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Reanalysis of Cost and Moist Air Oxidation Performance for CF8C-Plus and Other Alloys for AUSC Applications

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OAK RIDGE NATIONAL LABORATORY
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Materials Science and Technology Division

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ABSTRACT

This report provides an economic analysis of CF8C-Plus and other candidate materials for Advanced Ultra Supercritical (AUSC) applications, including 347HFG, HR6W, Sanicro 25, Super 304H, Grade 92, SAVE12AD, Inconel 617, and Inconel 740H. An assessment of their moist air oxidation performance is also included. When compared with the aforementioned alloys, CF8C-Plus shows a favorable balance between cost, creep strength and moist air oxidation resistance in the temperature range of 600-700°C. Furthermore, its castability makes it additionally attractive from a manufacturing perspective. Materials with higher Ni content, such as HR6W, Sanicro 25, Inconel 617, and Inconel 740H, have better creep strength but the improved performance comes with increased cost. Stainless steel 347HFG exhibits inferior creep strength and lower moist air oxidation resistance, but at a greater cost, compared with CF8C-Plus. Super 304H, another stainless steel, has similar creep strength and cost compared to CF8C-Plus at 700°C, but may not have as good moist air oxidation resistance. Grade 92 has lower creep strength and unfavorable economy compared with CF8C-Plus. SAVE12AD also has lower creep strength than CF8C-Plus, but has lower cost to use at 600°C. Both Grade 92 and SAVE12AD are also limited to the maximum use temperature of 649°C per ASME code case requirements.

1. INTRODUCTION

Advanced Ultra Supercritical (AUSC) power plants combine dual benefits of higher operation efficiency and reduced CO_2 emissions. However, the operating conditions of AUSC power plants, such as steam temperatures up to 760 °C and pressures in excess of 3,000 psi, also impose tremendous challenges on existing materials for coal-based power plants. In this report, we performed a cost analysis and an assessment of moist air oxidation rate for CF8C-Plus, and other AUCS candidate materials, i.e. 347HFG, HR6W, Sanicro® 25, Super 304H, Grade 92, SAVE12AD, Inconel® 617, and Inconel® 740H®, in the temperature range of 600-760 °C. The nominal compositions of the alloys investigated in this study are listed in Table 1.

Table 1 Composition of studied materials for AUSC application (wt%) [1-8]

	C	Si	Mn	Cr	Cu	Ni	Nb	N	B	Fe	Other
CF8C-Plus	0.1	0.5	4.0	19	-	12.5	0.8	0.25	-	Bal	0.3 Mo
347HFG	0.06-0.1	<0.75	<2	17-20	-	9-13	<1	-	-	Bal	-
HR6W	<0.1	<1	<1.5	21.5-24.5	-	Bal	0.1-0.35	<0.02	5-60 ppm	20-27	6-8 W, 0.05-0.2 Ti
Sanicro 25	≤0.1	0.2	0.5	22.5	3	25	0.5	0.23	-	Bal	3.6 W, 1.5 Co
Super 304H	0.07-0.13	<0.3	<1	17-19	2.5-3.5	7.5-10.5	0.3-0.6	0.05-0.12	-	Bal	-
Grade 92	0.07-0.13	0.5	0.3-0.6	8.5-9.5	-	0.4	0.04-0.09	0.03-0.07	10-60 ppm	Bal	0.3-0.6 Mo, 0.15-0.25 V, 1.5-2.0 W
SAVE12 AD	0.05-0.10	0.05-0.50	0.2-0.7	8.5-9.5	-	<0.2	0.05-0.12	0.005-0.015	70-150 ppm	Bal	2.5-3.5 W, 2.5-3.5 Co, 0.15-0.3 V, 0.01-0.06 Nd, 0.05-0.12 Nb+Ta
Inconel 617	0.05-0.15	<1	<1	20-24	<0.5	Bal	-	-	<60 ppm	<3	10-15 Co, 0.8-1.5 Al, 8-10 Mo, <0.6 Ti
Inconel 740H	0.03	0.15	<1	24.5	<0.5	Bal	1.5	-	6-60 ppm	<3	20 Co, 1.35 Al, 0.1 Mo, 1.35 Ti

2. ECONOMIC ANALYSIS

A cost analysis was performed assuming the candidate materials would be used to manufacture 2-inch OD tubes or 12-inch ID pipes and would have to withstand a design steam pressure of 24 MPa at temperatures between 600°C and 700 °C. Table 2 lists the material properties and cost information. Following the analysis of Li, Cedro and Conrad [10], it was assumed that the 12-inch ID pipe has a $5/lbs premium over the 2-inch OD tube for the Fe-based austenitic steels and a $10/lbs premium for the Ni-based alloys and high W alloys. It is also worth noting that for Grade 92 and SAVE12AD, the maximum use temperature is 649 °C from ASME code case 2179 and 2839, respectively. The allowable stress values at 650 °C in Table 2 for these two materials are provided for interpolation purposes only.

Table 2. Density, ASME allowable stress, and pricing information of studied materials

	Density (lbs/in^3)	ASME allowable stress* (MPa)			Raw material price** ($/lbs)	Price of tube or pipe*** ($/lbs)	
		600°C	650°C	700°C		2-inch OD tube	12-inch ID pipe
CF8C-Plus	0.282	108.20	74.30	50.20	1.02	4.73	9.73
347HFG	0.288	87.95	66.90	39.14	1.48	3.73	8.73
HR6W	0.306	103.00	80.60	58.40	2.77	23	33
Sanicro 25	0.290	122.00	111.00	64.40	1.94	20	25
Super 304H	0.285	92.30	78.00	46.90	0.74	4.22(min) 8(max)	9.22(min) 13(max)
Grade 92	0.29	77.0	38.3	-	0.23	3.26	8.26
SAVE12AD	0.285	103	44	-	0.85	3.39	8.39
Inconel 617	0.302	106.01	105.49	80.86	5.58	33	43
Inconel 740H	0.291	274.00	226.00	146.00	5.96	47	57

*For CF8C-Plus, ASME allowable stress is from [9] and for remaining materials, ASME allowable stresses are from [10]
**Based on CY 2015 alloy ingredient price from [10]
***For CF8C-Plus, price is from [11] and for remaining materials, prices are from [12] except for 347HFG from [13] and Super 304H from [13] and [14]

The thickness of the 2-inch OD tube or 12-inch ID pipe needed to withstand the steam pressure at temperature is calculated using the same practice as in [10], which is based on ASME Boiler and Pressure Vessel Code Section I Appendix A-317 "Cylindrical Components under Internal Pressure." According to this analysis, the equations to calculate the 2-inch OD tube and 12-inch ID pipe thicknesses are given by:

$$t_{tube} = \frac{D_0(1 - e^{-P/SE})}{2} + C + F \quad (1)$$

where:
D_0 = outside diameter (inch),
P = design pressure (MPa),
S = ASME allowable stress,
E = efficiency (assumed to be 1),
C = allowance for threading (assumed to be 0),
F = allowance for expanding (assumed to be 0).

$$t_{pipe} = \frac{D_i(e^{P/SE} - 1)}{2} + C + F \quad (2)$$

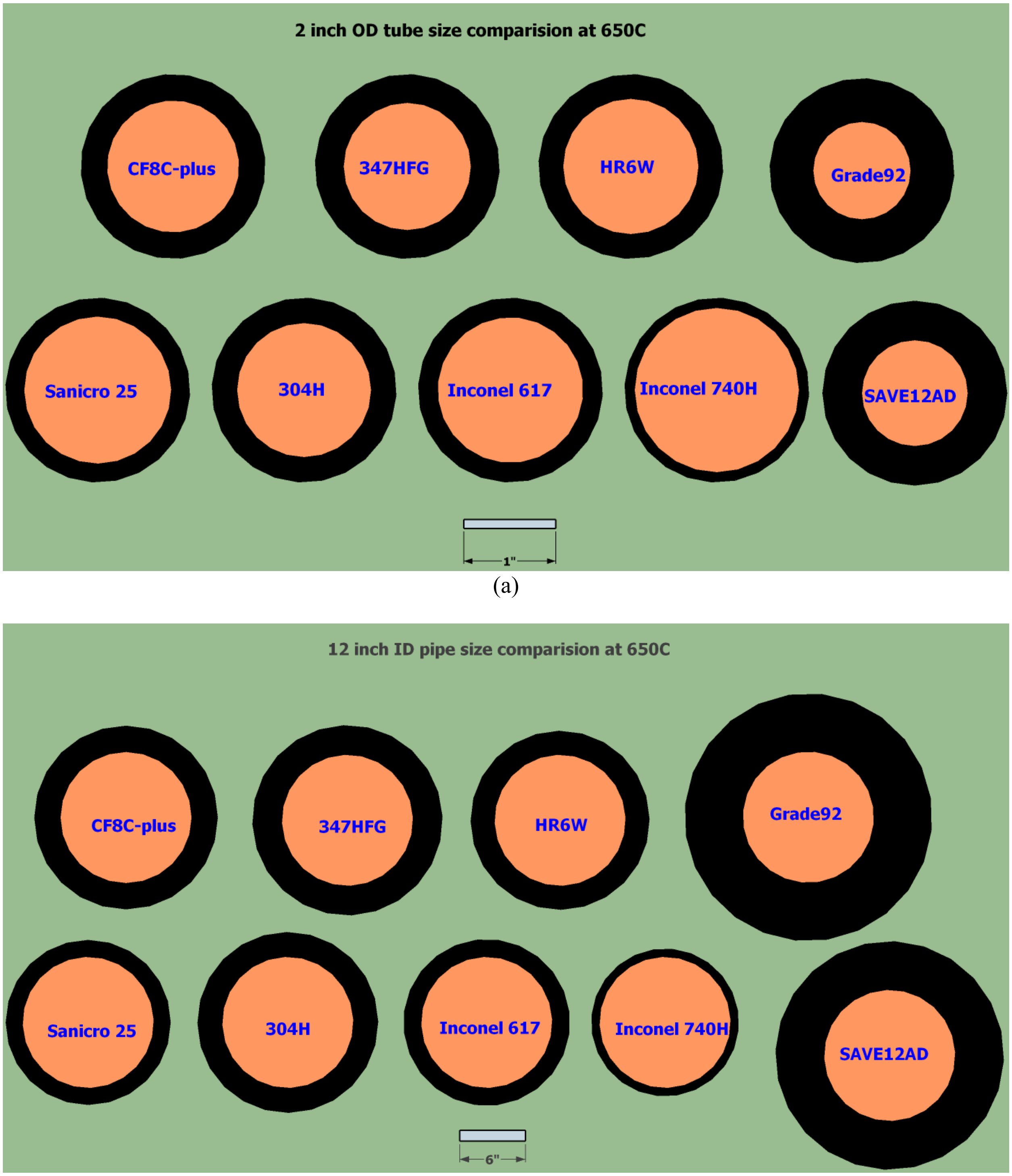
where:
D_i = inside diameter (inch),
P = design pressure (MPa),
S = ASME allowable stress,
E = efficiency (assumed to be 1),
C = allowance for threading (assumed to be 0),
F = allowance for expanding (assumed to be 0).

The resulting thickness values of the studied materials are shown in Table 3. In general, CF8C-Plus has a thinner wall thickness than 9Cr steels, such as Grade 92 and SAVE12AD, and the other two austenitic stainless steels, 347HFG and Super 304H, but has a thicker wall compared with materials with higher Ni contents, i.e. HR6W, Sanicro 25, Inconel 617 and Inconel 740H. The thickness values of the studied materials are further illustrated in Fig. 1 for 650°C. Compared with other AUSC candidate materials, tubes and pipes made from Grade 92 and SAVE12AD need much thicker wall due to significantly lower ASME allowable stress for both materials at 650°C.

Combining the material volume, density, and pricing data, we calculated the unit price among AUSC candidate materials for 2-inch OD tube and 12-inch ID pipe as well as 2-inch OD tube usable volume (open volume inside the tube) per dollar. The results are summarized in Table 4 and further illustrated in Fig. 2. Overall, CF8C-Plus exhibited impressive economical advantage over other materials except for the 2-inch OD tube form where 347HFG and Super 304H at the minimum price case show similar economy as compared with CF8C-Plus. In addition, SAVE12AD also indicates better economy over CF8C-Plus for the 2-inch OD tube and 12-inch ID pipe applications at 600°C

Table 3 Thickness of studied materials for AUCS applications

	2-inch OD tube thickness (inch)			12-inch ID pipe thickness (inch)		
	600°C	650°C	700°C	600°C	650°C	700°C
CF8C-Plus	0.200	0.277	0.382	1.499	2.303	3.703
347HFG	0.240	0.303	0.460	1.894	2.606	5.115
HR6W	0.209	0.259	0.338	1.584	2.094	3.070
Sanicro 25	0.179	0.195	0.313	1.312	1.457	2.728
Super 304H	0.230	0.266	0.402	1.793	2.176	4.037
Grade 92	0.268	0.466	-	2.194	5.228	-
SAVE12AD	0.208	0.420	-	1.574	4.352	-
Inconel 617	0.203	0.203	0.257	1.524	1.533	2.073
Inconel 740H	0.084	0.101	0.152	0.549	0.672	1.072



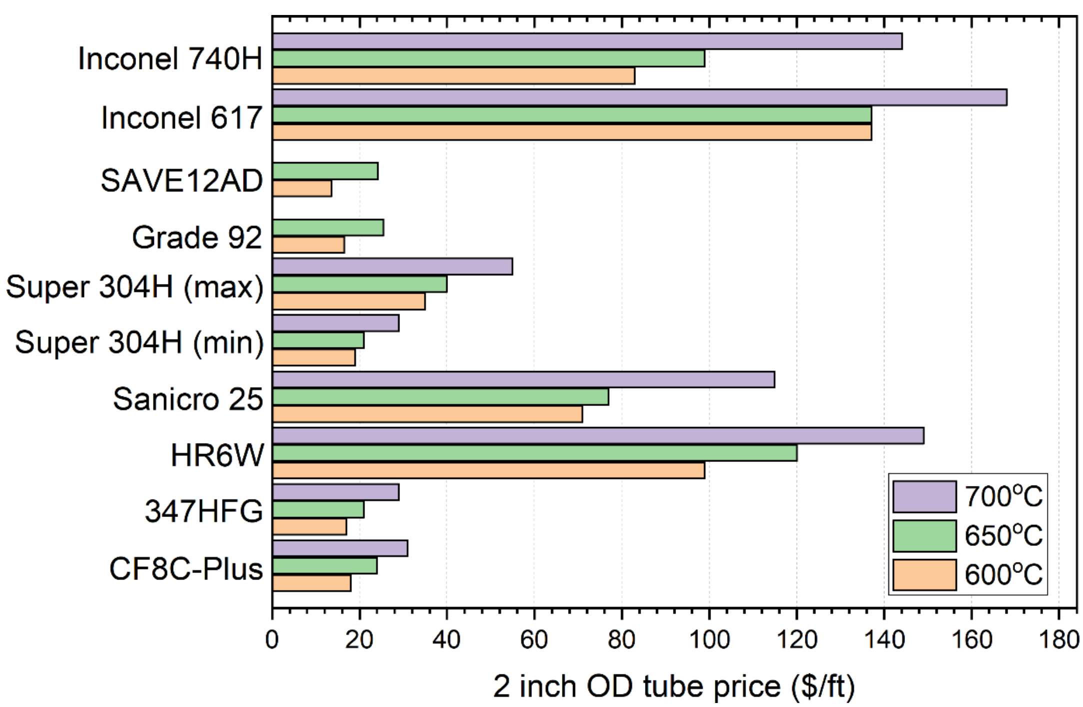
(a)

(b)

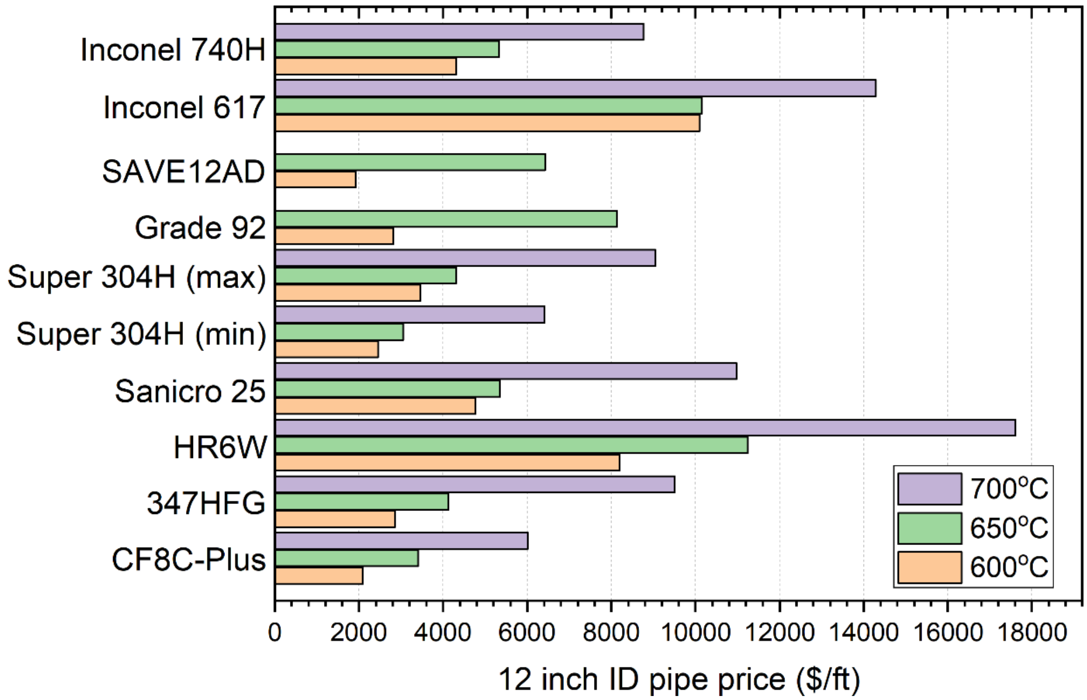
Fig. 1 Size comparison for AUSC candidate materials for (a) 2-inch OD tube and (b) 12-inch ID pipe

Table 4 Economical analysis of studied materials for AUCS applications

	2-inch OD tube price ($/ft)			2-inch OD tube usable volume ($in^3/\$$)			12-inch ID pipe price ($/ft)		
	600°C	650°C	700°C	600°C	650°C	700°C	600°C	650°C	700°C
CF8C-Plus	18	24	31	1.33	0.82	0.46	2092	3404	6012
347HFG	17	21	29	1.27	0.88	0.38	2495	3608	8299
HR6W	99	120	149	0.24	0.17	0.11	8192	11237	17613
Sanicro 25	71	77	115	0.36	0.32	0.15	4775	5359	10979
Super 304H	19(min) 35(max)	21(min) 40(max)	29(min) 55(max)	1.21(min) 0.64(max)	0.97(min) 0.51(max)	0.46(min) 0.24(max)	2450(min) 3454(max)	3055(min) 4308(max)	6414(min) 9044(max)
Grade 92	16.5	25.5	-	1.22	0.42	-	2813	8133	-
SAVE12 AD	13.6	24.2	-	1.74	0.52	-	1926	6416	-
Inconel 617	137	137	168	0.18	0.17	0.12	10093	10155	14285
Inconel 740H	83	99	144	0.38	0.31	0.19	4310	5327	8763



(a)



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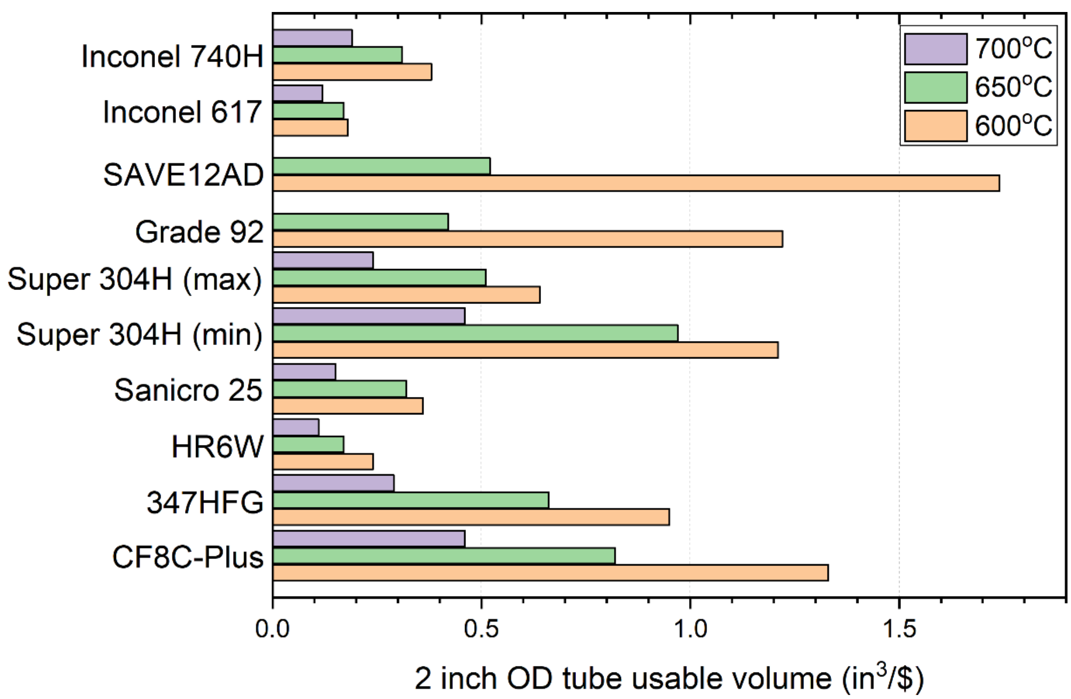


(c)

Fig. 2 Comparison of economy analysis results for AUSC candidate materials: (a) 2-inch OD tube price, (b) 12-inch ID pipe price, and (c) 2-inch OD tube usable volume

3. MOIST AIR OXIDATION

During the typical operation of AUSC power plants, materials will be subjected to high-temperature steam oxidation. It is critical that the candidate materials should have sufficient steam oxidation resistance during the plant operation. In this report, we compare the moist air oxidation (more aggressive environment than the pure steam) rates for CF8C-Plus, 347HFG, Super 304H, and Inconel 617 in the temperature range of 650-760 °C based on published literature results.

In the work of Dryepondt et al., [15], oxidation tests were performed at 650-800 °C in air + 10% vol. H_2O on CF8C-Plus and its compositional variations. At 650°C, a stable oxide scaled formed on CF8C-Plus and the thickness of the inner oxide layer was up to ~ 20 µm after 5,000 h exposure (<1.4 mil per year based on parabolic oxidation law). At 700°C, CF8C-Plus experienced scale spallation after ~ 3,000 h exposure with constant mass loss after then. The inner oxide layer was up to ~ 20 µm after 1000 h exposure. Assuming the oxide spallation rate is 20 µm per 1000 h, which is a conservative estimate, this translates into 6.9 mil per year moist air oxidation rate. Above 700°C, CF8C-Plus suffered rapid weight loss due to spallation of Fe-rich oxide nodules. Fig. 3 shows the specimen mass change in moist air environment for CF8C-Plus and its variant steels at 650-750 °C.

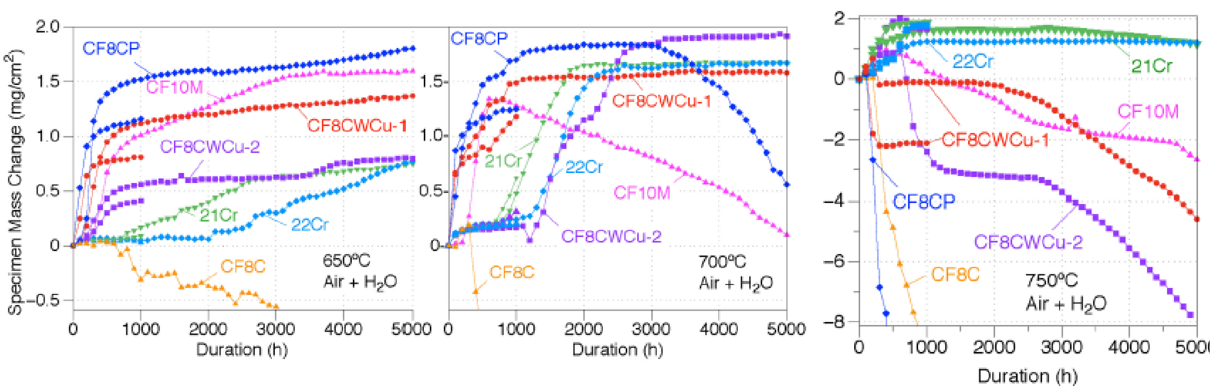


Fig. 3 Specimen mass change in moist air for CF8C-Plus and its variations at 650-750 °C [15]

Dudziak et al., conducted steam oxidation tests on 347HFG and Super 304H for 1000 h at 650 and 700 °C with three different steam flow rates (4, 16, 40 mm/s) referred to as low, medium, and high flow rates [16]. They found the steam oxidation rate increased with the temperature and steam flow rate. They also concluded Super 304H had slightly better steam oxidation resistance than 347HFG at 650 and 700 °C.

A direct comparison for the moist air oxidation performance between CF8C-Plus and 347HFG can be found in the work of Maziasz and Pint [17]. At 700 °C in air + 10% vol. H_2O environment, CF8C-Plus showed reasonable moist air oxidation rate whereas 347HFG specimen exhibited an apparent mass loss due to spallation of the Fe-rich oxide scale (Fig. 4). Since Super 304H only has slightly better steam oxidation resistance than 347HFG at 700°C [16], it is reasonable to expect that CF8C-Plus should also have better steam oxidation resistance than super 304H at 700°C. Indeed, CF8C-Plus has slightly higher Ni and Cr contents than both 347HFG and Super 304H as shown in Table 1. Based on the findings in [15& 18], austenitic alloys with high Cr and Ni contents are expected to have better steam oxidation performance.

Lastly, Holcomb et al., performed cyclic oxidation experiments of advanced alloys for ultra supercritical systems in humid air (50% water vapor + 50% air by volume) at 760°C [19]. They found Inconel 617 had virtually no net mass loss and developed a very thin oxide scale after 2000 h exposure as shown in Fig. 5. Among all studied materials, Inconel 617 exhibited the best moist air oxidation performance.

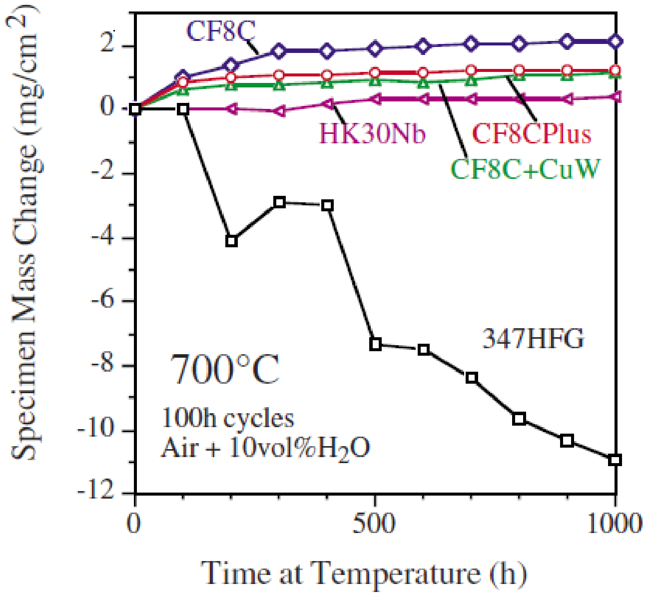
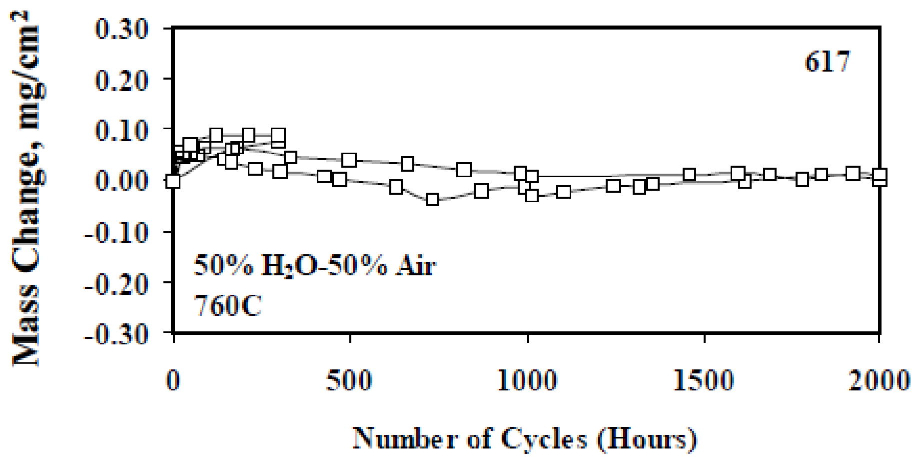
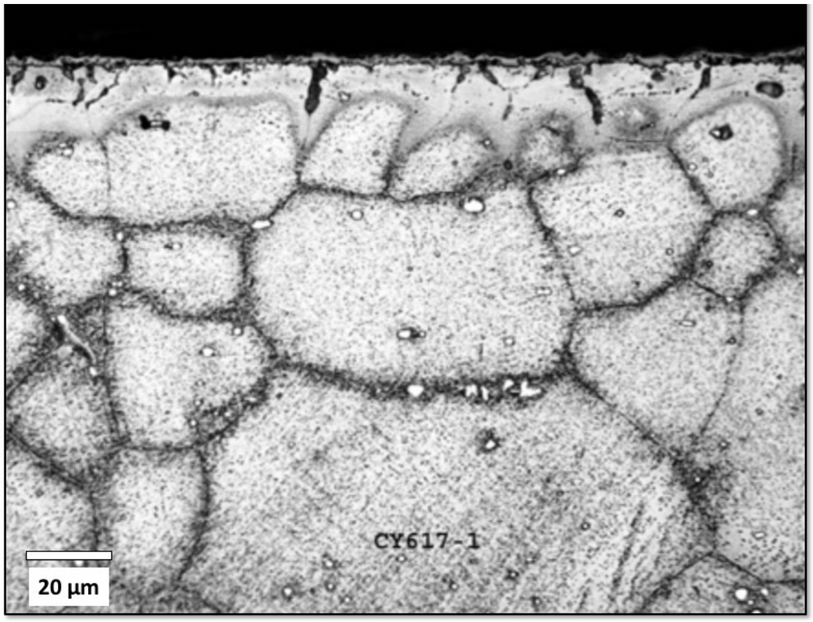


Fig. 4 Comparison of specimen mass change for various stainless steels in humid air at 700°C [17]



(a)

(b)



(c)

Fig. 5 Cyclic oxidation results for Inconel 617 at 760°C in 50% H2O-50% air up to 2000 h. (a) Mass change, (b) surface optical microscopy, and (c) cross-sectional metallography [17]

4. CONCLUSIONS

This report provides a brief techno-economic analysis for castable stainless steel, CF8C-Plus, and other candidate materials for AUSC applications, including 347HFG, HR6W, Sanicro 25, Super 304H, Grade 92, SAVE12AD, Inconel 617, and Inconel 740H. Overall, CF8C-Plus shows a favorable combination of material costs, creep resistance and moist air oxidation performance for AUSC applications in the temperature range of 600-700°C.

5. REFERENCES

1. Maziasz, P. J., Shingledecker, J. P., Evans, N. D., & Pollard, M. J. (2008). CF8C-Plus Heat-Resistant Cast Stainless Steel. Advanced Materials and Processes, 166(10), 27.
2. ASM Alloy Center Database.
3. SANDVIK, Sanicro® 25 datasheet.
4. Nippon Steel & Sumitomo Metal, Seamless steel tubes and pipes for boilers datasheet.
5. Special Metals, Inconel 617 datasheet.
6. Special Metals, Inconel 740H datasheet.
7. ASTM A336 / A336M-18a, Standard Specification for Alloy Steel Forgings for Pressure and High-Temperature Parts, ASTM International, West Conshohocken, PA, 2018, www.astm.org
8. Hamaguchi, T., Okada, H., Hirata, H., Kurihara, S., Semba, H., & Yoshizawa, M. (2018). Creep Rupture Strength and Microstructures of SAVE12AD Welded Joints, Nippon Steel & Sumitomo Metal Technical Report No. 119.
9. Pint, B. A., Wang, H., Maziasz, P. J., Hawkins, C. S., Miller, R. G., Swindeman, R. W., & Rahoi, D. W. (2014). ASME Code Case Progress for CF8C-Plus Cast Austenitic Stainless Steel. ASME BPV Code Week, August 18-22, 2014, Washington, DC.
10. Li, A., Cedro III, V., & Conrad, R. K. (2016). Cost Effectiveness of Potential AUSC Alloys. U.S. Department of Energy Mickey Leland Energy Fellowship Program Report, August 5, 2016.

11. Private communication with Michael Kemmer, MetalTek International, June 2018
12. Private communication with Vito Cedro III, August 2018.
13. Private communication with Vito Cedro III, September 2018.
14. Private communication with Daniel Purdy, September 2018.
15. Dryepondt, S., Pint, B. A., & Maziasz, P. J. (2015). New Creep-Resistant Cast Alloys with Improved Oxidation Resistance in Water Vapor at 650–800° C. Frontiers in Materials, 2, 55.
16. Dudziak, T., Łukaszewicz, M., Simms, N., & Nicholls, J. R. (2015). Steam oxidation of TP347HFG, super 304H and HR3C–analysis of significance of steam flowrate and specimen surface finish. Corrosion Engineering, Science and Technology, 50(4), 272-282.
17. Maziasz, P. J., & Pint, B. A. (2011). High-temperature performance of cast CF8C-plus austenitic stainless steel. Journal of Engineering for Gas Turbines and Power, 133(9), 092102.
18. Peraldi, R., & Pint, B. A. (2004). Effect of Cr and Ni contents on the oxidation behavior of ferritic and austenitic model alloys in air with water vapor. Oxidation of metals, 61(5-6), 463-483.
19. Holcomb, G. R., Covino Jr, B. S., Bullard, S. J., Ziomek-Moroz, M., & Alman, D. E. (2005). Oxidation of alloys for advanced steam turbines (No. DOE/ARC-2005-066). Albany Research Center (ARC), Albany, OR.