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Materials Performance in Fluidized-Bed Air Heaters*

by

K. Natesan and W. Podolski
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

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MATERIALS PERFORMANCE IN FLUIDIZED-BED AIR HEATERS

K. Natesan and W. Podolski
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

ABSTRACT

Development of cogeneration systems that involve combustion of coal in a fluidized bed and use of air heaters to generate hot air for turbine systems has been in progress for a number of years. The U.S. Department of Energy (DOE) sponsored the Atmospheric Fluidized-Bed Cogeneration Air Heater Experiment (ACAHE) to assess the performance of various heat exchanger materials and establish confidence in the resultant designs of fluidized-bed-combustion air heater systems. Westinghouse Electric Corporation, in association with Babcock &Wilcox, Foster Wheeler, and ABB/Combustion Engineering, prepared specifications and hardware for the ACAHE. Argonne National Laboratory, through a contract with the Rocketdyne Division of Rockwell International, conducted tests in the DOE 1.8 x 1.8 m atmospheric fluidized-bed combustion facility in El Segundo, California. This paper presents an assessment of the materials performance in fluidized bed environments and examines guidelines for materials selection on the basis of corrosion resistance in air and in combustion environments, mechanical properties, fabricability/thermal stability, and cost.

Keywords: air heaters, oxidation/sulfidation, corrosion, metal wastage, mechanical properties, fluidized-bed combustion

INTRODUCTION

Programs sponsored by the U.S. Department of Energy (DOE) have confirmed the viability of the concept of the atmospheric-fluidized-bed-combustion (AFBC) air heater for coal-fired power plants. A high-temperature heat exchanger located in the fluidized bed heats compressed air to temperatures of 816–871°C (1500–1600°F) to drive a turbine to generate electricity. The use of air heaters eliminates the need for a hot-gas cleanup system to minimize turbine erosion, corrosion, and deposition/fouling problems associated with the release of particulates and alkali compounds when firing coal directly into a gas turbine. However, concerns were expressed about the ability to select materials that will resist corrosive/erosive environments present in combustion systems and the reliability of information about the heat-transfer coefficients on which to base the design of the in-bed air heaters. Several different air heater cogeneration concepts were studied in these programs:[1] (a) fan- or turbine-exhaust-blown, bubbling AFBC; (b) fan- or turbine-exhaust blown, circulating AFBC with a separate fluidized-bed heat exchanger; (c) fan- or turbine-exhaust-blown coal pyrolyzer operated in series with AFBC (the pyrolysis gas is combusted to raise turbine inlet temperature); and (d) bubbling AFBC or coal pyrolyzer/AFBC that is pressurized to 3-5 atm by part of the exhaust from a high-pressure turbine while the remaining exhaust is expanded through a low-pressure turbine. Figure 1 is a schematic diagram of a generic fluidized-bed air heater cogeneration system. At low fluidizing velocities (about 2 to 3 m/s), bubbling beds are produced, while higher velocities (usually >5 m/s) are characteristic of circulating beds. A description of air heater cogeneration systems is given in Ref. 1. Table 1 summarizes the salient operating characteristics of several cogeneration plant concepts evaluated in the DOE study.

Natesan et al. prepared an assessment of information available in the literature on materials performance in fluidized-bed combustion environments.[2] Corrosion data produced over a period of 17 years by 13 organizations were tabulated and analyzed. The selected data were quantitative wastage measurements for alloys or coating/cladding combinations of alloys immersed in fluidized-coal-combusting beds at temperatures of 554 to 900°C (1029 to 1652°F) forvarious durations (few were shorter than 250 h) up to 10,000 h. However, the assessment emphasized data of 500 h or longer duration at temperatures higher than 650°C (1200°F), which are of interest for air heater applications. Based on the assessment study, a laboratory test program was conducted to evaluate the corrosion behavior of a number of candidate materials that included base alloys, coatings, claddings, and weldments. Five of the six tests were conducted at a metal temperature of 871°C (1600°F), while the sixth test useda metal temperature of 635°C (1150°F); pertinent test results are presented in a later section.[3]

Recently, the DOE-sponsored Atmospheric Fluidized-Bed Cogeneration Air Heater Experiment (ACAHE) was conducted to assess the performance of various heat exchanger materials (selected on the basis of laboratory test results) in order to establish confidence in designs of fluidized-bed air heater systems.[4] The ACAHE was carried out by two principal contractors working in parallel: Westinghouse Electric Corporation and Argonne National Laboratory (ANL). Westinghouse and its subcontractors (Babcock & Wilcox, Foster Wheeler, and ABB/Combustion Engineering) prepared specifications and hardware for the ACAHE. Through a contract with the Energy Technology and Engineering Center (ETEC, Rocketdyne Division of Rockwell International), ANL conducted tests in the DOE 1.8 x 1.8 m (6 x 6 ft) atmospheric fluidized bed combustor (FBC) in El Segundo, CA. Several different types of test hardware, including platens, uncooled rings and tabs, air-cooled rings of a number of candidate metallic alloys, coatings, claddings, and weldments, were exposed in this facility for1980 h under coal combustion conditions. Detailed microstructural examination of the specimens was conducted and the results were reported elsewhere.[4]

This paper presents an assessment of the factors that must be considered in the selection, fabrication, and performance of air heater components for service in fluidized-bed combustion systems.

MATERIAL REQUIREMENTS

The materials selected for application at elevated temperatures in air heaters of FBC systems should meet the following requirements:

1. Corrosion/erosion resistance in the FBC environment.
2. Resistance to oxidation in air.
3. Adequate mechanical properties.
4. Ease of fabricability, including welding.
5. Microstructural stability during service.
6. Low cost.

Among these requirements, the corrosion performance of the materials exposed to the FBC environment precludes a number of alloys that are otherwise acceptable in terms of requirements 2–6.

Corrosion/Erosion Resistance

Generally, wastage of materials exposed to FBC environments involve interactions between corrosion and erosion processes; however, at elevated temperatures of interest for air heaters, corrosion processes dominate and erosion has been of a minor contributor to the wastage phenomenon. Materials/environment interactions in FBCs indicate that structural alloys develop predominantly oxide scales when exposed to O_2–SO_2 gas mixtures of combustion atmospheres at elevated temperatures.[5,6] Figure 2 is a schematic diagram of corrosion-scale development and morphological changes in Cr_2O_3-forming alloys. The high–Cr alloys develop porous oxide scales (Fig. 2a), and some sulfides are also observed in the inner portions of the scale (in the vicinity of the scale/substrate interface). The sulfides are formed by reactions between substrate elements and sulfur that is released when chromium reacts with SO_2 to form an external oxide scale. Scale porosity enables SO_2 gas molecules to permeate to the scale/substrate interface (Fig. 2b), leading to further oxidation/sulfidation. The released sulfur is transported along the grain boundaries in the metal, leading to internal sulfidation of the alloy (Fig. 2c). Generally, for high–Cr alloys exposed to combustion atmospheres, the oxide scales are fairly thin and insensitive to time of exposure. As a result, the acceptable lifetimes for these alloys, when exposed to combustion atmospheres, are influenced by the depth of internal penetration, which is largely determined by alloy chemistry, temperature, SO_2 content of the gas phase, and the physical and chemical nature of the deposit. The alumina-forming alloys, in general, are much more resistant to corrosion in these environments, but their scales are susceptible to spallation. When spallation occurs, the exposed alloy surface is depleted in aluminum; as a result, repair of the protective oxide scale is impeded, and accelerated sulfidation of the base metal ensues. Based on metal wastage data developed over the years, high–nickel structural alloys are unacceptable for air–heater service in an FBC environment. Figure 3 shows the corrosion rates (based on parabolic kinetics) for 10 nickel-base alloys after exposure in various FBC systems. Inconels 601, 617, and 671 experienced breakaway corrosion in the FBC exposures represented in this figure. It is prudent to conclude that nickel–base alloys usually exhibit much higher corrosion rates than either iron– or cobalt–base alloys.

Extensive corrosion information has also been developed for a variety of structural alloys that were coated with reagent–grade $CaSO_4$ and/or $CaSO_4$–CaO mixtures (which form the spent–bed material in a well–run FBC system); however, it is conceivable that in certain locations within the bed, such as coal feedport regions and sections of bed bypassed by combustion air due to fouling/deposit, local gas chemistry may lead to deposits that contain CaS and/or a CaO–CaS mixture.[6] To examine the effect of such changes in deposit chemistry on corrosion of heat- exchanger materials, tests were conducted at 840°C (1544°F) with Incoloy 800 and Type 310 stainless steel coated with CaO/CaS, CaS/$CaSO_4$, CaO/$CaSO_4$ and CaO/CaS/$CaSO_4$ mixtures. Further, 3000–h laboratory corrosion tests were conducted with several candidate heat–exchanger materials in the presence of reagent–grade $CaSO_4$ and gas chemistries that simulate the highest sulfur pressure and lowest oxygen pressure (in the vicinity of the CaO–CaS–$CaSO_4$ triple point of the phase stability diagram).[6] In addition, spent–bed materials from two large FBC facilities (TVA–20–MW and IEA/Grimethorpe) were used as deposits in laboratory corrosion experiments to evaluate the roles of deposit chemistry and gas chemistry in the corrosion performance of structural alloys.[6]

The results of these studies have clearly established that the $CaSO_4$ deposit alone can lead to intergranular sulfidation of high–Cr alloys, even though the external scales are predominantly oxides. The results also showed that low oxygen pressure (pO_2) in the exposure environment can increase the corrosion of bare alloys, as well as of those coated with $CaSO_4$ and CaO, at temperatures above 600°C (1112°F). A gas–cycling (oxidizing/sulfidizing) experiment showed that sulfidation can be triggered even in Type 310 stainless steel with a cycle time of 100 h; no sulfidation was noted with a 10–h cycle time. Because the fraction of time spent under low–pO_2 conditions was the same in both 100- and 10–h–cycle time tests, it was concluded that a sustained exposure (>10 h) to a low–pO_2 atmosphere is required for initiation of sulfidation attack of the material. Further, variations in relative time periods for high and low pO_2 during an exposure cycle had almost no effect on the corrosion of alloys coated with either $CaSO_4$ or CaO, if the virgin specimens were exposed to a high–

pO_2 (similar to flue-gas oxygen pressure) atmosphere at the start of the first cycle. The results also showed that a number of structural iron-base alloys had acceptable corrosion rates but the rates determined in the laboratory were higher by a factor of ≈2 than the in-bed corrosion rates and these laboratory rates can be treated as upper-bound values if the alloys are not susceptible to breakaway corrosion.

Recently, a laboratory test program was conducted to evaluate the corrosion behavior of several metallic alloys, coatings, claddings, and weldments in support of the atmospheric fluidized-bed air heater experiment.[3] The program involved a total of six tests, five of which were conducted at a metal temperature of 871°C (1600°F), while the sixth was performed at a metal temperature of 635°C (1175°F). Three tests were conducted under simulated bubbling-bed conditions, while circulating fluid-bed conditions were maintained in the others. Reagent-grade $CaSO_4$ and ash from a circulating fluid bed system were used as the deposit materials to simulate the bubbling- and circulating-fluid beds, respectively, in the laboratory test program.

Two of the bubbling-bed simulation tests were of 3000-h (Test A2) and 2000-h (Test C) durations, and data from these tests are relevant for comparison with in-bed test data. In Test A2, the specimens were exposed in a sustained manner for 3000 h at 871°C (1600°F) in a low-pO_2 environment, simulating the worst possible combustion environment anticipated in FBC systems. The oxygen and sulfur partial pressures during the exposure were maintained at $\approx 3 \times 10^{-12}$ and $\approx 10^{-7}$ atm, respectively, at a gas temperature of 900°C (1652°F). The gas environment in Test C was cycled between a high-pO_2 mixture ($pO_2 \approx 10^{-3}$ atm) and a low-pO_2 mixture ($pO_2 \approx 3 \times 10^{-12}$ atm) every 100 h. The pS_2 values corresponding to the high- and low-pO_2 gas mixtures were $\approx 10^{-28}$ and 10^{-7} atm, respectively.

Figure 4 is a comparison of corrosion penetration depth for several alloys assembled in different probes and exposed at different location in the ETEC facility. Surfaces of all specimens in these probes were free of any deposit accumulation during the 1980 h of exposure. Penetration rates for the alloys ranged from 5 to 100 µm (which translates to 0.01 and 0.21 mm/yr, based on parabolic kinetics) after a 1980-h exposure to the FBC environment. Figure 5 is a comparison of the corrosion rates calculated for several candidate alloys exposed in Tests A2 and C and in the ETEC AFBC. The ETEC test data in this figure are differentiated as to whether the specimens were covered with bed material. The data show that some of the alloys, such as 800H, HK 40, HS 188 and HS 556, are susceptible to catastrophic corrosion when subjected to a sustained low-pO_2 and relatively high-pS_2 (dictated by the boundary between CaO and $CaSO_4$ phases) environment. The next-worst environment from the materials corrosion standpoint is the ETEC test exposure in the presence of bed deposit material. HP 50, and Sanicro 33 exhibited 4-6 mm/yr corrosion, whereas the other alloys, e.g., 253 MA, HS 556, HS 188, XM 19, and HK 40, had corrosion rates of ≈2 mm/yr. A well-controlled FBC system will not experience a sustained low-pO_2 atmosphere for thousands of hours and the materials corrosion data obtained in Test A2 may be overly pessimistic. Selection of materials based on these data will be highly conservative.

The gas-cycling (Test C) data showed that the alloys can generally tolerate oxidizing/reducing environments if they are exposed to an oxidizing condition in the startup cycle. Only alloy HS 188 exhibited high corrosion manifested by internal oxidation of the alloy. The results also show that a number of structural alloys (such as Types 304 and 310 stainless steel, HR 3C, FW 4C, 8XX, 330, and some of the chromized coatings) performed well under all environmental conditions used in the tests. Alloys such as 800, 188, and 330 were susceptible to catastrophic attack in the presence of $CaSO_4$ deposit. The chromized alloys exhibited a low rate of attack in the presence of FBC deposit. Attack-zone thicknesses were generally smaller than initial coating thicknesses, indicating resistance of the coated layers to catastrophic attack. Among the weldments tested with $CaSO_4$ deposit, the filler metals 309, 310, and 21-33 Nb showed very little corrosion even after 3000-h exposure to FBC environment. Alloys such as 253 MA, FW-4C, and 54E showed moderate corrosion, while alloys such as 53C and RV 8413 exhibited the least attack. Table 2 is a listing of the chemical compositions of alloys that have acceptable corrosion resistance in FBC atmospheres, based on all available data. Although some of the alloys exhibit higher-than-desirable corrosion rates, especially in the presence of deposits, they are included in the table to allow designers to select them for applications where deposits are not anticipated.

Corrosion rates for the acceptable alloys were in the range of 0.25–0.4 mm/yr (10–16 mils/yr) for temperatures between 775 and 871°C (1425 and 1600°F). If one considers air tubes of 5–6 mm in wall thickness, the above corrosion rates will lead to a thickness loss of 0.8–1.25 mm after 10 years of service in the FBC environment. Because off-normal excursions (e.g., the low-pO_2 condition during the second 500 h of the present test at ETEC) are anticipated during the operation of an FBC system, the material selected for the air tubes should possess adequate corrosion resistance even under perceived off-normal conditions.

Oxidation Resistance in Air

Very few data are presently available on oxidation/wastage of all the candidate alloys (listed in Table 2) in air at temperatures of 760 to 871°C (1400 to 1600°F). However, data available for an exposure temperature of 982°C (1800°F) have been used to calculate metal loss and penetration depths, assuming parabolic kinetics. The data shown in Fig. 6 indicate that several of alloys exhibit oxidation rates below 0.1 mm/yr at 982°C (1800°F) and that the rates will be lower by a factor of 2 at the exposure temperature of 871°C (1600°F) that is of interest in FBC air heaters.

Mechanical Properties

The material selected for application in the FBC air heaters will be subjected to temperatures that require designs based on time-dependent mechanical properties. Although the ASME code does not specify information for temperatures beyond 816°C (1500°F), the criteria on maximum allowable stress can probably be extrapolated to higher temperatures. These criteria specify that the maximum allowable stress for the material shall not exceed the lowest of the following:

- 100% of the average stress for a creep rate (secondary) of 0.01% in 1000 h.
- 67% of the average stress for rupture at the end of 100,000 h.
- 80% of the minimum stress for rupture at the end of 100,000 h.

A compilation has been made of the available data on the creep properties of candidate alloys to examine the effect of metal temperature on the 10,000-h and 100,000-h rupture strengths and stress values that will result in 1% creep strain in 10,000 h. Stress values to obtain 0.01% strain in 1000 h are not presently available. The compiled data are based on information developed in an air environment, and the 100,000-h rupture data are based on extrapolation of the available shorter-term data. Figures 7 and 8 show the 10,000 and 100,000 h rupture stress data, as a function of temperature, for some of the candidate alloys listed in Table 2. It is evident that at 871°C (1600°F), i.e., the maximum temperature of interest for the air heater tube in FBC systems, the 10,000-h rupture data show several alloys with rupture stress values of2000–4000 psi. At temperatures >871°C, the stress values show a substantial decrease. Further, the extrapolated 100,000-h rupture stress values for all the alloys (except 188) are1000–2000 psi at 871°C (1600°F). Figure 9 is a plot of stress values for 1% creep in 10,000 h as a function of temperature for several of the alloys.

Among the three criteria mentioned above for allowable stress calculation, 67% of the average stress for rupture at the end of 100,000 h (even though extrapolated) is used to calculate the allowable stress values. The present data are not sufficient to calculate with the creep rate and 80% minimum stress for the100,000-h criteria. Figure 10 shows the code allowable (many of the alloys are not coded under ASME rules, but it is assumed that the criteria used for the coded materials will be applicable to noncoded-alloy) stress values as a function of temperature.

Fabrication and Welding

In general, fabrication of tubes of the corrosion-resistant materials (identified above) should not be a problem. In fact, most of the alloys are presently available in tube/pipe forms and the compositions of others are such that fabrication/availability will not be a problem. Among the filler metals tested in FBC environments, alloys 309, 21-33, and 25-35R had acceptable corrosion behaviors. However, only limited information is available on weldability of the corrosion-resistant materials (identified above) with these filler metals and corrosion performance of such welded tubes in FBC environments.

Microstructural Stability during Service

Almost all of the alloys with acceptable corrosion behavior in FBC environments are iron-base alloys with high chromium contents ≈18 to 25 wt.% and are generally prone to sigma-phase formation during prolonged exposures above 650°C (1200°F). Qualitatively, alloys with nickel contents greater than 30 wt.% are less prone to sigma-phase formation. Similarly, alloys 330 and 800H are less susceptible to sigma-phase formation but are more susceptible to corrosion in FBC environments. The precipitation of Fe–Cr sigma phase, which occurs predominantly at grain boundaries in the alloy, can lead to substantial reduction in creep ductility at elevated temperatures and loss of fracture toughness when the components are cooled to room temperature. The 100,000-h creep stress data presented earlier are extrapolated values from short-time test data and do not account for the property reduction due to microstructural changes in the alloy.

Cost Analysis

A cost comparison of the candidate alloys is difficult to make because the unit cost of the tubing/piping of each alloy depends on the total amount procured and how common the alloy is from the manufacturing standpoint. For example, Type 304 stainless steel and Alloy 800 are widely used alloys, while 8XX and HR3C are relatively new. Further, the unit cost by itself is not sufficient for the final selection because an alloy with superior corrosion/creep properties will have a much longer service life; similarly, an alloy made by an expensive fabrication process may also have a longer life than a relatively cheaper alloy. Therefore, a detailed cost analysis of air heater systems requires knowledge of specific application of the cogeneration system, modus operandi, and short- and long-term financial data for the plant. Table 3 lists the relative costs of several alloy tubes that can be considered, along with their corrosion resistance and mechanical properties, to enable a judicious selection of alloys for air heater applications.

SUMMARY

Cogeneration systems based on atmospheric fluidized-bed combustion (AFBC) of coal and air heaters are viable systems for generation of electricity and process steam. In this paper, an assessment is made of candidate air heater alloys with regard to their corrosion performance in combustion environment, their air oxidation, and their mechanical properties at elevated temperatures. Several conclusions can be drawn from this assessment:

1. Austenitic stainless steels, e.g., Types 304, 310, and 330, and alloys such as HR 3C, FW 4C and 8XX exhibited low depths of oxidation/sulfidation penetration after exposure in (a) the ETEC AFBC facility, (b) a laboratory test under gas-cycling conditions, and (3) a more severe laboratory test under low-pO_2 conditions.

2. Alloys such as HS 188, HS556, HK 40, and 800H exhibited catastrophic corrosion in the presence of sustained low-pO_2 condition and deposit material, based on a 3000-h laboratory test. Even though the test conditions are more severe than those the materials will be subjected to in a typically well-run FBC system, the data nevertheless suggest the susceptibility of these materials to accelerated corrosion.

3. Alloys such as HH, HP 50, 253 MA, XM 19, Sanicro 33, HS 556, and HS 188 exhibited unacceptable corrosion behavior when the alloys were in contact with bed material.

4. Among the cladding alloys, Type 310 stainless steel on Type 304 stainless steel or Alloy 800H exhibited superior performance. This is consistent with the acceptable performance of Type 310 stainless steel base metal mentioned above.

5. Corrosion rates for several materials were in 0.25 to 0.4 mm/yr (10 to 16 mils/yr) at temperatures of 775 to 871°C (1425 to 1600°F). If one considers air tubes 5–6 mm in wall thickness, these corrosion rates will lead to a thickness loss of 0.8–1.25 mm after 10 years of service in the FBC

environment, even with built-in off-normal excursions."

6. A number of candidate alloys have adequate creep rupture strengths (1000–2000 psi) for application in air heaters in where air pressure is expected to be 200–300 psi.

ACKNOWLEDGMENTS

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Table 1. Plant Configuration and Performance Comparison

Process Conditions/ Performance	Fluidized Bed Type[a]								
	FBAFB	TBAFB	CFB	CFB	SFB	FBAFB	FBAFB	CFB	SFB
Process Steam (klb/hr)	210	210	249	210	210	210	210	210	210
Air Temperature (°C)	816	816	816	816	816	816	760	816	760
Steam Turbine	–	–	–	Yes	–	–	–	Yes	–
Carbonizer	–	–	–	–	–	Yes	Yes	Yes	Yes
Power Generation (MW)	19.2	16.3	18.8	23.1	25.6	33.4	30.9	33.4	31.6
Auxiliary Power (MW)	4.5	2.9	4.8	4.8	1.3	4.3	4.2	5.6	2.0
Process Air (klb/hr)	717	717	717	717	717	737	717	737	717
Turbine Inlet Temp. (°C)	816	816	816	816	816	1038	977	1038	977
Net Plant Efficiency (%)	82.3	84.	837	77.0	79.6	80.0	79.0	81.2	80.2

[a] Type of Fluidized Bed: FBAFB– Fan-blown; TBAFB– Turbine-blown; CFB– Circulating; SFB– Supercharged.

Table 2. Nominal or Actual Chemical Composition (wt.%) of Alloys for Air Heater Application

Material	C	Cr	Ni	Mn	Si	S	Mo	Al	Fe	Other
304	0.08	18.3	8.10	1.5	0.27	0.018	0.27	-	Bal.[a]	-
800H	0.08	20.1	31.7	1.0	0.24	0.006	0.30	0.39	Bal.	Ti 0.31, Cu 0.78
330	0.05	18.6	35.1	1.2	0.92	0.006	0.18	-	Bal.	Nb 0.12
310	0.07	25.0	18.7	1.2	0.64	0.006	-	-	Bal.	-
347	0.06	18.9	10.8	1.5	0.58	0.014	–	–	Bal.	Nb+Ta 0.57
188	0.08	23.4	23.3	0.7	0.40	-	0.60	0.22	1.40	Co 35.7, W 14.6,
556	0.10	22.0	20.0	1.5	0.40	-	3.00	-	Bal.	Co 20, W 2.5
253MA	0.10	20.7	10.9	0.3	1.80	-	-	-	Bal.	Ce 0.03
HK40	0.40	28.0	20.0	2.0	2.00	-	0.50	-	Bal.	Cu 0.5
HH	0.32	24.6	11.8	0.4	1.99	0.017	0.19	-	Bal.	-
HP 50	0.45	24.3	34.0	0.7	1.73	0.008	0.14	-	Bal.	-
XM 19	0.02	21.2	12.5	5.1	0.39	0.004	2.22	-	Bal.	Nb 0.2, V 0.2
Sanicro 33	0.07	22.1	30.3	4.5	0.13	0.003	-	-	Bal.	Nb 0.9, Ce 0.08
8XX	-	20.2	32.5					3.00	Bal.	-
FW 4C	0.05	19.5	20.0	4.9	2.60	-	-	1.40	Bal.	-
HR 3C	0.06	24.8	20.4	1.2	0.40	-	-	-	Bal.	Nb 0.48, N 0.25
21/33[b]	0.19	22.2	33.2	1.6	0.35	0.004	–	–	Bal.	Nb/Ta 2.49
25/35R[b]	0.42	26.3	35.3	1.8	1.06	0.050	–	–	Bal.	Nb 1.35
309[b]	0.11	23.0	14.7	0.5	0.74	–	–	–	Bal.	-

[a] Bal. = balance.

[b] Indicates use as a filler metal in weldments.

Table 3. Cost Comparison of Candidate Alloys

Alloy	$/ft, 2-in. OD x 0.300-in. wall
304H	18
347	24
310	35
330	46
800H	47
253	38
HR3C	32
556	90
310 clad/304H	50

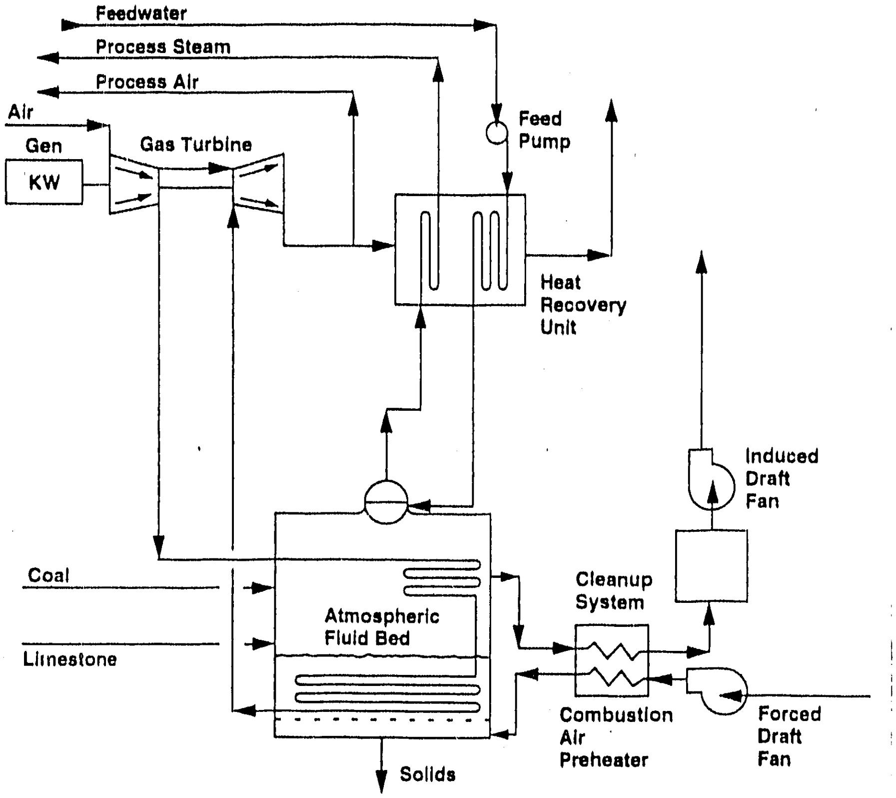

Fig. 1. Schematic diagram of generic fluidized-bed air heater cogeneration system

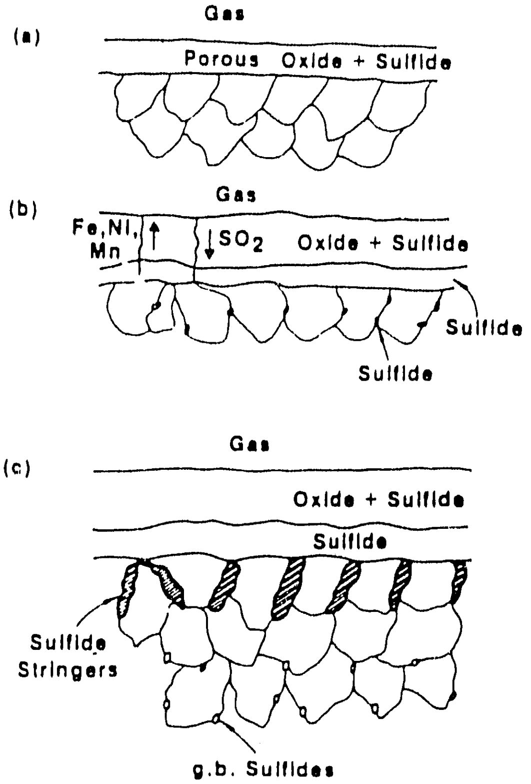

Fig. 2. Schematic diagram of corrosion scale data for several nickel-base alloys

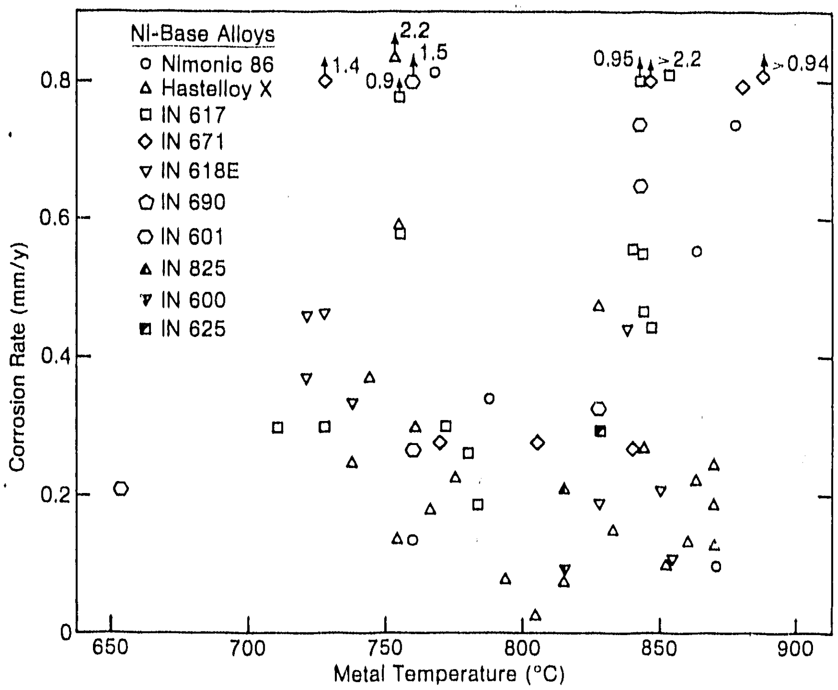

Fig. 3. Corrosion rates of several nickel-base alloys

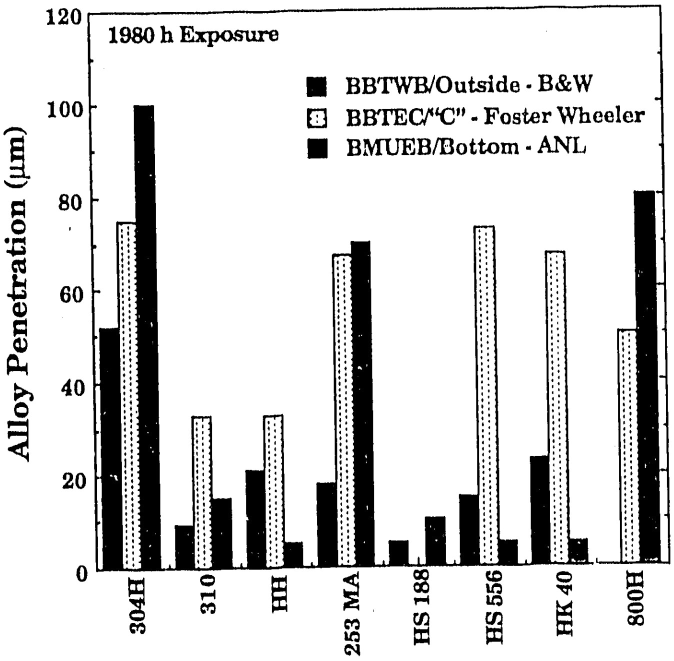

Fig. 4. Comparison of corrosion penetration depth for several alloys free of bed deposits after 1980 h exposure in ETEC facility

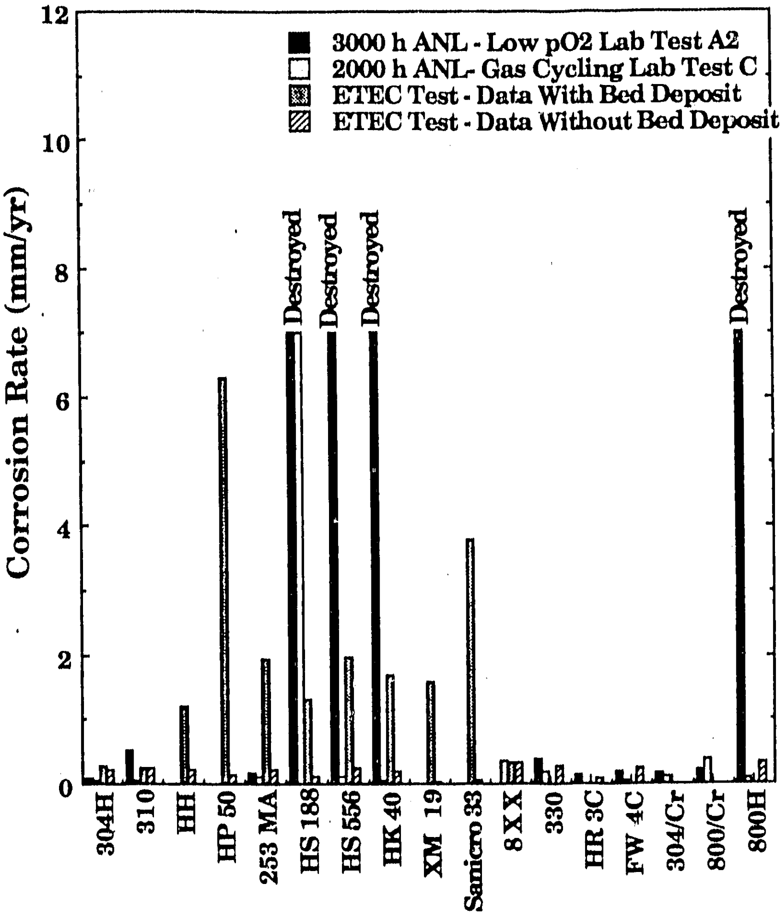

Fig. 5. Comparison of corrosion penetration rates for alloys tested under different combustion conditions in the laboratory with those obtained on specimens exposed in ETEC facility

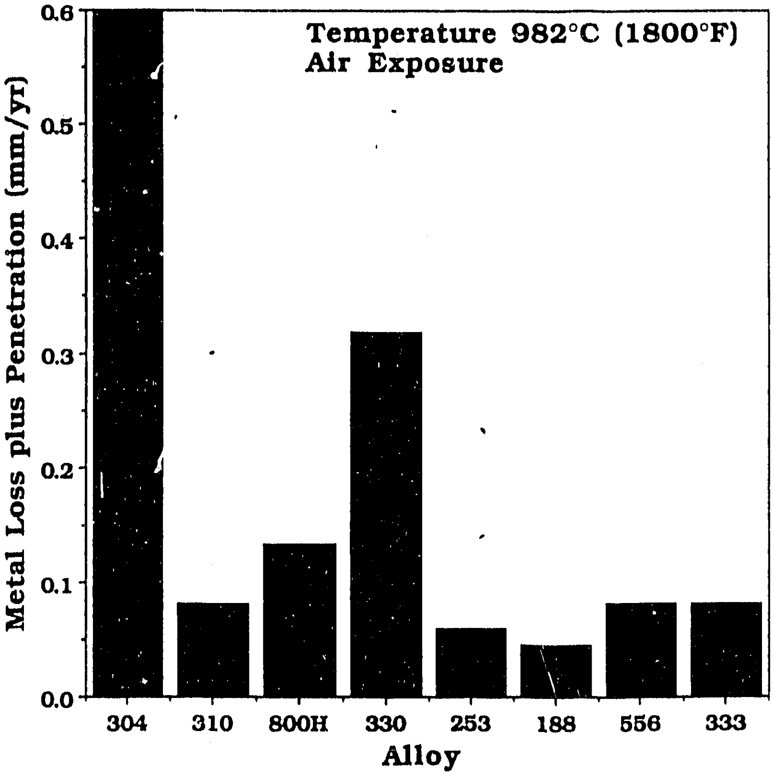

Fig. 6. Oxidation wastage for several alloys exposed in air at 982°C (1800°F)

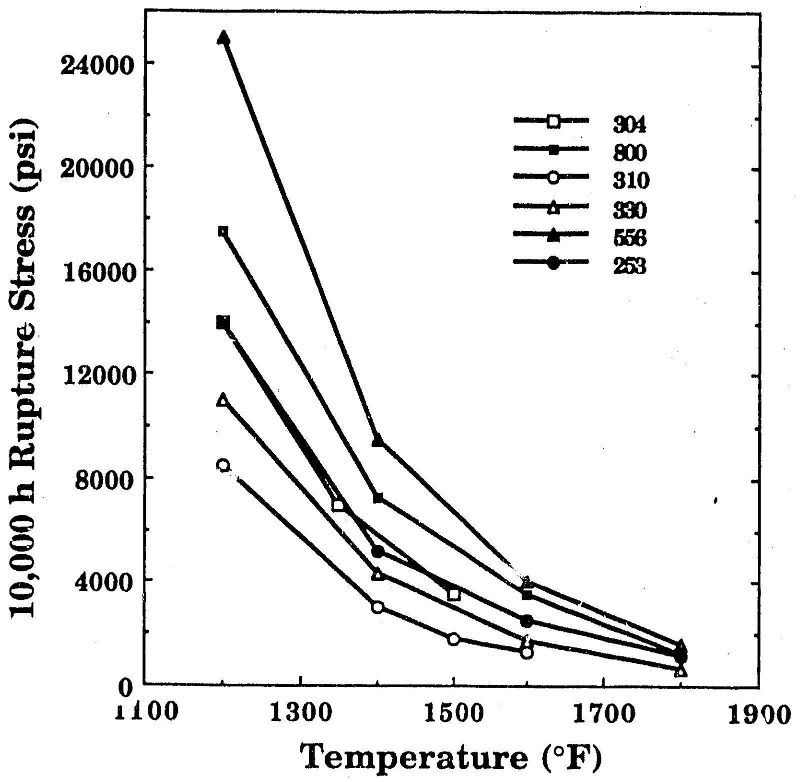

Fig. 7. 10,000-h creep rupture stress as a function of exposure temperature for several candidate alloys

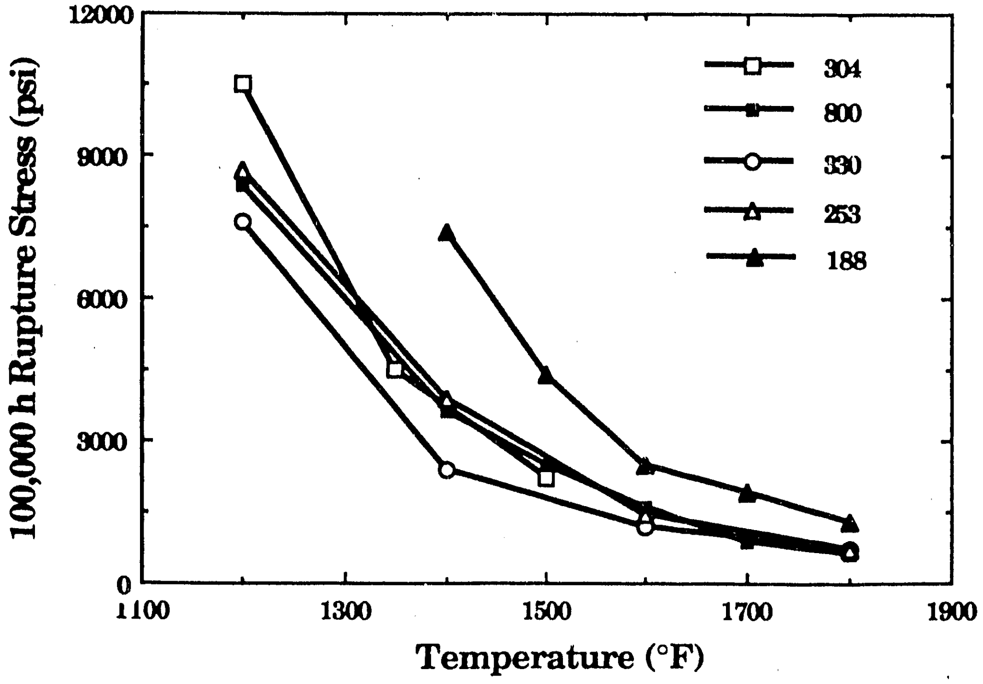

Fig. 8. 100,000-h creep rupture stress as a function of exposure temperature for several candidate alloys

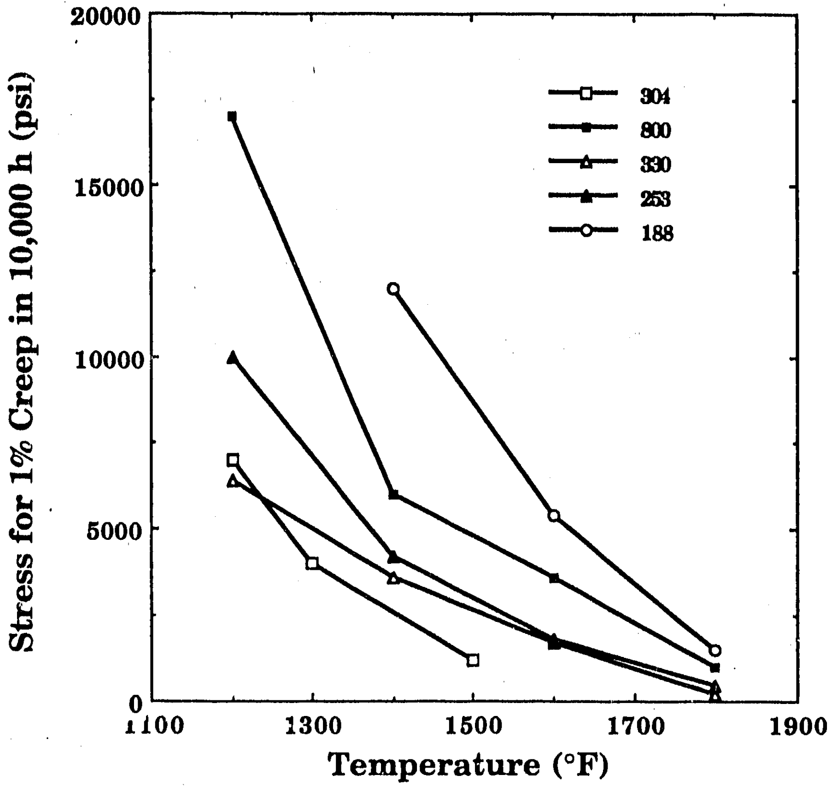

Fig. 9. Stress for 1% creep strain accumulation in 10,000 h as a function of exposure temperature for several alloys

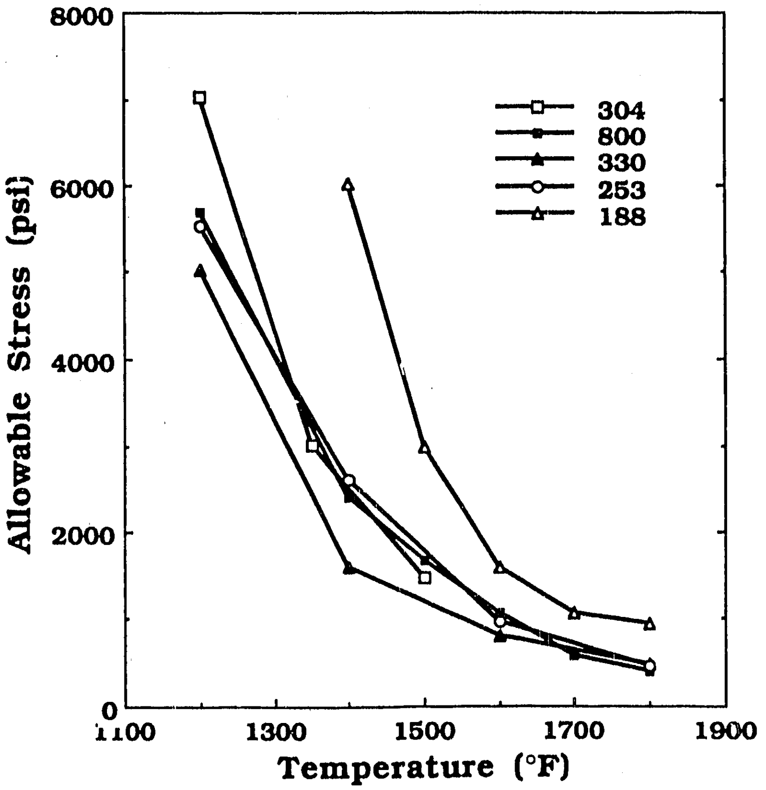

Fig. 10. Estimated allowable stress values as a function of temperature for several candidate alloys

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