RESPONSE TO PARAMETER VARIATION OF A ONE-INCH DIAMETER HYDROCYCLONE FOR PYRITIC SULFUR REMOVAL

by

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgments.</td>
<td>ii</td>
</tr>
<tr>
<td>List of Figures</td>
<td>v</td>
</tr>
<tr>
<td>List of Tables</td>
<td>vii</td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II. LITERATURE REVIEW</td>
<td>9</td>
</tr>
<tr>
<td>Definition of Hydrocyclone</td>
<td>9</td>
</tr>
<tr>
<td>Factors which influence particle movement in a hydrocyclone</td>
<td>9</td>
</tr>
<tr>
<td>Theories of hydrocyclone operation</td>
<td>10</td>
</tr>
<tr>
<td>Two types of hydrocyclones</td>
<td>14</td>
</tr>
<tr>
<td>Findings of Visman and LePage</td>
<td>14</td>
</tr>
<tr>
<td>III. PURPOSE OF THE INVESTIGATION</td>
<td>16</td>
</tr>
<tr>
<td>IV. THE HYDROCYCLONE</td>
<td>18</td>
</tr>
<tr>
<td>Background</td>
<td>18</td>
</tr>
<tr>
<td>Materials of construction</td>
<td>18</td>
</tr>
<tr>
<td>The need for a hydrocyclone</td>
<td>19</td>
</tr>
<tr>
<td>Disadvantages of the hydrocyclone</td>
<td>20</td>
</tr>
<tr>
<td>V. EXPERIMENTAL EQUIPMENT AND MATERIAL</td>
<td>21</td>
</tr>
<tr>
<td>Synthetic material</td>
<td>21</td>
</tr>
<tr>
<td>Tagged material</td>
<td>22</td>
</tr>
<tr>
<td>The hydrocyclone</td>
<td>23</td>
</tr>
<tr>
<td>The pump</td>
<td>30</td>
</tr>
<tr>
<td>The gauge</td>
<td>30</td>
</tr>
<tr>
<td>The motor</td>
<td>30</td>
</tr>
<tr>
<td>The pipe</td>
<td>30</td>
</tr>
<tr>
<td>The valves</td>
<td>31</td>
</tr>
<tr>
<td>The magnetic separator</td>
<td>31</td>
</tr>
<tr>
<td>VI. EXPERIMENTAL PROCEDURE</td>
<td>33</td>
</tr>
<tr>
<td>Three coals tested</td>
<td>33</td>
</tr>
<tr>
<td>Mixing of slurry</td>
<td>33</td>
</tr>
<tr>
<td>VII. ANALYSIS OF RESULTS</td>
<td>38</td>
</tr>
</tbody>
</table>
Tagged material technique versus float-sink method
Repeatability of data points using tagged material
Parameters that were investigated
Preliminary data points
Pocahontas #3 coal simulation
Hagy coal simulation
New Mexico coal simulation
Addition of 30 per cent limestone to
Pocahontas #3 coal
Comparison of simulated results to test on
actual Hagy coal

VIII. ECONOMIC ANALYSIS

Capital costs
Analysis

IX. RECOMMENDATIONS FOR FUTURE WORK

X. SUMMARY AND CONCLUSIONS

REFERENCES

APPENDIX A: Proof that magnetic material partition coefficients are identical with float-sink method partition coefficients and test data

APPENDIX B: Proof that magnetic material partition coefficients are repeatable and test data

APPENDIX C: Optimization data for Pocahontas #3 coal, Hagy coal, New Mexico coal, and Pocahontas #3 coal with 30 per cent limestone added

APPENDIX D: Pyritic sulfur rejection calculations
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Sources of Oxides of Sulfur</td>
<td>2</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Probable Errors of Different Diameter Hydrocyclones</td>
<td>6</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Partition Curves for 2&quot; Cyclone</td>
<td>7</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Cross-Section of Hydrocyclone Showing Tarjan's Equilibrium Planes</td>
<td>13</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Front View of Hydrocyclone</td>
<td>23</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Top View of Hydrocyclone</td>
<td>24</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Vortex Finder Detail</td>
<td>25</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Cone Detail</td>
<td>26</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Apex and Partition Detail</td>
<td>27</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Inlet Port Detail</td>
<td>28</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Experimental Setup</td>
<td>31</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Comparison of Weight Distribution of the Three Coals</td>
<td>33</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Geometry of Hydrocyclone When no Separation Occurred</td>
<td>43</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Geometry of Hydrocyclone With Most Solids Reporting to Underflow</td>
<td>44</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Variation of Vortex Finder Position, Pocahontas #3 Coal</td>
<td>45</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Variation of Inlet Diameter, Pocahontas #3 Coal</td>
<td>47</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Variation of Pressure, Pocahontas #3 Coal</td>
<td>49</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Variation of Cone Angle, Pocahontas #3 Coal</td>
<td>51</td>
</tr>
<tr>
<td>Figure 19</td>
<td>Recovery Partition Curves, Pocahontas #3 Coal</td>
<td>53</td>
</tr>
<tr>
<td>Figure 20</td>
<td>Variation of Vortex Finder Position, Hagy Coal</td>
<td>54</td>
</tr>
<tr>
<td>Figure 21</td>
<td>Variation of Inlet Diameter, Hagy Coal</td>
<td>56</td>
</tr>
</tbody>
</table>
Figure 22 - Variation of Pressure, Hagy Coal .................................. 58
Figure 23 - Variation of Cone Angle, Hagy Coal ................................. 60
Figure 24 - Recovery Partition Curves, Hagy Coal ................................. 61
Figure 25 - Variation of Vortex Finder Position, New Mexico Coal .......... 63
Figure 26 - Variation of Inlet Diameter, New Mexico Coal ..................... 65
Figure 27 - Variation of Pressure, New Mexico Coal .............................. 67
Figure 28 - Variation of Cone Angle, New Mexico Coal ......................... 68
Figure 29 - Recovery Partition Curves, New Mexico Coal ....................... 70
Figure 30 - Comparison of Recovery Partition Curves, 65 x 100 mesh, Pocahontas #3 Coal .................................................. 74
Figure 31 - Comparison of Recovery Partition Curves, 100 x 150 mesh, Pocahontas #3 Coal .................................................. 75
Figure 32 - Comparison of Recovery Partition Curves, 150 x 200 mesh, Pocahontas #3 Coal .................................................. 76
Figure 33 - Comparison of Recovery Partition Curves, minus 200 mesh, Pocahontas #3 Coal .................................................. 77
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Forms of Sulfur in Various Coals</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Float-Sink Analysis of Pocahontas #3 Coal</td>
<td>34</td>
</tr>
<tr>
<td>3</td>
<td>Float-Sink Analysis of Hagy Coal</td>
<td>35</td>
</tr>
<tr>
<td>4</td>
<td>Float-Sink Analysis of New Mexico Coal</td>
<td>36</td>
</tr>
</tbody>
</table>
I. INTRODUCTION

In recent years there has been a growing concern about the quality of the environment. Realization that technological growth has resulted in degradation of air, water, and land quality has caused pressure to be brought to bear on Congress and industry to correct the situation. Congress responded by creating the Environmental Protection Agency and by enacting laws designed to restore and protect the environment. Industry has started development of the technology required to comply with these new laws.

One of the targeted pollutants under these new laws is oxides of sulfur. Fossil-fuel generating stations account for approximately 60 per cent of the yearly emissions of oxides of sulfur in the United States. Figure 1 shows the major sources of sulfur oxides in the United States. (1)

Fossil-fuel electric plants have taken a two-fold approach in attempting to meet the sulfur emissions requirements. First, they used low sulfur fuels, and many plants have been converted from coal to oil or natural gas. In late 1973 the availability of these fuels was restricted, due to political factors, and the cost of these fuels increased dramatically. Other steam generation stations switched to low-sulfur coals. These coals are in limited supply in the eastern half of the nation, while the low sulfur western coals are economically unattractive because of their low BTU content and the high transportation costs charged to bring these coals to eastern coal-burning steam generation stations.
FIGURE 1 - SOURCES OF OXIDES OF SULFUR

- 60% COAL COMBUSTION
- 21.3% INDUSTRIAL
- 2.4% TRANSPORTATION
- 2% MISCELLANEOUS
- 0.2% I.W.T.
- 14% OTHER FUEL
The second approach was to add air pollution control equipment. Hot stack gases were routed through these devices in order to remove the pollutants. High capital costs and maintenance costs are associated with these devices with long delivery times. Many utility companies feel that these devices are not technically feasible.

Coal is one of the indigenous fuels which will enable us to meet our expanding energy requirements. These energy demands must be met without impairing air quality; therefore, it is necessary to develop an economic method of removing sulfur from coal.

Three forms of sulfur are found in coal: sulfate sulfur, organic sulfur, and pyritic sulfur. In an analysis the total sulfur, sulfate sulfur and pyritic sulfur are determined directly. The organic sulfur is determined by the difference between the total sulfur and the sulfate and pyritic constituents. (2)

Sulfate sulfur usually occurs in conjunction with calcium or iron. As sulfate sulfur accounts for only a small fraction of a per cent of the total sulfur, it is of minor importance. (2)

Sulfur also occurs in coal as an organic combination. Given and Wyss stated that organic sulfur is present as: mercaptan or thiol, sulfide or thio-ether, disulfide, or aromatic systems containing the thiophene ring. (3) Organic sulfur is chemically bound to the coal. Large amounts of energy must be supplied in order to break these bonds. Therefore, the organic sulfur content represents the theoretical lowest limit to which a coal can be cleaned by physical methods. Table 1 lists 17 American coals together with the total sulfur content and the
## Table 1 - Forms of Sulfur in Various Coals

<table>
<thead>
<tr>
<th>Coal Seam</th>
<th>Total Sulfur %</th>
<th>Pyritic Sulfur %</th>
<th>Organic Sulfur %</th>
<th>Pyritic Sulfur as % of Total Sulfur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pittsburgh</td>
<td>1.13</td>
<td>0.35</td>
<td>0.78</td>
<td>31.0</td>
</tr>
<tr>
<td>Upper Freeport</td>
<td>3.56</td>
<td>2.82</td>
<td>0.74</td>
<td>79.9</td>
</tr>
<tr>
<td>Thick Freeport</td>
<td>0.92</td>
<td>0.46</td>
<td>0.45</td>
<td>51.1</td>
</tr>
<tr>
<td>B</td>
<td>0.78</td>
<td>0.19</td>
<td>0.57</td>
<td>26.9</td>
</tr>
<tr>
<td>C Prime</td>
<td>2.00</td>
<td>1.43</td>
<td>0.54</td>
<td>73.0</td>
</tr>
<tr>
<td>Miller</td>
<td>1.25</td>
<td>0.56</td>
<td>0.65</td>
<td>48.0</td>
</tr>
<tr>
<td>No. 6</td>
<td>2.52</td>
<td>1.50</td>
<td>1.02</td>
<td>59.5</td>
</tr>
<tr>
<td>No. 9</td>
<td>3.28</td>
<td>1.05</td>
<td>2.23</td>
<td>32.0</td>
</tr>
<tr>
<td>No. 12</td>
<td>1.48</td>
<td>0.70</td>
<td>0.78</td>
<td>41.3</td>
</tr>
<tr>
<td>Freeburn</td>
<td>0.46</td>
<td>0.13</td>
<td>0.33</td>
<td>29.3</td>
</tr>
<tr>
<td>Elkhorn</td>
<td>0.68</td>
<td>0.13</td>
<td>0.51</td>
<td>25.0</td>
</tr>
<tr>
<td>Pocahontas No. 3</td>
<td>0.55</td>
<td>0.08</td>
<td>0.46</td>
<td>17.4</td>
</tr>
<tr>
<td>Eagle</td>
<td>2.48</td>
<td>1.47</td>
<td>1.01</td>
<td>59.3</td>
</tr>
<tr>
<td>Pratt</td>
<td>1.72</td>
<td>0.97</td>
<td>0.72</td>
<td>59.1</td>
</tr>
<tr>
<td>Lower Mercer</td>
<td>3.92</td>
<td>2.13</td>
<td>1.79</td>
<td>54.3</td>
</tr>
<tr>
<td>Deep River</td>
<td>2.32</td>
<td>1.52</td>
<td>0.80</td>
<td>65.5</td>
</tr>
<tr>
<td>8 - A</td>
<td>2.51</td>
<td>1.61</td>
<td>0.86</td>
<td>65.7</td>
</tr>
</tbody>
</table>

contribution of the pyritic and organic sulfur to this total.

The pyritic sulfur refers either to pyrite or marcasite. These two minerals have the same chemical formula, FeS$_2$, but have different crystalline forms. Pyrite is cubic while marcasite is orthorhombic. In American coals the pyrite structure predominates with the size of the pyritic particles ranging from nodules several feet in diameter to finely disseminated particles. (2) Once liberation has been achieved, a physical cleaning method may be used to separate the pyritic sulfur from the coal. Many coals liberate at approximately 65 mesh, but at present no cleaning device exists to remove pyritic sulfur from 65 x 0 mesh coal.

A review of the literature indicates that a small diameter hydrocyclone may be suited for separating pyritic sulfur from coal. Figure 2 shows the results of experimental work performed by Visman. (4) As the diameter of the hydrocyclone is decreased, the probable error is decreased. Figure 3 shows the results obtained for a 2.0" diameter hydrocyclone by LePage. (5) Extrapolation of the data indicates that a hydrocyclone of 1.0" in diameter would be suited for cleaning coal ranging in size from minus 28 mesh down to plus 10 microns.

A 1.0" diameter hydrocyclone was constructed from 303 stainless steel, and a number of interchangable parts were fabricated for the hydrocyclone. These parts allowed for variation of the inlet orifice diameter, the apex discharge diameter, the cone angle, the vortex finder diameter, and the vortex finder position. In addition, the feed pressure could be varied. Tests of the performance of the hydrocyclone with various combinations of parts were performed.
FIGURE 2 - PROBABLE ERRORS OF DIFFERENT DIAMETER HYDROCYCLONES
FIGURE 3 - PARTITION CURVES FOR 2" HYDROCYCLONE
The results of these tests were plotted as pyritic sulfur rejection versus the geometry of the hydrocyclone. The combination which yielded the greatest pyritic sulfur rejection value was considered the optimum configuration.
II. LITERATURE REVIEW

Definition of hydrocyclone

For the purpose of this investigation, a small diameter hydrocyclone is defined to be a steel cylinder 1.0" in diameter with a tangential feed inlet. The vortex finder extends through one closed end of the unit and an apex serves as the discharge. (6)

Factors which influence particle movement in a hydrocyclone

There are a number of factors which influence the movement of particles in a hydrocyclone. Dreissen and Fontein in their work on cyclones have determined the following factors to be of importance: (7)

1. Shape of the particles
2. Solids concentration
3. Feed pressure
4. Back pressure
5. Cyclone diameter
6. Diameter of the feed opening
7. Overflow opening
8. Apex opening
9. Length of the vortex finder
10. Cone angle
11. Specific gravity
12. Average grain size of the particles
13. Solids concentration of the inlet feed and apex discharge
14. Viscosity of the feed suspension and the liquid

Visman has stated that the diameter of the cyclone is a significant factor in determining the operating characteristics of the device. For design considerations, certain operating characteristics of the cyclone may be expressed as functions of the cyclone diameter. They are as follows, where D is the diameter of the cyclone. (8)

- Maximum particle size of coal processed \( \ldots \ldots \ldots \ldots \ldots \ldots \ldots D/10 \)
- Recommended maximum particle size (allowing for 15% oversize) \( \ldots \ldots \ldots \ldots \ldots \ldots \ldots D/10 \)
- Gravity cutpoint control is good over the specific gravity range of 1 to 2.5 for particles of greater diameter than \( \ldots \ldots \ldots \ldots \ldots \ldots \ldots D/300 \)
- The specific gravity cutpoint increases and the cutpoint range decreases as particle diameter decreases below \( \ldots \ldots \ldots \ldots \ldots \ldots \ldots D/300 \)

Theories of hydrocyclone operation

Investigators have tried to determine the mechanism of gravity separation which occurs inside of the hydrocyclone. The precise mechanism of separation in a hydrocyclone is not known at this time. A review of the literature reveals three major concepts. In general, it is held that inside of the hydrocyclone a dense medium is formed. Particles of intermediate and high specific gravity migrate to, and circulate in the conical section. These particles form a dense medium through which the lighter particles cannot penetrate. These lighter particles are entrained in the ascending vortex and report to the overflow. The refuse, composed of heavier material, is able to penetrate the dense medium and report to the underflow discharge. (9)
Fontein and Dijksman have noted that the dense medium cannot account for the separation because, in the absence of high gravity material, the low gravity fraction of the feed still reports to the overflow. They believe that the particles in a hydrocyclone are separated during their residence in the central region. While in the ascending vortex, the particles are subjected to centrifugal forces. During the initial period of acceleration, the influence of particle size on settling velocity is minimal. The equation for the centrifugal force acceleration on a particle may be expressed as follows:

\[ a = \frac{(M_p - M_f)}{M_p} \cdot \frac{V^2}{R} \]

where:

- \( a \) = acceleration of particle
- \( M_p \) = mass of the particle
- \( M_f \) = mass of fluid displaced by particle
- \( V \) = tangential velocity
- \( R \) = radius of cyclone

For particles in the same plane, this equation may be simplified and rewritten as:

\[ a = C(1 - \frac{1}{SG}) \]

where:

- \( C \) = constant
- \( SG \) = specific gravity

It may be seen that a dense particle will have a greater acceleration than a less dense particle. For example, consider a coal
particle with a specific gravity of 1.4 and a shale particle, of equal size, with a specific gravity of 2.6. The acceleration of the coal particle is 0.286C, while the acceleration of the shale particle is 0.615C. Therefore, the dense particle is more likely to migrate out of the ascending vortex and report to the apex discharge.

A basic flaw in this theory is that it is only applicable to the larger-sized particles. For very fine particles, the drag of the fluid cannot be neglected. For the larger particles the time required for fluid drag to influence particle movement is more than the time required for the movement of these particles to their proper product stream. The very small particles, however, tend to report to the clean-coal overflow. (10)

G. Tarjan presents a differing viewpoint. He proposes that a plane exists within the hydrocyclone in which equal size and specific gravity particles are in equilibrium with respect to centrifugal mass and centripetal drag forces. (11) Figure 4 shows the location of these planes for a hypothetical case. The higher density particles accumulate along the inner wall of the hydrocyclone. Tarjan postulates that this amassment of particles functions as a dense medium. It is this mechanism which is responsible for the gravity separation in a hydrocyclone. It is important to note the line \( v_a = 0 \), on Figure 4, which represents the points where the axial velocity equals zero. According to Tarjan this is the boundary between those particles which will report to the overflow and those which will report to the underflow discharge. The solids in equilibrium at this point give the limit
FIGURE 4 - CROSS SECTION OF HYDROCYCLONE SHOWING TARJAN'S EQUILIBRIUM PLANES
grain size of the separation. The specific gravity of the medium formed is the specific gravity of separation. Tarjan's theory does not explain separations at densities higher than 1.6. Such separations have been found to exist by other investigators. (12)

Visman feels that the mechanism of separation in a hydrocyclone is similar to that of the rheolauver. He assumes that the particles stratify into a bed according to specific gravity along the inner wall of the cone. This bed forms a barrier to the passage of large particles of low density which cannot penetrate this bed, and these large particles of low density then report to the overflow. The fine particles of higher density are also unable to penetrate the bed and report to the overflow. The large particles of high specific gravity report to the apex discharge. (13)

Two types of hydrocyclones

Hydrocyclones may be divided into two categories: those which classify particles on the basis of size and those which separate particles on the basis of specific gravity. The main difference between the two types of hydrocyclones is the geometry of the cone. Classifying hydrocyclones have very steep cone angles. The angle of the cone is greater than 60 degrees. Hydrocyclones which perform a separation on the basis of specific gravity are characterized by cones with angles of around 40 degrees. (13)

Findings of Visman and LePage

J. Visman has worked extensively on the application of hydro-
cyclones to the beneficiation of coal. Figure 2 shows probable errors for the various size fractions of coal processed through different size hydrocyclones. Probable error is defined as one half of the specific gravity interval spanned by the distribution curve in passing from the 25 per cent to the 75 per cent recovery ordinates. (14) A good, or sharp, separation has a low probable error. Figure 2 shows that as the diameter of the hydrocyclone is decreased, smaller particles of coal may be efficiently cleaned. Extrapolation of this data indicates that a 1.0" diameter hydrocyclone will effectively clean minus 65 mesh coal.

LePage has also used hydrocyclones to process run-of-mine fine coal. Figure 3 shows partition curves for various size fractions of coal plotted against specific gravity. The results are for a 2.0" diameter hydrocyclone. (5) A partition coefficient is the weight of a specific gravity fraction in a product stream divided by the total weight in that specific gravity fraction in the feed. Figure 3 is a plot of the overflow or clean coal partition coefficient. This figure shows that a 2.0" diameter hydrocyclone can effectively clean 10 x 120 mesh coal.

The above data indicate that a 1.0" diameter hydrocyclone may be suited for cleaning minus 65 mesh coal. Pyritic sulfur will be liberated in minus 65 mesh coal. The specific gravity of pyrite ranges from 4.95 to 5.17. (15) Therefore, the pyritic sulfur should report with the ash to the refuse product stream.
III. PURPOSE OF THE INVESTIGATION

Coal fired electric generating stations are a major source of oxides of sulfur. State regulatory agencies have adopted strict emission standards which require the burning of low sulfur coal in order to achieve compliance. Since few coal seams meet the required sulfur standards, it is necessary to remove the excess sulfur during the beneficiation process. Of the three forms of sulfur found in coal, only pyrite may be removed by a physical cleaning method. No cleaning device exists to separate pyritic sulfur from fine coal; accordingly it is necessary to develop an economical and reliable device to remove pyritic sulfur from 65 x 0 mesh coal.

Partition curve data for larger hydrocyclones indicated that a 1.0" hydrocyclone may be suitable for removing pyrite from 65 x 0 mesh coal. Therefore, a 1.0" diameter stainless steel hydrocyclone with interchangable parts was constructed and various combinations of the components were tested. The configuration which yielded the maximum pyritic sulfur rejection was considered the optimum.

The large number of data points required for an optimization study required that a new technique be developed to replace the time-consuming conventional float-sink method of determining partition coefficients. A magnetically tagged tracer material was introduced into the system. A data point on the partition curve could be obtained in a few minutes by comparing the amount of tracer material in the overflow product to the amount present in the underflow.

If successful, this project would have tremendous impact in the
electric utility and mining industries. Coal companies with reserves in coal seams which do not presently meet the sulfur requirements would be able to market these coals at an attractive price to power generating stations.

The magnetic tracer method of obtaining partition curve data will have great impact on the mining equipment industry. Designing and testing of new cleaning equipment will be facilitated by use of this technique. Preparation plant operators will be able to rapidly optimize plant performance to meet variations in the feed to the plant.

If the preliminary results of the investigation are encouraging, the next phase would involve a pilot plant installation of a hydrocyclone system. Should the pilot plant prove successful, full scale industrial trials would follow.

With further research and development, it would be possible to develop the magnetic tracer technique into a continuous monitoring device. By combining a process control computer with the magnetic sensing device, it would be possible to automate a coal preparation plant. This would allow the plant to be rapidly adjusted to changes in the composition of the feed and result in greater efficiency of plant operation.
IV. THE HYDROCYCLONE

Background

The hydrocyclone was developed by Fontein, and United States Patent, number 2,573,192, describes his invention. The Dutch State Mines, an independently operated corporation owned by the Netherlands, was an early leader in developing and distributing hydrocyclone systems. Significant work has been done in the field by the Australian Coal Research Laboratory, Ltd. Recently, Cyclones, Ltd. has entered the field and is marketing small diameter hydrocyclones. However, no application has yet been made of the hydrocyclone to the problem of removal of pyritic sulfur from coal.

Materials of construction

The best material from which to construct a hydrocyclone is 303 stainless steel. 303 stainless steel has excellent resistance to corrosion. This corrosion resistance is necessary because the intake water to a cleaning plant may be high in acidity and have a low pH. In addition, the pyritic sulfur may react in the plant circuits to produce acid water. Stainless steel also possesses excellent wear characteristics, which is necessary because the fine coal-water slurry is highly abrasive.

An alternate material of construction would be a corrosion resistant plastic with high abrasion resistance. The major advantage of plastic is the ease of fabrication, which will significantly lower the unit cost for individual hydrocyclones.
The need for a hydrocyclone

Current preparation plant practice is to treat fine coal in froth flotation cells. Problems associated with such cells fall into three main categories: operation, economics, and size. For efficient operation the feed to the flotation cell must be uniform. The cell is conditioned to handle one type of coal, and this means that the plant can handle only one type of coal. If the coal is oxidized, flotation ceases, and the water to the cell must be free of organic material that would interfere with the flotation process. The costs associated with froth flotation cells are high, and the capital investment required is high. Maintenance costs are high, as periodic replacement of the skimmers, troughs, and other parts is required. The cost of reagents must also be considered. Finally, if the cell fails, the whole plant operation must be stopped. This plant stoppage will result in a large amount of lost revenue. Finally, froth flotation cells require much space. A smaller system would result in a smaller, less expensive preparation plant.

Hydrocyclones do not have the problems discussed above. First, the mechanism of the hydrocyclone is gravity separation, and the gravity of separation of the hydrocyclone can be rapidly changed by adjusting the vortex finder depth. This means one preparation plant can handle a blend of coals, or different coals at different times. Because the mechanism of separation is gravity, oxidized coal presents no problems. The initial cost of the hydrocyclone system is less than for a froth flotation cell system. Because there are no moving parts,
maintenance costs are less. Reagent costs for the hydrocyclone are zero as none are required. If one hydrocyclone goes down, plant operation continues because other hydrocyclones are on line. A new hydrocyclone could be installed within minutes. Because of their small size and weight, it is possible to stack hydrocyclones. This results in less space being required for an equivalent hydrocyclone system than for a froth flotation system, and in a smaller, less expensive preparation plant.

Disadvantages of the hydrocyclone

The hydrocyclone has some disadvantages associated with it. The major disadvantage is that as the amount of near gravity material (defined as plus or minus 10 per cent specific gravity at the gravity of separation) increases to a quantity above 10 per cent, the sharpness of the separation decreases rapidly. Occasionally a hydrocyclone will clog, but this could be remedied by vibrating the unit or applying abck pressure. Finally, pumping costs are higher for hydrocyclones than for conventional froth flotation cells.
V. EXPERIMENTAL MATERIAL AND EQUIPMENT

Synthetic material

It was decided to use synthetic material in place of actual coal. The synthetic material was harder than coal and would not degrade into finer particles when it was used repeatedly for testing purposes. The synthetic material was constructed so as to duplicate coal with respect to specific gravity, size, and particle shape. It was compounded as follows:

Casting resin, specific gravity 1.24, was impregnated with barium sulfate which has a specific gravity of 4.7. Various ingots of material of specific gravities 1.2 - 1.3, 1.3 - 1.4, 1.4 - 1.5, 1.5 - 1.6, 1.6 - 1.7, 1.7 - 1.8, 1.8 - 1.9, were compounded. The formulas used were:

\[ CZ = W \]
\[ 1.24x + 4.7(z - x) = W \]
\[ R = 1.24x \]
\[ BS = 4.7(z - x) \]

where:

\( C \) = desired specific gravity of mixture
\( Z \) = volume of mixture in cubic centimeters
\( W \) = total weight of mixture in grams
1.24 = specific gravity of casting resin
4.7 = specific gravity of barium sulfate
\( R \) = required weight of resin in grams
\( BS \) = required weight of \( \text{BaSO}_4 \) in grams.
The resin was measured into an enamelled pan. The barium sulfate (minus 200 mesh) was sifted into the resin. The resin catalyst was then added. The mixture was agitated with a hand-held electric mixer until it began to set up. The agitation was required to prevent the barium sulfate from settling out before the mixture hardened. Approximately one hour elapsed between the addition of the catalyst and the setting up of the mixture.

After the mixture had hardened, it was crushed and ground. The ingots were first broken with a hammer into minus 3 inches top size. These pieces were then crushed in the Deco laboratory jaw crusher. After processing through the jaw crusher, the fragments were further reduced in the American Pulverizer hammer mill. During the crushing process it was necessary to mix dry ice with the fragments to be processed. This was due to the fact that the barium sulfate - casting resin ingots tended to deform rather than crush at room temperature.

The product from the hammer mill was screened in Tyler screens. The minus 65 mesh material was then separated by the float - sink technique at the desired specific gravity range to insure that no material outside of the specific gravity range was present. The finished material was placed in appropriately labeled containers. This was the material used to simulate the solids portion of the feed slurry.

Tagged material

To eliminate the need for float - sink operations to determine each data point on the partition curve, it was decided to use a
tracer. The tracer material consisted of a mixture of casting resin and magnetite, $\text{Fe}_3\text{O}_4$. The resulting material was identical with the synthetic coal material, except for the fact that it was strongly magnetic. The tagged material was compounded in the following specific gravities: 1.2 - 1.3, 1.3 - 1.4, 1.4 - 1.5, 1.5 - 1.6, 1.6 - 1.7, 1.7 - 1.8, 1.8 - 1.9. After crushing and float - sink separation by the procedure previously described, each specific gravity fraction was screened in Tyler screens into the following size fractions: 65 x 100 mesh, 100 x 150 mesh, 150 x 200 mesh and minus 200 mesh.

The hydrocyclone

The one inch diameter hydrocyclone was constructed of 303 stainless steel. 303 stainless steel was chosen because it is more easily machined than other stainless steel alloys and is resistant to abrasion and corrosion. The cyclone was constructed in such a manner that its configuration was easily variable. The following parts were fabricated:

- **Vortex finder inner diameters** 0.375", 0.250", 0.125"
- **Apex discharge diameters** 0.125", 0.145", 0.250", 0.375"
- **Inlet diameters** 0.125", 0.250", 0.367"
- **Cone angles** 20°, 40°, 60°

Figures 5 through 10 are shop drawings of the various component parts. Tolerances of ± 0.001 inches were held.
FIGURE 5 FRONT VIEW HYDROCYCLONE
FIGURE 6 - TOP VIEW OF HYDROCYCLONE
FIGURE 8 - CONE DETAIL
FIGURE 9 - APEX AND PARTITION DETAIL
The pump

A Lawrence centrifugal pump was used in this investigation. A centrifugal pump was chosen because of its inherent high degree of reliability and ease of maintenance. Because rust would interfere with the evaluation of the partition coefficients, the pump head, volute, impeller, and housing were cleaned with concentrated sulfuric acid and spray painted with epoxy paint. At the end of this investigation, observation revealed the epoxy coating to be intact.

The motor

The pump was driven by a direct coupled U. S. Vari-Drive Westinghouse Electric Motor. The motor was a 5 horsepower, 220 volt, 3 phase unit. The variable speed aspect aided in maintaining the exact desired pressure.

The gauge

A Duragaug e 0 to 30 psig diaphragm gauge was chosen. A diaphragm gauge was required because the slurry would clog a conventional gauge and render it inoperable.

The pipe

It was decided to use polyvinyl chloride Schedule 40 (ASTM) pipe. The advantages of plastic pipe are its ease of fabrication and its non-rusting properties. The principal disadvantage is its lack of rigidity. This necessitated scaffolding to support the pipe.
The valves

Bronze 1/2" gate valves were used in this experiment. Gate valves were preferred because they will seat even when the fluid is a slurry.

The magnetic separator

A Carpco Magnetic Separator serial number MWL3465 - 115 was used to remove the magnetically tagged material at the end of each run. This machine is a high intensity magnetic separator. A steel cage, which held steel ball bearings, sat between the pole pieces. The cage and balls were painted with epoxy paint to prevent rusting. A fluid stream containing the magnetic particles was directed through the balls. The magnetic particles were retained on the balls, while the rest of the slurry was returned to the reservoir. Figure 11 is a diagram of the system used in this experiment.
FIGURE 11 - EXPERIMENTAL SETUP
VI. EXPERIMENTAL PROCEDURE

Three coals tested

It was decided to optimize the hydrocyclone for three coals. Washability studies of a "light" coal, a "medium" coal, and a "heavy" coal were found in the literature. A Virginia Pocahontas #3 was selected as the light coal because most of its weight was in the 1.3 or lighter specific gravity fractions. The medium coal chosen was the Hagy seam found in Virginia. Most of its weight lies in the 1.4 - 1.5 specific gravity fraction. A coal from the Cortes area in New Mexico was selected as the heavy coal. Most of its weight is greater than 1.6 in specific gravity. Figure 12 shows the comparison by weight of these three coals. Tables 2, 3, and 4 show the washability data for the three coals. By optimizing the hydrocyclone for these three coals, it should be possible to extend the results of this investigation to any type of coal.

Mixing of slurry

After the coal to be investigated was chosen, it was necessary to mix a 10 per cent by weight slurry. It was decided to operate the system with 5400 milliliters of water. Therefore, 600 grams of solids were required. The 600 grams were added on a percentage basis to duplicate the specific gravity distribution of the selected coal. The solids exhibited a tendency to form a stable froth. To eliminate this froth, 3 milliliters of Dowell M - 45 defoamer, and 2 milliliters of Dowell F - 65 wetting agent were added to the system.
FIGURE 12 - COMPARISON OF WEIGHT DISTRIBUTION OF THE THREE COALS
<table>
<thead>
<tr>
<th>Specific Gravity</th>
<th>Weight in grams</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Float - 1.3</td>
<td>312</td>
<td>52.0</td>
</tr>
<tr>
<td>1.3 - 1.4</td>
<td>228</td>
<td>38.0</td>
</tr>
<tr>
<td>1.4 - 1.5</td>
<td>30</td>
<td>5.0</td>
</tr>
<tr>
<td>1.5 - 1.6</td>
<td>6</td>
<td>1.0</td>
</tr>
<tr>
<td>1.6 - 1.7</td>
<td>6</td>
<td>1.0</td>
</tr>
<tr>
<td>1.7 - 1.8</td>
<td>6</td>
<td>1.0</td>
</tr>
<tr>
<td>1.8 - 1.9</td>
<td>6</td>
<td>1.0</td>
</tr>
<tr>
<td>1.9 - Sink</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>Weight in grams</td>
<td>Percentage</td>
</tr>
<tr>
<td>-----------------</td>
<td>----------------</td>
<td>------------</td>
</tr>
<tr>
<td>Float - 1.3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1.3 - 1.4</td>
<td>12.0</td>
<td>2.0</td>
</tr>
<tr>
<td>1.4 - 1.5</td>
<td>378.0</td>
<td>63.0</td>
</tr>
<tr>
<td>1.5 - 1.6</td>
<td>72.0</td>
<td>12.0</td>
</tr>
<tr>
<td>1.6 - 1.7</td>
<td>54.0</td>
<td>9.0</td>
</tr>
<tr>
<td>1.7 - 1.8</td>
<td>24.0</td>
<td>4.0</td>
</tr>
<tr>
<td>1.8 - 1.9</td>
<td>6.0</td>
<td>1.0</td>
</tr>
<tr>
<td>1.9 - Sink</td>
<td>48.0</td>
<td>9.0</td>
</tr>
</tbody>
</table>
TABLE 5 - FLOAT SINK ANALYSIS OF NEW MEXICO COAL

<table>
<thead>
<tr>
<th>Specific Gravity</th>
<th>Weight in grams</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Float - 1.3</td>
<td>7.2</td>
<td>1.2</td>
</tr>
<tr>
<td>1.3 - 1.4</td>
<td>78.6</td>
<td>13.1</td>
</tr>
<tr>
<td>1.4 - 1.5</td>
<td>94.8</td>
<td>15.8</td>
</tr>
<tr>
<td>1.5 - 1.6</td>
<td>81.1</td>
<td>13.6</td>
</tr>
<tr>
<td>1.6 - 1.8</td>
<td>70.8</td>
<td>11.8</td>
</tr>
<tr>
<td>1.8 - Sink</td>
<td>267.5</td>
<td>44.5</td>
</tr>
</tbody>
</table>
VII. ANALYSIS OF RESULTS

Tagged material method verses float - sink technique

At the beginning of this investigation, it was necessary to prove that the use of tagged material to obtain partition coefficients yielded the same results as the conventional float - sink method. Ten data points were taken on different specific gravity fractions using the magnetic method. These ten data points were repeated using conventional float - sink techniques to obtain the data points. The two samples were tested using the statistical Student's t test. The results indicated that for an alpha of 0.05 the two methods yielded identical results. This proof is shown in Appendix A.

Repeatability of data points using tagged material method

After it was shown that the tagged material method yielded results which compared favorably with those obtained by float - sink analysis, it was necessary to insure that the data points were reproducible. Thirteen paired observations were taken. Statistical manipulation of the data using the Student's t test showed that for an alpha of 0.00 the data were reproducible. This proof is shown in Appendix B.

Parameters that were investigated

It was not possible to examine all of the numerous parameters which influence the performance of a hydrocyclone. Therefore, it was necessary to restrict this investigation to those parameters which
exercise a major impact on the system. Possible parameters which could have been investigated included:

1. apex diameter to vortex finder diameter ratio
2. slurry density
3. inlet diameter
4. pressure
5. cone angle
6. vortex finder position

It was decided to restrict this investigation to items 3, 4, 5, and 6.

The apex diameter to the vortex finder diameter ratio was felt not to be a critical factor. Weyher has stated that changing this ratio has a most pronounced effect on the separation. (12) The author found this to be correct during the initial familiarization runs. However, there is an extremely limited range in which the cyclone will function. With a very low ratio, no cycloning action took place. When the ratio was high, most of the material reported to the underflow product stream. Therefore, it was decided to run the hydrocyclone at the ratio which yielded the highest recovery of clean coal, while still maintaining the cyclone action. For this investigation this ratio was determined to be 0.38. This compares well with the ratio given by Weyher of 0.35 for a 5.5" diameter hydrocyclone. (19)

It was decided not to investigate the slurry density. Sands and Weyher have intensively investigated the effect of slurry density on the separation obtained with a hydrocyclone. (20) (19) They have shown that as the density of the slurry was increased, the gravity of separation was increased. It was decided to run the experimental
system at a 10 per cent slurry ratio by weight. This is the upper limit suggested by Weyher. A higher density of solids would increase the chances of clogging the hydrocyclone.

It was decided to investigate the effect of feed pressure. An increase in feed pressure was accompanied by an increase in throughput capacity. The adjustment of the inlet feed pressure provided a simple method of varying the feed to the hydrocyclone unit. This would allow control of the hydrocyclone to meet changes in rate or feed composition to a coal cleaning plant. The pressures investigated were 6 psig, 10 psig, and 15 psig. This compared well with the limits of 8 to 15 psig established by Weyher for 2" to 4" diameter hydrocyclones.

The cone angle has long been known to exert a great effect on the performance of a hydrocyclone. Visman stated that hydrocyclones with steep cone angles act as classifying hydrocyclones. That is, they separate the particles by size and not by differences in specific gravity. He found that low cone angles caused the hydrocyclone to separate the particles on the basis of specific gravity. Cone angles of 20 degrees, 40 degrees, and 60 degrees were investigated.

The effect of the position of the vortex finder with respect to the bottom of the unit was investigated. Weyher and Lovell found that the yields and ash values were heavily influenced by this parameter. They found that yield and ash increased as the vortex finder approached the bottom of the cone. As the purpose of this investigation was to maximize the pyritic sulfur rejection, it was necessary to investigate this parameter. Vortex finder positions, measured from the top of the outside of the unit, of 2.470 inches, 2.770 inches, 3.070 inches,
and 3.370 inches were investigated.

All of the data points taken during the course of this investigation may be found in Appendix C.

Preliminary data points

A number of data points was taken early in the course of this investigation. The purpose of these points was to gain familiarity with the system in general and the hydrocyclone in particular. For example, certain configurations of the hydrocyclone prevented the cycloning action from occurring. (See Figure 13.) In this case, it was found that the ratio of the apex discharge to the vortex finder diameter was too low. Other configurations resulted in no separation. Figure 14 shows that when the apex diameter exceeds the vortex finder diameter, most of the solids report to the underflow.

Pocahontas #3 coal simulation

The first stage of this investigation involved the simulation of the Pocahontas #3 coal. Pocahontas #3 is a coal which has most of its material in the lighter specific gravity fractions. (See Table 2.) In a float - sink analysis performed by Shelton, over 96 per cent of the material was lighter than 1.5 in specific gravity. (16) This coal served as the light endpoint for the purpose of the investigation.

The results of the variation of the vortex finder are shown in Figure 15. The four curves follow a basic trend. The rejection of pyritic sulfur first increases as the vortex finder is moved further away from the cone. This was consistent with the findings of Weyher...
DATE: 1/3/75
TIME: 9:00 a.m.
PERSONNEL: L. Amundson, E. Loud
COAL NUMBER: #1 Pocahontas #3
SPECIFIC GRAVITY UNDER INVESTIGATION: 1.2 - 1.3 65 x 100 mesh

BODY LENGTH: 3"
INLET DIAMETER: 0.375"  Overflow Volume in ml 900
CONE ANGLE: 40°  Underflow Volume in ml 0
VORTEX FINDER: 0.375"  Time in seconds 4.0
APEX DISCHARGE: 0.125"
PRESSURE: 6 psi
SLURRY DENSITY: 10 %
VORTEX FINDER POSITION: 2.770"

WT. OF TAGGED MATERIAL IN OVERFLOW: ----
WT. OF TAGGED MATERIAL IN UNDERFLOW: ----

PARTITION COEFFICIENT: ----

With this geometry no cycloning action occured

Figure 13 - Geometry of Hydrocyclone When no Separation Occurred
DATE: 1/3/75  
TIME: 3:00 p.m.  
PERSONNEL: L. Amundson, W. D. Bays  
COAL NUMBER: #1 Pocahontas #3  
SPECIFIC GRAVITY UNDER INVESTIGATION: 1.3 - 1.4 65 x 100  

BODY LENGTH: 3.0"  
INLET DIAMETER: 0.375"  
CONE ANGLE: 40°  
VORTEX FINDER: 0.250"  
APEX DISCHARGE: 0.375"  
PRESSURE: 6 psi  
SLURRY DENSITY: 10 %  
VORTEX FINDER POSITION: 2.770"  

Overflow Volume in ml 340  
Underflow Volume in ml 760  
Time in seconds 6.0  

WT. OF TAGGED MATERIAL IN OVERFLOW: 0.1408 g  
WT. OF TAGGED MATERIAL IN UNDERFLOW: 0.4783 g  

PARTITION COEFFICIENT: 22.7  

Figure 14 - Geometry of Hydrocyclone With Most Solids Reporting to Underflow
BODY LENGTH 3"
PRESSURE 6 psi
DENSITY 10%
CONE ANGLE 40°
INLET DIA. .375"
VORTEX DIA. .250"
APEX DIA. .145"
S.G. 4.7-5.1

FIGURE 15 - VARIATION OF VORTEX FINDER POSITION POCOHONTAS *3 COAL
They noted a decreasing recovery of ash as the vortex finder was raised. As the vortex finder was further raised, the rejection of pyritic sulfur was decreased. The author felt that this was due to short-circuiting of material. The vortex finder has been raised above the point where the particles had reached the wall and had been classified. No confirmation or rejection of the hypothesis was found in the literature.

It is important to note the fact that the pyritic sulfur rejection decreased with decreasing particle size. Good rejection was achieved with the 65 x 100 mesh size and the 100 x 150 mesh size material, yielding 98.3 per cent and 92.2 per cent pyritic sulfur rejection, respectively. The results for the 150 x 200 mesh size fraction were acceptable, resulting in 87.3 per cent pyritic sulfur rejection. The results for the minus 200 mesh size fraction were poor. Only 29.9 per cent of the pyritic sulfur reported to the apex discharge. This indicated that the one inch diameter hydrocyclone was too large to effectively handle material of this size. A smaller diameter hydrocyclone could perform a better separation on this material.

Figure 16 shows the results of the variation of the inlet diameter. The 0.250 inch inlet gave the best results. The pyritic sulfur rejection was 92.6 per cent for the 65 x 100 mesh size fraction, 91.5 per cent for the 100 x 150 mesh size fraction, 70.5 per cent for the 150 x 200 mesh size fraction, and 28.8 per cent for the minus 200 mesh size fraction.

As the inlet diameter was decreased, the pyritic sulfur rejection decreased. This may be due to the fact that the hydrocyclone was
BODY LENGTH 3"
PRESSURE 10 psi
DENSITY 10%
CONE ANGLE 40°
VORTEX DIA. .250"
VORTEX POS. 3.370"
APEX DIA. .145"
S.G. 4.7-5.1

FIGURE 16 - VARIATION OF INLET DIAMETER POCOHONTAS #3 COAL
underloaded. If this was so, the dense bed would not have developed as fully as it did when more material was present. No reference was found to this phenomena in the literature. Throughput capacity was substantially decreased at this smaller inlet diameter.

As the diameter of the inlet was increased to 0.375 inches from 0.250 inches, the rejection of the pyritic sulfur was decreased. This was due to the fact that as the throughput capacity was increased, the dense bed that formed along the inner wall of the hydrocyclone increased in thickness. This in turn resulted in an increase in the gravity of separation. Sands and Weyher have observed this fact.\(^{(20)}\) As the gravity of separation increased, the chances of entraining some pyritic particles increased.

These data show that the 1.0" diameter hydrocyclone could effectively remove pyrite from 65 x 150 mesh coal. The results of the tests on the 150 x 200 mesh size fraction were not as good. The 1.0" diameter hydrocyclone was not suited for cleaning the minus 200 mesh size fraction for this type coal.

Variations of the inlet pressure were investigated. The response of the hydrocyclone to inlet pressures of 6 psig, 10 psig, and 15 psig was observed. Figure 17 is a graph of these results. The best results were obtained at a pressure of 10 psig. This compared well with the limits of 8 to 15 psig for a 2.0" to 4.0" diameter hydrocyclone suggested by Weyher.\(^{(19)}\) At 6 psig the rejection of the pyrite was decreased. It may have been due to the fact that the inlet pressure was too low to give the particles the acceleration required to classify them according to specific gravity. At 15 psig the rejection of
S.G.  4.7 - 5.1
BODY LENGTH  3"
DENSITY  10%
CONE ANGLE  40°
INLET DIA.  .375"
VORTEX DIA.  .250"
VORTEX POS.  3.370"
APEX DIA.  .145"

FIGURE 17 - VARIATION OF PRESSURE POCOHONTAS #3 COAL
pyritic sulfur was decreased. This may be explained by the fact that the denser bed formed resisted penetration by the pyritic sulfur particles. This allowed the pyritic sulfur to become entrained in the vortex finder stream. (20)

The pyritic sulfur rejection was 92.5 per cent for the 65 x 100 mesh size fraction, 85.9 per cent for the 100 x 150 mesh size fraction, 70.8 per cent for the 150 x 200 mesh size fraction, and 25.8 per cent for the minus 200 mesh size fraction.

Three cone angles were investigated. The three cones measured 20 degrees, 40 degrees, and 60 degrees. The best results were obtained with the 40 degree cone. According to Visman, the best results were expected with a relatively flat cone. (13) The pyritic sulfur rejection was 92.5 per cent for the 65 x 100 mesh size fraction, 85.9 per cent for the 100 x 150 mesh size fraction, 70.8 per cent for the 150 x 200 mesh size fraction, and 25.8 per cent for the minus 200 mesh size fraction. These results are shown in Figure 18.

The flatter cone, the 20 degree cone, yielded decreased pyritic sulfur rejection. It may be that the thickness of the bed formed with this cone decreased the distance between the bed and the vortex finder current.

The 60 degree cone also yielded decreased pyritic sulfur rejection. This is due to the fact that 60 degrees is starting to approach the steeper cones which are found in classifying hydrocyclones. Visman states that the steep cones form very thin beds with no stratification. Therefore, the smaller particles, regardless of their specific gravity tend to report to the overflow product stream.
BODY LENGTH 3"
PRESSURE 10 psi
DENSITY 10 %
INLET DIA. 0.375"
VOXETX DIA. 0.250"
VOXETX POS. 3.370"
APEX DIA. 0.145"
S.G. 4.7 - 5.0

**Figure 18 - Variation of Cone Angle Pocahontas #3 Coal**
Figure 19 shows the partition recovery curves for the four size fractions. These curves were taken at the configuration which yielded the best pyritic sulfur rejection. This figure shows the trend of the smaller particles to report to the vortex finder product stream.

Hagy coal simulation

The second coal simulated was the Hagy seam. The washability study data performed by the author is shown in Table 3. The Hagy seam has the majority of its weight, 75 per cent, in the 1.4 - 1.6 specific gravity range. This coal served as the medium weight coal.

The results of the variation of the vortex finder position are shown in Figure 20. The curves for the four size fractions showed the same basic trend. When the vortex finder was at its highest point away from the cone, the pyritic sulfur rejection was at its lowest value. Short-circuiting of the material was probably responsible for this. As the vortex finder is moved closer to the cone, the pyritic sulfur rejection was increased. At the 2.770 inch position, the best pyritic sulfur rejection values were obtained. They are: 95.9 per cent for the 65 x 100 mesh size fraction, 80.6 per cent for the 100 x 150 mesh size fraction, 75.0 per cent for the 150 x 200 mesh size fraction, and 57.6 per cent for the minus 200 mesh size fraction. When the vortex finder was moved closer to the cone, to 3.070 inches, the pyritic sulfur rejection decreased. Other researchers have noted an increase in ash recovery as the vortex finder approached the cone. When the vortex finder was moved to its closest point to the cone, even more pyritic sulfur reported to the overflow product.
VORTEX POS. 2.770"
BODY LENGTH 3"
PRESSURE 6 psi
DENSITY 10%
INLET DIA. .375"
APEX DIA. .145"
VORTEX DIA. .250"
CONE ANGLE 40°

FIGURE 19 - RECOVERY PARTITION CURVES POCAHONTAS #3 COAL
BODY LENGTH 3"
PRESSURE 6 psi
DENSITY 10%
CONE ANGLE 40°
INLET DIA. .375"
VORTEX DIA. .250"
APEX DIA. .145"
S.G. 4.7-5.1

FIGURE 20—VARIATION OF VORTEX FINDER POSITION
HAGY COAL
The results of the variation of the inlet diameter are plotted on Figure 21. For the three finer sizes, the best results were obtained at the 0.250 inch inlet diameter. These results were 93.6 per cent rejection for the 100 x 150 mesh size fraction, 80.8 per cent for the 150 x 200 mesh size fraction, and 73.8 per cent for the minus 200 mesh size fraction. The best results for the 65 x 100 mesh size fraction were obtained at the 0.375 inch inlet diameter. However, it is felt that the 0.250 inch inlet diameter point is in error for the 65 x 100 mesh size fraction. This was reinforced by the fact that the value of the 100 x 150 mesh size fraction point, 93.6 per cent rejection, is approximately equal to the value of the 65 x 100 mesh point, 93.4 per cent rejection. If this premise was correct, then this graph followed the same trend as the Pocahontas coal.

As the diameter of the inlet increased to 0.375 inch, the pyritic sulfur rejection was decreased. Increasing the inlet diameter increased the throughput capacity. This caused the bed which formed along the inner cone wall to increase in thickness. This resulted in an increase in the gravity of separation. Sands has observed this fact. (20) As the gravity of separation increased, more pyritic sulfur reported to the overflow.

Decreasing the inlet diameter to 0.125 inch from 0.250 inch resulted in an increase in the amount of pyritic sulfur which reported to the overflow. This may be due to the fact that the hydrocyclone was underloaded. This prevented the dense bed from completely developing and resulted in more pyritic sulfur reporting to the overflow. No
BODY LENGTH 3"
PRESSURE 10 psi
DENSITY 10%
CONE ANGLE 40°
VORTEX DIA. .250"
VORTEX POS. 3.370"
APEX DIA. .145"
S.G. 4.7-5.1

FIGURE 21 - VARIATION OF INLET DIAMETER HAGY COAL
confirmation or rejection of this hypothesis was found in the literature. The throughput capacity of the hydrocyclone was substantially reduced at this inlet diameter.

Three inlet pressures were investigated. Figure 22 shows the response of the hydrocyclone at 6 psig, 10 psig, and 15 psig. The best results were obtained at an inlet pressure of 10 psig. The pyritic sulfur rejection was 95.9 per cent for the 65 x 100 mesh size fraction, 86.2 per cent for the 100 x 150 mesh size fraction, 75.7 per cent for the 150 x 200 mesh size fraction, and 67.5 per cent for the minus 200 mesh size fraction.

At a pressure of 6 psig the pyritic sulfur rejection was decreased. The author felt that this was because the particles had not received sufficient acceleration to classify them according to specific gravity.

At a pressure of 15 psig, the capacity of the unit was increased. This resulted in the formation of a denser bed along the inner wall of the cone. This caused an increase in the gravity of separation. With a higher gravity of separation, more pyritic sulfur particles reported to the overflow product stream. This was confirmed by the findings of Sands. (20)

Cone angles of 20 degrees, 40 degrees, and 60 degrees were examined with respect to their influence on pyritic sulfur rejection. It was anticipated that the best results would occur with a relatively flat cone. (13) The 40 degree cone yielded the best pyritic sulfur rejection. The results showed rejections of 96.9 per cent for the 65 x 100 mesh size fraction, 86.2 per cent for the 100 x 150 mesh size fraction, 75.7 per cent for the 150 x 200 mesh size fraction, and 67.5
S.G. 4.7 - 5.1
BODY LENGTH 3"
DENSITY 10%
CONE ANGLE 40°
INLET DIA. .375"
VORTEX DIA. .250"
VORTEX POS. 3.370"
APEX DIA. .145"

FIGURE 22 - VARIATION OF PRESSURE HAGY COAL
per cent for the minus 200 mesh size fraction. The bed which formed at this cone angle was thin enough so that there was sufficient clearance between it and the vortex finder. It was, at the same time, thick enough so that the hydrocyclone performed a separation by specific gravity and not by size. Figure 23 shows the results of this investigation.

The flatter, 20 degree cone, yielded decreased pyritic sulfur rejection. This was due to the fact that the thickness of the bed decreased the distance between it and the vortex finder. This caused more of the pyritic sulfur particles to report to the overflow.

The 60 degree cone also yielded decreased pyritic sulfur rejection. This cone is steep enough that the hydrocyclone was starting to respond as a classifying hydrocyclone. According to Visman the steeper cones form thin beds with no stratification. Therefore, the smaller particles tended to report to the overflow no matter what their specific gravity.

Figure 24 shows the recovery partition curves of clean coal for the Hagy coal. These points were taken at the configuration which yielded the best pyritic sulfur rejection. The curves show that the finer sized fractions tend to report to the overflow product stream.

New Mexico coal simulation

The third coal investigated was from the Cortes area in New Mexico. The coal seams in this area are currently under investigation and little data is available on them at this time. Washability studies reported by Duerbrock are shown in Table 4. This coal is extremely heavy. Over
BODY LENGTH 3"
PRESSURE 10 psi
DENSITY 10%
INLET DIA. .375"
VOXETX DIA. .250"
VOXETX POS. 3.370"
APEX DIA. .145"
S.G. 4.7 - 5.0

FIGURE 23 - VARIATION OF CONE ANGLE HAGY COAL
VORTEX POS. 2.770"  
BODY LENGTH 3"  
PRESSURE 6 psi  
DENSITY 10%  
INLET DIA. .375"  
APEX DIA. .145"  
VORTEX DIA. .250"  
CONE ANGLE 40°

FIGURE 24 - RECOVERY PARTITION CURVE HAGY COAL
69 per cent of its weight has a specific gravity greater than 1.5. This coal will serve as the heavy endpoint in this investigation.

The response of the hydrocyclone with respect to the location of the vortex finder is shown in Figure 25. For the three coarser size fractions, the best results were obtained at the 3.070 inch vortex finder position. The pyritic sulfur rejections were 87.7 per cent for the 65 x 100 mesh size fraction, 83.9 per cent for the 100 x 150 mesh size fraction, and 76.6 per cent for the 150 x 200 mesh size fraction. The vortex finder position is closer to the cone than the optimum position found for the previous, lighter coals. This may be explained by the fact that the New Mexico coal is significantly heavier. A greater residence time was required for this coal to be classified by specific gravity because of the large number of heavy particles. It is felt that they physically interfered with each other while they were being classified according to specific gravity.

As the vortex finder was raised, to the 2.770 inch position, short-circuiting occurred. This caused an increase in the amount of pyrite reporting to the overflow. As the vortex finder was further raised, to the 2.470 position, even more pyritic particles were entrained in the upward central current before they had time to reach the outer wall.

When the vortex finder was lowered to the 3.370 inch position, the amount of pyritic sulfur reporting to the overflow increased. This was due to the fact that the vortex finder was now close enough to the bed to be entraining heavy particles off of it.

The minus 200 mesh size fraction did not follow the pattern of the three coarser size fractions. The optimum position for the vortex
BODY LENGTH 3"
PRESSURE 6 psi
DENSITY 10%
CONE ANGLE 40°
INLET DIA. .375"
VORTEX DIA. .250"
APEX DIA. .145"
S.G. 4.7-5.1

![Graph of Pyritic Sulfur Rejection vs Vortex Finder Position](image)

**Figure 25 - Variation of Vortex Finder Position** New Mexico Coal
finder was 2.770 inch. The pyritic sulfur rejection at this point was 66.0 per cent. It appeared that size was exerting the controlling factor rather than specific gravity. When the vortex finder was closer to the bed, these small pyritic sulfur particles were unable to penetrate the bed before they were entrained in the upward central current. When the vortex finder was raised above the optimum point, the small particles were entrained in the vortex finder current before they had had time to reach the outer wall. Short-circuiting was occurring.

Figure 26 shows the results of the variation of the inlet diameter. The optimum point was the 0.125 inch inlet diameter. The pyritic sulfur rejections were found to be: 94.8 per cent for the 65 x 100 mesh size fraction, 92.9 per cent for the 100 x 150 mesh size fraction, 94.4 per cent for the 150 x 200 mesh size fraction, and 59.4 per cent for the minus 200 mesh size fraction. At the 0.125 inch inlet diameter the throughput volume of the hydrocyclone was restricted. This allowed the particles enough time to be classified before they reached the vortex finder.

The pyritic sulfur rejection was decreased as the diameter was increased. Since the New Mexico coal has a high particle density in the heavier specific gravity fractions, it was possible that these particles interfered with each other at the higher flow rate. Therefore, the percentage of pyrite reporting to the overflow increased. In addition, as the throughput volume was increased, the gravity of separation was increased. This also caused more of the heavier particles to report to the overflow. (19)
BODY LENGTH 3"
PRESSURE 10 psi
DENSITY 10 %
CONE ANGLE 40°
VORTEX DIA. .250"
VORTEX POS. 3.370"
APEX DIA. .145"
S.G. 4.7-5.1

Figure 26 - Variation of inlet diameter New Mexico coal
The results of the variation of the inlet pressure are shown in Figure 27. The best results were obtained at the 15 psig point. The pyritic sulfur rejections were: 87.5 per cent for the 65 x 100 mesh size fraction, 75.9 per cent for the 100 x 150 mesh size fraction, 69.2 per cent for the 150 x 200 mesh size fraction, and 51.9 per cent for the minus 200 mesh size fraction. It appeared that because most of the particles are greater than 1.6 in specific gravity, greater pressure was required to overcome the interference between the particles and thereby effect a good separation by specific gravity.

As the inlet pressure was reduced, first to 10 psig and then to 6 psig, the rejection of pyritic sulfur was decreased. It was felt that the acceleration given the particles was not enough to overcome the interference between them, and that good segregation by specific gravity was not achieved.

The response of the hydrocyclone to variations in the cone angle is shown in Figure 28. The best results were obtained with the 40 degree cone. The following pyritic sulfur rejections were obtained: 81.9 per cent for the 65 x 100 mesh size fraction, 73.9 per cent for the 100 x 150 mesh size fraction, 62.7 per cent for the 150 x 200 mesh size fraction, and 31.5 per cent for the minus 200 mesh size fraction. The bed formed with this cone angle was thin enough that there was sufficient clearance between it and the vortex finder, and thick enough so that the hydrocyclone separated on the basis of specific gravity. (13)

The 20 degree cone caused more pyritic sulfur to report to the overflow. This was due to the fact that the bed which formed was so thick that the distance between it and the vortex finder was signifi-
S.G.  4.7 - 5.1
BODY LENGTH  3"
DENSITY  10%
CONE ANGLE  40°
INLET DIA.  .375"
VORTEX DIA.  .250"
VORTEX POS.  3.370"
APEX DIA.  .145"

FIGURE 27 - VARIATION OF PRESSURE NEW MEXICO COAL
BODY LENGTH 3"
PRESSURE 10 psi
DENSITY 10 %
INLET DIA. .375"
VORTEX DIA. .250"
VORTEX POS. 3.370"
APEX DIA. .145"
S.G. 4.7 - 5.0

FIGURE 28 - VARIATION OF CONE ANGLE NEW MEXICO COAL
cantly decreased.

The 60 degree cone also yielded decreased pyritic sulfur rejection. This cone was steep enough that the hydrocyclone was starting to act as a classifying hydrocyclone.

The clean coal recovery curves are shown in Figure 29. They reflect the previously established trend that the finer particles tended to report to the overflow product stream.

Comparison of the Pocahontas #3 coal to the Hagy coal

The results of the tests on the Pocahontas #3 coal and the Hagy coal compared quite closely for the three coarser size fractions. Each coal followed the same trends with respect to the variations in vortex finder position, inlet diameter, inlet pressure, and cone angle.

However, for the minus 200 mesh size fraction there was considerable difference between the two coals. The rejection coefficients were much lower for the Pocahontas #3 coal than for the Hagy coal. This was explained by the fact that the Pocahontas #3 coal has a small quantity of near gravity material in the gravity of separation specific gravity fraction. The bed which developed was less dense for the Pocahontas #3 coal than for the Hagy coal. Therefore, with the Pocahontas #3 coal these very fine pyritic sulfur particles had a greater tendency to report to the overflow product stream.

It was expected that the slightly heavier Hagy coal would have a higher gravity of separation than the Pocahontas #3 coal. However, no conclusive results were obtained. Some points on the recovery partition curve were higher than for the Pocahontas #3 coal and some
VORTEX POS. 2.770"
BODY LENGTH 3"
PRESSURE 6 psi
DENSITY 10 %
INLET DIA. .375"
APEX DIA. .145"
VORTEX DIA. .250"
CONE ANGLE 40°

FIGURE 29 RECOVERY PARTITION CURVES NEW MEXICO COAL
were lower. Since the response of these coals was so similar, they will be treated together when compared to the New Mexico coal.

Comparison of the Hagy coal and the Pocahontas #3 coal to the New Mexico coal

Significant differences were observed between the results obtained for the New Mexico coal and the results from the tests on the Pocahontas #3 coal and the Hagy coal.

The first difference may be noted on the recovery partition curves for each coal. The New Mexico coal showed much higher recoveries. This may be attributed to the fact that the much heavier New Mexico coal gave a higher gravity of separation due to the heavier bed formed.

All three coals yielded the best pyritic sulfur rejection at the 40 degree cone angle. However, for the New Mexico coal, pyritic sulfur rejection was lower than for the two other coals. This was explained by the fact that the denser bed formed by the heavier New Mexico coal increased the gravity of separation. Therefore, more pyritic sulfur reported to the overflow.

A comparison of the results of the variation of the inlet pressure for the three coals showed a marked difference. Best results were obtained at 10 psig for the two lighter coals. For the New Mexico coal best results were obtained at 15 psig. Again, it appeared that the great amount of heavier particles in the New Mexico coal required more acceleration to properly classify according to specific gravity. It would be interesting to see if the sulfur rejection decreased at higher pressures. This would be expected as a thicker bed would be
formed due to the increase in throughput capacity. \(^{(20)}\)

Differences were noted between the heavy coal and the two lighter coals with respect to the inlet diameter variations. For the lighter coals, the best results were obtained at the 0.250 inch diameter inlet. For the heavy coal, best results were obtained at the 0.125 inch diameter inlet. The heavier coal evidently required a lower throughput for the particles to separate efficiently by specific gravity.

A comparison between the graphs of the two lighter coals and the heavy coal for the vortex finder positions showed differences. The lighter coals have the best sulfur rejection at the 2.770 inch vortex finder position. The New Mexico coal yielded the best results at the 3.070 inch vortex finder position. This indicated that a heavy coal required more residence time to classify than a lighter coal.

Addition of 30 per cent limestone to the Pocahontas #3 coal

The results of the comparison of the heavy coal to the two lighter coals showed that the recovery of clean coal was much higher for the heavy coal. It was decided to investigate the performance of the hydrocyclone on the Pocahontas #3 coal when heavy material was added. 30 per cent by weight of limestone was added to the reservoir. The 180 grams was sized to follow the size distribution of the synthetic material already in the system. The results of these tests are shown in Figures 30, 31, 32, and 33. In each case the recovery of clean coal was increased.

This finding may have application in an industrial installation of a hydrocyclone system. If the reject material were recycled into the
FIGURE 30 - COMPARISON OF RECOVERY PARTITION CURVES, 65 x 100 MESH, POCAHONTAS #3 COAL
VORTEX POS. 2.770"
BODY LENGTH 3.000"
PRESSURE 6 psig
DENSITY 10 %
INLET DIA. 0.375"
APEX DIA. 0.145"
VORTEX DIA. 0.250"
CONE ANGLE 40.0°

Figure 31 - Comparison of Recovery Partition
Curves, 100 x 150 mesh, Pocahontas #3 Coal
FIGURE 32 - COMPARISON OF RECOVERY PARTITION CURVES,
150 x 200 MESH, POCOHONTAS #3 COAL
FIGURE 33 - COMPARISON OF RECOVERY PARTITION CURVES, MINUS 200 MESH, POCOHONTAS #3 COAL
feed to the unit, it might be possible to raise the clean coal recovery without adversely affecting the pyritic sulfur rejection.

Comparison of simulated results to actual results on Hagy coal

The calculated pyritic sulfur rejection for the Hagy coal was 82.2 per cent. The results of laboratory analysis, using the method described in United States Bureau of Mines Bulletin 638, on actual Hagy coal showed a pyritic sulfur rejection of 66.2 per cent. (21) These data and calculations may be found in Appendix D.

The difference between the two values was thought to be due to the fact that the Hagy coal did not completely liberate at minus 65 mesh. An examination under the microscope confirmed this fact. It would be necessary to further reduce this coal in order to achieve the predicted pyritic sulfur rejection.

Results of test on Pittsburgh coal

It was decided to repeat the test on actual coal using a coal which liberated at 65 mesh. The Pittsburgh coal was chosen. The results of this test showed that 78.9 per cent of the pyritic sulfur was removed. These data may be found in Appendix D.
VIII. ECONOMIC ANALYSIS

This analysis will provide an estimate of the cost of a hydrocyclone system to process 100 tons per hour of coal. (22)

Capital Costs

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement</th>
<th>Unit Cost</th>
<th>Cost $/ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickener (installed)</td>
<td></td>
<td>$300,000.00</td>
<td></td>
</tr>
<tr>
<td>Vacuum Filter (installed)</td>
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<td>250,000.00</td>
<td></td>
</tr>
<tr>
<td>Floor space 200 ft.² @ $50.00/ft.²</td>
<td></td>
<td>10,000.00</td>
<td></td>
</tr>
<tr>
<td>Settling Pond, pipe, pumps</td>
<td></td>
<td>8,000.00</td>
<td></td>
</tr>
<tr>
<td>Pumps for Hydrocyclone</td>
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<td>2,200.00</td>
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<tr>
<td><strong>Total Capital Costs</strong></td>
<td></td>
<td><strong>$570,200.00</strong></td>
<td></td>
</tr>
</tbody>
</table>

Analysis

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement</th>
<th>Unit Cost</th>
<th>Processing Cost $/ton</th>
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</thead>
<tbody>
<tr>
<td>Direct Production Cost</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Hydrocyclones</td>
<td>6,800/year</td>
<td>$10.00/unit</td>
<td>0.091</td>
</tr>
<tr>
<td>Power</td>
<td>86,250 KW/year</td>
<td>.02/KW</td>
<td>0.002</td>
</tr>
<tr>
<td>Water</td>
<td>$1.7 x 10^9 gal/year</td>
<td>.03/1000 gal</td>
<td>0.065</td>
</tr>
<tr>
<td>Operating Labor</td>
<td>1 person/shift</td>
<td>$6.25/man/hr</td>
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<tr>
<td>Maintenance</td>
<td>5 % working capital</td>
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<tr>
<td>Supervision</td>
<td>1 person/week</td>
<td>$7.50/man/hr</td>
<td>0.019</td>
</tr>
<tr>
<td>Laboratory</td>
<td></td>
<td></td>
<td>0.050</td>
</tr>
<tr>
<td><strong>Sub-Total</strong></td>
<td></td>
<td><strong>0.312</strong></td>
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</table>
## Indirect Production Cost

<table>
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<th>Description</th>
<th>Percentage</th>
<th>Cost</th>
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<tr>
<td>Depreciation</td>
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</tr>
<tr>
<td>Plant Overhead</td>
<td>80% of labor</td>
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</tr>
<tr>
<td>Taxes and Insurance</td>
<td>2% yr. of capital</td>
<td>0.014</td>
</tr>
<tr>
<td>Interest on working capital @ 9% year</td>
<td></td>
<td>0.007</td>
</tr>
</tbody>
</table>

Sub-Total: 0.147

Net Production Cost in $/ton: $0.459
IX. RECOMMENDATIONS FOR FUTURE WORK

Bench scale studies illustrated that a substantial reduction in pyritic sulfur can be realized by processing coal through a 1.0" diameter hydrocyclone. According to preliminary estimates, the hydrocyclone process is economically attractive. It is obvious that removing the pyritic sulfur before burning will eliminate the need for expensive air pollution equipment to remove the sulfur oxides from the hot stack gases.

In order to investigate this method in more detail, a pilot scale study is recommended. It is suggested that a system which can process 10 tons per hour be installed at the Virginia Polytechnic Institute and State University power plant. A system of this size would provide needed operating data on abrasion, corrosion, and plugging characteristics of the hydrocyclones. The advantages of the close proximity of the Virginia Polytechnic Institute and State University power plant to the technical support facilities of the Division of Minerals Engineering cannot be discounted.

The magnetic material tracer method has substantially reduced the amount of time required to obtain partition curves. Further research is needed to refine this batch method into a continuous sensing system. Such a system could be installed in an operating preparation plant to provide a means of constantly monitoring plant performance. This would enable the cleaning plant to respond to changes in the feed and result in more efficient plant operation.
SUMMARY AND CONCLUSIONS

An investigation of the literature showed that as the diameter of a hydrocyclone was decreased, smaller particles could be effectively separated on the basis of specific gravity. Consequently, a laboratory scale study was conducted to determine the possibility of removing pyritic sulfur from fine coal using a 1.0" diameter hydrocyclone.

A 1.0" diameter hydrocyclone was constructed from stainless steel. The hydrocyclone was fabricated with easily interchangable parts that permitted rapid variations in the inlet diameter, apex discharge diameter, vortex finder diameter, vortex finder position, and cone angle. The feed pressure to the hydrocyclone could also be varied. A recirculating system was used.

Synthetic material was used in place of actual coal during this investigation. The synthetic material, made from casting resin and barium sulfate, duplicated the coal with respect to particle size, shape, and specific gravity distribution. The synthetic coal had the advantage of not degrading during the course of the experiment.

Three coals were simulated for the purposes of this experiment. Pocahontas #3 coal served as the "light" coal, the Hagy seam was selected as the "medium" coal, and coal from the Cortes area of New Mexico was chosen as the "heavy" coal. By optimizing the 1.0" diameter hydrocyclone for these three coals, it would be possible to extend the results of the investigation to any coal.

The results of the investigation showed that the 1.0" diameter hydrocyclone was an effective device for removing pyritic sulfur from
65 x 200 mesh coal. The results for the minus 200 mesh size fraction were not good. A smaller diameter hydrocyclone would be necessary in order to effectively process the minus 200 mesh size fraction.

The results of tests on the simulated Hagy coal showed that 82.2 per cent of the pyritic sulfur could be removed using the 1.0" diameter hydrocyclone. A test run on actual Hagy coal yielded a pyritic sulfur rejection value of 66.2 per cent. The difference between the predicted value and the actual value of pyritic sulfur rejection was explained by the fact that the Hagy coal did not liberate until crushed to approximately 150 mesh. Therefore, non-liberated pyrite particles were carried by the coal into the clean coal product stream.

The test was repeated on coal from the Pittsburgh seam. This coal liberated at approximately 65 mesh. The pyritic sulfur rejection was found to be 78.9 per cent.

Magnetically tagged material was used to rapidly obtain the data necessary to calculate partition coefficients. One gram of tagged material of the size range and specific gravity under investigation was introduced into the system. The weight of the tagged material in the overflow was divided by the weight of material in the overflow and underflow to yield the pyritic sulfur rejection coefficient. This method allowed a partition coefficient to be obtained within a few minutes. This method is much faster than the float-sink method.

The effect of introducing refuse material into the slurry was investigated. It was found that as the percentage of refuse in the slurry was increased the recovery of clean coal was increased.
An economic study was performed to determine the feasibility of using a 1.0" diameter hydrocyclone system to remove pyritic sulfur from coal. The hydrocyclone system was sized to process 100 tons of coal per hour. Included in the analysis are direct production costs, such as water and power, and indirect production costs, such as insurance and depreciation. The cost of processing coal through the system was estimated to be $0.459 per ton.
REFERENCES


17. Amundson, L., non-published laboratory data.


22. Personal communication to Mr. Frank Chamberlain from Monsanto Co., Inc., (1973).

APPENDIX A

PROOF THAT MAGNETIC MATERIAL PARTITION COEFFICIENTS ARE IDENTICAL WITH FLOAT-SINK METHOD PARTITION COEFFICIENTS AND TEST DATA
Proof that magnetic method equals float-sink method

DATA POINTS

<table>
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<tr>
<th>Test</th>
<th>Tagged Material Partition Coefficient</th>
<th>Float-Sink Partition Coefficient</th>
<th>$d_i$</th>
<th>$d_i^2$</th>
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<tr>
<td>1</td>
<td>60.0</td>
<td>57.0</td>
<td>3.0</td>
<td>9.0</td>
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<tr>
<td>2</td>
<td>59.9</td>
<td>65.0</td>
<td>-6.0</td>
<td>36.0</td>
</tr>
<tr>
<td>3</td>
<td>64.0</td>
<td>82.0</td>
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</tr>
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<td>4</td>
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<td>6</td>
<td>60.0</td>
<td>54.7</td>
<td>5.3</td>
<td>28.1</td>
</tr>
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<td>7</td>
<td>54.8</td>
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<td>8</td>
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<td>36.0</td>
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<tr>
<td>10</td>
<td>50.8</td>
<td>46.7</td>
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<td>16.8</td>
</tr>
</tbody>
</table>

$\bar{X}_1 = 60.9$  $\bar{X}_2 = 61.4$  $\Sigma d_i = 6.9$  $\Sigma d_i^2 = 642.8$

$d = .5$

$t = 10 - 1 = 9$

Hypothesis: $\bar{X}_1 = \bar{X}_2$

Choose $\alpha = .05$

$t_{.075} = 2.262$

Reject if $t < -2.262$ or $t > 2.262$

$t = \frac{d - 0}{S_d / \sqrt{N}}$

$S_d = \frac{642.8 - (6.9)^2/10}{9} = 70.9$

$t = \frac{-0.5}{8.4} = 0.19$

Therefore: accept hypothesis $\bar{X}_1 = \bar{X}_2$. 
<table>
<thead>
<tr>
<th>TEST NUMBER</th>
<th>COAL NUMBER</th>
<th>SPECIFIC GRAVITY UNDER INVESTIGATION</th>
<th>MESH</th>
<th>BODY LENGTH IN INCHES</th>
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<td>2</td>
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<tr>
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<td>2</td>
<td>1.4 - 1.5</td>
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<td>150 x 200</td>
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<td>minus 200</td>
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<tr>
<td>5</td>
<td>2</td>
<td>1.5 - 1.6</td>
<td>65 x 100</td>
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<td>2</td>
<td>1.5 - 1.6</td>
<td>100 x 150</td>
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<td>2</td>
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<td>150 x 200</td>
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<td>8</td>
<td>2</td>
<td>1.5 - 1.6</td>
<td>minus 200</td>
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</tr>
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<td>1.6 - 1.7</td>
<td>65 x 100</td>
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APPENDIX B

PROOF THAT MAGNETIC MATERIAL PARTITION

COEFFICIENTS ARE REPEATABLE AND TEST DATA
Proof that data is repeatable

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\( \bar{x}_1 = 62.4 \) \( \bar{x}_2 = 64.4 \) \( \Sigma d_i = -26.1 \) \( \Sigma d_i^2 = 342.81 \)

\( d = -2.0 \)

\( t = 13 - 1 = 12 \)

Hypothesis: \( \bar{x}_1 = \bar{x}_2 \)

Choose \( \alpha = .05 \)

\( t_{.05} = 2.160 \)

Reject if \( t < -2.160 \) or \( t > 2.160 \)

\[
 t = \frac{\bar{d} - 0}{s_d / \sqrt{N}} 
\]

\[
 s_d = \frac{342.81 - (26.1)^2/13}{12} \approx 24.2 
\]

\[
 t = \frac{-2.0}{4.9} = -1.47 
\]

Therefore: accept hypothesis \( \bar{x}_1 = \bar{x}_2 \).
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APPENDIX C

OPTIMIZATION DATA FOR POCAHONTAS #3 COAL,

HAGY COAL, NEW MEXICO COAL, AND

POCAHONTAS #3 COAL WITH 30 PER CENT LIMESTONE ADDED
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APPENDIX D

PYRITIC SULFUR REJECTION CALCULATIONS
CALCULATIONS OF PYRITIC SULFUR REJECTION

**Hagy coal**

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<th>Pyritic sulfur in per cent</th>
<th>Feed</th>
<th>Overflow</th>
<th>Underflow</th>
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<td>1.19</td>
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Pyritic sulfur in product in per cent

\[
(0.66 \times 0.61)/1.0 \times 1.19 = 33.8
\]

Pyritic sulfur rejection in per cent = 100.00 - 33.8 = 66.2

**Pittsburgh coal**

<table>
<thead>
<tr>
<th>Pyritic sulfur in per cent</th>
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<th>Overflow</th>
<th>Underflow</th>
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Pyritic sulfur in product in per cent

\[
(0.66 \times 0.39)/1.0 \times 1.22 = 21.1
\]

Pyritic sulfur rejection in per cent = 100.00 - 21.1 = 78.9
### CALCULATION OF THEORETICAL PYRITIC SULFUR REJECTION

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<th>Pyritic Sulfur Rejection Coefficient</th>
<th>Weight Pyrite Per Cent</th>
<th>Pyrite in Underflow Per Cent</th>
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<th>Cumulative Pyrite in Underflow Per Cent</th>
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The theoretical pyritic sulfur rejection is 82.2 per cent.
Lynn Vinzant Amundson was born in Washington, D. C. on January 12, 1949. She was granted a Bachelor of Science degree in Mining Engineering from Virginia Polytechnic Institute and State University in 1971. She was awarded a Master of Science degree in Mining Engineering from Virginia Polytechnic Institute and State University in 1973. The degree of Doctor of Philosophy in Environmental Sciences and Engineering was conferred by Virginia Polytechnic Institute and State University in June of 1976.

Lynn V. Amundson
RESPONSE TO PARAMETER VARIATION OF A ONE-INCH
DIA METER HYDROCYCLONE FOR PYRITIC SULFUR REMOVAL

by

Lynn Vinzant Amundson

(ABSTRACT)

The use of a 1.0" diameter hydrocyclone was investigated for the removal of pyritic sulfur from coal. The hydrocyclone was constructed to permit rapid changes in cone angle, inlet diameter, vortex finder position, vortex finder diameter, and apex discharge diameter.

Synthetic material which duplicated the actual coal with respect to size, shape, and specific gravity distribution was used during this investigation. The synthetic material provided close control of the specific gravity distribution and eliminated the problem of material degradation during the course of the investigation.

A new technique for obtaining float-sink data was developed. Magnetically tagged material, identical to coal with respect to size, shape, and specific gravity was introduced into the system. The weight of the tagged material in the overflow and underflow samples permitted rapid calculation of the partition coefficient.

Refuse material was introduced into the system. It was found that this increased the yield of clean coal.

An economic analysis of a hydrocyclone system designed to process 100 tons per hour of coal was performed.