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**Analysis of Air Distributor Plates from
Atmospheric Fluidized Combustors:
Rivesville and Alexandria**

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OAK RIDGE NATIONAL LABORATORY
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COMBUSTORS: RIVESVILLE AND ALEXANDRIA

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ANALYSIS OF AIR DISTRIBUTOR PLATES FROM ATMOSPHERIC FLUIDIZED COMBUSTORS: RIVESVILLE AND ALEXANDRIA*

R. T. King, R. J. Gray, J. M. Leitnaker,
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ABSTRACT

Samples of perforated type 310 stainless steel plates that were used as the air distributor grids for the Rivesville, West Virginia, and Alexandria, Virginia, atmospheric fluidized-bed combustors together with unexposed plate material were examined to determine the cause of cracking of the Rivesville plate. Intergranular cracks in the Rivesville plate are associated with massive sigma phase precipitates on grain boundaries. Both plates buckled during service, probably because of thermal stresses, but the greatest measured strain occurred in the Alexandria plate. Some operating history differences might explain why the Alexandria plate buckled but did not fail.

Either designing new air distributors to reduce thermal expansion strains or to allow free expansion or selecting a material that can deform under the service conditions without cracking might improve future plant operations.

1. SOURCE OF PARTS

Two atmospheric fluidized bed combustors (AFBC) were built and operated by Pope, Evans, and Robbins (PER) on a continuing program supported in succession by the Office of Coal Research, the Energy Research and Development Administration, and the Department of Energy. The smaller unit is a 0.5 MW(e) fluidized-bed boiler module at the PER laboratory in Alexandria, Virginia.¹⁻³ The larger unit is a 30-MW(e) multicell fluidized-bed boiler (constructed by Foster-Wheeler, Livingston, N.J.), whose design and initial operational history are described elsewhere.⁴⁻⁶ Representatives of Pope, Evans, and Robbins supplied sections of the as-fabricated air-distributor grid plate, the grid plate material used at Alexandria, and the grid plate used in the "D" or carbon burnup cell at Rivesville, West Virginia. All were reportedly from the same lot of material.

2. DESCRIPTION OF PART

The as-fabricated plate was nominally 1.6-mm-thick (1/16 in.) type 310 stainless steel, with a hexagonal array of 2.5-mm-diam (~ 0.1 in.) punched holes spaced on approximately 16-mm (5/8 in.) centers. The

*This work was done under the Failure Prevention and Analysis Program Sponsored by the Materials and Exploratory Research Branch of Fossil Energy.

holes admit air to the bottom of the beds. The as-fabricated plate section was about 300 x 300 mm. Plate from the Alexandria bed measured about 160 x 350 mm, and was still attached to a stiffening frame. The sample from the Rivesville bed was a 240 x 320-mm section that was flame-cut from a larger assembly that included stiffening frame members.

3. SERVICE CONDITIONS AND HISTORY

The Alexandria experimental AFBC (Fig. 1) was one of three experimental beds with about 10,000 h of operation over a wide range of fuels and operating modes.¹ Several air distributor designs were tested in that bed, including the perforated plate design used at the Rivesville, West Virginia AFBC. The perforated plate tests were run during June and July, 1975, under conditions simulating those at Rivesville as closely as possible. The maximum air distributor temperatures during operation and shutdown were about 843°C (1550°F) for an 1093°C (2000°F) bed temperature, and 650°C (1200°F) for an 815°C (1500°F) bed temperature; average air distributor temperatures were about 167°C (300°F) lower than the maximum temperatures.¹ During trial runs at 816°C (1500°F) and 1093°C (2000°F), temperature profiles were established for the air distributor plate. Measured variations were as high as 280°C (500°F) and commonly 55°C (100°F) over a 15-cm (6-in.) distance, indicating that

Fig. 1. The Alexandria 0.5-MW(e) Experimental Fluidized Bed.
Source: M. Pope, "Pilot and Research Plants: A Progress Report," pp. 123-132 and cover of *Proceedings of the Fourth International Conference on Fluidized-Bed Combustion*, December 9-11, 1975, M76-36, MITRE Corporation, McLean, Virginia (May 1976).

nearly adjacent regions of an air distributor may experience significant differences in operating history.²

Buckling of the punched plate in the Alexandria bed was observed¹ during the early trials of the bed, and this buckling increased with temperature until after the first 1093°C (2000°F) bed temperature test run. No change in the deformation pattern was observed after subsequent tests.¹ Details of the propane torch lightoff procedure at Alexandria are not known. The operating time-temperature history of the bed and the exact service conditions seen by the Alexandria plate are not known.

The 30 MW(e) boiler of the Rivesville AFBC (Fig. 2) consists of four cells, of which the "D" cell is intended for carbon burnup. It was the first cell to be ignited (December 7, 1976) and had the longest operating time of any cell, several hundreds of hours at the time the air distributor plates were removed. Two over-the-bed oil burners were backfired through about 22-27 cm of bed material to light the bed.^{4,7} While the normal operating conditions are 315°C (600°F) air on the lower side of the plate and 843°C (1550°F) bed material above the plate, the plate temperature history during backfiring is not known, but it may have reached the oil flame temperature. Additional thermal cycling may also result from unplanned bed slumping during the runs, although in early experiments at Alexandria, bed slumping did not increase air-distributor-plate temperature.¹⁻²

4. ANALYSIS

Several methods were used to investigate the cause of cracking of the "D" cell Rivesville air distributor plate. Optical metallographic examinations determined if any microstructural changes had occurred during service and characterized the mode of fracture. When a massive precipitate phase was observed at grain boundaries, a combination of x-ray diffraction analyses of electrochemically extracted phases and direct transmission electron diffraction methods identified the phase as sigma phase. Specimens of as-received plate were aged at 843°C (1550°F) and 650°C (1200°F) for 100 and 1000 h to determine thermal aging conditions under which sigma phase forms in the plate. To determine the effects of plant exposure on short-term mechanical properties, tensile tests at several strain rates at room temperature, 650°C, and 843°C were done on the as-fabricated plate and plate exposed at Rivesville. One test was run at 843°C on material aged at 843°C for 1000 h for comparison with plate exposed at Rivesville.

4.1 Optical Metallographic Analyses

The as-received, unused plate was sectioned, mounted, polished, and etched with a standard Murakami reagent⁸ to reveal ferrite, carbide particles, or sigma phase. No significant quantities of any of these phases were found by optical methods. The sample was then etched with aqua

Fig. 2. (a) Model and (b) Schematic of a Cell Similar to the Rivesville Multicell Atmospheric Fluidized Bed Boiler, Showing Location of Air Distributor Plate. Source: Robert L. Gamble, "Design of the Rivesville Multicell Fluidized Bed Steam Generator," pp. 133-152 in *Proceedings of the Fourth International Conference on Fluidized Bed Combustion, December 9-11, 1975*, Sponsored by US Energy Research and Development Administration, coordinated by MITRE Corporation, McLean, VA, published in May 1976, MITRE, McLean, VA.

regia to reveal the grain structure (Fig. 3). The structure is equiaxed with annealing twins; there are some nonmetallic precipitates (possibly silicates), and some evidence of banding or inclusion stringers in the plane of the plate. Chemical analyses of the as-received plate and used plates from both plants were done by the ORNL Spectrochemical Laboratory (Table 1). Within the stated limits of error, all were identified as type 310 stainless steel. However, all three samples were run in the same batch of analytical samples, and the precision of the measurements is probably better than the quoted $\pm 5\%$ of the value.

Fig. 3. Structure of the as-received air distributor plate etched with aqua regia.

Table 1. Chemical contents of air distributor plates from Rivesville and Alexandria plants.^a

Element	Amount of element present ^b (wt. %)			ASTM A 167-74, type 310 chemical requirements
	As-received plate	Rivesville plate	Alexandria plate	
Co	0.2	0.2	0.3	
Cr	25	23	25	24.0-26.0
Cu	0.25	0.2	0.05	
Mn	1.6	1.5	1.4	2.0 max
Mo	0.3	0.2	0.3	
Ni	21	22	20	19.0-22.0
Si	0.5	0.5	0.3	1.50 max
Ti	<0.005	<0.005	<0.005	
C				0.25 max
P				0.045 max
S				0.030 max
C				0.25 max

^aThe plates are stainless steel and therefore mostly iron.

^bPrecision estimated to be $\pm 5\%$ of the value for photoelectric analysis.

The plate from the Alexandria plant (Fig. 4) was welded to the frame that supported it. Although the plate buckled, there was no visible evidence of cracking. Visually, the top surface varied from location to location, but it was generally reddish and polished. The bottom surface was covered with a gray scale, probably a corrosion product. Sections were removed for metallographic analysis.

The microstructure of the plate (Figs. 5-8) includes five salient characteristics: 1. The surface is irregular with scale not exceeding 25 μm (0.001 in.) in thickness on either side. 2. General subsurface oxidation is usually not deeper than 25-50 μm (0.001-0.002 in.). 3. Cracks not exceeding about one grain diameter or 50-75 μm (0.002-0.003 in.) in length exist along a few grain boundaries that intersect the top surface of the plate. 4. A phase that decorates grain boundaries has been identified by electron transmission diffraction as sigma phase. 5. Light carbide precipitates decorate twin boundaries.

The approximate minimum one-dimensional radius of curvature of the Alexandria air distributor plate in the region from which samples were cut is 30 mm. Near the corners of the section, there are regions where the radius of curvature is about 10 mm. The corresponding maximum tensile strains on the top surface of the plate are estimated to be 2.5 and 7.7% respectively, from the one-dimensional bending relation:*

$$\text{strain} = \frac{\text{plate thickness}}{2 \times \text{radius of curvature}} \quad (1)$$

* Assuming that the centerline of the plate acts as a neutral axis, the change in length of a surface fiber, Δs , is readily gotten from $\Delta s = \Delta r \theta$ where r is radius of curvature and θ is angle.

Fig. 4. Air distributor plate from Alexandria plant. Material on the front of the frame member is silastic cement used to seal cracks during cold flow tests. The plate thickness ranged from 1.52 to 1.57 mm (0.060 to 0.062 in.).

Fig. 5. Alexandria air distributor plate, showing irregular top plate surface, scale on surface, and sigma phase at grain boundaries. Etched with Murakami's reagent.

Fig. 6. Alexandria air distributor plate, with grain boundary separations near surface.

Fig. 7. Alexandria air distributor plate, showing subsurface corrosion and partially separated grain boundary. Whether the corrosion products were sulfides, oxides, or both was not determined.

Fig. 8. Closeup of sigma phase formed on grain boundaries of type 310 stainless steel Alexandria air distributor plate. 1500x.

The 610-mm $\times$ 1220-mm air distributor plates from the Rivesville "D" cell (Fig. 9) were welded to bar stock that formed the frame for each section. There were obvious cracks and regions where weld repair of cracks had been attempted. The samples had been torch-cut from the plate, and the welds to the frame were broken manually (Fig. 10) to remove the samples.

A polished multicolored scale covered the top surface of the Rivesville plate; the bottom surface was covered with a rough, granular material that appeared to be fines which had fallen through the perforations from the bed, blown against the bottom surface of the plate, and stuck there. An analysis of the granular material supports this identification (Table 2). Material stuck in a hole in the plate (Fig. 11) was also analyzed and found to contain slightly less metallic material than the fines on the bottom of the plate, suggesting that some corrosion product mixed with the bed material on the bottom of the plate, or that some plate material was scraped off with the nonmetallic material.

Cracks in the Rivesville plate (Figs. 11 and 12) show fracture paths, which are clearly intergranular; wedge-type grain boundary cracks are present throughout the material. No significant reduction of area occurred at the fracture region (Fig. 13). Similar microstructures have been observed during elevated-temperature testing of type 310 stainless steels.^{9,10} Voids between the sigma phase and grains are visible, suggesting that the fracture propagates along these boundaries (Fig. 14). Some intragranular carbide precipitates are present, as well as precipitates on twin boundaries.

Fig. 9. Rivesville cell "D" air distributor plates after removal from boiler. Note the frame members and missing sections of plate which were torch-cut from the frames for analysis.

Fig. 10. Sample from the Rivesville air distributor plate.

Table 2. Chemical content of material attached to
Rivesville air distributor plate (wt %)

Element	Content, wt %	
	Material from bottom of plate	Material from hole in plate
Al	5	1
B	<0.01	<0.01
Ba	0.03	0.01
Ca	Major	Major
Co	<0.05	<0.05
Cr	0.2	<0.02
Cu	0.1	<0.01
Fe	2	1
K	0.1	0.05
Mg	3	1
Mn	0.2	0.02
Mo	<0.05	<0.05
Ni	0.1	<0.05
Si	0.6	0.4
Sr	0.4	0.5
Ti	0.2	0.05

Fig. 11. Polished section that shows cracks extending from hole in
Rivesville plate. Hole contains bed material. 10 $\times$.

Fig. 12. Cracking viewed in the plane of the Rivesville plate in the (a) etched and (b) unetched conditions. Note the intergranular fracture pattern and grain boundary cracking, and the extensive formation of sigma phase on grain boundaries.

Fig. 13. Transverse view through cracked plate from Rivesville boiler. (a) 100x. (b) 10x. Note the oxide scale on the top surface of the plate.

Fig. 14. Cracks at sigma-phase austenite boundaries in Rivesville plate. 1500 $\times$.

A transverse section through one of the cracks in the Rivesville plate shows a general scale on the top surface of not more than 25 μm (0.001 in.) thick, with deeper incursions at grain boundaries (Fig. 13). Some of this corrosion product was probably inadvertently characterized as an unidentified phase (Sect. 4.2.2.).

The radius of curvature at some prominent cracks in the Rivesville plate is estimated to be about 80 mm, with a corresponding approximate strain of about 1%.

4.2 Identification of Precipitate Phases in the Rivesville Plates

4.2.1 Extraction data and x-ray data on precipitates

Two anodic extractions at 1.5 V with 10% HCl-90% CH₃OH electrolyte at room temperature were done successively on the same 10 $\times$ 20 mm rectangle taken from the Rivesville plate (Table 3). The first extraction seemed consistent with the amount of grain boundary precipitate seen optically. To verify this, quantitative measurements were made as follows: Ten lines, 10 cm long, were ruled on each of ten micrographs taken at random within a sample. The fraction of the line length that intercepted the observed precipitate phase was taken as the volume fraction of the

Table 3. Data on extraction samples

Extraction	Material extracted (g)	Precipitate (wt %)	X-ray results on precipitate
1st ^a	0.263	2.89	M ₂₃ C ₆ , $\alpha_0 = 1.065 + 0.001 n$, Extra lines at d values of 0.248, 0.212, 0.209, and 0.184 nm
2nd	1.007	0.854	M ₂₃ C ₆ , $\alpha_0 = 1.0696 \pm 0.0004 n$, Weak extra lines at d values of 0.254, 0.228, and 0.191 nm

^aMicroprobe examination of the precipitate revealed the presence of Ca, Si, Al, Ti, and Cu.

precipitate phase (0.0241 ± 0.0043 , compared with a value of 0.029 based on the weight fraction extracted and the density of M₂₃C₆). The second extraction varied greatly from the first (Table 3), indicating that another approach might be useful.

4.2.2 Transmission electron microscopy

To determine the reasons for the discrepancy in the amounts of precipitate obtained by extraction and to resolve the nature of the large grain boundary precipitates (Fig. 14), a thinned specimen was examined by transmission electron microscopy; two kinds of precipitates were identified — M₂₃C₆ and sigma phase [Fig. 15(a)]. Both were identified by electron diffraction. The M₂₃C₆ precipitates appear as small parallelepipeds in the matrix. Their nature is revealed by the diffraction pattern [Fig. 15(b)], where the cube-on-cube morphology in a $\langle 310 \rangle$ matrix pole orientation is revealed. Figure 15(c) shows the diffraction pattern of the large precipitate particle identified as sigma in Fig. 15(a). Another large sigma phase precipitate particle is shown in transmission in Fig. 16(a), while the diffraction pattern is shown in Fig. 16(b). Both sigma-phase particles are at grain or subgrain boundaries. In metallographic work described below, sigma phase is identified by morphology and etching behavior.⁸

Not all the precipitates examined were of the two classes mentioned. A third kind (Fig. 17) has a different morphology. This unidentified precipitate is probably partially responsible for the extra lines in the x-ray diffraction pattern.

4.2.3 Interpretation

The grain boundary precipitate phase in the Rivesville plate shown by optical metallography (Figs. 12 and 14) is clearly identified as sigma by electron diffraction. The extraction procedure, which is a standard procedure for extracting sigma phase, dissolved it. This is particularly significant since sigma phase has been successfully extracted from other stainless steels on previous occasions by this procedure, although never before from type 310 stainless steel.

Fig. 15. Precipitates in Rivesville type 310 stainless steel plate. (a) Micrograph of grain boundary region showing sigma (marked) and small black precipitates of $M_{23}C_6$ within the grain. (b) Diffraction pattern of $M_{23}C_6$ in a $\langle 310 \rangle$ matrix pole in Rivesville plate. Matrix indices are noted. (c) Diffraction pattern of sigma phase of Rivesville plate.

Fig. 16. Another example of sigma phase. (a) Micrograph showing boundary and relative size of precipitate. (b) Diffraction pattern.

Fig. 17. Unidentified precipitate phase in type 310 stainless steel air distributor plate exposed at the Rivesville plant. It is suspected of being a corrosion product.

The Rivesville plate probably contains about 0.85 wt % of the $M_{23}C_6$ carbide phase (Table 3). The type 310 stainless steel contains 0.062 wt % carbon, which can theoretically react to form up to 1.1 wt % of $M_{23}C_6$. These results are in reasonable agreement.

The initial extraction, which yielded nearly 3 wt % precipitate, is clearly inconsistent with the second extraction. However, the heavy scale (Fig. 14) extended into cracks in the surface in many cases. The first extraction probably included a significant amount of this scale, which may be the "unidentified phase" of Sect. 4.2.2.

4.3 Tensile Test Data

Sets of tensile specimens with 1.52×3.17 mm (0.060×0.125 in.) cross sections and 19-mm (0.75-in.) gage lengths were cut from both the as-received plate and the Rivesville plate. The Rivesville plate samples were cut from selected areas of low curvature. The samples were tested in air on an Instron machine at various strain rates and temperature ranges from room temperature to 843°C (1550°F). The data (Table 4) are not

Table 4. Tensile properties of type 310 stainless steel air distributor plates,
as-received and exposed at Rivesville.

Test temperature	Nominal strain rate (min ⁻¹)		Strength, ksi (MPa)				Uniform strain	Total elongation (%)		Reduction of area (%)
			Yield		Tensile			Post-test measurement	Instron chart	
Room	6.7	As-received	62.6	(432)	90.3	(623)	<i>a</i>	4	<i>a</i>	54
	6.7	Rivesville	77.6	(535)	96.1	(663)	<i>a</i>	28	<i>a</i>	37
	0.067	As-received	59.4	(410)	87.1	(601)	34	35	37	37
	0.067	Rivesville	50.2	(346)	92.2	(636)	33	45	40	43
650°C (1200°F)	6.7	As-received	23.7	(163)	56.3	(388)	<i>a</i>	43	<i>a</i>	64
	6.7	Rivesville	28.4	(196)	54.7	(377)	<i>a</i>	24	<i>a</i>	75
	0.067	As-received ^b	25.5	(176)	53.8	(371)	27	30	37	47
	0.067	Rivesville ^b	29.5	(203)	47.3	(360)	19	34	22	21
	0.00027	As-received ^c	24.9	(172)	36.9	(254)	13	18	19	18
	0.00027	Rivesville ^c	27.8	(192)	33.1	(228)	4	16	15	14
843°C (1550°F)	6.7	As-received	29.8	(206)	37.1	(256)	<i>a</i>	43	<i>a</i>	44
	6.7	Rivesville	21.3	(147)	37.3	(257)	<i>a</i>	23	<i>a</i>	28
	0.067	As-received ^d	18.5	(128)	22.8	(157)	10	40	42	26
	0.067	Rivesville ^d	13.6	(94)	19.8	(137)	1.4	3	3	0.7
	0.067	Rivesville	15.2	(105)	22.3	(154)	5.3	21	20	15
	0.067	Aged 1000 h at 843°C ^e	8.8–10.9	(61–75)	23.3	(161)	11.2	41	44.7	30
	0.00027	As-received	8.0	(55)	8.0	(55)	<1	41	42	34
	0.00027	Rivesville	8.0	(55)	8.0	(55)	~0.5	22	23	15

^aThe test equipment instrumentation was probably too slow to follow the test, and the data are not considered reliable.

^bThe Instron load-deflection curve exhibited small serrations.

^cThe Instron load-deflection curve exhibited serrations late in the test.

^dThe Instron load-deflection curve exhibited one serration late in the test.

^eThe Instron load deflection curve exhibited two serrations just at yield that make the yield point difficult to define.

^fThe Instron load deflection curve exhibited serrations throughout the test, even in what appeared to be the "elastic" range.

suitable for use in design because of the pin grip method that was used, the lack of extensometry, and the specimen curvature, but they do indicate the effect of the Rivesville boiler exposure on the type 310 stainless steel air distributor plates under the special conditions that prevailed during early plant operations. The variations in possible history from point to point in the exposed plate made detailed comparisons moot — only major effects can be considered significant. The most significant test results are:

1. Exposure at Rivesville had no major effects on strength or ductility measured at either room temperature or 650°C.
2. Exposure at Rivesville drastically reduced the uniform strain, total elongation, and reduction of area for tests done at 843°C.

One sample of exposed material tested at a nominal strain rate of 0.067/min showed only 0.7% reduction of area and 3% elongation. The other sample tested under the same conditions showed 20% reduction of area and 15% elongation. These differences may be due to the thermal and stress histories of the samples (Ref. 2 indicates how high those were at the Alexandria plant), giving rise to different amounts of damage locally. It is even possible that unobserved cracks existed in the as-machined specimen that strained 3%, but no metallographic evidence to support this hypothesis was found.

Metallographic examinations of the exposed and unexposed samples tested at 0.067/min and 0.00027/min at 843°C (Fig. 18) assessed the mode of failure. The microstructures were observed in (a) the nominally unstrained shoulder region, (b) the gage section about 2 to 4 mm from the point of fracture, away from any necking, (c) the edge of the gage section at about the same area, and (d) the fracture region, viewed parallel to the plane of the plate (Figs. 19-22). All samples were etched with Murakami's reagent.⁰ Key observations are: (1) sigma phase forms in the relatively unstressed shoulders after about 1 to 6 h during testing [(Figs. 19(a), 20(a))]; (2) grain boundary cracking is associated with sigma phase [Figs. 19(b), 20(b), 22(b)]; (3) significant cracking at the edge of samples occurs [Figs. 19(c), 20(c), 22(c)]. Surface cracking may initiate fracture; surface cracks are present in some areas of the as-exposed Rivesville plate (Fig. 13); (4) little grain boundary cracking occurred in the gage section of the exposed sample tested at 0.067/min that only strained 3%. The first significant crack to begin propagating probably separated the specimen before others could grow, and that crack may have been present before the test began. The fracture mode is clearly intergranular (Fig. 23).

Y-155733

Fig. 18. Macroscopic comparison of specimens tested at 843°C. The exposed sample tested at 0.067/min strain rate is the one that strained 3%.

Fig. 19. As-received type 310 stainless steel tensile tested at 843°C and 0.067/min strain rate. (a) Unidentified grain boundary precipitates in shoulder region (1500 $\times$, etched). (b) grain boundary cracks in gage section away from fracture tend to be associated with sigma phase (1500 $\times$, etched). (c) Surface of gage section after testing showing thin oxide formed during test (200 $\times$, as polished). (d) fracture surface, showing frequency of association of cracks with sigma phase in the plane of polish (100 $\times$, as polished).

Fig. 20. As-received type 310 stainless steel tensile tested at 843°C and 0.067/min strain rate. (a) Sigma phase is on grain boundaries in shoulder region (1500 $\times$, etched). (b) grain boundary cracks in gage section away from fracture are sometimes associated with sigma phase (1500 $\times$, etched). (c) Surface of gage section showing scale formed during plant exposure and some cracks in gage section (200 $\times$, as polished). (d) intergranular fracture region with little cracking away from fracture and oxide formed after test. (100 $\times$, as polished).

Fig. 21. As-received type 310 stainless steel tensile tested at 843°C and 0.00027/min. (a) Sigma phase formed in shoulder region during test (1500x, etched). (b) Cracking at sigma phase in gage section away from fracture (1500x, etched). (c) Surface of gage section after testing showing oxidation of cracks that occurred during testing (200x, as polished). (d) fracture region showing extensive cracking at grain boundaries (100x, as polished).

Fig. 22. Type 310 stainless steel from Rivesville plate tested at 843°C and 0.00027/min. (a) Sigma phase and carbides in shoulder region formed during exposure and testing (1500 $\times$, etched). (b) Grain boundary cracks in gage section away from fracture are usually associated with sigma phase (1500 $\times$, etched). (c) Surface of gage section showing scale formed during plant exposure and some cracks in gage section (200 $\times$, as polished). (d) Fracture region showing extensive intergranular fracture (100 $\times$, as polished).

Fig. 23. Scanning electron microscopy of fracture surfaces of type 310 stainless steel plate exposed at Rivesville and tensile tested at 843°C. (a) Specimen tested at 0.067/min showing intergranular fracture somewhat masked by oxide formed during and after test. Side of specimen (upper left) exhibits no cracking. (100x). (b) Selected area of (a) at 300x magnification. (c) Specimen tested at 0.00027/min showing intergranular fracture and cracks on side of specimen, with heavier oxidation than specimen tested at 0.067/min (100x).

4.4 Effects of Thermal Aging

To help assess the temperature and time history to which the Rivesville air distributor plate may have been exposed, sections of as-received plate were thermally aged for 100 h and 1000 h at 650°C (1200°F) and 843°C (1550°F) in type 304 stainless steel foil packs (Fig. 24). Aging at 843°C for 1000 h [Fig. 24(d)] produces a microstructure similar to that of material from the Rivesville air distributor plate [Figs. 21(a), 22(a), 14], but with less sigma phase.

One tensile specimen was prepared from the material aged for 1000 h at 843°C, and it was tested at 0.067/min strain rate at 843°C (Table 4). While aging affected the strength of the type 310 stainless steel, no loss of ductility can be attributed to aging. A more sophisticated aging experiment or aging under stress may be required to simulate the effects of Rivesville exposure. Such work is beyond the scope of this activity.

4.5 Interpretation of Results

Thermal expansion stresses probably caused the buckling of the Alexandria and Rivesville AFBC air distributor plates. The bowing and buckling is not the uniform sagging between supports that would be expected if the weight of the bed were the major factor contributing to strain. Based on the mean coefficient of expansion of type 310 stainless steel from 20 to 1150°C,¹¹ a plate heated from 20 to 650°C expands approximately 0.012 (length per unit length). If the thicker supports expand more slowly than the plate because of unequal heating rates or if the supports are physically constrained from expanding by being tightly wedged into the boiler (which they were at Rivesville), then the plate must buckle or compress plastically to accommodate the strain. It is likely that the strains leading to cracking occur over a number of thermal cycles, but simple monotonic tensile testing at 843°C produces failures that closely resemble the cracks in the air distributor plate. It is not certain why local buckling of the Alexandria plate was more severe than the Rivesville plate, but differences in uniformity or rates of heating or differences of physical constraints may have been involved. Most of the buckling of the Alexandria plate occurred early in the operating life of the plate.

The effect of thermal aging on the elevated-temperature tensile ductility of type 310 stainless steel has been defined in more extensive studies. Aging 25 Cr-20 Ni steel for 7500 h at 704°C (1300°F) is known to reduce the tensile elongation and reduction of the area from 1 to 10% depending on prior heat treatment.⁹ Strengthening observed after this thermal aging may have been due to carbide precipitation or strain aging. Exposure of type 310 stainless steel to steam for up to 36,000 h at temperatures from 649 to 815°C also produced significant reductions of elevated-temperature tensile ductility.¹⁰ In both cases cited, the observed microstructures either after aging or after testing were consistent with our observations. However, the single specimen of material that we aged at 843°C for 1000 h and tested at 843°C did not exhibit a loss of tensile ductility.

Fig. 24. Type 310 stainless steel after aging. All micrographs taken after etching with Murakami's reagent. (a) 100 h at 650°C. (b) 100 h at 650°C (1500 $\times$). (c) 100 h at 843°C (500 $\times$). (d) 100 h at 843°C (500 $\times$).

Given that sigma phase was observed in both the Rivesville and Alexandria plates, and that the Alexandria plates suffered the greater strain without cracking, the operating histories of the plants provide three possible explanations of why the Alexandria plates did not crack:

1. The bulk of the deformation due to thermal cycling in the Alexandria plate may have occurred before the formation of significant amounts of sigma phase.
2. The Rivesville plate may have experienced both positive and negative strain cycling (fatigue) for some reason that may not have been experienced by the Alexandria plate.
3. The Rivesville plate may have cracked while straining at a temperature and strain rate at which the type 310 stainless steel has a lower ductility than the conditions under which the Alexandria plate was cycled.

5. RECOMMENDATIONS

1. Since the cause of the straining that led to failure of the Rivesville type 310 stainless steel air distributor plate was probably related to thermal expansion of a physically constrained plate, either redesigning the air distributor to relieve the constraints or to keep its operating temperature low (by cooling) should be considered.
2. Because embrittlement due to sigma phase formation probably played a role in the low-ductility failure of the air distributor plate, causing the plate to crack rather than deform plastically, the material selection for future air distributors should be limited to those that do not embrittle under the operating conditions likely to be encountered.
3. Practical trials of recommendations (1) and (2), singly or together, should be made at the Rivesville AFBC plant.

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