Publication No. 02-149-201

PNEUMATIC TRANSPORT, TRIBOELECTRIC BENEFICIATION FOR THE FLORIDA PHOSPHATE INDUSTRY

Prepared by
University of Kentucky

under a grant sponsored by

FIPR
Florida Institute of Phosphate Research

December 2003

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.

FIPR is located in Polk County, in the heart of the central Florida phosphate district. The Institute seeks to serve as an information center on phosphate-related topics and welcomes information requests made in person, or by mail, email, or telephone.

Florida Institute of Phosphate Research
1855 West Main Street
Bartow, Florida 33830
(863) 534-7160
Fax: (863) 534-7165
http://www.fipr.state.fl.us

PNEUMATIC TRANSPORT, TRIBOELECTRIC BENEFICIATION FOR THE FLORIDA PHOSPHATE INDUSTRY

FINAL REPORT

John M. Stencel
Principal Investigator

with

Xinkai (Kelvin) Jiang

UNIVERSITY OF KENTUCKY
Lexington, KY 40511

Prepared for:

FLORIDA INSTITUTE OF PHOSPHATE RESEARCH
1855 West Main Street
Bartow, FL 33830

Contract Manager: Patrick Zhang
FIPR Project Number: 01-02-149R

December 2003

DISCLAIMER

PERSPECTIVE

Patrick Zhang, Research Director - Beneficiation & Mining

In current phosphate beneficiation practice in Florida, deslimed phosphate ore is sized using a hydrosizer to produce a coarse (16 by 35 mesh) and a fine (35 by 150 mesh) flotation feed. The sized feed is dewatered to about 70% or higher solids and then conditioned with a fatty acid/fuel oil mixture at pH of about 9, followed by rougher flotation. The rougher concentrate is subjected to dewatering, acid scrubbing, and washing to remove reagent prior to amine flotation. Major problems associated with this process include the following:

- Generation of more than 3 million tons per day of dilute (about 3% solids) waste clay slurry, which is both costly and difficult to dispose of
- Use of tremendous amounts of chemicals
- Use of large amount of water

High-grade (around 72% BPL) phosphate rock is required for making animal feeds. A regular flotation concentrate analyzes about 69% BPL. Certain areas of a deposit have a better potential for producing the higher grade concentrates than others. Prospect data are used to identify these areas. When higher grade areas are mined, the flotation operators are made aware that they have a better chance of achieving the higher grade products that are required for animal feed. The product will be directed to a separate holding bin for assay in the lab. If the assay shows the bin is of sufficient animal feed grade, the bin is dumped on a high-grade section of the wet rock storage pile. This practice is tedious, and does not offer any guarantee of producing higher-grade rock. As the higher-grade deposits deplete, special measures must be taken to produce an acceptable higher-grade phosphate rock for animal feed.

Application of electrostatic separation technology in phosphate beneficiation has been looked at without much success. However, the pneumatic transport, triboelectric beneficiation technology invented by University of Kentucky has some unique features, including high throughput, broad size range, and an in-line drying mechanism. The feed to be beneficiated is fed to a transport line in which it is pneumatically conveyed and delivered to the top of a parallel plate electric field zone. The powder is distributed across this zone, injected at speeds between 5-15 m/s. Because its height is typically less than 25 cm, the residence time in the electric field zone is less than 0.05 s. Separation is achieved by the electric field on bipolar-charged particles established by particle-particle contacts in the fluid transport lines.

The system showed varied degrees of success in beneficiating phosphate matrix, rougher flotation feed, rougher concentrate, and amine concentrate. However, the best bet for this technology is upgrading amine concentrate for animal feed-grade phosphate rock. For such application, further investigation is necessary to determine the maximum moisture level for the system to work efficiently and the drying cost to achieve that moisture level.

ABSTRACT

The beneficiation of phosphate ores, fine feeds, rougher concentrates and flotation concentrates from the Four Conner and Hopewell, Florida plants of IMC was investigated using pneumatic transport, triboelectric separation technology. Because the system relies on establishing bipolar charge on physically distinct particles, four types of charging configurations were used, including horizontal and vertical tube chargers, and circular and octagonal triboroller chargers. Process parameters, including electric field strengths, gas transport speeds within the chargers and electric field zone, phosphate feedrates and triboroller rotation speeds were varied to examine their effect on removing silica and other insolubles from the phosphates.

Since triboelectric beneficiation is a dry technology, a cost estimation was performed for drying phosphates from 15% moisture down to 4% moisture. It is suggested that moisture below a 4% level is located within macropores or cracks within the particles.

The products from triboelectric separation had grades and P_2O_5 recoveries equivalent to the currently used wet, beneficiation technology for phosphate upgrading. Because triboelectric technology is not limited to processing only the +105 μm (150 mesh) particles, its application could be beneficial for the phosphate industry if precise cost calculations were performed to establish niche product applications and process drying requirements.

TABLE OF CONTENTS

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (CONT.)

Figure **Page**

EXECUTIVE SUMMARY

The beneficiation of phosphate ores, fine feeds, rougher concentrates and flotation concentrates from the Four Conner and Hopewell plants of IMC was investigated using pneumatic transport, triboelectric separation technology. Because this is a dry process dependent on establishing bipolar charge on physically distinct particles, four types of charging configurations were used. They included horizontal and vertical tube chargers, and circular and octagonal triboroller chargers. Other process parameters such as the electric field strength, transport speeds within the chargers and electric field zone, feed rate and triboroller rotation speed were varied to examine their effect on phosphate and silica separation.

Significant results of the study include:

- Hopewell fine feed at ~12% P_2O_5 was upgraded to 21-23% P_2O_5 with 81-87% P_2O_5 recovery;
- Four Corners rougher concentrate with ~19.5% P_2O_5 was upgraded to 25-26% P_2O_5 with between 90-94% P_2O_5 recovery;
- Increasing the feed rate of Hopewell rougher concentrate between 1-14 kg/hr created constant ~22.5% P_2O_5 grade product with increased P_2O_5 recovery;
- Depending on whether one or two stage processing was employed, the silica in Four Corners flotation concentrate was decreased by 7%-to-21% with 91%-to-95% P_2O_5 recovery (single stage-double stage) and silica in Hopewell flotation concentrate is reduced by 32-44% with 91-95% P_2O_5 recovery (single stage-double stage);
- Two phosphate particle charging methods, including turbulent gas transport and triborollers, gave equivalent beneficiation performance; and
- The estimated cost for building and operating a 100 ton/hour triboelectric phosphate upgrading plant is less than that for the current wet beneficiation technology.

These results point to triboelectric beneficiation as a new and promising direction for the phosphate industry. Its ability to beneficiate particulate below the current limit (105 μm) of wet beneficiation technology points to the potential of processing even the finest-sized component of phosphate ores that are currently landfilled. For such applications, it would be necessary to carefully determine drying costs because all phosphate processing in Florida now employs wet circuits. However, the extent to which phosphate particles have to be dried for successful triboelectric beneficiation is not yet known. Focused studies in which particulate drying to levels between 4% and 1% moisture content are needed. Furthermore, because the future of the phosphate industry lies in innovation, it is suggested that a whole new approach that encompasses totally dry processing may be of significant benefit.

INTRODUCTION

In 2000, the United States was the world's leading producer of phosphate rock, accounting for nearly 30% of total world production of 133 million tons. The US was also the largest consumer of phosphate rock and the largest exporter of phosphate fertilizers. Its phosphate industry made nearly 40 million tons of marketable products by upgrading phosphate rock (US Geological Survey 2001); these products had a value of $1 billion f.o.b. at the mine. Phosphate mining occurs in only four states, with Florida and North Carolina facilities accounting for 85% of the total domestic output. Two other states, Idaho and Utah, have drier climates and resources remote from the primary consumer of phosphate products--the agriculture sector.

Phosphorus is an essential element for plant and animal nutrition. All commercial and consumable phosphorus-containing materials originate from phosphate ore. It is upgraded into agricultural fertilizers, animal feed, elemental phosphorus, and industrial phosphates used in oil additives, foods, and many other consumer products. There are no substitutes for phosphorus. World demand for phosphate fertilizers continues to expand as the world population grows.

Currently, industry uses flotation for phosphate ore upgrading and product finishing (Gieseke 1985). This technology, developed by Arthur Crago in 1942, has experienced small, stepwise improvements since its invention (Zhang and others 1997). Typically, the -105 μm (-150 mesh) size split is not processed but rather is landfilled because it doesn't respond to flotation. The +105 μm is floated twice, first with a fatty acid and then with an amine. In Florida, nearly 100,000 tons/day of clay tailings/waste byproducts are generated; since the beginning of phosphate mining, over 1.5 billion tons of tailings have accumulated in Florida.

Although the Crago process is standard industrial practice, significant issues are associated with it, including:

- loss of nearly 30% of the phosphate mined because of the inability to upgrade the -150 mesh material;
- high reagent costs of $2.50-$4.00 per ton, increasing the price of finished products;
- inefficient flotation processing of silica/sand, necessitating over 30% of it to be floated twice;
- high consumption of aquifer water.

Florida encompasses the major phosphate producing area in the US and makes 30-40 million tons of phosphate products per year. The quality of its mined phosphate rock is declining because high-grade, more easily extracted resources have been depleted during the many years of mining. For example, the average P_2O_5 content in Florida ore reserves is near 6% whereas some waste impoundments contain P_2O_5 contents greater than 14%. As the quality decreases, it becomes more difficult to produce animal-feed

grade products using flotation processing. Also, as the grade of phosphate ores decline, mining and upgrading costs increase, the result of which is increased costs to users and consumers.

Crago processing of Florida phosphate consumes about 50 million gallons per day of aquifer water. The Florida phosphate industry also uses around 20 million gallons per year of various reagents (fatty acids, amines, fuel oil, soda ash, and sulfuric acid). An innovative process that removes silica more efficiently from the +150 mesh material and can beneficiate the -150 mesh material would benefit industrial productivity, consumer and the environment.

Hence, in this study a new, dry technology called pneumatic transport, triboelectric separation (Stencel and others 1998, 1999a, 1999b, 2001, 2002; Ban 1994; Li 1999; Gurupira 2001) was examined for its efficacy to upgrade phosphates from two Florida plants. Because it is a dry process dependent on establishing bipolar charge on physically distinct particles, four types of charging configurations were used, including horizontal and vertical tube chargers, and circular and octagonal triboroller chargers. Other process parameters, including the electric field strength, transport speeds within the chargers and electric field zone, feed rate and triboroller rotation speed were varied to examine their effect on phosphate upgrading.

METHODOLOGY

The triboelectric purification (TEP) system used during phosphate upgrading was a laboratory-scale unit, a general depiction of which is given in Figure 1. Samples were placed in a vibratory feeder from which they were dropped into either an air eductor for gas transport charging or a funnel leading to a triboroller charger. In the eductor in the air transport charging case, all samples were entrained in a turbulent air stream, the exit of which was into the electric field zone of the separator. The flow within this zone, although not laminar, had limited, small-scale turbulence. In the triboroller case, after exiting the roller, the samples were air-assisted/gravity fed to the inlet of the electric field zone of the separator.

The separator contained parallel plate electrodes across which was placed a high voltage between 0-30,000 volts. For air-transport charging, either two or three products emanated from the separator.

Tubing chargers and a newly-developed, triboroller charger were used during the tests. For the latter, three products were made, including a P_2O_5-enriched, recycle, and silica-enriched. In scale-up of the technology to commercial sizes, the recycle product can be reprocessed in a second stage operation.

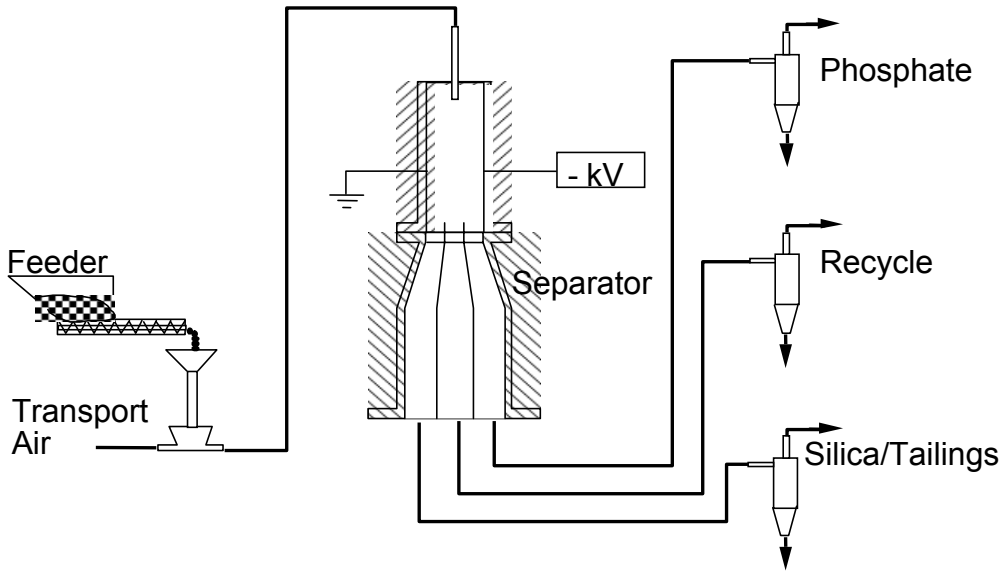

Figure 1. Schematic of Bench-Scale Triboelectric Purification System Used During Phosphate Beneficiation Tests.

For triboroller charging, the three products from stage one were individually processed again, thereby creating nine products. After collection in cyclones, product masses were measured and their sum compared to the feed mass to calculate mass balances between feed and products.

The three products included a P_2O_5-enriched, recycle, and silica-enriched products. They were individually processed again, the nine product masses were then measured and analyzed for P_2O_5 and insoluble concentrations.

A two-product outlet was used for most of the tests employing a tube charger. The analyses of these products were accomplished in the same way as for a three product TEP system.

Product P_2O_5 and insoluble concentrations were measured at the Center for Applied Energy Research (CAER), University of Kentucky and at FIPR. The CAER analyses were accomplished using the procedures supplied by FIPR. The P_2O_5 and mass yield data enabled recovery curves (% P_2O_5 recovered-versus-P_2O_5 content) and yield curves (% product mass-versus -P_2O_5 content) to be calculated.

The method of turbulent air/pneumatic transport charging was developed at the University of Kentucky and is employed in a commercial coal combustion byproduct separation system in Colorado Springs. This method uses a known volume flow rate of air with a known mass feedrate of phosphate particles. The air transports the phosphate through specially designed pipes and then into the electric field zone of the separator. Because it has been employed to beneficiate numerous minerals at the University, an extensive data base exists giving proper conditions for optimizing bipolar charging of particles.

The second method of charging particles was used on the majority of the work performed. Called the triboroller charging method, it was developed during the PhD dissertation research of Mr. Xinkai (Kelvin) Jiang.

The triboroller shapes used during the testing included cylinders and octagons (Figure 2). The triborollers were rotated within an enclosed chamber through which the phosphate particles were passed under slow (typically ~0-5 m/s) air transport conditions. Particles are charged by collision with the copper surface of the roller and by particle-particle collisions under the highly turbulent conditions existing near the roller surface.

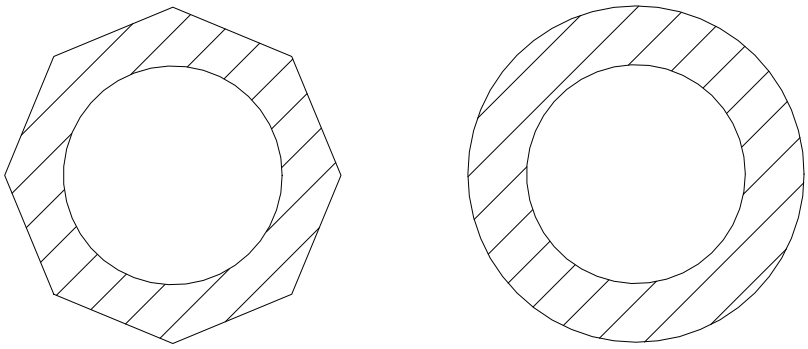

Figure 2. The Shapes of the Triboroller Chargers Used During Triboelectric Phosphate Beneficiation Testing.

Phosphate samples were obtained from the IMC plants at Hopewell and Four Corners in Florida. Included were the matrix or ores, fine feeds, rougher concentrates and flotation concentrates. Each sample was subjected to laboratory-scale triboelectric beneficiation.

RESULTS AND DISCUSSION

Ores

In Crago processing, phosphate ores are subjected to desliming and sizing before flotation. The -105 µm fraction (called slime or clays) is discarded in settling ponds. The +105 µm is called the flotation feed and is the material to be upgraded.

The recovery and yield curves for upgrading the Hopewell ore using two-stage TEP processing and an octagonal triboroller charger are shown in Figure 3. The charger surface was covered with copper sheathing; its rotation speed was 7000 rpm, giving a surface speed of 32 m/s. The phosphate transport speed through the charger was 3.75 m/s.

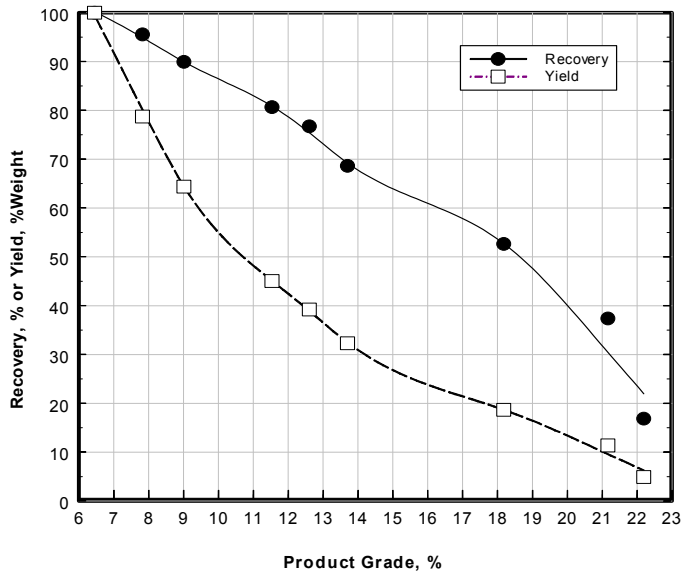

Figure 3. Recovery of Phosphate from Hopewell Ore; an Octagon Triboroller Charger Was Used.

The differences between the recovery and yield curves indicate significant beneficiation. With the feed grade at 6.4% P_2O_5, the highest concentrate grade obtained was 22.2 % P_2O_5 but only at 4.9% yield. At 12% P_2O_5, the yield was 34%; these values imply 77% recovery of the P_2O_5 in the ore.

Table 1 shows results of upgrading Four Corners ore using a horizontal tube charger. This single stage processing started with a 2.68% P_2O_5 Four Corners feed which

was upgraded to 3.37 %P_2O_5 at 90% P_2O_5 recovery. The P_2O_5 content in the silica-rich product was 0.94 %P_2O_5.

Table 1. Triboelectric Beneficiation Results for Four Corners Ore Using a Horizontal Tube Charger Configuration (N = negative plate; P = positive plate).

Sample	Product Weight, %	P_2O_5, %	P_2O_5 Recovery, %
Four Corners Feed	100.0	2.7	100.0
Four Corners Conc. (N)	71.5	3.4	90.0
Four Corners Tailings (P)	28.5	0.9	10.0

Results from using a two-stage process and an octagonal triboroller charger for the Four Corners ore are shown in Figure 4. The P_2O_5 recovery with the highest grade was 10% at a 3% yield; it contained 11.60% P_2O_5, a 3.3 enrichment ratio. By comparing the data in Table 1 and Figure 4 it is possible to see that, at a 90% yield, the tube charger increased the P_2O_5 content by 26% above the feed P_2O_5 content and the triboroller charger increased the P_2O_5 content by 22% above the feed P_2O_5 content. Hence, both charger configurations have similar ore upgrading potential.

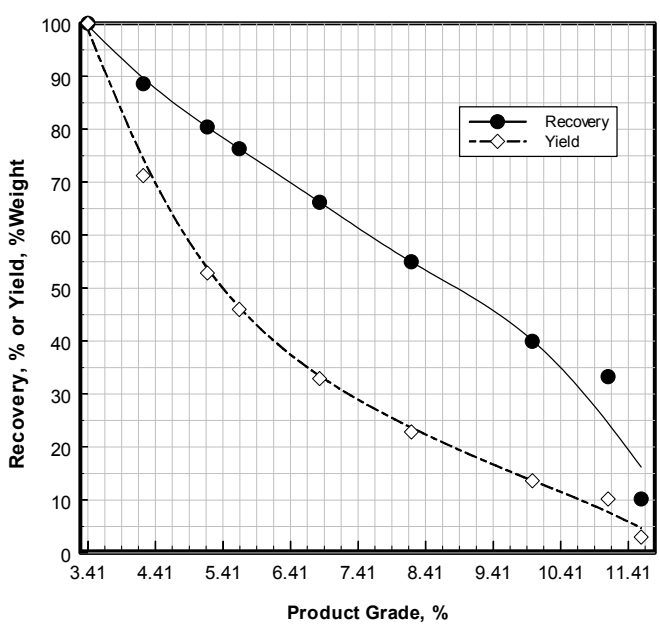

Figure 4. Recovery of Phosphate from Four Corners Ore; an Octagon Triboroller Charger Was Used During the Triboelectric Beneficiation Tests.

Fine Feeds

Two-stage processing data for the Hopewell fine feed using an octagon triboroller charger are presented in Table 2 and Figure 5. They show the fine feed responded better to TEP than did the ore (compare Figure 3 and Table 1). At 90% P_2O_5 recovery, the P_2O_5 content in the product from the fine feed was increased 66% whereas the P_2O_5 content in the product from the ore was increased only 38%. This enhanced performance is easily noted by simply examining the shape of the recovery and yield curves in Figures 3 and 5.

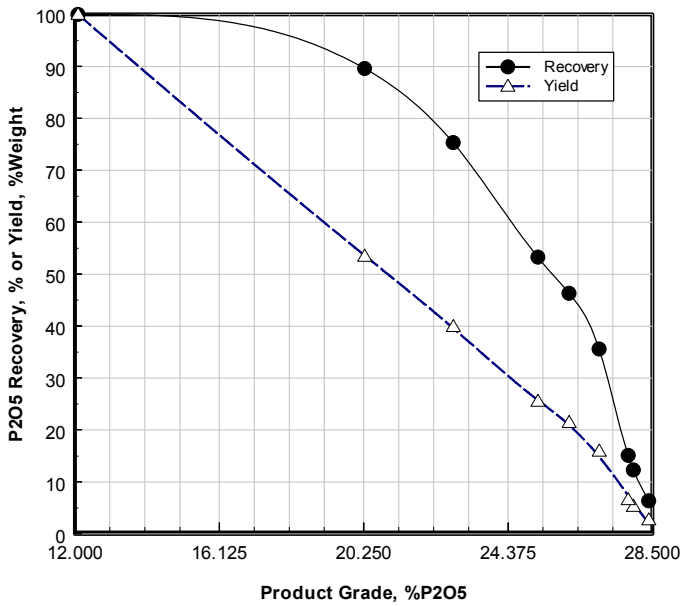

Figure 5. Recovery of Phosphate from Hopewell Fine Feed.

At a 50% product yield for the Hopewell fine feed, 88% of the P_2O_5 was recovered at a 21% P_2O_5 grade. The tailings, at 46.6% of the feed, were removed with only 10% loss of the P_2O_5. This performance was as good as or better than the beneficiation performance of Crago processing since the rougher concentrate product obtained from the Hopewell plant had a 19.5% P_2O_5 content. Although overall P_2O_5 recovery for fine feed at the Hopewell plant is not known, it is expected to be near 90%.

Table 2. Beneficiation Results for Hopewell Fine Feed Using an Octagon Triboroller Charger Configuration.

Individual	Yield, %	2.7	2.6	1.2	9.4	5.5	4.1	14.4	13.5	46.6
	Grade, %P_2O_5	28.4	27.5	27.2	26.4	23.6	20.6	18.5	12.8	2.7
	P_2O_5 Recovery, %	6.3	6.0	2.8	20.5	10.7	7.0	22.0	14.3	10.4
Accumulated	Yield, %	2.7	5.3	6.6	16.0	21.5	25.5	39.9	53.4	100.0
	Grade, %P_2O_5	28.4	28.0	27.8	27.0	26.1	25.2	22.8	20.3	12.1
	P_2O_5 Recovery, %	6.3	12.3	15.1	35.6	46.3	53.3	75.3	89.6	100.0

The residence time of particles in the electric field zone of the triboelectric system decreases as the speed of the particles injected into the electric field zone increases. For example, at a 2 m/s injection speed, the residence time is ~0.09 second; at a 10 m/s injection speed, the residence time is ~0.02 seconds. This injection speed is related to the air speed within the triboroller. Hence, data presented in Table 3 on the Hopewell fine feed show the effects of varying air transport speeds between ~0 m/s-to-6.3 m/s on phosphate recovery. Because only small differences between the grades of the P_2O_5-rich product and the recycle product occurred, the data also have a column in which these products were combined. Overall, the best P_2O_5 recovery was for air transport speeds near 1.0 m/s.

Table 3. Effect of Transport Air Speeds Within the Triboroller Charger on the Beneficiation of Hopewell Fine Feed.

Air Speed m/s	%P_2O_5					P_2O_5 Recovery,%				Silica Rejection,%	
	Silica-Rich	Recycle	P_2O_5-Rich	Recycle & Phosphate-Rich	Silica-Rich	Recycle	P_2O_5-Rich	Recycle & Phosphate-Rich	Silica-Rich	Recycle	P_2O_5-Rich
0.0	4.4	21.1	23.8	21.7	17.8	62.0	20.2	82.2	56.7	33.9	9.4
0.5	5.2	23.4	25.0	23.8	24.7	55.4	20.0	75.3	65.3	26.1	8.6
1.2	5.7	22.6	25.9	23.5	28.0	50.1	21.9	72.0	66.3	24.7	9.0
2.0	5.6	21.4	25.2	22.5	26.2	50.8	23.1	73.8	63.6	26.6	9.8
3.5	5.7	19.2	23.0	20.2	24.8	52.1	23.1	75.2	58.2	30.9	10.9
6.3	6.5	16.7	21.9	18.0	24.7	54.2	23.8	78.0	49.9	38.1	12.0

A further breakdown of these beneficiation data is presented in Figures 6-8, with Figure 6 showing data on product grades; Figure 7 showing P_2O_5 recovery; and Figure 9 showing gangue (or silica) recovery. In all of these, an injection speed near 1 m/s provided the best recoveries and product grades. Hence, further tests were performed to measure upgrading as the rotation speed of the triboroller charger was changed.

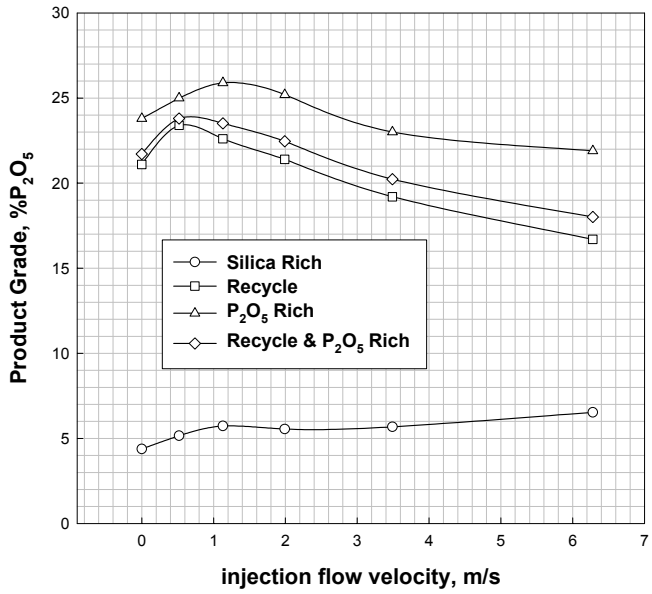

Figure 6. Effect of Transport Air Speed Within the Triboroller Charger on P_2O_5 Product Grades for Hopewell Fine Feed.

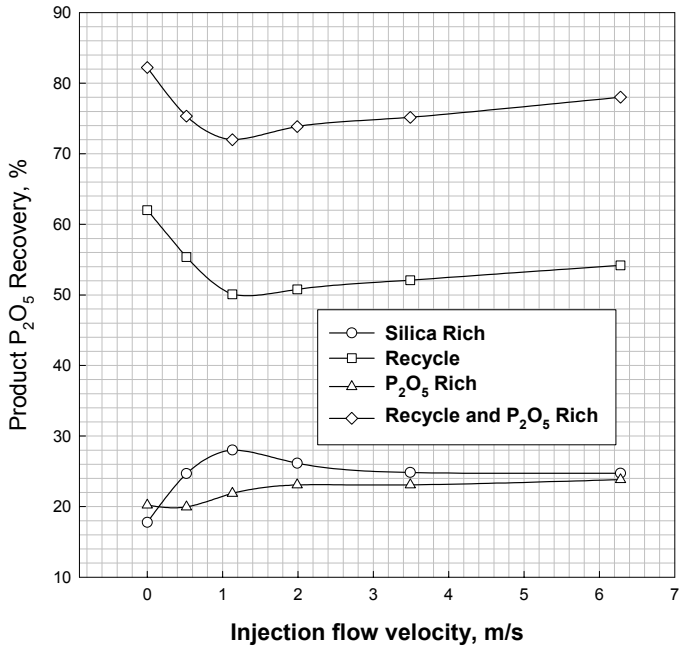

Figure 7. Effect of Transport Air Speeds Within the Triboroller Charger on P_2O_5 + Recycle Product Recoveries for the Hopewell Fine Feed.

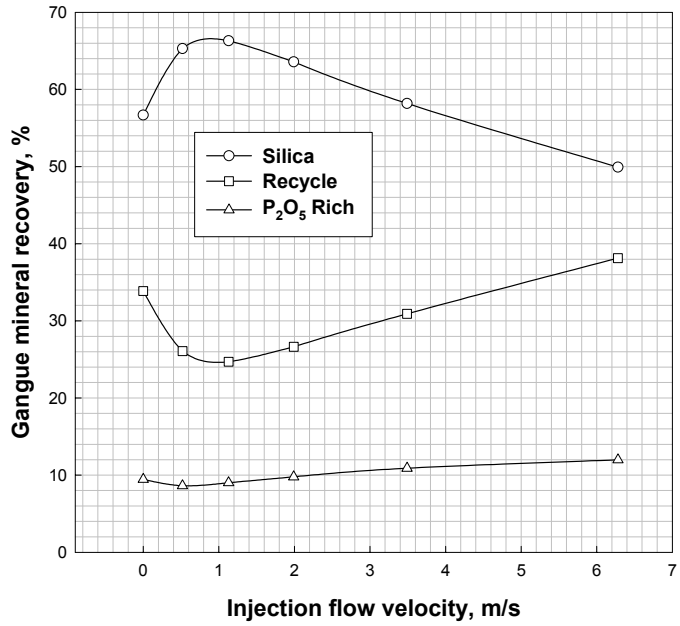

Figure 8. Effect of Transport Air Speeds Within the Triboroller Charger on Silica-Rich Product Recoveries for the Hopewell Fine Feed.

Figure 9 displays beneficiation data for the Hopewell fine feed as the rotation speed of the triboroller charger was varied between ~5 m/s-to-35 m/s. In this range, the best recovery performance was achieved at a triboroller surface speed of 13.96 m/s, i.e. higher surface speeds did not continuously increase product recovery and grade. The shape of recovery curves did not change as the speed was increased, implying that charging mechanisms within the triboroller was constant with rotation speed. The decrease in performance at higher speeds suggests that excess gas turbulence was present at the exit of the triboroller which then affected flow stability within the electric field section of the separator.

Beneficiation data for the Hopewell fine feed as the triboroller surface speeds were changed are presented in Table 4 and Figures 10-12. The single stage data in Table 4 for the combined 'recycle + P_2O_5-rich' product show the ~12% P_2O_5 feed could be increased to 23.7% P_2O_5 with 77% P_2O_5 recovery as the rotation speed was increased to 18.6 m/s, or increased to 20.5% P_2O_5 with 87% P_2O_5 recovery when the rotation speed was 9.3 m/s. Higher rotation speeds did not increase either the product grades or yields. These data suggest that, if a triboroller was used for particle charging, the best surface speed would be between 10-20 m/s.

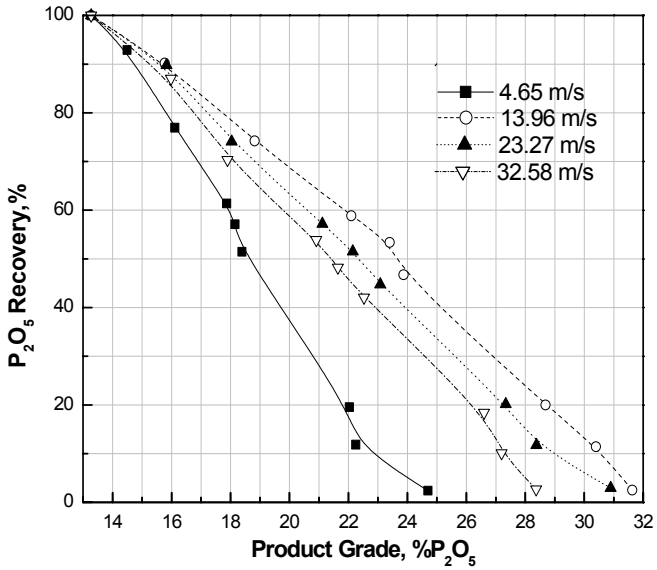

Figure 9. Recovery Curves for Hopewell Fine Feed Using an Octagonal Triboroller Charger at Different Surface Speeds.

Table 4. Effect of Triboroller Surface Speed on Hopewell Fine Feed Beneficiation While Using an Air Transport Speed of 1 m/s.

Tribo-roller Speed (m/s)	%P_2O_5					P_2O_5 Recovery, %				Silica Recovery	
	Silica-Rich	Recycle	P_2O_5-Rich	Recycle & Phosphate-Rich	Silica-Rich	Recycle	P_2O_5-Rich	Recycle & Phosphate-Rich	Silica-Rich	Recycle	P_2O_5-Rich
~0.0	6.0	13.7	19.6	14.8	10.4	66.9	22.6	89.6	24.0	62.2	13.7
9.3	3.7	18.4	27.0	20.5	13.0	58.7	28.3	87.0	50.0	38.6	11.4
18.6	5.0	22.9	25.9	23.7	22.6	54.6	22.8	77.4	63.4	27.1	9.6
27.9	5.5	22.2	24.5	22.8	26.7	52.4	20.8	73.3	64.9	26.0	9.1
37.2	7.3	21.1	21.1	21.1	39.2	43.8	17.0	60.8	68.6	22.6	8.8

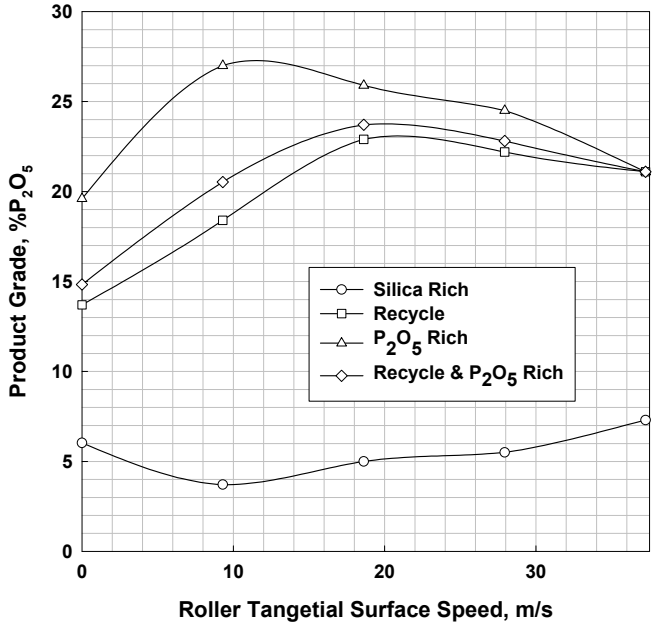

Figure 10. P_2O_5-Enriched Product Grade Versus Triboroller Surface Speed for Hopewell Fine Feed at an Air Transport Speed of 1 m/s.

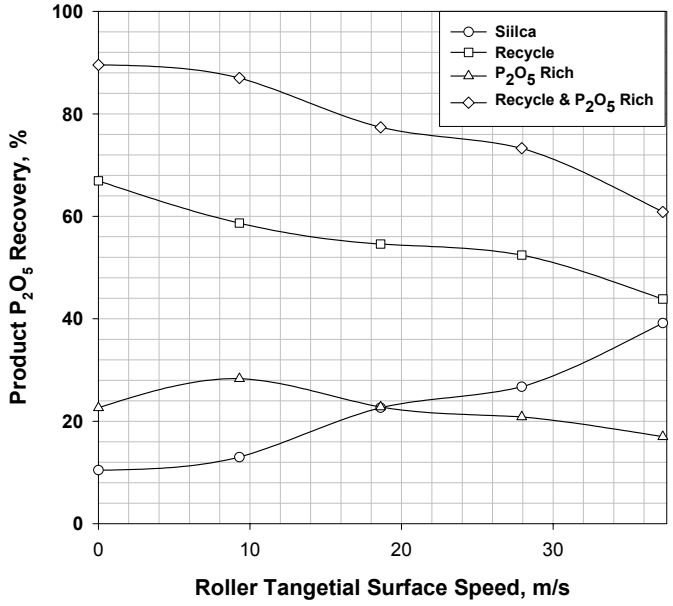

Figure 11. P_2O_5 Recovery Versus Triboroller Surface Speed for Hopewell Fine Feed at an Air Transport Speed of 1 m/s.

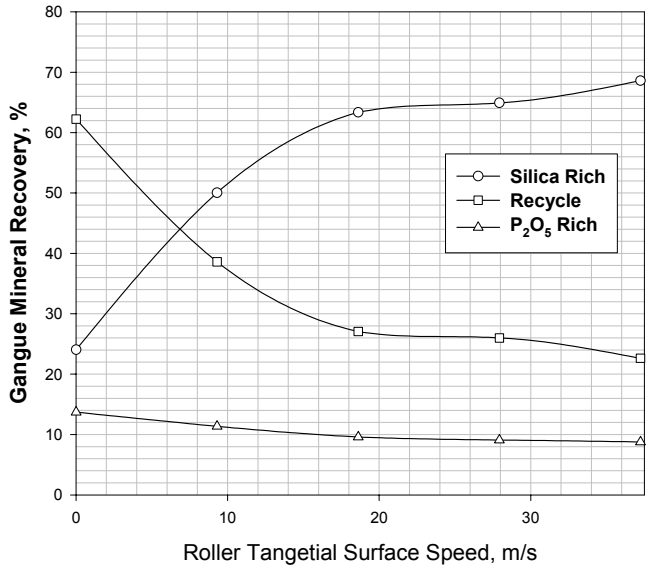

Figure 12. Silica-Rich Product Recovery Versus Triboroller Surface Speed for Hopewell Fine Feed at an Air Transport Speed of 1 m/s.

Because the electric field intensity in the separation zone controls the extent to which positive and negative particles are defected toward the electrodes, experiments were performed using the Hopewell fine feed as the voltage across the separation cell was increased from 0-to-25,000 V. The results, presented in Table 5 and Figures 13 and 14, show the concentration of P_2O_5 in the P_2O_5-enriched product increased as the electric field intensity was increased up to 200 kV/m. The P_2O_5 concentration in the recycle product continued to increase up to 400 kV/m and, hence, the P_2O_5 concentration in the combination of (P_2O_5-rich + recycle) product continued to increase. However, as displayed in Figure 14, the recovery of P_2O_5 in the P_2O_5-rich product remained low at about 20% whereas the recovery of P_2O_5 in a (P_2O_5-rich + recycle) product was near 85% at 200 kV/m.

The data in Table 5 show it is possible to upgrade to a 23% P_2O_5 product from the 12.5% P_2O_5 Hopewell fine feed and to simultaneously recover greater than 80% of the P_2O_5 in the feed. For comparison, the Hopewell rougher concentrate had a P_2O_5 concentration of 19.5%. Therefore, one stage TEP processing is capable of upgrading phosphate fine feeds very efficiently. If it is necessary to further increase P_2O_5 recovery, the silica-rich product from stage one processing could be reprocessed.

Overall, the beneficiation data on the Hopewell fine feed signified that it is highly responsive to triboelectric processing. This behavior is also observed in the beneficiation of the rougher and flotation concentrates.

Table 5. Effect of Electric Field Intensity on the Beneficiation of Hopewell Fine Feed.

Voltage (kV/m)	Silica-Rich %P_2O_5	Recycle %P_2O_5	Phosphate Rich %P_2O_5	Recycle & Phosphate-Rich %P_2O_5	Silica-Rich P_2O_5 Recovery %	Recycle P_2O_5 Recovery %	Phosphate-Rich P_2O_5 Recovery %	Recycle & Phosphate-Rich P_2O_5 Recovery, %
0.00	11.5	12.4	13.1	12.6	9.1	66.6	24.3	90.9
98.4	6.1	13.1	9.3	12.4	11.4	76.8	11.8	88.6
196.8	4.7	15.6	22.9	16.9	14.5	64.3	21.2	85.5
295.3	4.5	18.7	25.7	20.2	18.1	59.4	22.4	81.8
393.7	4.5	21.8	27.0	23.1	19.4	57.0	23.6	80.6
492.1	2.1	21.9	26.4	23.2	9.8	50.2	24.8	75.0

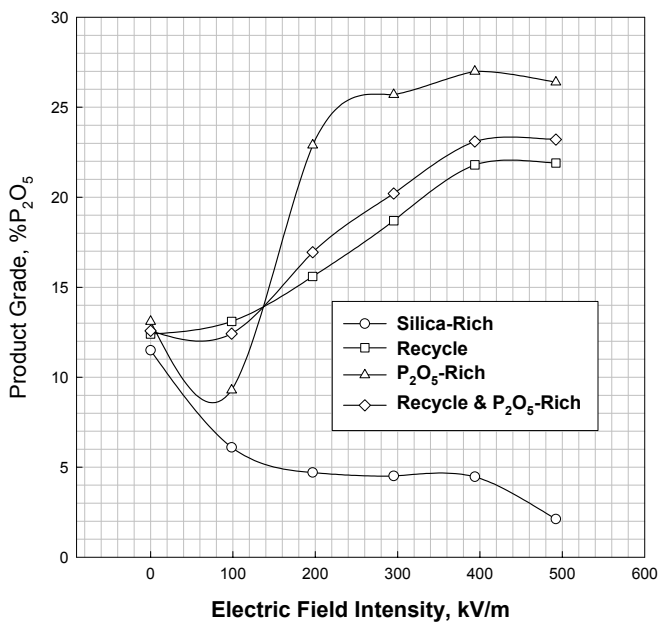

Figure 13. Effect of Electric Field Intensity on Product Grades When Beneficiating Hopewell Fine Feed.

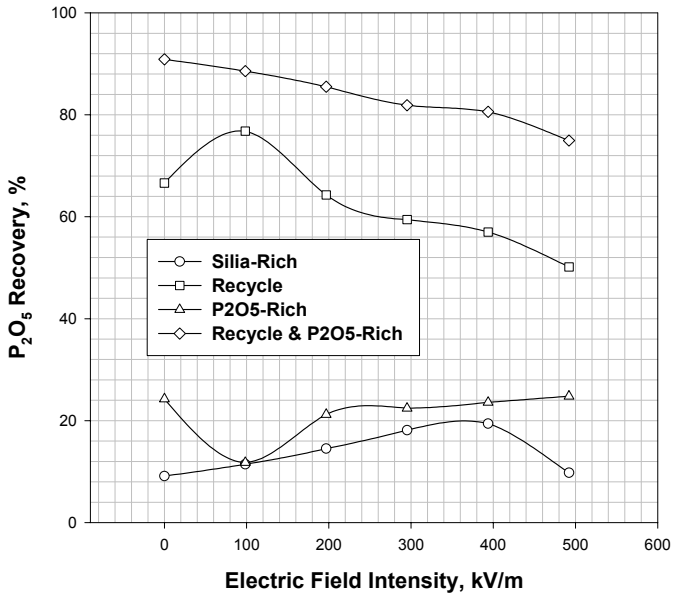

Figure 14. Effect of Electric Field Intensity on P_2O_5 Recovery When Beneficiating Hopewell Fine Feed.

Rougher Flotation Concentrates

Drying feed material represents a major cost concern for TEP to be used by industry. Due to the large amount of feed needed to produce one ton of finished product, it may not be cost effective to process phosphate ore or other low P_2O_5 feeds even if the dry process technique was highly efficient. However, dry beneficiation may be an alternative way to process rougher concentrates to avoid the acid rinse and silica flotation in the Cargo process.

Figure 15 compares the performance of circular and octagonal triborollers during the beneficiation of the Hopewell rougher concentrate sample. The octagonal roller increased the recovery at any P_2O_5 concentration by a minimum of 10% above the cylindrical triboroller charger. This effect is probably associated with enhanced particle-roller collisions on the octagonal versus the cylindrical surface of the rollers. Overall, the octagonal triboroller increased the P_2O_5 content in the product by 18% relative to the circular roller at a P_2O_5 recovery of 85%.

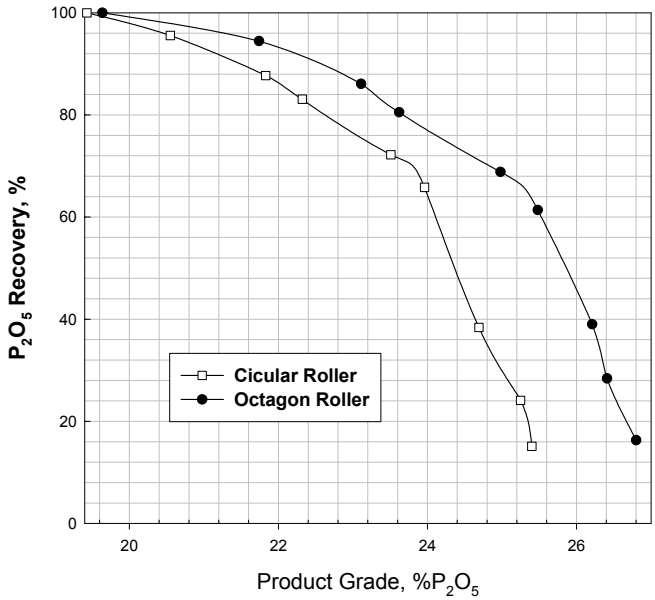

Figure 15. Effect of Roller Shape on Upgrading Hopewell Rougher Concentrate.

Triboelectric beneficiation data for the Four Corners rougher concentrate is presented in Table 6 and Figure 16. Starting at a feed grade of 19.6% P_2O_5, products were made at 26.1% P_2O_5 with 90.6% P_2O_5 recovery, or at 25.4% P_2O_5 with 93.7% P_2O_5 recovery. It is also significant that, for two-stage processing in which nine products are made for analyses, the silica is contained predominantly in the last three columns of the table. These columns represent the silica-enriched products from stage one of processing. Hence, the Four Corners rougher flotation concentrate would respond effectively to TEP even with only single-stage processing.

Table 6. Beneficiation of Four Corners Rougher Flotation Concentrate Using an Octagon Triboroller Charger Configuration.

Individual	Yield, %	18.7	8.8	16.8	9.3	6.6	8.1	4.5	10.1	17.0
	Grade, %P_2O_5	28.6	27.5	27.0	25.9	25.2	18.2	13.7	7.3	2.9
	P_2O_5 Recovery, %	27.2	12.2	23.0	12.2	8.5	7.5	3.2	3.8	2.5
	Yield, %	18.7	27.5	44.2	53.5	60.2	68.3	72.8	83.0	100.0
Accumulated	Grade, %P_2O_5	28.6	28.2	27.8	27.4	27.2	26.1	25.4	23.2	19.7
	P_2O_5 Recovery, %	27.2	39.4	62.4	74.6	83.1	90.6	93.7	97.5	100.0

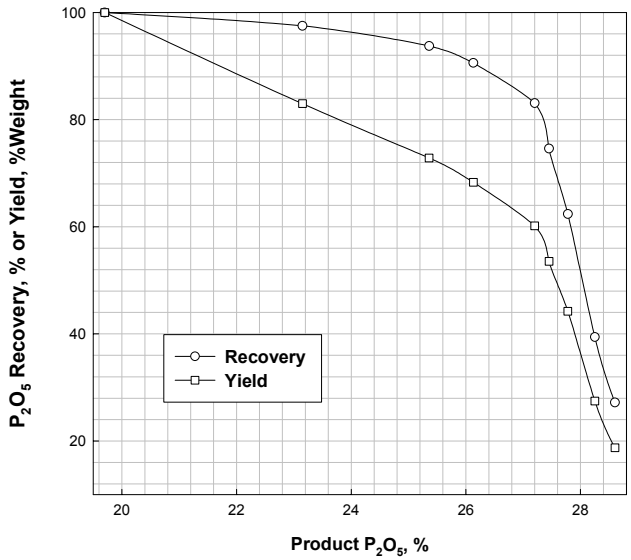

Figure 16. Recovery and Yield Curves for Triboelectric Beneficiation of Four Corners Rougher Flotation Concentrate Using an Octagonal Triboroller Charger.

It is generally true for most mineral processing technologies that beneficiation efficiencies decrease with higher feed rates. Hence, the rougher flotation concentrate feed rates were varied to examine the capabilities of TEP beneficiation. These data are presented in Figures 17 and 18.

Figure 17 shows that the silica responded smoothly as the feed rate was increased whereas the P_2O_5-rich product grade decreased and then increased as the feedrate was increased. Nevertheless, the grade of the combined 'recycle & P_2O_5-rich' product was constant over the entire range of 1-14 kg/hr. Simultaneously, the recovery of the 'recycle & P_2O_5-rich' product increased from 60% to 90% over the entire feed rate range. This behavior may be a result of increased particle charging as a higher density of particles are charged in the triboroller, creating more opportunities for particle-particle collisions. Therefore, the TEP system responded very well to feed rate changes, a factor important within commercial installations.

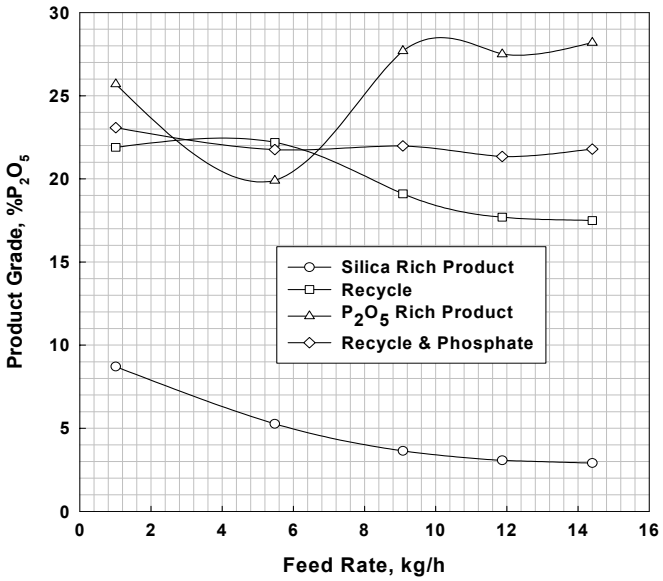

Figure 17. Effect of Feed Rate on Product P_2O_5 Grade for Hopewell Rougher Concentrate.

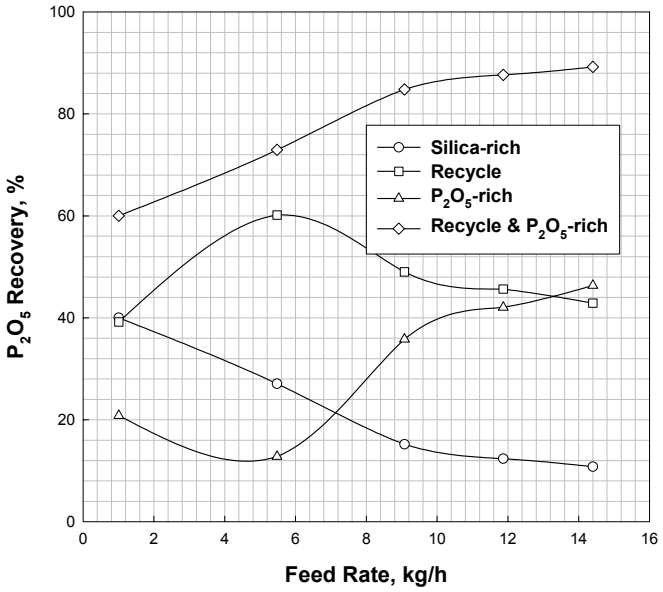

Figure 18. Effect of Feed Rate on Product P_2O_5 Recovery Hopewell Rougher Concentrate.

Flotation Concentrates

The Cargo double-float process produces 2%-to-4% insoluble concentration products. These concentrations are sufficient for high quality animal feed phosphate. However, as the phosphate ore qualities continue to decrease, it is becoming more difficult to maintain the quality of this animal feed. Hence, TEP tests were performed on the flotation concentrates to examine whether it would efficiently decrease insoluble (silica) contents at high product recoveries.

The Four Corners and Hopewell flotation concentrates were also TEP processed using a octagonal triboroller charger with a three product outlet. These beneficiation curves are presented in Figures 19 and 20.

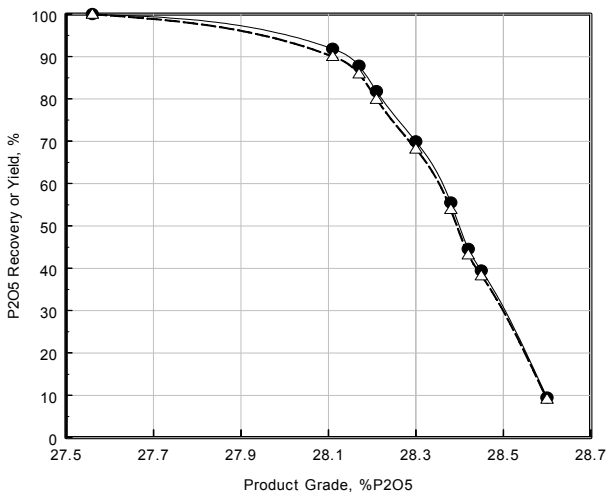

Figure 19. P_2O_5 Recovery and Mass Yields for the Four Corners Flotation Concentrate Using an Octagonal Triboroller Configuration.

Table 7 presents the P_2O_5 and % insoluble data on the Hopewell and Four Corner flotation concentrates and the TEP beneficiation products when using air transport charging. The tests were performed using both vertical or horizontal laboratory-scale triboelectric systems. They are single stage data using a two-product outlet system.

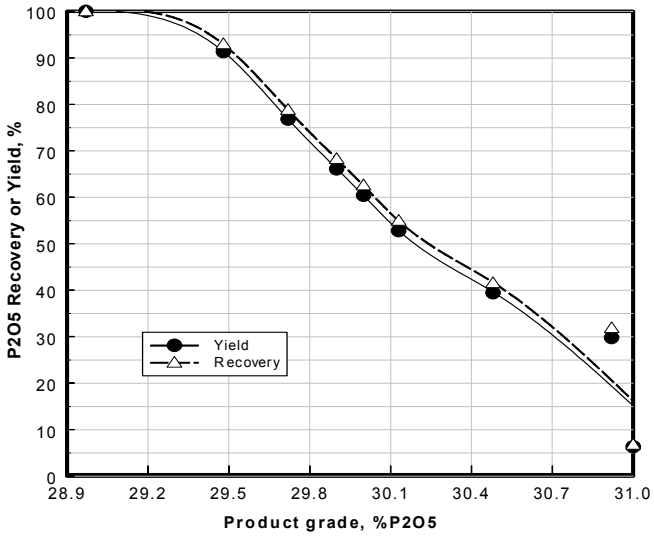

Figure 20. P_2O_5 Recovery and Mass Yields for the Hopewell Flotation Concentrate Using a Triboroller Charger.

Table 7. Beneficiation Data for Hopewell and Four Corners Flotation Concentrates Using Air Transport Charging and Single-Stage Processing.

		CAER data			*FIPR data*	
Plant	Sample	% Insols	$\%P_2O_5$	Yield	%Insols	$\%P_2O_5$
Four Corners	Concentrate	6.5	27.6		5.3	33.1
	#1, P_2O_5-rich	5.6		95.2	5.1	32.8
	#1, silica-rich	18.5			18.0	28.0
	#2, P_2O_5-rich	5.9		95.8	4.8	33.0
	#2, silica-rich				17.3	28.4
Hopewell	Concentrate	4.9	28.9		4.1	34.4
	#1, P_2O_5-rich	3.9		95.3	3.0	34.6
	#1, silica-rich	18.9			17.9	28.7
	#2, P_2O_5-rich	4.1		95.4	2.3	34.7
	#2. silica-rich	22.9			24.0	26.6
	#3, P_2O_5-rich	3.9		95.7	3.0	34.5

The data in Table 7 were obtained using analyses from both the CAER and FIPR, whereas all other P_2O_5 concentrations in this report were obtained at the CAER. They enable a comparison between the analytics of the two laboratories and also give insight into data presented in previous sections of this report.

The FIPR %P_2O_5 data are 20% greater than the CAER %P_2O_5 data. The FIPR % Insols are up to 45% lower than the CAER % Insols data. It is reasonable that the FIPR data are more representative of 'true' values because FIPR has extensive expertise in phosphate analyses whereas phosphate analyses at the CAER were first accomplished during this study. If so, the beneficiation data presented in the previous Figures and Tables would be better than shown because of values were obtained at the CAER. Nevertheless, the trends in Table 7 for both the CAER and FIPR are in agreement.

The data in Tables 7 and 8 show that the Four Corners concentrate did not respond as well as did the Hopewell concentrate to TEP processing. They also show the use of a triboroller provided products with lower insoluble content for the Four Corners flotation concentrate than did the pneumatic transport, tube charger. For the Hopewell concentrate, the tube charger provided products with lower insoluble content than did the triboroller processing.

A direct calculation of the overall product grade using two-stage processing is presented in Table 8. The decrease in the % Insols was 21% for the Four Corners sample and it was 44% for the Hopewell samples at a 91% yield. ????

Table 8. Calculated % Insols at 91% Yields for Two-Stage Processing of the Flotation Concentrates (Standardized to FIPR data).

Sample	% Insols	% Yield
Four Corners Concentrate	5.3	
P_2O_5-Rich Product	4.2	91
Hopewell Concentrate	4.1	
P_2O_5-Rich Product	2.3	91

Phosphate Drying Cost Estimate

Control of the relative humidity of the transport gas used in processing and the amount of surface moisture on the feed material are important to successfully operating TEP systems. High moisture levels lead either to low particle charging or rapid discharging of already charged particles. More than 50% relative humidity within the transport gas has been shown to decrease charging to be less than 20% of the maximum attainable for a powder (Ban 1994).

Operating under a 'dry' condition is of concern to phosphate processing because of the potential high costs associated with it. For example, the phosphate industry worked during the 1950s-1970s to develop dry phosphate upgrading technologies (Zhang 1999). Although commercialization of a design similar to that of the Carpco, free-fall V-Stat technology was considered imminent, it did not occur because the 'energy-crisis' of

the 1970s eliminated low-cost fuel, at which time dry beneficiation technologies became unattractive.

What is known about current phosphate upgrading costs in comparison to TEP costs includes the following:

a. the current cost to make phosphate rock products by flotation is ~$20/ton;
b. the cost of construction, operational personnel and maintenance of a 10 ton/hour TEP system like that used for beneficiating combustion ash in Colorado Springs, CO over a 10-year lifetime is near $3.00/ton of feed;
c. the total electrical operating costs (for all operating systems including air compressors, air dryers for decreasing the humidity of the transport and co-flow air, screw feeders, controllers, etc.) of the same 10 ton/hour TEP system is equivalent to 50 kWh/ton of feed. Hence, if industrial electrical fees are $0.05/kWh, the total electrical cost for processing would be $2.50/ton of feed.

Therefore, the cost for the TEP processing of fine minerals, without mineral drying, would be near $5.50/ton of feed. Nevertheless, phosphate drying will be necessary for effective TEP processing because a wet or sticky feed material will not respond to tribocharging.

For phosphates, the moisture content at which free flow occurs is approximately 3%. Oppositely, at a 4% moisture level, phosphate particles are sticky and do not flow freely. The free flowing nature at 3% moisture suggests that, rather than it residing on the surface of the particles, the remaining moisture is contained within cracks and macropores. This suggestion is borne out by the following calculations.

Table 9 presents results from a simple calculation of water film thickness versus moisture levels on phosphate particles for spherical particles with water layers of various thicknesses on the surface of these particles. If the TEP focus is on particles having diameters similar to rougher and flotation concentrates, which have particle sizes greater than 105 μm, the data in Table 1 show a free flowing (~3% moisture), 100 μm phosphate particle would have ~2.5 μm water layer on its surface whereas the same sized particle with 4% moisture would have a ~3.0 μm surface water layer. The 0.5 μm difference between these two water film thicknesses is considered too small to cause flow characteristics to change from 'free' to 'sticky.' Additionally, for particle sizes greater than 300 μm, the moisture layer would need to be greater than ~5 μm thick to create overall moisture levels greater than 3%. Hence, it is suggested that moisture levels near 3% are related primarily to water contained with macropores and cracks.

Table 9. Moisture Content for Different Thickness Water Layers on Phosphate Particles.

Water Thickness (µm)	% Moisture for Phosphate Particle Sizes		
	100µm	300 µm	600µm
0.175	0.35	0.11	0.06
1.0	1.95	0.62	0.31
3.0	6.01	1.92	0.95
4.0	8.17	2.57	1.26
5.0	10.24	3.23	1.59

Water is a small, highly polar molecule and is strongly adsorbed by polar surfaces as a result of large contributions from electrostatic forces. Phosphate particles tend to equilibrate rapidly under high humidity conditions and water adsorption is expected to occur first within the high surface energy sites contained within macropores/cracks. Hence, to calculate energy costs for phosphate drying, it is necessary to look at it as a two-step process, first to remove surface moisture (~15% down to 4%) and then to remove adsorbed moisture (4% down to below 3%) from cracks and macropores. For the latter, the heat required may become >2-3 times the value of ΔH of bulk water depending on the size of the macropores/cracks and the size of the particles.

To calculate the removal of surface moisture, i.e., from 15% to 4%, the following information is used: feed rate of phosphate to the coal-fired thermal dryer; the amount of water evaporated from the phosphate; the amount of water remaining after drying; the air temperature at the furnace inlet and outlet; the air humidity at the furnace inlet and outlet; furnace radiation heat losses; gas flow rates; and the coal heating value. With these parameters, it is estimated that the total energy required for decreasing the moisture content of +105 µm phosphate particles from 15% to 4% moisture is about 3.7×10^5 $kcal \cdot hr^{-1} \cdot MT^{-1}$ (1.4×10^6 $Btu \cdot hr^{-1} \cdot ton^{-1}$). Using a heating value for coal of 6930 $kcal \cdot kg^{-1}$ (12,500 $Btu \cdot lb^{-1}$) at a coal cost of $30.00/ton, the energy cost for drying from 15% to 4% moisture would be near $1.65/ton. If ΔH of the moisture in the phosphate macropores is 10 times greater than the ΔH for 'bulk' surface moisture, then the energy cost for drying from a 4%-to-3% moisture level would also be near $1.65/ton.

Therefore, the total cost for the TEP upgrading of +105 µm phosphate particles over a ten year period would be:

~ $5.50/ton (TEP without drying) + $3.30/ton (drying) + $x/ton (thermal dryer capital) + financing; or

~ $8.80/ton + thermal dryer cost/ton. + financing

Excluding financing costs, and assuming that a 100 ton plant is constructed with a thermal dryer cost near $1.20/ton over a 10 year operational life, the overall TEP system cost for upgrading phosphate would be ~$10.00/ton. Even adding a 50% contingency, the cost would be 25% less than current costs.

Although the throughput of TEP technology is >15,000 $kg \cdot hr^{-1} \cdot m^{-2}$, a value 10 times greater than previously developed electrostatic technologies, the phosphate feed still has to be 'dry'. What is not known about the extent of phosphate drying includes the following:

- How dry do phosphates have to be for them to be efficiently upgraded using TEP technology?
- What would then be the amount of energy required for this drying?

Therefore, an important unknown is the phosphate moisture level at which sufficient charging occurs for the phosphate. It would be relatively easy to measure this level experimentally.

CONCLUSIONS AND RECOMMENDATIONS

TEP technology can successfully upgrade phosphate fine feeds, rougher flotation concentrates and flotation concentrates from the IMC Four Corners and Hopewell plants. Significant results include: Hopewell fine feed at ~12% P_2O_5 is upgraded to 21-23% P_2O_5 with between 81-87% P_2O_5 recovery; Four Corners rougher concentrate with ~19.5% P_2O_5 is upgraded to 25-26% P_2O_5 with between 90-94% P_2O_5 recovery; increasing the feedrate of Hopewell rougher concentrate between 1-14 kg/hr creates constant ~22.5% P_2O_5 grade product within increasing P_2O_5 recovery; and, depending on whether one or two stage processing is employed, the silica in Four Corners flotation concentrate is decreased by 7-21% with 91-95% P_2O_5 recovery (single stage-double stage) and silica in Hopewell flotation concentrate is decreased by 32-44% with 91-95% P_2O_5 recovery (single stage-double stage).

Two phosphate particle charging methods, including turbulent gas transport and triborollers, produced equivalent beneficiation performance for the Hopewell and Four Corners samples. Commercial experience in using gas transport charging on combustion ash shows it to be effective and scaleable for commercial applications.

An overall estimate of costs for building and operating a 100 ton/hour phosphate upgrading plant suggest that it would be 25% less expensive than currently used wet beneficiation technology. However, important information yet to be developed is the cost of drying phosphates from approximately 4% moisture down to an unknown level at which particles can be charged effectively.

REFERENCES

Ban H. 1994. Non-intrusive measurement of particle charge: electrostatic dry coal cleaning [DPhil thesis]. Lexington: University of Kentucky.

Gieseke EW, editor. 1985. Florida phosphate rock. In: SME Mineral Proc. Handbook. Littleton (CO): SME Inc. Chapter 21.

Li TX. 1999. An experimental study of particle charge and charge exchange related to triboelectric beneficiation [DPhil thesis]. Lexington: University of Kentucky.

Gurupira TZ. 2001. Dry separation of powdered materials by size and density using pneumatic triboelectrostatic techniques [MS thesis]. Lexington: University of Kentucky.

Stencel JM, Schaefer JL, Ban H, Finseth D, inventors; University of Kentucky Research Foundation, assignee. 1998. 1998 May 26. Method and apparatus for triboelectric-centrifugal separation. US patent 5,755,333.

Stencel JM, Schaefer JL, Ban H, Neathery JK, inventors; University of Kentucky Research Foundation, assignee. 1999a. 1999 Aug 17. Apparatus and method for triboelectrostatic separation. US patent 5,938,041.

Stencel JM, Schaefer JL, Ban H, Neathery JK, Li TX, inventors; University of Kentucky Research Foundation, assignee. 1999b. 1999 Aug 31. Triboelectric separator with mixing chamber and pre-separator. US patent 5,944,875.

Stencel JM, Schaefer JL, Neathery JK, Ban H, Finseth D, inventors; University of Kentucky Research Foundation, assignee. 2001. 2001 Nov 27. Particle separation system using parallel multistage electrostatic separators. US patent 6,323,451.

Stencel JM, Schaefer JL, Neathery JK, Ban H, Finseth D, inventors; University of Kentucky Research Foundation, assignee. 2002 Dec 24. Electrostatic particle separation system, apparatus, and related method. US patent 6,498,313.

Stencel JM, Gurupira TZ. 2002. US Provisional Patent Application S.N. 60/378,118.

U.S. Geological Survey. January 2001. Mineral Commodity Summaries.

Zhang P, Yu Y, Bogan M. 1997. Challenging the "Crago" double float process. II. Amine-fatty acid flotation of siliceous phosphates. Minerals Engineering 10 (9): 983-94.

Zhang P, Albarelli GR, Stewart KJ. 1999. Phosphate beneficiation bibliography. Bartow (FL): Florida Institute of Phosphate Research. FIPR Publication nr 02-114-157.