U.S. DEPARTMENT OF ENERGY | Nuclear Energy

High Temperature Materials Overview

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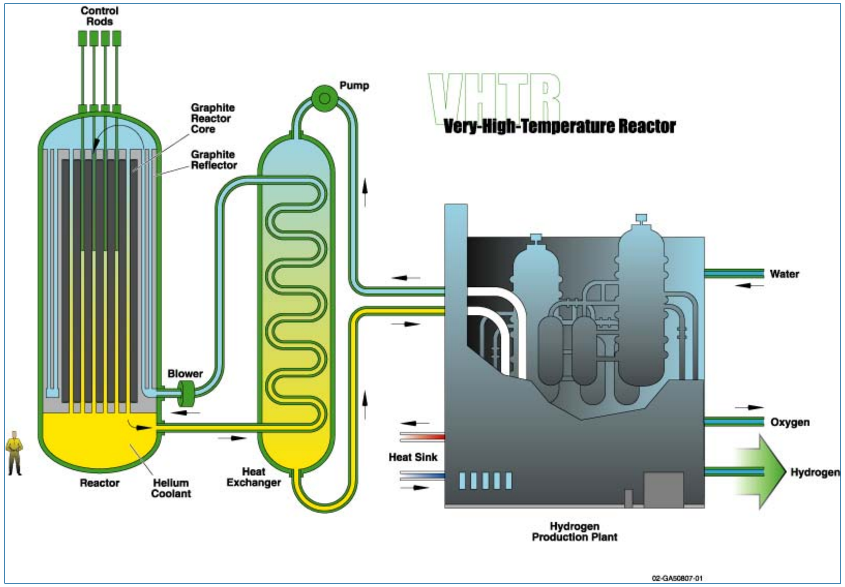
Idaho National Laboratory

Advanced Reactor Technologies
September 17, 2015

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 950ºC
  - 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

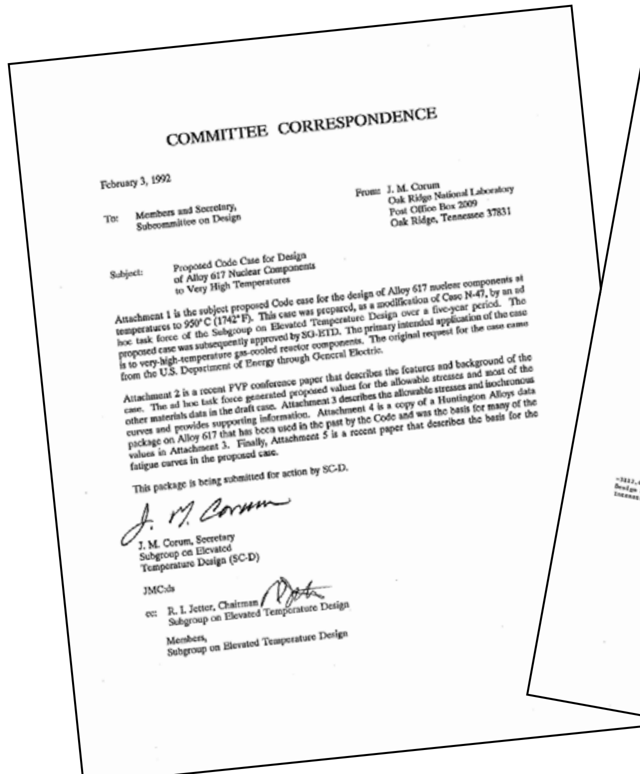
Leveraging High Temperature Materials Research and Development

- **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  - Code Case was withdrawn and did not receive final action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**



COMMITTEE CORRESPONDENCE

February 3, 1992

To: Members and Secretary, Subcommittee on Design

From: J. M. Corum
Oak Ridge National Laboratory
Post Office Box 2009
Oak Ridge, Tennessee 37831

Subject: Proposed Code Case for Design of Alloy 617 Nuclear Components to Very High Temperatures

Attachment 1 is the subject proposed Code case for the design of Alloy 617 nuclear components at temperatures to 950°C (1742°F). This case was prepared, as a modification of Case N-47, by an ad hoc task force of the Subgroup on Elevated Temperature Design over a five-year period. The proposed case was subsequently approved by SG-ETD. The primary intended application of the case is to very-high-temperature gas-cooled reactor components. The original request for the case came from the U.S. Department of Energy through General Electric.

Attachment 2 is a recent PVP conference paper that describes the features and background of the case. The ad hoc task force generated proposed values for the allowable stresses and most of the other materials data in the draft case. Attachment 3 describes the allowable stresses and isochronous curves and provides supporting information. Attachment 4 is a copy of a Huntington Alloys data package on Alloy 617 that has been used in the past by the Code and was the basis for many of the values in Attachment 3. Finally, Attachment 5 is a recent paper that describes the basis for the fatigue curves in the proposed case.

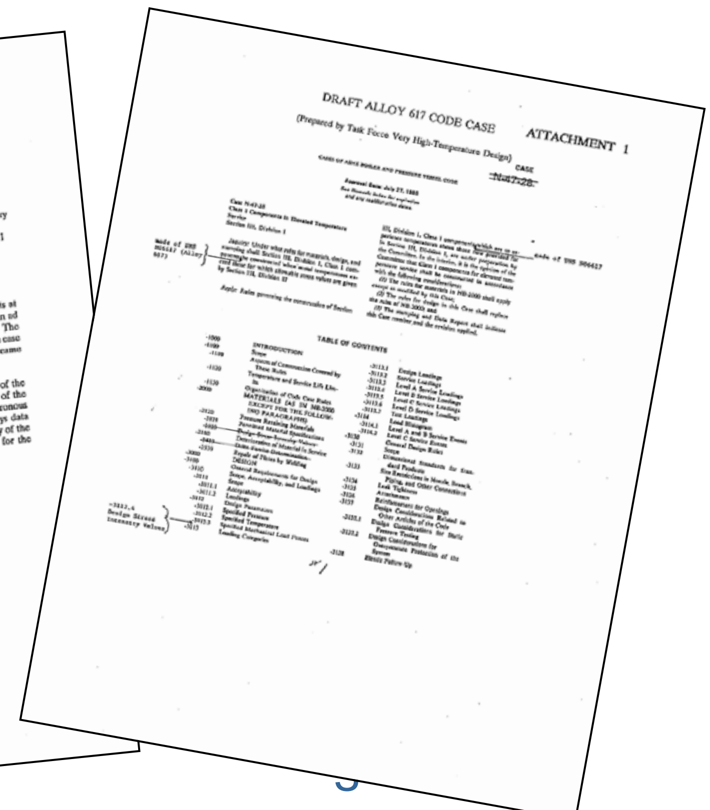
This package is being submitted for action by SC-D.

J. M. Corum, Secretary
Subgroup on Elevated
Temperature Design (SC-D)

JMC:ds

cc: R. I. Jetter, Chairman
Subgroup on Elevated Temperature Design

Members,
Subgroup on Elevated Temperature Design



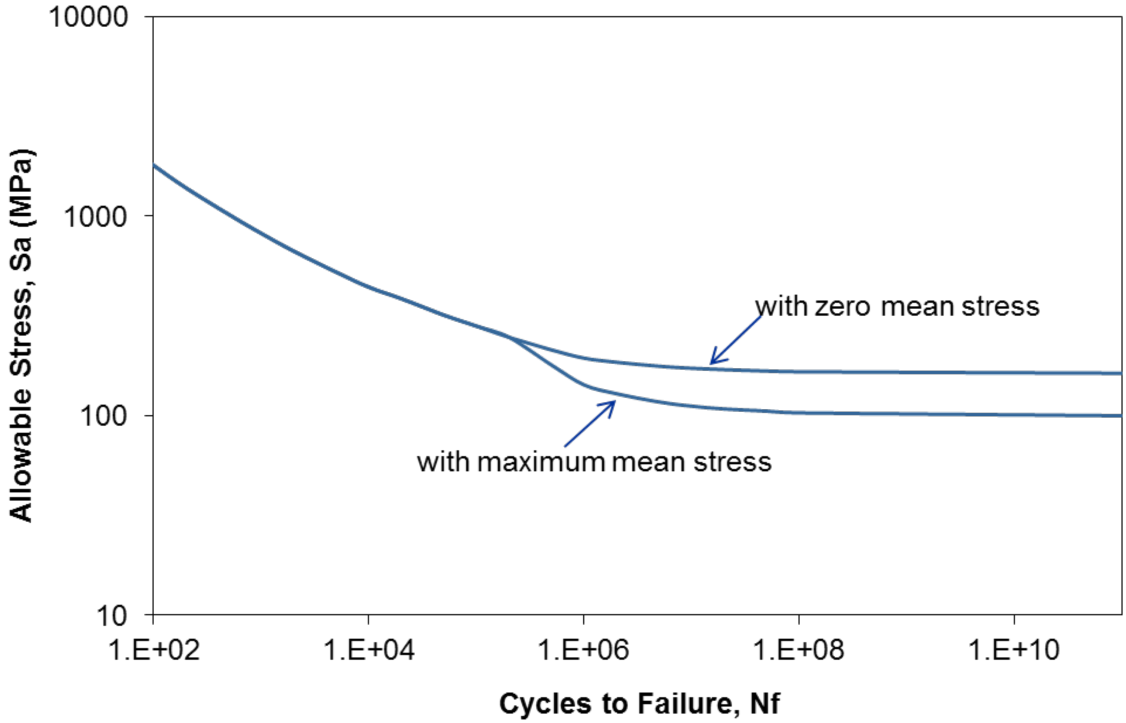
DRAFT ALLOY 617 CODE CASE ATTACHMENT 1
(Prepared by Task Force Very High-Temperature Design)

ASME High Temperature Materials Code Qualification Approach

- **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 427ºC
  - NB Subsection B for temperatures up to 950ºC
- **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 427ºC 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 950ºC 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 Rules for Time Dependent Allowable Stress

- **ASME Code, Section III, Division 5**
  - Stress Intensity Limits for Design

    S_t = 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, the S_t values shall be the lesser of:

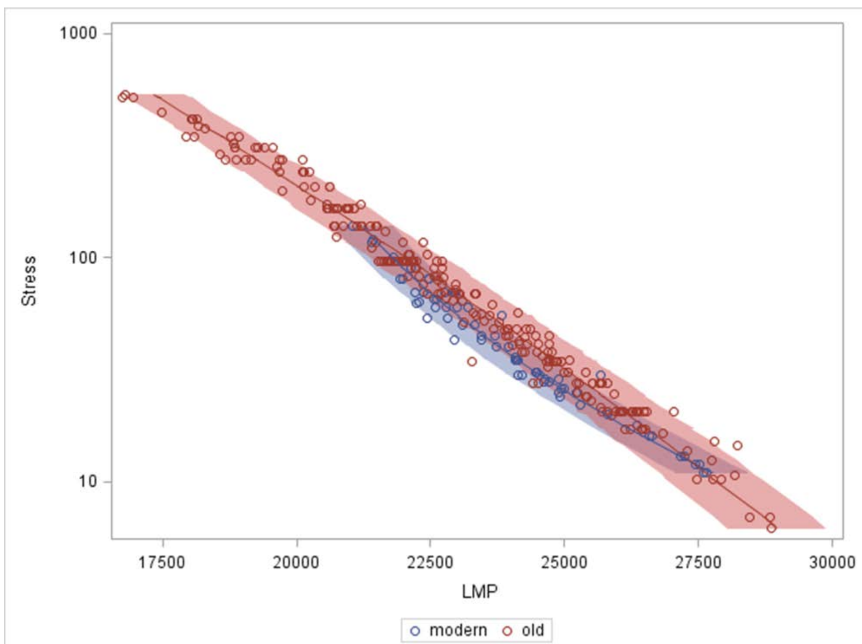
    80% of the minimum stress to cause initiation of tertiary creep

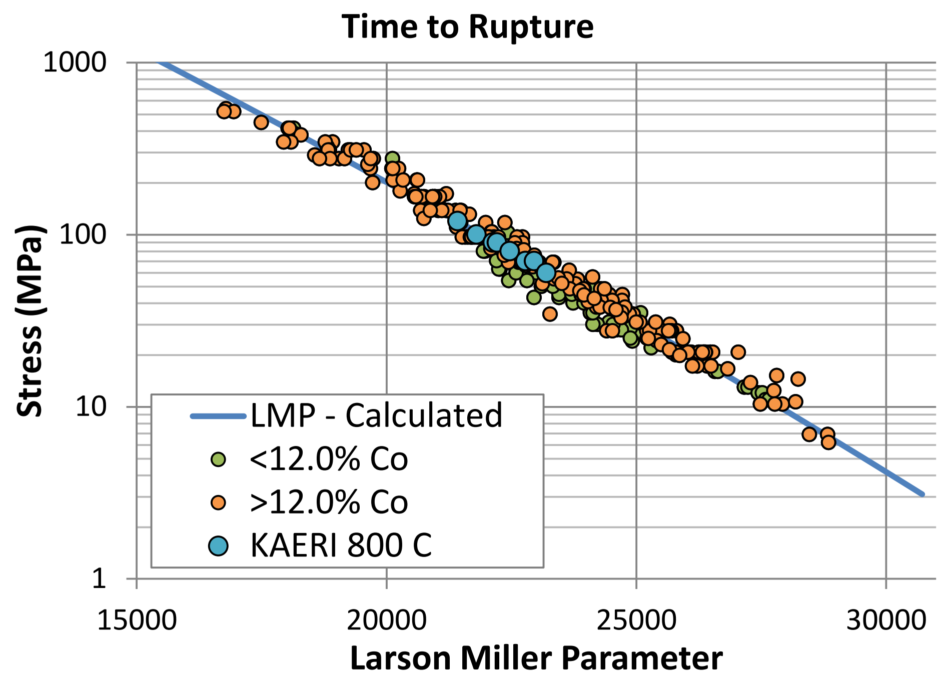
    67% of the minimum stress to cause rupture

    100% of the average stress required to obtain a total (elastic, plastic, primary, and secondary creep) strain of 1%

Larson-Miller: Stress-Rupture

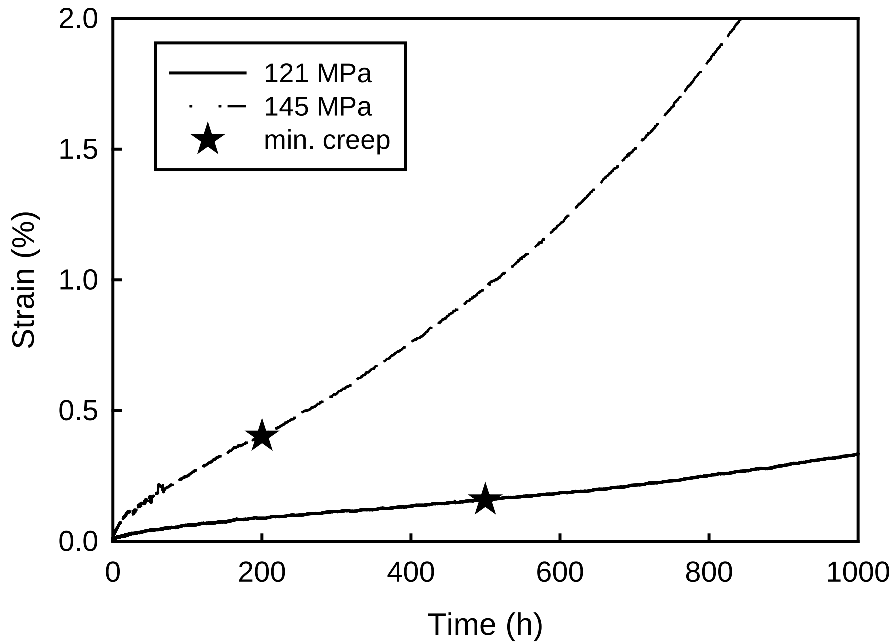
- Larson-Miller Plot created using data set comprised of information from 296 creep specimens
- Majority of results from INL, ANL, KAERI fall in lower portion of dataset – although difference cannot be said to be statistically significant
- Low cobalt content, not melt practice, causes shorter creep-rupture lives

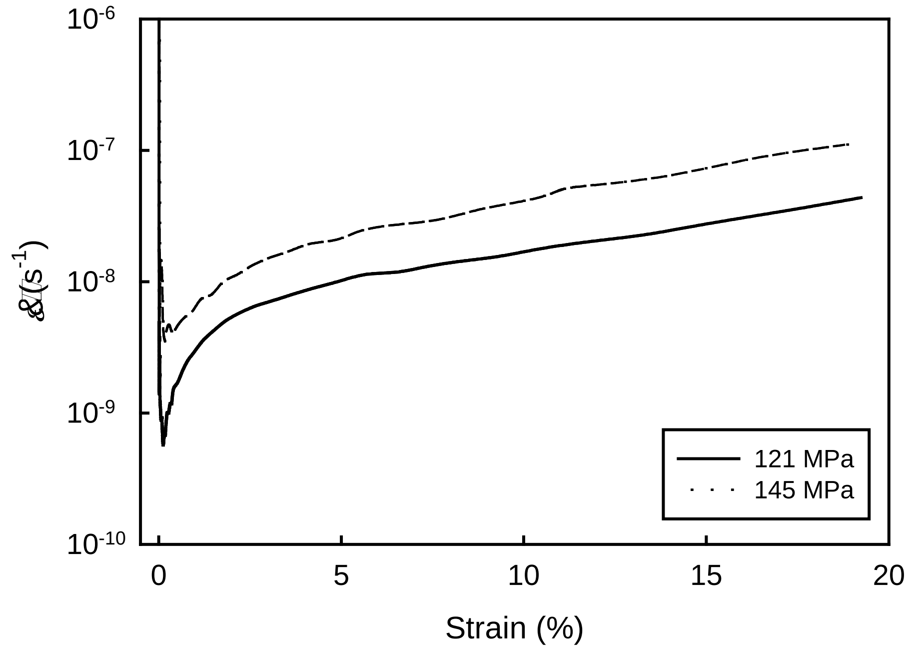




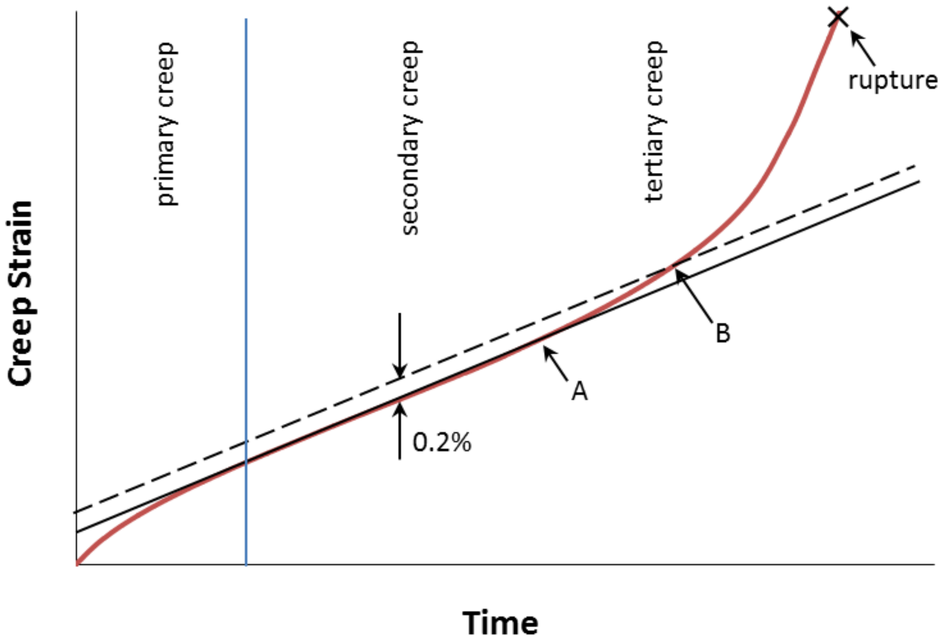
Minimum Creep Rate at 750ºC

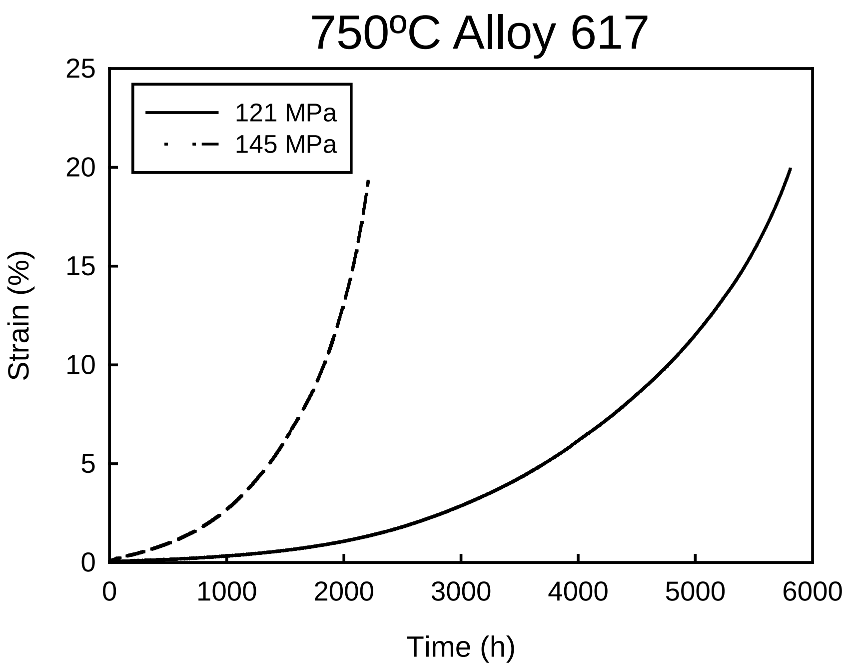
- Minimum creep rates obtained within the first 200 - 500 hours at 750° C
- Strain rate vs. strain highlights similarity of shape and the continually increasing strain rate after the minimum creep rate is reached at small strains





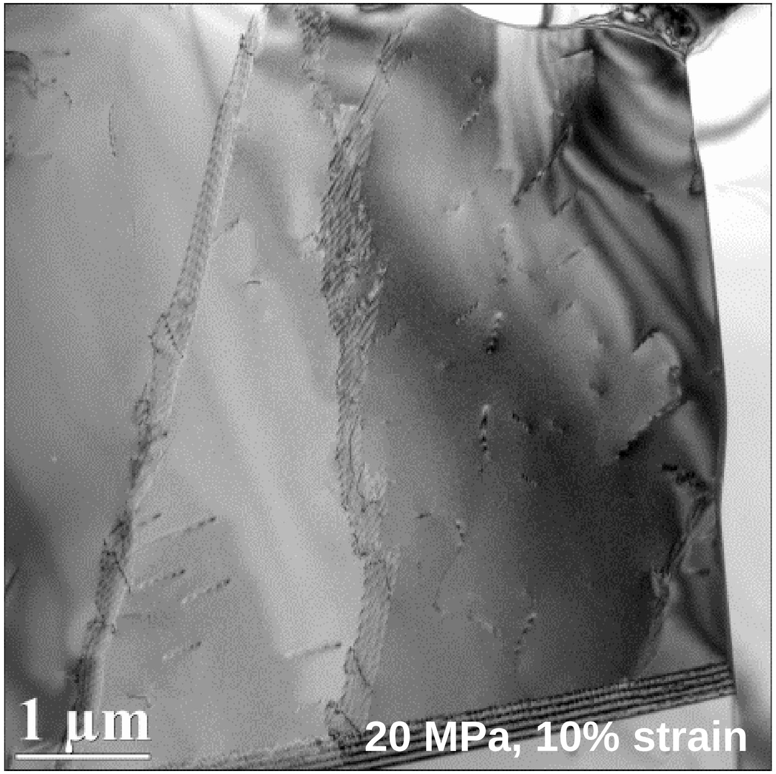
Onset of Tertiary Creep for Textbook and Non-classical Creep Curves

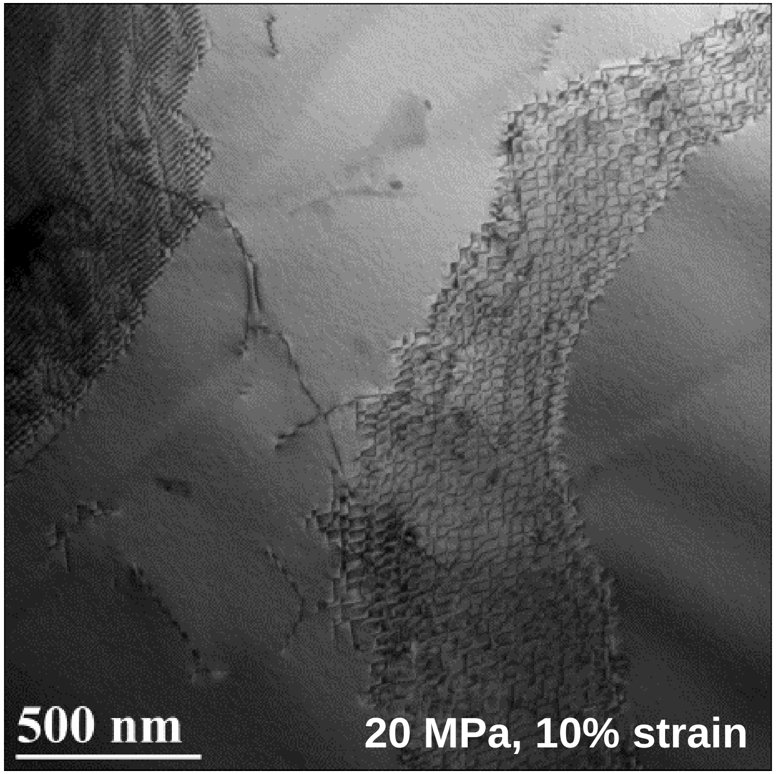




Interrupted Creep at 1000ºC – High Strains

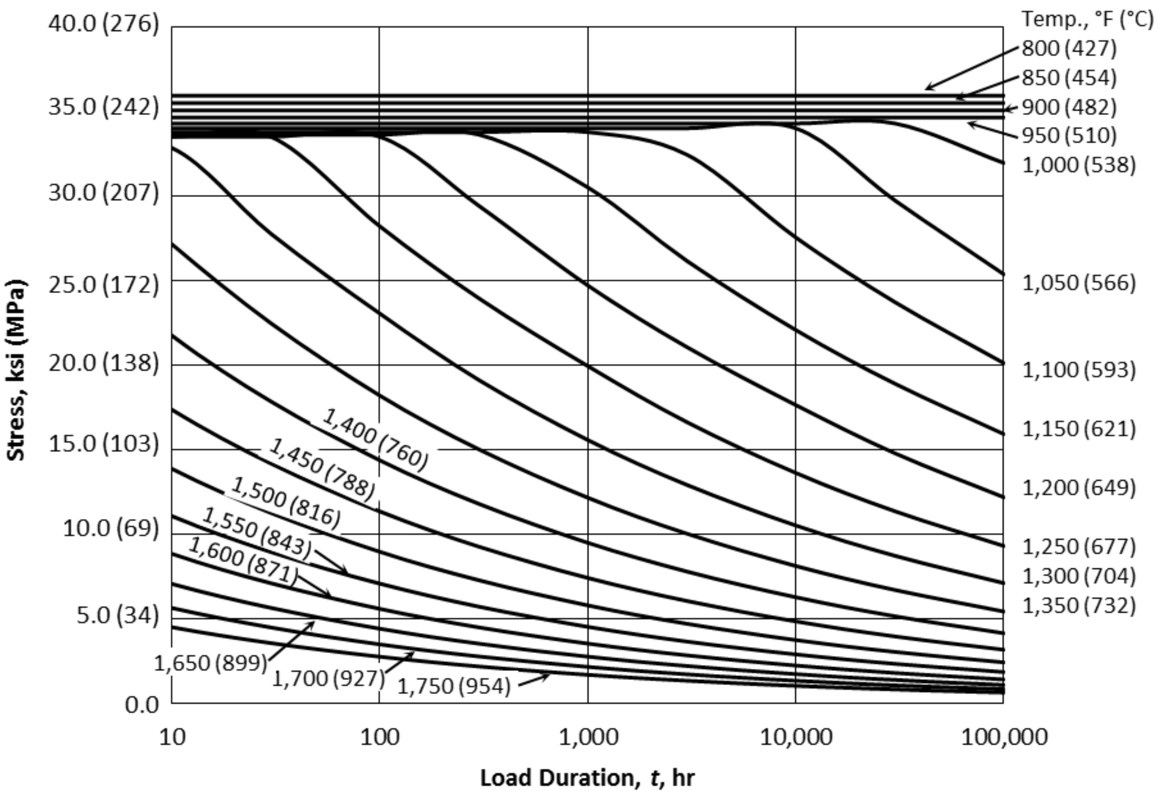
- Tertiary creep has initiated at 10% total strain (~2.4% tertiary creep strain)
- Dislocations rearranging to form organized structures – subgrain boundary formation
- Low dislocation density in the cell interiors
- For Alloy 617 re-arrangement of dislocation substructure, rather than void formation,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

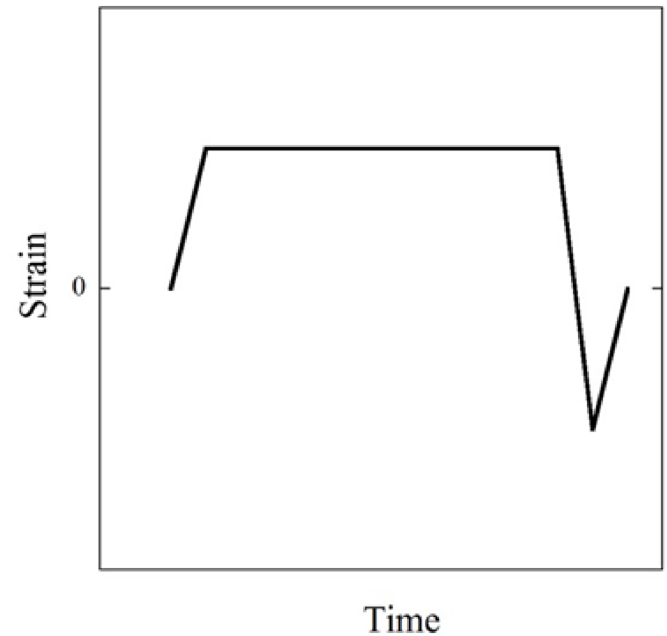
1% Strain	Tertiary Creep	Rupture

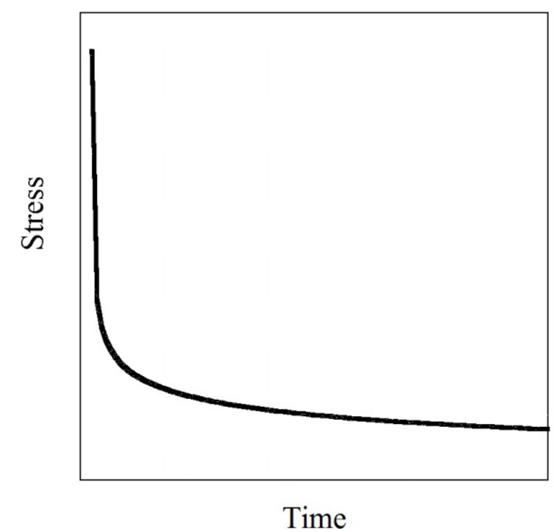
	Stress (MPa)										
Time (h)→	**1**	**3**	**10**	**30**	**100**	**300**	**1000**	**3000**	**10000**	**30000**	**100000**
Temperature (C) ↓	Minimum, All Criteria										
425	245	245	245	245	245	245	245	245	245	245	245
450	245	245	245	245	245	245	245	245	245	245	245
475	242	242	242	242	242	242	242	242	242	242	242
500	240	240	240	240	240	240	240	240	240	240	240
525	238	238	238	238	238	238	238	238	238	238	238
550	235	235	235	235	235	235	235	235	235	233	199
575	234	234	234	234	234	234	234	234	220	190	162
600	233	233	233	233	233	233	233	213	180	155	131
625	232	232	232	232	232	232	204	175	148	126	106
650	231	231	231	231	231	201	169	144	120	101	83
675	231	231	231	231	197	167	140	116	95	80	65
700	231	231	231	198	164	137	112	93	76	63	51
725	231	231	197	165	133	110	89	74	60	49	40
750	231	201	163	134	108	89	72	59	47	39	31
775	202	166	133	109	87	71	57	47	38	31	25
800	167	136	109	88	71	57	46	37	30	24	19
825	138	112	89	72	57	46	37	30	24	19	15
850	114	92	72	58	46	37	29	24	19	15	12
875	94	75	59	47	37	30	23	19	15	12	9.3
900	77	62	48	39	30	24	19	15	12	9.4	7.3
925	64	51	39	31	24	19	15	12	9.3	7.4	5.7
950	53	42	32	25	20	16	12	9.5	7.4	5.8	4.5

Creep-Fatigue Interaction Diagram

Creep-Fatigue

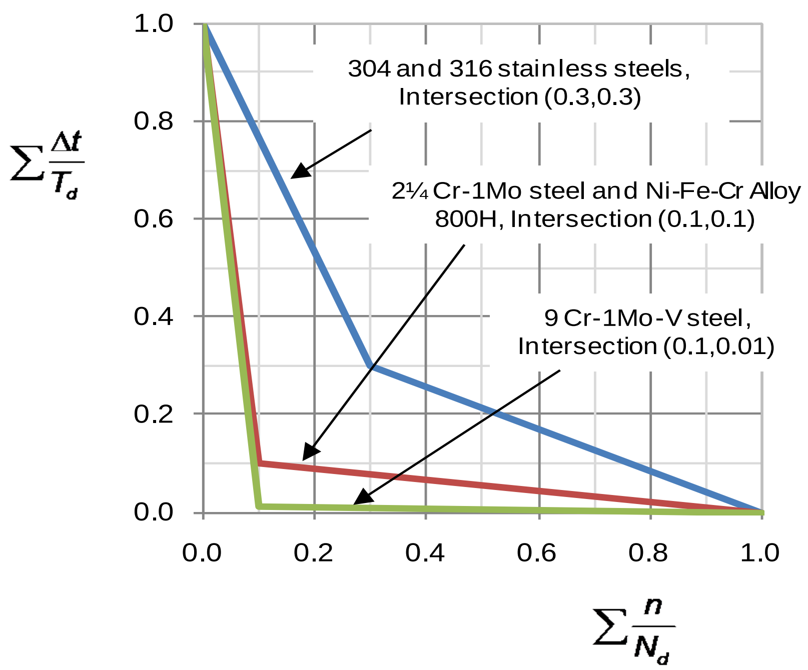
- Creep-Fatigue interaction is thought to be life-limiting degradation mode at high temperatures
- Data sufficient to support the creep-fatigue interaction diagram for plate material have been obtained
- Creep rupture data play a critical role in calculating equivalent creep strain during strain hold
- Characterization of weldments will require additional testing

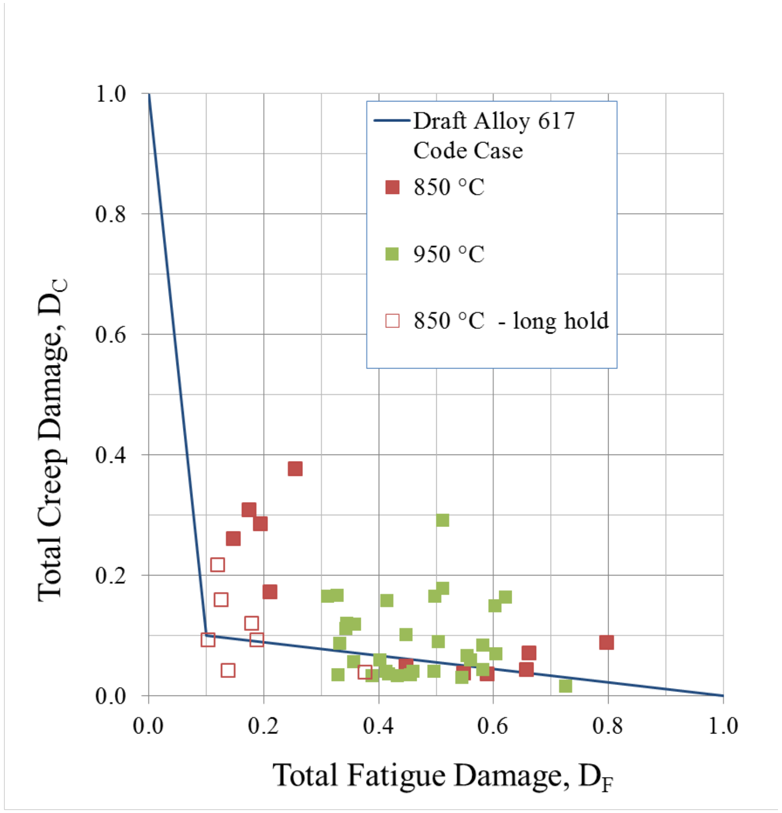




Creep-Fatigue D-Diagram

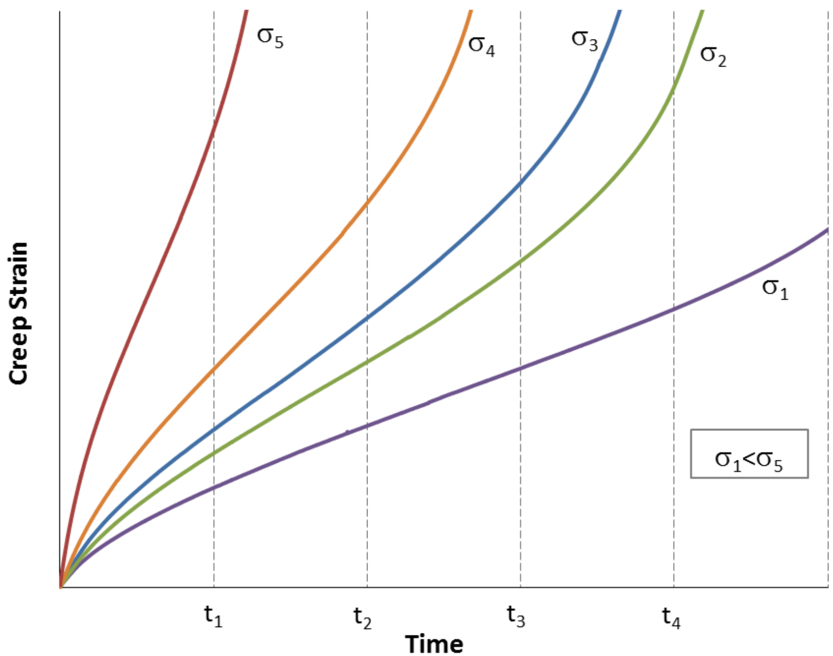
- **Preliminary analysis indicates 0.1, 0.1 intersection is representative of average behavior**
- **Denominator of creep damage fraction is determined from rupture data**
- **Addition of literature data, peer review, and validation in progress**

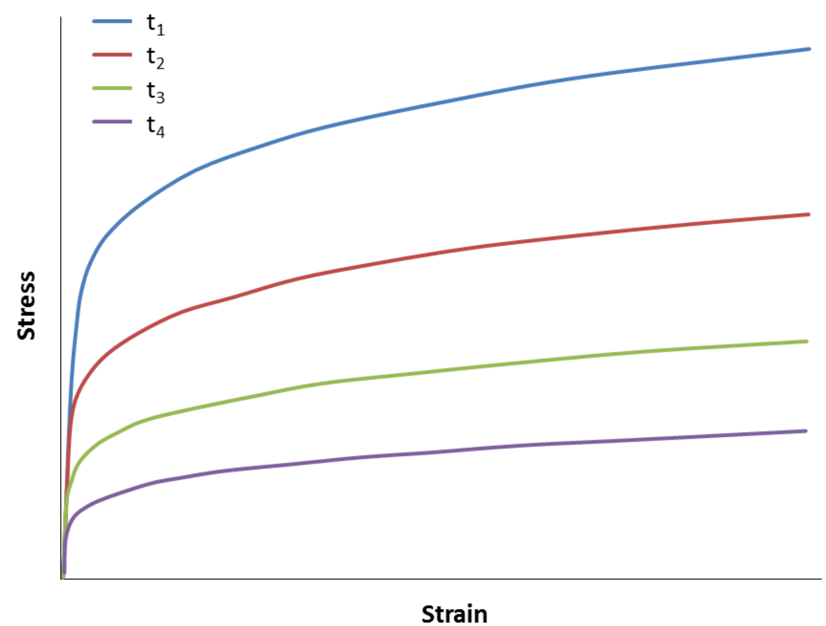




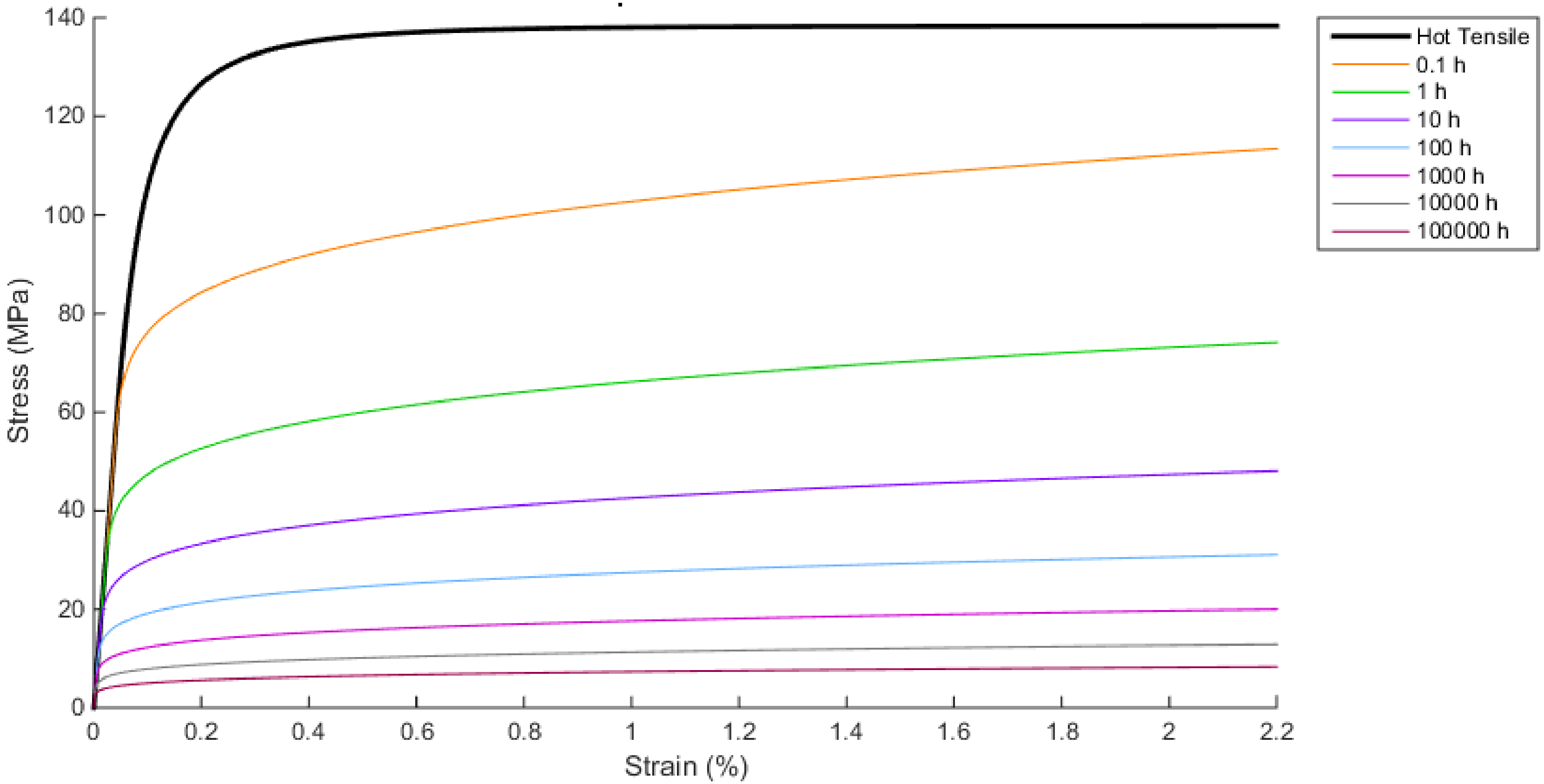
Isochronous Stress Strain Curves

Concept of Isochronous Stress-Strain Curves





950ºC Hot Tensile and Isochronous



Summary

- **Program Goals**
  - Alloy 617 Code Case for ASME Boiler and Pressure Vessel Code allowing use in nuclear construction up to 950ºC 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
  - 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 behavior determines limits on allowable cold work
  - Rupture behavior of weldments determines reduction factor on allowable stresses
- **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