

Abrasion and Erosion Testing of Materials Used in Power Production From Coal

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ABSTRACT

The Albany Research Center (ARC) has a long history of studying abrasive wear, related to mineral testing, handling, and processing. The center has also been instrumental in the design and development of wear test procedures and equipment. Research capabilities at ARC include Pin-on-Drum, Pin-on-Disk, and Dry Sand/Rubber Wheel abrasion tests, Jaw Crusher gouging test, Ball-on-Ball Impact test, and Jet erosion tests. Abrasive and erosive wear studies have been used to develop both new alloys and improved heat treatments of commercial alloys. As part of ARC's newest iteration on wear testing to evaluate materials for use in new and existing pulverized coal combustion and gasifier power systems, the ARC has designed and constructed a new High Temperature Hostile Atmosphere Erosion Wear Test (HAET). This new piece of test apparatus is designed for erosive particle velocities of 10-40 m/sec and temperatures from room temperature (23°C) to 800+°C, with special control over the gas atmosphere. A variable speed whirling arm design is used to vary the impact energy of the gravity fed erosive particles. The specimens are mounted at the edge of a disk and allow a full range of impingement angles to be selected. An electric furnace heats the specimens in an enclosed retort to the selected temperature. Tests include both oxidizing conditions and reducing conditions. A range of gases, including CO, CO₂, CH₄, H₂, H₂S, HCl, N₂, O₂, and SO₂ can be mixed and delivered to the retort. During the erosion testing a stream of abrasive powder is delivered in front of the specimens. This apparatus is designed to use low abrasive fluxes, which simulate real operating conditions in commercial power plants. Currently ~270 μm SiO₂ particles are being used to simulate the abrasive impurities typically found in coal. Since operators are always striving for longer lifetimes and higher operating temperatures, this apparatus can help elucidate mechanisms of wastage and identify superior materials. This talk will present some initial results from this new environmentally controllable erosion test apparatus.

INTRODUCTION

Wear and erosion are problems that reduce power plant availability, cause shutdown, and add to the cost of operation. Different areas in a plant can experience wear related problems. Moving raw coal and bottom ash can result in abrasion problems. In coal

gasification and coal combustion power plants the equipment experiences high temperature erosion and corrosion problems. In coal combustion power plants, heated air, which accelerates corrosion, carries the coal fines through metal pipes to the burner units¹⁻². The moving fines erode these pipes. At the end of the pipes, the fines are injected into the boiler through nozzles, which are exposed to wear (erosion by the coal fines) and oxidation (a result of the high temperatures)³. Products of combustion, waste silica and exhaust gas can erode a boiler's heat exchange tubes⁴⁻⁸. In coal gasification power plants, the heat exchanger tubes can experience corrosion due to H₂S and HCl in the syngas, as well as erosion from the waste ash⁸⁻¹¹. This paper will describe the design of an apparatus to investigate the combined effects of erosion and corrosion on materials in coal gasification and coal combustion power plants.

To investigate materials resistant to the combined actions of erosion and corrosion, it is necessary to simulate, as closely as possible in the laboratory, the conditions in the power plants. The main variables that influence erosion are the size, shape, velocity, angle of impact, and composition of the eroding particles, the properties of the surface being eroded, and the temperature of the system³⁻⁶. The main variables that influence corrosion are the gas chemistry, the temperature of the system, and the properties of the surface being corroded⁸⁻¹¹. One key factor to consider in determining whether the laboratory conditions match the plant conditions is to look at the wastage rates. For syngas coolers, material wastage rates for the heat exchanger tubes must be less than about 0.1 mmpy (4 mpy) to obtain a service life of 25 years^{9, 10}. To approach this rate a target wastage rate of 0.1 to 1.0 mmpy was made for this study.

A number of the variables in this study were matched to the conditions within the range experienced in coal gasifiers. These variables include the temperature, the velocity of the particles, and the gas chemistry. The temperature range experienced by fireside of the heat exchangers in coal gasifiers is about 350°C to 420°C^{8, 10}. The velocity of the eroding particles is about 10 m/s to 40 m/s^{5, 6}, and the gas chemistry (volume percent) is in the range of 15 to 64 CO, 2 to 15 CO₂, 10 to 30 H₂, 0 to 4 CH₄, 0 to 20 H₂O, 0.03 to 1.2 H₂S, 0.02 to 0.12 HCl, and 1 to 57 N₂¹⁰⁻¹³. Since silica is usually the mineral in the ash that causes the most erosion^{5, 6, 10, 14}, silica sand was chosen as the erodent. The feed rate of the silica sand was adjusted to produce the target wastage rate (with the estimated feed rate in the range of 0.05 to 0.5 g/minute), and the time of the test was the minimum time to produce useful weight losses.

EXPERIMENTAL PROCEDURE

HAET apparatus

The Hostile Atmosphere Erosion Test (HAET) apparatus follows a long line of accepted test apparatus designed to measure wear. Test apparatus are typically designed to simulate specific wear conditions, environments, and challenges. The Pin-on-Drum abrasion test, for example, was designed to simulate the high-stress scratching abrasion that occurs during ore handling in minerals processing environments. For the handling of

raw coal, slag, and bottom ash, this and the Dry Sand/Rubber Wheel Abrasion test are useful testing potential materials. The Jaw Crusher tests materials using the faces of a jaw crusher to determine the materials' ability to resist gouging wear. The Ball-on-Ball impact wear test measures different materials' abilities to resist repeated impacts. These two tests are useful in testing of materials for coal grinding and pulverizing. The elevated temperature and room temperature Jet Erosion tests use an abrasive flux propelled by a gas through a nozzle to cause erosion on a target. These two erosion tests could be useful for studying the effects of pulverized coal handling. All of these tests have been used for years to help develop new materials and industries identify cost-effective, low wear materials.

The HAET test, building on years of successful wear test apparatus development, was designed to address problems specific to the power plant industry. Pulverized coal power plants handle two different abrasive materials, pulverized coal and ash, that generate different wear challenges. The elevated temperatures in the plants' systems can generate serious erosion and corrosion problems. Gasifiers have additional wear issues involving the reducing conditions the materials are required to perform in. The HAET test apparatus, fig 1, was designed to simulate the abrasive material, hostile environment, and processing machinery/systems in the power industry, thus helping the industry identify materials that will minimize costly, dangerous, and frustrating wear problems.

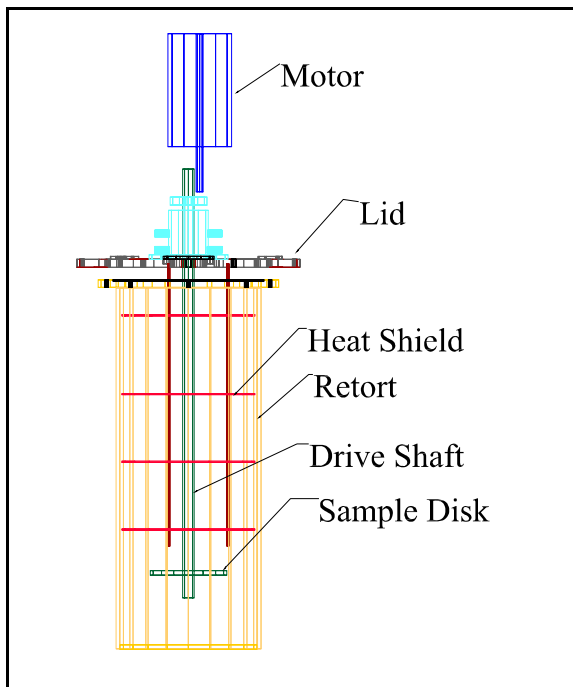


Figure 1. Diagram of the HAET apparatus.

The lid supports the drive shaft, heat shields, abrasive feed tube, and gas inlet/ outlet tubes. When in operation, the retort is brought up to and bolted on to the lid of the apparatus, creating an enclosed test environment. A long drive shaft, which is driven by a variable speed motor and supported by both a bearing and a gas tight feed through, is inserted vertically through the lid. The drive shaft holds and rotates the central

assembly's sample mounting disk providing the velocity component of the erosive particle-material impact energy for the abrasion test.

A long abrasive feed tube, fed by gravity, is design to produce a curtain of $\sim 270 \mu\text{m}$ SiO_2 abrasive that will cover the surface of the samples as they spin through and impact on the abrasive stream. An auger screw feeder is used to control the feed rate of the abrasive. This screw feeder, which is mounted on a scale, is located in a gas tight box above the rest of the apparatus. The scale allows constant feedback of the abrasive flow during a test and also measures in real time the total amount of abrasive flow to the test samples. The abrasive is fed from the screw feeder into a feed tube that runs from the gas tight box to the drop tube and into the furnace/retort area. This gas tight box has a constant flow of nitrogen, which minimizes any hostile gasses damaging the scale and screw feeder.

The majority of the gases used in the test (including all of the hostile gases) are fed into the lid and released at the top of the enclosure. They are mixed and heated as they flow down the retort. The exhaust gases are removed from the system by a tube that extends past the heat shields to a location just above the central core's sample mounting disk. The available gases can be mixed to simulate neutral, oxidizing, and reducing atmospheres. Table 1 shows the gasses and flow rates available. For the test described below two different atmposheres were used, one with 21 pct O_2 and 79 pct N_2 , and a second simulated gasifier gas with 30 pct CO , 8 pct CO_2 , 2 pct CH_4 , 20 pct H_2 , 0.8 pct H_2S , 0.02 pct HCl and 40 pct N_2 . A total flow rate of one liter per minute is used during a test.

Gas	Minimum, liters per min.	Maximum, liters per min.
CO	0	1.300
CO₂	0	0.500
CH₄	0	0.080
H₂	0	0.600
H₂S	0	0.024
HCl	0	0.003
N₂	0.20	2.100
O₂	0	0.080
SO₂	0	0.040

Table 1, Available flow rates for gases in HAET test. Normal flow is 1 l per min.

There are four heat shields that hang horizontally from the lid into the core of the retort. These heat shields serve several important purposes. First, they ensure a uniform temperature for the test samples by breaking the retort's volume down into subcylinders. Second, the gases moving between the heat shields and the retort guarantees that the gases will mix. Finally, the heat shields can help dampen vibrations inside the retort, which can help protect the drive shaft that holds the sample mounting disk assembly.

At the lower end of the drive shaft is a 17 cm diameter sample mounting disk with test samples mounted in it. There is a drop of about 63 cm from the lid to the sample mounting disk which is used to accelerate the abrasive, and ensure that the samples are at

a uniform temperature. The 12 x 10 mm test samples are capacitive discharge welded to 6.4 mm diameter 304 SS stubs. These stubs, with the samples attached, are inserted in the periphery of the sample mounting disks and locked into place with wires that were fed through holes in both the disks and the stubs, as shown in figure 2. The disk/sample assembly looks somewhat like a ceiling fan made with small sample “blades”. For 20 m/sec velocities it is possible to use up to 8 samples at a time. For 40 m/sec, four samples is the limit if the test requires the entire front of the sample to be eroded.

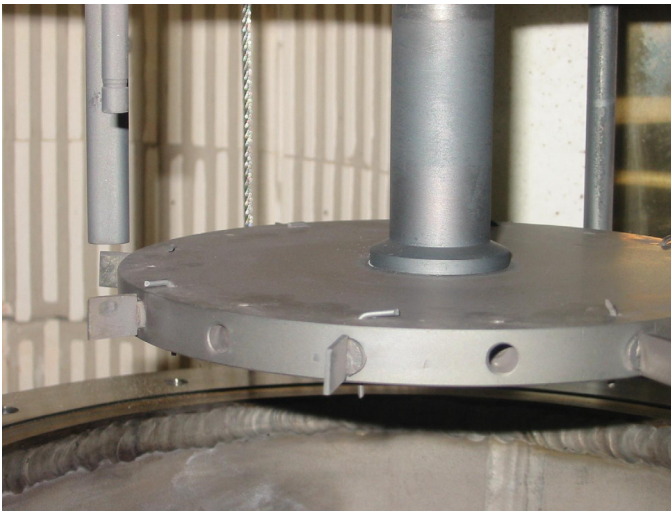


Figure 2. Photo of test specimens mounted in specimen disk, and abrasive feed tube.

Running a HAET test is a fairly straightforward process. After the samples are welded to the 304 SS stubs, they are ground smooth and flat using abrasive papers, cleaned and weighed to the nearest 0.01mg.

If a 20 meters per second test is being run, two samples of each material are inserted into the sample mounting disk as erosion-corrosion samples. To separate the corrosion effect from the erosion, additional corrosion samples are hung from the bottom heat shield. When conducting a 30 meters per second test there is a choice of only six samples of each material or not having the entire front surface of the erosion-corrosion sample eroded.

The retort is drawn, using a winch, to the lid and bolted closed. Nitrogen is then used to purge the system of air. During the purging stage the furnace is mounted around the retort. After several hours of purging the drive motor is turned on. The furnace is then turned on and brought up to the chosen temperature (from room temperature up to 700°C). After the samples reaches the chosen temperature the desired gas chemistry is introduced and the abrasive feed is started.

HAET tests have been conducted for 120 hours (for five days). At that point, the furnace, gas, and abrasive feed are turned off. Nitrogen is used to flush the system as the system cools. Once the system is cooled, the furnace is removed, the retort is detached from the lid, and the samples are removed, visually examined, and cleaned. The samples are weighed and again examined visually. One sample from each erosion corrosion sample

is cross sectioned while the other samples are examined using scanning electron microscopy (SEM). The corrosion, erosion-corrosion, and total loss rates are determined using gravimetric calculations.

Materials

In this series of tests a series of common boiler tube metal materials were chosen. They represent a range of inexpensive common material (T-22 type 2 ¼ Cr 1 Mo steel), to high alloyed steels (310 SS and Incoloy 800 steels). These are all ASME boiler code rated materials and are used in pulverized coal and gasifier plants.

	Fe	Al	C	Cr	Mn	Mo	Ni	Si	Ti
2 1/4 Cr 1 Mo Steel	bal.		0.12	2.25	0.45	1		0.35	
304 Stainless Steel	bal.		<0.8	17.5-20	<2		8.5-10.5	<1	
310 Stainless Steel	bal.		<0.25	24-26	<2		19-22	<1.5	
Incoloy 800	bal.	0.15-0.60	<.1	19-23	<1.5		30-35	<1	0.15-0.60

Table 2. Alloy tested in HAET test and their composition.

Test conditions

There were five separate runs of the HAET apparatus. Tests were conducted in the following conditions:

- Room temp, air, and 20 m/sec velocity.
- 500°C, air, and 20 m/sec velocity.
- 500°C, simulated gasifier gas (30 pct CO, 8 pct CO₂, 2 pct CH₄, 20 pct H₂, 0.8 pct H₂S, 0.02 pct HCl and 40 pct N₂), at 20 m/sec velocity.
- 500°C, simulated gasifier gas, at 30 m/sec velocity.
- 600°C, simulated gasifier gas, at 20 m/sec velocity.

For all of these tests ~270 µm SiO₂ abrasive was used. The feed rate for the abrasive was approximately 0.18 g of SiO₂ per min. All of the elevated temperature tests were run for 5 days (120hr).

RESULTS

After weighing the samples were analyzed by visual and SEM examination, and finally gravimetric calculations were performed.

Visual examination

When a 20 m/sec test was run at room temperature with air, all four of the test materials performed well. On each sample the visual inspection noted no more than a roughing of the surface that was exposed to the erosion. The lack of erosion was further verified when the samples were weighed and very low levels of weight loss were measured.

In 500°C 20 m/sec surface velocity test with a air atmosphere, the stainless samples that performed well, experiencing only a light coat of oxide on their surfaces and a general roughening of the surface that experienced the erosion. The 2 ¼ Cr 1 Mo steel had a light layer of corrosion that was easily removed when cleaning the samples prior to weighing.

In the 500°C 20 m/sec surface velocity test with a gasifier atmosphere, all of the samples showed some discoloration. The 310 SS appeared to perform the best. The second best performers were the Incoloy 800 specimens. The backsides of the Incoloy samples were clean and any scale sloughed off the surfaces easily. The front sides of the Incoloy specimens had a tightly bonded scale in the eroded area while the scale at the bottom of the samples simply fell off. The 304 SS specimens had some easily removed scale on the backsides of the samples; the front sides had a layer of tightly bonded scale. The tightly bonded scale on both the 304 SS and the Incoloy 800 affected the gravimetric measurements by reducing the samples' apparent loss rate. The 2 ¼ Cr 1 MO samples scaled badly. The erosion of the front sides of these samples was taking place on the scale, since erosion was not severe enough to completely remove the scale.

In the 500°C 30 m/sec surface velocity test conducted in a gasifier atmosphere all of the samples showed some discoloration. Again, the 310 SS samples appeared to be in the best shape, followed by the Incoloy 800. On both of these specimen types, the surfaces still looked smooth on the corrosion samples and the backside of the erosion-corrosion samples. The 2 ¼ Cr 1 Mo samples scaled badly. The erosion of the front side of the 2 ¼ Cr 1 Mo sample was removing the scale and completely eating through the upper edge of the sample.

At 600°C in a gasifier atmosphere and a surface velocity of 20 m/sec the 310 SS samples, as seen in fig 3, looked to be in the best condition. The next best material was Incoloy 800. The 304 SS had some easily removed scale on the backside of the erosion samples. The 2 ¼ Cr 1 Mo samples, shown in fig 4, showed catastrophic scaling. The erosion to the front side of the 2 ¼ Cr 1 Mo samples was taking place on the scale, which the erosion was not severe enough to remove.



Figure 3. 2 ¼ Cr 1 Mo steel after HAET test at 600°C and 20 m/sec. Corrosion sample is on the left and the erosion-corrosion sample is on the right.

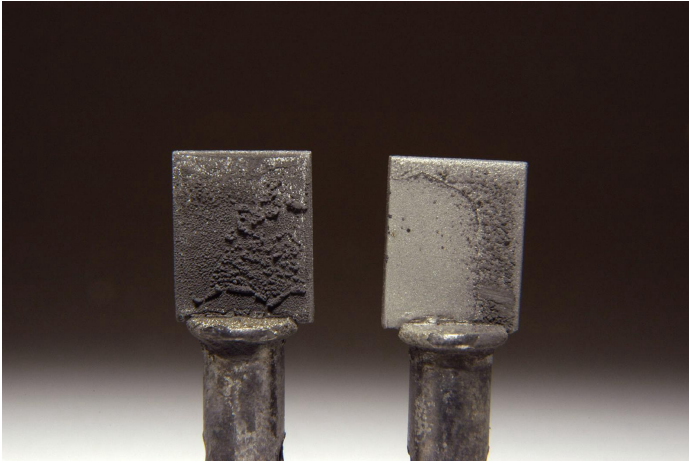


Figure 4. 310 SS after HAET test at 600°C and 20 m/sec. Corrosion sample is on left and erosion-corrosion sample is on the right.

SEM examination

A scanning electron microscope was used to examine samples from a gasifier test run at 600°C and 20 m/s. Both cleaned surface samples and cross-sectioned samples were examined. Generally, a blocky angular scale formed on the surface of the specimens. On areas subjected to the SiO₂ erodent, the energy of the erosion particle impact was not sufficient to wear through the corrosion-induced scale. However, erosion did cause the scale to become much smoother and denser.

The 310 SS surfaces shown in Fig 5 show examples of the eroded and corroded surfaces. The eroded surface shows an example of the flatter, denser scale. A similar strongly adherent eroded area was observed on the other high chrome steels throughout the gasifier runs. This suggests that the scale could actually protect the surface against erosion in certain cases. The corroded sample in the figure shows the rough scale separating from the smooth underlying material, which still shows the preparatory grinding marks. The cross sections of the samples show roughly 12 μm of surface scale on the corroded surface, while the eroded-corroded surface shows only about 5 μm of scale.

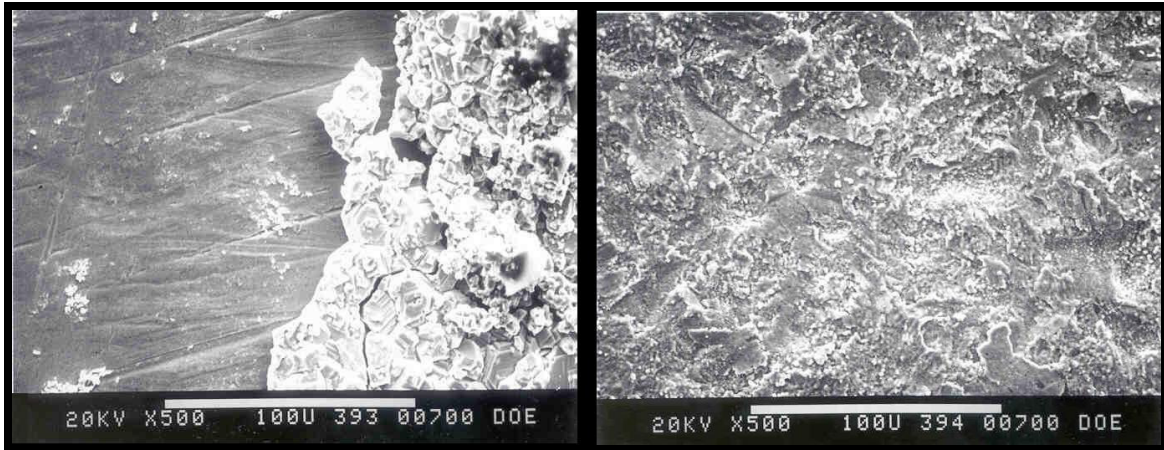


Figure 5. Pictures showing corroded (on left) and eroded-corroded (on right) surfaces of 310 SS after exposure at 600°C in simulated gasifier gas for 120 hrs.

The 304 SS surface, when examined using the SEM, showed the similar adherent scale on the eroded surface area. In this case a coarse scale on the corroded surfaces was easily removed and the underling surface was relatively smooth, and showed marks from the preparation grinding. The loose coarse scale was a Fe-Ni-S compound. Below this outer corrosive layer was a sub-layer of primarily Fe-S. The smooth surface was coated with a layer of a Cr-Fe-S. The cross section sample showed the even this thin ~20 μm layer was cracked, separating from the metal below. The eroded side showed a thinner layer, ~14 μm , that was also separating from the steel substrate.

The Incoloy 800 sample exhibited a fairly smooth surface. The corroded surface was generally smooth, characteristic of the Cr-Fe-S compounds; however, it also had some rough areas of Fe-Ni-S compounds. The eroded surface showed a Cr-Fe-S surface roughened by the impact of the SiO_2 abrasive. The corrosion cross section showed a 25 μm thick layer of scale with cracks running parallel to the surface. The eroded side showed a thinner, ~20 μm , Cr-Fe-S scale layer with similar parallel cracks running through it.

The 2 ¼ Cr 1 Mo steel had a thick layer of scale that very loosely attached. The top of this scale was smooth on the corrosion sample, but showed scars and roughness on the eroded areas of the erosion corrosion sample. Some of this survived on the corroded sample and is shown in fig 6. The figure also shows a crack though this surface scale. The thick scale on the eroded surface came off more readily; fig 6, shows a mostly wavy surface with some areas having small patches of Fe-S scale stuck to the rest of the surface. When cross sectioned the samples showed a thick, >100 μm , layers of scale still remained on the surface. The composition of this scale changes from, starting from the metal base, an S rich region, then a Fe low S region, to a Fe-S region, with a Cr-Fe high S region on top.



Figure 6. Pictures showing corroded (on left) and eroded-corroded (on right) surfaces of 2 ¼ Cr 1 Mo steel after exposure at 600°C in simulated gasifier gas for 120 hrs.

Gravimetric calculations

The corrosive loss was calculated by measuring the weight change of the sample ($W_{ic} - W_{fe}$), and then subtracting the weight change of the stub. The weight change multiplied by the hours in a year was divided by sample area multiplied by the density of the sample multiplied by the test time necessary to produce a loss rate in mmpy.

$$L_c = \frac{(W_{ic} - W_{fe}) - (S_{ic} - S_{fe}) * 8760 * 10}{A * d * t}$$

Results of loss due to corrosion are shown in table 3. This shows for alloys exposed to oxidizing condition up to at least 500°C having a relatively low corrosion rate with the 2 ¼ Cr 1 Mo steel doing the worst. In the simulated gasifier environments the 2 ¼ Cr 1 Mo steel has an excessive corrosion rate at 500°C and should not be used at this or high temperatures. The 310 SS performed the best in corrosion in this environment.

Conditions			Alloy, loss in mmpy			
Temp, deg C	Atmosphere	Speed, m/sec	2 ¼ Cr 1 Mo	304 SS	310 SS	Incoloy 800
Room	Air	20	0.0	0.0	0.0	0.0
500	Air	20	0.7	-0.1	0.0	-0.1
500	Gasifier	20	7.5	1.3	-0.1	2.7
500	Gasifier	30	7.3	1.8	-0.1	2.6
600	Gasifier	20	13.0	0.5	-0.2	1.2

Table 3. Corrosion loss for various conditions, in mmpy.

The erosive loss was calculated using a similar formula. The total weight loss of each erosion-corrosion sample was measured then the weight change due to corrosion and the weight change experienced by the stub were subtracted. The weight change due to erosive loss was multiplied by the hours in a year and then divided by the erosion area

multiplied by the density of the sample multiplied by the test time required to obtain the erosion loss rate.

$$L_e = \frac{(W_{ie} - W_{fe}) - (W_{ic} - W_{fc}) - (S_{ic} - S_{fc}) * 8760 * 10}{A * d * t}$$

Results of loss due to erosion-corrosion are shown in table 4. All of the materials performed similarly at room temperature. At 500°C in an oxidizing atmosphere the high chrome alloy continued to do well. The 2 ¼ Cr 1 Mo steel had an dangerously high erosion rate in air when exposed to an erodent at 20 m/sec. The 304 SS and Incoloy 800 appeared better against erosion in the gasifier atmosphere because of the accumulation of the adherent scale that remained on these samples.

Conditions			Alloy, loss in mmpy			
Temp, deg C	Atmosphere	Speed, m/sec	2 ¼ Cr 1 Mo	304 SS	310 SS	Incoloy 800
Room	Air	20	0.5	0.6	0.6	0.5
500	Air	20	12.7	0.7	0.5	0.8
500	Gasifier	20	20.9	8.4	22.4	7.6
500	Gasifier	30	30.2	16.7	20.9	4.5
600	Gasifier	20	24.5	11.7	9.2	7.0

Table 4. Erosion loss for various conditions, in mmpy.

Adding the corrosion loss value and the erosion loss value results in the erosion-corrosion rate. Again, all of these material preformed well at room temperature. The 2 ¼ Cr 1 Mo looks even worse at 500°C in the oxidizing atmosphere as the losses due to corrosion and erosion are combined. At elevated temperatures in the gasifier environment the loss on the 2 ¼ Cr 1 Mo was catastrophic. The other materials may have some utility in these conditions, but their loss is substantial. The despite the apparent loss rates for 304 SS in certain conditions the 310 SS and Incoloy 800 performed better. For regular use better materials than any these would needed, for use in gasifiers at these temperatures.

Conditions			Alloy, loss in mmpy			
Temp, deg C	Atmosphere	Speed, m/sec	2 ¼ Cr 1 Mo	304 SS	310 SS	Incoloy 800
Room	Air	20	0.5	0.6	0.6	0.5
500	Air	20	13.3	0.6	0.4	0.7
500	Gasifier	20	28.4	9.7	22.2	10.3
500	Gasifier	30	37.5	18.4	20.7	7.1
600	Gasifier	20	37.5	12.2	8.9	8.1

Table 5. Total loss rates for various test conditions.

CONCLUSIONS

A new high temperature hostile atmosphere erosion test apparatus has been demonstrated. It has been shown to produce useful information on the loss of material due to the effects of both corrosion and erosion in both high temperature oxidizing and gasifier conditions.

While these results correlate with accepted practice that both 310 SS and Incoloy 800 are superior alloys for power plant hot areas none of the sample steels run would have acceptable lifetimes for use in gasifiers at 500 or 600°C. Finding better materials for these conditions will be the grounds for further work.

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