High Temperature Materials Overview

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Advanced Reactor Technologies
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Objectives

Provide Technology Development to Support Future Design and Deployment of Very High Temperature Gas Cooled Reactors:
- Pressure Vessel
- Steam Generator and Intermediate Heat Exchanger (IHX)
- Support Codes and Standards Activities for SiC/SiC composites and Materials Handbook

Program Goals
- Alloy 617 Code Case Submittal for ASME approval by FY15 allowing use up to 950°C
- Develop experimentally validated elevated temperature design methods applicable to any high temperature nuclear system
- Resolve Materials Issues Beyond Code Qualification that will allow design of components for life of plant

Significance of Creep Properties
- Larson-Miller plot for rupture is used in analysis of creep-fatigue interaction
- Creep curves and Larson-Miller plot are used in establishing isochronous stress-strain curves
- Time dependent allowable stresses are determined from analysis of creep curves and rupture lives
- Creep determines limits on allowable cold work
- Rupture behavior of weldments determines reduction factor on allowable stresses
Leveraging High Temperature Materials Research and Development

- **Development and Demonstration in Germany and Japan**
  - Extensive Alloy 800H steam generator materials research
  - Alloy 617 and Hastelloy X (Alloy XR in Japan) steam generator and Intermediate Heat Exchanger (IHX) materials characterization

- **Draft ASME Code Case submitted in US in 1990**
  - Alloy 617 Code Case Submittal for ASME approval
  - Code Case was withdrawn and did not receive final action

- **Fossil Energy Ultra-supercritical Materials research in US and Europe**

- **Partners in Generation IV International Forum**
Elevated Temperature Design Methods

Subsections NB and NH have been incorporated into Section III Division 5 High Temperature Reactors effective 2015 edition

Provide design curves derived from experiments
- Section HB Subsection A and Section HC Subsection A for temperatures up to 427°C
- NB Subsection B for temperatures up to 950°C

A Task Group on Alloy 617 Code Qualification has been established to provide guidance, review, and comment on the process

Staff associated with the High Temperature Materials R&D have become members of relevant Code committees to facilitate the Code Case
Alloy 617 ASME Code Qualification Schedule

- Code Case for nuclear design in the elastic regime Section III Division 5 qualification to 427°C is in ballot process
  - Alloy 617 Code Case includes tensile properties, modulus and fatigue design curves

- A draft Code Case for Alloy 617 for elevated temperature components will be completed August 31, 2015
  - Use temperature up to 950°C for time up to 100,000 hours

I-9.5M from ASME Section III Appendices (UNS N06003, N06007, N06455, and N10276 for T≤425°C)
Time Dependent Allowable Stresses
ASME Code, Section III, Division 5

- Stress Intensity Limits for Design

\[ S_t = \text{a temperature and time-dependent stress intensity limit; the data considered in establishing these values are obtained from long-term, constant load, uniaxial tests. For each specific time, } t, \text{ the } S_t \text{ values shall be the lesser of:} \]

80% of the minimum stress to cause initiation of tertiary creep

67% of the minimum stress to cause rupture

100% of the average stress required to obtain a total (elastic, plastic, primary, and secondary creep) strain of 1%
- Larson-Miller Plot created using data set comprised of information from 296 creep specimens
- Majority of results from INL, ANL, KAERI fall in lower portion of dataset – although difference cannot be said to be statistically significant
- Low cobalt content, not melt practice, causes shorter creep-rupture lives
Minimum Creep Rate at 750°C

- Minimum creep rates obtained within the first 200 - 500 hours at 750°C
- Strain rate vs. strain highlights similarity of shape and the continually increasing strain rate after the minimum creep rate is reached at small strains
Onset of Tertiary Creep for Textbook and Non-classical Creep Curves

750°C Alloy 617

- 121 MPa
- 145 MPa

Creep Strain vs. Time

Primary creep
Secondary creep
Tertiary creep
Rupture

Strain (%)

0 5 10 15 20 25

Time (h)

0 1000 2000 3000 4000 5000 6000

0.2%
Tertiary creep has initiated at 10% total strain (~2.4% tertiary creep strain)
Dislocations rearranging to form organized structures – subgrain boundary formation
Low dislocation density in the cell interiors
For Alloy 617 re-arrangement of dislocation substructure, rather than void formation, leads to onset of tertiary creep behavior
Allowable Stress Intensity Values, $S_t$

- Temperature and time-dependent stress intensity limit obtained from creep tests
- The lesser of:
  - 100% average stress to a total strain of 1%
  - 80% minimum stress to initiation of tertiary creep
  - 67% minimum stress to rupture
# Governing Criterion

1% Strain

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Tertiary Creep Rupture
Creep-Fatigue Interaction Diagram
Creep-Fatigue interaction is thought to be life-limiting degradation mode at high temperatures.

- Data sufficient to support the creep-fatigue interaction diagram for plate material have been obtained.
- Creep rupture data play a critical role in calculating equivalent creep strain during strain hold.
- Characterization of weldments will require additional testing.
Preliminary analysis indicates 0.1, 0.1 intersection is representative of average behavior.

Denominator of creep damage fraction is determined from rupture data.

Addition of literature data, peer review, and validation in progress.
Isochronous Stress Strain Curves
Concept of Isochronous Stress-Strain Curves
950°C Hot Tensile and Isochronous
Program Goals
- Alloy 617 Code Case for ASME Boiler and Pressure Vessel Code allowing use in nuclear construction up to 950°C and 100,000 hours is complete in draft form

Significance of Creep Properties
- Larson-Miller plot for rupture is used in analysis of creep-fatigue interaction
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Additional Work
- Creep-fatigue behavior of weldments is still poorly understood
- Component tests may be necessary to resolve issues with tertiary creep criteria
- Creep ductility in the presence of notches remains to be characterized