PHOSPHATE MATRIX PIPELINE DESIGN DATA
AND TOOLS FOR EFFICIENCY IMPROVEMENT

PREPARED BY
GIW TESTING LABORATORY
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The Florida Institute of Phosphate Research was created in 1978 by the Florida Legislature (Chapter 378.101, Florida Statutes) and empowered to conduct research supportive to the responsible development of the state's phosphate resources. The Institute has targeted areas of research responsibility. These are: reclamation alternatives in mining and processing, including wetlands reclamation, phosphogypsum storage areas and phosphatic clay containment areas; methods for more efficient, economical and environmentally balanced phosphate recovery and processing; disposal and utilization of phosphatic clay; and environmental effects involving the health and welfare of the people, including those effects related to radiation and water consumption.

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FINAL REPORT

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PHOSPHATE MATRIX PIPELINE DESIGN DATA AND TOOLS FOR EFFICIENCY IMPROVEMENT

BY

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1 August 1987 to 26 August 1988

Performed for
THE FLORIDA INSTITUTE OF PHOSPHATE RESEARCH
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For many years the phosphate industry has recognized that the hydraulic transport of phosphate matrix from the point of mining to the wash plant is not energy efficient. Changes that would contribute to greater efficiency are operating at lower slurry velocities -- closer to the critical velocity -- pumping at higher percent solids concentrations and utilizing smaller diameter pipe sizes. In practice, however, the need to maximize production and provide system reliability takes precedence over the incentive to minimize energy consumption. This results in a tendency to overdesign the system. Overdesign can be partly justified by the fact that matrix pumping characteristics can vary over short periods of time and the system must handle the full range of these variations. However, the absence of easy to use, reliable design methods and fundamental design data contribute to the tendency to overdesign.

In August of 1987 the Institute contracted with GIW Industries, Inc. to develop rapid and reliable techniques for designing phosphate matrix pumping systems. The project's specific goals were to collect field and laboratory data and to develop user friendly, computer software suitable for designing the large scale, multiple pump systems common to modern Florida mining operations. The economic justification for the project was to increase the energy efficiency of this important unit operation.

The project consisted of three major work elements:

-- Collection of matrix samples and field pump and pipeline performance data at operating mines, and subsequently, testing these samples in GIW's laboratory pipeline test loop over a range of pipeline diameters, specific gravities and velocities.

-- Analysis and correlation of the field and laboratory data and development of algorithms to project performance data over the full range of possible operating conditions.

-- Preparation of a menu driven, PC software package that does the following for each matrix type:

   -- Calculates specific energy consumption and head loss for each slurry concentration, velocity and pipe diameter.

   -- Evaluates an existing pipe system against a given set of pumps and predicts the system operating characteristics.

   -- Selects for a specified pipe system the best pump(s) to achieve a recommended operating rate or velocity.
Calculates pipeline pressure gradients and energy requirements for a specified system under both steady state and startup conditions.

An important aspect of the work was recognizing that different matrix samples behave differently in terms of their pumping characteristics. Some are reported as easy to pump while others are viewed as more difficult. This consideration led to the need to conduct the tests with a number of different types of matrix -- easy to pump, average and difficult -- and the need to establish a practical system of characterizing these different types. The system chosen to characterize matrix types was the commonly used parameters of size classification, namely the percentage distribution of pebble, feed and fines. Consequently, the algorithms developed to solve the design problems require only data from operating mines that are readily available to the field engineer.

This report describes in detail the tests that were run and summarizes the data collected. Individual test data tabulations for both lab and field work are contained in a set of Appendices that are available in the Institute's library. The computer program manual is being published as a separate report. In addition to this report, copies of both the computer program (on 5-1/2" floppy disks suitable for loading to hard disk) and the manual are available to interested parties on written request.

GIW has agreed to update the computer software when appropriate for a period of three years. By applying the program to a greater variety of matrix types than the three chosen for this project and with feedback from program users, we expect a more accurate and precise model will evolve.
TABLE OF CONTENTS

I.  INTRODUCTION
II. EXECUTION OF THE WORK
III. GEOLOGICAL ANALYSIS
IV. LAB TESTS AND ANALYSIS OF PIPELINE DATA
V.  FIELD TESTS
VI. EXTRUSION RHEOMETER
VII. PUMP PERFORMANCE ANALYSIS

COMPUTER PROGRAM MANUAL (Published Separately)

APPENDICES

A. Original Proposal and Contract
B. Calibration Data for Lab Tests
C. Test Data for Lab Tests
F. 'Continuous Measurement of the Density of Flowing Slurries' by Roland Clift and Diana Manning Clift.
G. Photographs
H. Extrusion Rheometer Test Data
I. Sieve Analysis Test Data
NOTATION

A  Pipe cross-sectional area

Cw  Delivered weight concentration

D  Pipe diameter

d  Particle diameter, mesh size

E  Specific energy

G  Gravitational acceleration

I  Hydraulic gradient

L  Length

M  Mass flow rate

P  Fraction of pebbles

AP  Static pressure difference

Q  Volumetric flow rate

R  Fraction of material in sliding bed.

Re  Reynolds number

Rec  Critical Reynolds number (Laminar-Turbulent Transition)

S  Specific gravity

V  Mean velocity

Vc  Critical velocity

Vs  Velocity at threshold of suspension

Vo  Velocity of settling infinite fluid

Voh  Velocity of hindered settling

\( \alpha \)  Shear stress ratio-\( \tau_y/\tau_o \)

\( \varepsilon \)  Pipe roughness

\( \eta \)  Plastic viscosity

\( \lambda \)  Friction factor
\( \mu \) Dynamic viscosity
\( \nu \) Kinematic viscosity
\( \rho \) Density
\( \tau_0 \) Wall shear stress
\( \tau_y \) Yield stress

**SUFFIXES**

\( f \) Fluid
\( i \) Element
\( m \) Suspension
\( s \) Solids
\( w \) Water
\( ca \) carrier
I. PHOSPHATE MATRIX PIPELINE DESIGN DATA AND TOOLS FOR EFFICIENCY IMPROVEMENT

A. INTRODUCTION

Mining of phosphate is one of the major industries in Florida which produces some 30% of the world requirements. Drag-lines are used to remove the matrix from the ground after which it is transported as a water phosphate slurry by pipeline to the processing plant. The nominal diameters of the pipelines used in practice are 16, 18 and 20 inches in diameter and the pipelines are up to 8 miles in length.

It will be realized that the power consumption of one such line, 10 miles in length and 18 inches in diameter, in which phosphate is being pumped at a concentration of 50% by weight, is likely to be in the region of 11,500 H.P. (8.6 MW). Clearly, with power consumptions of this order it is essential that reliable operation should be sought at the minimum specific energy attainable.

It was for this reason and because of the variability of the size distribution, associated with the phosphate matrix material, that the Florida Institute of Phosphate Research commissioned the Georgia Iron Works Company and the unique capabilities of the GIW Hydraulic Test Laboratory to undertake a study into the flow characteristics of phosphate slurries as outlined in Appendix I.

The proposal entitled "Phosphate Matrix Pipeline Design Data and Tools for Efficiency Improvement" therefore, originated out of a desire to improve the efficiency and reliability of matrix slurry pipelines and at the same time provide the data and tools to help the practicing Florida Phosphate Mine Engineer carry out this work.

The overall objective of this proposal was therefore to assemble a comprehensive set of data on the full size pipeline and pump
performance of phosphate matrix slurry and put it in a form suitable for Florida phosphate matrix designers, to make it possible for them to improve the efficiency of new and present systems.

Specifically this was to be achieved by carrying out a series of tests in both the laboratory and the field at different conditions on selected phosphate matrix samples and by analysis and correlation of the data into easily used forms.

The matrix to be tested and analyzed was to be identified and selected by a geological survey for its type and pumpability so that the tests and later results best cover a fully representative range of Florida matrix transport conditions. Three matrix samples were to be used. The pipelines employed in the test would be full size 16", 18" and 20" diameter and the pumps would also be full size units now used in the field.

The data collected was to be pipeline head loss, slurry deposit velocity, pump head loss and pump efficiency at transport concentrations now pumped and higher in the different pipeline diameters noted earlier over a full range of velocities.

The correlated data presentation forms were to be designed to maximize the benefit to all levels of engineering users. It was intended that the data would be made available as raw tabulated data, pipe friction plots, algebraic relationships and in an easy to use menu driven computer program tool for use on a PC computer. It was expected that the computer program would include an energy analysis for a complete system, pump selection, pump spacing and startup sequence recommendation capabilities.

A full copy of the technical section of the original proposal (and later contract) is attached as Appendix A.
II. EXECUTION OF THE WORK

A project of this size and breadth involved a number of different investigations of varying types, using different facilities and personnel.

In spite of its extensive system of pipe loops, the GIW Laboratory could not carry out the tests in its existing loops as specified. A special test loop was therefore built in the GIW Hydraulic Test Laboratory to carry out the pipeline and pump lab phase test work. The main features of this were the use of the three full size series connected pipe sizes of 16", 18" and 20" diameter with full 100 diameter entrance sections and a loading system that allowed a dump truck to load into the system in a few minutes.

The tests were limited for economic considerations to three types of slurries. It was essential, therefore, that these represented as well as possible the range of Florida matrix types. A geological assessment of the matrix being pumped by all of the Florida mines was necessary before the three test slurries were selected.

The geological analysis of the different matrix types was carried out by a Consultant, Henry Lamb, in conjunction with the project director. As a result of this three mines were chosen as best representing the range of Florida mine matrix. The mines chosen were Noralyn at IMC, Suwannee River at Occidental and Hooker's Prairie at W R Grace. A detailed report on the geological work is located in Section 3.

Henry Lamb and the GIW Florida Manager, Roy Duvall, in turn
coordinated with the mines and the lab, the trucking of the slurry back to Georgia for the lab tests, and of sampling and sizing the slurries.

Thirty 14 ton capacity truckloads of matrix were transported from the three selected mines to the lab for use in each of the five test concentrations. Six additional truckloads were brought in for the two additional concentration tests on a different pump type.

The pump used in the majority of tests was a GIW 18x20VBC54 matrix pump. An offer from Thomas Foundries to supply a pump for the pump performance comparison tests was not taken up; thus a GIW 18x18WS044 pump was used in the comparison tests.

Site tests were carried out at each of the selected mines using a specially designed field test unit comprising a vertical 'U' loop with magnetic flowmeter, and density meter along with transducers and a computer data acquisition system. The field test work is described in Section 4 of this report.

The lab test phase of the work was carried out under the direction of GIW Test Engineer, John Maffett, with the assistance of Test Technician Steve Kerr, and the lab workmen. John Maffett also supervised each of the three site tests and wrote that section of the report. The massive amount of lab test particle size analysis work was carried out by Steve Kerr and his assistants.

The complimentary viscometer work of the fine portion of each of the three slurries was carried out by Lab Technician Steve Kerr and his assistants, in the GIW vertical 1/2" diameter extrusion rheometer.

The description of the GIW lab test work phase is covered in Section VII of the report. Analysis of the pipeline data and the
writing of that section of the report was carried out by Dr. Alan
Duckworth, who also established the pipe friction correlation and the
algorithm for the computer program.

Section VIII of the report covers the pump performance on solids
analysis which was carried out by Dr. Anders Sellgren.

The computer program as specified is menu driven and user
friendly. It uses the algorithm noted earlier and is based on the
original GIW selection, database and system analysis programs that the
writer worked on originally. The FIPR program now called "PAPES" was in
the main written by Todd Pike, with documentation by Carol Pike.

Consultant David Strout also provided specialist input and advice
from the mine engineers viewpoint.

The computer program allows system analysis evaluation for a
selected slurry type. Pump selection is carried out against a file of
pump performance data. No reply was received from Thomas Foundries to
a letter requesting test data on their pumps, so only pumps tested at
full size in the GIW lab and considered suitable for matrix service are
included. These comprise approximately fifteen pumps, three of which
are of Thomas manufacture and the remainder by GIW. The ability to add
pumps at any time, however, is included.

The computer program is set up for a PC with a hard disk and EGA
monitor, although with relatively simple changes it can be used on
virtually any MS DOS machine. Source listings and executable versions
have been provided to FIPR in the IBM PS2 machine that comprises part
of this contract. The program manual is contained in Section IX. This
section is written so it can be handed out on its own with the computer
program. As such it has its own list of contents and appendices.
In general, the test work was carried out as expected. After a lot of early delays the tank loading/unloading system worked very well, allowing the slurry to be loaded with minimal degradation and loss of time.

The largest part of the project was the lab test work which as noted earlier, was reported by Dr. Duckworth. Dr. Duckworth in this section also comments on the extrusion rheometer tests work results, comparison of the field test work results with the lab data, and correlation.

A paper entitled 'Full Scale Experimental Study of the Pipeline Transport of Phosphate Matrix Slurries' has been written by Dr. Alan Duckworth (co-authored by John Maffett and the writer) on the Noralyn Mine matrix phases of the test work, and has been presented at the 11th Annual Hydrotransport Conference at Stratford-upon-Avon in England. An expanded version of this paper, along with a description of the computer program, has also been presented by Dr. Alan Duckworth and the writer at the AIME meeting in Bartow, Florida on the 29th of October. Copies of these are enclosed as Appendices D and E.
III. GEOLOGICAL ANALYSIS

A. PRODUCTION ENVIRONMENT

Phosphate rock is produced from two districts in the State of Florida (Figure III-1). The Central Florida District has been most productive in terms of annual and total tonnage. The district lies south of Lakeland and occupies parts of Polk, Hillsborough, Manatee, Hardee, and DeSoto counties. Eleven (11) companies operate or have the potential to operate at nineteen (19) mine sites. The phosphate deposits of Hardee, Manatee, and DeSoto counties are often referred to as the South Florida Phosphate District or the Southern Extension of the Central Florida Phosphate District. While historically mining has been centered in Polk and Hillsborough counties, future production will move southward.

The North Florida Phosphate District is located north of Lake City in Columbia and Hamilton counties. Production is limited to one (1) company operating two (2) mine sites.

The combined annual production capacity for the Central and North Florida Phosphate Districts is in excess of 50 million short tons. Table III-1 provides a list of companies and mine sites.

Phosphate rock products from Florida are primarily used in the manufacture of fertilizer. Consumptive chemical plants are located near the Central and North Florida mine sites and in the southern portions of the mid-west, principally along the Mississippi River. Additional phosphate rock is sold on the international market.

B. GEOLOGIC ENVIRONMENT

The Florida phosphate deposits are mined from two geologic formations:
### TABLE III-1. Phosphate Rock Mining Companies and Mine Sites

<table>
<thead>
<tr>
<th>Operator</th>
<th>Mine Site</th>
<th>Capacity</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMC Fertilizer Corporation</td>
<td>Noralyn/Phosphoria</td>
<td>5.0MM</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Clear Springs</td>
<td>3.0MM</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Kingsford</td>
<td>4.0MM</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Haynsworth</td>
<td>2.5MM</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Fort Lonesome</td>
<td>2.0MM</td>
<td>I (1)</td>
</tr>
<tr>
<td></td>
<td>Four Corners (50%)</td>
<td>2.0MM</td>
<td>I (1)</td>
</tr>
<tr>
<td>C.F. Industries</td>
<td>Hardeee Complex I</td>
<td>1.0MM</td>
<td>A</td>
</tr>
<tr>
<td>W.R. Grace &amp; Company</td>
<td>Four Corners (50%)</td>
<td>2.0MM</td>
<td>I (1)</td>
</tr>
<tr>
<td>Freeport-McMoRan Resource Partners</td>
<td>Payne Creek</td>
<td>2.5MM</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Fort Green</td>
<td>3.5MM</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Rockland (50%)</td>
<td>1.0MM</td>
<td>A</td>
</tr>
<tr>
<td>USX Agri-Chemicals</td>
<td>Rockland (50%)</td>
<td>1.0MM</td>
<td>A</td>
</tr>
<tr>
<td>Estech, Inc.</td>
<td>Silver City</td>
<td>1.5MM</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Watson</td>
<td>1.0MM</td>
<td>A (2)</td>
</tr>
<tr>
<td>Seminole Fertilizer Company</td>
<td>Hookers Prairie</td>
<td>2.8MM</td>
<td>A</td>
</tr>
<tr>
<td>Gardinier, Inc.</td>
<td>Fort Meade</td>
<td>3.0MM</td>
<td>A</td>
</tr>
<tr>
<td>Mobil Mining and Minerals Company</td>
<td>Fort Meade</td>
<td>3.0MM</td>
<td>A (2)</td>
</tr>
<tr>
<td></td>
<td>Nichols</td>
<td>1.8MM</td>
<td>I (3)</td>
</tr>
<tr>
<td></td>
<td>Big Four</td>
<td>2.5MM</td>
<td>I (3)</td>
</tr>
<tr>
<td>Hopewell Land Corporation</td>
<td>Hopewell</td>
<td>0.6MM</td>
<td>A (4)</td>
</tr>
<tr>
<td>Nu-West</td>
<td>Wingate Creek</td>
<td>1.8MM</td>
<td>I (5)</td>
</tr>
<tr>
<td>Occidental Chemical Company</td>
<td>Suwannee River</td>
<td>2.0MM</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Swift Creek</td>
<td>1.5MM</td>
<td>A</td>
</tr>
</tbody>
</table>

**Notes:**

'A' denotes active mine as of November 1, 1988
'I' denotes inactive mine as of November 1, 1988

1. The Four Corners Mine is a 50-50 joint venture between IMC Fertilizers and W.R. Grace. Operational management has transferred from Grace to IMC. Negotiations are underway to transfer full ownership to IMC. The mine is expected to re-open in 1989.
2. The Watson and Fort Meade mines are expected to cease operation within the next two years.
3. The Nichols and Big Four mines are expected to re-open within the next two years.
4. Hopewell Land Corporation is a fully owned subsidiary of Noranda. In January, 1989, ownership is expected to be transferred from Noranda to Hopewell Land Partners Limited.
5. The Wingate Creek Mine was recently acquired by Nu-West from Becker Phosphate Company. The mine is expected to be reactivated in 1989.
1) the Bone Valley Formation; and 2) the Hawthorne Formation. These deposits are Miocene to post-Miocene in age. There is an effort within the Florida Bureau of Geology to subordinate the Bone Valley to a member of the Hawthorne while elevating the Hawthorne to group status.

Within a regional context the phosphate occurs in essentially flat lying, blanket-type deposits. There is no impact on mining by structures related to faulting or folding. Generally, the phosphate horizon is 10-20 feet thick. Deposits in the Southern Extension of the Central Florida District increase in thickness to average in the range of 35-45 feet.

The phosphate matrix (ore) is overlain by a blanket of Pliocene-Pleistocene, unconsolidated sand and clay. This overburden ranges in thickness from five to more than fifty feet. Typically the thickness is 15-30 feet.

The matrix is underlain by limestone bedrock or a stiff, phosphate-barren, bed clay.

Historically, the matrix composition has been described as 1/3 phosphate pebble, 1/3 phosphate feed, and 1/3 clay waste. While this description is easy to remember and repeat, the industry wide analysis of matrix size performed as part of this study confirms that the classic definition is outdated and will become more outdated as new mines are opened. Basically, the matrix size characteristics are becoming more dominated by the feed size fraction at the expense of the pebble.

C. MINING ENVIRONMENT

Phosphate rock mining is accomplished by open pit strip mining techniques. The process begins with general land clearing using bulldozers.
Large, walking draglines with 20-65 cubic yard buckets are then used to strip the overburden and cast it into adjacent mined areas. The uncovered matrix is mined by the dragline and dumped into an earthen pit, a 'well', where it is broken down under hydraulic pressure. Usually three monitors, equipped with nozzles 2.5-3.0 inches in diameter, attack the matrix with water at a rate of 6,000-8,000 gallons per minute and pressures ranging from 200-250 psi.

One exception to the dragline mining has been the application of dredges for overburden removal and matrix mining at a small mine in Manatee County.

The matrix slurry begins its journey to the washer/beneficiation plant by passing over a grizzely. The grizzely is designed to remove exceptionally large particles (limestone boulders, roots, stumps, etc.) from the slurry. The slurry enters the pumping system through a suction arm and immediately passes into the pit pump. Pit pumps are typically driven by 1250-1500 horsepower electric motors. Booster pumps (1000-1500 horsepower) are located along the pipeline at intervals ranging from 2500-4500 feet depending on matrix pumping characteristics. The pipeline is constructed from 50-100 foot joints of steel pipe with diameters varying from 16-20 inches.

Generally, pumping distances increase with mine life. The average distance over the mine life is perhaps 3.0 miles. With the high capital cost of constructing new mines, there has been a growing tendency to increase pumping distances and absorb the increased cost of production. Pumping distance of more than 8 miles are becoming more commonplace.

The washer/beneficiation plant separates the matrix slurry into phosphate rock products (pebble and concentrate) and waste materials (tailings sands and clay). The pebble products are separated at the washer. Depending on deposit characteristics, pebble products are typically minus 3/4 inches plus 14 or 16 mesh in size. In the feed preparation section, the clay waste (-150 mesh) is
removed from the feed (-14 or -16 mesh plus 150 mesh). The feed is composed of sand and silt size particles. Flotation techniques are employed to segregate the phosphate and quartz grains to yield a concentrate product and a sand tailings waste.

From a geologic context the project scope called for the laboratory and field testing of three types of phosphate rock matrix. These types were further defined as difficult to pump, typical to pump, and easy to pump. Needless to say these relative terms opened the door for all forms of discrepancies. Material difficult for one producer may be considered 'gravy' by another.

It was the function of GIW's geologic advisor to identify the geologic factors which most strongly influenced the matrix pumpability. Many descriptive factors were considered. Since the overall project scope included the development of a user friendly pumping system design program the descriptive factors defining the matrix types had to be based on information readily available in each operator's phosphate rock reserve database. The matrix size distribution was determined to be the most appropriate and universally available factor.

One final logistical demand was placed on the test site selection. Because the laboratory and field tests would be occurring over a period of time (2-3 weeks), the test site was required to be as uniform as possible for the collection of matrix samples from various points as the dragline proceeded along its mining cuts.

D. PROCEDURES

Information about the matrix size characteristics (% pebble, % feed, and % clay waste) was requested from several operating companies. This data was
provided for each dragline at each mine as it appears in the company's reserve
database. The area for which the data were obtained was generally limited to
the area in the six month mine plan for January to June, 1988. In some cases
additional data were requested and provided for the period of June to

The size distribution percentages for each dragline were plotted on a
triangular chart as shown in Figure III-2. This plot provided a visual
analysis of the variation to be encountered during mining. Mining areas with
a high variability (Figure III-3) were avoided in favor of areas exhibiting
low to moderate variation (Figure III-4).

The procedures used in classifying the matrix are similar to those of
Paugh, et. al. (1981).

To facilitate the data analysis a brief computer program written in
FORTRAN was developed by Mineral Resource Associates. A copy of the program
is included as Appendix III-1.

To compare the mining area the average matrix size distribution for each
dragline was calculated and plotted on a single chart (Figure III-5.) This
chart revealed that the concept of 1/3 pebble, 1/3 feed, and 1/3 clay was no
longer the rule but the exception. Figure III-5, coupled with industry
experience and practice, provided the basis for identifying difficult, typical,
and easy pumping characteristics.

Difficult to pump matrix was defined as that material which most closely
approximated an equal proportion of pebble, feed, and clay. Industry practice
has been to use maximum horsepower (1500 hp) and close booster pump spacings
(2500 feet) when transporting this type of matrix.

The typical matrix was characterized by 15-20% pebble, 50-60% feed, and
25-30% clay. For this type of matrix moderate horsepower (1000-1250 hp) and
Figure III-2. Triangular coordinate paper for plotting matrix size characteristics.
Figure III-3. Matrix Size Characteristics for a Mining Site with a High Variability.

Average % Pebble: 17.93
% Feed: 60.22
% Fines: 21.85
Number of Data Points: 40

Occurrence Code:
1 = 1 occurrence, 2 = 2 occurrences, ...
A = 10 occurrences, B = 11 occurrences, ...
Figure III-4. Matrix Size Characteristics for a Mining Site with a Low to Moderate Variability.

Average % Pebble: 37.62
% Feed: 33.40
% Fines: 28.86
Number of Data Points: 32

Occurrence Code:
1 = 1 occurrence, 2 = 2 occurrences, ...
A = 10 occurrences, B = 11 occurrences, ...
Figure III-5. Industry Wide Matrix Size Characteristics by Dragline.

100% Pebble

1

Test Site No. 1

1 111
12 3111
121212
1 211

Test Site No. 3

Test Site No. 2

100% Fines

100% Feed

Occurrence Code:
1 = 1 occurrence, 2 = 2 occurrences, ...
A = 10 occurrences, B = 11 occurrences, ...
moderate booster pump spacings (3000-3500 feet) are normal.

Finally, the easy to pump matrix is virtually lacking in pebble (<5%) and dominated by feed (75-85%) with a minor to normal clay content (10-20%). Moderate horsepower and long booster pump spacings (4000-4500 feet) are general practices in this type of matrix.

E. SITE SELECTION

1. Test Site No. 1

Selection of the difficult to pump matrix presented little difficulty. From an analytical standpoint the site was very obvious. See Figure III-5. Field inspection confirmed the exploration data.

Mining sites such as represented by Test Site No. 1 are becoming rare in the Florida Phosphate Industry. They are generally limited to small areas such as relic sinkhole or stream channel structures.

Exploration data for Test Site No. 1 suggested the pebble-rich matrix was relatively uniform over an area of 200-300 acres. The overburden was 20-25 feet thick. The matrix was 25-30 feet thick. Some stratigraphic variation in the matrix was noted. In general the clay content increased with depth at the expense of the feed and pebble fractions.

Test Site No. 1 most closely approximates the historical definition for the particle size distribution of the phosphate matrix components. Based on thirty-two (32) drill holes, the average pebble content was 37.6% of the matrix, the feed fraction represented 33.1% and the clay (-150 mesh) was 28.9%. The missing 0.4% may be due to rounding errors in the data provided by the operator or related to oversize material discarded during the exploration laboratory analysis of the matrix.

Site inspection and sampling at the time of bulk sampling and during the
field test confirmed the anticipated matrix size distribution within reasonable limits of variation. Samples taken during the field test and bulk sampling program averaged 46.2% +14 mesh pebble, 26.2% -14 + 150 mesh feed, and 27.6% -150 mesh fines.

The matrix size distribution for Test Site No. 1, as represented by the exploration drill data, is illustrated in Figure III-6.

2. Test Site No. 2

The second test site was selected with little difficulty. A site dominated by feed size material was sought and identified. Test Site No. 2 was considered to represent material in the easy to pump category.

Based on eighty-nine (89) drill holes, the pebble, feed, and clay contents were estimated at 1.9%, 76.7% and 21.5%, respectively. Site inspection and sampling during the field test verified the high percentage of feed, lack of coarse pebble, and moderate clay content. Field samples indicated 1.0% +14 mesh pebble, 87.4% -14 +150 mesh feed, and 11.6% -150 mesh fines. Operational personnel at this mine reported a shift in pumping characteristics as the size distribution varied from fine-grain (-65 Mesh) to medium-grain (35-65 Mesh) to coarse-grain (+35 Mesh) feed.

Data for the test area indicated a relatively uniform, feed-dominate matrix over a broad geographic area. Stratigraphically, the matrix appeared as a uniform ore bed. No concentrations of pebble or clay were noted other than a thin clay seam approximately one foot thick near the upper contact. The matrix zone was 15-20 feet thick and overlain by 10-15 feet of overburden.

Additional laboratory and field tests to examine pumping characteristics as the feed size distribution changes were not within the project scope. However, in the future as matrix characteristics become more dominated by feed
Figure III-6. Test Site No. 1 Matrix Size Characteristics Based on Exploration Data.

Average % Pebble: 37.62
% Feed: 33.40
% Fines: 28.86
Number of Data Points: 32

Occurrence Code:
1 = 1 occurrence, 2 = 2 occurrences, ...
A = 10 occurrences, B = 11 occurrences, ...
size material, the impact of such variances should be investigated.

The matrix size distribution for Test Site No. 2, as represented by the exploration drill data, is illustrated in Figure III-7.

3. Test Site No. 3

The third test site, representing the typical matrix, was the most difficult to select. Those draglines with average matrix size characteristics for a six-month mine plan also demonstrated a wide range of extremes on a hole-by-hole basis. Thus, for many potential test sites the condition of matrix uniformity for the laboratory and field test period could not be guaranteed. These conditions were offset by organizing the field test and matrix sampling and transport activities into the shortest time span possible, approximately one week.

The matrix size characteristics for most 'typical' sites are also influenced by stratigraphic variations. In many cases the upper one-third of the matrix is pebble dominated and may approach the size characteristics of Test Site No. 1. The lower two-thirds of the matrix is feed dominate and is similar to Test Site No. 2 with perhaps an increase in clay content of 5%-10%. Fortunately, the mining and slurrying process usually results in a mixing of the upper and lower zones.

The matrix size characteristics for Test Site No. 3, as represented in fifty-six (56) drill holes, was 13.6% pebble, 60.4% feed, and 26.1% clay. Pit inspection during the field test and matrix sampling did not indicate significant variations from the expected size characteristics. Field samples contained 11.5% +14 mesh pebble, 60.9% -14 +150 mesh feed, and 27.6% -150 mesh fines.
Figure III-7. Test Site No. 2 Matrix Size Characteristics Based on Exploration Data.

Average % Pebble: 13.56
% Feed: 60.38
% Fines: 26.06
Number of Data Points: 56

Occurrence Code:
1 = 1 occurrence, 2 = 2 occurrences, ...
A = 10 occurrences, B = 11 occurrences, ...
The matrix size distribution for Test Site No. 3, as represented by the exploration drill data, is illustrated in Figure III-8.

F. FIELD PROCEDURES

After selecting the test sites using analytical methods, each site was visited to confirm its suitability. Visual inspection supported the matrix size distribution as reported in the geologic reserve database. The matrix exposed in the mining pit walls was inspected to insure a reasonable degree of matrix uniformity would prevail throughout the laboratory and field testing period.

At each site approximately 250-300 tons of phosphate matrix was recovered by the dragline and stockpiled. The stockpiled material was then loaded into bulk hauler trailers with a 20-ton capacity and transported to the GIW Hydraulic Laboratory in Grovetown, Georgia. GIW trucks and trailers transported the matrix.

Whenever possible a representative of Mineral Resource Associates was present during sample collection and truck loading. When MRA personnel were not available representatives of GIW were at the site or supervisory arrangements were made with operational personnel who were knowledgeable about the project. The project scope called for 150 tons of matrix to be transported from each test site to the laboratory. Care was taken to insure the test site sample was representative and not contaminated by overburden. The recovery of excess material, stockpiling and loading process coupled with the stockpiling and rehandling at the GIW Laboratory served to thoroughly mix the matrix prior to injection into the GIW pumping loop.
Figure III-8. Test Site No. 3 Matrix Size Characteristics Based on Exploration Data.

Average % Pebble: 1.86  
% Feed: 76.68  
% Fines: 21.46  
Number of Data Points: 89

Occurrence Code:
1 = 1 occurrence, 2 = 2 occurrences, ...
A = 10 occurrences, B = 11 occurrences, ...
G. REFERENCES

APPENDIX III-1. TRIANGULAR PLOT COMPUTER PROGRAM

The following program was developed by Mineral Resource Associates and is written in FORTRAN. Significant modifications may be required to optimize the program and install it on other computer systems.

Data input is from a specially prepared database. The user may elect to modify the data file identification sequence and the format code to utilize existing databases. Additional FORTRAN statements will be required to convert tons per acre to percentages for the various size components.

For additional assistance contact Henry J. Lamb of Mineral Resource Associates.
PROGRAM TRIPLT
LOGICAL IBL, IDOT, IBLK
DIMENSION IPLOT(21,41), IPLOTT(21,41), IHOLE(2), IFILE(6),ICODE(2)
DIMENSION IOPER(25), IMINE(20), IDLN(5), IDLM(15)
DATA IDOT, IBLK, IBL, ISC, IPR/'.', '.007,1,2/.

C INTRODUCTION
WRITE(4,1100)
1100 FORMAT('3X,'PROGRAM SERIES: MATRIX CLASSIFICATION SYSTEM',
     1 '3X,'PROJECT: GIW-RIPR',
     2 '3X,'PROGRAMMER: HENRY J. LAMB DATE: FEB-MAR, 1988',
     3 '3X,'THESE PROGRAMS ARE WRITTEN IN FORTRAN. SIGNIFICANT',
     4 '3X,'CHANGES MAY BE NECESSARY PRIOR TO INSTALLATION ON ANOTHER',
     5 '3X,'SYSTEM. ')
1104 WRITE(4,201) IBL.
201 FORMAT('5X,'READY TO CONTINUE? (Y/N): ',A1)
   READ(4,1101) IA
1101 FORMAT(A1)
   IF (IA.EQ.'Y') GOTO 1102
   IF (IA.EQ.'N') GOTO 999
   WRITE(4,1103) IBL
1103 FORMAT('3X,'INCORRECT ANSWER. REPLY WITH Y (YES) OR N (NO). ')
   GOTO 1104

C FILE IDENTIFICATION SEQUENCE - INPUT FILE
1102 WRITE(4,10) IBL.
10 FORMAT('3X,'THE DATA FOR THIS PROGRAM IS ENTERED FROM A FILE.'
   1 '3X,'IDENTIFY THE INPUT DATA FILE.'
   2 '3X,'ENTER (LUN,IFILE,DRIVE): (X,XXXXXXXXXX,X)',A1/30X)
   READ(4,11)LUN,IFILE,IPR
11 FORMAT(I10,1X,5A2,A1,1X,I1,1X)
   CALL OPEN (LUN,IFILE,IPR)
   READ(LUN,12)
12 FORMAT(1X)

C TRIANGLE INITIALIZATION
997 DO 90 I=1,21
   DO 90 J=1,41
      IPLOT(I,J)=0
90   IPLOT(I,J)=IBLK
   DO 91 J=1,41
91   IPLOT(21,J)=IDOT
      J=21
   DO 92 I=1,20
      IPLOT(I,J)=IDOT
92   J=J-1
   J=22
   DO 93 I=2,20
      IPLOT(I,J)=IDOT
93   J=J+1
      AN=0.
      SPEB=0.
      SPEED=0.
      SFINE=0.
C DATA INPUT SEQUENCE
READ (LUN, 120) IOPER, IMINE, IDLN, IDLM
120 FORMAT (1X, 25A2/1X, 20A2/1X, 5A2/1X, 15A2)
998 READ (LUN, 100, END=999) ICODE, ISEC, ITMP, IRNG, IHOLE, PCPEB, PCPEED, PCSL,
   *IDRAG
100 FORMAT (2I3, 1X, 3I2, 1X, A2, I3, 3F6.3, 1X, I1)
   SFD=SFED+PCPE
   SPEE=SPEED+PCPEED
   SFINE=SFINE+PCSL
   AN=AN+1.

C PLOTTING COORDINATE CALCULATION SEQUENCE
   IX=(21.-((21.*PCPB)/100.))0.5
   K=41-(21-IX*X2)
   AX=IX*1.
   AK=K*1.
   IY=(AK*(PCPB/(PCPB+PCSL)))+1.+(21.-AX)
   IPOINT(IX, IY)=IPOINT(IX, IY)+1
   WRITE (1PR, 150) ISEC, ITMP, IRNG, IHOLE, PCPEB, PCPEED, PCSL, IX, IY
150 FORMAT (1X, 3I2, 1X, A2, I3, 1X, 3F7.2, 2(2X, I2))
   IF (IDRAG.EQ.1) GOTO 9999
   GOTO 998

C PLOTTING CODE ASSIGNMENT
9999 DO 990 I=1, 21
   DO 990 J=1, 41
      IF (IPOINT(I, J).EQ.1) IPOINT(I, J)=1'
      IF (IPOINT(I, J).EQ.2) IPOINT(I, J)=2'
      IF (IPOINT(I, J).EQ.3) IPOINT(I, J)=3'
      IF (IPOINT(I, J).EQ.4) IPOINT(I, J)=4'
      IF (IPOINT(I, J).EQ.5) IPOINT(I, J)=5'
      IF (IPOINT(I, J).EQ.6) IPOINT(I, J)=6'
      IF (IPOINT(I, J).EQ.7) IPOINT(I, J)=7'
      IF (IPOINT(I, J).EQ.8) IPOINT(I, J)=8'
      IF (IPOINT(I, J).EQ.9) IPOINT(I, J)=9'
      IF (IPOINT(I, J).EQ.10) IPOINT(I, J)=A'
      IF (IPOINT(I, J).EQ.11) IPOINT(I, J)=B'
      IF (IPOINT(I, J).EQ.12) IPOINT(I, J)=C'
      IF (IPOINT(I, J).EQ.13) IPOINT(I, J)=D'
      IF (IPOINT(I, J).EQ.14) IPOINT(I, J)=E'
      IF (IPOINT(I, J).EQ.15) IPOINT(I, J)=F'
      IF (IPOINT(I, J).EQ.16) IPOINT(I, J)=G'
      IF (IPOINT(I, J).EQ.17) IPOINT(I, J)=H'
      IF (IPOINT(I, J).EQ.18) IPOINT(I, J)=I'
      IF (IPOINT(I, J).EQ.19) IPOINT(I, J)=J'
      IF (IPOINT(I, J).EQ.20) IPOINT(I, J)=K'
      IF (IPOINT(I, J).EQ.21) IPOINT(I, J)=L'
      IF (IPOINT(I, J).EQ.22) IPOINT(I, J)=M'
      IF (IPOINT(I, J).EQ.23) IPOINT(I, J)=N'
      IF (IPOINT(I, J).EQ.24) IPOINT(I, J)=O'
      IF (IPOINT(I, J).EQ.25) IPOINT(I, J)=P'
      IF (IPOINT(I, J).EQ.26) IPOINT(I, J)=Q'
      IF (IPOINT(I, J).EQ.27) IPOINT(I, J)=R'
      IF (IPOINT(I, J).EQ.28) IPOINT(I, J)=S'
      IF (IPOINT(I, J).EQ.29) IPOINT(I, J)=T'
IF (IPLONT(I,J) .EQ. 30) IPLONT(I,J) = 'U'
IF (IPLONT(I,J) .EQ. 31) IPLONT(I,J) = 'V'
IF (IPLONT(I,J) .EQ. 32) IPLONT(I,J) = 'W'
IF (IPLONT(I,J) .EQ. 33) IPLONT(I,J) = 'X'
IF (IPLONT(I,J) .EQ. 34) IPLONT(I,J) = 'Y'
IF (IPLONT(I,J) .GE. 35) IPLONT(I,J) = 'Z'
APEB = SPEB/AN
APEED = SFEED/AN
AFINE =SFINE/AN

C PLOT TO SCREEN SEQUENCE
WRITE (ISC, 101)
101 FORMAT (35X, '100% PEBBLE')
   DO 99 I = 1, 21
99 WRITE (ISC, 102) (IPLONT(I,J), J = 1, 41)
102 FORMAT (20X, 41(A1))
WRITE (ISC, 103)
103 FORMAT (16X, '100% FINES', 30X, '100% FEED')

C PLOT TO PRINTER
WRITE (IPR, 111)
111 FORMAT (1HL///////////35X, '100% PEBBLE')
   DO 199 I = 1, 21
199 WRITE (IPR, 112) (IPLONT(I,J), J = 1, 41)
112 FORMAT (20X, 41(A1))
WRITE (IPR, 113)
113 FORMAT (16X, '100% FINES', 30X, '100% FEED')
WRITE (IPR, 114) IOPER, IMINE, IDLN, IDLM
114 FORMAT (/16X, 25A2/16X, 20A2/16X, 'DRAGLINE NUMBER:', 5A2/16X,
      'DRAGLINE MODEL: ', 15A2)
WRITE (IPR, 115) APEB, AFEEP, AFINE, AN
115 FORMAT (/30X, 'AVERAGE % PEBBE':, F6.2/30X, 'AVERAGE % FEED:',
      F8.2, /30X, 'AVERAGE % FINES:', F7.2/30X, 'NUMBER OF POINTS:', F6.0)
WRITE (IPR, 116)
116 FORMAT (/1HL)
GOTO 997
999 CONTINUE
END
IV. THE GIW HYDRAULIC LABORATORY TESTS AND ANALYSIS
OF THE LAB AND FIELD PIPELINE DATA

A. INTRODUCTION

Although there are several semi-empirical methods for the
prediction of the flow characteristics of phosphate slurries, the
variation of the size distribution of phosphate matrix material coupled
with the differing rheological behavior of slurries formed from this
matrix, made it essential that a detailed experimental study be carried
out.

In order to examine the influence of pipe size, concentration and
the type of phosphate material on the hydraulic gradient velocity
characteristic, the experimental studies cover the pumping of slurries
made up of three types of phosphate material in pipes of 16, 18 and 20
inches in diameter at concentrations of up to 50% by weight.

In the body of this report, emphasis is placed upon the
methodology of the work carried out with respect to:-

(i) The experimental studies carried out at the GIW Hydraulic
Laboratory and in the field,
(ii) The analysis and discussion of the experimental results.
(iii) The development of algorithms for the prediction of the
resistance characteristics of the pipeline system, the
extensive sets of experimental data, computer listings,
specimen calculations and diagrams, etc. being presented in
the appendices.
Additionally, the underlying thinking which pays particular attention to the application of the results of this work to the phosphate industry is discussed. The latter is considered to be of particular importance in that the analysis and the algorithms that follow from this take into account the information available to engineers in the field and to their experience. In particular, as we might expect, although the size distribution and mineralogy of a phosphate matrix material have a very significant influence upon the flow characteristics of phosphate slurries in pipelines, we nevertheless have to consider the fact that engineers in the field, have only limited information available to them. Such information is normally in the form of the triangular plots defining the relative fractions of pebble, feed and fines, together with the industry's first hand experience of the influence of the clays. The algorithms have been so developed that they provide solutions based upon such limited information on size and information of the mineralogy rather than upon detailed size distributions.

The computer solution for the total system is approached from precisely the same point of view, in that input requested by the computer is information that is readily available to engineers, and the practical import of this too is discussed.

B. THE SELECTION OF PHOSPHATE TEST MATERIALS

Since the objective of the project was to provide design information needed for the pumping of the wide range of phosphate matrix materials currently handled, and since for practical reasons it was only practically feasible for a limited number of types of material
to be examined, considerable judgement had to be exercised in the selection of three types that were suitable for the study.

In making the selection we relied upon the experience of the industry, the mineralogical expertise of Mr. Henry Lamb, and our own experience in the pumping of coarse and fine materials, either separately or in combination.

A detailed discussion of the mineralogical work and the basis for the selection of the materials to be tested is given in Section III, The Geological Analysis.

Coarse materials have been long known to be difficult to pump, compared with fine materials; this is dramatically illustrated in the case of coarse and fine coal pumping. The long distance pumping of coal is achieved at hydraulic gradients of the order of 0.01 - .02 (ft of water/ft), and at specific energies of the order of 0.1 (HPhr/Ton mile). This is achieved by grinding to a top size of approximately 1 mm with a $d_{50}$ of 200 microns. Coarse coal on the other hand, may require hydraulic gradients and specific energies as high as ten times that of fine coal, though work by Duckworth et. al (1,2), has shown that the high gradients in energy consumption can be significantly reduced by combining fine and coarse materials.

In selecting the materials, we thus attempted to obtain matrix types which represented the extremes so far as particle size was concerned. It is clear from the triangular plots of Figure 1, that the Noralyn phosphate of the IMC Fertilizer Co. represents the coarse extreme with some 40% of the material in pebble form, whilst the Suwannee River phosphate of the Occidental Chemical Company, with a 2% pebble component, represents the fine extreme. Experience in the field
Figure 1. Diagram showing the pebble, feed and fines distributions of phosphate matrix materials at various mines (a) Noralyn, (b) Suwannee River, (c) Hookers Prairie.
confirmed that the Noralyn and Suwannee River slurries, were difficult and easy to pump, respectively. A phosphate material which fell between these two extremes, with some 10-14% in the form of pebble, is to be found in the Hooker Prairie phosphate of W.R. Grace & Company.

In all cases clays were found to associate with the phosphate matrix materials and these had the effect of transforming the carrier liquid portion of each slurry from water to a non-Newtonian Bingham Plastic type of fluid. The Noralyn and the Hookers Prairie types of phosphate matrix material have a higher fines content (28%) than the Suwannee River material (<21%) and this results in different rheological properties, higher yield stresses and higher plastic viscosities being associated with the Noralyn and Hookers Prairie slurry carriers.

Thus these three materials were selected, a Noralyn phosphate, a Hookers Prairie phosphate and a Suwannee River phosphate to enable us to assess the relative influence that pebble size and fines have on the pumping of phosphates in the Florida region. We now turn to consider the experimental program that has been carried out to quantify these and other factors which influence the pumpability of phosphate slurries.

C. THE EXPERIMENTAL STUDIES

1. General

While numerous studies of the flow characteristics of slurries in pipes have been undertaken since the pioneering work of Durand (3), and many different types of correlation have been developed, few of these
have found general acceptance. Where we are interested only in very rough approximations to performance many of the correlations are appropriate. However, as in this case, we are anxious to obtain equations and correlations that will give a reasonably close agreement between prediction and operating experience, it is considered essential to carry out carefully controlled experiments using the types of material and their slurry form that are to be found in the field. It is reasonable to expect that the correlations based on such work will produce predictions that will be in close agreement with practice. Furthermore, by carrying out the experiments in pipes of the same diameter as those to be used in the field, we avoid the problems that can be involved in scaling up the data. We should not be surprised by this move to full scale testing, for although the aircraft industry has used soundly based model testing since its inception, the tendency has been towards full scale testing, made possible by the development of large scale wind tunnel test facilities.

The large scale testing facilities available at the GIW Hydraulic Testing Laboratory for the testing of slurry flows in a pipe have made it possible to carry out full scale tests in a controlled laboratory environment. Additionally, the company's experience in on-line data acquisition and analysis has enabled it to carry out field trials on pipelines of the same diameters carrying slurries that are substantially the same as those tested in the laboratory.

2. The GIW Test Facility

A detailed account of the GIW Hydraulic Laboratory has been given in reference 2 and therefore only the features of the facility that
have made this study possible are discussed here; the availability of a motor with a power output of 1500 KW, and a data logging and analysis system that is capable of handling the data generated by some 30 transducers, many of which are used to instrument the test equipment of this study. The instrumentation available in the laboratory is as follows:

(i) piezoresistive transducers, Bourdon tube pressure gauges and manometers,
(ii) magnetic flowmeters, bend meters and tanks for volumetric flow measurement and calibration,
(iii) 4-IC thermistor-type temperature transducers,
(iv) 1100; 2200; 25,000 and 50,000 Nm torque bar units,
(v) magnetic coupling and photoelectric eye tachometers,
(vi) gamma ray attenuation, vertical U-tube and a sampler collector and weighing system for slurry density measurement.

All instruments are normally duplicated and are calibrated prior to a testing program. A typical set of calibration data obtained prior to this project is given in Appendix B. The control of motors and valves is by electrical or pneumatic control devices actuated from the control room. Data collection is performed at a minimum of 20 readings per second over any of the available 32 channels of 12 bit accuracy,
and is under the control of software programs. Monitoring, averaging and storage of the data may be varied during a test.

3. The Test Equipment

In addition to the availability of the above equipment it was clearly necessary to build a dedicated test loop for the testing of pipes of 16, 18 and 20 inches in diameter, of sufficient length to provide for the attainment of fully established flow in the test sections. A method of loading was devised which was capable of loading some 20 tons of material into the system in as little as one or two minutes, (and every effort was made to achieve this), the latter requirement arising from the need to keep degradation, due to recirculation around the loop to a minimum. It was also necessary to provide for the periodic flushing of the system so that water only tests could be carried out throughout the test program, and to provide for the test material to be periodically renewed. For this purpose a by-pass circuit fitted with a cyclone separator was installed.

The above features are shown in Figure 2 where we see that the pipes are arranged in series and are provided with slurry at a sensibly constant concentration by means of a centrifugal pump having a capacity of some 20,000 USGPM (75.7 cu.m./minute) at a head of some 300 ft of water (91 m. of water). Each test pipe is fitted with a test length of about 50 pipe diameters preceded by an approach length of about 75 pipe diameters of straight pipe. Two sets of pressure taps, A and B, are fitted in the upper part of each test pipe, one on each side of the plane of symmetry, two pressure transducers being connected in parallel
Figure 2. Diagrammatic layout of test loop for phosphate slurries.
across each pair of taps "A" and taps "B", for the measurement of the hydraulic gradient.

The flow rate was measured by means of a magnetic flowmeter and a bend meter and the delivered slurry S.G. was measured by means of the vertical U-tube S.G. loop and by a gamma-ray attenuation density meter. Pressure transducers were connected across the two sections of the U-tube, one across the rising pipe section and one across the falling pipe section for the S.G. measurement and across the bend meter for the flow measurement. Measurements were also made of the pump speed and torque for the analysis of the pump performance.

Perhaps one of the most challenging problems was that of loading very large quantities of phosphate into the system, and the method whereby this was achieved is shown in Figure 3. This loading system consists essentially of a dump truck of 20 tons in capacity which feeds the material directly into a sump, partially filled with water. A set of four nozzles, 4 inches in diameter, are arranged in parallel and are supplied with high pressure fluid, initially water and then slurry when the material has passed through the pump. These nozzles serve to break up large agglomerates of the phosphate, wet and de-aerate the material, and generally assist in the rapid loading of the material into the system. In order to assist in the entrainment of the material and its passage into the pump suction pipe, the return line feeds directly into the sump at a location immediately opposite the entrance to the suction pipe.

The material unloading system, is shown in Figure 2, and includes a knife-gate valve which serves to by-pass the slurry from the system.
Figure 3. Loading system for phosphate material.
and allows the slurry to pass to a cyclone separator. The latter separates the water from the material, returning the water to the sump, and dumping the material into a hopper from which it is periodically discharged into trucks for disposal.

While this unloading system was appropriate in the case of the coarse Noralyn phosphate slurries, this method proved to be inappropriate in the case of slurries formed from the Suwannee River and Hookers Prairie phosphate materials. In these latter slurries, the water combined with the phosphate fines to form virtually homogeneous Newtonian or non-Newtonian slurries, which could not be adequately dewatered by the cyclone, and in such cases the slurry was simply discharged from the pipe onto the ground and allowed to dewater naturally by evaporation.

D. THE EXPERIMENTS

As mentioned previously, in order to minimize degradation it was necessary to keep the time during which the material was circulating in the loop to a minimum and to avoid as far as possible the use of valves for flow control by throttling. To this end estimates were made of the amount of material required to attain the required concentration, this amount of material then being made available in a truck or trucks. The pump was run up to speed sufficient to provide a flow of some 12,000 USGPM and the material was then dumped into the sump. This worked reasonably satisfactorily, and even at the highest material loading flow rates of 2 Ton/minute the pump did not have any difficulty in ingesting the material. There was, however, one traumatic experience during
loading which occurred when a batch of material became hung up in the
dump truck with the angle of the truck at about 60 degrees to the
horizontal and then suddenly slid as a solid mass and caused some
permanent damage to the sump entrance. The pump appeared, however, to
carry on as though nothing had occurred.

Once the material had been loaded and drawn into the pipe loop the
pump was shut down, the material allowed to settle in the pipe, and the
air entrained during the loading process was vented to atmosphere
through the specially provided vents. If, during the period in which
the slurry was circulating, the S.G. of the slurry, as measured by the
vertical U-tube, was close to that required, the tests were begun.
Otherwise, an additional amount of material was added as discussed
above to attain the required S.G.

Tests were carried out at a sensibly constant delivered
concentration for a range of flows up to the maximum attainable of
20,000 USGPM corresponding to a slurry velocity of approximately 28
ft/s in a pipe of 17.25 inches in internal diameter. Variation of the
flow was achieved by altering the pump speed by means of a fluid drive,
each test taking about one hour for 15 sets of readings. This was the
minimum time required and meant that the material made some 70 circuits
around the pipe loop. A typical set of data so obtained is given in
Table 1.

Other tests carried out included water tests before and after the
circulation of sand through the loop to assess the water resistance
characteristic and hence the roughness ratio, e/D, the particle size
analysis by both wet and dry sieving, and the settling velocity of the
various solids that make up the phosphate material. The roughness was found to be of the order of $5 \times 10^{-5}$, the shape factor 0.26, and typical size distributions are given in Figures 4 and 5. A detailed discussion of the size analysis is given in the Experimental Results section.

E. THE EXPERIMENTAL RESULTS

1. **Hydraulics Laboratory**

   The experimental data acquired by means of an on-line data acquisition and computing system is of the form shown in Table 1, the complete sets of such data for the three materials studied being given in Appendix C. However, for the purpose of discussion of the results it is convenient to present them in the form of the characteristic hydraulic gradient-velocity curves for which the concentration has been maintained sensibly constant. Typical sets of such curves for slurries of Noralyn, Suwannee River and Hookers Prairie phosphate matrix flowing in a pipe of 17.25 inches in internal diameter are shown in Figure 6, 7 and 8.

   In Figure 6, we see that the curve for the Noralyn slurry, which has a pebble fraction of 0.46, is of the form expected in which coarse material is present and the coarse material flows in the form of a sliding bed, particularly at velocities close to the minimum hydraulic gradient condition. The curves for the Suwannee River slurry, shown in Figure 7, on the other hand, having a pebble fraction of the order of 0.01, appears to have no tendency to form the familiar hooked curve form of a settling suspension even at a concentration of 50% The
Figure 4. Typical size distribution for the Noralyn Phosphate Material
Figure 5. Typical size distributions for the Suwannee River and Hookers Prairie phosphate material.
Figure 6. Test loop hydraulic gradient-velocity characteristic curves for the transport of Noralyn phosphate slurries at a temperature of 70°F in a pipe of 18'' nominal diameter.
Figure 7. Test loop hydraulic gradient-velocity characteristic curves for the transport of Suwannee River phosphate slurries at a temperature of 70°F in a pipe of 18 inches nominal diameter.
Figure 8. Test loop hydraulic gradient-velocity characteristic curves for the transport of Hookers Prairie phosphate slurries at a temperature of 70°F in a pipe of 18" nominal diameter.
curve could be construed as a curve of a Newtonian fluid or a non-Newtonian fluid of low yield stress. The hydraulic gradients in the operating region of velocities of 10-15 ft/s are seen to be some 25% lower than the Noralyn slurry, thus confirming that the Suwannee River slurries are easy to pump.

The final slurry to be examined in the laboratory was the Hookers Prairie slurry and the characteristic curve is shown in Figure 8. This slurry had a pebble fraction of the order 0.115, and was expected to be of intermediate pumping difficulty. However, the laboratory data suggests that this slurry is difficult to pump, the hydraulic gradients at a concentration of only 40% being similar to those of the Noralyn slurry at 50%. Furthermore, the shape of the curves suggests that the slurry is behaving as a non-Newtonian Bingham type fluid. We should not be surprised at this, since a relatively low pebble fraction (0.115) implies that these is a large fraction of feed plus fines (0.885), and it is the fines, (-600 microns), fraction, of about 0.8, and the associated clays that govern the rheology of the slurry carrier fluid. Whether the apparent rheological behavior of the slurry flowing in the pipe of 18 inches in diameter in the laboratory is characteristic of the behavior in the field situation and to the behavior deduced from small scale tube-rheometer tests remains an open question until we consider the results of these other sets of experimental data.

2. **Field Tests**

The experiments that were carried out in the laboratory could not be wholly replicated in the field tests at the Noralyn, Suwannee
River and Hookers Prairie mines due to the difficulties of controlling the variables during production. However, this was partially overcome by using an on-line data acquisition and computing system that was very similar to that used in the laboratory and the same S.G. loop that had been used. The methodology of the field study is given in the separate Field Test section, Section V of the report and this will not therefore be discussed further. However, the experimental data has been extracted from Section V for the purpose of comparison with the laboratory data.

In order to illustrate the correspondence between the laboratory and the field data, the results have been plotted in the form of hydraulic gradient-velocity curves and these are given in Figures 9, 10 and 11. It is clear that only in the case of the Noralyn slurry is there a close agreement between the laboratory data and the field data. It will be noted that due to the inevitable variability that occurs in the field there is considerable scatter in the data shown in Figure 12, and therefore the field data are expressed as a single point, together with an indication of the spread of the data.

By far the greatest discrepancy between the laboratory and the field data is seen to occur in the case of the Hookers Prairie slurry. Now, in considering this we recall that the Hookers prairie slurry, and to a lesser extent the Suwannee River slurry, appear to behave as non-Newtonian slurries of the Bingham type. We may expect, therefore, the rheological properties of such slurries to be altered due to circulation through the pipe test loop in the laboratory, this being caused by the degradation of the material to produce more fines and the
Figure 9. Comparison of test loop hydraulic gradient-velocity characteristic curves for the Noralyn slurries at a temperature of 70°F and the corresponding field data.
Figure 10. Comparison of test loop hydraulic gradient-velocity characteristic curves for the Suwannee River slurries at a temperature of 70°F and the corresponding field data.
Figure 11. Comparison of test loop hydraulic gradient-velocity characteristic curves for Hookers Prairie slurries at a temperature of 70°F and the corresponding field data.
Figure 12. Field trial data for the pumping of Noralyn phosphate in a pipe of 18 (in) in nominal diameter.
associated release of clays as the material continually passes through the pump. In fact during the duration of a single test, normally about one hour, the material could make as many as 70 passes and this is to be compared with a maximum in the field equal to the number of pumps in the line. In the actual field tests measurements were made after the 4th, 2nd and 5th pumps for the Noralyn, Suwannee and Hookers Prairie slurries, respectively.

We may therefore expect in general to obtain higher gradients in the laboratory tests, this being particularly so in the case of the slurries of high feed and fines content (i.e. low pebble). In order to attempt to resolve this question a series of rheological tests were carried out using fines from the laboratory test loop, following the tests, and from material that had not been circulated through the loop. If the supposition, that degradation during pumping through the loop had created fines and released clays, with a corresponding change in the rheological properties were true, then this might be borne out by the results of rheological studies.

3. Rheological Tests

The test procedure adopted and the experimental data are presented in Extrusion Rheometer section, Appendix H of the report and the details of this testing will not be discussed. The raw data obtained during the tests will, however, be analyzed in order to determine the rheological properties of yield stress, $\tau_y$, and the plastic viscosity, $\eta$, of the several slurries, and to determine the functional relationship between these properties and the volumetric
concentration. Use is made of the fact that the specific gravity of a slurry is related to the volumetric concentration by the variable, \((S_{mca} - 1)\). The preparation of plots showing the relationship between the rheological properties and \((S_{mca} - 1)\) presents no problem in the case of the rheological test data. However, to assess the equivalent curves from the pipeline test data, it is necessary to determine the hydraulic gradient of the carrier fluid, \(i_c\), by subtracting the total hydraulic gradient, \(i_m\), the component arising from the pebble content. The equations used for this purpose will be discussed subsequently in the analytical section that follows.

The results obtained from the rheological tests and the pipeline tests are shown in Figure 13 and 15 and since, it is more convenient, from the point of view of the computer to express the relationship in a mathematical form, power laws of the following form have been fitted to all the data,

\[
\tau_y = C_y (S_{mca} - 1)^N
\]

\[
\eta = \mu_w \left( C_e (S_{mca} - 1)^M + 1 \right)
\]

where \(N\) and \(M\) are constants having values of 3.78 and 2.2, respectively, and \(C_y\) and \(C_e\) vary according to the slurry under consideration and its previous history.

One of the most striking features of the curves of Figure 13, relates to the curves for the Hookers Prairie slurry. In this case we see that each of the curves exhibits markedly different behavior. The
Figure 13. Relationship between the yield stress of Noralyn, Suwannee and Hookers Prairie carrier fluids and data obtained from a $S_{\text{mca}-1}$ based on rheometer and a test loop pipeline.
Figure 14. Relationship between the plastic viscosity ratio ($((\eta/\mu_{app})-1)$ and ($S_{mca}-1$) based on rheometer and test loop pipeline.
Figure 15. Hydraulic gradient-velocity characteristic curves for the transport of Noralyn phosphate slurries at a temperature of 70°F in a pipe of 17.25 (in) in internal diameter.
first rheological test used a slurry that had been obtained from the pipeline in the laboratory at the conclusion of the test at 50% concentration by weight, the second slurry was made from the raw material and the pipeline curve was based upon the pipeline data. The differences may be explained as follows:

(i) The first test had been carried out on material that had been degraded during the pipeline tests, but in this case it had been left some considerable period before being tested. The effect of aging is to allow the floc structure of the slurry, which would have been broken down during pumping, to rebuild, thereby increasing the yield stress.

(ii) The pipeline test curve relates to basically the same type of slurry, but without the aging effect.

(iii) The curve of the second rheological test relates to a slurry formed from the raw material which had not been subjected to degradation.

The important curves from the point of view of explaining the discrepancy between the laboratory test data and that of the field test are the pipeline test curve and the second rheological test curve of Figure 13. It can be seen that the constant $C_y$ for the pipeline is twice that of the second rheological test (i.e. the yield stresses are in the ratio of 2:1). Now, since during the field trials the slurry had only passed through five pumps it is unlikely to have been significantly degraded and may be expected to behave in the same
way, from a rheological point of view, as the slurry used in the second rheological test. This supposition is borne out when we see that the hydraulic gradients obtained in the laboratory and the field are in the ratio of about 2:1.

The rheological tests for the Noralyn slurry carrier seem to have substantially the same yield stress as that obtained from the second rheological test of the Hookers Prairie slurry. This is to be expected, since the fines contents of the two materials are approximately the same (i.e. 28%). The fact that the yield stress of the Noralyn slurry taken from the laboratory pipeline and that formed from the raw material were not significantly different is thought to be due to the fact that this material had a high pebble content, and did not suffer from significant degradation.

In the case of the Suwannee River slurry carrier, it would appear that there was considerable degradation during pumping in the laboratory leading to a yield stress that was 10 times as great as that obtained from the rheological tests on the slurry formed from the raw material. From similar reasoning to that used above, it would appear to be reasonable to assume that the rheology obtained for the slurry formed from the raw material provides a good model for the pipelines in the field.

So far as the plastic viscosity is concerned, there is considerable scatter in the data, though the Noralyn and the Hookers Prairie carriers appear to behave similarly, a constant of $C_e = 150$ appearing to give the best fit to the data. The Suwannee River carrier follows the same trend as the yield stress in that higher viscosities appear to be associated with the laboratory pipeline test data than
with the slurry formed from the raw material. However the value of $C_e = 110$, which is that obtained for the pipeline test compared with a value of 50 obtained for the raw material slurry, appears to fit the field data better, though this is as yet unexplained.

4. Size Analysis

Throughout the test program the materials were sized using wet screens covering a size range of $75 < d < 12500$ microns. Tests were carried out on the material as received after being trucked from Florida to Augusta and also after the material had been pumped through the test loop during the tests. Sampling from the pipeline was effected by means of tapping off the slurry from either a pipe of 2 inches or a pipe of 6 inches in diameter, located in the bottom of a horizontal section of the main pipe.

In considering the results of the size analysis carried out at the GIW Laboratory, it is important to note that both the trucking and the sampling technique used during the pipeline tests have the effect of biasing the measured size distribution in such a way that the fraction of the larger material is greater than it should be. When the results of the analysis are compared with the analysis carried out by H.H. Lamb, the results of which are reported in the Geological Analysis of Section III, it is found that the pebble sized fraction of the Noralyn phosphate is of the order of 0.4, compared with a mean value of 0.55 as measured at GIW. There is also a discrepancy in respect to the fines, the Geological Analysis reporting a fines fraction of some 0.29 compared with a value of 0.19.
The differences are considered to be due to the segregation of fines to the bottom of the truck during trucking, this being particularly so in the case of the high pebble Noralyn phosphate. It is virtually impossible to remix such a large quantity and it is suspected that the sample was taken from a volume of material close to the surface. The problem of segregation is much less in the case of the Suwannee River and the Hookers Prairie phosphates because of the lower pebble contents. In fact, the mean values of the pebble fraction are 0.011 and 0.136 for the Suwannee River and Hookers Prairie materials, respectively. These values are to be compared with values of 0.0186 and 0.136 given in the Geological Report.

The fines fractions obtained from the analysis at GIW give a mean value of 0.07 with a standard deviation of 0.07 for the Suwannee River phosphate and a mean value of 0.287 with a standard deviation of 0.042 for the Hookers Prairie material. The above mean values are to be compared with values of 0.2146 and 0.26 given in the Geological Report. While the Hookers Prairie fines fraction is in reasonable agreement the large discrepancy in the case of the Suwannee River fines may be due to sampling. It is interesting to note that there is a closer agreement for the Suwannee River material when the sample is taken from the pipeline, values of 0.0186 and 0.11 being obtained for the pebble and fines, respectively. This is thought to be due to the homogenization of the whole truck load coupled with the biasing towards the high end of the size distribution due to sampling from the bottom of the pipe.
### SUMMARY OF MEAN VALUES OF PEBBLE AND FINES
(Before Pumping)

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>MEAN</th>
<th>SDEV</th>
<th>MEAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>GiW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noralyn*</td>
<td>0.547</td>
<td>0.067</td>
<td>0.376</td>
</tr>
<tr>
<td>Pebble</td>
<td>0.19</td>
<td>0.07</td>
<td>0.2886</td>
</tr>
<tr>
<td>Noralyn</td>
<td>0.0114</td>
<td>0.067</td>
<td>0.0186</td>
</tr>
<tr>
<td>Fines</td>
<td>0.074</td>
<td>0.076</td>
<td>0.215</td>
</tr>
<tr>
<td>Suwannee River Pebble</td>
<td>0.136</td>
<td>0.067</td>
<td>0.136</td>
</tr>
<tr>
<td>Suwannee River Fines</td>
<td>0.2865</td>
<td>0.042</td>
<td>0.26</td>
</tr>
<tr>
<td>Hookers Prairie Pebble</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hookers Prairie Fines</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Note. In view of the large discrepancy between the pebble fraction as measured by GiW and Mineral Resource Associates a mean value of 0.46 is used in the analysis of the data for the hydraulic transport.

Although the intention of measuring the size distribution, following the pumping of the slurry through the pipe test loop, was to assess the extent of degradation, in the event the sampling technique caused a distortion of the size distribution such that in the case of all the slurries tested the fraction of the pebble size increased and the fines decreased. Since this is clearly not possible we have regrettably to ignore these data.

In conclusion of this section, in which we have discussed the pipeline tests in the laboratory and the field, the rheological tests and the size analysis, we have been able to reconcile the differences between the laboratory and field data and lay the foundations for the development of a semi-empirical mechanistically based model. This model is subsequently to form the basis for the algorithm for the computer program.
F. THEORETICAL CONSIDERATIONS AND ANALYSIS

Clearly, it is of practical importance to develop equations for the relationship between the hydraulic gradient and the velocity in order that the hydraulic gradient-velocity characteristic may be predicted for any required concentration, pipe size and particle size distribution. Such predictions are particularly important to the pump designer for the selection of the most suitable pump for operation at a point close to the high efficiency condition. It is important to the operator also in that he benefits considerably in terms of reduced energy consumption, a major consideration in the type of application being considered. However, the equations developed from the data obtained for the very specific type of material are likely to lack generality since any constants obtained from the experimental data will reflect the characteristics of the phosphate material and the carrier fluid.

We need not be too concerned about this, provided that in carrying out an analysis we base it on sound physical principles. By so doing we are likely to obtain a form of equation that is generally applicable and for which the constants that may have to be determined experimentally will reflect the different behavior, if any, arising from the transport of materials of differing origins, types and size distributions. Furthermore, the equations developed in this way are likely to give us some insight into the effect of scale, thus making it possible to predict the flow characteristics in large pipes from experiments carried out in smaller pipes.

Clift, et al (6) have extended the mechanistic sliding bed model, that has been developed by Wilson (7) over the past 20 years, to the
flow of slurries in which there is a sliding bed and a suspended component contribution to the excess hydraulic gradient that occurs when solids are added to a fluid such as water. However, they assume that the two components are due to the sliding bed flow and the homogeneous flow and assume further that the fraction of the total solids that moves in the form of a sliding bed is related to the ratio of the velocity required to suspend a solid, $V_{su}$, and the fluid velocity, $V_m$. This approach has led to a relatively simple method of scaling and appears to be particularly useful in cases where the spread of sizes is not too great, and where any fines present do not form a carrier fluid which is different from water.

Almost without exception settling slurry flows, of particle $d > 1$ mm, have a sliding bed component especially in the operating region which is normally close to the condition of the minimum hydraulic gradient. In the suspended portion of the flow, by far the major portion of the particles do not, except at high velocities far removed from the operational region, flow homogeneously, i.e. in the form of a sensibly constant continuum analogous to a liquid. Instead they flow in a region in which there is a concentration gradient which decreases from the upper region of the pipe to the surface of the sliding bed. If this is so then there would appear to be merit in including the very fine particles, which could conceivably behave in a pseudo homogeneous way, with the non homogeneous suspended particles.

In cases where the finer particles, which at higher velocities, (i.e. velocities greater than 10 ft/sec) flow in suspension above the sliding bed, do not when combined with water form a fine slurry having
properties different from water (e.g. form a Newtonian slurry of density and viscosity higher than that of water), such a fine particle-water suspended flow is characterized by slip between the particles and the faster moving surrounding water. Duckworth and Addie (8) have shown that this form of suspended flow produced an excess gradient, \((i_m - i_w)\), component in addition to that produced by the sliding bed, where this excess gradient component may be expressed by a term

\[
\left( \frac{i_m - i_w}{S_m - 1} \right) = (1 - R) \frac{V_{\infty h}}{V_m}
\] (3)

We shall, however, see later that where the water carrier loses its identity by combining with the fine particles and associated clay particles to form a homogenous carrier, the approach discussed above is inappropriate.

However, let us now turn to the major component of the excess gradient, due to the sliding bed. Some 30 years ago Newitt et.al. (9) developed an equation for the sliding bed region which showed that for cases in which the whole of the material was in the bed, the excess gradient was given by

\[
\frac{i_m - i_w}{S_m - 1} = \text{constant}
\]
Subsequent work by Clift et al. (loc cit), modified this equation to take into account the fact that normally where there was a spread of sizes some of the material would be in suspension and the remainder would be in the sliding bed, such that

\[
\left(\frac{i_m - i_w}{S_m - 1}\right) = \text{constant} \left(\frac{V_{su}}{V_m}\right)^m \quad (4)
\]

where

\[
V_{su} = V_{\omega h} \frac{8/\lambda_w}{\lambda_w} \exp\left(\frac{45}{d/D}\right) \quad (5)
\]

the term \((V_{su}/V_m)^M\) being a measure of the fraction of material in the sliding bed. In this approach experiments have to be carried out to determine, for a given slurry, the constant and the index \(m\) in equation 4.

From an analysis of the Noralyn (NP) slurry data the above equation 4 has been found to reduce to

\[
\frac{i_m - i_w}{S_m - 1} = 0.11 \left(\frac{V_{su}}{V_m}\right)^{0.57} \quad (6)
\]

In addressing the same problem, Duckworth et al (loc cit), have been able to show that, provided the size distribution of the particles is known, as in the case of the (NP), as shown in Figure 4, the fraction of particles in the sliding bed may be expressed by
\[
R = \sum_{d_{su}} (V_{su} / V_m)^{1.7} \Delta \psi
\]

(7)

where \( V_{su} \) is the suspension velocity, equation 5, of particles of size \( d \), having a proportion \( \Delta \psi \) of the assemblage of particles, and \( d_{su} \) is the particle size at incipient suspension, (i.e. \( V_{su} = V_m \)). For the particular size distribution of Figure 4, the equation for (NP) slurries, due to Duckworth et al, reduces to

\[
\frac{(i_m - i_w)}{(S_m - 1)} = 0.18R + (1-R)(V_{\infty h} / V_m)
\]

(8)

Since \( R \) and \( V_{\infty h} \) each depend upon the size distribution and concentration, and \( R \) also depends on the pipe size and the concentration, and 0.18 is a constant, equation 7 suggests that it should be possible to predict the excess pressure gradient from a knowledge of the size distribution and the concentration for a range of velocities, \( V_m \), and for pipes of arbitrary size.

Such predictions are compared with the measured values of \( i_m \), for the (NP), in a pipe of 18 inches in diameter, in Figure 15 and it is evident that the predicted and measured values are in reasonable agreement over the practical range of operational velocities of 10-20 ft/sec.

However, as has been pointed out already, the size distribution available to engineers in the phosphate industry, in terms of pebble, feed and fines, is not sufficiently detailed for \( R \) of equation 7 to be
determined, and on this basis the form of equation given in equation 6 would be the preferred form to be used in this work, if we were dealing only with the (NP) type of material.

In fact, such is not the case, for we have to be able to deal with a range of phosphate materials from very coarse, pebble fraction = 0.4, to very fine, pebble fraction = 0.01. Furthermore, we must also be able to deal with phosphate matrix materials with differing amounts of fines present. During the latter stages of the project when the Suwannee River (SRP) and the Hookers Prairie (HPP) slurries were examined, it became clear, that while the form of equation 6 might be appropriate for high pebble content (i.e. low feed and fines fraction), an equation of general applicability would have to take account of the rheology of the carrier liquid associated with each of the phosphate materials, in addition to the pebble fraction and the slurry concentration, $C_w$. To meet these requirements, an equation, based upon the form of equation 5, may be formulated as follows:

$$ (i_m - i_{ca}) = [(S_m/S_{mca}) - 1] C V^{-m} \tag{9} $$

where

- $i_m$ is the hydraulic gradient of the slurry
- $i_{ca}$ is the hydraulic gradient of the carrier fluid
- $S_m$ is the SG of the slurry
- $S_{mca}$ is the SG of the carrier fluid
- $V_m$ is the velocity of the slurry
- $C$ is a constant
- $m$ is a constant power index.
The hydraulic gradient of the carrier, $i_{ca}$, will clearly depend upon the rheological properties of the carrier fluid, these properties depending upon the variable $(S_{mca} - 1)$, as discussed in the section on the experimental results in connection with the rheological tests. Once the functional relationships between the rheological properties, the yield stress, $\tau_y$, and the plastic viscosity, $\eta$, and the variable $(S_{mca} - 1)$ are known (i.e. the constants $C_y$ and $C_e$ of equations 1 and 2 are known), then the experimental data obtained in the laboratory and in the field may be used to determine the constant $C$ and the index $m$. In the Rheological Tests section of the Experimental Results the form of the functional relationships for the rheological properties was discussed and these relationships expressed in graphical form in Figures 13 and 14 and in the generalized form of equations 1 and 2. However, the derivation of yield stress, $\tau_y$, and the plastic viscosity, $\eta$, from the experimental data was deferred and we now consider this.

It will be recalled that the raw data obtained during the rheological tests, and given in Appendix H of the report, consisted primarily of values of the wall shear stress, $\tau_0$, and the corresponding pseudo shear rate, $8V/D$. However, we are interested not in these values per se, but in the rheological properties that can be derived therefrom. For this purpose we use a modified form of the Buckingham equation which applies in the region of high flow rates, thus,

$$\tau_0 = 4\tau_y/3 + (8V/D)\eta$$

(10)
From the experimental values of $\tau_o$ and $(8V/D)$ it is clear that the $\tau_y$ and $\eta$ may be calculated using equation 10, since when $(8V/D) = 0$, $\tau_y = (3/4) \tau_o$ and the slope of the curve $\tau_o$ versus $(8V/D)$ gives us $\eta$. Values so calculated for a range of values of $(S_{mca} - 1)$ have thus been used to plot the curves of Figures 13 and 14. If we use the power law form of equation 1 and 2 given by,

$$\tau_y = C_y (S_{mca} - 1)^N$$

$$\eta = \mu_w (C_e (S_{mca} - 1)^M + 1)$$

we find that for the Noralyn and Hookers Prairie slurry carrier fluids,

$$C_y = 30 \text{ (lbf/sq.ft)}, \quad C_e = 150, \quad N = 3.70 \text{ and } M = 2.2$$

whereas, for the Suwannee River carrier fluid,

$$C_y = 1.5 \text{ (lbf/sq.ft)}, \quad C_e = 110, \quad N = 3.70 \text{ and } M = 2.2$$

Now while it was an easy matter to determine the value of the SG of the carrier, $S_{mca}$, during the rheological tests, if we are to determine $S_{mca}$ for the carrier that is formed during the transport of a particular slurry in the pipeline then we need to develop relationships from which this may be calculated. In order to be able to do this we assume that the carrier is formed from the feed plus the fines and the water in the slurry, the fraction of the feed plus the fines being
equal to \((1-P)\) where \(P\) is the pebble fraction. This assumption is considered to be reasonable, since in the rheological tests, the material used consisted of fines having a size, \(d < 600\) microns, and for the materials examined in the pipeline tests, for which \(d < 600\) microns, the fraction is not significantly different from \((1-P)\), the greatest discrepancy being in the case of the Noralyn phosphate. In the latter case, since \(P\) is relatively large, \(S_{mca}\) tends to be small, \((S_{mca} - 1)\) tends to zero and it is apparent from equations 1 and 2 that the errors in \(\tau_y\) and \(\eta\) due to the error in the fines fraction is also small.

Turning now to the relationship between \(S_{mca}\) and the pebble fraction, \(P\), and the concentration, \(C_w\), it can be shown that,

\[
S_{mca} = \frac{1}{1 - C_{wca} \frac{(S_s - 1)}{S_s}}
\]

where

\[
C_{wca} = \frac{(1-P)(C_w/(1-C_w))}{((1-P)(C_w/(1-C_w)) + 1)}
\]

\(S_s\) being the SG of the phosphate material. We thus see that from a knowledge of \(P\), \(C_w\) and \(S_s\), the carrier SG, \(S_{mca}\), may be determined and hence the rheological properties can be determined for any of the three phosphate matrix materials being conveyed in slurry from under conditions of known pebble fraction and concentration.

We are now in a position to calculate the wall shear stress, \(\tau_o\), and hence the hydraulic gradient of the carrier, which for laminar flow conditions may be obtained from the Buckingham equation,
\[ \tau_y D / 8 \eta V = \alpha / [1 - 4 \alpha / 3 + \alpha 4 / 3] \]  \hspace{1cm} (13)

and

\[ i_{ca} = 4 \tau_o / 1.94 S_{mca} \cdot gD \]  \hspace{1cm} (14)

where

\[ \alpha = \tau_y / \tau_o, \]

for turbulent flow,

\[ i_{ca} = \lambda_{ca} \frac{V^2}{2gD} \]  \hspace{1cm} (15)

where,

\[ (1/\lambda_{ca}^{\frac{1}{3}}) = 1.14 - 2 \log_{10} [(\varepsilon / D) + 21.25 Re_{ca}^{-0.9}] \]  \hspace{1cm} (16)

(\varepsilon / D) being the pipe roughness ratio.

and the Reynolds number of the carrier, \(Re_{ca}\) is given by

\[ Re_{ca} = \rho_w \cdot S_{mca} \cdot V_m \cdot D / \eta \]  \hspace{1cm} (17)

the density of water, \(\rho_w\), being equal to 1.94 (slugs/cu.ft)

The demarcation between laminar and turbulent flow conditions is governed by the equation,
\((1 + \tau_y D/6n V_c) = Re_c/(9.12 - 16. \log_{10}(\varepsilon/D + 21.25 Re_c^{-0.9}))^2 \) (18)

where \(V_c\) is the critical velocity and the Reynolds number, \(Re_c\), is given by

\[ Re_c = \rho_w \cdot S_{mca} \cdot V_c D/n \] (17a)

and \(\rho_w = 1.94\) (slugs/cu.ft).

Equation 18 may be solved by trial and error to give \(V_c\) and \(Re_c\) and hence we may select the appropriate equations to determine \(i_{ca}\) for either the laminar or turbulent region.

We finally use the above relationship for \(i_{ca}\), corresponding to particular conditions of pebble fraction, \(P\), concentration, \(C_w\), and pipe diameter, \(D\), in conjunction with equation 9 and the experimental data obtained during the pipeline tests, to determine the constant, \(C\), and the index \(m\). Now since \(C\) and \(m\) determine the contribution to the hydraulic gradient, \(i_m\), that is due to the pebble material, it is appropriate that we should use the experimental data for the Noralyn phosphate slurry, which has the highest pebble fraction, to determine \(C\) and \(m\).

When this is done for a slurry \(SG, S_m = 1.452\), a concentration, \(C_w = 50\%\), a pebble fraction, \(P = 0.46\) and a pipe diameter of \(D = 17.25\) (in), we find that \(C = 1.2\) and \(m = 0.64\). Thus, the final form of the equation from which the hydraulic gradient \(i_m\) may be calculated is given by,
Equation 19 has been used to calculate the values of \( i_m \) for a range of velocities, for the three phosphate materials and for the three pipe sizes at two concentrations to produce the sets of curves given in Figures 16 to 24. The equation has also been used to determine the yield stress and the plastic viscosity of the carrier fluid in the pipeline tests for the Hookers Prairie and the Suwannee River matrix materials. The values of the yield stress and the plastic viscosity so obtained have been plotted on Figure 13 and 14 together with the values obtained for the rheological tests.

We thus see in conclusion to this section that the hydraulic gradient, \( i_m \), for all of the phosphate materials examined, may be predicted by the equation,

\[
i_m = i_{ca} + 1.2 \left(\frac{S_m}{S_{mca}} - 1\right) v_m^{-0.64}
\]

where

\[
S_m = \left[1-C_w(1-S_s)/S_s\right]^{-1}
\]

\[
S_{mca} = \frac{1}{1 - C_{wca} (S_s - 1)/S_s}
\]

\[
C_{wca} = \frac{(1-P)(C_w/(1-C_w))/((1-P)(C_w/(1-C_w) + 1)}
\]

\[
i_{ca} = 4 \tau_y/(1.94 S_{mca} \cdot gD)
\]

\[
\tau_y = C_y(S_{mca} - 1)N
\]

\[
\eta = \mu_w(C_e(S_{mca} - 1)^M + 1)
\]
Figure 16. Comparison of the hydraulic gradient-velocity lab data and that predicted by equation 19 for a Noralyn slurry flowing in a test loop pipe of 20 inches nominal diameter.
Figure 17. Comparison of the hydraulic gradient-velocity data and that predicted by equation 19 for a Noralyn slurry flowing in a test loop of 18 inches nominal diameter and with that obtained in the field.
Equation 19 (C_w = 50%)

Equation 19 (C_w = 35%)

Noralyn Pebble Fraction 0.46

C_w %

50% Lab

35% Lab

D(in) - 16

Figure 18. Comparison of the hydraulic gradient-velocity lab data and that predicted by equation 19 for a Noralyn slurry flowing in a test loop pipe of 16 inches nominal diameter.
Figure 19. Comparison of the hydraulic gradient-velocity data and that predicted by equation 19 for a Hookers Prairie slurry flowing in a test loop of 20 inches nominal diameter and with that obtained in the field.
Figure 20. Comparison of the hydraulic gradient-velocity lab data and that predicted by equation 19 for a Hookers Prairie slurry flowing in a test loop pipe of 18 inches nominal diameter.
Figure 21. Comparison of the hydraulic gradient-velocity lab data and that predicted by equation 19 for a Hookers Prairie slurry flowing in a test loop of 16 inches nominal diameter.
Figure 22. Comparison of the hydraulic gradient-velocity data and that predicted by equation 19 for a Suwannee River slurry flowing in a test loop of 20 inches nominal diameter and with that obtained in the field.
Figure 23. Comparison of the hydraulic gradient-velocity lab data and that predicted by equation 19 for a Suwannee River slurry flowing in a test loop of 18 inches nominal diameter.
Figure 24. Comparison of hydraulic gradient-velocity lab data and that predicted by equation 19 for a Suwannee River slurry flowing in a test loop of 16 inches nominal diameter.
For the Noralyn and the Hookers Prairie phosphate slurries,

\[ C_y = 30 \text{ (lbf/sq.ft), } C_e = 150, \ N = 3.78 \text{ and } M = 2.2 \]

and for the Suwannee River slurries,

\[ C_y = 1.5 \text{ (lbf/sq.ft), } C_e = 110, \ N = 3.78 \text{ and } M = 2.2 \]

Additionally, in solving the equation 19 we need to know whether the flow is laminar or turbulent and for this purpose we solve the equation,

\[ (1 + \frac{\tau_y D}{6^n V_c}) = \frac{Re_c}{(9.12 - 16 \cdot \log_{10} (\epsilon/D + 21.25 Re_c^{-0.9}))^2} \quad (18) \]

where \( V_c \) is the critical velocity and the Reynolds number, \( Re_c \), is given by

\[ Re_c = \rho w S_{mca} V_c D/n \quad (17a) \]

In cases where the velocity, \( V_m \) is less than \( V_c \) the flow is laminar and \( i_{ca} \) is determined from equation 14 using a value of wall shear stress, \( \tau_o \), calculated using the Buckingham equation, equation 13. For velocities greater than \( V_c \) the flow is turbulent and \( i_{ca} \) is obtained from equation 14 using a value of the wall shear stress, \( \tau_o \), determined from,

\[ \tau_o = \frac{\lambda}{\rho w S_{mca} V_m^2 / 8} \quad (21) \]
where

\[
\frac{1}{\lambda_{ca}^{\frac{3}{2}}} = 1.14 - 2 \log_{10} \left[ (\varepsilon/D) + 21.25 \left( \frac{V_m}{\text{Re}_{ca}} \right)^{-0.9} \right]
\]  

(16)

and \((\varepsilon/D)\) is the pipe roughness ratio and

\[
\text{Re}_{ca} = \rho_w \cdot \frac{S_{mca}}{\text{D/n}} \cdot V_m \cdot \frac{D}{n}
\]

(17)

The above equations are the ones used to determine the variation of the hydraulic gradient, \(i_m\), with the velocity of the slurry, \(V_m\), for the various types of phosphate likely to be encountered in the phosphate industry of Florida, and accordingly the equations form a part of the computer program that has been developed from this work. Whether or not a particular phosphate matrix behaves as a Suwannee River slurry is considered to be governed by the fines content, as defined by the industry’s mineralogists in Section III of this report. Whence, for a fines content less than 20% the flow behavior of a slurry is considered to be similar to that of the Suwannee River slurry when operating under the same conditions of pebble content, \(P\), concentration, \(C_w\), and flow velocity. On the other hand, for a fines content greater than 20% the slurry is considered to behave as the Hookers Prairie and the Noralyn slurries operating under the same conditions. We thus see that the flow characteristics of all phosphate slurries can be catered for by one main equation, equation 19, a knowledge of the fines content which governs the hydraulic gradient of the carrier fluid, the pebble fraction, concentration and pipe size. The computer program is so arranged that it asks for this information and solves for the hydraulic gradient-velocity characteristic accordingly.
F. **SAFE CONVEYING VELOCITIES**

The conveying velocity, below which it is unsafe to operate, is of particular importance for the conveyance of coarse particles (i.e. pebble material) in water or in a non-Newtonian carrier fluids having low yield stresses and low plastic viscosities. In the case of the phosphate slurries this fact is well illustrated by the Noralyn type of phosphate material which has a high pebble content, P, (i.e. P > 0.4). In such cases, the hydraulic gradient-velocity characteristic curves, shown in Figures 6, 7 and 8, exhibit a minimum hydraulic gradient. This minimum is associated with the dominance of the sliding bed mode of transport and the onset of unstable flow conditions. Although the velocity corresponding to the minimum hydraulic gradient, often referred to as the minimum transport velocity, is a desirable operating velocity from the point of view of power consumption, it is often also close to the deposition velocity $V_s$, at which the deposition of particles begins.

Now while the flow tends to be unstable in the region of the minimum transport velocity condition, due to incipient deposition, the instabilities can be exacerbated by the interaction of the system resistance and the pump characteristics. In order to understand this, let us imagine that there is a perturbation in the flow, arising for example from an increased throughput; then such a change causes the higher head demand on the pump to increase and the flow velocity to decrease to accommodate the increase in head. The flow is now in the unstable deposition region and depending upon the resistance and pump characteristics the flow may or may not stabilize. If the system does not stabilize then it is highly probable that there will be a blockage.
The danger of unstable operation and blockage due to the deposition of particles when the velocity of operation is equal to or less than the minimum transport velocity thus leads us to operate at velocities some 10-20% greater than this velocity.

Now although the minimum transport velocity may be obtained from the plots of hydraulic gradient versus the slurry velocity, it is practically more useful to be able to predict this minimum velocity by calculation and we now consider the equations which may be used for this purpose.

In order to obtain the equations for the minimum velocity we differentiate the hydraulic gradient, \( i_m \), given by equation 19

\[
i_m = i_{ca} + 1.2 \left( \frac{S_m}{S_{mca}} - 1 \right) V_m^{-0.64}
\]

(19)

with respect to the slurry velocity, \( V_m \), and equate this differential to zero. Solutions will be considered for both the turbulent and the laminar flow regimes though the turbulent flow solution is the one of most practical use and we consider this solution first.

1. **Turbulent Flow Solution**

   We first substitute for \( i_{ca} \) in equation 19 using equation 15 and thus obtain,

   \[
i_m = \lambda_{ca} V_m + 1.2 \left[ \frac{S_m}{S_{mca}} - 1 \right] V_m^{-0.64}
\]

(22)

and assuming to a first approximation that \( \lambda_{ca} \) is constant we may express equation 22 in the form,
\[ i_m = C_1 V_m^2 + C_2 V_m^{-0.64} \]  \hspace{1cm} (22a)

where

\[ C_1 = \frac{\lambda_{ca}}{2gD} \text{ and } C_2 = 1.20\left(\frac{S_m}{S_{mca}}\right)^{-1} \]

Differentiating equation 22a with respect to \( V_m \) gives,

\[ \frac{d(i_m)}{dV_m} = 2C_1V_m - 0.64C_2V_m^{-1.64} \]

and equating \( \frac{d(i_m)}{dV_m} \) to zero and letting \( V_m = V_{\text{min}} \), we have

\[ V_{\text{min}} = \left(0.32 \frac{C_2}{C_1}\right)^{0.379} \]  \hspace{1cm} (23)

In solving this equation we assume first of all that \( V_{\text{min}} = 15 \text{ ft/s} \) and use equation 16 to calculate \( \lambda_{ca} \). We may now calculate \( V_{\text{min}} \) which we then compare with the assumed value of 15 ft/s. If the \( V_{\text{min}} \) values do not agree we repeat the procedure until the assumed value of \( V_{\text{min}} \) and the value calculated by equation 23 are in agreement. Such an iterative procedure has been built into the computer program.

2. **Laminar Flow**

If the minimum transport velocity, \( V_{\text{min}} \), should occur when the flow is laminar, an improbable situation of largely academic interest due to the strong possibility that the coarse pebble fraction will have settled to form a stationary bed, then we use equation 22, but replace equation 16 by the equation.

\[ \lambda_{ca} = \frac{64}{Re_{ca}} \]  \hspace{1cm} (24)
where

\[ \text{Re}_{ca} = \rho_w S_m c_a V_m D / \nu_{pp} \]  

and

\[ \nu_{pp} = \eta [(\tau_y D / 6 n v) + 1] \]  

substituting for \( \lambda_{ca} \) in equation 22 leads to

\[ I_m = c_3 + c_4 V_m + c_2 V_m^{0.64} \]  

where

\[ c_3 = 16 \tau_y / 3 \rho_w S_m c a gD, \quad c_4 = 32/\rho_w S_m c a gD^2 \]

differentiating and equating to zero leads to,

\[ V_{\text{min}} = (0.64 C_2 / C_4)^{1/1.64} \]  

Clearly, \( V_{\text{min}} \) is only given by equation 23 if \( V_{\text{min}} \) is greater than the critical velocity, \( V_c \), and is only given by equation 27 if \( V_{\text{min}} \) is less than \( V_c \).

G. THE VELOCITY OF STATIONARY DEPOSITION

Although the recommended operating velocity has been discussed on the basis of the stability to be achieved by operating at some 10-20% above the minimum transport velocity, it is important to determine also the slurry velocity at which we may expect the particles to come to rest.

The equations that govern this have been developed by Wilson (7,10) and the results of his work are now used to determine the
deposition velocity, $V_s$. For this purpose we use the nomograph given in Figure 25, which gives us, for a known pipe diameter and particle size, the maximum value of the deposition velocity, $V_{sm}$, this maximum occurring at relatively low concentrations. Once having determined $V_{sm}$ we apply a correction for concentration and finally obtain the actual value of $V_s$ for a particular concentration.

The correction to be applied is quite complicated and in order to determine the correction we make use of another nomograph, given in Figure 26. Before we can use the latter nomograph however, the delivered volumetric concentration ratio, $Cr$, where $Cr$ is given by,

$$Cr = \frac{C_{vd}}{Cb} \quad (28)$$

where $C_{vd}$ and $Cb$ are the delivered and bed volumetric concentrations respectively, and the maximum value of this ratio, $Crm$, is given by,

$$Crm = 0.16 \ D^{-0.84} \quad (29)$$

where $D$ is in meters and $d$ is in mm.

In order to determine the deposit velocity, $V_s$, corresponding to a given concentration we use an equation of the form,

$$\frac{V_s}{V_{sm}} = \emptyset (Cr, Crm) \quad (30)$$

where, because of the complexity of the function $\emptyset$ we solve the equation by means of the nomograph of Figure 26.
Figure 25. Nomograph for the determination of the velocity of deposition, showing solutions for the maximum value, $V_{sm}$, for pipes of 15.25, 17.25 and 10.25 (in) in internal diameter.
Figure 26. Nomograph for the relative deposit velocity, \( (V_c/V_{sm}) \), for 
\[ C_{r} \approx 0.33 \] in terms of the relative concentration, 
\[ C_{r}^{m/2} \approx (C_v/C_b). \]
We now use the two nomographs of Figures 25 and 26 to determine the deposit velocities for pipes of 16, 18 and 20 inches in nominal diameter, selecting for this purpose the particle size which has the greatest settling velocity for given conditions, which is of the order of 1mm. It can be seen from Figure 25 that the values of \( V_{sm} \) are 14, 15 and 16ft/s for pipes of 16, 18 and 20 inches in diameter, respectively.

To determine the actual deposition velocity at a concentration of 50% by weight, (27.4% by volume), we first assume that the volumetric concentration of a loosely packed bed is 60% and use this to calculate \( Cr \), thus from equation 28,

\[
Cr = \frac{0.274}{0.6} = 0.456
\]

Now from equation 29 for the three pipes using a particle size of 1 mm we find that the value of \( Cr_m \) varies between 0.109 for the pipe of 16 inches in diameter to a value of 0.12 for a pipe of 20 inches in diameter. By using a value of 0.456 for \( Cr \) and the values of \( Cr_m \) we obtain a value of \( V_s/V_{sm} \) of 0.5, and thus the deposition velocities for the three pipes are 7, 7.5 and 8 ft/s for the pipes of 16, 18 and 20 inches in diameter.

We thus see that the deposition velocity is, for all pipe sizes, and for a concentration by weight of 50%, less than the recommended operating velocity of 12ft/s. It should be noted however, that the theoretical analysis that has been used is based upon the assumption that the coarse particles \( d > 1.2 \)mm are conveyed in a carrier fluid.
that is water and not the Bingham Plastic carrier of this work. In the absence of information on the influence of a Bingham Plastic carrier it is considered that the deposition velocities will in fact be less than the above values in cases where the pebble fraction is less than 0.2. This appears to be largely in agreement with the experimental studies of this work which has shown that there is no significant drop in the slurry density, which would occur if there were deposition, until the velocities had fallen to about 5ft/s.

In the foregoing discussion it has been shown that for the worst case, i.e., particles of the order of 1 mm, where it is assumed that water is used as the carrier fluid, the pebble content is high, P > 0.2, and the concentration, \( C_w \), is equal to 50%, we may expect deposition velocities of about 8ft/s. Emphasis has been placed upon the concentrations because of the cost effectiveness of operating at high concentrations due to the low specific energies (note the exception in the case of HPP slurries which show a disproportionate increase in the hydraulic gradient for concentrations above about 40%). If for some reason it becomes necessary to operate at low concentrations the deposition velocities tend towards the \( V_{sm} \) values and (therefore in such cases) it may be necessary to operate at velocities of the order of 16-17ft/s.

3. **Illustrative Example**

In order to illustrate the solution of the several equations developed in this section of the report the following example has been worked out by means of a computer program, the listing and computer solution being given in Appendix A of this section.
A phosphate material, which is considered to have a fines content of 28%, has a pebble fraction of 0.4 and the SG of the material is 2.65. It is required that this material should be pumped in the form of a water-phosphate slurry at a concentration of 40% by weight in a pipe of nominal diameter, 16 inches and internal diameter of 15.25 inches. If the pipe roughness is 0.00005 inches, determine the hydraulic gradient velocity characteristic for both the laminar and turbulent flow zones, the critical velocity and the minimum transport velocity. A graphical illustration of this computer prediction of the hydraulic gradient-velocity characteristic for a Noralyn type phosphate slurry is given in Figure 27.

H. CONCLUSION

Three different types of phosphate matrix material have been examined experimentally in the GIW Hydraulics Laboratory and in the field operations of IMC Fertilizer, Occidental Chemical and W. R. Grace Companies. A considerable amount of information of practical importance has been acquired and analyzed.

As one of its prime objectives the study set out to develop algorithms and their associated computer programs for the design of pipeline systems for the phosphate industry of Florida. It was intended that the analysis and the computer programs which arose from it would provide for a generalized solution of the problem which required no further input than that which was readily available to the industry by way of mineralogical surveys and knowledge concerning quantities of associated clays with the ore body.
Figure 27. Graphical illustration of computer prediction of the hydraulic gradient velocity characteristic curve for a Noralyn type phosphate slurry having a pebble fraction $P = 0.4$, at concentration $C_W = 40\%$, for a flow in a pipe of nominal diameter, 16(in) and an internal diameter of 15.25(in).
In order to achieve this generality three types of material were selected, and it appears from the results of the work that the variation in the behavior of the slurries formed from the materials has covered a spectrum which has enabled a generalized treatment to be formulated.

The work has indicated quite clearly that the system resistance may be predicted from the equations developed from an a priori knowledge of the pebble fraction, the fines content and the specified concentration. The basic equation for this purpose has been developed from the experimental findings of this work and from the previous experience of the GIW Company. In particular, the equation uses two main concepts to arrive at a generalized form,

(i) at high pebble fractions the equation should take the form of a sliding bed model in which the pebble fraction is of prime importance, particularly in the operating region.

(ii) at low pebble fractions the equation should take the form of a non-Newtonian carrier fluid in which the rheological properties of the carrier fluid are of prime importance, these properties being uniquely related to the concentration of the slurry formed from the feed plus the fines material.

Thus, the resulting equation takes the following simplified form,

\[(1_m - 1_{ca})=((S_m/S_mca)-1) = C \nu^{-m}\]

where
The hydraulic gradient of the carrier fluid may be determined from the Buckingham equation for laminar flow, equation 16 for turbulent flow and a knowledge of the rheological properties of the carrier, which are related by power laws to the carrier density, this in turn being related to the pebble fraction and the slurry concentration, \( C_w \). Clearly, the above equation enables the hydraulic gradient for a given pipe diameter to be determined for a given velocity, provided that the pebble fraction, \( P \), the concentration, \( C_w \), and the constants and the indices for the power laws governing the rheological properties are known. The computer model that has been prepared is so designed that for an input of pebble fraction, \( P \), concentration, \( C_w \), pipe diameter and flow rate the hydraulic gradient may be determined for a single flow or for a range of flows, the solution for a range of flows giving the resistance characteristic of the system.

The significantly different behavior of low fines (< 20%) slurries, compared with the other phosphate slurries examined, has been taken into account as noted earlier by altering the plastic viscosity and yield stress to reflect the results using 20% as the changeover point.
In practice, phosphate matrix will vary from mine to mine and location to location and will not necessarily reflect exactly any of the three slurries tested.

For this reason we have added two additional correction factors, a feed size multiplier and a viscosity correction factor for the purposes of fine tuning and adjusting the correlation on the basis of field experience and/or other information.

The feed size multiplier is normally unity, and is a simple multiplier factor of the non-carrier particle friction component of the head loss in equation 19.

The viscosity correction factor concerns itself with the carrier component of equation 19 being normally unity again and being applied as a direct multiplier to the plastic viscosity in the calculation of eta in equation 2.

A chart, Figure 28, showing the multiplier and correction factor values for optimum correlation fit of the data for the three tested slurry types in the three pipe sizes at concentrations of 30 and 50% by weight is included. This chart also includes comments on the effect of the multiplier as a guide to their use.

Turning next to the minimum transport velocity, $V_{\text{min}}$, equations have been developed for the calculation of this velocity, and the algorithm for the practically important turbulent flow solution is included in the computer program. In the case of materials having a high pebble content, the minimum transport velocity occurs at relatively high velocities of the order of 10 ft/s and in such cases the minimum operating velocity should be some 10-20% greater than the minimum transport velocity corresponding to the minimum hydraulic
## CORRELATION ACCURACY AND CORRECTIONS

<table>
<thead>
<tr>
<th>Mine</th>
<th>Noralyn</th>
<th>Suwannee</th>
<th>Hookers Phaiahie</th>
</tr>
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<tbody>
<tr>
<td>% Pebble</td>
<td>APPROX 46</td>
<td>APPROX 1</td>
<td>APPROX 12</td>
</tr>
<tr>
<td>% Fines</td>
<td>APPROX 28</td>
<td>APPROX 12</td>
<td>APPROX 28</td>
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<tr>
<td>Comments</td>
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<td>EASY PUMPING (FINES &lt; 20%)</td>
<td>MEDIUM</td>
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### 15 1/4" PIPE DIA

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<th>Accuracy of Curves with ① and ② = 1</th>
<th>% Fit at 15 FT/S</th>
<th>1% for Cw=50%</th>
<th>5% for Cw=35%</th>
<th>5%</th>
<th>2%</th>
<th>Error is Greater for High Concentration Curve (50%) at Low Velocities (&lt;15 FT/S)</th>
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<tr>
<td>Suggested Optimum Values</td>
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### 17 1/4" PIPE DIA

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<th>2%</th>
<th>Error is Greater for High Concentration Curve (50%) at Low Velocities (&lt;15 FT/S)</th>
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### 19 1/4" PIPE DIA

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</table>

### General Comments

Due to the large pebble %, the feed size multiplier has a greater effect than the viscosity correction factor. Feed size multiplier and viscosity correction factor values less than 1 produce a decrease in the magnitude of head loss, and vice-versa.

In general, both the feed size multiplier and the viscosity correction factors have only a slight effect on the magnitude of head loss. Again, the direction of the effect is similar to that of the Noralyn phosphate.

Effects are similar to those for Suwannee River phosphate, except at high concentrations and/or after a lot of movement thru pumps such as in lab tests. Tendency for increases in viscous head loss due to clays.

**Figure 28**
gradient condition. Instabilities associated with the deposition of coarse particles and the interaction of the pump and the system characteristics are avoided by selecting the operating velocity in this way. However, in the case of the slurries of low pebble content the minimum hydraulic gradient occurs at relatively low velocities, well below the practical operating velocities.

The experimental data obtained during the field trials have, in the case of the Noralyn slurries, been found to be in substantial agreement with the corresponding values obtained during the laboratory test program. The fluctuation in the specific gravity of the slurries tested in the field and which arose because of the non-steady state conditions associated with feeding and the variability of the inventory constituted the main difference between the field and the laboratory trials. System design should take into account this variability of the specific gravity and design for the maximum value of the slurry specific gravity.

The field hydraulic gradients for both the Suwannee River and Hookers Prairie slurries are substantially less than the corresponding values measured in the laboratory and this has been shown to be due to the degradation of the material caused by circulation through the pipeline and the pump. It is also worthy of note that the higher initial fines content of the Hookers Prairie phosphate and possibly its greater pumpability caused a very large increase in the hydraulic gradient caused by circulation in the test loop. In the latter case, the hydraulic gradient was twice that of the field trial data under corresponding conditions of flow and concentration. Nevertheless, by carrying out careful rheological studies and analysis of the pipeline
data obtained in both the laboratory and the field, equations have been developed which enable the data to be predicted which is in reasonably close agreement with the field data in the case of all three of the phosphates examined.

Finally, it is considered that the broad objective of the project, which was to provide, through experiment and analysis, a methodology for pipeline system design that would be sufficiently general to be applicable to the phosphate industry of Florida as a whole, has been achieved. Only time will tell whether this assessment is correct, when the industry has had an opportunity of testing the results of the work in the field. It is of course difficult to generalize from a small sample, though it is believed that the difficulty can be reduced by a careful choice of the test samples. In this work the selection of materials for the test program which were thought to fall into the categories which were difficult, less difficult and easy to pump, have been found to behave substantially in this way. It has therefore been possible to develop equations which are expected to cover the majority of types of material that occur. From discussions with engineers and others with experience in the industry, and from the range of pebble, feed and fines experienced in the Florida ore bodies, coupled with the results of this work, we are reasonably confident that the algorithms developed and their incorporation in the computer program will provide the phosphate industry with a tool of immense practical importance. The programs developed will no doubt need to be refined from time to time as a result of the experience gained through their use in the field and through a continuation of the close association of FIPR and the industry with GIW.
TABLE I

Test results obtained during the transport of a phosphate matrix material at a concentration of 35% in a pipe of 17.25 (in) internal diameter.

<table>
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<th>TEMP</th>
<th>S.G.</th>
<th>S.G.</th>
<th>VOLUME:WEIGHT</th>
<th>MASS</th>
<th>REYNOLDS</th>
<th>PIPELINE LOSSES</th>
<th>FRICTION FACTORS</th>
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REFERENCES


V. FIELD TEST

Part of the FIPR Contract called for field tests at each of the three mines to verify the results obtained in the GIW Hydraulic Laboratory tests. The original plan was to simply carry some pressure gauges to the field and to measure the pipeline pressures at two points to obtain the pressure drop, to measure the suction and discharge pressures to obtain pump head and to rely on the field instrumentation for flow, density, and pump power. This was later determined to be unacceptable to provide an accurate verification.

To achieve the reliability needed for the measurements GIW decided to build a portable field test unit complete with computer, data acquisition system, instrumentation and transducers capable of measuring flow, density, differential pressures, and kilowatts. This was set up in a 5' x 8' utility trailer complete with air conditioning unit. The trailer could then be towed to the field test site, set up, and left for the duration of the test.

GIW also constructed an 18" diameter, 30' tall vertical specific gravity loop complete with magnetic flowmeter and calibrated bend flowmeter. The SG loop shown in Figure V-2 consists of a U-loop with the pressure differential measured between two points in the upward flowing leg and also between two points in the downward flowing leg. The device, first proposed and patented by Hagler (1956) is analyzed in a brief communication by Clift and Clift (1981) included in Appendix F.

The layout for the field test setup is included in Figure V-1.
FIGURE V-1: FIELD TEST MEASUREMENT

- CONTROL BOX
  LOCATE C.T.s & P.T.s ON MOTOR LINE AFTER ALL CONTROL SWITCHES AND STARTER.
- PURGE WATER SUPPLY FROM GLAND OR OTHER CLEAN SOURCE OF WATER GREATER THAN DISCHARGE PRESSURE.
- FIELD TEST TRAILER MUST LOCATE WITHIN 50' OF S.G. LOOP AND MOTOR CONTROL BOX OR SPECIAL CABLES REQUIRED.
- SPECIFIC GRAVITY LOOP (see detailed drawing)
- AT LEAST 150' OF STRAIGHT UNIFORM LEVEL PIPE AS ENTRANCE
- HEAD LOSS PRESSURE TAPS 300' SECTION MUST BE STRAIGHT, AND LEVEL. CHECK IF SECTION TO THE HEAD LOSS NECESSARY ADJUST LEVEL WITH A MEASUREMENT SECTION. TRANSIT OR LEVEL GAGE.
- PUMP
- SUCTION PRESSURE TAPS
- REDUCERS, ELBOWS AND FLEXIBLE JOINTS SHOULD PROBABLY BE INCLUDED WITH PUMP
- DISCHARGE PRESSURE TAPS
FIGURE V-2: SPECIFIC GRAVITY LOOP FOR FIELD TESTS.

250# FLANGES 28" O.D. WITH 24 1 3/8 BOLT HOLES ON 24 3/4 DIA. BOLT CIRCLE LOCATED OFF & AS SHOWN.

18" OD, 17.25" ID. ST'D. STEEL PIPE ST'D. LONG RADIUS ELBOWS ST'D. 250# FLANGES
The pumping station was chosen by the mine personnel to give the best accessibility, ease of installation of the SG loop and other instrumentation, and a straight and level pipe run on the pump suction side for the friction head loss measurement section. The SG loop was installed by the mine maintenance personnel with the necessary reducers and adapters to fit the mine piping. The SG loop was located in the pipeline on the suction side of the pump and a minimum of 30' upstream of the pump fittings. This allowed for a minimum of 30' of straight uniform pipe as an entrance section before the suction tap. The magnetic flowmeter was located in the upward flowing leg of the SG loop and while there were two bend meters available, the bend in the downward flowing leg was used for all the field tests.

The friction head loss measurement section was located upstream of the SG loop. A distance of at least 15' was left between the end of the head loss section and the SG loop to eliminate any exit effects. A distance of at least 150' of straight uniform level pipe was provided upstream of the head loss section to insure uniform entrance conditions. In reality there were actually several thousand feet of essentially straight pipe upstream at all the mines. The distance between the head loss pressure taps was 300'. On some of the tests an extra set of taps 100' apart was installed inside the 300' length as a backup set for additional verification of data.

Suction and discharge taps were installed in the straight pipe sections before and after the pump. All of the pump's associated fittings, reducers, elbows, flexible joints and couplings, etc. were included between the suction and discharge taps. The associated losses
through these fittings were therefore included with the pump losses and charged against the pump's efficiency. To obtain the true pump head and efficiency these fitting losses should be estimated and added back to the pump head. In addition to transducers measuring suction and discharge pressure, a differential pressure transducer was connected between them giving two different means of determining pump head.

The piezometer taps for the suction, discharge and head loss section were installed by the mine maintenance personnel according to Figure V-3. Two taps were installed at each location with transducers connected to both to provide duplicate or backup readings. The taps were located at 45° above the horizontal centerline on each side of the pipe. A 1/4" NPT pipe coupling was welded onto the pipe then a 1/4" diameter hole drilled through the pipe and deburred. A collection pot, 4 inches in diameter and 1 foot tall with bleeds at the top and bottom was closely connected to the taps with clear flexible nylon tubing. The pots were then connected to the pressure transducers located in the field test trailer using the same nylon tubing. A high pressure purge water supply connected to the pump gland water supply was used to fill the transducer lines and pots with clear water. Any slurry that migrated from the pipeline into the transducer lines during the tests was intermittently forced back into the pipeline using this purge water supply. It was also used to remove and eliminate any blockages of the piezometer taps. The collection pots were used to trap and remove any slurry that migrated from the pipeline before it could reach the transducer lines thus, eliminating any height correction errors. Solid particles settle to the bottom of the pot where they can be bled off,
WELD ON 1/2" LONG PIPE COUPLING WITH 1/4" NPT FEMALE PIPE THREADS
THEN DRILL 1/4" HOLE THRU PIPE AND DEBUR

TRY NOT TO PLACE TAPS TOO CLOSE TO PIPE JOINTS ESPECIALLY IF THE JOINT IS UPSTREAM OF THE TAP

FIGURE V-3: FIELD TEST PRESSURE TAPS FOR DISCHARGE, SUCTION AND HEAD LOSS MEASUREMENTS.
and likewise air bubbles rise to the top where they are bled off also.

A transducer type kilowatt meter was also part of the field test unit. Potential transformers (PT's) with a 40:1 ratio and current transformers (CT's) with a 400:5 ratio were supplied by GIW and connected into the 4160 volt motor supply. The secondaries were then connected to the 100 volt 5 amp Rochester Instrument Systems PCE-20 Watt Transducer located in the field test trailer according to the wiring diagram in Figure V-4. The CT's and PT's were installed in the motor control box on the motor line after all the resistors, capacitors, starter, and other switch gear. This eliminated the inefficiencies of the starter and controller so that only the motor efficiency had to be considered when calculating the horsepower.

The field test trailer was located in close proximity between the control box and the SG loop to minimize the lengths of cabling for the magnetic flowmeter and kilowatt meter as well as the connecting tubing for the pressure transducers. AC power for the computer and instrument power supplies was taken directly from the control box. An isolation transformer type filter was available in the trailer but found to be unnecessary for the tests.

The instrumentation was completely assembled and installed in the trailer at the GIW Hydraulic Laboratory. The pressure transducers were calibrated against the three lab standards, a 20 foot water column, an inclined mercury manometer and a dead weight tester. The magnetic flowmeter totalizer was checked against a secondary calibrator in the lab and before each test in the field. The SG loop was installed in the lab pipeline complete with the magnetic flowmeter. The pressure
FIGURE V-4.: FIPR WIRING FOR RIS WATTMETER.
transducers were also connected in duplicate with the lab instruments as was the kilowatt meter. A complete calibration reference comparison test was run using the field test equipment and the lab test equipment simultaneously to compare the flow, density, power and all pressure measurements. This not only verified the instrument calibrations but also the computer software and data acquisition system prior to shipment to the field.

The instrumentation along with each's usage, description, range and units of calibration, calibration reference, and coefficients is included in Table V-1. Each of the instruments has a 4-20 milliamp output which is converted through a 200 ohm 0.01% precision resistor to a 0-4 volt signal. The 13 bit accuracy analog to digital (A/D) conversion unit converts this voltage to a digital reading with 8191 digits = 4 volts = 20 ma. The A/D is setup to read 11 channels at a rate of seven readings per second. The channels are scanned a number of times and then the digital readings averaged for each channel. The number of readings averaged for each point is controlled and set by the operator on the computer console. The averaging period can be lengthened to eliminate fluctuations and increase the stability of the data or it can be shortened to look at the instantaneous readings and study the actual fluctuations. During the FIPR field tests, either 5, 10 or 20 readings were averaged.

Once the digital readings are averaged, the quadratic calibration coefficients are applied to convert the reading into selected engineering units. The FORTRAN computer program then makes all necessary calculations to come up with the displayed results.
### Table V-1

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the FIPR tests, a new data point was displayed and printed approximately 1-5 times per minute depending on the number of readings being averaged.

A sample copy of the output for the field tests is included in Table V-2. The full results are too voluminous for this report and are kept on file at GIW. The header for the output which applies to the first line of the output for each point is self explanatory. The second line for each point is the averaged digital reading for each of the 11 channels, and the third line is the converted readings in the units of calibration for each instrument.

Photographs of the instruments, the field test trailer, the setup in the lab, and the layout at each of the mines are included in the Photograph Section of this report.

GIW would like to thank each of the companies for their participation in this project. We would especially like to thank the maintenance and operating personnel at IMC Noralyn, Occidental Suwannee River, and W.R. Grace Hookers Prairie for their help and cooperation in executing these field tests.

A. IMC NORALYN FIELD TESTS

During the period May 25-27, 1988 field tests were run at the IMC Noralyn Mine. The SG loop and other instrumentation were set up at the Number 5 lift pump in the 1250W pumping system. Mr. Ron Hartung of IMC coordinated the installation of the SG loop prior to the arrival of GIW personnel and provided IMC maintenance personnel and equipment required.
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| 4797 | 6344 | 6836P | 2141 | 2953P | 2917 | 3517 | 4956 | 3918 | 5001P | 3498 |
| 329.72 | 156.94 | 177.16 | 3.8747 | 3.3974 | 3.8424 | 3.4217 | 2.0306 | 0 | 14240 | .28229 |

TAKEN

| 14328 | 15.57 | 136.0 | 60.5 | 127.1 | 855.3 | 1089.4 | 621.1 | 57.0 | 1.35 | 4.21 | 139 | 08:12 |
| 4602 | 5935 | 6753P | 2178 | 3073P | 2952 | 3543 | 5809 | 3973 | 5017P | 3639 |
| 314.26 | 139.53 | 174.23 | 4.1417 | 4.0266 | 3.9554 | 3.4690 | 2.1763 | 0 | 14328 | .29733 |

TAKEN

| 14119 | 15.67 | 137.2 | 62.0 | 138.3 | 883.8 | 1125.5 | 636.4 | 56.7 | 1.35 | 4.07 | 142 | 08:12 |
| 4653 | 5923 | 6853P | 2157 | 3027P | 2928 | 3519 | 4971 | 3858 | 5243P | 3443 |
| 326.75 | 142.99 | 177.89 | 4.0822 | 4.0659 | 3.3779 | 3.4233 | 2.1977 | 0 | 14119 | .27818 |

TAKEN

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| 4437 | 5954 | 6783P | 2157 | 2953P | 2946 | 3405 | 4693 | 3640 | 5249P | 3441 |
| 318.23 | 142.41 | 175.24 | 4.0220 | 3.7221 | 3.9360 | 3.2164 | 1.9759 | 0 | 14444 | .2712 |

TAKEN

| 6 | 14397 | 15.67 | 136.9 | 60.9 | 127.4 | 843.3 | 1073.7 | 612.3 | 57.3 | 1.32 | 4.11 | 140 | 08:12 |
| 4575 | 5844 | 6429P | 2176 | 3041P | 2971 | 3389 | 4680 | 3873 | 3839P | 3363 |
| 311.41 | 140.52 | 173.74 | 4.1978 | 4.1087 | 4.0199 | 3.1871 | 1.9397 | 0 | 14397 | .26332 |

TAKEN

| 7 | 14568 | 15.87 | 137.9 | 59.8 | 132.3 | 854.5 | 1088.2 | 646.1 | 59.4 | 1.33 | 4.23 | 140 | 08:12 |
| 4451 | 5775 | 6599P | 2157 | 3082P | 3026 | 3421 | 4695 | 3844 | 5091P | 3368 |
| 314.17 | 135.77 | 177.90 | 4.2342 | 4.2142 | 3.2457 | 1.9704 | 0 | 14580 | .26703 |

TAKEN

| 3 | 14487 | 15.76 | 136.7 | 61.4 | 127.3 | 866.2 | 1153.1 | 626.6 | 56.6 | 1.35 | 4.41 | 137 | 08:12 |
| 4417 | 5901 | 6737P | 2216 | 3141P | 3044 | 3510 | 4977 | 3849 | 5099P | 3412 |
| 315.87 | 141.79 | 173.69 | 4.5653 | 4.4147 | 4.2323 | 3.4087 | 2.1185 | 0 | 14486 | .27269 |

TAKEN

| 9 | 14504 | 15.78 | 133.1 | 59.6 | 123.7 | 854.0 | 1087.6 | 612.6 | 56.3 | 1.35 | 5.42 | 137 | 08:21 |
| 4341 | 5777 | 6417P | 2163 | 3143P | 3059 | 3528 | 4984 | 3848 | 5063P | 3387 |
| 307.81 | 137.53 | 169.67 | 4.2773 | 4.4285 | 4.2975 | 3.4969 | 2.1312 | 0 | 14503 | .26688 |

TAKEN

| 2 | 14528 | 15.79 | 131.3 | 56.8 | 123.6 | 869.2 | 1086.8 | 620.9 | 56.1 | 1.37 | 4.64 | 135 | 08:21 |
| 4332 | 5789 | 6629P | 2214 | 3144P | 3137 | 3566 | 5033 | 3541 | 5264P | 3419 |
| 303.46 | 131.29 | 171.89 | 4.3469 | 4.6381 | 4.5599 | 3.6765 | 2.2594 | 0 | 14507 | .27161 |

...ing on 3 readings per monitor V-12
to set up the instrumentation and equipment. The first day was spent setting up the instrumentation for the tests. John Maffett supervised the setup and testing for GIW. Additional GIW personnel assisting with the tests included Messers Graeme Addie, C.W. (Bucky) Bell, Roy Duvall, Todd Pike and William Windisman. Mr. Henry Lamb provided assistance with sampling and evaluating the matrix being pumped. Messieurs Robert Akins and Don McFarlane witnessed part of the testing for FIPR.

The layout of the 1250W pumping system is shown in Figure V-5. The GIW 18x18V6044 pump at the Number 5 lift pump station has associated fittings shown in Figure V-6. The elevation levels of the pressure taps is shown in Figure V-7. A height correction of 1.6 feet was included in the test program to account for the difference between the suction and discharge taps and give the correct total dynamic head produced by the pump. The difference in the head loss taps was ignored in this case since the worst case error was only 0.03 feet per 100 feet. Photographs of the IMC layout are included in the Photograph Section.

The GIW 18x18V6044 pump with AH/4RV hydraulics was direct connected to a 4160 volt, 1500 hp, 590 rpm constant speed motor. A motor efficiency of 95% was used to calculate the brake horsepower from the measured kilowatts and eventually determine the efficiency of the pump. A water performance curve for the pump is included in Figure V-8.

The preparations were completed and actual testing commenced at 14:59 on Thursday, May 26, 1988. After running 15 minutes the testing was halted to rearrange some of the instrumentation. The pipeline
FIGURE V-5: IMC NORALYN 1250W PUMPING SYSTEM.
- 18 X 18 WSO-44 PUMP
- 1,500 H.P. 590 R.P.M.
  CS MOTOR (DIRECT COUPLED)
- ALL PIPE & FITTINGS
  17 1/4" I.D 250# FLANGES.
- PIPE: ONE END IS SINGLE
  DRILLED, OTHER END IS
  DOUBLE DRILLED.

**FIGURE V-6:** IMC NORALYN #5 LIFT PUMP
1250W PUMPING SYSTEM.
FIGURE V-7.: PRESSURE TAP ELEVATIONS
FOR FIELD TEST AT IMC, NOVALYN MINE.
FIGURE V-8 IMC PUMP CURVE

SECOND PERFORMANCE TEST ON THE 18/18 LSA 44 AH WITH A STANDARD 4 VANES INPELLER AFTER PERFORMING 3 NPSH SIGMA TESTS. NOSE CLEARANCE WAS 0.030" AT THE CLOSEST POINT AND 0.116" AT THE FARTHEST POINT. BEP 71.6% AT 11,000 GPM.
pressures were much higher than had been predicted by IMC. The discharge pressure exceeded the 300 psi range of the transducer available. The differential pressure and suction pressure also occasionally exceeded the 100 psi range of those transducers. The 300 psi transducer was connected to the differential pressure to get the total head for the pump. A separate discharge pressure reading could not be measured but could be back calculated from the differential and suction pressures.

Testing was recommenced at 16:23 and continued until 18:10 at which time the pump was shut down briefly. Upon restart the flow had dropped dramatically. It was decided to stop and reconvene next morning, however, due to a lack of communication and forethought, the pipeline was shutdown early next morning to change out the pump parts on the Number 5 pump. The testing was restarted at 12:51 when the pipeline was brought back up, and continued until 13:55. With over 200 data points collected the testing was stopped and the instrumentation was removed from the system.

All of the collected data are held on file at GIW. The pipeline information, i.e. velocity, friction head loss, and specific gravity are plotted versus time in strip chart fashion in Figures V-9 and V-10.

During the first day, May 26, the velocity varied from 14.5 to 19.7 ft/sec with the normal being about 17 ft/sec. The specific gravity ranged from 1.16 to 1.43 SG with an average around 1.3 or 37% concentration by weight. The pipeline losses varied from 3.8 to 7.5 feet of water per 100 feet of pipe with a mean of approximately 6
The ranges on the second day of testing, May 27, were velocity 16.0 - 20.6 ft/sec, SG 1.2 - 1.43, and head loss 4.8 - 7.6 ft/100 ft. While exhibiting some scatter, the data seemed to indicate periods of stability at different operating conditions. Some of these rough averages are listed below

<table>
<thead>
<tr>
<th>Velocity V, ft/sec</th>
<th>Friction Head Loss ( j_m, \text{ ft/100 ft} )</th>
<th>Specific Gravity ( S_m )</th>
<th>Concentration ( C_w % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>7.0</td>
<td>1.37</td>
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<td>18</td>
<td>5.0</td>
<td>1.25</td>
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<td>16</td>
<td>5.2</td>
<td>1.26</td>
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<tr>
<td>17</td>
<td>5.0</td>
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</tr>
<tr>
<td>19</td>
<td>6.8</td>
<td>1.34</td>
<td>41</td>
</tr>
</tbody>
</table>

One observation noted is that the head loss seemed to be affected much more by concentration than by velocity. Changes in specific gravity of 0.1 SG showed immediate changes of 1.0 to 1.5 ft/100 ft in head loss whereas shifts in velocity of 1 to 2 ft/sec often showed no appreciable change in head loss.

B. OCCIDENTAL FIELD TESTS

During the period June 15-17, 1988 the instrumentation was set up for the FIPR field tests at Occidental's Suwannee River Mine. The tests were then run on June 22-23, 1988. Mr. Eric Norman of OXY coordinated
the installation of the field test equipment at the #3 Booster Pump in the #1 Pumping System at the Suwannee River Mine. Mr. Bob Fisch also provided assistance with organizing OXY maintenance personnel and equipment to install the SG loop and other instrumentation. GIW personnel included Messrs. C. W (Bucky) Bell, Roy Duvall, John Maffett, Coleman Newman, Todd Pike and Wayne Pryor. The set up for the testing was completed on Thursday, June 16, 1988, during a scheduled shutdown of the OXY #1 pumping system. The testing was originally scheduled to coincide with the restart on Friday; however, delays in repair of the dragline postponed the testing. The dragline was brought back on-line on Tuesday, June 21, 1988 and GIW arrived on Wednesday to start the testing. John Maffett supervised the testing for GIW and Todd Pike provided the computer expertise. Mr. Henry Lamb collected samples from the pit for sieve analysis and evaluation.

The layout of the OXY #1 pumping system is shown in Figure V-11. The GIW 16x18W040 pump at the #3 booster station is shown in Figure V-12 with all fittings and associated piping. The elevation levels of the pressure taps are included in Figure V-13. A height correction of 1.2 feet was applied for the total dynamic head calculation. The elevation difference in the head loss length was insignificant. Photographs of the OXY set up are included in the Photography Section of this report.

The GIW 16x18W040 pump had A/4RV hydraulics and a 39" diameter impeller. Figure V-14 shows the water performance characteristic curve for the pump. The pump was powered by a directly connected Toshiba 4160 volt, 1250 hp wound rotor motor. A five stage set point
FIGURE V-11.: OCCIDENTAL SUWANEE RIVER MINE.
PUMPING SYSTEM #1, 20" O.D., 19 1/4" I.D PIPELINE.
FIGURE V-12: OCCIDENTAL SUWANNEE RIVER, #3 LIFT PUMP

PUMP: 16 X 18 WQO-40
A/4RV
39" IMPeller

MOTOR TOSHIA 1250 H.P.
595 R.P.M.
WOUND MOTOR
4160V

100' PIPE SECTION-20"
5' SPOOL
WILL HAVE DISCHARGE TAPS

20" X 45° E.BOW
20" X 18" REDUCER
18" FLEXIBLE 7' LONG
18" X 15" REDUCER

18" PIPE
20' LONG
W/18"250# FLANGE

18" PIPE
20' LONG
W/18"250# FLANGE

GWin "U" LOOP

18" X 20" REDUCER

20" X 12" SPOOL

50' SECTION-20" PIPE

18" X 22 1/2" ELBOW
18" FLEXIBLE 7' LONG
18" X 22 1/2" ELBOW
18" CLEANOUT

1/2" VALVE TO CLEANUP HOSE

APPROX. 20'

APPROX. 60'

MOTOR CONTROL

PRESSURE TAPS-PUMP SUCTION
PRESSURE TAPS-FRICTION LOSS
PRESSURE TAPS-PUMP DISCHARGE
FIGURE V-13.: PRESSURE TAP ELEVATIONS
FOR FIELD TEST AT OCCIDENTAL, SUIANNE RIVER MINE.
FIGURE V-14 OXY PUMP CURVE

FINAL PUMP PERFORMANCE TEST OF GIW 16/18 WOG 39 HP TYPE H12-3/3/4 RV12-3/3-PUMP

SPEED: 1,720 RPM
IMP 1:0 RAT 1.000:39:DA.

GALLONS PER MINUTE (US)

DATE 07/08/81

RECALCULATION ON 07/10/81 AFTER CALIBRATING ALL PRESSURE TRANSDUCERS
controller was used to vary the speed of the motor and pump. At full speed, fifth stage, the motor and pump operated at 592-593 rpm and a 95% motor efficiency was used to calculate brake horsepower and pump efficiency. The pump was occasionally operated at reduced speeds and the motor efficiency should have been much lower. At reduced speed the erroneously high motor efficiency caused the brake horsepower to be calculated erroneously high and therefore the pump efficiency to be calculated erroneously low. Reduced speed points should not be considered when evaluating pump horsepower and efficiency. The fourth stage speed varied from 555-562 rpm and third stage was measured from 492-509 rpm depending on the load. First and second stage runs occurred only for short duration at startup and shutdown and no speed measurements were obtained.

The actual data collection began at 16:23 June 22, 1988. The pump was shut down at 16:43 and testing halted until it was restarted at 16:56. The pump was shut down again at 18:04 and testing was halted for the day. The dragline stripped overburden and prepared a full 'face' for testing to resume next morning. Data collection began at 8:40 June 23, 1988 when the pit pump was started and flow was first noticed on the instrumentation. Water only was being pumped through the pipeline and lift pump #3 was still off. It was noted on the printout as the pump started, staged, then stopped and restarted as the line was being loaded. The first solids reached our station at 9:03 and operating density was attained at 9:10. Data collection was halted at 10:48 when a printer head jammed and a ribbon had to be replaced. Testing resumed at 11:04 and continued non-stop until 14:13 at which time it was decided enough data had been collected.
Over 1000 data points were collected and these are held on file at GIW. The plots of the pipeline data versus time are included as Figures V-15 - 17.

During the first day of testing the operating conditions of the pumping system varied greatly. The velocity varied from 5-17 ft/sec, specific gravity ranged from 1.05 - 1.50 and friction head loss varied from 0.5 - 4.0 ft/100 ft. While the conditions changed quite a bit these were not wild fluctuations, but instead the system operated fairly stably at one point for a time, then shifted to another level and operated there for a while. This may have been due to the fact that the dragline and system had been down and were just coming back on line and getting the cut back in shape. On the second day the system was amazingly stable. During most of the day the velocity stayed between 14-15 ft/sec, the specific gravity was 1.4-1.5 SG and the losses were 3-4 ft/100 ft. Later in the day we requested that the pump speeds be varied occasionally to allow us to collect data at some other operating points. Compared to the IMC pipeline, which fluctuated fairly wildly, the OXY system operated very smoothly.

There were a few occasions were the pump cavitated violently as if the suction were blinded. The suction pressure went negative and the pump continued to run indicating that the pressure sensing switch was not operating correctly since it never shut the pump off. There were no water hammers, however, as was seen at IMC.

Table V-4 contains some representative data points averaged from the data collected.
FIGURE V-17
SEISMOGRAM FOR FIBER FIELD TEST TO OCCIDENTAL
5/29/88 SUWANNEE RIVER MINE

SPECIFIC GRAVITY (g/mL)

FREEZE-THAW LOSSES (FT/100FT)

VELOCITY (FT/SEC)

V-31
TABLE V-4  
Representative Data from OXY Field Tests

<table>
<thead>
<tr>
<th>Velocity V, ft/sec</th>
<th>Friction Head Loss $i_m$, ft/100 ft</th>
<th>Specific Gravity $S_m$</th>
<th>Concentration $C_w$ %</th>
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C. **W R. GRACE HOOKERS PRAIRIE FIELD TESTS**

The final field test for the FIPR project was conducted at the W.R. Grace Hookers Prairie Mine during the period August 11-12, 1988. The test was set up at the #6 Booster Pump in the #14 Pumping System at Hookers Prairie. Mr. Jackie Purcell, Production Superintendent for W.R. Grace (WRG), organized the men and equipment to install and set up the equipment. Mr. Mike James, Mining Engineer, also assisted in coordinating the testing with production and providing communications with the operating personnel. GIW personnel were Roy Duvall, Steve Kerr, Phil Lee, Todd Pike and John Maffett who supervised the set up and testing for GIW. Mr. Henry Lamb again collected samples for evaluating the matrix.

The layout of the WRG #14 Pumping System is shown in Figure V-18. The #6 Booster Pump was a GIW 18x18WS044 A/3ME pump with reducers and connecting pipe and fittings as shown in Figure V-19. The elevation levels shown in Figure V-20 were taken into account in the computer program. A height correction of 1.6 feet was applied for the total dynamic head calculation, whereas the elevation difference in the head loss section was insignificant and therefore ignored. Photographs of the WRG set up are included in the Photography Section.

The GIW 18x18WS044 pump had A/3ME hydraulics and a 42" diameter impeller. The water performance characteristic of the pump is included in Figure V-21. The pump was directly connected to a 4160 volt, 1500 rpm, 585 rpm wound rotor motor with a starter plus six stage set point controller. The pump speed was continually changed throughout the testing with no more than a few minutes at any one speed. The majority
FIGURE V-18: W.R. GRACE HOOKERS PRAIRIE #14 PUMPING SYSTEM.
FIGURE V-19.
(REF. GHACE/FIPH TEST)
FIGURE V-20.: PRESSURE TAP ELEVATIONS
FOR FIELD TEST TO W.R. GRACE, HOOKERS PRAIRIE MINE.
FIGURE V-21 WRG PUMP CURVE
of the time was spent at speed points 3, 4 and 5, however, the pump operated at full speed point six occasionally and also at lowest speed with the starter only. The speed was measured with a manual tachometer on many instances and the average speeds for each set point are listed in Table V-5.

A motor efficiency of 95% at full speed was used to determine pump horsepower. This pump ran very seldom at full speed and changed so frequently that a reasonable motor efficiency could not be entered. The pump horsepower and efficiency numbers are therefore virtually meaningless and the pump's efficiency is much higher than indicated by the computer except for very short periods of time. An attempt was made to track the controller setting. Table V-6 shows the fluctuations over a one hour period.

The changes were so frequent that it was decided this could not be coordinated with the pump data and that pump efficiency and horsepower should be ignored for this test.

Table V-5
W. R. Grace Average Pump Speeds

<table>
<thead>
<tr>
<th>Controller Setting</th>
<th>Average Speed RPM</th>
</tr>
</thead>
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<tr>
<td>Starter Only</td>
<td>420</td>
</tr>
<tr>
<td>Stage 1</td>
<td>445</td>
</tr>
<tr>
<td>Stage 2</td>
<td>470</td>
</tr>
<tr>
<td>Stage 3</td>
<td>500</td>
</tr>
<tr>
<td>Stage 4</td>
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<tr>
<td>Stage 5</td>
<td>569</td>
</tr>
<tr>
<td>Stage 6</td>
<td>600</td>
</tr>
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</table>

The pump head from the computer should still be reliable data, but without a reliable speed reading it is not of much value.
The first day was spent mostly on installing and settling up the instrumentation. Just as the computer was ready to monitor and collect data, the pipeline was shut down. After waiting a couple of hours for the pipeline to restart, inquiries revealed that a pipeline fitting had been blown and would not be repaired until sometime overnight. Plans
were made to start first thing next morning with everything ready for a full day of testing.

After purging all transducers and checking calibrations, data collection commenced at 8:21 AM Friday, August 12, 1988. The system operated fairly stably at about 14,500 gpm around 1.35 SG and 4-5 ft/100 ft losses for about 30 minutes. This was followed by a short period of fluctuating flows up to 16,000 gpm and density peaks up to 1.4 SG. Next the flow and density gradually decreased as the system was washed out and then shut down at 9:08 AM. Due to lack of communications and forethought, the system had been repaired and brought backup overnight and the cut was mined out. The system would be down most of the day while the dragline striped overburden to prepare a new face. After much discussion and cajoling, WRG was convinced to strip only enough for a few hours running and to restart at noon.

Testing was resumed at 12:26 PM and ran continuously until 3:30 PM. Over 600 data points were collected. These are stored on file at GIW. The data is also plotted against time in Figures V-22 and V-23.

Over the period of the tests the velocity ranged from 10 ft/sec to as high as 18 ft/sec. The density varied from dirty water at 1.05 SG to over 1.4 SG while the friction pressure loss ranged from 3 to 6 ft/100 ft. While the operation fluctuated considerably the norms appeared to be about 16-18 ft/sec, 1.35-1.40 SG, and 5 ft/100 ft. From the data there are segments of relatively stable data which can be roughly averaged to give representative data points as shown in Table V-7.
The data are much more stable than expected with the continual speed changes on the pumps. This may be necessary to maintain sump control, but the writer believes this would be a much more stable and reliable operating system if part of this speed control was removed. More of the pumps should be constant full speed units. The efficiency and power usage probably could be reduced considerably and it might be possible to even remove one pump from the line if more of the others ran full speed.

<table>
<thead>
<tr>
<th>Velocity $V$, ft/sec</th>
<th>Friction Head Loss $i_m$, ft/100 ft</th>
<th>Specific Gravity $S_m$</th>
<th>Concentration $C_w$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.7</td>
<td>4.2</td>
<td>1.34</td>
<td>40.8</td>
</tr>
<tr>
<td>15.8</td>
<td>4.6</td>
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<td>44.2</td>
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<td>18.0</td>
<td>4.7</td>
<td>1.32</td>
<td>38.9</td>
</tr>
</tbody>
</table>
VI. EXTRUSION RHEOMETER TESTS

The following procedure was used to examine the rheology of the phosphate carrier during the FIPR testing contract. The carrier in these tests is defined by all material passing through a #30-600 micron sieve.

Two series of tests were performed on this carrier in the lab. The first series of tests were on matrix which had been through the pump numerous times and was collected while unloading the system. The material was passed through the #30-600 micron sieve without the addition of water. The material was then diluted to concentrations of 1.18, 1.21 and 1.31 SG. This first series of test did not include the Occidental Suwannee River matrix because it was found to settle out at these concentrations.

The second series of tests were performed on matrix which was straight from the mines and was unaltered except for the 600 micron screening. This material was washed through the sieve with water to insure all material less than 600 microns was retained, the matrix was then dried to the appropriate SG for testing which ranged from 1.53 to 1.30 depending on the matrix.

The d50 of matrix tested in this series was higher than the previously tested matrix because of this washing. The concentrations in this series of test were higher allowing the Occidental Suwannee River matrix to be included in the tests.

The apparatus used for the rheology testing consists of a vertical test pipe of drawn steel tubing of 13 ft (4 m) in length and having an inside diameter of 0.43 inches (10.9 mm) which connects two vessels.
The upper vessel was flexibly connected and suspended from a load cell. Air under constant pressure is supplied to the space above the free surface in the lower vessel, B, to provide the required flow rate to the upper vessel, A, in which the free surface is at atmospheric pressure. The outputs from the load cell and from a pressure transducer connected to the air space in the lower vessel are connected to a computer data-logger.

In order to carry out the experiments a measured quantity some two gallons of each slurry of known specific gravity, was poured into vessel A. The computer data logger was so programmed that it determined the wall shear stress, defined $\tau_0$, and the shear rate, defined by $8V/D$ when a predetermined mass of slurry has been transferred from vessel B to vessel A.

The above procedure was used for a range of flow rates to provide the following rheograms.

The printouts are labelled indicating the origin of the material, the concentration tested and additional information pertaining to the test. Any comments pertaining to the tests can be found in the lower right hand corner of either the printouts or the rheograms.

During the course of these tests extensive sampling was done before and after testing to assure that the SG was maintained throughout the test.
Size Breakdown of FIPR Phosphate Matrix as Received at GIW Hydraulic Lab

Taken from Sieve Analyses of Material Directly off Truck

<table>
<thead>
<tr>
<th>Sample</th>
<th>Truck No.</th>
<th>Pebble %</th>
<th>Feed %</th>
<th>Fines %</th>
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<tr>
<td>IMC</td>
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<td>1</td>
<td>54</td>
<td>26</td>
</tr>
<tr>
<td>Noralyn</td>
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<td>3</td>
<td>54</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>11</td>
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<td>26</td>
<td>11</td>
<td>42</td>
<td>33</td>
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<td>12</td>
<td>54</td>
<td>31</td>
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<tr>
<td></td>
<td>31B</td>
<td>12</td>
<td>57</td>
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<td>From Removed</td>
<td>58</td>
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<td>Pipe Section</td>
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<td>93</td>
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<td>OXY Field Test Sample</td>
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<td>30?</td>
<td>14</td>
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VI - 3
VII. EFFECT OF PHOSPHATE MATRIX SLURRIES ON CENTRIFUGAL PUMP HEAD AND EFFICIENCY

A. INTRODUCTION

Clear water head and efficiency of centrifugal pumps are generally lowered by the presence of solids. The pumping cost is related to the operating conditions in a complex way because the performance is affected by the solids in the slurry. Detailed information on the solids effect is needed in order to achieve energy-efficient operation of phosphate matrix pipelines. For example, the pump power needed in a line of a length of up to 10 miles (16 km) with a diameter of 18" (0.46m) can be in the region of 10 MW.

Earlier investigations reported in the literature have been reviewed, for example, by Sellgren (1979). Most investigational work has been carried out with ore products, coals and sands in relatively small pumps with impeller diameters of less diameter than 20" (0.5m). Very few data are available with larger units but reductional effects should generally be small or in larger pumps (Sellgren, et.al 1986). However, reliable scaling criteria are not known at present.

Some experimental results with phosphate matrix pumping from the GIW Laboratory (Addie, 1982) with a unit with an impeller diameter of 31" (0.8m) indicated drops in head and efficiencies of about 15% for a solids concentration by weight, $C_w$, of about 32%. No data have been available on the effect of phosphate matrix slurries on the performance of large centrifugal pumps with impeller diameters of 44"-51" (1.1 - 1.2m).
B. OBJECTIVES

The objective has been to evaluate the influence of representative Florida phosphate matrix slurries on the performance of large centrifugal GIW pumps. The aim has here been to represent the results of the analysis in a simple form suitable for quick estimations. More detailed results will also be given as an algorithm in a computer program developed by GIW as a tool for the hydraulic design of phosphate matrix pipelines.

C. EXPERIMENTAL STUDY

The pumps used in the tests were a 18x18LSA type of pump with an impeller diameter of 44" (1.1m) and a 18x20WBC pump with an impeller of 51" (1.2m). The WBC-pump was used for tests with three different products while the LSA-pump was used for a coarse product only. The experimental facility and measurement procedures, etc. have been described earlier in this report.

D. RESULTS

The results covered flow rates of 4,000-24,000 USGPM (16-96 m³/min) and rotary speeds mainly in the range of 350 to 490 rpm.

In terms of particle size and distribution phosphate matrixes are normally characterized by the content by weight of pebbles (+1200 microns), the feed product (105-1200 microns) and fines (-105 microns). In the Florida phosphate fields the content of fines is mainly 20 to 35% while the content of pebbles varies from some few percents up to nearly 40%
Pump test results with a coarse matrix product is shown in Figure VII-1.

The influence of solids on the performance was small for the two pumps tested compared to effects normally encountered with smaller pumps. The results shown in Figure VII-1 for the coarsest product investigated represents the largest effects observed.

Most experimental data were collected at solids concentrations by weight of about 35%. The measured data showed no significant dependence of reductional effects with the solids concentration. This can be explained by the solids degradation effect which took place.

Figure VII-1. Depression in head and efficiency for a coarse phosphate matrix product when pumped at $C_w = 50\%$. Pebble content (+1200 microns) = 38%. Pump type: GIW 18x20WBC54(51.2), rotary speed = 485 rpm.
during a test period. Particle sample test results on a before and after basis indicated that breaking down of agglomerates and degradation reduced the particle sizes substantially for the coarsest products tested. The detailed experimental results indicated that the dependence of solids concentration is masked by solids degradation effects. Based on reported experiences with smaller pumps it is reasonable here to assume a linear concentration dependence of the reduction in head and efficiency for phosphate matrix concentrations by weight of up to 50%.

Most experimental results showed a slight trend of decreased solids effects on the head with increased flow rates. An opposite trend was found for the efficiency, see Figure VII-1.

The reduction of clear water head and efficiency for a constant flow rate and rotary speed was defined by the following ratios

\[
\text{Reduction ratio in head: } RH = \frac{\Delta H}{H_0} \quad (1)
\]

\[
\text{Reduction ratio in efficiency } RE = \frac{\Delta \eta}{\eta_0} \quad (2)
\]

where

\( \Delta H \) = head reduction developed in slurry service, feet (meters) of slurry

\( \Delta \eta \) = efficiency reduction developed in slurry service

\( H_0 \) = head developed in wake service, feet (meters) of water

\( \eta_0 \) = pump efficiency in water service

These variables are schematically defined in Figure VII-2 at two different flow rates, \( Q_1 \) and \( Q_2 \).
In industrial operation, flow rates are normally 60 to 70% of the flow rate at the best efficiency point, \( Q_{BEP} \). For these flow rates and neglecting minor differences of the solids effect between the two pumps the following overall results have been summarized, Table VII-1.

![Schematic representation of reductional variables for pump head and efficiency.](image)
Table VII-1

Overall values of relative reduction in head and efficiency for phosphate matrix pumping with GIW pumps with impellers of 44" to 51" (1.1 - 1.2m), related to a \( C_w \) of 35%. Pump rotary speeds of 350 to 500 rpm. Matrix product characterized by its pebble content (+1200 microns).

<table>
<thead>
<tr>
<th>Pebble Content</th>
<th>RH (eq. 1)</th>
<th>RE (eq. 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>38% (max.)</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>13%</td>
<td>5%</td>
<td>3%</td>
</tr>
<tr>
<td>2% (min.)</td>
<td>5%</td>
<td>2%</td>
</tr>
</tbody>
</table>

With the reductional effects related linearly to the solids concentration then for example the RH and RE values in Table VII-1 are magnified by a factor of 45/35 = 1.29 when pumped at \( C_w = 45\% \).

E. DISCUSSION OF RESULTS

The comparatively small effects of the solids investigated here for large GIW pumps clearly demonstrate the importance of relating reductional effects to the size of the pump. With small pumps with impellers of about 20" (0.5m) the corresponding reductions would probably have been about 20%.

It is known from other studies (Sellgren, 1979) that the influence of individual solids properties on head is generally more moderate than the influence on efficiency. This may explain the negligible effect in head of the solids composition shown in Table VII-1. Furthermore, the trend in Table VII-1 with a decrease in reductional effects in efficiency with a decreased amount of coarse particles can be explained by turbulent dampening and non-Newtonian effects of the fine particles portion of the slurry. These effects may cause a decrease of the disc...
friction within the pump which nearly compensate the extra hydraulic losses due to solids.

Finally, it must be emphasized that the small effects of solids obtained here sometimes were within the range of the practical possible evaluation accuracy in light of the experimental difficulties encountered with particle degradation, etc. Furthermore, in industrial applications a stage is reached where the suggestive wear within the pump affects the performance to a larger degree than the effects of solids.

The detailed results of the evaluations will be given as input to other GIW-pump data in a hydraulic design computer program for phosphate matrix pipelines. The algorithm for the effects of solids on the pump performance is shown separately in the Appendix VII-1.

F. CONCLUSIONS

The detailed results of the influence of phosphate matrix slurries on the head and efficiency on two GIW-pumps have been given in an algorithm (see the Appendix) for use in the overall hydraulic design computer program described elsewhere in this report.

The overall results are here summarized in a simple form related to normal operating conditions and a solids concentration by weight of 35%. Compared to clear water values the reduction in head was approximately 5% for all matrix products tested. The reduction in efficiency varied from about 2% for the finest product to about 5% for the coarsest product. With concentrations by weight of up to 45-50% it is suggested that the reductional values given above are modified in proportion to the deviation from 35%.
G. REFERENCES


APPENDIX VII-I

ALGORITHM

Input clear water pump data are given by type, rpm, actual flow rate, \( Q_x \), and flow rate at BEP, \( Q_{\text{BEP}} \). Furthermore, the solids concentration by weight \( C_w \) is given together with the pebble content in percent in the matrix.

The fact that the solids effects were small means that the parameters can be linearly related in an algebraic relationship. The solids effect were related to four constants \( RH_1, RH_2, RE_1 \) and \( RE_2 \). The constants were defined as follows, see Figure VII-2.

\[
RH_1 = \frac{\Delta H_1}{H_{o1}} \quad RE_1 = \frac{\Delta n_1}{\eta_{o1}}
\]

\[
RH_2 = \frac{\Delta H_2}{H_{o2}} \quad RE_2 = \frac{\Delta n}{\eta_{o2}}
\]

The experimental results have been evaluated in terms of the constants defined above.

Legend:

\[
\begin{array}{c|c|c|c}
\hline
\text{Pebble content(\%)} & 38\% & 13\% & 2\% \\
\hline
\text{Pump Type} & \text{RH1} & \text{RE1} & \text{RH2} & \text{RE2} \\
\text{LSA} & 0.03 & 0.03 & 0.03 & 0.03 \\
WBC & 0.06 & 0.07 & 0.05 & 0.03 & 0.05 & 0.02 \\
\text{Type} & & & & \\
\hline
\end{array}
\]

VII-I-1
The dependence of flow rate is related linearly to $Q_x$ with $Q_1 = 0.5$ $Q_{BEP}$ and $Q_2 = Q_{BEP}$ (Figure 2) through the following parameters.

$$Q_{FACT} = \frac{Q_{BEP} - Q_x}{Q_2 - Q_1} = \frac{Q_{BEP} - Q_x}{0.5 Q_{BEP}}$$

Furthermore, the influence of solids concentration is directly related to a reference concentration of 35%. The reductions in head and efficiency at an arbitrary flow rate is then calculated by the following relationship.

$$\Delta H_x = (Q_{FACT} (RH1 - RH2) + RH2) \cdot \frac{C_W}{0.35} \cdot H_{ox}$$

$$\Delta \eta_x = (Q_{FACT} (RE1 - RE2) + RE2) \cdot \frac{C_W}{0.35} \cdot \eta_{ox}$$

$$RH_x = \frac{\Delta H_x}{H_{ox}}$$

$H_x$ and $\eta_x$ are then used further use in the program while $RH_x$ and $RE_x$ are given as information.