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April 1984

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LIQUID-SOLID PARTICLE SLURRY EROSION OF STEELS

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ABSTRACT

The erosion behavior of candidate steel alloys for liquid-solid particle slurry service in coal conversion equipment was determined over a range of testing conditions. Higher solids loading and larger particles in the coal-kerosene slurries used resulted in greater erosion. The greater the lubricity of the carrier liquid is, the lower is the erosivity of the slurry. Low elevated temperatures can cause a decrease or an increase in the erosivity of the slurry, depending on the nature of the liquid carrier, the alloy tested and the test temperature. The mechanism of erosion was determined to be of a platelet formation type, similar to that observed in gas-solid particle stream erosion of ductile metals. However, the cold worked zone caused by the striking particles is located at the surface in liquid-solid particle erosion, while it is beneath the surface in gas-solid particle erosion. The relative erosion resistance of the carbon, low alloy, chromium bearing and austenitic steels tested could not be readily related to their composition, morphology, or common mechanical properties. A possible relation to the strain hardening behavior of the alloys was indicated.

INTRODUCTION

The flow of particle laden, non-aqueous liquids in the passages of coal liquefaction systems causes erosion degradation of the containment metal surfaces. The degradation is similar in mechanism to that which occurs on ductile metals exposed to streams of solid particles in gases. In the relatively low velocity regimes in coal

conversion equipment, the knowledge of erosion mechanisms gained in either the gas or liquid fluid media can be used to understand the mechanism of metal removal in the other. Measuring the effects of several test variables such as flow velocity, particle size, solids loading, and temperature on the erosion of steel alloys provides information to determine the behavior of steel containment materials in slurry flow service. This paper will present data on the performance of several steel alloys exposed to coal-kerosene slurry flows.

EXPERIMENTAL CONDITIONS

A slurry pot test device was used to determine the effect of slurries of coal in an organic solvent on the surface material loss of a group of steel alloys that are commonly used in the flow passages of chemical process equipment. The steels tested are listed in Table 1. The device simulates various aspects of the environment of the slurry flow in the region of a coal liquefaction system where the pulverized coal is mixed with the heated process solvent. The principal condition that is not simulated is the pressure of the slurry, which is not felt to be a significant consideration in the erosion process. The chemical activity of the liquid in the tests that were conducted is considerably different from that of process solvent. The once-through aspect of the particles in the actual process plant flow is also not simulated; however, very little comminution of particles occurs in the tests. The principal variables that affect the erosion process, i.e., velocity, impingement angle, solids loading, particle size, and the combination of viscosity of the slurry and its temperature are simulated in the tests described.

The test device used directs an effective flow of coal particles in a liquid kerosene carrier at 3mm diameter cylindrical specimens 5cm long by rotating the vertically oriented test cylinders on the end of arms attached to a motor-driven rotating shaft in a controlled environment pot of slurry of 3 liters capacity. Figures 1 and 2 show the exterior appearance of the slurry pot tester and its design cross section, respectively. A vortex is prevented by placing metal baffles around the inside periphery of the pot and settling of the coal particles is prevented by a small propeller that is mounted near the bottom of the rotating shaft. The slurry pot operating temperature is controlled by cooling or heating from 25°C to 250°C.

DATA REPRODUCIBILITY

The slurry pot tester is used to study materials erosion behavior by determining the weight loss of the cylindrical test specimens after rotating in slurry for incremental times up to 5 hours. The angle of impingement of the slurry's particles on the cylinder varies around the front half of the cylinder; so the weight loss is an integration of weight losses over the spectrum of impingement angles from 0 to 90°.

The reproducibility of the slurry pot test device is shown in Figure 3 for two alloys, A53 mild steel and 304SS. Their overlapping erosion behavior is consistently observed over a large variation in test conditions.

EFFECT OF ALLOY COMPOSITION

Figure 4 shows how a number of alloys eroded in a cumulative plot of erosion loss over a two-hour exposure period. Figure 5 shows the variation in erosion behavior of several austenitic stainless steels compared to A53 mild steel. It can be seen that the A53 and 304SS eroded similarly along with the 321SS, which is a stabilized version of the 304SS. A higher chromium content steel, 310SS, eroded less, and a steel containing 2 1/2% molybdenum, 316SS, eroded the least.

Figures 6 - 10 attempt to correlate the erosion rates plotted in Figures 4 and 5 with some of the properties and chromium content of the alloys tested. It can be seen that no correlation exists for the properties selected and only a general correlation for the chromium content. There is a slight trend toward higher hardness resulting in lower erosion rates, but spreads in hardness between alloys nearly 40 BHN did not change the erosion rates. More work is required to determine which properties can be positively related to the erosion resistance of chromium containing steel alloys.

EFFECT OF PARTICLE SIZE AND SOLIDS LOADING

The effect of velocity on the erosion of steel as a function of coal solids loading in the carrier liquid and the particle size distribution of the coal are shown in Figures 11 - 13. Figure 11 shows that both A53 and 304SS behave similarly. The greater solids loading of the 50 wt% coal slurry results in a significantly greater amount of erosion, even though its effective viscosity is higher than that of the 20 wt% coal slurry.

Figure 12 plots the amount of erosion when -30 mesh coal is used in the slurry. The particle size distributions of the -200 mesh coal and the -30 mesh coal were determined using a Tyler sieve analysis, and are shown in Table 2. It can be seen in Figure 12 that the larger size coal grind results in a considerably greater amount of erosion at the higher velocities, and that the difference in erosivity between the two solids loadings is much less for the larger size coal. The effect of velocity on the erosion rate is also markedly increased when the coarser coal grind was used. Table 3 shows the velocity exponents for the two grinds of coal. The differences between the two coal grinds can be seen more graphically in Figure 13 for the 20 wt% coal slurries. Four times as much erosion occurred on the samples exposed to the larger particles of coal than to the smaller particles at 12 m/s velocity. The difference between the two grinds is markedly less at the lower velocities.

EFFECT OF LUBRICITY OF LIQUID

In order to determine the effect of the lubricity of the carrier liquid on the erosivity of coal containing slurries, a solvent was selected whose lubricating properties could be varied by means of a small addition that did not affect its viscosity appreciably. A long-chain hydrocarbon solvent, hexadecane, was used in these tests. The addition of 1/2 mole percent of hexadecanoic acid to the solvent is known to increase the lubricity of the solvent without changing its viscosity. The addition of the acid to the solvent polarizes the hydrocarbon chain, ordering the hydrocarbon chains perpendicular to the metal surface, imparting lubricity. Shorter chain hydrocarbons and

their acids cause a similar effect but at lower viscosities.

Figure 14 compares the erosion of A53 mild steel in a 30wt%, -200 mesh coal-hexadecane slurry without acid addition to that of a 30 wt%, -200 mesh coal-kerosene slurry. It can be seen that the hexadecane-coal slurry is more erosive than the kerosene-coal slurry. Figure 15 shows the effect of the addition of the hexadecanoic acid addition to increase the lubricity of the solvent in room-temperature slurry erosion tests of A53 and 304SS steels. The increased lubricity decreased the amount of erosion in a 120 min exposure by 3 times. Both alloys behaved in a similar manner. In a test series performed at 95°C, the difference was more pronounced. Figure 16 shows that the erosion rate in the hexadecane plus acid slurry was one quarter of that which occurred in the straight hexadecane for the A53 mild steel. A greater difference in erosion occurred between the two metals in the hexadecane slurry at 95°C than occurred at room temperature.

EFFECT OF TEMPERATURE

The elevated temperature tests in a slurry pot tester for a number of steel alloys resulted in a behavior pattern that has been observed at low elevated temperatures for ductile metals in gas-solid particle erosion tests. In general, the erosion rate initially decreased with increasing test temperature. Figure 17 shows the effect of temperature on six alloys tested. The A53 and 304SS alloys behaved in a similar manner. Their rates of erosion were markedly higher than those of the other four alloys tested, particularly at room temperature and 95°C and they did not show a decrease at the 95°C test temperature.

The four, more erosion-resistant alloys had a lower erosion rate at 95°C (200°F) than at 25°C (75°F). The A106 alloy is a finer grain size mild steel of the same nominal composition as the A53 pipe steel. Its lower erosion rate can probably be attributed to its finer grain size. The significant increase in erosion for all alloys at 175°C (350°F) is probably more the result of changes in the nature of the slurry than of changes in the erosion resistance of the alloys. A marked reduction in the viscosity of the liquid that generally occurs at elevated temperature could cause the increase to occur.

Figure 18 plots seven alloys' cumulative erosion vs time of exposure curves at 95°C for a slurry velocity of 6 m/s. At the five-hour test time, the spread in amount of erosion ranged from 2 to 6×10^{-4} gm/cm², the highest eroding material having three times the erosion of the lowest.

Figure 19 shows the cumulative erosion vs time curves for six of the alloys at a higher velocity, 12 m/s at 95°C. It can be seen that the erosion rate markedly increases as the velocity of the slurry is increased, the A53 steel eroding five times more at 12 m/s than at 6 m/s after five hours of exposure. It is also interesting to note that the order of erosion rate changed among the alloys tested, and that the A53 and 304SS rates separated from those of the other alloys that were bunched together in a far lower erosion rate range.

The effect on the erosion of the test alloys at 175°C, the temperature at which slurries are prepared in a coal liquefaction process, is shown in Figure 20 for a slurry velocity of 6 m/s. The same type of spread in performance as occurred at 95°C and 25°C was

observed. However, the order of the alloys' erosion rates was different. Again, the greatest amount of erosion occurred on the A53 mild steel. As the erosion time increased, the spread in the amount of erosion between the alloys increased significantly. At this higher temperature, the difference in erosion between the A53 mild steel and the 304SS begins to reflect the higher strength of the stainless steel at elevated temperatures.

Increasing the erosion velocity to 12 m/s at 175°C, Figure 21, has an interesting effect on the erosion behavior. All of the curves are essentially straight. Also, the amount of erosion increased up to eight times greater at the higher velocity than at 6 m/s as can be seen in Figure 22.

Figures 18 - 22 are cumulative erosion rate curves for the various alloys tested. Several of the curves are straightline, indicating that little comminution of the eroding particles is occurring. However, some of the curves change slope as the tests progressed. In order to gain more insight into the different shapes of the curves, incremental erosion rate curves were plotted using the same raw data. Figure 23 shows the incremental rate curves for the alloys tested at 95°C whose cumulative rate curves are shown in Figure 19. Figure 24 shows the incremental rate curves for the alloys tested at 175°C whose cumulative rate curves are shown in Figure 21.

All of the alloys tested had their highest incremental erosion rates at the first weight measurement, after 1 hour of testing. The rates for subsequent times decreased or leveled out toward a steady state condition. In the case of the 95°C test, the variations in

shapes of the cumulative rate curves corresponded with the variations in the shapes of the incremental rate curves. The straight line cumulative rate curve for A53 steel relates to the incremental rate curve for A53 (1018) that reached a steady state after 2 hours of testing. The 304SS cumulative rate curve that sloped up corresponds to the incremental rate curve that had a slight increase in rate at 5 hours compared to its rate at 2 hours. The other alloys that had the same concave down slope in their cumulative rate curves had decreasing incremental erosion rates throughout the 5 hour test period.

The correspondence of changing curve shapes between the cumulative and incremental rate curves for the test performed at 175°C was similar to that which occurred at 95°C. All of the alloys whose curves had a concave downward shape in Figure 21 had continuously decreasing incremental erosion rates, as shown in Figure 24. The one straightline curve in Figure 21 for the 410SS corresponds to the near steady state incremental rate curve in Figure 24. The reason or reasons for the correspondence of curve shapes between the cumulative and the incremental erosion rate curves is not known at this time.

METALLOGRAPHY

The texture of the eroded surface of a metal exposed to a liquid-solid particle eroding media and a gas-solid particle media are quite different. Figure 25 shows the surface of a 304SS specimen eroded by a 30 wt% coal-kerosene slurry. The surface is very smooth, almost polished with few indentations to indicate that 74µm size particles had been striking it with sufficient force to remove material. In contrast, the surface of 1020 steel eroded by 200µm SiC particles

carried to the surface in an air blast shown in Figure 26 is highly deformed. Platelets and shallow craters occur in profusion. The particle velocities were 15 m/s for the coal and 30 m/s for the SiC. While the differences in velocity and erosivity between the two erodent particles favor more severe erosion by the SiC, the striking difference between the surfaces shown in Figures 25 and 26 is still a valid comparison. The viscosity, lubricity and cooling capability of the kerosene compared to those of air are primarily responsible for the great difference in texture between the two surfaces.

A careful analysis of cross sections of the specimens eroded by the coal-kerosene slurry are required to observe the mechanism of erosion. Figure 27 shows a cross section of the surface of an A53 steel eroded specimen. It can be seen that shallow craters are present on the surface along with their extruded platelets that lie parallel to the surface. In some places the platelets covered over near-by craters. Viewed from above, the surface at this cross section would appear similar to that in Figure 25. Close inspection of the platelet at the left side of Figure 27 shows part of it extending over the crater with a crack appearing in the platelet at the edge of the crater. The next particle to strike the area could knock off the part of the platelet extending over the crater. The long platelet on the right side of the photo shows that the platelets formed during slurry erosion have decidedly different geometries than those formed in gas-solid particle erosion. However, basically the erosion removal mechanism is the same in the two fluids.

DISCUSSION

Effect of Alloy Composition

The effect of alloy composition and the standard mechanical properties on relative erosion behavior of the alloys tested was not clearly discernible in the tests performed as can be seen in Figures 6 - 9. The chromium content had some apparent relationship with the erosion rate as was shown in Figure 10, but the effect was not a strong one. At 18% Cr content, the erosion rates varied over 50%. It was felt that the curves in Figures 6 - 10 were not indicative enough of relationships between erosion behavior and properties to carry out a statistical analysis of the data.

While the ductility of the alloys tested in gas-solid particle erosion (1) can be used to relate the erosion behavior of different alloys with the more ductile alloys having lower erosion rates, no such correlation was possible in the liquid-solid particle erosion behavior reported herein. The relatively low elongation of the A53 steel (25%), and the much higher elongation of the 304SS (55%), made no difference in their erosion rates, which were nearly the same in all of the room temperature tests performed in coal-kerosene slurries.

Other properties of the alloys tested will have to be investigated before correlations can be made that will be helpful to designers in alloy selection and materials developers to produce more erosion resistant steels. For example, the strain hardening coefficient of an alloy shows promise of relating to erosion resistance. This will be discussed further later in this section.

Effect of Particle Size and Solids Loading

The effect of particle size and solids loading on the erosion rate of A53 steel and 304SS, the two highest erosion rate alloys tested, showed that more particles and larger particles generally resulted in more erosion (Figures 11 - 13). However, the larger size particle grind (-30 mesh) eroded the steels more than the finer grind only at higher velocities, Figure 13. At 3 m/s both coal grinds caused nearly the same amount of erosion. Also, while the finer sized particles showed a consistent difference in erosivity as a function of solids loading at all velocities, Figure 11, the larger coal particles showed a difference only at the higher velocities, Figure 12.

The combination of velocity and particle size effects on erosion relates to the kinetic energy of the particles and the degree of effective protection that the viscosity of the liquid provides to the metal surface from the particles trying to impact it. The fact that the higher effective viscosity of the 50wt% coal slurry caused more erosion to occur than the 20wt% coal slurry, Figures 11 and 12, indicates that it is the viscosity of the liquid and not that of the total slurry that affects the erosivity of the slurry.

Apparently there is some critical level of particle kinetic energy at which the insulating capability of the liquid is reduced enough to permit a more direct relationship between the kinetic energy of the particles and erosion of the metals to occur. At the lowest test velocity used, the mass difference between -30 mesh and -200 mesh size particles is not sufficient to change the kinetic energy of the particles enough to cause a significant difference in the erosion rates

to occur, Figure 13. However at the higher velocities, the mass difference between the two sizes of particles is enough to affect their kinetic energy to the degree necessary to result in different erosion rates.

Effect of Lubricity

The ability of the carrier liquid to protect the impacting particles from the target metal surface was investigated by using a liquid whose lubricity effect could be separated from its viscosity, which can also affect the ability of the particles to impact their kinetic energy to the target metal.² The two curves, Figures 15 and 16, which show the results of the experiment very effectively indicate the role of lubricity of the liquid in modifying the erosivity of the slurry. The change to a greater level of lubricity, as the result of adding the small amount of acid, significantly decreased the erosivity of the slurry to less than one-third of its level in the untreated solvent.

Determining that there is a significant effect of lubricity on the erosivity of non-aqueous slurries opens the way for an analytical treatment of the erosion behavior of ductile metals in these slurries. Now the lubrication literature can be used in conjunction with the fluid mechanics of two-phase flow and the latest models for the erosion mechanism of metals to develop a model that can describe the transfer of kinetic energy from a particle through the carrier liquid to the metal surface being eroded.

Effect of Temperature

The effect of temperature on the erosion behavior of steels in the temperature regime that occurs in the slurry mixing stages of coal liquefaction systems, $\sim 175^{\circ}\text{C}$ (350°F), follows a pattern first seen in gas-solid particle erosion.³ Four of the six alloys plotted in Figure 17 had lower erosion rates at slightly elevated temperatures than they had at room temperature. This effect could be due to interactions between the solvent and the coal particles that effectively increased the viscosity of the slurry, or to small but important modifications in behavior of the alloys in resisting erosion. It is not possible at this time to know exactly what caused the decrease in the amount of erosion. In the case of the gas-solid particle erosion, it is fairly certain that increased ductility of the alloys tested at elevated temperatures was responsible for decreased erosion.

The large spread in the amount of erosion occurring on a number of steel alloys at 95°C and 175°C of similar mechanical properties, shown in Figures 18 - 22, cannot be readily explained. The relative erosion resistance of the various alloys and the changing of the order of that resistance as a function of the slurry velocity is also not explainable. The consistent higher erosion of A53 carbon steel, which is particularly pronounced in Figures 19 and 20, persists at low elevated temperatures as does the considerably lower erosion of its finer-grained counterpart, A106 steel.

A very important observation can be made based upon the incremental erosion rate curves of Figures 23 and 24. The fact that the erosion rates decrease as the test proceeds indicates that there is

a significant difference between at least part of the mechanism of erosion in liquid-solid particle erosion compared to gas-solid particle erosion.

In gas-solid particle erosion,⁴ the erosion process causes the surface to heat up as a result of the plastic deformation which occurs when the eroding particles strike the surface. Beneath the hot, eroding surface the energy of the particles are sufficient to cause sub-surface cold working of the metal. The combination of the heated surface and the sub-surface cold worked zone results in a pattern of incremental erosion rate where the rate is lowest at the beginning of the test and subsequently increases to a higher steady state erosion rate.

Figures 23 and 24 show that this pattern of erosion does not occur in liquid-solid particle erosion. The highest incremental rate occurs near the beginning of the test and the erosion rate decreases subsequently. This behavior implies that the surface rather than the sub-surface is being cold worked and, as the test proceeds, the harder surface retards the erosion process.

The reason for this difference between gas-solid particle erosion and liquid-solid particle erosion is thought to be the cooling effect of the liquid. Its much greater cooling capacity, compared to that of a gas, keeps the surface from being heated by the plastic deformation which occurs as erosion occurs. The surface is then able to be cold worked by the erosion process and becomes more resistant to further erosion as the process proceeds. At some point a steady state cold worked condition is reached at the surface and the incremental erosion

rate from that time on will be a constant, low rate. Thus, the strain hardening coefficient of an alloy appears to be an important alloy selection and development property which will be investigated further.

Metallography

Efforts to determine the mechanism of erosion that occurs in non-aqueous slurries using metallographic observations are considerably more difficult in liquid-solid particle erosion than in gas-solid particle erosion of ductile metals. This is due to the marked decrease in the amount of plastic deformation which occurs on the metal surface in liquid-solid particle erosion. It is speculated that the reason for the much smaller amount of deformation in the slurry tests relates to the differences in the transfer of the kinetic energy of the impacting particles to the metal surface and the heat transfer at the eroding surface in the two transfer liquids that were discussed above. However the mechanism of erosion is still the formation and removal of platelets of metal by the erodent particle impact.

CONCLUSIONS

1. The slurry pot tester is a low-cost effective tool for studying the erosion behavior of materials in liquid-solid particle slurries.
2. Different steel alloys display erosion behaviors that vary significantly as a function of testing conditions and cannot be readily related to their composition, morphology, or mechanical properties.

3. In general, higher solids loadings in a slurry and larger particles result in higher erosion rates.
4. The use of a liquid carrier fluid for a stream of particles, compared to a gaseous carrier fluid, reduces the kinetic energy of the particles that is transferred to the target metal surface, and hence their erosivity.
5. A liquid carrier fluid acts as both a lubricant and a coolant to reduce the erosivity of impacting solid particles in slurry erosion.
6. Erosion in liquid-solid particle erosion causes cold working of the eroding surface to occur which decreases the incremental erosion rate as the process proceeds.
7. The mechanism of platelet formation and removal is the same for both gas-solid particle and liquid-solid particle erosion.
8. There was no correlation between the measured erosion rates of the alloys tested and their tensile properties and hardness. There was an indication that the erosion rates would relate to the strain hardening coefficient of the alloys.

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FIGURES

1. Exterior view of slurry pot tester.
2. Cross section design of slurry pot tester.
3. Reproducibility of erosion measurements in slurry pot test.
4. Cumulative erosion of several steel alloys at 12 m/s.
5. Cumulative erosion of several austenitic stainless steels and A53 mild steel at 12 m/s.
6. Correlation of erosion rate after 2 hrs vs tensile strength (psi) at 25°C, 12 m/s.
7. Correlation of erosion rate after 2 hrs vs yield strength (psi) at 25°C, 12 m/s.
8. Correlation of erosion rate after 2 hrs vs elongation at 25°C, 12 m/s.
9. Correlation of erosion rate after 2 hrs vs hardness (Bhn) at 25°C, 12 m/s.
10. Correlation of erosion rate after 2 hrs vs chromium content (wt%) at 25°C, 12 m/s.
11. Effect of velocity on two solid loadings coal-kerosene slurries using -200 mesh coal.
12. Effect of velocity on two solids loadings coal-kerosene slurries using -30 mesh coal.
13. Comparison of coal grinds on erosion of steels in 20 wt% coal-kerosene slurry.
14. Erosion of A53 steel at 25°C (75°F) in coal-kerosene and coal-hexadecane slurries.
15. Erosion of A53 steel at 25°C (75°F) in hexadecane and hexadecane + 1/2% hexadecanoic acid.
16. Erosion of A53 steel at 95°C (200°F) in hexadecane and hexadecane + 1/2% hexadecanoic acid.
17. Erosion of steel alloys vs test temperature.
18. Cumulative erosion of steel alloys at 95°C (200°F), 6 m/s.
19. Cumulative erosion of steel alloys at 95°C (200°F), 12 m/s.

20. Cumulative erosion of steel alloys at 175°C (350°F), 6 m/s.
21. Cumulative erosion of steel alloys at 175°C (350°F), 12 m/s.
22. Comparison of erosion of steel alloys at 175°C (350°F) at two velocities.
23. Incremental erosion of steel alloys at 95°C (200°F), 12 m/s.
24. Incremental erosion of steel alloys at 175°C (350°F), 12 m/s.
25. Eroded surface of 316SS in coal-kerosene slurry.
26. Eroded surface of 1020 steel in SiC-air erosive stream.
27. Cross section of A-53 steel showing presence of platelets.

Table I

STEEL COMPOSITIONS

Alloy Designation	<u>Typical Composition in Wt%</u>						
	Cr	Ni	Mo	Mn	Si	C	Fe
A53 (1018)	-	-	-	1.2	-	0.30	BAL
A106	-	-	-	1.0	0.1	0.30	BAL
2-1/4Cr-1Mo	2.25	-	0.5	0.5	0.5	0.15	BAL
5Cr-1/2Mo	5	-	0.5	0.5	0.5	0.15	BAL
9Cr-1Mo	0	-	1	0.5	0.5	0.15	BAL
410SS	12	-	-	1	1	0.15	BAL
304SS	18	8	-	2	1	0.08	BAL
310SS	25	20	-	2	1	0.25	BAL
316SS	16	10	2.5	2	1	0.08	BAL
321SS	17	9	-	2	1	0.08	BAL

Table 2

Coal Particle Size Distribution (in wt%)

<u>Size Range</u>	<u>-200 mesh</u>	<u>-30 mesh</u>
<600 μ m	0.24	2.46
495 - 600 μ m	0.67	2.14
300 - 495 μ m	0.57	7.72
150 - 300 μ m	0.24	24.78
90 - 150 μ m	3.09	25.29
38 - 90 μ m	68.05	20.61
<38 μ m	27.14	17.00

Table 3

Erosion Velocity Exponents

		<u>A53 Steel</u>	<u>304SS</u>
20wt% Coal-kerosene	-200 mesh	1.91	1.82
	-30 mesh	2.97	2.83
50 wt% Coal-kerosene	-200 mesh	1.68	2.15
	-30 mesh	3.07	3.00

CBB 817-6704

Fig. 1. Exterior view of slurry pot tester.

XBL 803-8458

Fig. 2. Cross section design of slurry pot tester.

XBL 814-717

Fig. 3. Reproducibility of erosion measurements in slurry pot test.

XBL809-11980

Fig. 4. Cumulative erosion of several steel alloys at 12 m/s.

XBL 809-11981A

Fig. 5. Cumulative erosion of several austenitic stainless steels and A53 mild steel at 12 m/s.

Fig. 6. Correlation of erosion rate after 2 hrs vs tensile strength (psi) at 25°C, 12 m/s.

XBL 841-5

XBL 8312-7452

Fig. 7. Correlation of erosion rate after 2 hrs vs yield strength (psi) at 25°C, 12 m/s.

XBL 8312-7455

Fig. 8. Correlation of erosion rate after 2 hrs vs elongation at 25°C, 12 m/s.

XBL 8312-7453

Fig. 9. Correlation of erosion rate after 2 hrs vs hardness (Bhn) at 25°C, 12 m/s.

XBL 8312-7454

Fig. 10. Correlation of erosion rate after 2 hrs vs chromium content (wt%) at 25°C, 12 m/s.

XBL 817-10712A

Fig. 11. Effect of velocity on two solid load-
ings coal-kerosene slurries using
-200 mesh coal.

XBL 817-10709

Fig. 12. Effect of velocity on two solids
 loadings coal-kerosene slurries
 using -30 mesh coal.

XBL 817-10710B

Fig. 13. Comparison of coal grinds on erosion of steels in 20 wt% coal-kerosene slurry.

XBL 817-10719

Fig. 14. Erosion of A53 steel at 25°C (75°) in coal-kerosene and coal-hexadecane slurries.

XBL 817-10721

Fig. 15. Erosion of A53 steel at 25°C
in hexadecane and hexadecane + 1/2%
hexadecanoic acid.

Fig. 16. Erosion of A53 steel at 95°C (200°F) in hexadecane and hexadecane + 1/2% hexadecanoic acid.

XBL 817-10720

Fig. 17. Erosion of steel alloys vs test temperature.

XBL 8110-7151C

Fig. 18. Cumulative erosion of steel alloys at 95°C (200°F), 6 m/s.

XBL 8110-7147A

XBL 8110-7157A

Fig. 19. Cumulative erosion of steel alloys
at 95°C (200°F), 12 m/s.

XBL 8110-7141A

Fig. 20. Cumulative erosion of steel alloys at 175°C (350°F), 6 m/s.

XBL 8110-7156A

Fig. 21. Cumulative erosion of steel alloys
at 175°C (350°F), 12 m/s.

XBL 8110-7152A

Fig. 22. Comparison of erosion of steel alloys
at 175°C (350°F) at two velocities.

Fig. 23. Incremental erosion of steel alloys
at 95°C (200°F), 12 m/s.

XBL 8312-7451

XBL 8312-7450

Fig. 24. Incremental erosion of steel alloys
at 175 °C (350 °F), 12 m/s.

XBB 802-2395

10 μ m

Fig. 25. Eroded surface of 304SS in coal-kerosene slurry.

Fig. 26. Eroded surface of 1020 steel in SiC-
air erosive stream. XBB 8110-9318

5 μm

4 mm

Fig. 27. Cross section of A-53 steel showing presence of platelets.

XBB 817-6592A

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