ATTRITION AND ABRASION MODELS FOR OIL SHALE PROCESS MODELING

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Attrition and Abrasion Models for Oil Shale Process Modeling *

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ABSTRACT

As oil shale is processed, fine particles, much smaller than the original shale are created. This process is called attrition or more accurately abrasion. In this paper, models of abrasion are presented for oil shale being processed in several unit operations. Two of these unit operations, a fluidized bed and a lift pipe are used in the Lawrence Livermore National Laboratory Hot-Recycle-Solid (HRS) process being developed for the above ground processing of oil shale.

Abrasion occurs so commonly in the handling and processing of particulate materials that numerous studies have been conducted to first characterize the phenomena and secondly to attempt to minimize it. In the review of the literature, materials which have been studied for attrition potential are examined as are the specific unit operations for which either experimental or modeling studies have been conducted. Several papers are discussed in which attrition in fluidized beds or lift pipes is addressed.

In two reports, studies were conducted on the attrition of oil shale in unit operations which are used in the HRS process. Carley reported results for attrition in a lift pipe for oil shale which had been pre-processed either by retorting or by retorting then burning.1 The second paper, by Taylor and Beavers, reported results for a fluidized bed processing of oil shale.2 Taylor and Beavers studied raw, retorted, and shale which had been retorted and then burned. In this paper, empirical models are derived, from the experimental studies conducted on oil shale, for the processes occurring in the HRS process. The derived models are presented along with comparisons with experimental results.

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Introduction

The Hot-Recycle-Solid (HRS) process, shown in Fig. 1, uses burnt shale as the recycled solid heat carrier. In this process, fine material, defined as solid with particle diameter less than 0.2 mm, is separated from the larger solids in the Fluid Bed Classifier (FBC). Heat contained in the recycled, burned shale is transferred to the raw shale in the Fluid Bed Mixer (FBM). A proper analysis of this process includes consideration of the entire solid stream including the fine material. In this paper, the attrition and abrasion of oil shale is described, experimentally and with mathematical models in order to develop a better understanding of the influence of these phenomena on the HRS process.

Literature Review

Attrition and abrasion occur so commonly in the handling and processing of particulate materials that numerous studies have been conducted to first characterize the phenomena and secondly to attempt to minimize it. In this review, we will examine materials which have been studied for attrition potential followed by the specific unit operations for which either experimental or modeling studies have been conducted. We will then discuss two papers which specifically examine attrition of oil shale in a fluidized bed and in a lift pipe.

Materials Previously Studied

Much of the experimental work on attrition has been conducted on specific materials for which the authors had an direct interest. Because of the complexity of the phenomena, the material characteristics of shape, size, and chemical composition become tightly entangled with the processes characteristics which are causing the attrition.

Figure 1. Hot-Recycle-Solid (HRS) Process (1-Delayed Fall Combustor, 2-Fluid Bed Classifier or Combustor, 3-Fluid Bed Mixer, 4-Pyrolysor, 5-Lift Pipe).

Some of the materials which have been studied for attrition potential include coal,4,5,6,7,8 carbon char,9,10,11 carbon electrode particles,12 calcium carbonate (limestone),11 sodium carbonate,13 glass,14 cracking catalysts,15 urea,16 and oil shale.1,2,17,18,19,20

Studies have also been conducted with model or mock materials composed of glass with a small
particle size (approximately 75 μm) which are held together with a bonding material, for which the authors had an estimate of the inter-particle strength, to form larger particles. In one study by Kono\textsuperscript{6} water was used as the bonding material and in a second study by Shamlo\textsuperscript{2} a polymer with an adjustable strength was used. The degree of cross linking in the polymer was changed to obtain different strength characteristics.

For oil shale attrition, material considerations are very important. It has been suggested by Taylor that the principle and perhaps only measurement that need be made, to predict the final amount of attrition which occurs in retorting, is the amount of kerogen or total organic carbon in the shale sample.\textsuperscript{21} The reason that the kerogen concentration is so important is that in some cases the kerogen is the principle component which is holding the shale particle together. A very simplistic picture of an oil shale particle is that it is composed of only a mineral component and kerogen. If the kerogen content is low then the tensile strength of the particle is dependent on the spatially continuous regions of mineral, with kerogen embedded within this connected matrix of mineral. If the kerogen is removed, then the strength of the shale particle is similar to the shale before the kerogen was removed. If, on the other hand, the kerogen content is high the spatially continuous component is kerogen and the mineral is dispersed in the kerogen. When the kerogen is removed the strength approaches zero and very small forces on the particle will cause the mineral components to abrade.

In the series of papers by Grimm and Swaney, experimental results are described for the attrition of oil shale which is processed in a rotary furnace. In different experiments purge gasses of nitrogen, air, or carbon dioxide were passed though the furnace as it was rotated.\textsuperscript{17,18,19,20} The amount of attrition is then measured by sieving the material after having been rotated a specified number of times. Because this work is conducted at process temperatures, loss of kerogen and particle strength due to heating, pyrolysis or combustion is expected. After the kerogen is removed the resulting strength is only due to the remaining char, if any, or any continuous mineral matrix which might be present.

Grimm and Swaney presented some of their results as a plot of the particle size distribution of the oil shale versus the temperature at which the test was conducted.\textsuperscript{20} The number of rotations was fixed at 800 for this series of tests. Under pyrolysis conditions the mass fractions of all the particle size classes changed monotonically but for combustion conditions a maximum occurred in the fines size classes at about 600 K and the mass fraction of the smallest material decreases. They attributed this size increase to sintering.

Unit Operations Previously Studied

A few of the unit operations which have been studied for attrition potential include fluidized beds,\textsuperscript{14,5,16,2,11} a lift pipe,\textsuperscript{1} a ball mill,\textsuperscript{8} and heated rotary furnaces.\textsuperscript{17,18,19,20} In this paper lift pipes, fluidized beds, and heated rotary furnaces will be examined specifically, because of their application to oil shale processing.

In the fluidized bed attrition experiments, two types of beds were used. In the coal and char experiments, a bed of sand was first fluidized and then the sample material was added. In the other fluidized bed experiments, only the sample material was in the fluidized bed. In the work of Taylor and Beavers on oil shale, only oil shale was used in the bed.\textsuperscript{2} The attrition mechanisms developed from these experiments are clearly different. If the sample material was added to a bed of sand, the rate of attrition was found to be proportional to the weight of sample left in the bed at any time, divided by its particle size, which is proportional to the total particle surface area. However, when only the sample material was used in the fluidized beds a zeroth order mechanism was found. In this case, a zeroth order mechanism means that the amount of attrition is not proportional to the mass of sample material in the bed at a specific time, but it is proportional to time raised to a power. If one plots the log of the mass attrited in the experiments using a sand bed versus time, a straight line is obtained. However, when only
the sample material is used, a plot of the log of the mass attrited versus the log of time will give a straight line.

In all of the fluidized bed experiments described in this paper, the rate of attrition was determined by accumulating the fine material which was elutriated out of the bed. Two processes are therefore occurring. First, the material is being attrited or abraded and secondly, the fine material is elutriated. The mechanism for the 'pure' process of elutriation is reported by Levenspiel and by Kunii and Levenspiel to be first order with respect to the mass of fine material.\textsuperscript{22,23} I say 'pure' because his model assumes that at time zero a fixed mass of fine material is in the bed, and the fine material is blown out, or elutriated. If one assumes that the emulsion phase of a fluidized bed, which is where the solids are present, is well mixed, then a first order model naturally follows. It should be noted, however, that for very small amounts of attrition it is difficult to tell the difference between a zeroth, first or even second order process.

Shamliou studied the attrition of 2 mm diameter by 2 mm long cylinders of 75 μm particles held together by a polymer resin.\textsuperscript{14} The strength of the resin was modified by changing the degree of cross-linking. This granular material was then fluidized in a 14 cm diameter fluidized bed. An empirical relationship was obtained for the rate of abrasion as a function of the superficial gas velocity minus the minimum fluidization velocity, the particle density, the bed diameter squared, time to a power, and the number of original particles, as shown in Eq. 1. They found a linear dependence between the rate of attrition and the superficial gas velocity, U, minus the minimum fluidisation velocity, \( U_{mf} \). They claim this implies that attrition occurs in the bulk emulsion phase and not at the bottom of the bed near the distribution plate. In their experiments, only the sample material was present in the fluidized bed and the rate of attrition was found to be proportional to time, \( t \), raised to a power, that is, a zeroth order mechanism with respect to the mass of sample. In their analysis summarized in Eq. 1, the size of the original particles was assumed to be constant. Several other terms are used in Eq. 1. The variable \( n_p \) is the number of fine particles of size \( d_p \), \( k \) and \( \delta \) are empirical constants, \( N_p \) is the number of large particles of size \( D_p \) in the bed, \( D_T \) is the bed diameter, \( h_{mf} \) is the height at minimum fluidization, \( \epsilon_{mf} \) is the void fraction at minimum fluidization, \( \rho_p \) is the particle density, \( g \) is the gravity constant, and \( f_e \) is the tensile strength.

\[
\frac{\partial n_p}{\partial t} \propto kN_p\left(\frac{D_p}{d_p}\right)^{3}\frac{D_T^2}{h_{mf}(1-\epsilon_{mf})}\rho_p g(U-U_{mf}) t^{\delta-1} \frac{1}{f_e}
\]  

(1)

A paper on the attrition of limestone and coal ash by Fuertes and associates reported an empirical expression for the cumulative attrition in a fluidized bed, \( w \).\textsuperscript{11} Their expression is given in Eq. 2. The values of \( R_{\infty} \), \( t_R \), \( a \), and \( b \) are empirical constants. The rate of attrition data reported in this paper appeared to go to zero for the experiments using limestone after 900 min. The solids used in the study had a particle sizes between 0.5 and 1.0 mm, the gas velocity was 0.7 m/s for the limestone and 0.65 m/s for the coal ash, the static bed depth was about 60 mm, and the bed diameter was 0.14 m.

\[
w = \frac{R_{\infty}}{t_R} \int_0^\infty \left[1 + \frac{a}{(1 + bt)^2}\right] e^{-\frac{t}{t_R}} dt
\]  

(2)

Taylor and Beavers studied the long term attrition of oil shale in a fluidized bed.\textsuperscript{2} They derived an equation for the weight loss due to attrition, which is given as Eq. 3. In this equation \( w \) is the mass fraction of fine material in the fluidised bed at time, \( t \), and \( W_o, F_o, k, F_t \) are constants. The time dependence is present in the last term and in the exponential term. This equation indicates a combination of a first order and a zeroth order mechanism.

\[
w = (W_o - \frac{F_o}{k})(1 - e^{-kt}) + tf_t
\]  

(3)

A similarity exists between these last two model forms and a form derived by Whitby to describe the rate of flow of material through a sieve.\textsuperscript{24} The model developed by Whitby included two portions, the first was a zeroth order equation
and the second was a first order equation. The zeroth order term was used to describe the early time flow of the material passing through the sieve and the first order term was used to model the late time flow. The difference between these two approaches and that by Whitby is that in the model by Whitby only one term is active at any time, but in the model by Taylor and Beavers and the both terms are used concurrently.\textsuperscript{24, 25, 11}

The justification for the two terms in the Whitby model given by Allen is that for early times the material passing through the sieve is much smaller than the effective size of the hole in the sieve.\textsuperscript{26} At later times either material very close to the size of the sieve passes through the sieve or attrition of the material in the sieve occurs. A fluidized bed can be thought of as a size separation device with particles smaller than the terminal velocity limiting size being blown out of the top of the bed and larger particles remaining in the emulsion phase in the bed. At early times, both existing fine material, and easily created fine material will be blown out. At later times, an attrition or abrasion process is required to create new fine material, which is then blown out of the fluidized bed.

One way that the Whitby model is used in sieving processes is to determine the proper amount of time required to sieve a sample. A series of preliminary tests is used to determine the critical time at which the rate of material passing through the sieve is no longer described by a zeroth order model and is subsequently described by a first order model. In later sieving operations, the material is sieved slightly longer than this critical time.

Another comparison that can be made is that between the results reported by Shamlou and the results reported by Taylor and Beavers.\textsuperscript{14, 2} Since fluidized beds were used in both of these studies, it is possible to make at least a qualitative comparison between their results. Shamlou reported an attrition mass fraction of 0.11 after 100 min. of bed operation for the most friable of their particles. The tensile strength of the most friable particle was reported to be 1.2 MPa. Taylor and Beavers reported an attrition mass fraction for raw shale with a grade of 100 L/Mg of 0.1364 after 100 min. Taylor and Beavers did not report a tensile strength for the shale which they studied, however, Young and associates have reported tensile strengths of various types of oil shale versus grade.\textsuperscript{26} A large range exists in their data at a fixed grade for a specified type of shale. In addition, the tensile strength can vary for different types of oil shale. For example, one oil shale with a grade of 100 L/Mg has a strength between 0.75 and 1.25 MPa and another had a strength between 3. and 6. MPa. In addition, the process variables for the two experiments were somewhat different, for example, Taylor and Beavers fluidized bed was operated at a superficial gas velocity which was twice the minimum fluidization velocity, whereas, Shamlou used a maximum value of only 1.3. The oil shale particle size used by Taylor and Beavers was nominally 1.4 mm and the particles used in Shamlou's experiments were cylinders with a length and diameter of 2. mm. The particle density of the oil shale was 2.2 gm/cm\textsuperscript{3} and Shamlou's particles had a density of 2.0 gm/cm\textsuperscript{3}. The comparison is, nevertheless, encouraging. It appears that an accurate measure of particle tensile strength may be a useful experimental measurement for future attrition studies.

Gwyn reported that the attrition of cracking catalysts could be described as a zeroth order process, as shown in Equations 4 and 5.\textsuperscript{15} Woodburn and Kalligeris-Skontzos also used a zeroth order model to describe the size reduction process of ball mill grinding.\textsuperscript{8} In both of these equations m and k are empirically determined constants.

\begin{equation}
    w = kt^m
\end{equation}

\begin{equation}
    \frac{\partial w}{\partial t} = kmn^{m-1}
\end{equation}

A more detailed analysis of the attrition process indicates that the mechanism may be controlled by either zeroth, first or second order. If, as Levenspiel assumes, the material which becomes elutriated from the fluidized bed is present at the start of the process and no more is generated,
then a first order process would be appropriate. If the mechanism for generating the fine material is a particle-particle impact, then one might expect that the process is second order, that is, the frequency of impacts would be a function of the number concentration of the two impacting particles. If the material eroded is relatively quickly eroded from the bed, then a second order process might be reasonable. A second order process would be consistent with only a minor change in the bulk density and original shale particle character as the surface is eroded.

Previously Reported Experimental Results for the Attrition of Oil Shale

Carley reported results for attrition in a 6 m tall lift pipe for oil shale which had been preprocessed either by retorting or by retorting then burning. The attrition was studied at two gas flow rates and with two original grades of oil shale. Other variables that were investigated, included the vibrator motor speed and solids flow rate; however, the gas flow rate, the original shale grade, and processed state (retorted or burnt) appeared to have the largest impact on attrition.

Several interesting results were reported by Carley. He concluded, for example, that the principle phenomena responsible for the attrition of oil shale in a lift pipe is abrasion, that is, the surface of large particles is eroded away by solid contact. Sharp corners appear to be rounded and the maximum length to diameter appears to decrease. It appears that the most likely contact-abrasion surface is the inner wall of the lift pipe, however this will be discussed in more detail latter in this paper. The alternative phenomena for attrition, fracture, appears to occur less frequently.

Carley presented a model to describe the increase in total particle surface area caused by a lift pipe. The model developed by Carely is given in Eq. 6. In his model, the initial surface area, \( S_{p0} \), of the shale was used as a parameter in his correlation. The values of the initial surface area and the constant \( a \) are given as parameters for each sample state tested (ie, whether it was retorted only or retorted and burnt) and for each level of kerogen tested (ie, either 79 or 150 L/Mg). The values for the exponents for the velocity, \( V \), and the number of passes, \( N \), were also determined empirically. The reported values for the exponent for \( N \) varied from 0.45 to 0.89. An intermediate value of 0.7 was selected for the correlation. The velocity, \( V_m \), used by Carley had units of gram/sec.

\[
S_p = S_{p0} + aN^{0.7}V_m^2
\]

Taylor and Beavers reported results for fluidized bed processing of oil shale. They studied raw, retorted, and shale which had been retorted and then burned. The bed used in the experiment had a diameter of 57 mm and a height of 600 mm. The oil shale had a nominal size of 1.4 mm. The original grade of the shale was 79 L/Mg. The superficial gas velocity used in the experiment was 0.455 m/s, which is approximately twice the minimum fluidization velocity.

The two results which were obtained from Taylor and Beavers' experiments that are relevant to this paper are the bed weight versus time and that the size distribution of the material eroded from the bed consisted of particles which were much smaller than the parent material. We might assume then that the principle attrition phenomena for oil shale in a fluidized bed is abrasion, as it is in the lift pipe. The attrition or abrasion data was reported as a function of time for each of the oil shale samples. They presented this data both as a table of fluidized bed weight versus time and as a correlation of bed weight versus time data, for the raw shale material. The experiments were conducted for up to 1000 min.

Model Development

In the previous section, several models of abrasion for fluidized beds are described. Most have been developed for units which experience low
levels of abrasion, that is less than a few percent. The experimental data by Carley and Taylor and Beavers indicate that the amount of abrasion for some oil shales can be higher than 15%.

Only one model has been found in the literature to describe the abrasion of a granular material which is transported in a lift pipe, that by Carley. In the following sections models will be presented for a fluidized bed composed entirely of oil shale and for the abrasion of oil shale in a lift pipe.

Model of Abrasion for Oil Shale in a Fluidized Bed

Our model for the abrasion of oil shale in a fluidized bed has been derived directly from the data reported by Taylor and Beavers. This data consisted of a table of the weight of the abraded material versus time. This data can be plotted in various ways to help determine the appropriate mechanistic rate equation. For example, if the log of the material remaining in the bed is plotted versus time and a linear curve is obtained, then the rate equation is first order. If the log of the mass attrited is plotted versus the log of time and a linear curve is obtained, then the rate equation is zeroth order. If a plot of the inverse of the weight remaining minus the inverse of the weight in the bed at the start of the experiment is plotted versus time and a linear curve is obtained, then the rate equation is second order. In Figs. 2 and 3, the data from Taylor and Beaver is plotted along with the results from a second order model. The value for the second order rate constant, $k$, was $1.46 \times 10^{-3}$ min$^{-1}$ for the raw shale and $3.7 \times 10^{-2}$ min$^{-1}$ for the burnt shale. It can be seen that a reasonable fit has been obtained.

The rate of abrasion is given in Eq. 7. The variable "$w$" is the mass fraction of fine material created based on the original mass of the bed. An advantage of this form of the rate equation over a combined zeroth order and first order equation such as that developed by Whitby, is that it isn't necessary to specify a time to switch between the two forms.

$$\frac{\partial w}{\partial t} = k(1 - w)^2$$

(7)

It should be noted that the data taken by Taylor was taken at ambient conditions and not at elevated temperatures. Miller and associates have
reported measurements of the tensile strength of oil shale at elevated temperatures.\(^2\) They found that the strength for a 100 L/Mg grade shale was 11.8 MPa at 25 °C and 0.9 MPa at 380 °C. It is assumed, however, that the effects of temperature can be included as part of the state of the shale, that is, raw or burnt. When kerogen is removed from the shale, the strength of the particle is reduced and the effect of temperature on this weakened particle is assumed to be small.

An Abrasion Model for Oil Shale in a Lift Pipe

Our model for abrasion occurring a lift pipe is derived directly from the experimental work by Carley.\(^1\) Carley presents the results from several abrasion experiments carried out on retorted and burnt oil shale. Two grades of shale were used, 79 and 150 L/Mg. The size distribution of the fine material found by Carley is similar to that found by Taylor and Beavers for a fluidized bed abrasion test.\(^2\) Carley also found that the solids flow rate had little effect on the abrasion of the solid dispersed in his lift pipe. He concluded that the primary solid abrasion mechanism in the lift pipe was dependent on solid-wall contact.

In Fig. 4, the data from Carley's experiments is presented as a plot of fines (material with a particle size less than 0.2 mm) versus gas velocity. Data is presented for two processed states, retorted or retorted and burnt and two original oil shale grades.

Multiple linear regressions of these data were performed with two independent variables, the gas velocity, \(V_g\), squared and the mass fraction of kerogen, \(x_k\), in the raw shale. The mass fraction of kerogen was calculated from the oil shale grade, \(G\), (in gal/ton) using an equation reported by Diaz and Braun and is given in Eq. 8.\(^2\) The gas velocity was calculated by using an average air temperature of 301.5 K, the air mass flow rate, and the diameter of the lift pipe. Carley intentionally did not report gas velocities used in his experiments because he correctly assumed that they would change as the gas moved up the lift pipe.\(^1\) The velocities reported here are calculated superficial gas velocities. A multiple regression was performed on the data for each of the two process states, retorted or retorted and burned. The equation used for both of the regression analyses is given in Eq. 9 and the coefficients obtained are given in Table 1. The fit to the data is shown in Figs. 5 and 6.

\[
x_k = 0.005395(G + 1.026) \tag{8}
\]

\[
w = c_0 + c_1 V_g^2 + c_2 x_k + c_3 V_g^2 x_k \tag{9}
\]

Figure 4. Weight of Fines From a Lift Pipe versus Superficial Gas Velocity with the Grade of Oil Shale and Process State as Parameters.

Table 1. Regression Equation Coefficients for Lift Pipe Experiment.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Retorted</th>
<th>Burnt</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_0)</td>
<td>0.069</td>
<td>-0.054</td>
</tr>
<tr>
<td>(c_1)</td>
<td>0.0</td>
<td>0.000008</td>
</tr>
<tr>
<td>(c_2)</td>
<td>0.067</td>
<td>1.577</td>
</tr>
<tr>
<td>(c_3)</td>
<td>0.00045</td>
<td>0.0019</td>
</tr>
</tbody>
</table>

It should not be a surprise that a good agreement is achieved. Essentially only two values were used for each independent variable. The main advantage of using the multiple linear regression was that all of the data points could be used directly.
The average abrasion rate can be calculated using Eq. 9 and the time required for the shale to pass through the lift pipe of length $L$. The loss rate is given in Eq. 10.

$$\frac{\partial w}{\partial t} = \frac{wL}{V_s} \quad (10)$$

The effect of number of passes through the lift pipe is included in Eq. 11. The two constants, $d_1$ and $d_2$, were obtained by fitting the equation to abrasion data for burnt oil shale and have the following values, 6.45 and -10. The fit to the data is shown in Fig. 7.

$$w_N = w \frac{e^{((d_1+d_2x_s)x_s)}N}{e^{(d_1+d_2x_s)x_s}} \quad (11)$$

It is assumed that the effects of temperature can be included as part of the process state. As shale is burned and kerogen is removed from the shale, the shale's strength decreases, causing an increased abrasion rate. It is believed that a similar increase in abrasion would have occurred if it had been heated.

**Figure 5. Weight of Fines From a Lift Pipe versus Superficial Gas Velocity for Retorted Oil Shale with Predicted Values.**

**Figure 6. Weight of Fines From a Lift Pipe versus Superficial Gas Velocity for Burnt Oil Shale with Predicted Values.**

**Figure 7. The Cumulative Increase in Mass Fraction of Solid Abraded in the Lift Pipe During Multiple Passes.**

**Comparison to HRS-Process Experimental Data**

Four sets of data are available from the HRS-Process runs, H-8, H-10, H-11 and H-12. A complete description of these tests is given by Cena and Thorness. The experimental variables that are of interest to this present paper are given in Table 2. A reasonable agreement is found between experimental results and the combined abrasion predicted using the sum of Eqs. 7 and 10 assuming that all of the solid can be treated as though it was first pass material. The constants used in these equations were for burnt shale. Because the process is operated at temperatures well over the apparent kerogen softening temperature, it was assumed that the bonding strength of the kerogen was small as discussed earlier.
When the effect of repeated passes through the process is included in analysis, the prediction is lower by about 40%. During the experiments reported by Carley, the shale was passed through a lift pipe either one time or ten times. The amount of abrasion increased with nine more passes through the lift pipe in a nonlinear fashion, as shown in Fig. 7. The effect of number passes through the lift pipe is given in Eq. 6 in the term N^{0.7} and in Eq. 11. The values of the exponent reported by Carley were between 0.45 and 0.89. For burnt rich shale, the value was 0.45.

An additional reason that the attrition predictions may be low is that the effect of mineral thermal decomposition has been neglected. If the dolomite in the shale decomposes as the shale is burned, then the resultant strength of the shale will be reduced. This effect has not been included in the model.

Table 2. HRS-Process Data

<table>
<thead>
<tr>
<th>Run</th>
<th>H-8</th>
<th>H-10</th>
<th>H-11</th>
<th>H-12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade (L/Mg)</td>
<td>100</td>
<td>100</td>
<td>142</td>
<td>142</td>
</tr>
<tr>
<td>Recycle</td>
<td>3.2</td>
<td>3.4</td>
<td>3.0</td>
<td>3.4</td>
</tr>
<tr>
<td>V_{L} Lift (m/s)</td>
<td>8.9</td>
<td>9.2</td>
<td>7.9</td>
<td>8.4</td>
</tr>
<tr>
<td>( \tau_{FBC} ) (s)</td>
<td>69</td>
<td>63</td>
<td>73</td>
<td>67</td>
</tr>
<tr>
<td>( \tau_{FBM} ) (s)</td>
<td>37</td>
<td>35</td>
<td>38</td>
<td>35</td>
</tr>
<tr>
<td>Gas in FBC</td>
<td>Air</td>
<td>N(_2)</td>
<td>N(_2)</td>
<td>N(_2)</td>
</tr>
<tr>
<td>( T_f ), °C</td>
<td>712</td>
<td>644</td>
<td>678</td>
<td>665</td>
</tr>
<tr>
<td>Exp. Fines</td>
<td>0.35</td>
<td>0.29</td>
<td>0.51</td>
<td>0.57</td>
</tr>
<tr>
<td>Pred. Fines</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lift Pipe</td>
<td>0.185</td>
<td>0.187</td>
<td>0.271</td>
<td>0.275</td>
</tr>
<tr>
<td>Fluid-Beds</td>
<td>0.061</td>
<td>0.057</td>
<td>0.064</td>
<td>0.059</td>
</tr>
<tr>
<td>Fines in Feed</td>
<td>0.07</td>
<td>0.07</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>Total</td>
<td>0.316</td>
<td>0.314</td>
<td>0.475</td>
<td>0.475</td>
</tr>
</tbody>
</table>

In Fig. 8, the mass fraction of solid in the HRS process versus number of passes through the process is shown. A recycle ratio of three is typically used in the HRS-Process, so 25% of the solid is first pass material. When effect of abrasion is included in the calculation, the curve shifts slightly.

![Figure 8. Mass Fraction of Solid in the HRS Process With and Without Abrasion.](image)

**Conclusion**

The models presented in this paper which are derived from the available data in the literature appear to only approximately describe the abrasion of oil shale in the 4-ton/day HRS process retort. The effects caused by multiple passes through the lift pipe are not yet well understood. In addition, no data is available on the attrition capability of the delay fall combustor and the effect of dolomite decomposition on oil shale strength is not known.

Several variables which may be important have not been included in these models. For example, if oil shale can be correctly thought of as a composite of small mineral particles held together by kerogen, then the strength of the bond holding the fine particles will decrease as the kerogen is either pyrolysed or burnt. In the fluidized bed or, more importantly, in the lift pipe the abrasion process is occurring as the solid passes through the unit. The rate of abrasion for the complete unit will then be an integral of a breakage function evaluated at each particular vertical position. This breakage function will be a dependent on the relative velocities of each of the solid size class in the dispersed solid relative to the lift pipe wall, the instantaneous kerogen content of each solid size class, the original kerogen distribution in each size class and the temperature of each size class. A series of tests to examine the rate of abrasion as the shale is passing through the lift pipe would be useful. This series of tests
might also help sort out the effect of multiple passes.

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References


