a factor
  - Creep-fatigue, environment, fluence interaction is more prominent
  - Engineered materials (Superalloys, ODS) might be considered
  - Change from metals to ceramics or composites might be considered

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HTGR Components

- **Primary system vessels**
- **Hot duct**
- **Core internal materials**
- **Shutdown cooling system**
- **Helium purification system piping and valves**
- **Main circulator**
- **Heat exchangers**
  - Steam Generator (He to steam/water)
  - Intermediate Heat Exchanger (gas to gas) – advanced HTGRs
  - Cavity cooling system exchanger (air to water or air to air)
  - Shutdown cooling system heat exchanger (He to water)
  - Core conditioning system heat exchanger (He to water)
- **Helium pressure boundary piping**
- **Helium high temperature valves**
- **Reactor vessel safety relief valve**

High Temperature Design Methodology

- **For component design the following factors must be identified and considered:**
  - Key system or component functions
    - Normal system functions
    - Anticipated safety functions
  - Anticipated operational environment (normal and accident)
    - Temperatures
    - Loadings
    - Fluences
    - Chemistry
  - Important issues with respect to high temperature material performance, examples:
    - Material emissivity for RV
    - High temperature fatigue for control rods

Material Selection Considerations

Example: Reactor vessel cross vessel, and steam generator vessel

- **Key Functions**
  - Contain and support the components of the reactor core, reactor internal supports and other internal structures and subcomponents
  - Maintain the relative position of the core and the control rods – RV only
  - Provide a decay heat and residual heat removal path, primarily by radial conduction, during conduction cooldown – RV only
  - Maintain primary pressure boundary integrity and containment of primary fluids and radionuclides consistent with the assumptions imposed in the safety analyses

- **Anticipated Operational Environment (near term HTGRs)**
  - Temperature
    - Normal Ops - <325 °C
    - Accident – TBD
  - Loadings
    - Pressure – 6 to 9 MPa
  - Fluence
    - <LWR - but harder neutron spectrum and different irradiation temp
  - Helium chemistry
    - Gas impurities (N_2, H_2, CO_2, CO, O_2, CH_4, H_2O)

- **Important Issues**
  - The large size
  - The high vessel temperature during accidents
  - The He primary coolant chemistry
  - No need for internal cladding
  - The heat transport role of the reactor vessel

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High Temperature Design Codes and Testing Standards

- **Components in potential high temperature conditions**
  - Pressure vessels
  - Heat exchangers
  - Rotating equipment - circulators
  - Specialty components (core barrel, insulation, control rods, supports, etc.)
- **ASME Boiler and Pressure Vessel Code**
  - High temperature metallics – Subsection NH
  - Code cases N-499, N-253, N-201, N-205
  - Nonmetallics
    - Ceramics
    - Composites
- **ASTM Standards**
  - Metallics
  - Ceramics and Composites

Material Qualification

- **Two qualification paths exist - both will likely be needed**
  - Codification by the ASME B&PV Code or equivalent
  - Qualification by testing and analysis for specific HTGR application or design condition
- **Candidate materials are categorized and prioritized as follows:**
  - Material meets design requirements, is included in a consensus standard, and NRC has reviewed and approved it for similar applications
  - Material meets design requirements, is included in a consensus standard, but the NRC has not reviewed or approved it
  - Material meets design requirements, is not in a consensus standard, and it requires the NRC review and approval
  - Material meets design requirements, is included in a consensus standard, and no NRC review is required

Codes and Standards
Status and Schedule of Ongoing C&S Work

- **Current ASME Code rules do not completely cover HTGR conditions**
- **Recommendations has been made to the ASME in a multi phase “roadmap” to develop design rules for HTGRs**
  - Phase I, Part A – Modify existing elevated temperature design rules for immediate needs
  - Phase I, Part B – Develop new rules for plant to be designed in the next ten years that reflect the current design conditions being considered for the HTGR demonstration plant
  - Phase II – Develop rules for advanced HTGRs - plants that will be designed ten years or more from now with significantly higher temperatures
- **ASME/DOE Gen IV Project**
  - A multi phase Code development and upgrade to address near-term and long term needs of HTGR/VHTGR material codification
  - Currently drafting a new Division 5 that would incorporate the rules from Code Cases N-499, N-467, N-257, N-254, N-253, and N-201

Codes and Standards
Status and Schedule of Ongoing C&S Work

- **Phase- I Part A - priority code work for short term needs (metallics)**
  - Existing Code and organizational structure should be used to update Subsection NH and Code Case N-499, N-201, and possibly N-253
    - Extend temperature limits for key materials
    - Extend qualified lifetimes from 300,000 hours to ~600,000 hours

Codes and Standards
Near-Term Code Update Needs

Alloy	Applicable ASME Code Section	Notes
Alloy 800H	Section III, Subsection NG Code Case N-201-5	Allow use of Alloy 800H at higher temperatures based on German Standard KTA 3221, which allows usage to 1000°C.
Hastelloy X	Section III, Subsection NG Code Case N-201-5	Include Hastelloy in Code Case N-201-5 based on studies which support use up to 871°C during normal operation and up to 938°C for under 3000 hours at 1000 psi.
Modified 9Cr-1Mo	Section III, Subsection NG Code Case N-201-5	Include Modified 9Cr-1Mo in Code Case N-201-05.
Other High Temperature Alloys	Section III, Subsection NH, Code Case N-201-5	Extend qualified design life from 300,000 to 600,000 hours to cover 60 years design life.

Codes and Standards
Near-Term Code Update Needs

- **Review and update Code rules for SA-508/SA-533 at or near ASME NB Code limits and those provided in Code Case N-499-2**
  - Use of LWR steel in ASME Code Case for HTGR service conditions
  - Evaluate expected performance
  - Assess R&D needed to use the full potential of LWR steel in HTGR application
- **Investigate update of ASME Code NH to include Alloy X**

Non-Code Components

- **Qualify behavior and performance characteristics of materials based on analysis specific to HTGR application**
- **Attributes of the qualification program include:**
  - Performance criteria based on HTGR requirements
  - Compilation and analysis of existing industry data
  - Additional test to supplement existing data
  - Analytical or empirical models to describe material behavior

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High Temperature Material Performance Modeling

- The ability to mathematically predict material performance at high temperature HTGR conditions is limited
- To establish design rules and codification at HTGR conditions, material testing and characterization is performed
- Characterization identifies material performance limits, degradation and failure mechanisms at elevated temperature

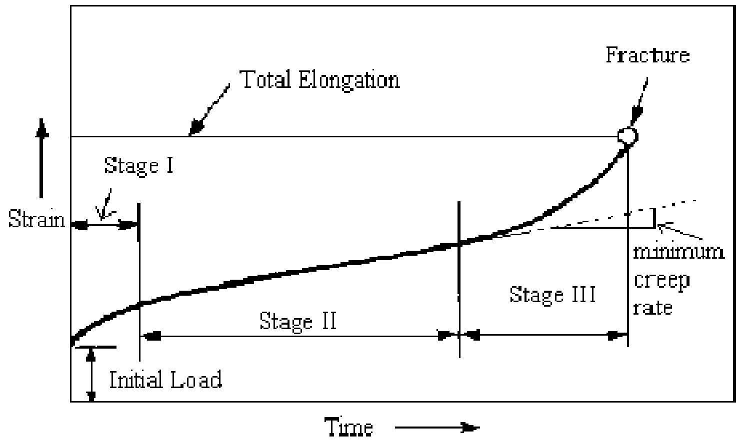
High Temperature Material Performance Modeling

- **Component design**
  - Identify operating and accident environmental conditions
    - Radiation damage – fluence
    - Design Conditions – temperature and pressure
    - Helium Impurities – Oxygen, Nitrogen, Methane, dust, etc.
  - Establish performance requirements
    - Maintain pressure boundary integrity
    - Material physical properties – material strength, heat capacity, thermal conductivity, and surface properties (emissivity)
  - Evaluate environmentally assisted material degradation
    - Creep, creep-fatigue
    - Effect of oxidation, carburization or decarburization

- **Required material performance data at high temperature**
  - Mechanical properties
  - Aging in the application environment
  - Material degradation mechanism

Creep

- **High temperature creep Model**
- **High temperature is material dependant**
- **Creep test**
  - Constant load at a constant temperature
  - Strain is then measured over a period of time
  - Strain or creep rate - slope of the curve
- **Primary creep, Stage I**
- **Secondary creep, Stage II**
- **Tertiary creep, Stage III**



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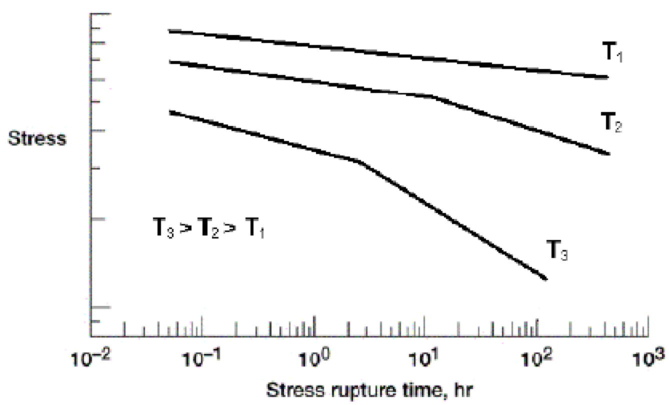
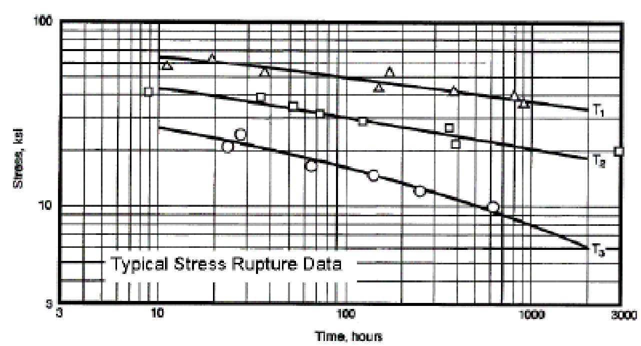
Stress-Rupture

- **Stress rupture is similar to creep but at higher stresses**
- **Stress rupture testing is done until failure**
- **Creep testing is done to determine minimum creep rate in Stage II**
- **Stress rupture tests are used to determine the time to cause failure**
  - Data is plotted log-log as in the chart below
  - Extrapolate time to failure for longer times
  - Changes in the slope of the stress rupture line are due to structural changes in the material
- **It is significant to be aware of these changes in material behavior, because they could result in large errors when extrapolating the data**





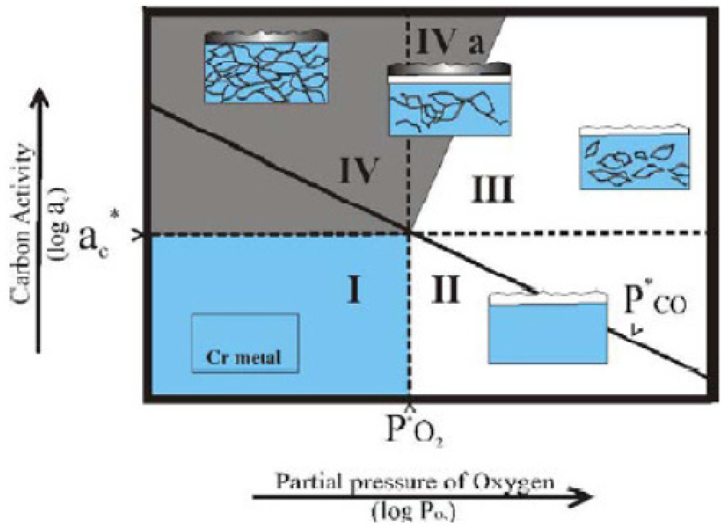
High Temperature Materials Environmental Effects

- **Degradation caused by time and impurities**
- **Oxidation**
- **Carburization – Decarburization**
- **Radiation damage**

Typical reactor helium impurities (µbar)

	H_2O	H_2	CO	CO_2	CH_4	O_2	N_2
Dragon	0.1	0.1	0.05	0.02	0.1	0.1	0.05
Peach Bottom	0.5	10	0.5	<0.05	1.0	-	0.5
Fort St. Vrain	1	7	3	1	0.1	-	-
AVR	0.15	9	45	0.25	1		22
THTR	<0.01	0.8	0.4	0.2	0.1		0.1

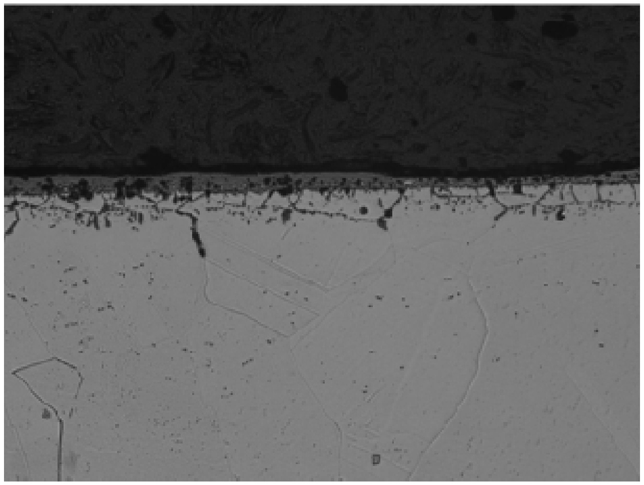
Modified Ellingham Diagram



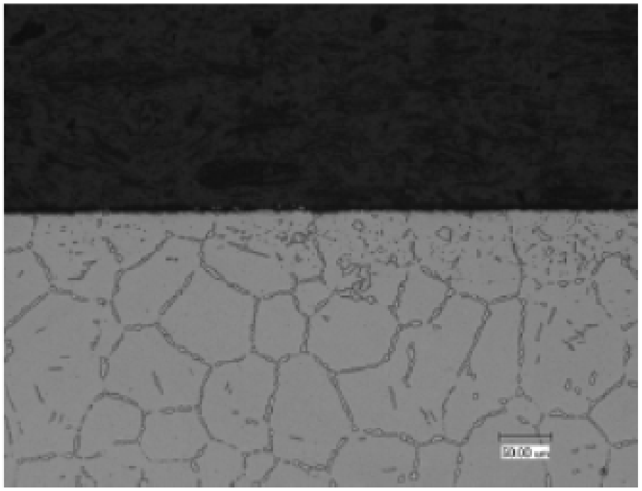
A modified Ellingham diagram depicts the potential reactions between nickel based alloys and the impurities in reactor Helium.

- Regions I, and IV represent decarburization and carburization
- Regions II, and IVa represent carburization an decarburization beneath an oxide layer
- Region III represents the most stable region for the alloy, with a protective oxide scale and carbide stability

Environmental Effects
IN 617

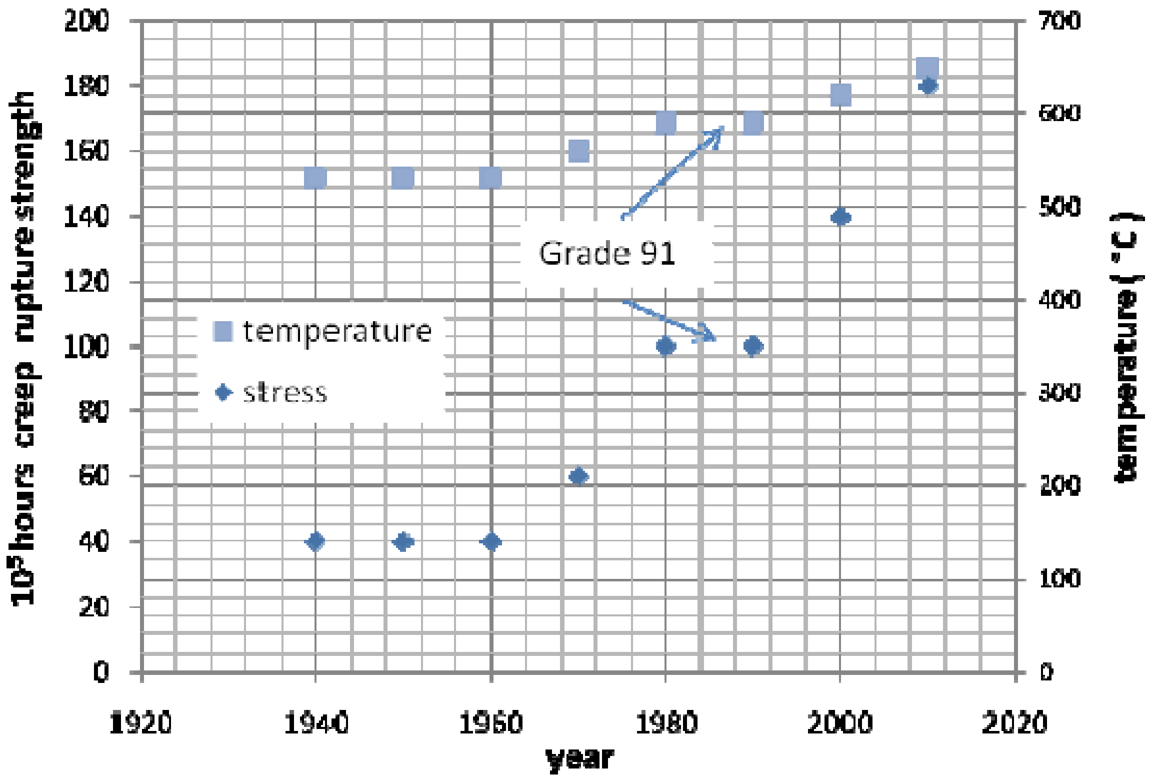


Oxidizing conditions



Carburizing conditions

High Temperature Materials Development History



NGNP Candidate High Temperature Materials

- **Potential near term HTGR needs**
  - SA-508 Grade 3 Class 1 / SA-533 Type B Class 1
  - Type 316H Stainless Steel
  - Alloy 800H
  - Alloy X
  - Modified 9Cr-1Mo Grade 91
  - 2.25Cr-1Mo Grade 22
- **Long term needs (Advanced HTGRs or VHTR)**
  - Alloy 617
  - Alloy XR
  - Haynes 230
  - Mod 9Cr-1Mo Grade 91 (for vessel material)
- **Other metallics and ceramics will likely be required as design progresses**

SA-508 Grade 3 Class 1/ SA-533 Type B Class 1

- **Potential applications**
  - RV, SG vessel and cross vessel
- **Important considerations**
  - Strength, creep fatigue, emissivity, thermal diffusivity, oxidation and irradiation
- **Related experience**
  - Pressure boundary components in LWRs for over 40 years
    - Historically used with success at operating temperature of 325°C
- **Current qualification status**
  - NRC approved and ASME Code Section III, Subsection NB (< 371°C limit for normal operation)
    - Current HTGR objective calls for vessel operating temperature within LWR operating envelope due to industry concerns with operating close to the 371°C limit for long durations
  - ASME Code Case N-499-2 approved for limited high temperature excursions up to 427°C for 3000 hours and 538°C for 1000 hours
  - Irradiation effects addressed by 10 CFR 50 and detailed in Reg. Guide 1.99
  - Further evaluation: Emissivity and oxidation

Type 316H Stainless Steel

- **Potential applications**
  - Metallic internals with temperature above 650°C during normal operation or accident
    - Core barrel, control rod guide tubes, steam generator tubing
- **Important considerations**
  - High temperature strength, creep strength, irradiation resistance, relative low cost
- **Related experience**
  - The austenitic stainless steels of Type 304 and Type 316 are commonly used for light water reactor internals, such as fuel support structures, core barrel and flow baffle plates. These are however all low temperature applications, in aqueous conditions and materials used all comply to the low-carbon versions i.e. Type 304L or Type 316L.
- **Current qualification status**
  - Maximum temperature limit
    - 427 °C Section III (time independent stress limit)
    - 816 °C Section III Subsection NH (Elevated temperature Class 1)
    - 816 °C Section VIII (Non-nuclear pressure vessels)
    - 816 °C Code Case N-201-5 (Core support structure)
  - Further evaluation: High temperature strength, creep strength of large grain products (relevant to large forgings), irradiation effects

Alloy 800H

Component	Temp.	Temp. Limit	Key Considerations
Core barrel	<400°C	427/760°C	Strength, emissivity, thermal diffusivity, irradiation
Control rods	~440°C	427/760°C	Strength, creep, irradiation
SG tubing	~600°C	427/750°C	Creep, thermal conductivity, corrosion
Hot duct liner	~800°C	N/A	Creep

- **Related experience**
  - SG tubing and heat exchanger components at FSV, AVR and THTR
    - Cumulative operation of 34 years, with AVR operating 20 years
- **Current qualification status**
  - Maximum temperature limit
    - 427°C Section III (time independent stress limit)
    - 760°C Section III Subsection NH (Elevated temperature Class 1)
    - 899°C Section VIII (Non-nuclear pressure vessels)
  - Some internals exceed limit during normal operation or accident
    - Draft German standard KTA 3221 allows use up to 1000°C
    - Joint ASME & DOE effort to obtain and use this data to increase Code allowable temperature is underway
  - Further evaluation: Temperature limit, emissivity, oxidation and irradiation

Hastelloy X/XR

- **Potential applications**
  - Metallic internals with temperature above 750°C during normal operation or accident
    - Control rods, CR guide tubes, upper plenum shroud and hot duct liner
- **Important considerations**
  - High temperature strength, time dependent stress effects, irradiation, dose
- **Related experience**
  - Japanese HTTR hot duct liner and IHX tubing for over 10 years
    - Material used with success at operating temperature of 850°C with excursions up to 950°C
- **Current qualification status**
  - Hastelloy X
    - Maximum temperature limit of 427°C for Section III and 899°C for Section VIII Division 1 (Guidance)
    - Industry experience reports the potential for a normal operating limit of 871°C and abnormal condition limit of 938°C for <3000 hours and <1000 psi stress, but this will need to be supported by QAed references
    - Cobalt (0.5-2.5 wt%) could potentially create high dose issues for Hastelloy X
  - For Hastelloy XR
    - Industry experience reports the potential for a normal operating limit of 927°C and abnormal condition limit of 940°C for <3000 hours and <1000 psi stress but this will need to be supported by QAed references
  - Ideally Code Case N-201-5 and NH would be expanded to consider Hastelloy X/XR
  - Further evaluation: High temperature strength, time dependent stress effects, irradiation effects

Modified 9Cr-1Mo Grade 91

- **Potential applications**
  - Metallic core support structure, including core barrel (normal operation ~350°C)
- **Important considerations**
  - High temperature strength, time dependent stress effects, emissivity, thermal diffusivity, irradiation effects and corrosion resistance
- **Related experience**
  - Tubing in super-heaters of power boilers at about 600°C for over 20 years
  - Extensive studies on high temperature and time dependent properties
    - Twice strength of 2.25Cr-1Mo at 500°C
- **Current qualification status**
  - Maximum temperature limit
    - 371°C Section III NG (time independent stress limit)
    - 650°C Section III Subsection NH (Elevated temperature Class 1)
  - Ideally Code Case N-201-5 would be expanded to consider Mod 9Cr-1Mo
  - Further evaluation: Emissivity, irradiation and oxidation effects

2 ¼ Cr-1Mo Grade 22

- **Potential applications**
  - Cold end SG tubing, Core support structures (normal operation ~400°C)
- **Important considerations**
  - High temperature strength, time dependent stress effects, thermal conductivity, corrosion resistance
- **Related experience**
  - Japanese HTTR reactor and heat exchanger vessels, which have operated at about 400°C for over 10 years.
  - FSV and THTR cold end SG tubing
  - Extensive studies on high temperature and time dependent properties
    - Comparable strength to Mod. 9Cr-1Mo up to about 430°C
- **Current qualification status**
  - Maximum temperature limit
    - 371°C Section III (time independent stress limit)
    - 593 °C (300,000 hrs) Code Case N-201-5 (reactor internals)
    - 650 °C (1000 hrs) Code Case N-201-5 (reactor internals)
    - 650 °C Section III Subsection NH (Elevated temperature Class 1)
  - Further evaluation: none- well characterized material

Long Term View (Advanced HTGRs)

- **Alloy 617, Haynes 230**
  - Potential IHX material, control rod sleeves
  - Work is underway at INL to characterize the high temperature performance of these materials
- **Modified 9Cr – 1Mo**
  - Potential vessel material for VHTR
  - Large forging availability
  - Thick section welding

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Nonmetallic Components
- Ceramics and Composites -

- **Ceramics and composites are generally unique, non-standard and have proprietary designs/architecture**
- **Qualification path includes**
  - Material selection - manufacturer
  - Coordinated testing similar to DOE sponsored graphite testing
    - Initiate performance testing
    - Examine results
    - Acceptance review
    - Initial applications in low-fluence environments
- **Composites are generally engineered to be superior materials to monolithic ceramics**
  - Higher strength – specially in tension
  - Insensitive to maximum HTGR temperatures in helium environment
  - Higher Weibull modulus – more uniform failure
  - Much higher damage tolerance - fracture toughness

Nonmetallic Components
Composites

- **Composites are being considered as alternatives to reference metallic components in certain near-term HTGR applications in low-fluence environments**
  - Retention devices for top reflectors (pebble reactors), upper plenum insulation (prism reactors)
  - Core restraint devices
- **Composites may be required as enabling for advanced applications at higher temperatures and in high-fluence areas**
  - Hot gas duct liners, other internals, control rod components
- **Composites properties offer the potential for improved performance and reliability**

Nonmetallic Components
Composites

- **Industrial standards (ASME), regulatory basis for use of composites in HTGRs has not yet been established**
  - In near-term, would require qualification by testing
  - ASME Section III Subgroup on Graphite Core Components has a charter to develop appropriate standards, but has not yet started
  - Composites are not qualified as a material but must be qualified as an architecture
- **Additional considerations**
  - Properties of a given composite are dependent upon raw materials (fiber and matrix), architecture, and processing
  - Composite materials tend to be unique and often proprietary; implying need to qualify specific materials by specific manufacturers for specific applications
  - Qualification for design life of 60 years
  - Qualification for high-fluence applications (advanced HTGRs)

Nonmetallic Components
Ceramics

- **Ceramics may be useful, particularly in advanced HTGRs to reduce the temperatures seen by surrounding metallic components (e.g., core support structure/core barrel, reactor vessel)**
  - Candidate materials include baked carbon and fused silica
  - Would generally be used in low-fluence environments
- **Ceramic insulation has been previously used in nuclear applications, including HTGRs**
  - Baked carbon insulation used in Fort St. Vrain, HTTR (Japan) and HTR-10 (China)
  - MASROCK, a sintered fused silica insulation material and Kaowool were used in Fort St. Vrain; GLASROCK, a similar material was qualified for use in the German HTGR program

Nonmetallic Components
Ceramics

- **Industrial standards (ASME) and regulatory basis for use of ceramics in HTGRs has not yet been established**
  - Approach for qualification would be similar to that for graphite; however, fluence would not be a significant factor (subject to confirmation for fused silica, as noted below)

- **Additional considerations**
  - Baked carbon is similar to graphite, with the principal difference being reduced processing temperatures to minimize graphitization that would lead to higher thermal conductivity
    - This suggests that the experience base for qualification of graphite would largely apply to baked carbon
  - Fused silica is sensitive to fluence (radiolysis). While not expected to be a factor based on extrapolated data, confirmation is required
  - Qualification for design life of 60 years

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Summary

- **Component design and material selection complexity varies significantly with the operating conditions; there are significant differences between the near-term 750 °C applications and the advanced applications > 950 °C**

- **Going to higher temperatures**
  - Material strength becomes an important factor
  - Creep becomes more of an issue
  - Operating environment becomes a factor (He with impurities)
  - Creep-fatigue, environment, irradiation interactions become more prominent
  - Use of engineered materials (Superalloys, ODS) become a consideration
  - Change from metals to ceramics and composites

Summary

- **Near term application – HTGR**
  - The required metallic, ceramic and composite materials for HTGR components that operate at high temperatures are generally commercially available
    - Ferritic, martensitic steels, austenitic SS, and Nickel-based super alloys
  - Extension of existing qualification envelope is underway
  - Regulatory acceptance review must be based on HTGR safety case
- **Long term applications – Advanced HTGR or VHTR**
  - New materials for higher temperature advanced HTGR applications must be designed, developed and codified
    - ODS / nano-precipitates, refractory alloys, ceramics
  - Qualification and codification by ASME (new HTGR Code Division) or design justification by testing and analytical techniques
  - Regulatory acceptance review must be based on HTGR safety case

Suggested Reading

- U.S. Nuclear Regulatory Commission (NRC), NUREG/CR-6816, Review and Assessment of Codes and Procedures for HTGR Components, 2003
- U.S. Nuclear Regulatory Commission (NRC), NUREG/CR-6824, Material Behavior in HTGR Environments, 2003
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