Development of Empirical Stress Corrosion Factor for Creep-Rupture Model of Alloy 690 Steam Generator Tube

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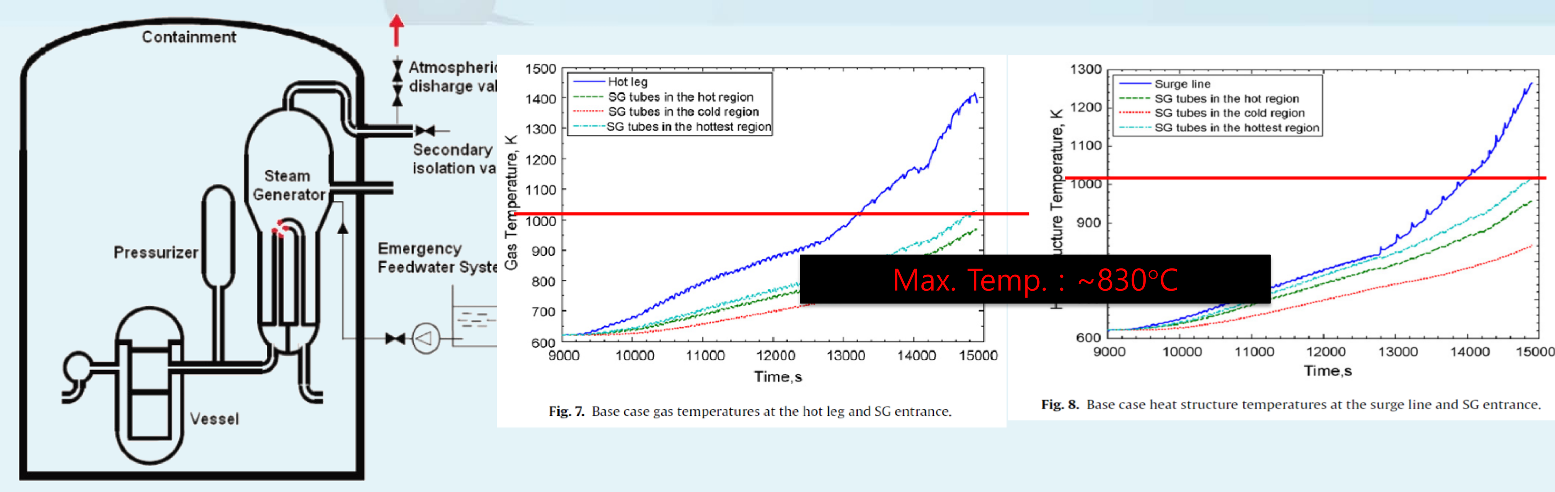
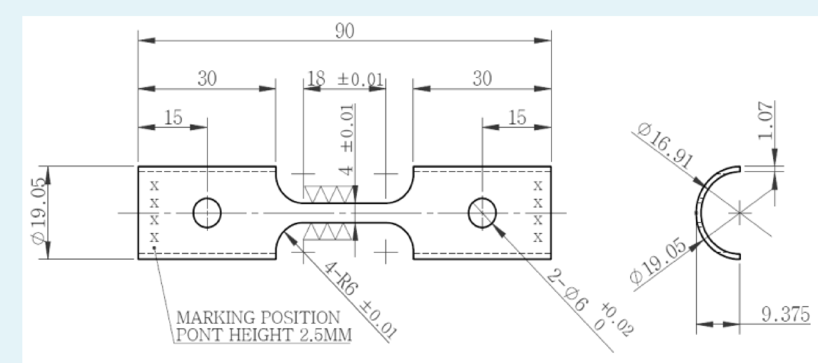
[Introduction]

<Creep and Creep-rupture of Alloy 690 SG tube>

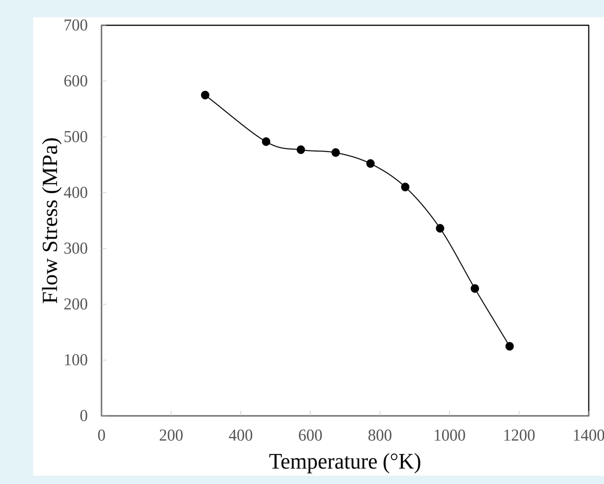
- Steam generator (SG) tube is one of the important components that make up the pressure boundary, and there is a risk of a significant radioactive release to the outside due to high temperature damage of single tube and subsequent chain failure of tubes in case of severe accident condition (ex. Station Black Out, SBO)
- SG tubes exhibit creep behavior during the high temperature (>0.4 X melting temperature), and damage is accumulated during temperature/pressure transient. Creep failure studies of the recently replaced or installed Alloy 690 material was insignificant.
- Since the creep and creep rupture prediction models so far was based on Alloy 600 material, the creep-rupture model for Alloy 690 material needs to be developed.
- In this study, creep-rupture tests were performed for Alloy 690 SG tubes with crack, and an empirical stress correction factor of the creep-rupture model for Alloy 690 SG tube was proposed.



[SBO transient and temperature of SG tube]



[Geometry of tensile and creep specimen]



[Flow stress of Alloy 690 material]

[Creep-Rupture Prediction]

- An EDM notch is inserted in the center of the specimen and both ends are welded. The specimen was designed to have a crack depth of 50% to 80% and crack length of 1 inch.
- The temperature for rupture tests were 600°C, 700°C, 800°C, and 900°C, and the pressure ramp rates were 2300 psi/min, 230 psi/min and 23 psi/min. In this study, a constant temperature-pressure ramp test was conducted until failure. The rupture test equipment was manufactured to simulate a change in the temperature and pressure.
- Flow Stress Model (ANL, NUREG-1570)

$$\sigma = \frac{\overline{\sigma(T)}}{m_p} \qquad \overline{\sigma(T)} = \sigma_{eff} = m_p\sigma \qquad m_p = \frac{1-\alpha\left(\frac{a}{h}\right)\frac{a}{mh}}{1-\frac{a}{h}}$$

- Creep-rupture Model (Linear time-fraction damage rule, Calculated using Excel VBA)

$$\int_0^{t_r} \frac{dt}{t_R(T, m_p\sigma)} = 1 \qquad t_r = 10\text{^}\left(\frac{P_{LM}}{T} - 13.8\right)$$

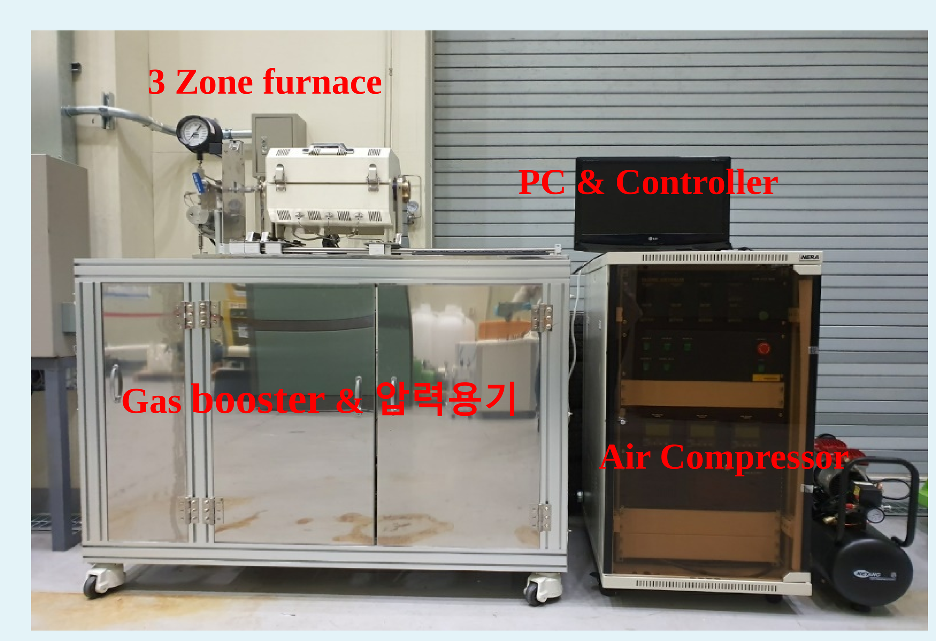
Larson-miller parameter for Alloy 690 SG tube material (From Authors' previous research results)

[Results of Alloy 690 tube rupture tests]

ID	Temp. (°C)	Pressure Rate (psi/min)	Flaw Depth (%)	Test P_{sc}(bar)	Flow Stress Model P_{sc}(bar)	Creep Rupture Model P_{sc}(bar)	Diff. Of Flow Stress (%)	Diff. of Creep Rupture (%)
1	600	2300	50	304	299	526	2	-42
2	600	2300	60	263	256	457	3	-42
3	600	2300	70	211	212	380	0	-44
4	600	2300	80	156	164	298	-5	-48
5	700	2300	50	265	243	434	9	-39
6	700	2300	60	227	208	377	9	-40
7	700	2300	70	187	172	318	9	-41
8	700	2300	80	143	133	248	8	-42
9	800	2300	50	236	167	337	41	-30
10	800	2300	60	197	143	294	38	-33
11	800	2300	70	165	118	248	40	-34
12	800	2300	80	127	91	197	39	-36
13	900	2300	50	156	90	242	73	-35
14	900	2300	60	126	78	212	63	-41
15	900	2300	70	116	64	181	81	-36
16	900	2300	80	94	49	145	90	-35
17	700	230	60	207	208	309	-1	-33
18	700	230	80	126	133	206	-5	-39
19	800	230	60	154	143	220	8	-30
20	800	230	80	94	91	150	3	-37
21	700	23	60	192	208	240	-8	-20
22	800	23	80	108	133	162	-19	-33
23	700	23	60	129	143	151	-10	-15
24	800	23	80	65	91	104	-29	-38

Stress correction factor is not applied → significant difference in the experimental results at all temperatures

[Specimens for tube rupture test]



[Design of high-temperature tube rupture facility]

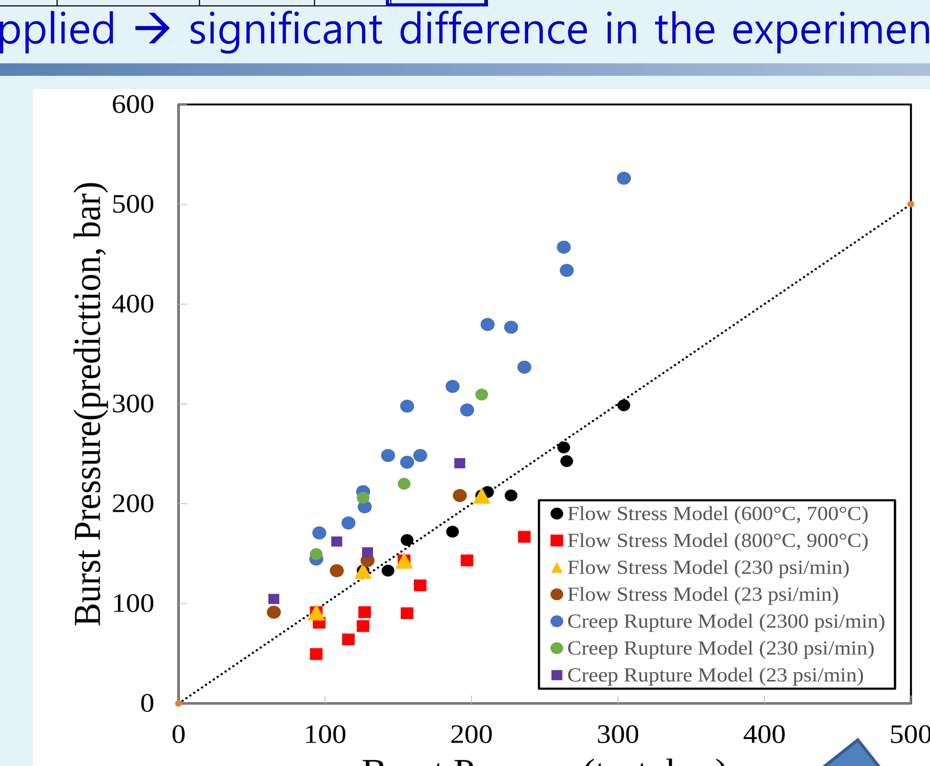
[Results and Discussion]

<Empirical Stress Corrosion Factor >

- Compared to the experimental results, the difference between the flow stress models at 800°C and 900°C was substantial, and the creep rupture model showed a significant difference in the experimental results at all temperatures. This indicated that the flow stress model does not represent creep damage, and the m_p used in the creep rupture model was also not suitable for Alloy 690 material. There is a difference between creep damage mechanism and plastic deformation of Alloy 600 and Alloy 690 material. In this study, the following correction factor of the creep rupture model is proposed for the alloy 690 material:

$$\sigma_{eff} = Gm_p\sigma$$

- Here, G is the correction factor of the Alloy 690 material in the creep rupture model that specifies the stress state of a cracked tube. In this study, the correction factor G was determined to be 1.7 based on the experimental results.
- When the correction factor is applied, the creep rupture model is in good agreement with the experimental results at all temperatures and pressure rates.
- In summary, predicted rupture pressure by the creep rupture model (correction factor is not applied.) in Table shows large difference from the rupture pressure in tests. If the correction factor provided in this study is applied to the creep rupture model, it is in good agreement with the experimental results.



$$\sigma_{eff} = m_p\sigma$$

$$\sigma_{eff} = 1.7m_p\sigma$$