312
3/20/60

DR. 903

ornl

MASTER

ORNL/TM-7114

**OAK
RIDGE
NATIONAL
LABORATORY**

**UNION
CARBIDE**

**The Oxidation of Selected
Alloys During 25,000 h in
Superheated Steam
at 482 and 538°C**

J. C. Griess
W. A. Maxwell

**OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A03 Microfiche A01

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ORNL/TM-7114
Distribution
Categories UC-77
and UC-79h, -k, -r

Contract No. W-7405-eng-26

METALS AND CERAMICS DIVISION

HTGR BASE TECHNOLOGY PROGRAM

Structural Materials Program (189a 01332) and Field Task
No. OR 1.7 (AF 15 10 15 MSTMC)

THE OXIDATION OF SELECTED ALLOYS DURING 25,000 h IN
SUPERHEATED STEAM AT 482 AND 538°C

J. C. Griess and W. A. Maxwell

Date Published: March 1980

NOTICE This document contains information of a preliminary nature.
It is subject to revision or correction and therefore does not represent a
final report.

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

CONTENTS

ABSTRACT	1
INTRODUCTION	2
EXPERIMENTAL PROCEDURES	2
RESULTS	3
Alloy 800	5
Alloy 617	9
Type 304 Stainless Steel	9
Sandvik HT-9	12
Sumitomo 9 Cr-2 Mo Steel	15
9 Cr-1 Mo Steel	16
9 Cr-Mo Experimental Alloys	18
5 to 9 Cr-1 Mo Steels	23
2 1/4 Cr-1 Mo Steel	24
DISCUSSION	28
SUMMARY	32
ACKNOWLEDGMENTS	33
REFERENCES	34

THE OXIDATION OF SELECTED ALLOYS DURING 25,000 h IN
SUPERHEATED STEAM AT 482 AND 538°C

J. C. Griess and W. A. Maxwell*

ABSTRACT

We are studying the corrosion of several ferritic and austenitic materials in flowing superheated steam at 482 and 538°C (900 and 1000°F). Results obtained during the first 12,000 h of the test were presented previously. This report summarizes the results obtained during the first 25,000 h. The test specimens are mounted in a nonrecirculating loop that receives steam from the superheater circuit of a fossil-fired power plant.

At both temperatures all materials exhibited parabolic oxidation kinetics during the first year and subsequently have oxidized at low constant rates. The ferritic steels containing 2-1/4 and 9% Cr have oxidized at about the same rates, averaging 4.2 and 8.6 $\mu\text{m}/\text{year}$ (0.17 and 0.34 mils/year) at 482 and 538°C, respectively, after the first year. Sandvik HT-9 (11.4% Cr) has corroded at slightly lower rates. Annealed and cold-worked surfaces of these alloys have exhibited identical behavior. At 482°C all materials have retained their corrosion products completely, but at 538°C some began experiencing exfoliation after 12,000 h. The data suggest that a high silicon content in the alloy minimizes exfoliation.

Cold-worked surfaces of alloy 800 are corroding at lower rates than annealed and pickled ones, but in both cases the rates are very low. Alloy 800 specimens that had been intergranularly corroded before exposure to steam are oxidizing at much higher rates, but intergranular penetration has not progressed. Type 304 stainless steel is corroding nonuniformly, but the attack rates are low at both temperatures. Alloy 617 is corroding at the lowest rate of any material in the loop; even after 25,000 h surface films are thin enough to show interference colors.

* NUS Corporation, 2536 Countryside Boulevard, Clearwater, Florida 33515.

INTRODUCTION

A general knowledge of the corrosion behavior of materials in water and steam is essential in any energy conversion system that uses the steam cycle. However, in fossil-fired power plants corrosion damage on the aqueous side of evaporator or superheater tubes is so small compared with that caused by the hot combustion gases on the fire side that there has been little need to determine quantitative corrosion rates in steam or water. On the other hand, in advanced nuclear power plants such as high temperature gas-cooled (helium) or liquid-metal-cooled (sodium) reactors, virtually all the corrosion is produced by steam or water. Consequently, corrosion rates in aqueous systems of such reactors need to be known to establish corrosion allowances.

Because few data exist concerning the corrosion of materials in high-temperature steam (or boiler water), we established a test program to acquire long-term corrosion data for a variety of alloys in superheated steam. In an earlier publication¹ we summarized the reported information on steam corrosion in the temperature range 482 to 593°C, described in detail our experimental procedures, and presented data obtained during the first 12,000 h of test. We have now completed 25,000 h, and this report presents data obtained to that time. The test is continuing.

EXPERIMENTAL PROCEDURES

In our earlier report¹ we presented details of our experimental methods. Therefore, only a brief summary of our test procedures is given here.

All test specimens are mounted in a nonrecirculating loop made of alloy 617. The loop is located at the Bartow Plant of the Florida Power Corporation in St. Petersburg, Florida, and is operated for us by the NUS Corporation. The loop contains two autoclaves, and most of the same materials are exposed in each. The temperature of the steam that is taken directly from the superheater of the power plant is adjusted to 482°C (900°F) before it enters the first autoclave. After leaving the first

autoclave, the steam is heated to 538°C (1000°F) before it enters the second autoclave. After leaving the second autoclave, the steam is condensed, and the condensate is discarded. The mass flow rate of steam through the loop is 45 kg/h (100 lb/h), which corresponds to a nominal velocity of 1.5 m/s (5 ft/s) past the test specimens. Steam pressure is 10.5 MPa (1525 psi).

The specimens consist of flat rectangular strips for weight change measurements and of similar strips bent into U-shapes for evaluating the effect of stress. The radius of curvature of the bends is 13 mm (1/2 in.), and their legs are held parallel by stainless steel bolts. The specimens are nominally 73 by 13 by 1.6 mm (2-7/8 by 1/2 by 1/16 in.) with a 4.8-mm-diam (3/16-in.) hole near each end for mounting. Autogenous and filler metal welds of both types of specimens are also exposed. In the U-bends the welds are located at the bottom of the bend in the region of highest strain. All specimens are periodically removed for visual examination, and the flat ones are weighed.

The amount of metal oxidized is calculated from the specimen weight gain by assuming that all the corrosion products are retained and that the composition of the corrosion products is known. In this report the oxidation products are assumed to be the following spinel-type compounds: $\text{Cr}_2\text{O}_3 \cdot \text{FeO}$, $\text{Fe}_2\text{O}_3 \cdot \text{NiO}$, $\text{Fe}_2\text{O}_3 \cdot \text{FeO}$, and $\text{Mo}_2\text{O}_3 \cdot \text{FeO}$.

Table 1 lists the composition of all the alloys in test.

RESULTS

The weight gains experienced by most of the materials are presented graphically on linear coordinates in this report. For about the first 5000 to 8000 h, log-log plots of weight gain vs time yielded straight lines with slopes of 0.4 to 0.5, indicating parabolic oxidation kinetics. However, after longer exposures the weight gains fell below extrapolations of the shorter term data and appeared to increase at a constant rather than at a decreasing rate. In presenting the results this point is illustrated for each alloy that corroded at a measurable rate by graphically showing a weight gain-vs-time curve for the specimen that had

Table 1. Composition of test materials

Alloy	Note	Composition, wt %									
		C	Cr	Ni	Mo	Fe	Mn	Si	V	W	Other
Alloy 800	Used for both weight-change specimens and welds	0.08	19.77	31.90		43.36	0.78	0.46			0.44 Ti
Alloy 800	Used for mill-annealed specimens	0.05	20.58	31.39		45.28	0.95	0.36			0.46 Ti
Alloy 617		0.07	20.30	57.35	8.58	1.01	0.05	0.16			11.76 Co, 0.76 Al
304 stainless steel		0.06	18.04	8.96		Balance	1.84	0.55			
Sandvik HT-5	Used for both annealed and ground specimens	0.19	11.4	0.50	1.00	Balance	0.50	0.26	0.27	0.49	
Sandvik HT-5	Specimens supplied by General Atomic (GA) - heat 451774	0.20	11.2	0.51	0.97	Balance	0.50	0.32	0.29	0.51	
Sandvik HT-9	Specimens supplied by GA - heat 454191	0.18	11.3	0.50	0.93	Balance	0.52	0.35	0.29	0.51	
Sumitomo 9 Cr-2 Mo	Specimens supplied by GA	0.04	3.80	0.13	2.06	Balance	0.50	0.29			
9 Cr-1 Mo steel	Air-melted heat 316381A	0.08	3.79	0.38	1.00	Balance	0.34	0.46			
9 Cr-1 Mo steel	Argon-oxygen decarburization (AOD) heat 31377	0.05	10.43	0.44	1.02	Balance	0.56	0.03	0.20		
9 Cr-1 Mo steel	AOD heat 31378	0.07	9.60	0.29	0.86	Balance	0.44	0.01	0.16		
9 Cr-1 Mo steel	AOD heat 31446	0.06	10.21	0.17	0.95	Balance	0.61	0.03	0.27		
9 Cr-1 Mo steel	AOD heat F-5349	0.10	8.75	0.11	0.93	Balance	0.42	0.37	0.21		
EXPT 9 Cr-1 Mo	Material supplied by Combustion Engineering (CE) - Electroslag-Re melted (ESR) heat XA-3177	0.09	9.58	0.08	0.80	Balance	0.44	0.17	0.15	0.46	0.11 Nb
EXPT 9 Cr-1 Mo	Material supplied CE - ESR heat XA-3178	0.10	9.52	0.16	1.55	Balance	0.50	0.21	0.30		0.14 Nb
EXPT 9 Cr-1 Mo	Material supplied by CE - ESR heat 91887	0.10	9.22	0.08	1.01	Balance	0.38	0.03	0.22		0.15 Nb
7 Cr-1 Mo steel	ESR heat XA-3477	0.09	7.05	0.05	0.98	Balance	0.34	0.17	0.22		0.14 Nb
7 Cr-1 Mo steel	ESR heat XA-3478	0.09	7.00	0.05	1.02	Balance	0.34	0.14	0.22		0.37 Nb
5 Cr-1 Mo steel	ESR heat XA-3475	0.10	5.18	0.16	1.02	Balance	0.32	0.14	0.21		
5 Cr-1 Mo steel	ESR heat XA-3476	0.09	5.01	0.06	1.01	Balance	0.34	0.11	0.21		0.38 Nb
2 1/4 Cr-1 Mo steel	Used for weight-change specimens and for welds to alloy 800	0.11	2.01		0.98	Balance	0.54	0.22			
2 1/4 Cr-1 Mo steel	Used for autogenous weld specimens	0.12	2.19		1.00	Balance	0.44	0.25			
ERNiCr-3		0.02	20.03	72.50		1.16	3.07	0.03			0.39 Ti, 2.51 Nb

been in test for the longest times at 482 and 538°C (900 and 1000°F). To illustrate the specimen-to-specimen variability we have made similar plots for the eight specimens of each alloy (four at 482°C and four at 538°C) that have been in test for the longest times. Furthermore, the corrosion rates calculated from the slope of the straight line and the penetration obtained on extrapolation of the straight line to time zero are presented tabularly. Most of these specimens were installed in the loop at different times and are among those with the longest exposures. In the following sections the oxidation behavior of the individual alloys is discussed.

Alloy 800

Weight-change specimens initially installed in the loop were prepared at the same time, and all were ground on a 100-mesh belt grinder. After grinding, half the specimens were solution annealed at 1177°C (2150°F) for 30 min in argon and were air cooled. This group was then pickled in an HNO₃-HF solution to remove thin tarnish films. The rest of the specimens were tested as ground.

Figure 1 shows the weight gains of the pickled specimens at 482 and 538°C (900 and 1000°F) and those of a single ground specimen exposed at

Fig. 1. Weight gains of alloy 800 in superheated steam.

538°C. The linearity of the curves after an initial period and the relatively large weight gains of the pickled specimens are apparent.

As noted in the earlier report,¹ the pickled specimens had undergone severe intergranular attack before installation in the loop. They had apparently been cooled at too slow a rate following the anneal, and this resulted in grain boundary attack during film removal in the HNO₃-HF solution. Figure 2 shows the cross section of a specimen exposed for 19,666 h at 538°C. Before exposure to the steam, the maximum intergranular attack was about 200 μm (8 mils). Assuming that the original surface is marked by the line of metallic phase near the surface [Fig. 2(a)], the depth of intergranular penetration has not increased as a result of the steam exposure. At 482°C attack was less but similar to that shown in Fig. 2.

Table 2 shows the initial penetrations and penetration rates calculated from the weight gain data.

Specimens with ground surfaces corroded at very low rates, as indicated by the 538°C data shown in Fig. 1. After 25,167 h weight gains were 0.61 and 0.96 g/m² at 482 and 538°C, respectively. These small weight gains correspond to alloy penetrations of only 0.21 and 0.32 μm (0.008 and 0.013 mils), respectively, during the nearly three-year exposure.

It has been established that ground (cold-worked) surfaces of alloy 800 corrode less in steam than annealed surfaces.² To evaluate this effect under our conditions, seven specimens with "as-received" mill-annealed and pickled surfaces were placed in each autoclave. These specimens have now been weighed four times, and the average weight gains are shown in Table 3. Unexpectedly, after 8837 h those specimens exposed at 538°C have shown lesser weight gains than those at 482°C. However, regardless of this fact the weight gains are significantly greater than for ground specimens.

Further evidence of the effect of grinding is provided by a comparison of the autogenously welded specimens (mill-anneal finish) with the filler metal welded specimens (ERNiCr-3 filler wire), whose flat surfaces had been ground. After 25,167 h at 482°C the former specimens had gained 1.74 g/m² compared with 0.78 g/m² for the specimens with the filler metal; at 538°C weight gains were 2.18 and 1.17 g/m², respectively.

Fig. 2. Cross sections through an alloy 800 specimen after 19,666 h in superheated steam at 538°C (1000°F). The intergranular attack was produced by an HNO_3 -HF pickle of sensitized material before steam exposure.

Table 2. Penetrations and corrosion rates calculated from weight gain-time curves for alloy 800 that had been intergranularly corroded before exposure to steam

Total time in test (h)	Penetration calculated from extrapolation of weight gain-time curve, μm		Corrosion rate after first year, $\mu\text{m}/\text{year}$	
	482°C	538°C	482°C	538°C
25,167	5.8	13.2	2.3	3.3
24,663	3.1	11.4	1.8	3.8
23,546	2.5	12.5	2.0 ^a	4.6 ^a
22,116	2.5	10.7	2.0	5.1

^aTest time was 19,665 h.

Table 3. Average weight gains of alloy 800 with mill-annealed and pickled surfaces in superheated steam

Time at weighings (h)	Weight gain, g/m^2	
	482°C	538°C
2,615	1.7	2.1
5,551	2.4	2.5
8,837	3.1	2.5
12,718	3.7	2.7

We prepared U-bends of strips that contained autogenous as well as filler metal welds of alloy 800 joined either to itself or to 2-1/4 Cr-1 Mo steel (ERNiCr-3 filler metal). The specimens evidenced no damage attributable to strain. However, while forming the bends with both types of filler metal welds, there was a lack of fusion in a few isolated areas, which created small crevices. After 25,000 h there is no evidence of significant attack in these regions.

Alloy 617

The alloy 617 specimens, including welded and U-bend types, had ground surfaces and have shown very little corrosion during the test. Weight gains on entire specimens (0.0024 m^2) exposed for up to 25,167 h have not exceeded 1.6 mg (0.67 g/m^2) at 538°C (1000°F) and 0.8 mg (0.33 g/m^2) at 482°C (900°F). These weight gains correspond to corrosion rates of 0.045 and $0.089 \text{ }\mu\text{m/year}$ (0.002 and 0.004 mils/year) at 482 and 538°C , respectively, averaged over 25,167 h. The corrosion rates of welded specimens were about a factor of 2 greater than for the unwelded specimens, but the cast structure of the filler metal (alloy 617) experienced no obvious preferential attack.

The U-bend specimens showed no unusual effects, and the oxide on the surfaces appeared identical to that on the unstressed specimens. Metallographically polished cross sections showed no localized attack, and the surface oxide was so thin that it could not be detected at 500 $\times$ magnification.

Type 304 Stainless Steel

Only annealed specimens with ground surfaces are exposed in the loop. The weight gains experienced by the specimens exposed for the entire 25,167 h are shown in Fig. 3. The reproducibility obtained with four type 304 stainless steel specimens is illustrated in Table 4, where corrosion rates and initial penetrations calculated from weight gain data are presented. Although the variation among the specimens was relatively large, the penetrations and corrosion rates were small compared with those for the ferritic steels (see later sections). At 538°C (1000°F) the surfaces were covered with a very adherent black oxide, whereas at 482°C (900°F) the surfaces had thin irregular oxides showing interference colors in localized areas.

Though weight gains increased at a constant rate after an initial period, attack on the steel has not been uniform. Figure 4(a) and (b) shows cross sections through specimens exposed for 18,235 h at 482 and 538°C , respectively. At 482°C only one area of attack is shown in the

Fig. 3. Weight gains of type 304 stainless steel in superheated steam.

Table 4. Penetrations and corrosion rates calculated from weight gain-time curves for type 304 stainless steel in superheated steam

Total time in test (h)	Penetration calculated from extrapolation of weight gain-time curve, μm		Corrosion rate after first year, $\mu\text{m}/\text{year}$	
	482°C	538°C	482°C	538°C
25,167	0.33	8.4	0.56	3.3
24,663	0.18	4.8	0.18	2.5
23,546	-0.18	6.1	0.61	3.3
18,235	0.58	6.1	0.10	3.6

field of view; at 538°C the attack is more general but still nonuniform. In both cases the corrosion product consists of two layers with the boundary between the two, presumably representing the original surface of the specimen.

Fig. 4. Cross sections through type 304 stainless steel specimens after 18,235 h in superheated steam (a) at 482°C and (b) at 538°C.

Sandvik HT-9

The HT-9 test specimens were made from 31.8-mm-OD (1 1/4-in.) pipe with a 3.6-mm (0.142-in.) wall. The pipe was quartered axially, and the pieces were rolled to a thickness of 1.6 mm (1/16 in.). The flats were solution annealed at 1050°C (1922°F) for 30 min in argon, were furnace cooled, were tempered at 760°C (1400°F) for 30 min in argon, and again were furnace cooled. Specimens were then machined from the flat strips. Those specimens installed originally were ground on a 100-mesh belt grinder. Later in the test another set of specimens from the same material was included in the test array, but their surfaces were not ground after removal from the furnace.

The weight gains of the ground specimens that have been in test for the longest time are shown in Fig. 5. All specimens had very uniform dark gray scales, with no evidence of oxide exfoliation. The initial penetration and continuing corrosion rates for the four specimens with the longest exposures are presented in Table 5.

Cross sections of the oxide on specimens exposed for 18,235 h are shown in Fig. 6(a) and (b). A distinct third layer of oxidation products adjacent to the metal is observed in the oxide formed at 482°C (900°F).

Fig. 5. Weight gains of Sandvik HT-9 in superheated steam.

Table 5. Penetrations and corrosion rates calculated from weight gain-time curves for Sandvik HT-9 specimens with ground surfaces in superheated steam

Total time in test (h)	Penetration calculated from extrapolation of weight gain-time curves, μm		Corrosion rate after first year, $\mu\text{m}/\text{year}$	
	482°C	538°C	482°C	538°C
25,167	9.9	14.5	3.1	3.6
24,663	10.4	15.0	3.3	3.3
23,546	9.9	12.5	3.3	4.1
18,235	9.4	12.2	3.8	4.3

Fig. 6. Cross sections through Sandvik HT-9 specimen after 18,235 h in superheated steam (a) at 482°C and (b) at 538°C.

whereas the third layer is missing from the oxide formed at 538°C (1000°F). This same observation was noted in oxides formed during shorter times, but in the early stages of oxidation a small third layer was noted at 538°C.¹ The oxides formed at 482°C are more uniform in thickness and contain less macroporosity than those formed at 538°C.

The specimens with the annealed surfaces have now been in test for 17,000 h and appear to be corroding at rates comparable with those with ground surfaces. Cross sections through the corroded surfaces also have the same appearance as those on ground surfaces. However, additional exposure time will be required to determine whether subtle differences in oxidation behavior exist between the two types of surface treatments.

Specimens of two additional heats of Sandvik HT-9 (heats 451774 and 454191) were supplied by the General Atomic Company (GA). These specimens had been machined from large-diameter thick-wall pipe. One set of specimens was machined from each material so that one face of the specimen was the interior pipe wall surface. This surface was as received from the mill and was covered with a relatively thick black scale that was not disturbed during preparation. The opposite face and edges were ground before test. Specimens from heat 454191 were also machined from the middle of the pipe wall, and all their surfaces were ground. Some of the latter specimens were subsequently heavily pickled in HNO₃-HF solution to remove the cold-worked layer. So far the testing time for the group of HT-9 specimens supplied by GA has been 16,173 h. Their average weight gains are shown in Table 6.

Table 6. Average weight gains of Sandvik HT-9 specimens after 16,173 h in superheated steam

Heat	Surface condition	Weight gain, g/m ²	
		482°C	538°C
451774	Covered with mill oxide — ground	29.0	49.1
454191	Covered with mill oxide — ground	30.6	50.1
454191	All ground	42.4	72.5
454191	Pickled	42.0	83.1

Weight gains of specimens from the two heats of HT-9 with part of their surfaces covered with mill scale agree very well. Comparison of the weight gains of these specimens with those of the all-ground specimens shows that the mill scale has had a significant beneficial effect. Furthermore, comparison of the weight gain of the all-ground specimen with the data shown in Fig. 5 also shows reasonably good agreement. The effect of pickling is not clear; at 482°C there was no effect, but at 538°C the pickled specimens had average weight gains about 15% greater than those of the ground specimens.

Sumitomo 9 Cr-2 Mo Steel

Specimens of this alloy were also supplied by GA. They were also machined from heavy-wall pipe. One group of specimens was machined so that one of the "flat" surfaces was the interior wall of the pipe, which was covered with a black scale. These specimens were ground on all other surfaces. A second group of specimens was machined from the interior of the pipe wall, and their surfaces were ground. Part of this group was heavily pickled to remove cold-worked surfaces.

The specimens have now been in test for 16,173 h, and the average weight gains are shown in Table 7.

Table 7. Average weight gains of Sumitomo 9 Cr-2 Mo steel after 16,173 h in superheated steam

Surface condition	Weight gains, g/m ²	
	482°C	538°C
Covered with mill oxide — ground	41.6	106.4
All ground	52.8	112.0
Pickled	48.2	115.7

The effect of mill scale on the oxidation of 9 Cr-2 Mo steel was less than observed on HT-9. At 482°C (900°F) a significant beneficial effect was noted, but at 538°C (1000°F) the effect was almost nonexistent. At both temperatures the effect of pickling was not detectable.

9 Cr-1 Mo Steel

All the specimens from this air-melted heat of 9 Cr-1 Mo steel (heat 316381A) had ground surfaces (100-mesh belt grinder), and all have completely retained their oxidation products in testing to date. Figure 7 shows weight gains observed on those specimens in test for 25,167 h, and Table 8 presents both the corrosion rates calculated from the linear part of the curves and the penetrations corresponding to extrapolation of the linear part to time zero for the four specimens in test for the longest times.

Figure 8(a) and (b) shows cross sections of the corroded surfaces of specimens exposed for 18,235 h. Except for the thickness the oxide has not changed since the first examination after 3000 h.¹ As with the HT-9 specimens, a three-layer oxide has formed, but in contrast to HT-9 the third layer is thicker at 538°C (1000°F) than at 482°C (900°F). Widely scattered small areas on the surface have undergone only slight attack, even after 18,000 h. One such region is shown in Fig. 8(b).

Fig. 7. Weight gains of 9 Cr-1 Mo steel (heat 316381A) in superheated steam.

Table 8. Penetrations and corrosion rates calculated from weight gain-time curves for 9 Cr-1 Mo steel (heat 316381A) specimens with ground surfaces in superheated steam

Total time in test (h)	Penetration calculated from extrapolation of weight gain-time curves, μm		Corrosive rate after first year, $\mu\text{m}/\text{year}$	
	482°C	538°C	482°C	538°C
25,167	11.4	18.3	3.6	5.1
24,663	10.2	21.3	3.6	5.6
23,546	9.9	18.5	3.8	6.4
18,235	12.5	16.5	4.1	7.1

Fig. 8. Cross sections through air-melted 9 Cr-1 Mo steel after 18,235 h in superheated steam (a) at 482°C and (b) at 538°C.

9 Cr-Mo Experimental Alloys

Three experimental alloys of 9 Cr steel with minor alloying additions were supplied by Combustion Engineering Corporation (CE). We received the material as 1.6-mm-thick (1/16-in.) sheets normalized at 1038°C (1900°F) for 10 min in argon, air cooled, tempered at 760°C (1400°F) for 1 h, and again air cooled. Specimens were made from the sheets, and all surfaces were ground on a 100-mesh belt grinder before test. All three alloys were from electroslog-remelted (ESR) heats.

The maximum exposure time has been 21,793 h. At 482°C (900°F) all specimens have completely retained their oxidation products, but at 538°C (1000°F) at least some specimens of each alloy have shown evidence of exfoliation or blistering of the oxide. Some specimens of all heats showed small blisters in the oxide after 12,900 h, but ESR heat XA-3177 seems to be the most susceptible to blistering and exfoliation. With increased exposure time small amounts of oxide separated from the blisters and additional blisters formed, but even after 21,793 h only two specimens have shown weight losses on subsequent weighings. Up to this time exfoliation has not been extensive.

Figure 9 shows weight gains experienced by the three alloys. Each point represents the average weight gain of three specimens installed in the loop at the same time. The specimen-to-specimen variation is shown in Table 9. Examination of these data shows that corrosion among the three alloys differs little; all are corroding at low rates after the initial period of more rapid attack.

Figures 10, 11, and 12 show cross sections of the oxide formed on the different alloys. Figure 10(a) shows the oxide formed on a specimen of heat XA-3177 during 17,912-h exposure at 482°C, and Fig. 10(b) and (c) shows the oxide formed at 538°C during the same time. Figure 10(a) and (b) shows the three-layer oxide characteristic of 9 Cr steels; at both temperatures the middle oxide layer has appreciable porosity. Figure 10(c) shows a different field of view from the same specimen in Fig. 10(b). Even though there was no evidence of exfoliation or blistering in the region from which the metallographic section was prepared, five layers can be distinguished in the oxide. The larger number of oxide layers seems to

Fig. 9. Weight gains of 9 Cr-Mo steels in superheated steam.

Table 9. Penetrations and corrosion rates calculated from weight gain-time curves for three experimental 9 Cr alloys in superheated steam

Test time (h)	Penetration calculated from extrapolation of weight gain-time curves, μm		Corrosion rate after first year, $\mu\text{m}/\text{year}$	
	482°C	538°C	482°C	538°C
<i>Heat XA-3177</i>				
21,793	10.9	18.3	4.8	9.7
20,094	9.1	18.5	4.6	8.6
20,094	8.6	17.5	4.6	10.4
17,912	13.0	16.8	4.8	9.9
<i>Heat XA-3178</i>				
21,793	11.7	19.6	5.1	9.1
20,094	9.4	19.8	4.3	8.6
20,094	8.1	19.8	5.1	8.9
17,912	11.7	20.8	4.8	8.4
<i>Heat 91887</i>				
21,793	12.7	22.6	4.8	9.9
20,094	7.9	22.6	4.8	10.9
20,094	9.4	23.9	4.8	10.4
17,912	13.2	24.4	4.8	9.9

Fig. 10. Cross sections through 9 Cr-Mo steel, electroslog-remelted heat XA-3177, after 17,912 h in superheated steam (a) at 482°C and (b) and (c) at 538°C.

Fig. 11. Cross sections through 9 Cr-Mo steel, electroslag-remelted heat XA-3178, after 17,912 h in superheated steam (a) at 482°C and (b) and (c) at 538°C.

Fig. 12. Cross sections through 9 Cr-Mo steel, electroslog-remelted heat 91887, after 17,912 h in superheated steam (a) at 482°C and (b) at 538°C.

indicate that at some time the oxide became detached from the base metal, a new oxide formed, and in time the old and new oxides grew together.

Figure 11(a) shows the oxide that formed on heat XA-3178 at 482°C, and Fig. 11(b) and (c) shows the oxide formed at 538°C. At both temperatures the exposure time was 17,912 h. At 482°C there is a hint of a third layer, but it is much less obvious than on heat XA-3177 [Fig. 10(a)]. The cross section shown in Fig. 11(b) was taken through a region where exfoliation had occurred. Again a multilayer oxide is observed, and separation between two of the layers is noted. Figure 11(c) shows a 500x magnification adjacent to an area on the same specimen where spalling had occurred. The separation between two of the layers and the concentration of voids at the interface between the two outermost oxide layers are clearly visible. The extension of exfoliation into this area of the specimen would probably have occurred soon had this specimen remained in test.

Figure 12(a) and (b) shows representative cross sections of oxide formed on heat 91887 at 482 and 538°C during 17,912 h. These cross sections were prepared from a specimen that showed no evidence of blistering or exfoliation, and only the three layers of oxide characteristic of this type of alloy are discernible.

5 to 9 Cr-1 Mo Steels

Recently a group of specimens ranging in concentration from 5 to 9% Cr and containing 1% Mo were placed in test in the alloy 617 loop. All had lightly ground surfaces. In addition to evaluating the specific oxidation resistance of these materials, we wanted to obtain a measure of the effect of silicon on corrosion.

At the last examination these specimens had been in test for 2556 h, and the average weight gains for duplicate specimens at each temperature are shown in Table 10. It should be recognized that these are very preliminary data and that a minimum of two additional years will be required before definitive statements about the oxidation behavior of these alloys can be made. Nevertheless, it is interesting to note that there is a rough inverse correlation between weight gain and silicon content, independent of the chromium concentration.

Table 10. Average weight gains of duplicate specimens of several chromium-molybdenum steels during a 2556-h test in superheated steam

Alloy	Heat	Si content (wt %)	Weight gain, g/m ²	
			482°C	538°C
5 Cr-1 Mo ^a	3475	0.14	22.6	45.9
5 Cr-1 Mo ^a	3476	0.11	23.3	47.4
7 Cr-1 Mo ^a	3477	0.17	21.5	43.6
7 Cr-1 Mo ^a	3478	0.14	23.0	45.2
9 Cr-1 Mo	31377	0.03	23.1	61.8
9 Cr-1 Mo	31378	0.01	24.4	68.1
9 Cr-1 Mo	31446	0.02	23.5	53.2
9 Cr-1 Mo	F-5349	0.36	18.8	34.4

^aMade from electroslog-remelted material; all other material produced by argon-oxygen decarburization.

2 1/4 Cr-1 Mo Steel

Specimens of this alloy with three different surface finishes have been in the loop since the test began. After machining, all specimens were ground on a 100-mesh belt grinder, and one set was tested in this condition. The rest of the specimens were annealed in argon for 2 h at 732°C (1350°F) and were furnace cooled. Half of these were tested without further surface preparation, even though impurities in the argon caused slight discoloration of the specimens. To remove this film the remaining specimens were pickled in HNO₃-HF solution before test.

Within the reproducibility of the data, there have been no differences in the weight gains experienced by the specimens with the different surface treatments or in their tendency to suffer exfoliation. At 482°C (900°F) only a single 2-1/4 Cr-1 Mo steel specimen has lost oxide. This specimen showed a few small blisters after 10,000 h and after 16,000 h had lost substantial amounts of oxide. No signs of oxide blistering or exfoliation can be detected on the many other specimens that have been in the loop at 482°C for up to 25,000 h. On the other hand, most of the

specimens at 538°C (1000°F) have developed blisters and many have lost oxide. The first signs of oxide detachment began after 12000 h, and with increasing exposure the frequency and extent of exfoliation have increased. However, the amount of oxide lost on all specimens except two has been so small that subsequent weighing still shows greater weights than the previous weighings.

The weight gains experienced by the specimens with different surface preparations that have been in test for the longest time are shown in Fig. 13. Although the data points differ somewhat, the difference is small, and only one curve has been drawn for each temperature. Further confirmation of the agreement among the oxidation behavior of the three different surface preparations is presented in Table 11, where corrosion rates and extrapolated penetrations determined from weight gain data for different specimens with varying surface treatments are shown.

Figure 14(a), (b), and (c) shows cross sections of the oxide formed on 2-1/4 Cr-1 Mo steel. Figure 14(a) shows a typical two-layer oxide formed at 482°C after 19,666 h, and Fig. 14(b) shows a similar view of an oxide formed at 538°C during 20,782 h in test. The porosity is greater at 538°C. Figure 14(c) shows a cross section taken at an area where oxide exfoliation had occurred. The contrast between the different layers is

Fig. 13. Weight gains of 2 1/4 Cr-1 Mo steel in superheated steam.

Table 11. Penetrations and corrosion rates calculated from weight gain-time curves for 2 1/4 Cr-1 Mo steel with different surface treatments in superheated steam

Test time (h)	Surface preparation	Penetrations calculated from extrapolation of weight gain-time curves, μm		Corrosion rate after first year, $\mu\text{m}/\text{year}$	
		482°C	538°C	482°C	538°C
25,167	Ground	13.7	21.1	3.1	7.9
24,663		13.0	20.8	3.6	6.9
23,546		9.9	19.8	3.6	6.6
22,116		9.7	17.3	4.1 ^a	1.4 ^a
25,167	Annealed	13.5	18.8	3.6	9.1
24,663		13.5	29.7	3.6	5.1
23,546		13.2 ^b	17.0 ^b	3.6	11.4
22,116		11.2	16.0	3.8	13.5
25,167	Pickled	15.0	21.6	4.1	7.6
24,663		15.0	26.9	3.8	6.9
23,546		11.4	22.6	3.6	8.4
18,235		9.1	14.7	4.1	11.2

^aExposure time - 18,235 h.

^bExposure time - 19,666 h.

poor, but examination under the microscope revealed four layers in the oxide.

The specimens with autogenous welds that have been in the loop since the test began gained weight at the same rate as the other 2-1/4 Cr-1 Mo steel specimens and at 538°C began to blister and suffer minor exfoliation after 12,000 h. The U-bends with autogenous welds at the bottom of the bends have not been weighed but visually exhibit the same behavior as the flat specimens, except that blisters and exfoliation have not occurred in the highly strained regions. The U-bends in which 2-1/4 Cr-1 Mo steel is joined to alloy 800 with ERNiCr-3 filler metal have shown the expected behavior: relatively heavy attack on the 2-1/4 Cr-1 Mo steel, with spalling at 538°C, and very little attack on alloy 800 or on the filler metal.

Fig. 14. Cross sections through 2 1/4 Cr-1 Mo steel after exposure to superheated steam (a) for 19,666 h at 482°C and (b) and (c) for 20,782 h at 538°C.

DISCUSSION

In our last report¹ we pointed out that weight gain is valid as a measure of corrosion only so long as all the corrosion product remains on the specimen and the composition of the corrosion product is known. We believe that, until visible flakes of oxide are lost, our results meet both conditions and that we can use weight gain as a dependable measure of corrosion. Nevertheless, specimens of each material removed at different times will ultimately be descaled, and weight gain will be compared with the actual weight of metal oxidized.

In most cases, even where oxide has been lost, the amount has been small, and weight gain measurements are still useful in estimating the extent of oxidation. However, as exfoliation progresses weight change measurements will become progressively less useful. Even though we will no longer be able to follow the rate of oxidation by weight gain once excessive spallation begins, we will descale all specimens at the end of the test and determine the weight of the alloy oxidized.

In our last report we compared our data with that reported by other investigators and showed that our results were in substantial agreement with theirs. Our test was designed to obtain quantitative data and has now been extended to a longer time than that of any other known investigator. Consequently, direct comparisons are not possible with our data acquired during the last 13,000 h. One point that our data have clearly demonstrated is that the kinetic process changes after about one year at both 482 and 538°C (900 and 1000°F) for all materials that have measurable corrosion rates. Although other data have indicated that this occurs in some specific cases, our long-term data demonstrate this point more clearly.

We previously indicated that oxidation rates followed parabolic kinetics at both temperatures for about the first year and that the specimens subsequently appeared to oxidize at a constant low rate. Data obtained since that time seem to reinforce this observation. The data shown in the weight gain-vs-time curves show that the individual points fit the straight lines very well. However, it should be noted that the

data beyond 8000 h also fit reasonably well to a relationship of the type: $W = kt^x$, where W is the weight gain, k is a constant, t is time, and x is in the range of 1/4 to 1/3. Continued exposure of the specimens at 482°C and those at 538°C that have not spalled is needed to establish which relationship best describes the oxidation kinetics after the first year.

The more highly alloyed materials, including type 304 stainless steel, alloy 617, and annealed alloy 800, continue to corrode at low rates. For alloy 617 the rates are so low that the kinetics of the oxidation process cannot be determined from our data. Both the ground and annealed surfaces of alloy 800 are corroding at higher rates than alloy 617, but even these rates are so low that the kinetics of the process cannot easily be established. In agreement with other data,² cold-worked (ground) surfaces continue to oxidize at lower rates than annealed surfaces. On the other hand, the alloy 800 specimens that had undergone substantial intergranular penetration before steam exposure have corroded appreciably and show the same type behavior as type 304 stainless steel and the 2-1/4 to 11-1/2% Cr steels that we tested, that is, parabolic oxidation kinetics for about the first year followed by a constant oxidation rate. Corrosion of the intergranularly corroded alloy 800 was appreciably less than on the chromium-molybdenum alloys, but greater than for type 304 stainless steel. Alloy 617, type 304 stainless steel, and alloy 800 (except for the intergranularly corroded alloy 800) could be safely used in superheated steam at substantially higher temperatures than we have tested.

There appears to be little difference in oxidation resistance among the 2-1/4 to 9 Cr-Mo steels, except that at 538°C the 2-1/4 Cr-1 Mo and the electroslog-remelted heats of 9 Cr (from CE) are showing a greater tendency to exfoliate than the standard air-melted 9 Cr-1 Mo alloy. Tables 8, 9, and 11 illustrate the similarities in general corrosion behavior of the chromium-molybdenum steels. Considering all the data in these tables the average values for the initial penetration are 11.4 and 20.2 μm (0.45 and 0.80 mils) at 482 and 538°C, with standard deviations of 2.1 and 3.4 μm , respectively. Corresponding values for oxidation rates are 4.2 and 8.6 $\mu\text{m}/\text{year}$ (0.17 and 0.34 mils/year), with standard deviations of 0.6 and 2.0 $\mu\text{m}/\text{year}$ respectively. Other specimens of the same alloys

are in test, but they have not been exposed long enough to reliably determine similar values. Results obtained from these specimens in the future will increase our confidence in the data. The Sandvik HT-9 specimens that contain 11.4% Cr have experienced slightly less corrosion than the other chromium-molybdenum steels. This should not be surprising since the chromium content of this alloy is approaching that of stainless steels.

Hurst and Cowen³ and McCoy and McNabb⁴ observed similar behavior among the chromium-molybdenum ferritic steels and noted that, in the range of 2 to 9% Cr, silicon was more important in determining corrosion behavior than chromium content. Silicon content was not varied widely in our tests, but we could detect no significant differences in general corrosion behavior within the range in which we worked. The 2-1/4 Cr-1 Mo steel contained 0.26% Si, the experimental alloys from CE had 0.08 to 0.21% Si, and there was 0.46% Si in the air-melted 9 Cr-1 Mo steel. However, for exfoliation our data indicate that silicon content is important. The 2-1/4 Cr-1 Mo and the experimental 9 Cr alloys have the lowest silicon contents, and at 538°C exfoliation has occurred on some of these specimens. However, there is no sign of exfoliation on any of the air-melted 9 Cr-1 Mo steel specimens with the higher silicon content. Our preliminary data from the group of specimens containing 5 to 9% Cr (Table 10) suggest that high silicon content reduces weight gain. Nevertheless, much longer exposure times will be required before the significance of these data can be assessed. We are also planning to install other chromium-molybdenum alloys in the loop, and some of these will have greater silicon content than those presently in the loop. Unfortunately, at the temperatures of our test, meaningful comparisons among the different alloys cannot be obtained until after about two years of exposure.

At this time we do not have a quantitative measures of how exfoliation influences the corrosion rate of the substrate metal. Undoubtedly, loss of oxide will increase the corrosion rate, and one would assume that eventually a constant higher rate would be observed. In view of the low rates that we are observing, even these higher rates may not be excessive with respect to the proposed service lifetimes. Of more importance in the

operation of a power plant than such accelerated corrosion rate may be the erosive effect of the detached oxide on downstream components such as valves and turbine blades. As noted by Lux⁵ this is a problem in many power plants, and periodic chemical cleaning of the superheater circuit is required. The longer an alloy retains its oxide, the fewer chemical cleanings will be required during the life of the plant, and the greater will be the plant availability. Thus, an assessment of the effect of silicon and perhaps other elements on the ability of chromium-molybdenum alloys to retain their oxides has practical importance.

Where exfoliation has occurred cross sections of the oxide [Figs. 10(c), 11(b) and (c), and 14(c)] have much the same appearance as the oxide produced on 2-1/4 Cr-1 Mo steel in much shorter times at the same temperature but with a high heat flux across the corroding surface.⁶ Under these conditions multilayer oxides and substantial porosity are noted. McNary⁷ also noted multilayered oxides on superheater and reheater tubes from a power plant; even where gross spallation had not occurred. To account for this observation he concludes that a gap forms between the metal and the oxide, a new duplex oxide then grows on the steel, and the old and new layers combine. The gap between the metal and the oxide presumably forms as a result of thermal cycling. Since the thermal expansion of magnetite is less than that of steel, cooling from operating temperature results in a shear stress at the metal-oxide interface. Outward deflection of the scale relieves the stress and creates the gap where new oxide subsequently grows. The heat transfer data referenced above and our present data generally conform to McNary's scenario and, in addition, show that although heat flux acts as an accelerant, it is not necessary to produce multilayered scales.

The most intriguing feature of our results is that all the materials that have oxidized at measurable rates appear to have done so generally the same at both temperatures — parabolic behavior for about the first year, followed by a constant low oxidation rate. We have no obvious explanation for the apparent change in kinetics after about one year, which occurs at about the same time for the low-alloy steels and for type 304 stainless steel at both 482 and 538°C. By the behavior of fresh specimens inserted

in the loop, we have established that the change is not associated with drifting temperatures or an altered steam chemistry. Examination of the oxide shows no change in composition or structure, that is, the relative thickness of the two oxide layers remains the same, and no increase in porosity is noted before and after the first year. Continued exposure of the present and additional specimens may provide clues to the cause of this behavior.

SUMMARY

This report presents the data obtained during the first 25,000 h of a long-term test to determine the behavior of a variety of materials in flowing superheated steam at 482 and 538°C (900 and 1000°F). The principal observations are summarized below.

1. Alloy 617 and alloy 800 specimens with both mill-annealed and ground surfaces have corroded at very low rates at both temperatures. Alloy 800 that had been sensitized and intergranularly corroded during pickling has corroded more extensively than other specimens during steam exposure, but intergranular penetration has not progressed.

2. Type 304 stainless steel has oxidized nonuniformly, but attack has been relatively light. Oxidation followed parabolic kinetics at both temperatures for about the first year, but since that time the oxidation rate has been constant. There has been no loss of oxide.

3. Specimens of 2 1/4 Cr-1 Mo steel exhibited identical corrosion behavior whether annealed, pickled, or cold worked. At 482°C all specimens except one have retained their scales completely. During the first year the oxidation decreased with time, but since then the rates have been constant and low. Similar behavior has been observed at 538°C, except that specimens began to experience exfoliation of oxide after about 12,000 h, and by 25,000 h most had lost some oxide. After the first year average corrosion rates have been 3.7 and 8.5 $\mu\text{m}/\text{year}$ (0.15 and 0.33 mils/year) at 482 and 538°C, respectively.

4. Specimens from the air-melted heat of 9 Cr-1 Mo steel (0.46% Si) have retained all their oxide at both temperatures and have shown essentially the same general behavior and corrosion rates as 2 1/4 Cr-1 Mo steel.

On the other hand, three electroslog-remelted heats of 9 Cr steel with low silicon contents have shown appreciable exfoliation at 538°C but none at 482°C. Except for exfoliation, results from the two types of 9 Cr steel are about the same.

5. The corrosion of Sandvik Ht-9 (11.4% Cr) is slightly less than for the 2 1/4 and 9 Cr steels, but the general behavior — constantly decreasing rate for first year, followed by low constant rate — is the same. Preliminary data indicate little difference between annealed and cold-worked material.

6. No unusual corrosion of welds and no signs of localized attack in U-bend specimens have been noted. Highly strained regions of 2 1/4 Cr-1 Mo steel U-bend specimens appear to retain their corrosion products better than their legs, which were not plastically deformed.

7. The present data suggest that increasing the silicon content of chromium-molybdenum steels improves their ability to resist exfoliation. Results obtained from specimens of several different chromium-molybdenum steels with different silicon contents, either recently added to the loop or to be added in the future, should help define the role of silicon in exfoliation.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the Florida Power Corporation for allowing the tests to be conducted at their Bartow Plant and to the following people whose help in conducting the test and in preparing this report is gratefully acknowledged: R. E. Johnson of the NUS Corporation for maintaining the loop and examining the specimens, J. F. King for supervising the welding, E. J. Lawrence for preparing specimens, M. D. Allen for preparing the metallographic specimens, and B. G. Ashdown for editing the report.

REFERENCES

1. J. C. Griess and W. A. Maxwell, *The Corrosion of Several Alloys in Superheated Steam at 482 and 538°C*, ORNL/TM-6465 (November 1978).
2. S. Leistikow, "Isothermal Steam Corrosion of Commercial Grade Austenitic Stainless Steels and Nickel Base Alloys in Two Technical Surface Conditions," pp. 278-290 in *4th Proc. Int. Cong. Metallic Corrosion*, N. E. Hammer, Ed., National Association of Corrosion Engineers, Houston, Texas, 1972.
3. P. Hurst and H. C. Cowen, "The Oxidation of 9 Cr-Mo and Other Steels in 6.9 MN/m² Steam at 748 and 823°K," paper 62 in *Int. Conf. Ferritic Steels for Fast Reactor Steam Generators* (May 30-June 2, 1977) British Nuclear Energy Society, London.
4. H. E. McCoy and B. McNabb, *Corrosion of Several Metals in Supercritical Steam at 538°C*, ORNL/TM-5781 (May 1977).
5. J. A. Lux, "Superheater and Reheater Oxidation Products and Turbine Integrity," *Proc. Am. Power Conf.* 36:790-96 (1974).
6. J. C. Griess, J. H. DeVan, and W. A. Maxwell, "Effect of a High Heat Flux on the Corrosion of 2 1/4 Cr-1 Mo Steel in Superheated Steam," *Mater. Perform.* 17:9-15 (1978).
7. T. A. McNary, *The Exfoliation of Steamside Scale in Reheater Tubing of Croloys 2 1/4, 5, and 9*, Babcock and Wilcox Co. Research Report 7724 (July 15, 1966).

ORNL/TM-7114
Distribution
Categories UC-77
and UC-79h, -k, -r

INTERNAL DISTRIBUTION

1-2. Central Research Library	37. B. Heshmatpour
3. Document Reference Section	38. F. J. Homan
4-5. Laboratory Records Dept	39. P. R. Kasten
6. Laboratory Records, ORNL RC	40. J. R. Keiser
7. ORNL Patent Section	41. Jar-Shyong Lin
8. J. T. Bell	42. K. H. Lin
9. C. R. Brinkman	43. C. T. Liu
10. J. V. Cathcart	44. J. E. Mack
11. C. W. Collins	45. R. E. Pawel
12. R. H. Cooper, Jr.	46. P. L. Rittenhouse
13. J. H. DeVan	47. G. M. Slaughter
14. G. R. Gessel	48. P. T. Tortorelli
15. T. G. Godfrey, Jr.	49. A. L. Bement, Jr. (Consultant)
16-30. J. C. Griess	50. W. R. Hibbard, Jr. (Consultant)
31. M. L. Grossbeck	51. E. H. Kottcamp, Jr. (Consultant)
32. J. P. Hammond	52. M. J. Mayfield (Consultant)
33. C. E. Helms	53. J. T. Stringer (Consultant)
34-36. M. R. Hill	

EXTERNAL DISTRIBUTION

- 54-55. DOE, DIVISION OF NUCLEAR POWER DEVELOPMENT, Washington, DC 20545
G. A. Newby
A. J. Pressesky
- 56-57. DOE, DIVISION OF REACTOR RESEARCH AND TECHNOLOGY, Washington, DC 20545
Director
58. SAN-DEVELOPMENT, SAN DIEGO AREA OFFICE, P.O. Box 81325, San Diego, CA 92138
Senior Program Coordinator
59. DOE, SAN FRANCISCO OPERATIONS OFFICE, 1333 Broadway, Wells Fargo Building, Oakland, CA 94612
Manager
- 60-61. DOE, OAK RIDGE OPERATIONS OFFICE P.O. Box E, Oak Ridge, TN 37830
Assistant Manager, Energy Research and Development
Director, Nuclear Research and Development Division

62-382. DOE, TECHNICAL INFORMATION CENTER, P.O. Box 62, Oak Ridge, TN
37830

For distribution as shown in TID-4500 Distribution Category,
UC-77 (Gas Cooled Reactor Technology); UC-79h (Structural
Materials and Design Engineering); UC-79k (Components); and
UC-79r (Structural and Component Materials Development)