Risks of non-conservative design for pressure vessels subjected to long-time service in creep range according to ASME Section VIII Div.2

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KAERI

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Outline

1. Introduction

2. ASME Section VIII Division 2 for high-temperature design of pressure vessel (PV)

    2.1 How creep is considered

    2.2 Technical issues of ASME VIII(2)

3. Quantification of conservatism in ASME VIII(2)

    3.1 Application to a heat exchanger (IHX)

    3.2 Application to a pressure vessel (Reservoir)

4. Securing integrity in ASME VIII(2) design for long-term creep conditions

5. Concluding remarks

1. Introduction

❖ **Design rules for pressure boundary components (pressure vessel, HXs etc.)**

- **Non-nuclear grade**
  - **ASME Section VIII Div.1 (Design-By-Rule : DBR) & Div.3**
  - **ASME Section VIII Div.2 (Design-By-Analysis : DBA, Part 5) ⇒ 'ASME VIII(2)'**
- **Nuclear grade**
  - **ASME Section III Div.1 Subsection NB (-3200, sub-creep)**
  - **ASME Section III Div.5 Subsection HB ('ASME-HB')**
  - **RCC-MRx RB**

❖ **Technical issues on 'ASME VIII(2)' for long-term operation at high temperature**

- **No explicit consideration of creep (consider through max allowable stress)**
- **Design evaluation results do not change depending on operation time at high temperature**

2. ASME VIII(2) for high-temperature design of PV*

❖ ASME Section VIII Div.2 requirements

- Protection against the failure modes (Part 5, DBA)

① Plastic collapse $P_m \le S$, $P_L \le S_{PL}$, $(P_L + P_b) \le S_{PL}$

② Local failure $(\sigma_1 + \sigma_2 + \sigma_3) \le 4S$

③ Collapse from buckling

④ Ratcheting assessment $\Delta S_{n,k} \le S_{PS}$

⑤ Failure from cyclic loading $D_f = \sum_{k=1}^{M} D_{f,k} \le 1.0$

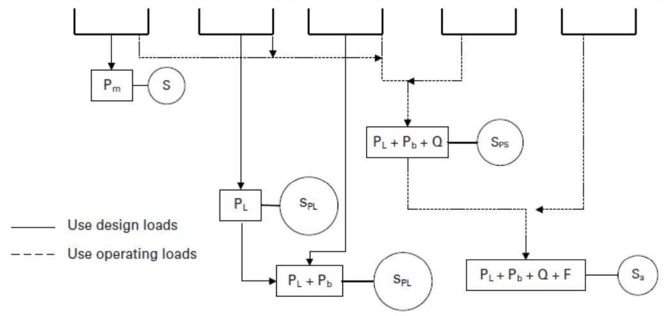
$$\Delta\sigma_{ij,k} = {}^{m}\sigma_{ij,k} - {}^{n}\sigma_{ij,k}$$

$$\Delta S_{p,k} = \frac{1}{\sqrt{2}}\left[\left(\Delta\sigma_{11,k} - \Delta\sigma_{22,k}\right)^2 + \left(\Delta\sigma_{11,k} - \Delta\sigma_{33,k}\right)^2 + \left(\Delta\sigma_{22,k} - \Delta\sigma_{33,k}\right)^2 + 6\left(\Delta\right.\right.$$

$$S_{alt,k} = \frac{K_f \cdot K_{e,k} \cdot \Delta S_{P,k}}{2}$$

Figure 5.1
Stress Categories and Limits of Equivalent Stress

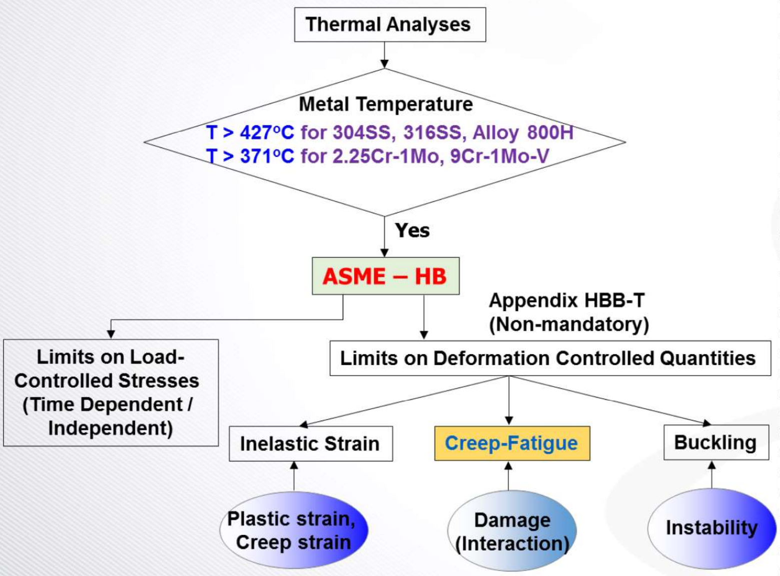
Stress Category	Primary			Secondary Membrane plus Bending	Peak
	General Membrane	Local Membrane	Bending		
Description (For examples, see Table 5.2)	Average primary stress across solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads.	Average stress across any solid section. Considers discontinuities but not concentrations. Produced only by mechanical loads.	Component of primary stress proportional to distance from centroid of solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads.	Self-equilibrating stress necessary to satisfy continuity of structure. Occurs at structural discontinuities. Can be caused by mechanical load or by differential thermal expansion. Excludes local stress concentrations.	1. Increment added to primary or secondary stress by a concentration (notch). 2. Certain thermal stresses which may cause fatigue but not distortion of vessel shape.
Symbol	P_m	P_L	P_b	Q	F



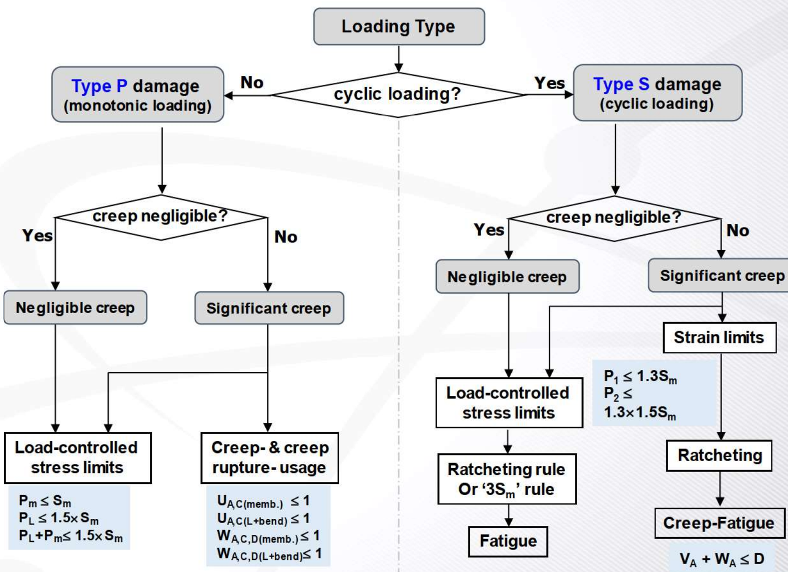
*PV : Pressure Vessel

High-Temperature Design Rules (nuclear grade)

❖ ASME-HB*



❖ RCC-MRx



How creep is considered in ASME VIII(2)

❖ Allowable stress (*S*) in creep range

(1) $\sigma_{avg.}$ to produce a creep rate of 0.01%/1,000h

(2) 67%* of $\sigma_{avg.}$ to cause rupture at 100,000 h.

(3) 80% of σ_{min} to cause rupture at 100,000 h

➢ min. in the above ⇒ *S*

* : In general 100 F_{avg} %

❖ Allowable stress (*S*) in non-creep range**

(1) 1/3 TS (σ_{TS})***

(2) 2/3 YS (σ_{TS})****

➢ min. in the above ⇒ *S*

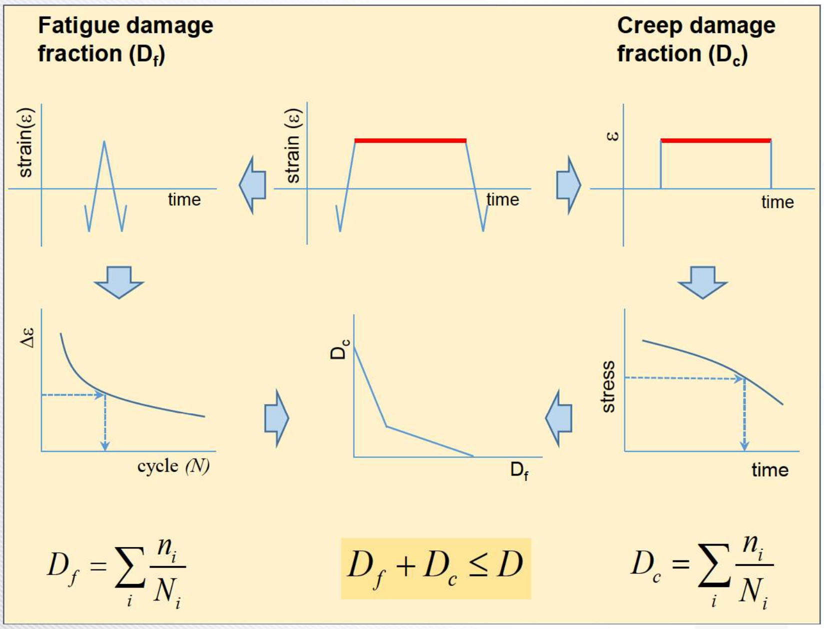
**T ≤ 427°C : 304SS, 316SS, Alloy 800H (ASME-HB)
T ≤ 371°C : 9Cr-1Mo-V, 2.25Cr-1Mo

*** min. TS @ RT or TS @ temperature.

**** min. YS @ RT or YS @ temperature

Technical Issues on ASME VIII (2) in application on PVs

❖ **Creep-Fatigue Damage Evaluation in ASME-HB & RCC-MRx**



❖ **Consideration of creep in ASME VIII (2)**

(1) $\sigma_{avg.}$ to produce a creep rate of 0.01%/1,000h

(2) 67%* of $\sigma_{avg.}$ to cause rupture at 100,000 h.

(3) 80% of σ_{min} to cause rupture at 100,000 h

Hold (operation) time @ high temp. does not affect design evaluation results

Explicit consideration of creep
⇒ ASME-HB or RCC-MRx RB-3200

3. Quantification of conservatism in ASME VIII(2)

❖ **Operating conditions : long-term operation at high temperature in creep range**

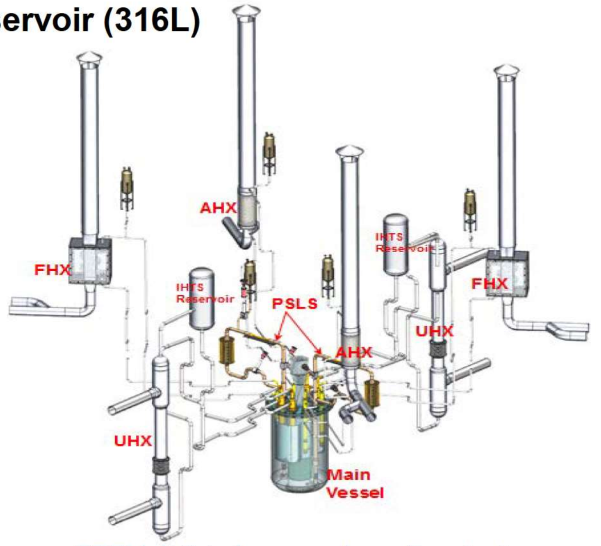
❖ **Actual applications : IHX (heat exchanger, P91 steel), Reservoir (316L)**

❖ **Design rules** (Influence of hold time)

- **ASME VIII Div.2** (implicit consideration of creep)
- **ASME-HB***
- **RCC-MRx**

⇒ **Code comparison (conservatism) :**

ASME VIII(2), ASME-HB*, RCC-MRx

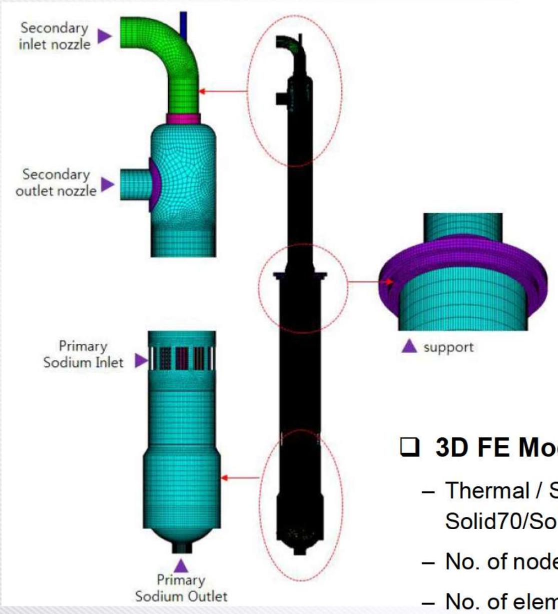


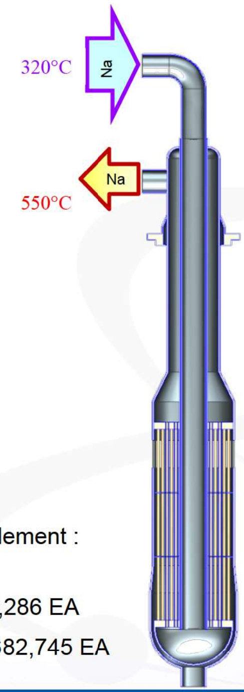
STELLA-2 (a large-scale sodium test facility under construction at KAERI.

* : ASME-HB Div.5 : no material properties at high temp. for 316L SS

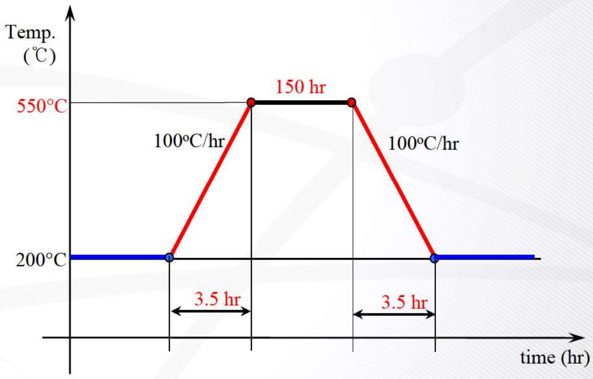
Application – IHX (1/5)

❖ IHX (P91 steel)





❑ Design Transients

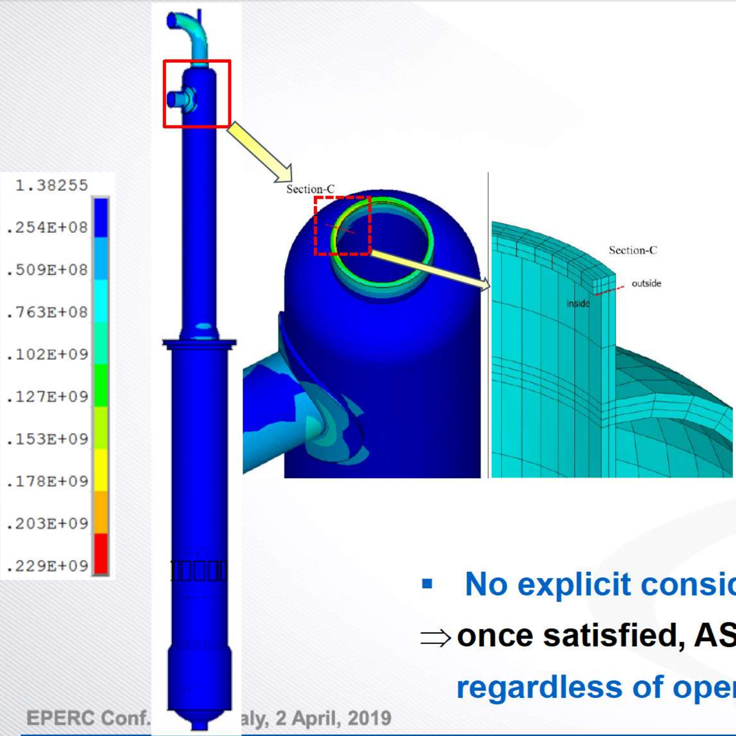


Fluid (sodium) temperature (shell-side)

❑ 3D FE Model

- Thermal / Stress element : Solid70/Solid185
- No. of nodes : 554,286 EA
- No. of elements : 682,745 EA

Application – IHX (2/5)



❖ Evaluation results as per ASME VIII(2)

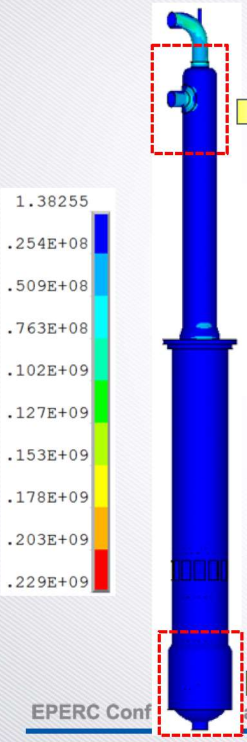
Cases	Criteria	Maximum stress (MPa)	Allowable stress (MPa)	Ratio
Plastic collapse	P_m	9.3	115.0	0.081
	P_L	9.3	172.5	0.054
	P_L+P_b	16.4	172.5	0.095
Local failure	$\sigma_1+\sigma_2+\sigma_3$	3.8	460.0	0.008

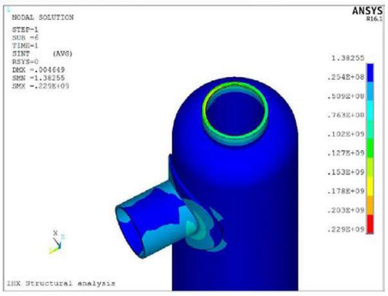
Criteria	Max stress range (MPa)	Allowable stress (MPa)	Ratio
$\Delta S_{n,k}$ (P_L+P_b+Q) Range	119.8	345.0	0.347

- **No explicit consideration of creep in the above rules.**

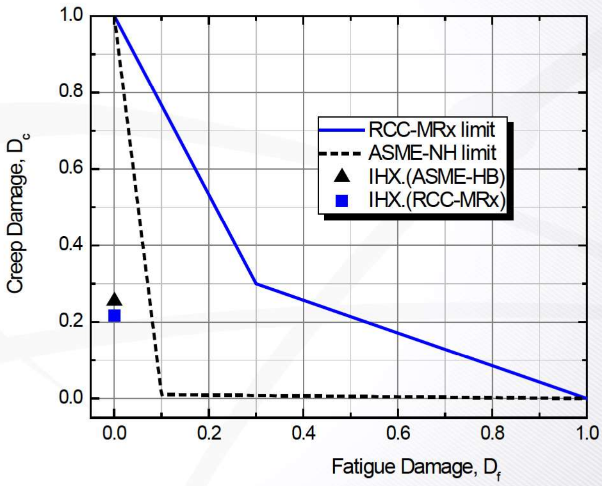
⇒ **once satisfied, ASME VIII(2) requirements always satisfied regardless of operation time.**

Application – IHX (3/5)





❖ **Evaluation results as per ASME-HB & RCC-MRx**



Creep-Fatigue Damage evaluation results
(Design lifetime : 20-Year (75,000h @550°))

- **Explicit consideration of creep**

⇒ **C-F damage satisfied for design lifetime.**

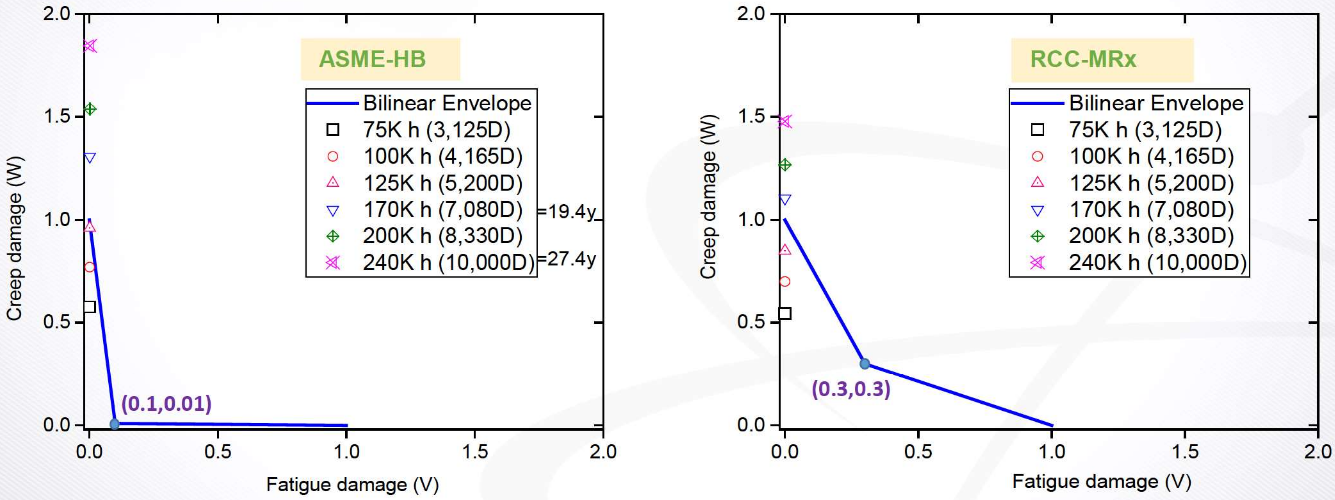
Application – IHX (4/5)

❖ Sensitivity analysis results on operation time (RCC-MRx)

Evaluation Items			Limit value	Calculated					
				20-Y	26.7-Y	33-Y	45.3-Y	53.3-Y	64-Y
Hold time, hr(day)			·	75,000 (3,125)	100,000 (4,165)	125,000 (5,200)	170,000 (7,080)	200,000 (8,330)	240,000 (10,000)
P Type Damage	Negligible Creep	$P_m < S_m$	126	9.9749	9.9749	9.9749	9.9749	9.9749	9.9749
		$P_L < 1.5S_m$	189	9.9749	9.9749	9.9749	9.9749	9.9749	9.9749
		$P_L + P_b < 1.5S_m$	189	12.905	12.905	12.905	12.905	12.905	12.905
	Significant Creep	$U(\Omega P_m)$	1	1.8266E-5	2.4355E-5	3.0443E-5	4.1403E-5	4.8710E-5	5.8452E-5
		$U(P_m+P_b)$	1	6.4619E-5	8.6159E-5	0.0001	0.0001	0.0001	0.0002
		$W(1.35P_m)$	1	4.8528E-5	6.4704E-5	8.0880E-5	0.0001	0.0001	0.0001
		$W[1.35(P_m+\Phi P_b)]$	1	0.0001	0.0002	0.0002	0.0003	0.0004	0.0005
S Type Damage	Negligible Creep	$P_1 < 1.3\ S_m$	163.8	34.887	34.887	34.887	34.887	34.887	34.887
		$P_2 < 1.3 \times 1.5\ S_m$	245.7	39.682	39.682	39.682	39.682	39.682	39.682
		$Max(P_m + P_b) + Max\ q(j,j') < 3\ S_m$	378	134.92	134.92	134.92	134.92	134.92	134.92
		Fatigue Damage	1	Negligible	Negligible	Negligible	Negligible	Negligible	5.0105E-6
	Significant Creep	$\varepsilon_{plastic} + \varepsilon_{creep}$ $(1.25\ P_1) < 0.5\ \%$	0.5	0.0166	0.0183	0.0198	0.022	0.0232	0.0247
		$\varepsilon_{plastic} + \varepsilon_{creep}$ $(1.25\ P_3) < 1\ \%$	1	0.0256	0.0282	0.0304	0.0338	0.0358	0.0381
		Fatigue Damage	Bilinear Envelop in Fig. 1	Negligible	Negligible	Negligible	Negligible	Negligible	5.0105E-6
		Creep Damage		0.5443	0.6999	0.849	1.1047	1.2679	1.478
Evaluation Results			·	OK	OK	OK	Fail	Fail	Fail

Application – IHX (5/5)

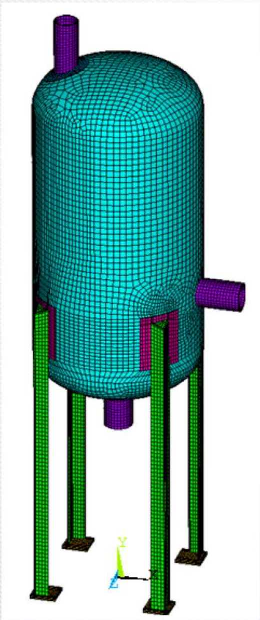
❖ **Creep-Fatigue Damage (P91 steel)**

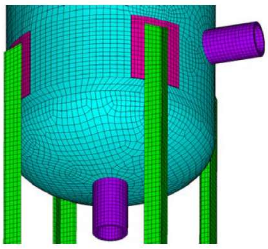


❖ **Conservatism : ASME VIII (2) > ASME-HB > RCC-MRx**

Application – Reservoir (1/4)

❖ **Reservoir (304 SS)**



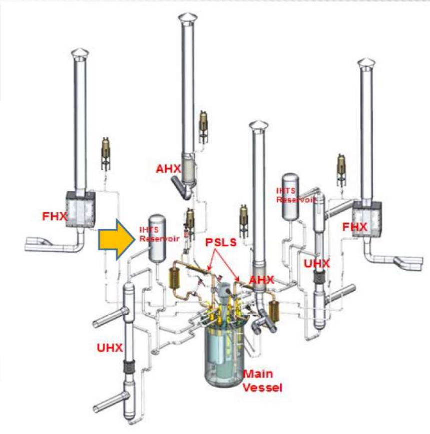


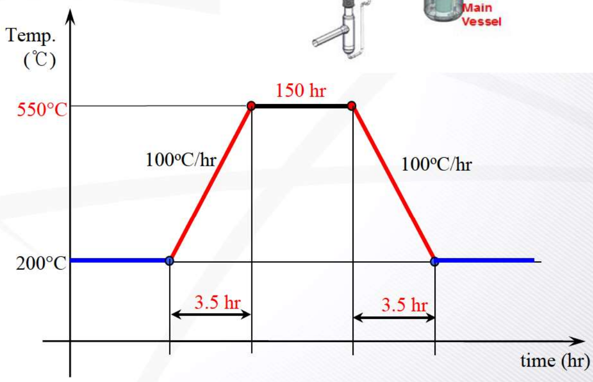
❑ 3D FE Model

– Thermal / Stress element : Solid70/Solid185

– No. of nodes : 43,706 EA

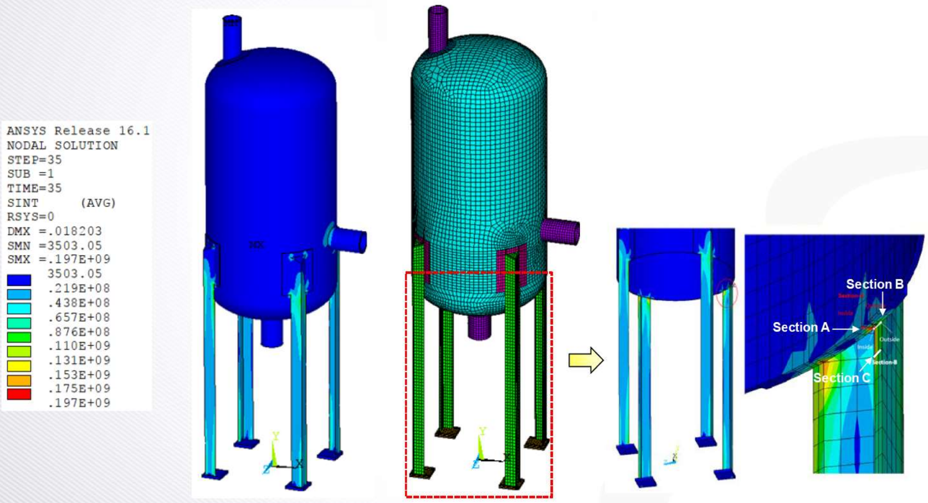
– No. of elements : 29,193 EA

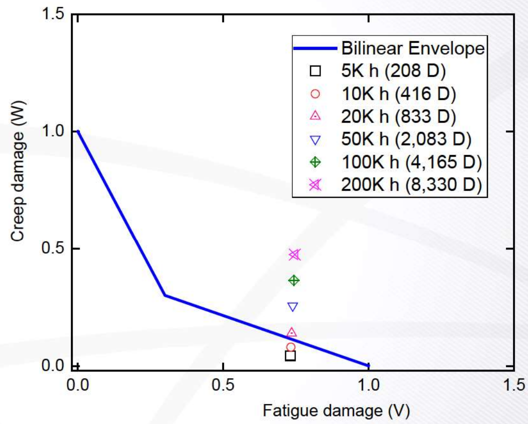




Design Transients

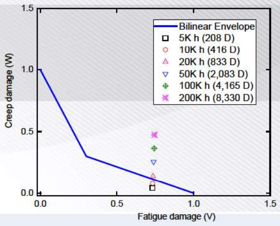
Application – Reservoir (2/4)





Creep-Fatigue Damage evaluation results (304SS)

Application – Reservoir (3/4)



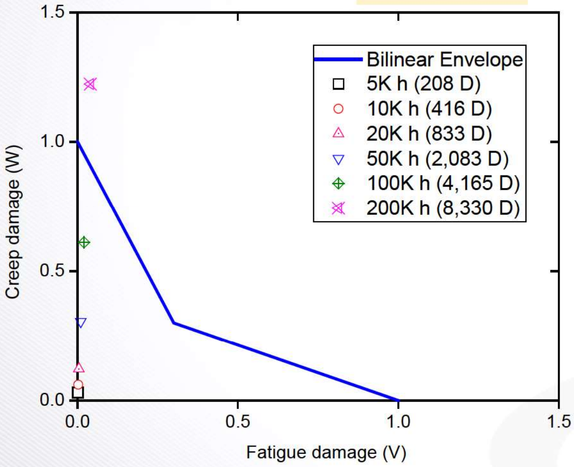
❖RCC-MRx analysis results

Evaluation Items			Limit value	Calculated					
Hold time, hr(day)			·	5,000 (208 D)	10,000 (416 D)	20,000 (833 D)	50,000 (2,083 D)	100,000 (4,165 D)	200,000 (8,330 D)
P Type Damage	Negligible Creep	$P_m < S_m$	77.16	16.593	16.593	16.593	16.593	16.593	16.593
		$P_L < 1.5S_m$	115.74	16.593	16.593	16.593	16.593	16.593	16.593
		$P_L + P_b < 1.5S_m$	115.74	16.749	16.749	16.749	16.749	16.749	16.749
	Significant Creep	$U(\Omega P_m)$	1	6.0379E-7	1.2075E-6	2.4151E-6	6.0379E-6	1.2075E-5	2.4151E-5
		$U(P_m+P_b)$	1	5.9884E-7	1.1976E-6	2.3953E-6	5.9884E-6	1.1976E-5	2.3953E-5
		$W(1.35P_m)$	1	2.6186E-7	5.2373E-7	1.0474E-6	2.6186E-6	5.2373E-6	1.0474E-5
		$W[1.35(P_m+\Phi P_b)]$	1	2.5968E-7	5.1937E-7	1.0387E-6	2.5968E-6	5.1937E-6	1.0387E-5
S Type Damage	Negligible Creep	$P_1 < 1.3\ S_m$	100.3	54.702	54.702	54.702	54.702	54.702	54.702
		$P_2 < 1.3 \times 1.5\ S_m$	150.46	54.959	54.959	54.959	54.959	54.959	54.959
		$Max(P_m + P_b) + Max\ q(j,j') < 3\ S_m$	231.48	197.08	197.08	197.08	197.08	197.08	197.08
		Fatigue Damage	1	0.7318	0.7332	0.7354	0.7394	0.7431	0.7466
	Significant Creep	$\varepsilon_{plastic} + \varepsilon_{creep}\ (1.25\ P_1) < 0.5\ \%$	0.5	0.0786	0.1138	0.1376	0.149	0.159	0.1766
		$\varepsilon_{plastic} + \varepsilon_{creep}\ (1.25\ P_3) < 1\ \%$	1	0.0784	0.1135	0.1373	0.1488	0.1587	0.1763
		Fatigue Damage	Bilinear Envelop in Fig. 2	0.7318	0.7332	0.7354	0.7394	0.7431	0.7466
		Creep Damage		0.0427	0.0792	0.1386	0.2559	0.3641	0.4736
Evaluation Results			·	OK	OK	Fail	Fail	Fail	Fail

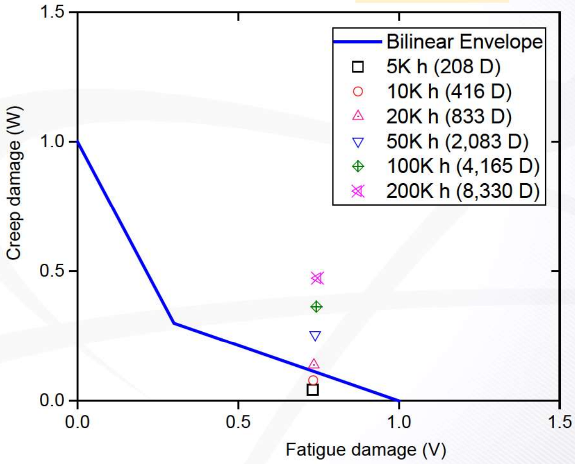
Application – Reservoir (4/4)

❖ Creep-Fatigue Damage

RCC-MRx



ASME-HB



❖ **Conservatism : ASME VIII (2) > RCC-MRx > ASME-HB**

4. Securing integrity in ASME VIII(2) design (for long-term creep condition)

❖ **If pressure vessels to be designed for long-term service as per ASME VIII(2)**

- Creep effects should be quantified based on nuclear codes (ASME-HB or RCC-MRx)
- If creep effects are not negligible, design should be checked as per ASME-HB or RCC-MRx.
- If creep effects are negligible, design evaluation just as per ASME VIII(2) would be OK.

❖ **If PVs designed as per ASME VIII(2) already under operation in long-term service**

- Creep effects need to be quantified based on the nuclear codes
- If creep effects are not negligible from the evaluations,
  - ➢ Prior actions against creep rupture need to be taken
  - ➢ Reinforced NDE required associated with creep damage.

5. Concluding remarks

❖ **Technical issues on pressure vessel design as per ASME VIII(2) subjected to long-term creep conditions**

- Creep (Hold Time) : implicitly considered
- ASME VIII(2) once satisfied, design is satisfied regardless of HT

❖ **Comparison of conservatism under long-term operation in creep range (IHX)**

- ASME VIII(2) : design satisfied regardless of hold time
- ASME-HB : design limit exceeded over HT ≥ 125K h (creep-Fatigue Failure)
- RCC-MRx : design limit exceeded over HT ≥ 170K h (creep-Fatigue Failure)

❖ **ASME VIII(2) might be non-conservative for long-term creep conditions**

THANK YOU

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