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고온원자로용 재료 기술기준 등재현황

(ASME BPV III Division 5)

2021.10.20

구 경 회

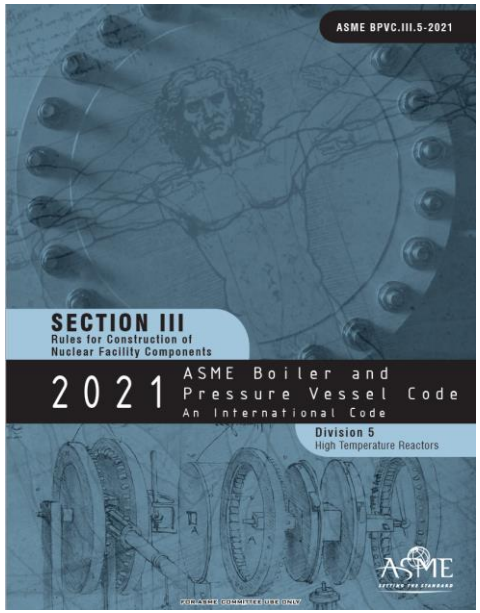
KAERI Korea Atomic Energy Research Institute

Contents

1 Introduction of ASME BPVC III Division 5

ASME BPV III Code Structure

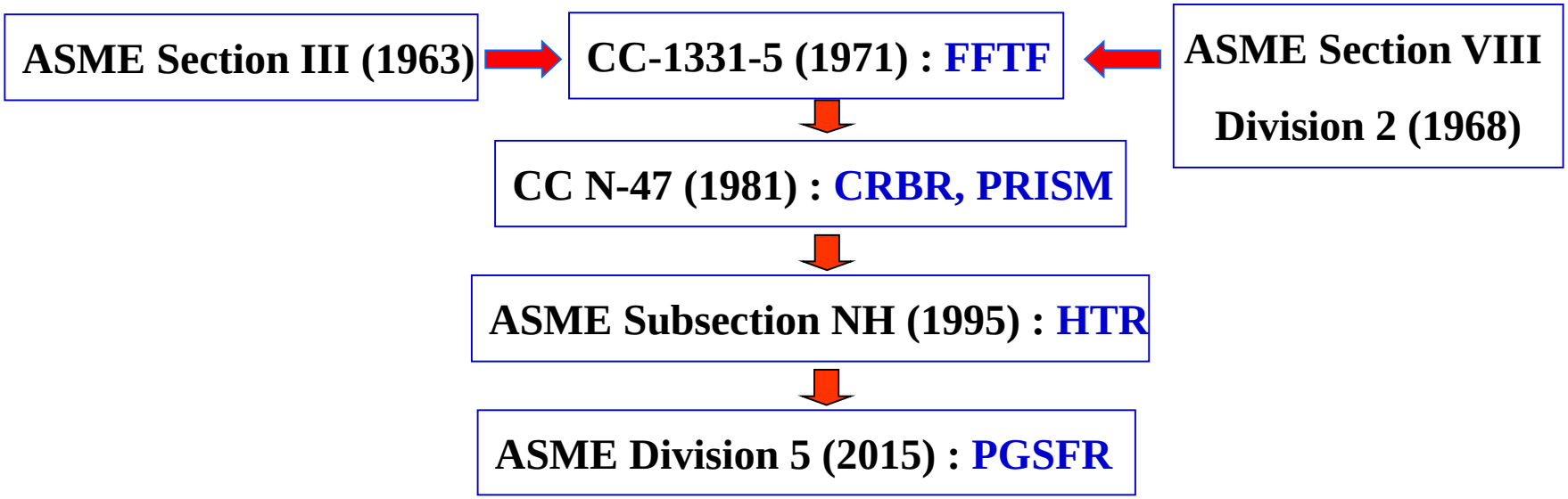
- **BPV Code, Sec. III, Rules for Nuclear Components**
  - Division 1 – 8 Subsections
    - NCA: General Requirements
    - NB : Class 1 Components
    - NC : Class 2 Components
    - ND : Class 3 Components
    - NE : Class MC Components
    - NF : Supports
    - NG : Core Support Structures
    - ~~NH : Class 1 Components in Elevated Temp. Service~~
  - Division 2 – Concrete Containments
  - Division 3 – Transport Packaging
  - Division 4 – Fusion Reactor
  - Division 5 – High Temperature Reactors



2015 Ed ~

History of ASME Elevated Temperature Design C&S

- ASME Subsection NH : Class 1 Components (From 1995Edtion)
- Code Case N-201 : Class CS Components
- Code Case N-499 : Use of SA-533 and SA-508 for Limited Elevated Temp. Service
  (Annulled 2012 -> Div5 App. HBB-II)
- Code Case N-253 : Construction of Class 2 or 3 Components
- Code Case for Alloy 617



Code Structure of Division 5

- **Subsection HA: General Requirements**
  - Subpart A: Metallic Materials
  - Subpart B: Graphite and Composite Materials
- **Subsection HB: Class A Metallic Pressure Boundary Components**
  - Subpart A: Low Temperature Service
  - Subpart B: Elevated Temperature Service
- **Subsection HC: Class B Metallic Pressure Boundary Components**
  - Subpart A: Low Temperature Service
  - Subpart B: Elevated Temperature Service
- **Subsection HF: Class A and Class B Metallic Supports**
  - Subpart A: Low Temperature Service
- **Subsection HG: Class SM Metallic Core Support Structures**
  - Subpart A: Low Temperature Service
  - Subpart B: Elevated Temperature Service
- **Subsection HH: Class SN Nonmetallic Core Components**
  - Subpart A: Graphite Materials
  - Subpart B: Composite Materials

2 Lists of Div5 Materials for Class A

HBB Materials

Base Material	Spec. No.	Product Form	Types, Grades, or Classes
Types 304 SS and 316 SS [Note (1)], [Note (2)], [Note (3)]	SA-182	Fittings & Forgings	F 304, F 304H, F 316, F 316H
	SA-213	Smls. Tube	TP 304, TP 304H, TP 316, TP 316H
	SA-240	Plate	304, 316, 304H, 316H
	SA-249	Welded Tube	TP 304, TP 304H, TP 316, TP 316H
	SA-312	Welded & Smls. Pipe	TP 304, TP 304H, TP 316, TP 316H
	SA-358	Welded Pipe	304, 316, 304H, 316H
	SA-376	Smls. Pipe	TP 304, TP 304H, TP 316, TP 316H
	SA-403	Fittings	WP 304, WP 304H, WP 316, WP 316H, WP 304W, WP 304HW, WP 316W, WP 316HW
	SA-479	Bar	304, 304H, 316, 316H
	SA-965	Forgings	F 304, F 304H, F 316, F 316H
	SA-430	Forged & Bored Pipe	FP 304, FP 304H, FP 316, FP 316H
Ni-Fe-Cr (Alloy 800H) [Note (4)]	SB-163	Smls. Tubes	UNS N08810
	SB-407	Smls. Pipe & Tube	UNS N08810
	SB-408	Rod & Bar	UNS N08810
	SB-409	Plate, Sheet, & Strip	UNS N08810
	SB-564	Forgings	UNS N08810
2¼Cr-1Mo [Note (5)]	SA-182	Forgings	F 22, Class 1
	SA-213	Smls. Tube	T 22
	SA-234	Piping Fittings	WP 22, WP 22W [Note (6)]
	SA-335	Forg. Pipe	P 22
	SA-336	Fittings, Forgings	F 22a
	SA-369	Forg. Pipe	FP 22
	SA-387	Plate	Gr 22, Class 1
	SA-691	Welded Pipe	Pipe 2¼ CR (SA-387, Gr. 22, Cl. 1)
9Cr-1Mo-V	SA-182	Forgings	F91
	SA-213	Smls. Tube	T91
	SA-335	Smls. Pipe	P91
	SA-387	Plate	91

HBB Materials

Recommended Restrictions

Element	Type 304	Type 316
(a) Chemical Composition [Note (1)]		
Carbon	0.04–0.06	0.04–0.06
Nitrogen	0.04–0.07	0.04–0.07
Silicon	0.6	0.6
Manganese	1.0–2.0	1.0–2.0
Nickel	8.00–10.00	11.00–12.5
Chromium	18.5–20.00	17.00–18.00
Molybdenum	0.2	2.5–3.0
Sulfur	0.02	< 0.02
Phosphorus	0.045	< 0.03
Niobium	0.02 [Note (2)]	...
Aluminum	0.05	0.05
Antimony	0.02	0.02
Boron	...	0.003 [Note (3)]
Lead	0.003	0.003
Selenium	0.015	0.015
Tin	0.015	0.015
Vanadium	0.05	0.05
Zinc	0.01	0.01
(b) Grain Size (ASTM)	3–6	3–6
(c) Melt Practice	AOD or AOD/ESR	AOD or AOD/ESR
(d) Suggested upper long-term use limit for improved performance:		
Temperature, °F (°C)	1,100 (595)	1,100 (595)

SA-533 Type B Class 1 Plate & SA-508 Grade 3 Class 1 Forging

(a) The design rules of Division 1, Article NB-3000 shall be satisfied for all Design, Service, and Test Loadings for which metal temperatures do not exceed 700°F (370°C). The design conditions shall be as defined in Division 1, Article NB-3000.

(b) Metal temperatures exceeding 700°F (370°C) are permitted only for loadings associated with Level B, C, and D Service Limits. The applicable rules of Article HBB-3000 shall be satisfied for these conditions.

(c) Metal temperatures shall not exceed 800°F (425°C) for loadings associated with Level B Service Limits. Metal temperatures shall not exceed 1,000°F (540°C) for loadings associated with Level C or Level D Service Limits.

(d) The component design shall be based on a maximum cumulative time of 3,000 hr at metal temperatures in the range of 700°F (370°C) to 800°F (425°C) and 1,000 hr at metal temperatures exceeding 800°F (425°C) up to 1,000°F (540°C).

(e) The number of anticipated operating conditions where metal temperatures exceed 800°F (425°C) shall be limited to a total of three.

3 Characteristics of Class A Materials

Characteristics of Div5 HBB Code Materials

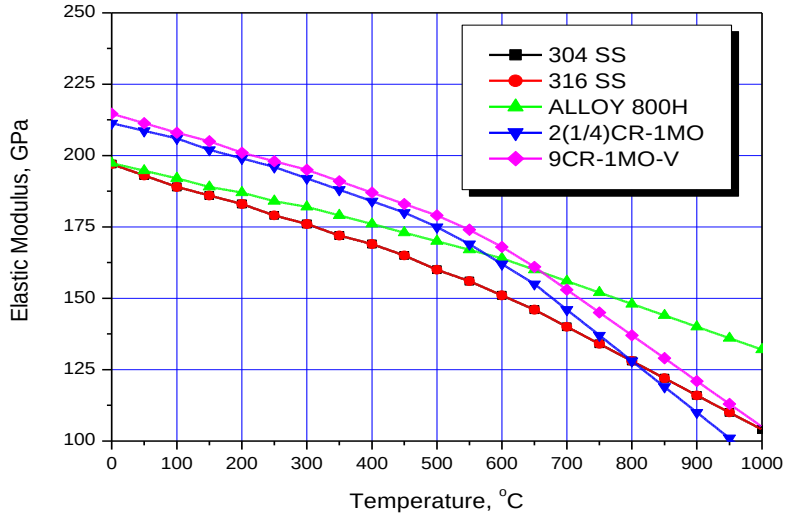
- For ISSC, the maximum metal temperatures allowed in the ASME Sec.III-Division 5 materials are 816°C for stainless steel, 760°C for Alloy800H, and 649°C both for 2.25Cr-1Mo and 9Cr-1Mo-V. All materials except the 2.25Cr-1Mo steel, the maximum allowable time is 300,000 hours.

Material	Maximum Temperature, °F (°C)	Maximum Temperature, °F (°C)	Maximum Time, hr
304 SS	800 (427)	1,500 (816)	300,000
316 SS	800 (427)	1,500 (816)	300,000
Alloy 800H	800 (427)	1,400 (760)	300,000
2¼Cr–1Mo	700 (371)	1,200 (649)	300,000
9Cr–1Mo–V	700 (371)	1,200 (649)	300,000

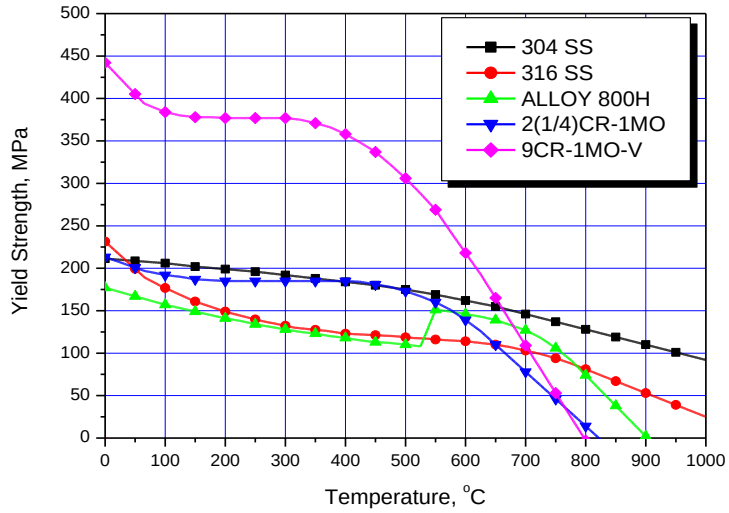
Characteristics of Div5 HBB Code Materials

- Elastic modulus: the Cr-Mo steels such as 9Cr-1Mo-V and 2(1/4)Cr-1Mo steel have much higher elastic modulus than those of the austenitic stainless steels in the design temperature of the PGSFR(545°C). However, the elastic modulus significantly decreases specially in case of the Cr-Mo steels as increasing the temperature.

- Yield strength: 9Cr-1Mo-V steel reveals very high value compared with the other materials. Therefore, the structures may response in an elastic behavior for the design loads when using the 9Cr-1Mo-V steel other than the austenitic stainless steels.



(Elastic Modulus)

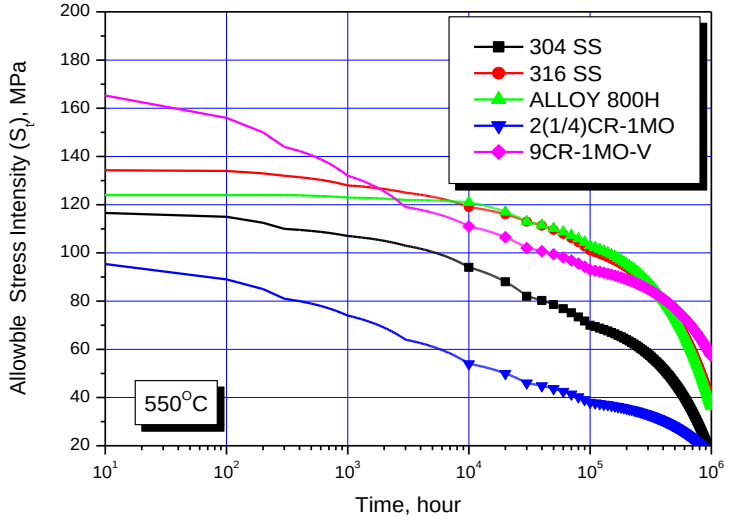


(Yield Strength)

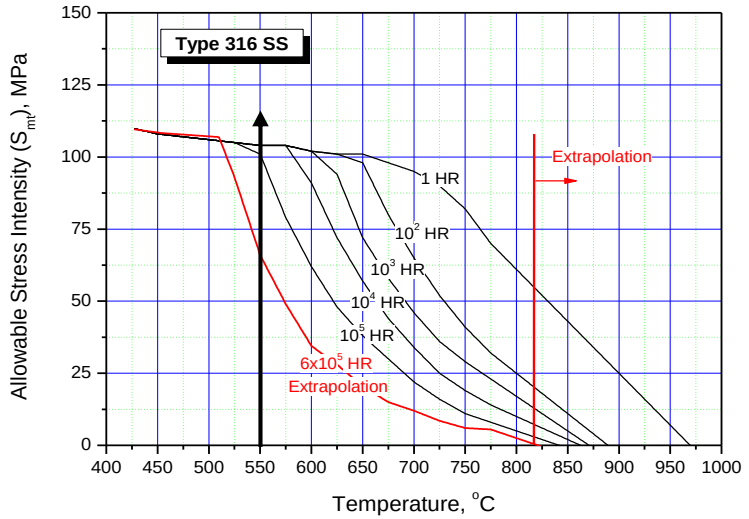
Characteristics of Div5 HBB Code Materials

- Time-dependent allowable stress intensity value (S_t, S_{mt}): When the metal temperatures exceed the ranges of the Section III, Subsection NB, the time-dependent allowable stress intensity values are required as the criteria of the primary stress limits.

- At 550°C, 9Cr-1Mo-V steel has larger values of S_t than those of the austenitic stainless steels in range less than 2,000 hours but over that time, the values significantly decrease and become lower than those of Type 316SS and the Alloy 800H. At end of the 60 years design lifetime, the value of the 9Cr-1Mo-V steel is almost same as those of Type 316SS and Alloy 800H.



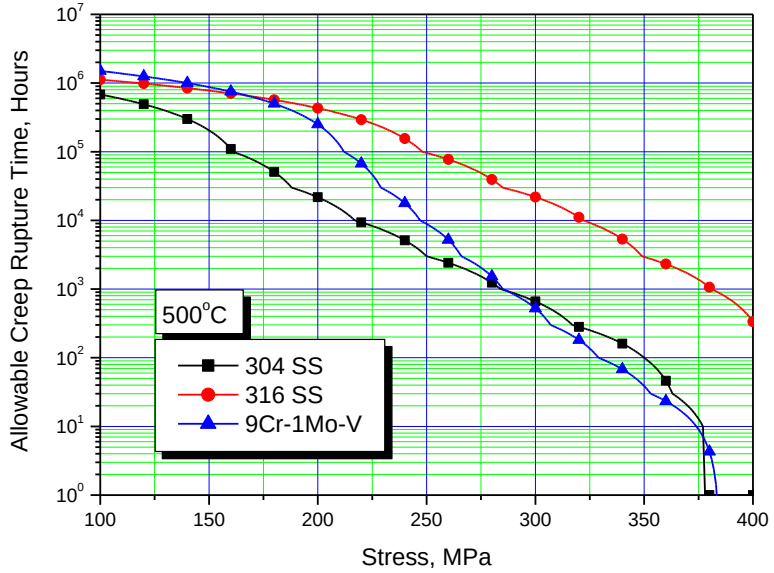
(Allowable Stress, S_t)



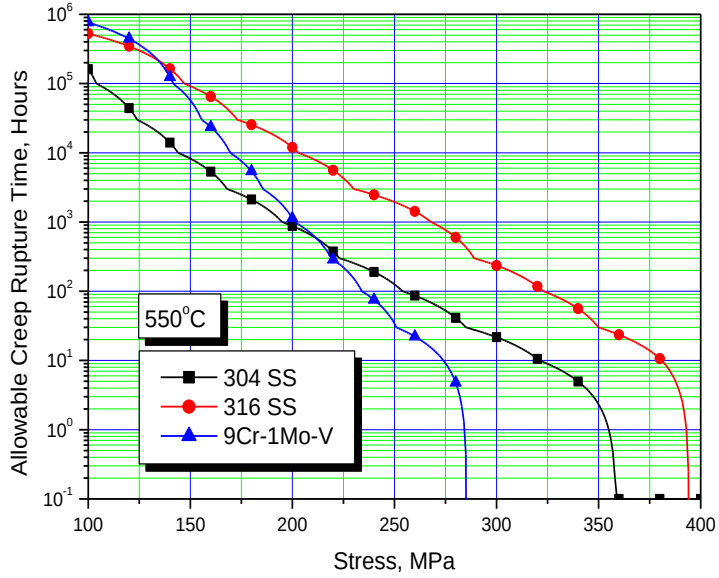
(Allowable Stress, S_{mt})

Characteristics of Div5 HBB Code Materials

- Expected minimum stress-to rupture value (Sr): The Sr values are the expected minimum stress-to-rupture strength required for the Level D Service Limits and the creep damage limits evaluation. As increasing the time and temperature, the creep resistance of the 9Cr-1Mo-V steel is not better than the 316 SS material. Over 1.0×10^5 hours and 510°C, the Type 316SS has higher values of expected minimum stress-to-rupture values than the 9Cr-1Mo-V steel. Type 316 SS has the better performance than the others. Type 316SS is recommended as the creep resistant design material when the design temperature is less than 550°C.



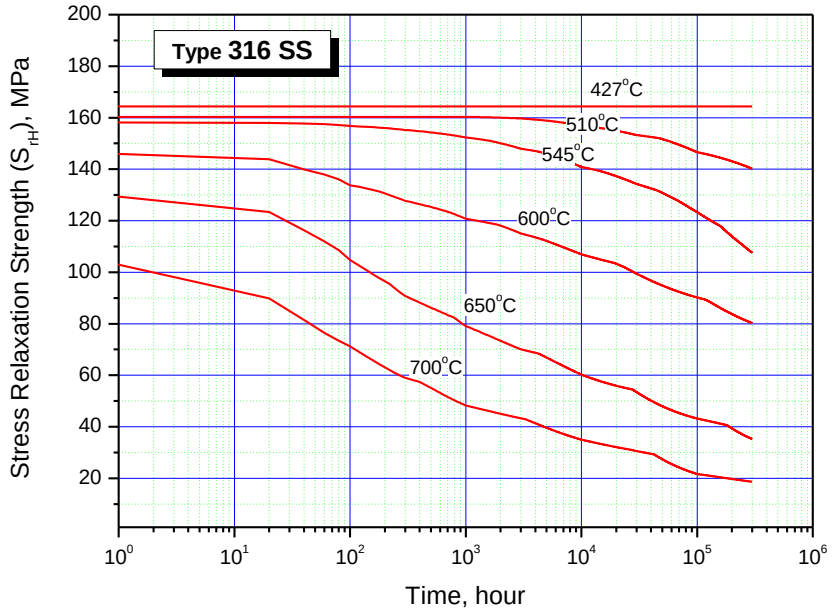
(Allowable Creep Rupture Time at 500°C)



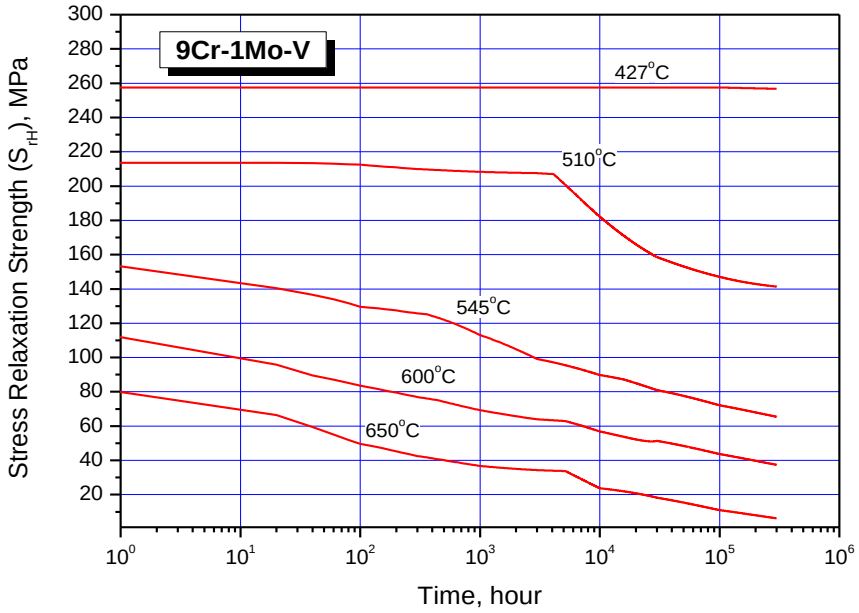
(Allowable Creep Rupture Time at 550°C)

Characteristics of Div5 HBB Code Materials

- Stress Relaxation Strength: By using the isochronous stress-strain curves, the stress relaxation time history data for the creep damage evaluations and the relaxation strength, S_{rH}, can be determined. At 510°C and $1x10^4$ time duration, the stress relaxation strength is about 156 MPa for Type 316SS and 180 MPa for 9Cr-1Mo-V steel. As the time duration and the temperature increase, the S_{rH} values of 9Cr-1Mo-V steel decreases rapidly and become lesser than those of Type 316 SS.



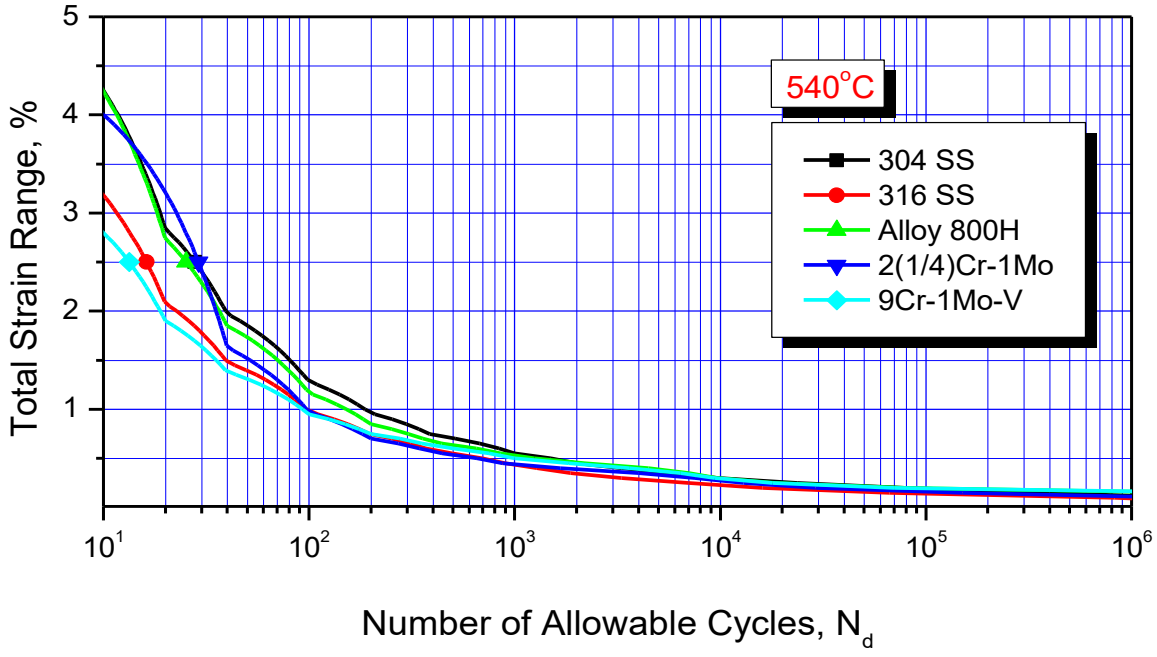
(Stress Relaxation Strength of Type 316SS)



(Stress Relaxation Strength of 9Cr-1Mo-V)

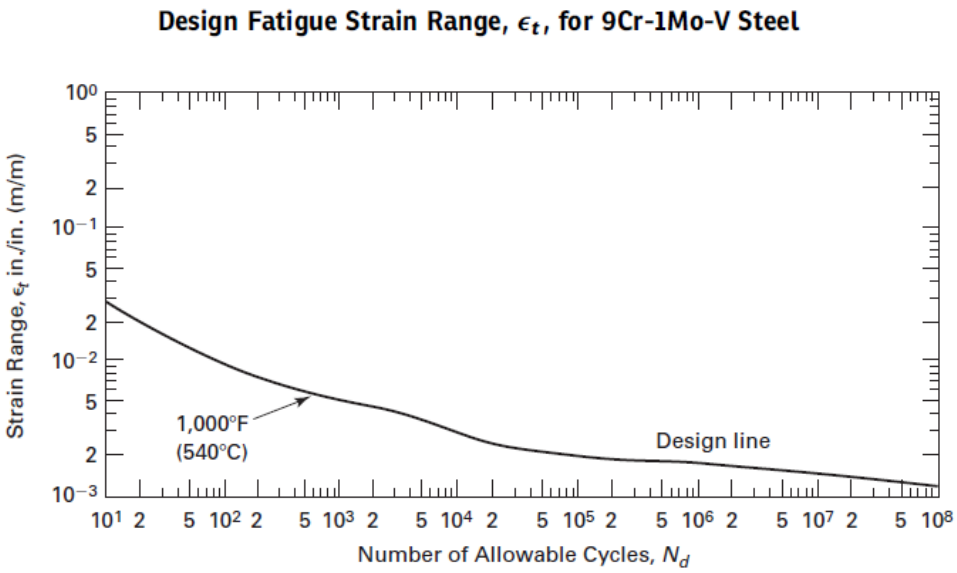
Characteristics of Div5 HBB Code Materials

❖ Design Fatigue Curves: For the design fatigue curves at a design temperature of the PGSFR, Type 304SS and Alloy 800H materials reveal a good fatigue strength but Type 316SS and 9Cr-1Mo-V materials are relatively not good in lower cycle regions. In general, all ASME Sec.III-Division 5 design materials have almost the same fatigue strength at high cycle regions.



(Design Fatigue Curves)

9Cr-1Mo-V Temp. Dependent Design Fatigue Data



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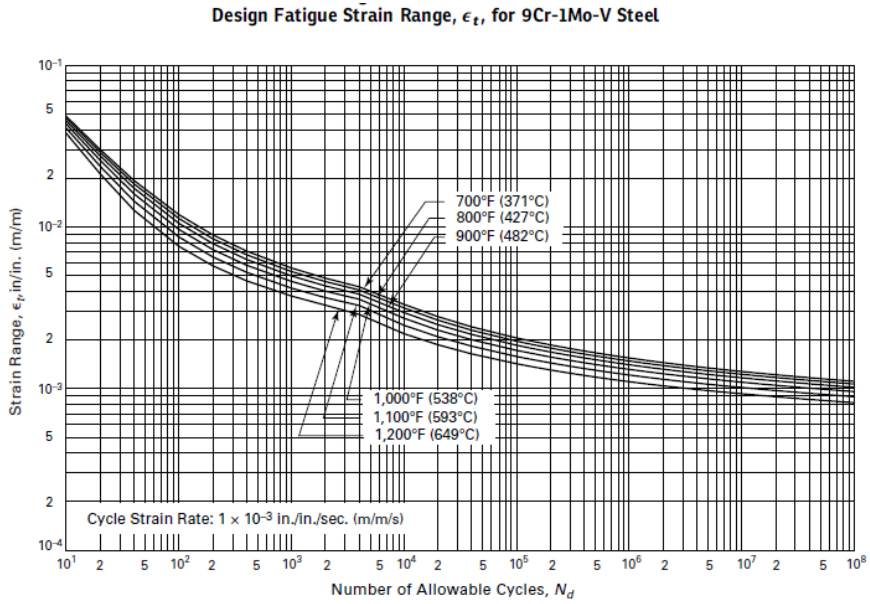

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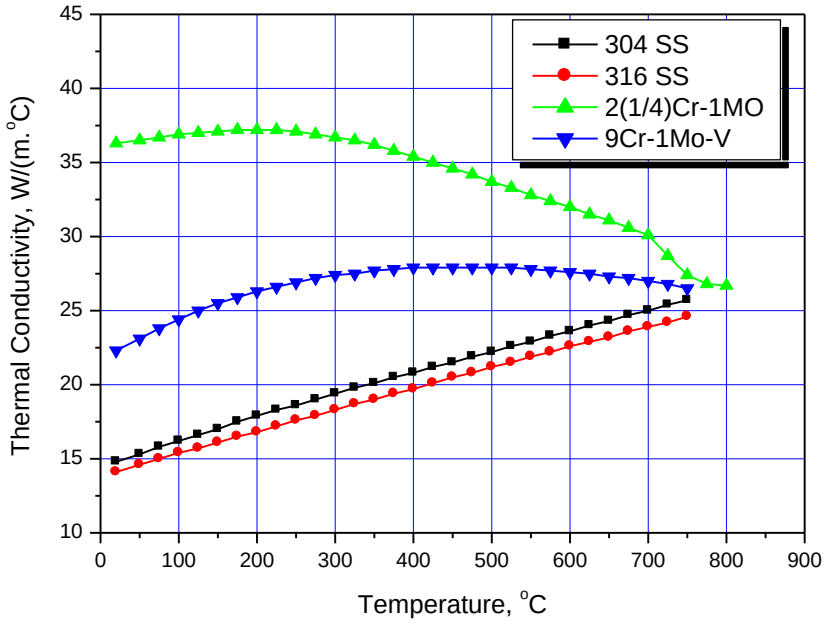
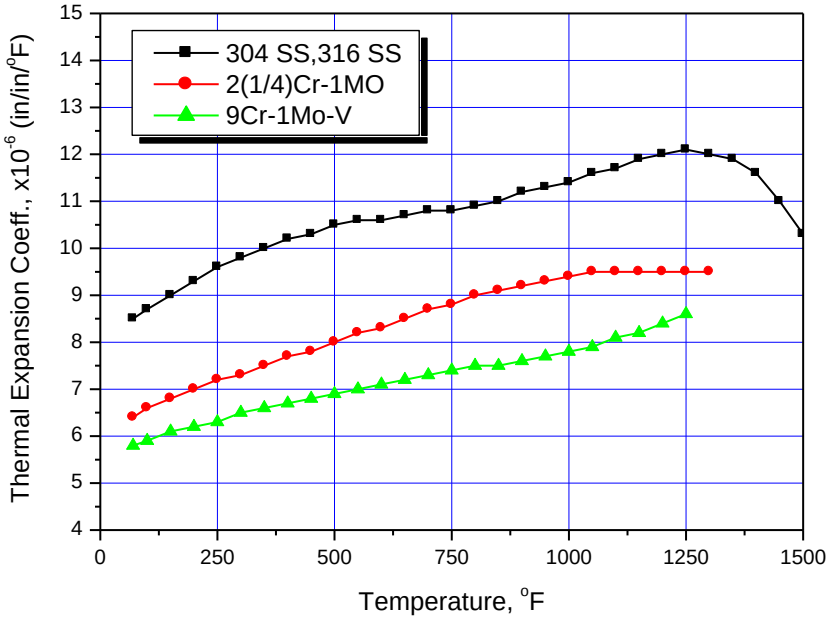
Implemented JSME Data

Characteristics of Div5 HBB Code Materials

- Material Physical Properties: 2(1/4)Cr-1Mo steel and 9Cr-1Mo-V steel have an excellent characteristics of the thermal conductivity compared with the austenitic stainless steel. For the thermal expansion coefficients, the austenitic stainless steel has much higher values than the Cr-Mo steel. Therefore, 9Cr-1Mo-V steel is selected for design material in application to the long structures such as sodium pipes and heat exchanger's tubes.



(Thermal Conductivity)



(Thermal Expansion Coefficient)

Example Design Materials for PGSFR NSSS Components

Components	Design Materials
Reactor vessel	Type 316SS
Containment vessel	2(1/4)Cr-1Mo
Reactor head	Type 316SS
Reactor support	Type 316SS
Reactor internals	Type 316SS
IHX assembly	9Cr-1Mo-V
PHTS Pump	Type 316SS
DHX assembly	9Cr-1Mo-V
CRDM housing	Type 316SS
IVTM master cylinder	Type 316SS
Fuel transfer port	Type 316SS
IHTS piping	9Cr-1Mo-V
IHTS expansion tank	9Cr-1Mo-V
SWRPRS piping	9Cr-1Mo-V
DHRS piping	9Cr-1Mo-V
AHX assembly	9Cr-1Mo-V
FHX assembly	9Cr-1Mo-V

4 Guideline for Design Data Needs for New Materials

Non-mandatory Appendix HBB-Y

For Article HBB-Y-2000: Load-Controlled Limits

- Time-Independent Data
  : Sec II App 5 Data,
  : Monotonic tensile stress-strain curves
  : Thermal expansion coefficients
  : Thermal conductivity and diffusivity
  : Density
  : Poisson’ s ratio
  : Young’ s modu;us

- Time-Dependent Data [So, Smt, St]
  : 100% of the average stress required to obtain 1% total strain
  : 80% of the minimum stress to cause the initiation of tertiary creep
  : 67% of the minimum stress to cause rupture
  : Minimum stress-to-rupture curves

- Tensile Reduction Factors for Aging
  : Yield strength with time and temperature ranges
  : Tensile strength with time and temperature ranges

Non-mandatory Appendix HBB-Y

For Article HBB-Y-3000: Deformation-Controlled Limits

- Isochronous Stress-Strain Curves
- Relaxation Strength Data
- Creep-Fatigue Data
- Creep-Fatigue data for Weldments
- Cyclic Stress-Strain Curves
- Inelastic Constitutive Model
- Huddleston Multiaxial Failure Criterion
- Time-Temperature Limits for External Pressure Charts

Non-mandatory Appendix HBB-Y

For Article HBB-Y-4000: Other Considerations

- Cold-Forming Limits
- Environmental Effects

5 Recent Approval of Alloy 617

Alloy 617 Code Case Background

- Initiated in 2010 to support Very High Temperature Gas Cooled Reactor (VHTR).
- Earlier Code Case (1991) completed but not submitted for BPV-III approval.
  - Program cancelled.
  - Elastic analysis based simplified methods limited to 1200°F.
  - Limited scope & data.
- Current Code Case complies with Appendix Y "…Data Needs for New Materials".
- New Elastic-Perfectly Plastic (EPP) analysis methodology not temperature limited.
- Low temperature rules in CC N-872.

Balloting Actions

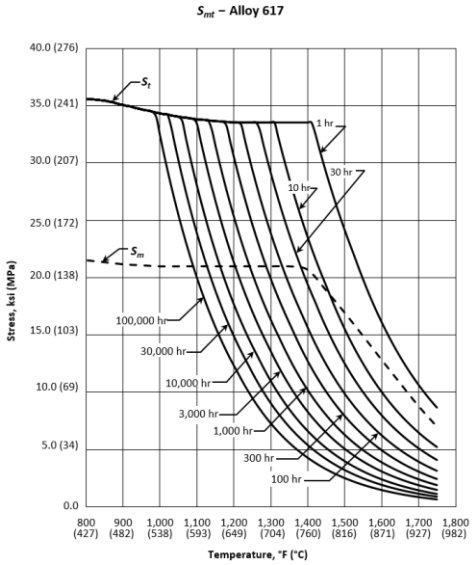
RC #	Item	Section II and III Committees (See Color Key Below For Balloting Actions)								
16-994	Permissible base and weld materials, allowable stress values	WG-ASC	SG-ETD	SG-HTR	SG-MFE	II-SG-NFA	II-SG-SW	BPV-II		
16-995	Physical properties and extension of modulus values to higher temperatures	WG-ASC	SG-ETD	SG-HTR	SG-MFE	II-SG-NFA	II-SG-PP	BPV-II		
16-996	Temperature-time limits for NB buckling charts	WG-AM	SG-ETD	SG-HTR	SG-MFE	II-SG-EP	BPV-II	II-SG-NFA	SC-D	
16-997	Huddleston parameters, ISSCs	WG-ASC	SG-ETD	SG-HTR	II-SG-NFA	BPV-II	SC-D			
16-998	Negligible creep, Creep-Fatigue: D-diagram and EPP	WG-CFNC	SG-ETD	SG-HTR	SC-D					
16-999	EPP strain limits	WG-AM	SG-ETD	SG-HTR	SC-D					
16-1000	Fatigue design curves	WG-CFNC	WG-FS	SG-ETD	SG-HTR	SG-DM	SC-D			
16-1001	Alloy 617 Overall Code Case	WG-ASC	WG-AM	WG-CFNC	WG-FS	SG-ETD	SG-HTR	SG-MFE	SC-D	BPV-II
		BPV-III								

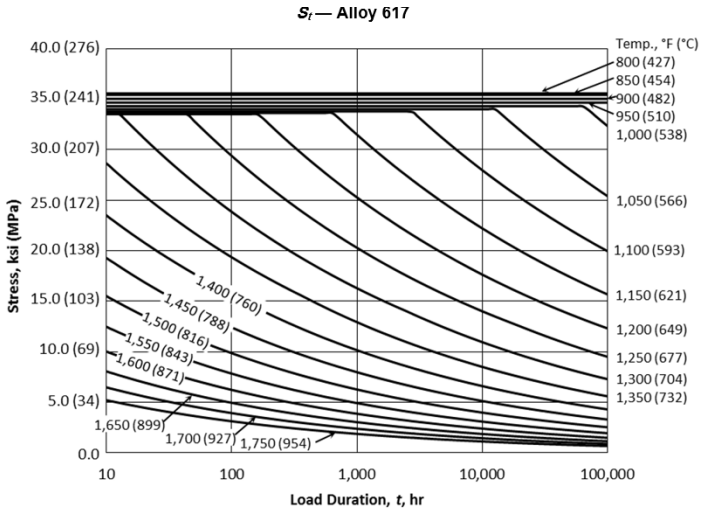
Color Key	Balloting Action
	For Review and Approval
	For Review and Comment

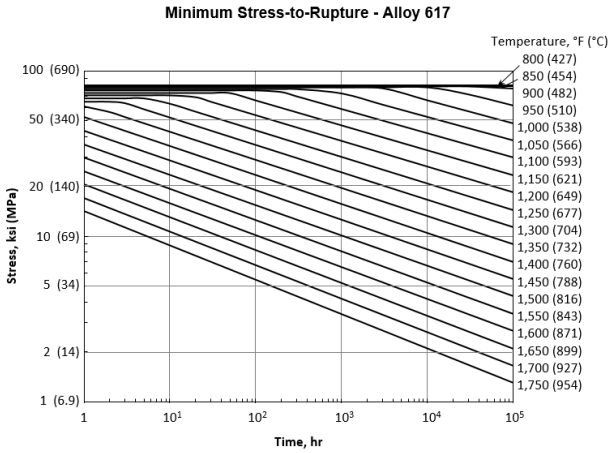
Data Package (RC16-994)

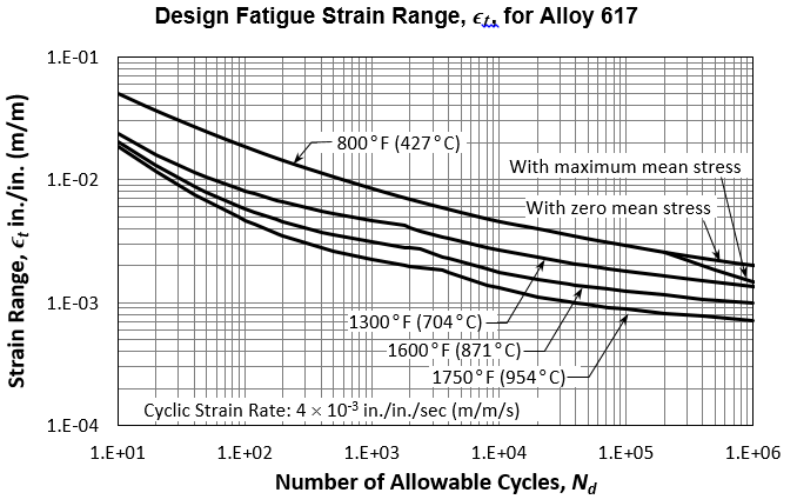
- HBB-I-14.1(a) Permissible Base Materials
- HBB-I-14.1(b) Permissible Weld Materials
- HBB-3225-1 Tensile Strength Values, *Su*
- HBB-I-14.5 Yield Strength Values, *Sy*
- HBB-I-14.2 Maximum Allowable Stress Intensity, So
- HBB-I-14.3 Allowable Stress Intensity, Smt
- HBB-I-14.4 Allowable Stress Intensity, St
- HBB-I-14.6 Minimum Stress-to- Rupture, Sr
- HBB-I-14.10 Stress Rupture Factors for Welded Alloy 617
- HBB-4800 Relaxation Cracking
- HBB-3225-2 Strength Reduction Factor Due to Long Term Prior Elevated Temperature Service
- HBB-4212 Effects of Forming and Bending Processes
- Appendices with Data Compilations support the above

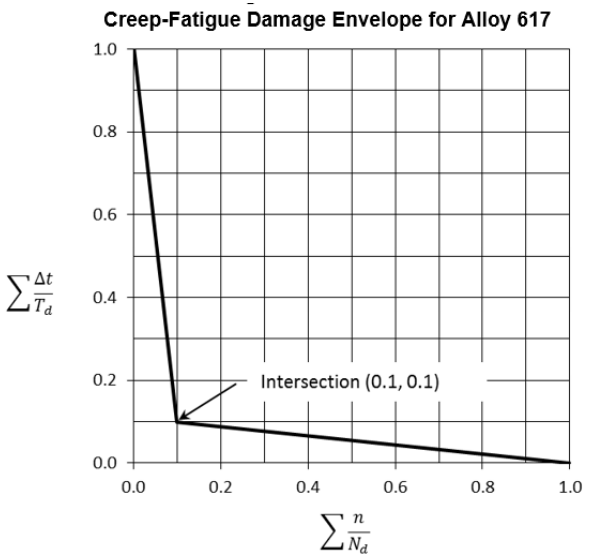
Data Package (RC16-994)

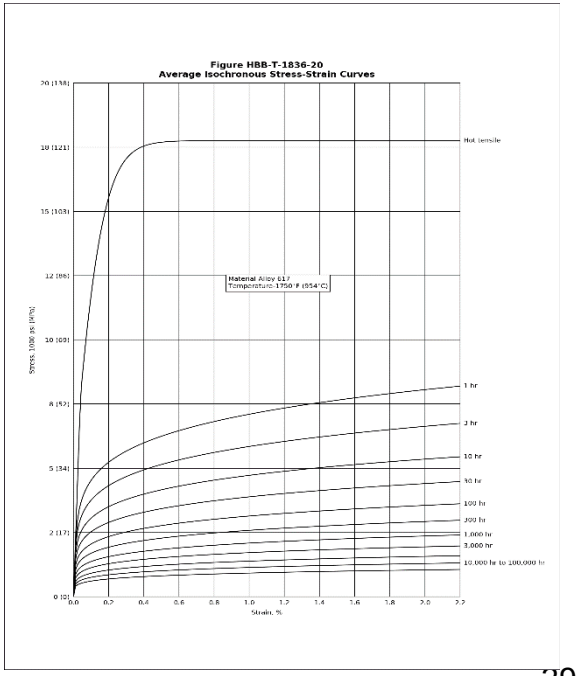












ASME Div 5 Main Issues

Item	Brain storming topics - no order	HTLR	HTGR	2017 Code Edition	beyond 2017
1	New simplified analysis methods that replace current linear analysis (EPP)	Y	Y	X	
2	Evaluation of margins on allowable stresses such as Su at very high temperatures	Y	Y	X	
3	Adequacy of the definition of S values used for the design of Class B components, which is based on extrapolated properties at 100,000 hours, in light of application to 500,000 hours design	Y	Y	X	
4	Design rules for cladded structures	Y	N		X
5	Design rules for "compact" heat exchanges, not just for gas cooled reactors but for other reactor types such as sodium fast reactors and fluoride salt-cooled reactors	Y	Y		X (work starts now)
6	Incorporation of new materials such as Alloy 617 and Alloy 709 (austenitic stainless steel)	Y	Y	617	709
7	NCA rewrite: Division 5 needs to consider design specification requirements.	Y	Y	X ?	
8	Design rules for composites such as SiC-SiC	Y (salt)	Y?		X
9	Revisiting component classification: Is Class B really necessary?	Y	Y		X
10	Pursuit of "all temperature code"	Y	Y		X (work starts now)

ASME Div 5 Main Issues

11	Design rules for "very high temperatures" with the term "very high temperature" clearly defined	N?	Y		X (work starts now)
12	Issues on bonding including evaluation procedures of welded joints at very high temperatures for compact heat exchanger	Y	Y		X (work starts now)
13	Extension of Alloy 800H for 500,000 hr-design	N	Y	X	
14	Extension of SS304, 316 for 500,000 hr-design	Y	Y	X	
15	Extension of Grade 91 for 500,000 hr-design	Y	Y	X	
16	SMT creep-fatigue design method - without D-diagram	Y	Y		X
17	Inspection techniques	Y	Y		X (work starts now)
18	Flaw evaluations	Y	Y		X (work starts now)
19	Flaw tolerance design	Y	Y		X
20	Thermal striping	Y	Y	X (Koo)	
21	Disimilar Metal Welds	Y	Y		X

Thank You !