

Design evaluations of high temperature piping system in sodium test facility

-ASME B31.1, RCC-MRx

2017.05.19

손 석 권, 이 형 연, 정 지 영

skson0831@kaeri.re.kr

SFR 계통설계부



한국원자력연구원

Korea Atomic Energy Research Institute

Introduction(1/5)

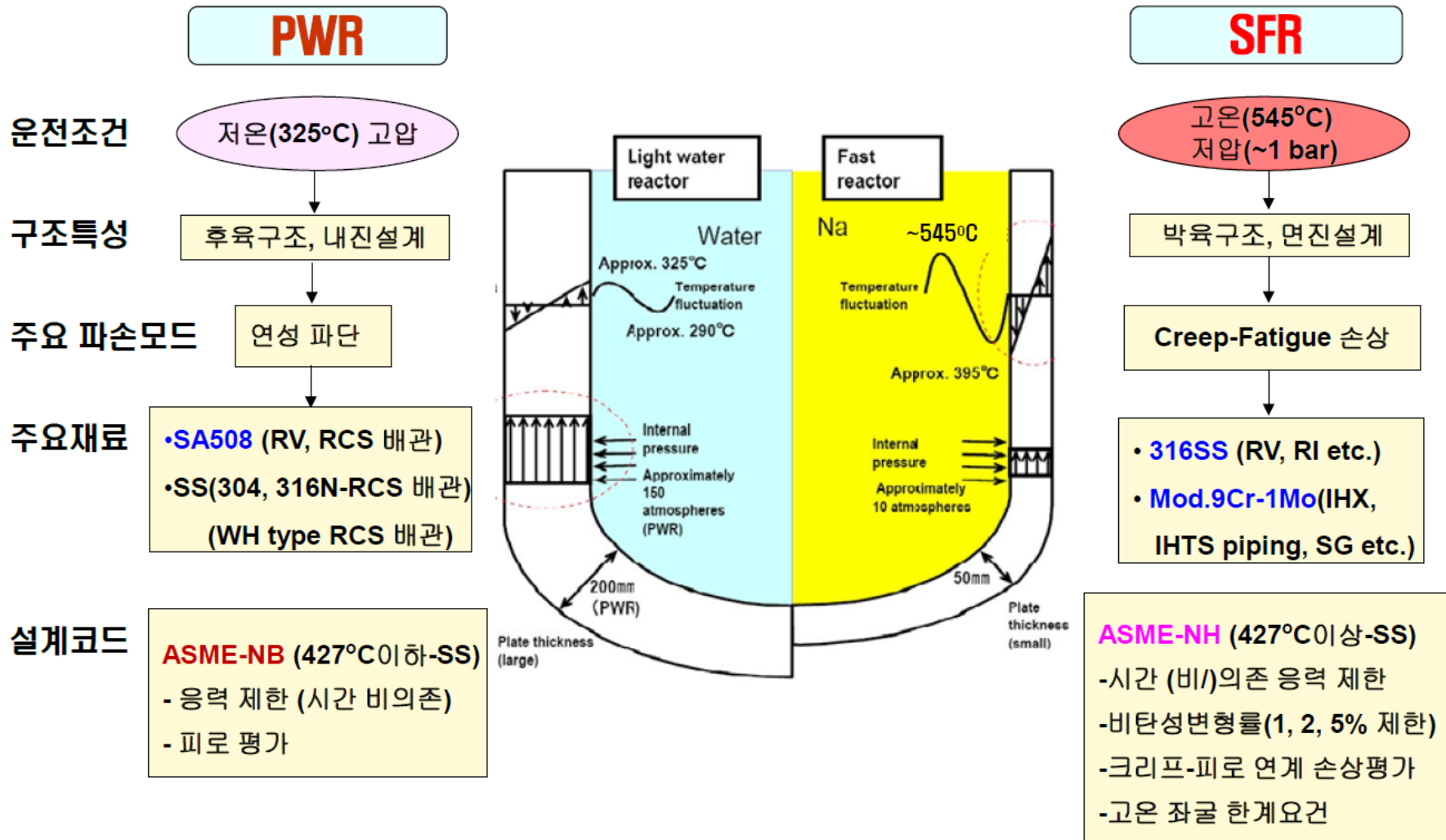


- ❖ 본 연구는 SFR 시험시설의 고온배관에 대해 설계기술기준인 ASME B31.1과 RCC-MRx(RD-3600, RB-3200) 설계 및 구조건전성 평가를 수행함.
 - SFR의 기계구조물은 고온저압의 운전조건에서 가동되고, 열응력 완화를 위해 박육구조를 채택하고 있음.
 - SFR의 배관은 큰 직경 및 길이에 비해 두께가 매우 얇음. 배관 설계 및 건전성 평가를 수행할 때 1D pipe element model을 사용하는 것이 3D solid element model보다 편리함.
 - 산업용 압력배관 설계기술기준인 ASME B31.1 및 원자력등급인 RCC-MRx RD-3600을 사용하여 SFR 고온 배관설계 평가를 수행함. 이 두 설계기술기준은 creep-fatigue interaction를 고려하지 못하기 때문에, 동 interaction영향의 정량적 분석을 위해 RB-3200(DBA)를 적용함.
 - 설계기술기준 DBR (B31.1 & RD-3600) 및 DBA(RB-3200)의 보수성을 비교 분석함.

Introduction(2/5)



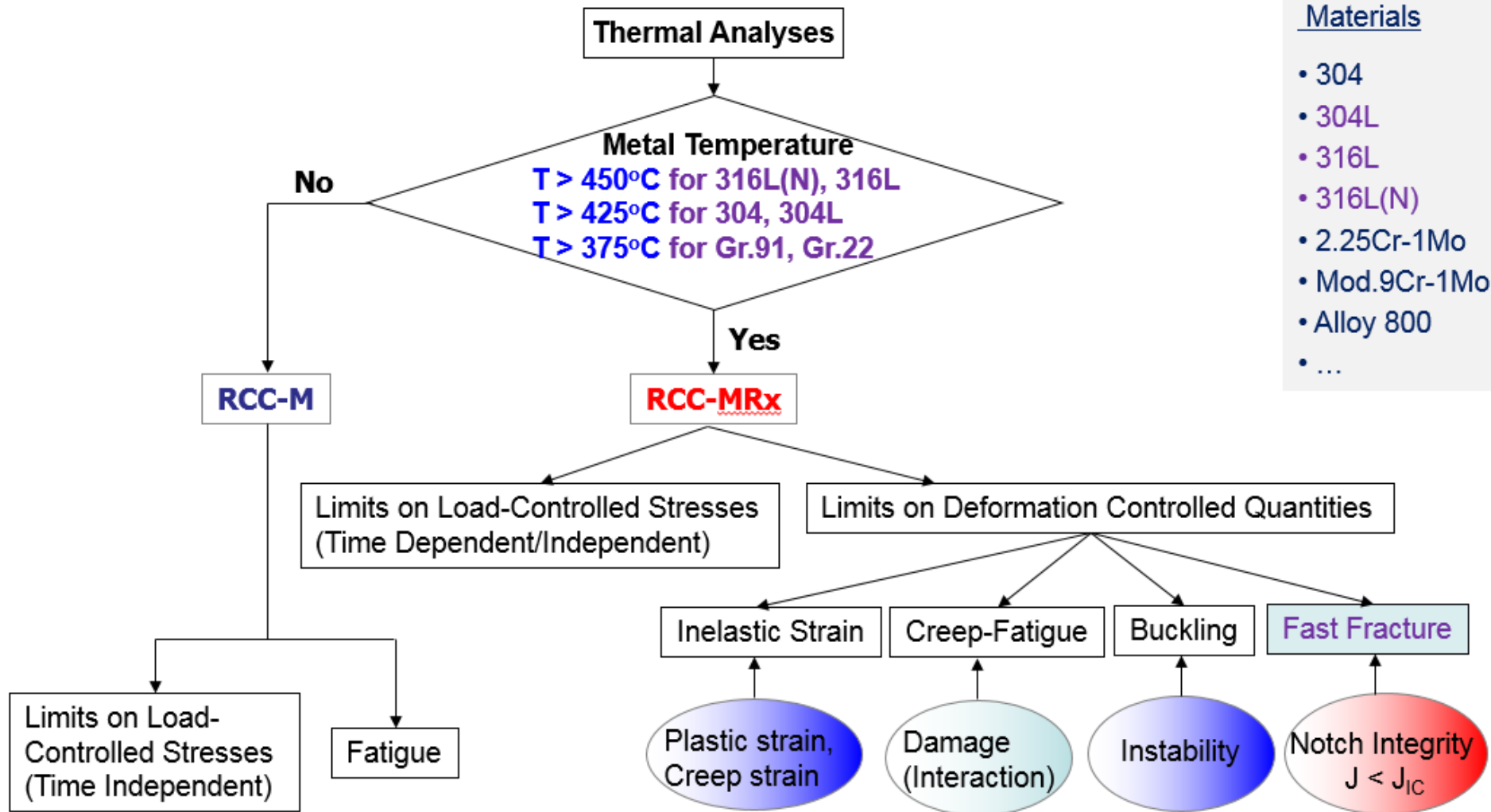
❖ Design feature of PWR and SFR



Introduction(3/5)



❖ RCC-MRx overall procedures



Materials

- 304
- 304L
- 316L
- 316L(N)
- 2.25Cr-1Mo
- Mod.9Cr-1Mo
- Alloy 800
- ...

Introduction(4/5)



STELLA-2* IHTS** Hot leg

* High temperature condition on SFR test facility

** Intermediate Heat Transfer System

DBR (Design-By-Rule)

DBA (Design-By-Analysis)

ASME
B31.1

RCC-MRx
RD-3600

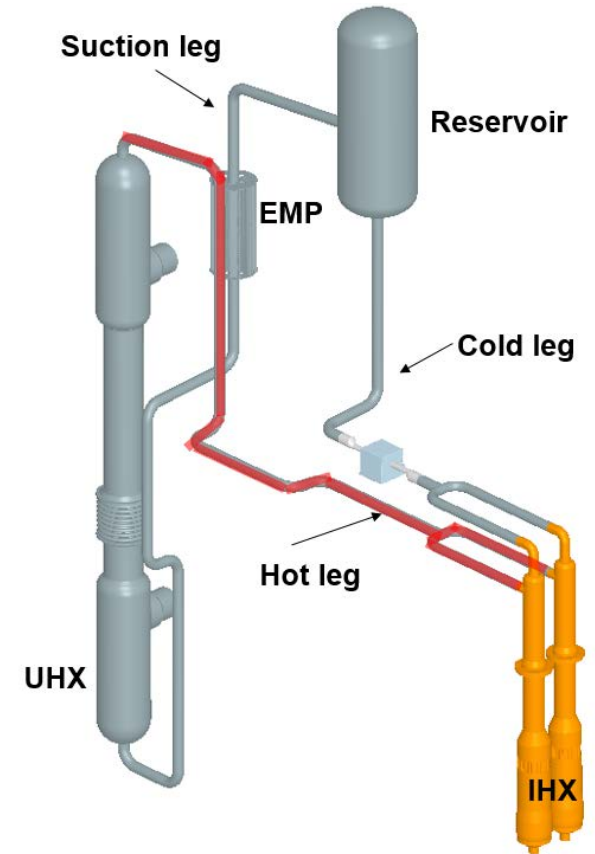
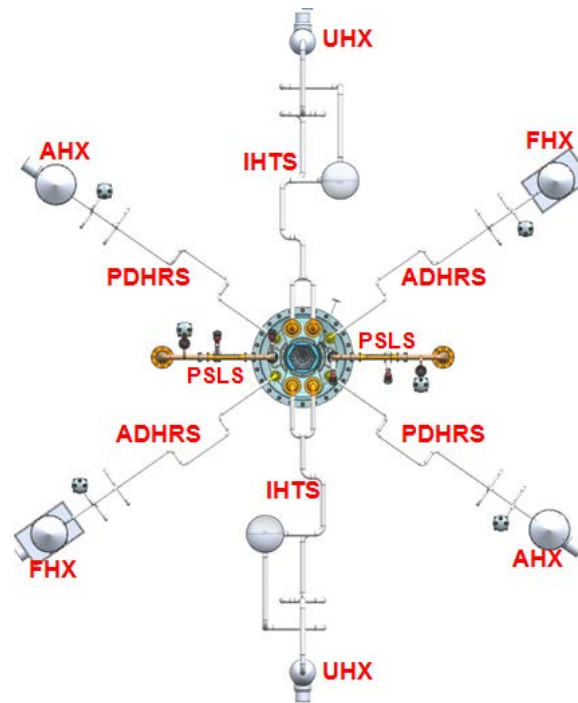
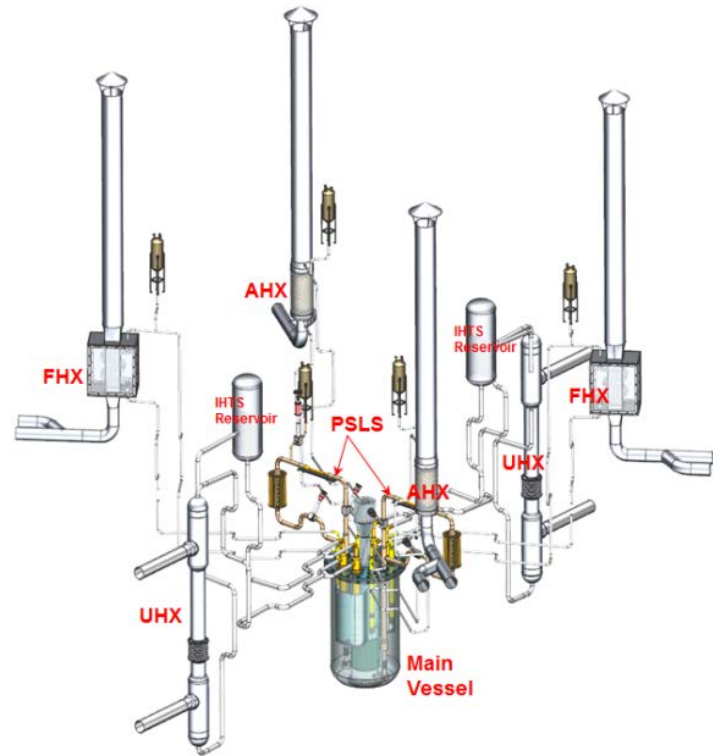
RCC-MRx
RB-3600

RCC-MRx
RB-3200

Evaluation and Comparison of conservatism

Introduction(5/5)

❖ STELLA-2* General Arrangement



<IHTS** piping for evaluation>

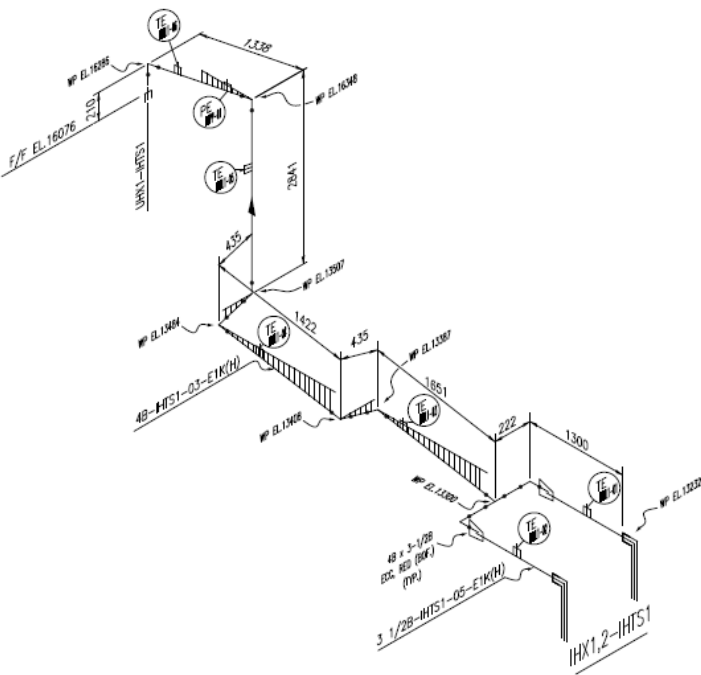
* GEN IV PGSFR 인허가 관련 열유체 검증 소동시험 시설

** Intermediate Heat Transfer System

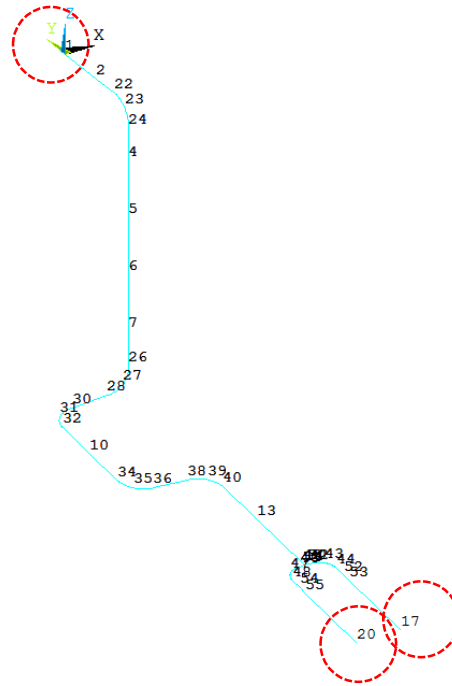
Analysis model

❖ STELLA-2 IHTS Hot leg

- Design pressure/temperature : 0.5 MPa / 600 °C
- Operating pressure/temperature : 0.1 MPa / 550 °C



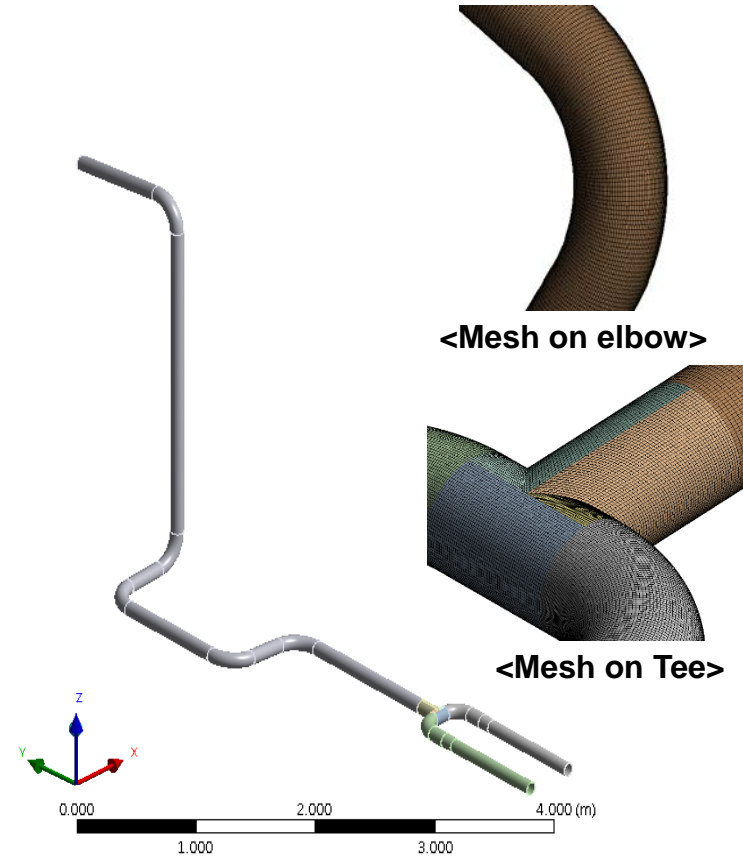
<Iso-drawing of IHTS hot leg>



<1D Pipe element model>

1D Pipe element model

- Type of elements : Pip16, Pipe18



<3D solid element model>

3D solid element model

- Type of elements : HEX8(Solid 185)

- Number of elements : 957,960

- Number of nodes : 1,276,020

Boundary conditions

❖ Mechanical load conditions

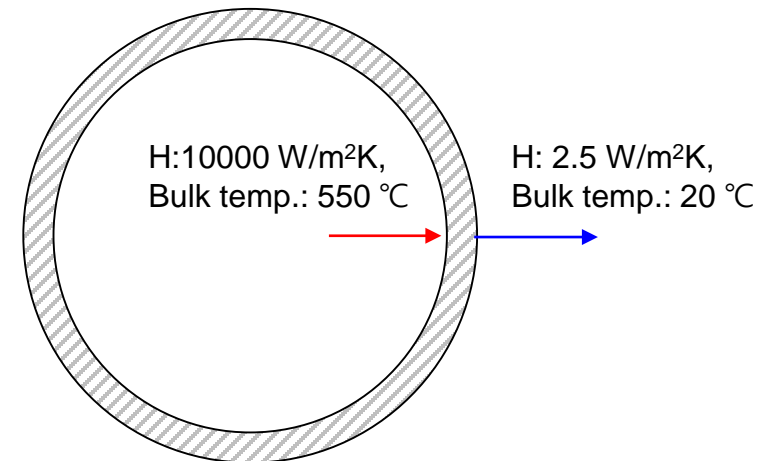
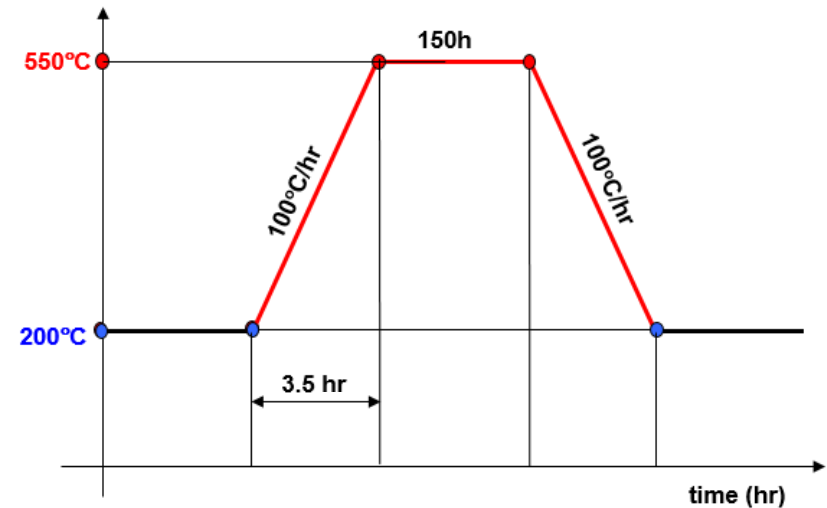
- Inner pressure : 0.1 MPa (Oper. pressure)
- Dead weight and live weight(sodium) considered.

❖ Thermal load conditions

- Inner face of pipe : convection
H: 10000 W/m²K, Bulk temperature : 550 °C
- Outer face of pipe : convection
H: 2.5 W/m²K, Bulk temperature : 20 °C

❖ Design cycle and hold time

- Hold time : 150 hr/cycle
- Design number of cycle : 500 (25 x 20 yr)



<Boundary conditions for thermal analysis>

DBR evaluation results : B31.1 and RD-3600

ASME B31.1

Sustained loads

$$S_L = \frac{PD_o}{4t_n} + \frac{0.75iM_A}{Z} \leq 1.0S_h$$

Occasional loads

$$\frac{PD_o}{4t_n} + \frac{0.75iM_A}{Z} + \frac{0.75iM_B}{Z} \leq kS_h$$

Thermal expansion loads

$$S_E = \frac{iM_C}{Z} \leq S_A + f(S_h - S_L)$$

RCC-MRx RD-3600

Sustained loads

$$0.5 \left(\frac{PD_e}{2h_c} \right) + 0.75i \left(\frac{M_R}{Z} \right) \leq S_h$$

Occasional loads

$$0.5 \left(\frac{PD_e}{2h_c} \right) + 0.75i \left(\frac{M_R}{Z} \right) \leq 1.2 S_h$$

Thermal expansion loads

$$SE = i \frac{[m(j, j')]_R}{Z} \leq f[1.25S_c + 0.25S_h]$$

Sustained + Thermal expansion loads

$$STE \leq S_A + f[1.25S_c + 0.25S_h]$$

- Mechanical loads(Unit : MPa)

Node	Type	ASME B31.1			RCC-MRx RD-3600		
		Value	Limit	Ratio	Value	Limit	Ratio
Max 1	Butt weld	42.7	57.7	0.74	40.7	74.0	0.55
40	Elbow1*	13.4	57.7	0.23	13.4	74.0	0.18
46	Elbow2**	8.9	57.7	0.15	8.9	74.0	0.12
49	Tee1	13.6	57.7	0.24	11.5	74.0	0.16
55	Reducer1	6.6	57.7	0.11	6.6	74.0	0.09

- Thermal loads(Unit : MPa)

Node	Type	ASME B31.1			RCC-MRx RD-3600		
		Value	Limit	Ratio	Value	Limit (SE)	Ratio
20	Butt weld	113.8	194.5	0.58	107.8	177.3	0.61
Max 30	Elbow1*	139.4	206.5	0.68	139.4	177.3	0.79
42	Elbow2**	71.1	208.9	0.34	71.1	177.3	0.40
49	Tee1	119.4	202.4	0.59	94.8	177.3	0.54
55	Reducer1	33.2	209.4	0.16	33.2	177.3	0.19

* Elbow1: R/D=2, **Elbow2: R/D=1.5

- Conservatism under mechanical loads : B31.1 > RD3600***
- Conservatism under thermal expansions : B31.1 < RD3600***
- Design evaluations are within allowable limits under all loads

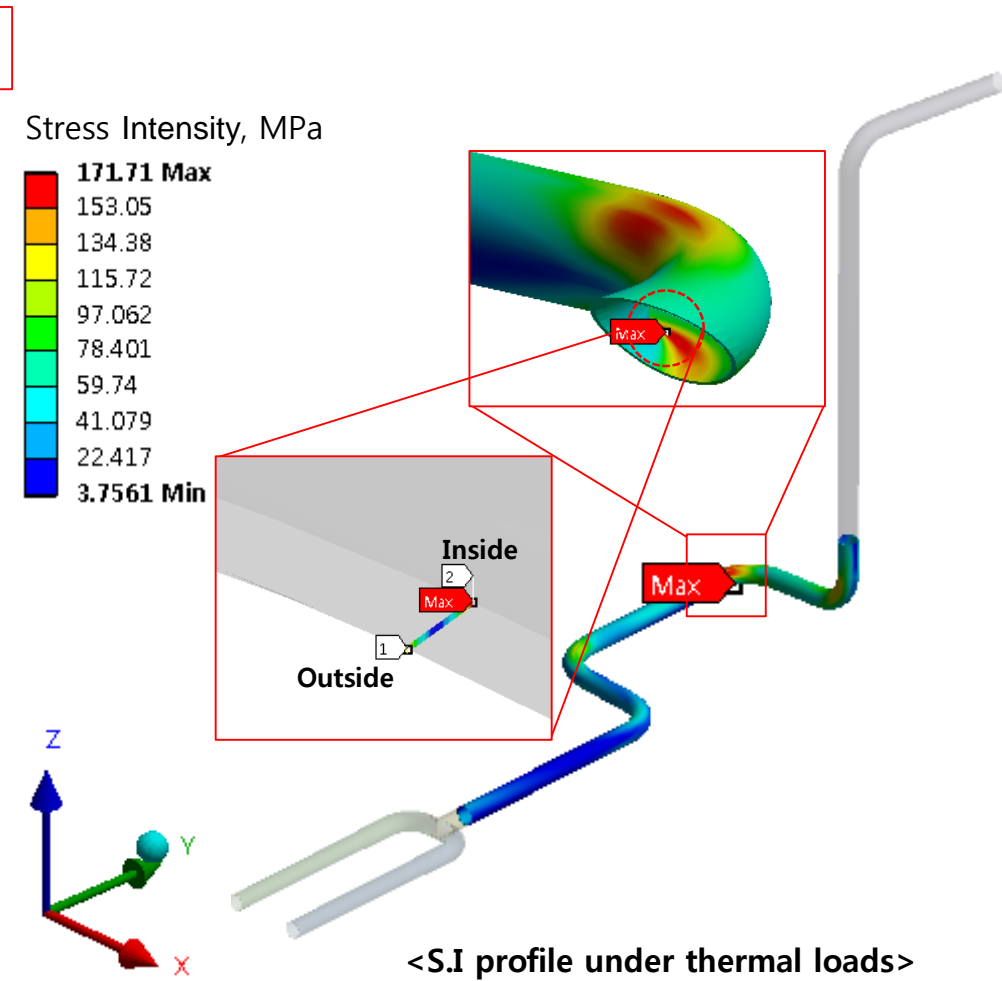
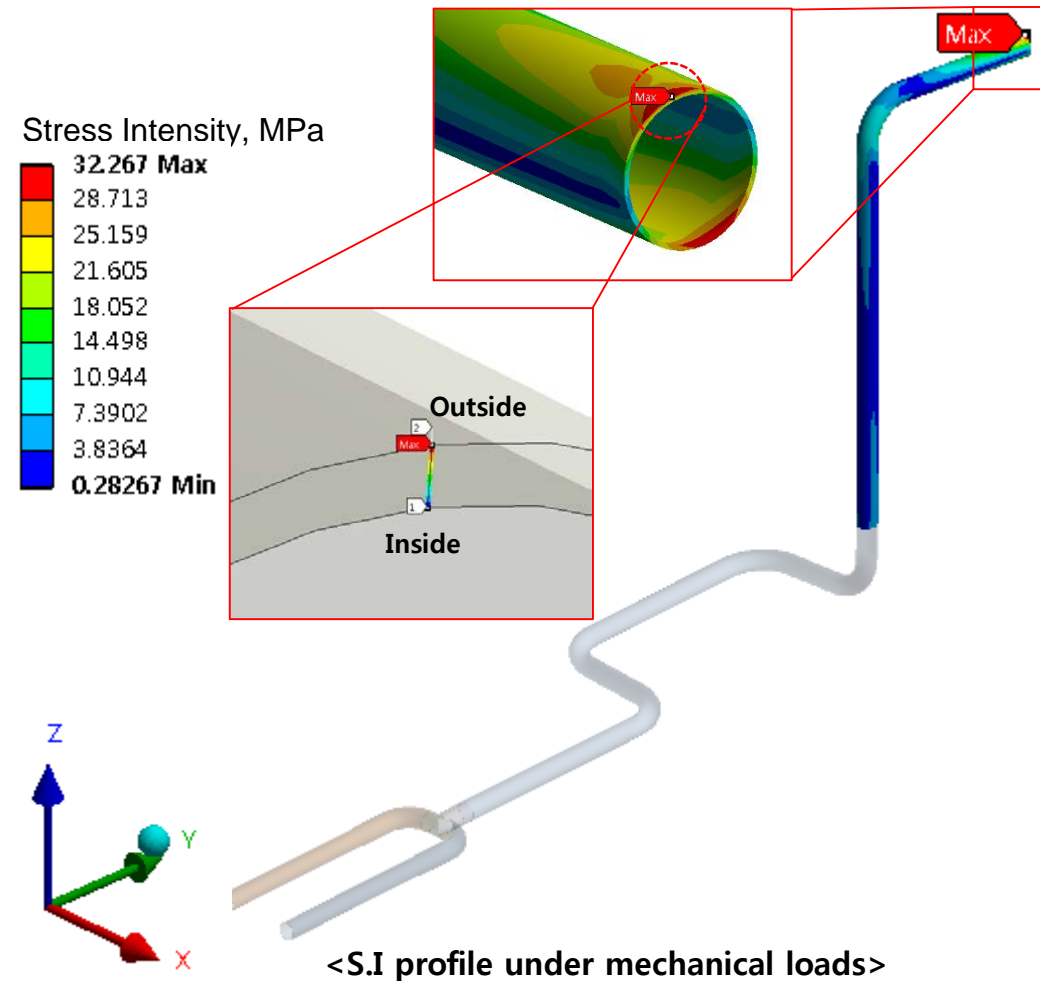
DBA Analysis results

❖ Mechanical loads

- Butt weld(Pipe end)

❖ Thermal loads

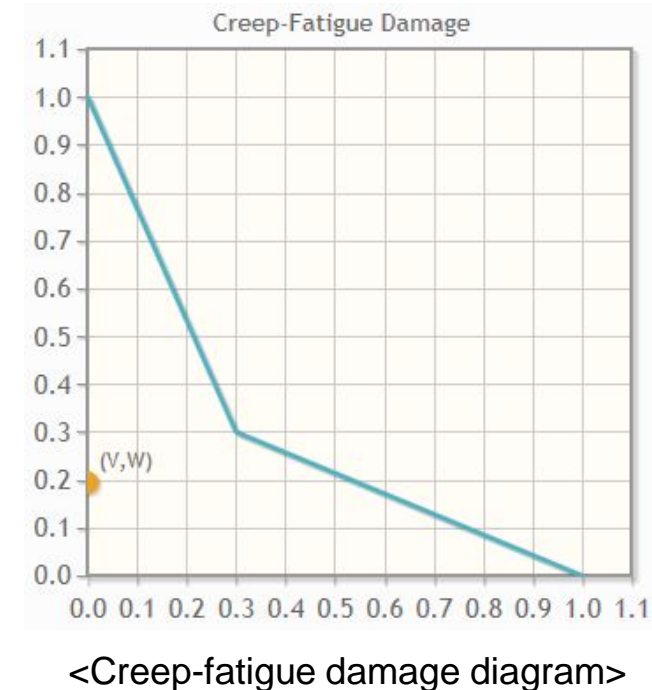
- Elbow



DBA evaluation results : RB-3200



RCC-DBA_RB-3200						
Material	SS 316L					
Service Level	Level A					
Max. Temp	550 °C					
Total hold Time	75000 hr (150 hr x 500 cycle)					
Hold Temperature	550 °C					
Evaluation Items		Calculated (MPa)	Limit value (MPa)	Ratio	Remark	
Load-Controlled Limits	$P_m < S_m$	26.643	77	0.35	OK!!	
	$P_L < 1.5S_m$	26.643	115.5	0.23	OK!!	
	$P_L + P_b < 1.5S_m$	32.736	115.5	0.28	OK!!	
	Creep usage	$U(\Omega P_m)$	5.0374E-8	1	0.00	OK!!
		$U(P_m + P_b)$	6.0617E-7	1	0.00	OK!!
	Creep rupture usage	$W(1.35P_m)$	7.4762E-5	1	0.00	OK!!
$W[1.35(P_m + \Phi P_b)]$		0.0002	1	0.00	OK!!	
Inelastic Strain Limits	$P_1^* < 1.3 S_m$	67.042	100.1	0.67	OK!!	
	$P_2^{**} < 1.3 \times 1.5 S_m$	74.313	150.15	0.49	OK!!	
	$\epsilon_{plastic} + \epsilon_{creep} (1.25 P_1) < 1 \%$	0.1695	1	0.17	OK!!	
	$\epsilon_{plastic} + \epsilon_{creep} (1.25 P_3) < 2 \%$	0.2522	2	0.13	OK!!	
Creep-Fatigue Damage	Fatigue Damage	4.1866E-5	See diagram	-	OK!!	
	Creep Damage	0.1939		-	OK!!	



* The effective primary membrane stress intensity

** The effective primary stress intensity of the sum of primary stresses

Evaluation summary



Item		DBR	DBA
Mechanical loads	Location	Butt weld (Pipe end)	Butt weld (Pipe end)
	Ratio	0.74 (B31.1) / 0.55 (RD-3600)	0.28
Thermal Loads	Location	Elbow	Elbow
	Ratio	0.68 (B31.1) / 0.79 (RD-3600)	0.49
Damage	Fatigue damage	n/a (B31.1 & RD-3600)	4.1866E-5
	Creep damage	n/a (B31.1 & RD-3600)	0.1939

- 기계적 하중 및 열하중에 대한 구조건전성 평가시, DBR이 DBA보다 보수적으로 평가됨.
- B31.1 및 RD-3600은 운전횟수*는 고려하지만 유지시간(hold time)은 제시하지 않으므로 creep fatigue interaction의 영향은 미평가함.

* ASME B31.1 및 RCC-MRx RD-3600은 f (총 N 회 반복조건에 의한 응력범위 감소계수)만 적용

Conclusion



- 선행연구에서 언급된 바와 같이, 기계적 하중에 대해서는 B31.1이 RD-3600보다 보수적인 것으로 나타났고, 열하중에 대해서는 RD-3600이 보수적인 것으로 평가됨.
- 기계적 하중 및 열하중 평가결과는 모두 허용치를 만족하였고 DBR이 DBA보다 보수적으로 평가됨.
- SFR과 같이 고온배관에서는 운전횟수 및 유지시간(hold time)에 지배적인 영향을 받으나 DBR(B31.1 & RD-3600)의 경우 이에 대한 평가항목은 없는 상태임.
- ASME B31.1 및 RCC-MRx RD3600은 운전횟수를 반영하는 수식이 있지만, 유지시간(hold time)은 고려하지 않아 creep-fatigue interaction을 평가할 수 없음.
- 현재 RB3600은 RB3200과 동일한 평가항목(creep-fatigue interaction 고려)을 가지므로 이를 따라 RCC-MRx의 DBR vs DBA에 대한 보수성의 비교 분석을 진행 중에 있음