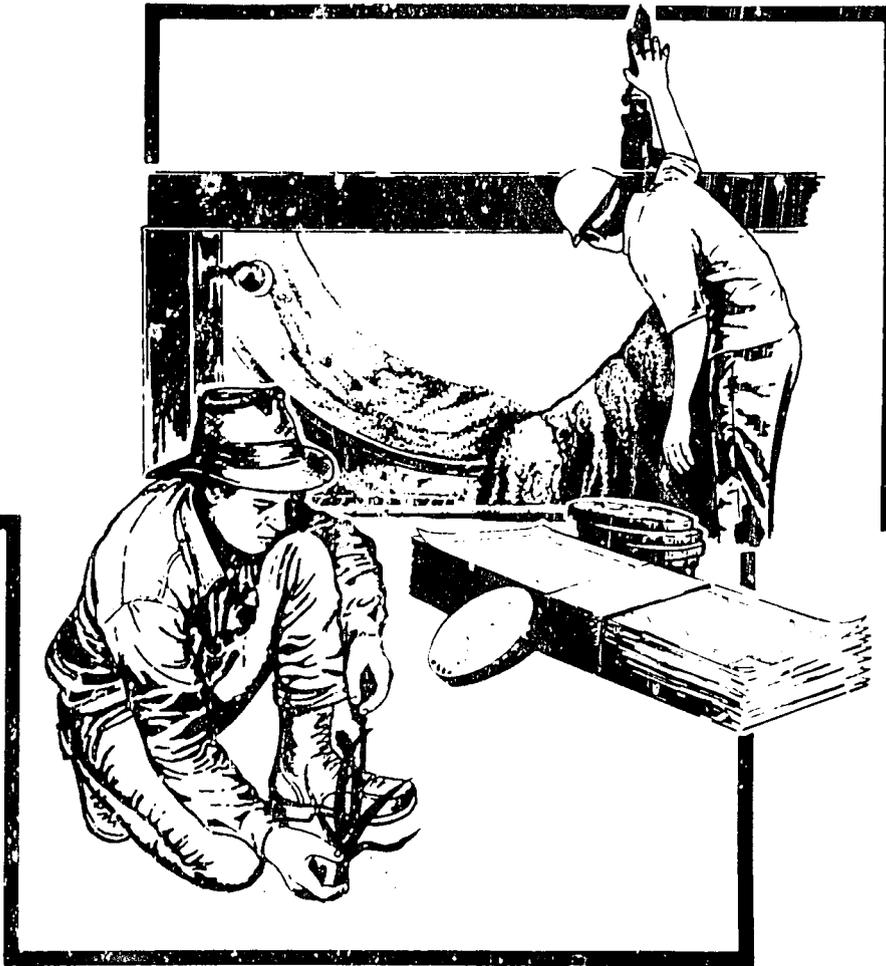


PN-ABE-242  
10/15/62

# **Sulfuric Acid-Based Partially Acidulated Phosphate Rock**



**-ITS PRODUCTION, COST, AND USE-**

**INTERNATIONAL FERTILIZER DEVELOPMENT CENTER, MUSCLE SHOALS, ALABAMA U.S.A.**

**Library of Congress Cataloging in Publication Data**

Sulfuric acid based partially acidulated phosphate rock—  
its production, cost, and use.

(Technical bulletin ; T-31)

Prepared by James J. Schultz and others.

Bibliography: p.

1. Superphosphates. I. Schultz, James J.,  
1936- . II. International Fertilizer Development  
Center. III. Series: Technical bulletin (International  
Fertilizer Development Center) ; T-31.  
TP963.4.S9S85 1986 668:625 86-93  
ISBN 0-88090-056-3

**International Fertilizer Development Center**

**P.O. Box 2040**

**Muscle Shoals, Alabama 35662**

**Phone No. 205-381-6600**

**TWX-810-731-3970 IFDEC MCHL**

**Edited by E. D. Frederick and E. N. Roth**

**Cover Design and Layout by T. L. McGee**

**Internal Illustrations by F. Rudolph**

IFDC publications are listed in *Publications of the International Fertilizer Development Center*, General Publication IFDC-G-1, which is available free of charge.

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## Abstract

Phosphate deposits are located in many tropical countries. Many of these deposits have had little commercial significance in the past because they were either too low in grade, too unreactive, or associated with excessive quantities of unwanted impurities. One means of utilizing these indigenous phosphates to the benefit of countries having such deposits is to increase the plant-available phosphate by chemical conversion to a partially acidulated phosphate rock (PAPR) product. The partial acidulation concept, indicating the use of less acid than that needed to convert the rock to superphosphate, often makes it possible to process problem ores into useful fertilizer products when the use of conventional processing methods is not feasible. The PAPR products may be especially attractive to producers who rely upon

imported sulfur or sulfuric acid because less acid is used and a significant saving in foreign exchange can be realized.

The process technology, production cost estimates, and agronomic performance of a number of sulfuric acid-based PAPR (SAB-PAPR) products described in this bulletin often compare favorably with those of conventional superphosphate fertilizers.

The factory-gate cost of  $P_2O_5$  obtained from SAB-PAPR is estimated at about 80% of that obtained from single superphosphate. Likewise, the agronomic performance of the SAB-PAPR products is comparable to that of conventional superphosphate under the appropriate conditions (acidic soils with high phosphorus-fixation capacities).

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## Summary

In conventional superphosphate products—single superphosphate (SSP) and triple superphosphate (TSP)—usually more than 90% of the total phosphate ( $P_2O_5$ ) is in a form available to plants, i.e., soluble in a neutral ammonium citrate (NAC) solution. Most of the available  $P_2O_5$  is also soluble in water.

The superphosphate-type products described in this bulletin contain lesser amounts of available  $P_2O_5$  because only a portion (usually about 30%-50%) of the sulfuric acid required to fully acidulate the phosphate rock to conventional SSP is used.

Agronomic research and demonstration performed by the International Fertilizer Development Center (IFDC) and others in several developing countries show that PAPR is usually as effective as highly soluble phosphate fertilizers on many tropical and subtropical soils (1, 2, 3, 4, 5). With sulfur-deficient soils, the agronomic response to SAB-PAPR substantially exceeded that to sulfur-free fertilizers such as TSP.

The production of SAB-PAPR is relatively simple; the method used is basically the same as that for SSP production. The SAB-PAPR can be produced as a powdered or semigranular, run-of-pile (ROP) material, or it can be granulated. A completely granular product can be made by granulating ROP material in a separate processing step, or it can be made directly by using a single-step acidulation/granulation process developed by IFDC (6).

Production cost estimates indicate that the SAB-PAPR products are less expensive to produce than conventional SSP when evaluated according to the assumptions used in this bulletin. In all cases the saving in cost is attributed primarily to the use of less sulfuric acid. A ranking of the production cost of SAB-PAPR relative to ground phosphate rock and SSP is shown in Figure 1.

These estimates and indicated saving for SAB-PAPR compared with SSP are based on the assumptions described in this bulletin. The actual cost of production must be determined on a case-by-case basis after considering the site-specific cost and operating factors.

Compared with SSP, the SAB-PAPR products are more concentrated with respect to total  $P_2O_5$ , thus leading to some savings in the cost of physical distribution of the  $P_2O_5$  nutrient to the farm level. However, when compared

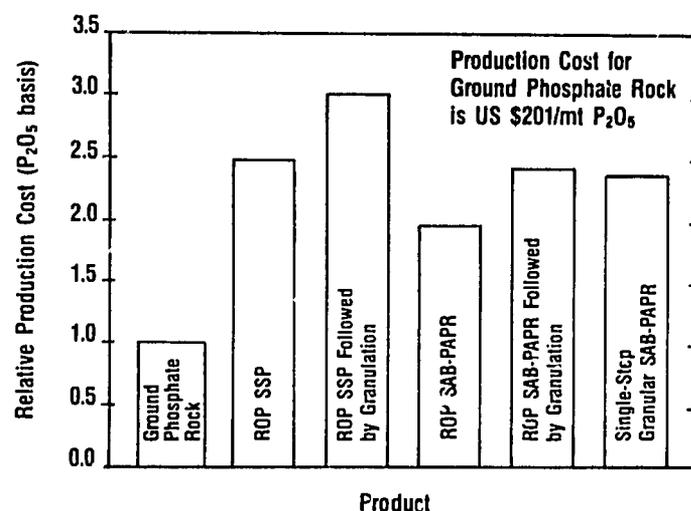


Figure 1. Relative Production Cost of SAB-PAPR Compared With Alternative Phosphate Products.

with a more concentrated phosphate fertilizer such as TSP, the cost of physical distribution per unit of nutrient will be higher even if allowance is made for the sulfur nutrient in the SAB-PAPR product. The comparison between the production and distribution cost of SAB-PAPR and that of alternative sulfur-free phosphate fertilizers is not included in this bulletin.

The use of SAB-PAPR production technology may make it possible to process phosphate rocks that are not suitable for producing SSP. Some phosphate rocks are either too unreactive or contain too many impurities for conventional processing. The ability of SAB-PAPR technology to cope with many types of phosphate rocks may make it possible to use indigenous materials in a number of developing countries.

Although commercial production of SAB-PAPR began at least 55 years ago in Europe, its widespread replacement of conventional phosphate fertilizers is unlikely. In the developing world, government incentives designed to increase the use of indigenous phosphate resources and decrease the use of imported fertilizers will probably be needed in many cases to fully exploit the advantages of this technology.

## Introduction

The element phosphorus was discovered by the German physician and alchemist, Henning Brandt, in the 17th century. Its subsequent extraction from urine and bones in the 18th century and from the earth's crust in the 19th century paved the way for the development of the phosphate fertilizer industry as we know it today. By the middle of the 19th century the agronomic usefulness of phosphorus was established, and the world production of phosphate rock grew from about 5,000 mt in 1850 to about 135 million mt in 1984 (7). An annual production of phosphate rock in the order of 200 million mt is projected for 1990 (8).

The chemistry of the phosphate fertilizer industry has changed little during the past century—sulfuric acid remains a major industrial ingredient for solubilizing the phosphate and making it more available as a fertilizer. Single superphosphate (SSP) is a product made from a mixture of phosphate rock and sulfuric acid. Usually it contains about 16%-22%  $P_2O_5$ , and it has been the basic phosphate fertilizer for more than 100 years. Acidulation of phosphate rock with phosphoric acid to produce triple superphosphate (TSP), usually containing 45%-48%  $P_2O_5$ , was first begun about 1870 but did not become popular until about 1950. The rapid growth in phosphoric acid production during the past 30 years has resulted largely in replacement of SSP with TSP and ammonium phosphate, principally diammonium phosphate (DAP) usually containing 18% nitrogen and 46%  $P_2O_5$ .

Phosphoric acid-based technology further intensified the dependency of the phosphate industry on sulfuric acid. For example, 1 mt of soluble  $P_2O_5$  in the form of SSP requires approximately 1.8 mt of sulfuric acid, whereas 1 mt of soluble  $P_2O_5$  in the form of TSP and DAP requires about 2.0 and 2.8 mt of sulfuric acid, respectively.

Temperate zone agriculture is typified by relatively cool climates, moderate rainfall, short growing seasons, a wide range of soil properties, and intensive farming practices, which have created the need for highly soluble and concentrated fertilizers. This explains the current position of the phosphate fertilizer industry. World phosphate consump-

tion in the 1983/84 fertilizer year amounted to approximately 33 million mt of  $P_2O_5$ . Of this amount of  $P_2O_5$ , about 38% was contained in multinutrient (compound) fertilizers, 33% in superphosphates, 22% in ammonium phosphates, 4% in the form of phosphate rock for direct application, and 3% in miscellaneous phosphate materials including thermally altered phosphates and basic slag (9).

In many tropical and subtropical locations, phosphate fertilizers with less water solubility are desirable for a number of agronomic and economic reasons. Furthermore, the agronomic value of both SSP and sulfuric acid-based partially acidulated phosphate rock (SAB-PAPR) is usually enhanced by the presence of the secondary elements calcium and sulfur. Sulfur deficiencies are becoming apparent in phosphorus-deficient tropical regions because of the widespread use of sulfur-free fertilizers such as TSP and DAP (10). It has been suggested that a  $P_2O_5$ -to-S ratio of 3:1 will give maximum efficiency of phosphorus (11). SAB-PAPR-50 (50% acidulated) supplies approximately this ratio, whereas SSP supplies about twice the suggested amount of sulfur. Thus, some value should be assigned to the sulfur in SAB-PAPR because it is an essential element that is often deficient.

The apparent usefulness of less soluble forms of phosphate containing an appropriate amount of sulfur (especially on acidic tropical soils), together with the objective of developing suitable methods for processing a variety of indigenous phosphate rock materials occurring in the developing countries, provided the basis for IFDC's interest in further development of partial acidulation technology. The data described in this bulletin were developed over a period of several years of laboratory- and pilot plant-scale testing of a large number of phosphate rocks. Concurrent with the technical studies, comparative agronomic evaluations of a majority of the products were performed in greenhouses, research stations, and farmers' fields. The technical, economic, and agronomic advantages and limitations of the SAB-PAPR family of phosphate products identified as a result of these studies are discussed in the bulletin.

## Terminology

To facilitate a uniform interpretation of the PAPR process technology and economics described in this bulletin, the following terms are defined.

### Fully Acidulated Phosphate Rock

This term describes a phosphate rock that has been treated with the theoretical (stoichiometric) quantity of acid required to fully convert the insoluble phosphate mineral,

usually fluorapatite, to the water-soluble form—monocalcium phosphate monohydrate (MCP). Determination of the precise amount of acid required to fully acidulate a phosphate rock is difficult because of the influence of variable quantities of acid-producing and acid-consuming constituents in the rock. In practice, a reasonable estimate of the stoichiometric amount of acid required can be made by multiplying the level of certain constituents in the rock by positive and negative factors (Table 1). These factors describe the theoretical amount of acid required to convert each

**Table 1. Factors for Estimating Quantity of Sulfuric Acid Required to Fully Acidulate Phosphate Rock<sup>a</sup>**

Phosphate Rock Component	Acidulation Factor
MgO	2.433
CaO	1.749
Na <sub>2</sub> O	1.582
K <sub>2</sub> O	1.041
Al <sub>2</sub> O <sub>3</sub>	0.962
Fe <sub>2</sub> O <sub>3</sub>	0.614
F	(-)1.650
SO <sub>3</sub>	(-)1.225
P <sub>2</sub> O <sub>5</sub>	(-)0.691

a. To estimate kilograms of sulfuric acid (100% basis) required to fully acidulate 100 kg of phosphate rock, multiply weight-percent of each component by appropriate acidulation factor and total.

major constituent of the phosphate rock into the acidulation products normally found in SSP. In most cases acid consumption data reported by commercial phosphate fertilizer producers agree closely with these estimates, although many producers may use slightly more acid than indicated (usually 5%-10%) to compensate for normal process inefficiencies and to ensure optimum conversion of the phosphate to the available form.

### Partially Acidulated Phosphate Rock

The term PAPR refers to a phosphate rock that has been treated with only a portion of the acid required to fully convert the insoluble tricalcium phosphate to the water-soluble form (MCP).

It is recognized that various acids (sulfuric, phosphoric, nitric, hydrochloric, or a combination of these) can be used to acidulate most phosphate rocks although, for economic reasons, sulfuric acid is usually the preferred choice for producing PAPR. The quantity of acid used can be varied, depending upon the characteristics of the phosphate rock and the desired quality of the final product (discussed later).

To facilitate a uniform identification of PAPR products, the following nomenclature is used to describe the raw material and composition of the products discussed in this bulletin—for example, SAB-PAPR-50.

**SAB**—Denotes sulfuric acid-based.

**PAPR**—Indicates that the material is a partially acidulated phosphate rock product instead of a fully acidulated product such as SSP.

**50**—Indicates the degree of acidulation (expressed as a percentage) relative to a fully acidulated SSP product. As previously indicated, the amount of acid required to fully acidulate a phosphate rock varies quite widely, depending upon the characteristics of the phosphate rock. Therefore, the amount of acid required to obtain a certain degree of acidulation also varies with the composition of the phosphate rock.

Although only SAB-PAPR products are described in this bulletin, it is evident that a uniform and systematic nomenclature for PAPR products is helpful in facilitating communication. It is unlikely that the nutrient content of the PAPR products can be universally incorporated into the nomenclature because of the large variability in the composition of the candidate rocks and possible levels of acidulation; therefore, the nutrient content of the products described in this bulletin is specified separately.

### Available Phosphate

Available phosphate as used in this bulletin is defined as the phosphate (normally expressed as % P<sub>2</sub>O<sub>5</sub>) that is soluble in a neutral ammonium citrate solution. This includes the water-soluble fraction when the sample is processed and analyzed in accordance with procedures established by the Association of Official Analytical Chemists (AOAC) (12). In this procedure the water-soluble P<sub>2</sub>O<sub>5</sub> fraction is determined first, and the NAC-soluble P<sub>2</sub>O<sub>5</sub> fraction is determined on the remaining non-water-soluble fraction. The NAC-soluble phosphate reported in this bulletin does not include the water-soluble fraction, unless it is so indicated.

A comparison of available P<sub>2</sub>O<sub>5</sub> results obtained by the NAC test method with those from other widely used methods—2% citric acid and 2% formic acid—is shown in Table 2 for unacidulated rocks and in Table 3 for a number of SAB-PAPR products (13, 14). Normally the citric and formic acid test methods are used to measure the reactivity of phosphate rocks for direct application and are usually not used on chemical- or water-soluble fertilizers.

### Unavailable Phosphate

In this bulletin phosphate that is found to be insoluble in an NAC solution is designated unavailable.

### Free Acid

The free acid (H<sub>3</sub>PO<sub>4</sub>, expressed in % P<sub>2</sub>O<sub>5</sub>) of the SAB-PAPR products described in this bulletin is determined by washing the sample with acetone to remove residual (unreacted) phosphoric acid (15). In superphosphate chemistry, phosphoric acid is an intermediate product of the sulfuric acid and fluorapatite reaction. The phosphoric acid continues to react with more fluorapatite to form the final SAB-PAPR product—a mixture of mono- and dicalcium phosphate, calcium sulfate, and unreacted fluorapatite (phosphate rock). A limitation of this determination is that any free acidity contributed by unreacted sulfuric acid is not detected. However, it is not likely that the PAPR products normally would contain free sulfuric acid.

Table 2. Chemical Composition and Relative Reactivity of Phosphate Rocks Evaluated in Laboratory- or Pilot Plant-Scale SAB-PAPR Studies

Phosphate Rock Source	Total P <sub>2</sub> O <sub>5</sub>	P <sub>2</sub> O <sub>5</sub> Soluble in			CaO	Fe <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>	MgO	CO <sub>2</sub>	F	SiO <sub>2</sub>	Na <sub>2</sub> O	K <sub>2</sub> O	SO <sub>3</sub>	Relative <sup>a</sup> Reactivity
		NAC	2% Citric Acid	2% Formic Acid											
(%)															
Central Florida (U.S.A.)	31.0	4.2	11.2	17.8	46.6	1.3	0.89	0.38	4.1	3.5	6.8	0.64	0.11	1.10	Medium
El-Hassa (Jordan)	30.4	4.5	13.9	27.8	50.0	0.31	0.44	0.21	6.8	3.9	7.1	0.58	0.02	1.52	Medium
Hahotoe (Tbgo)	35.9	3.0	7.2	14.3	51.3	1.3	1.1	0.05	1.9	4.0	4.6	0.23	0.04	0.50	Medium
Huila (Colombia)	20.7	3.5	7.8	15.1	40.0	0.6	1.7	0.17	8.3	2.7	23.6	0.16	0.09	0.95	Medium
Kodjari (Burkina Faso)	25.3	1.9	6.2	10.6	33.5	3.1	4.0	0.29	1.3	3.1	25.7	0.09	0.43	0.08	Low
Media Luna (Colombia)	30.0	2.3	10.5	22.6	45.5	0.44	0.47	0.12	4.6	3.6	12.5	0.12	0.07	0.75	Low
Mussoorie (India)—Concentrate	25.0	0.4	2.1	6.6	45.3	5.0	0.55	1.2	10.0	2.5	5.1	0.19	0.16	8.25	Low
Mussoorie (India)—Run-of-Mine	18.6	1.0	2.8	7.5	43.8	4.0	1.7	1.4	13.6	1.8	15.4	0.26	0.45	5.74	Low
Parc W (Niger)	28.5	2.6	7.5	14.9	39.9	1.9	1.0	0.03	1.2	1.5	23.2	0.13	0.04	0.10	Low
Pesca (Colombia)	19.5	3.3	10.0	15.1	27.9	1.0	1.4	0.15	1.3	2.1	40.3	0.14	0.15	0.45	Medium
Sukulu Hills (Uganda)	37.9	2.7	1.5	4.8	50.5	2.8	0.77	0.05	0.6	2.4	1.9	0.20	0.03	0.05	Low
Tahoua (Niger)	27.9	2.5	7.6	16.0	39.2	10.3	2.1	0.2	1.5	2.8	11.7	0.15	0.12	0.45	Low
Tilemsi Valley (Mali)	26.2	4.2	12.1	19.9	39.5	6.3	2.5	0.55	2.3	3.1	11.5	0.29	0.16	0.7	Medium
Utah (U.S.A.)	30.2	2.4	5.4	16.6	47.6	1.0	1.0	0.54	3.7	3.5	8.7	0.55	0.32	2.5	Low

a. Relative reactivity criteria: NAC-soluble P<sub>2</sub>O<sub>5</sub>, 0%-2.9%—Low.  
 NAC-soluble P<sub>2</sub>O<sub>5</sub>, 3.0%-4.9%—Medium.  
 NAC-soluble P<sub>2</sub>O<sub>5</sub>, 5.0% and above—High.

Table 3. Typical Product Characteristics—Granular SAB-PAPR

Phosphate Rock Source	Degree of Acidulation	Total P <sub>2</sub> O <sub>5</sub>	P <sub>2</sub> O <sub>5</sub> Soluble in				Free Acid (P <sub>2</sub> O <sub>5</sub> Basis)	Free Water
			Water	NAC <sup>a</sup>	2% Citric Acid <sup>a</sup>	2% Formic Acid <sup>a</sup>		
(%)								
<b>Laboratory-Scale Production</b>								
Central Florida (U.S.A.)	40	23.3	10.7	3.1	7.3	9.8	<0.1	1.0
El Hassa (Jordan)	15	28.0	3.8	4.8	11.5	19.2	0.1	0.9
	30	26.5	7.5	4.2	11.4	16.7	0.2	0.7
Hahotoe (Tbgo)	25	28.7	4.9	3.8	10.0	13.8	0.3	1.1
	50	25.1	10.6	2.5	7.8	10.3	0.4	0.6
Huila (Colombia)	50	14.8	6.1	2.8	5.8	7.7	0.1	0.5
Kodjari (Burkina Faso)	30	20.5	0.7	5.2	7.1	7.3	<0.1	1.9
	50	18.6	3.0	4.8	10.0	9.8	<0.1	0.6
Media Luna (Colombia)	50	23.4	10.1	1.6	6.8	11.4	0.8	2.1
Mussoorie (India)—Concentrate	50	20.3	7.4	2.6	3.6	6.9	0.3	2.0
Mussoorie (India)—Run-of-Mine	35	14.7	3.6	2.3	4.2	7.3	0.2	2.0
Parc W (Niger)	25	24.3	4.4	3.4	7.3	10.8	0.1	0.6
	50	22.3	9.3	2.8	7.0	8.4	<0.1	0.8
Pesca (Colombia)	20	17.5	4.3	2.2	NA <sup>b</sup>	NA	0.7	1.7
	40	16.2	5.7	3.6	6.9	8.6	0.1	0.1
Sukulu Hills (Uganda)	25	30.3	6.1	1.0	2.0	5.1	<0.1	0.4
	50	26.8	12.1	1.5	2.5	5.0	<0.1	0.4
Tahoua (Niger)	25	24.3	1.1	4.7	8.5	10.7	<0.1	1.0
	50	23.0	2.5	4.6	7.8	9.8	0.2	1.4
Tilemsi Valley (Mali)	15	25.6	0.6	5.3	11.8	15.2	<0.1	2.0
	30	22.7	1.6	6.6	12.3	14.6	<0.1	1.8
<b>Pilot Plant-Scale Production</b>								
Central Florida (U.S.A.)	30	25.6	5.4	4.4	11.3	16.2	0.3	1.7
	50	21.9	9.6	4.2	9.0	11.8	0.7	2.8
Utah (U.S.A.)	30	25.3	7.3	1.2	NA	NA	0.2	0.9
	50	22.5	11.1	1.8	7.7	11.9	0.2	1.3

a. Does not include P<sub>2</sub>O<sub>5</sub> soluble in water.  
 b. Not analyzed.

## Rock Reactivity

Phosphate rocks used for direct application may be classified according to their "reactivity" as determined by their solubility in various solutions (16, 17). Such a general classification or grouping is especially useful when attempting to estimate the processing or agronomic potential of a relatively unknown or untested rock.

The reactivity of a rock refers to the ease with which the phosphate can be converted (by chemical processing or reaction in the soil) into an available form. The reactivity is influenced by a combination of physical and chemical characteristics unique to each rock. With few exceptions those rocks that display a high level of carbonate substitution within the apatite structure or have a high surface area are usually found to be the most reactive. Particle size and surface area data for several phosphate rocks used in the IFDC SAB-PAPR studies are shown in Table 4. It should be emphasized that a relatively large surface area does not always indicate a highly reactive rock. For example, the Kodjari (Burkina Faso) and Tilemsi Valley (Mali) phosphate rocks (Table 4) have a high surface area (about 15 m<sup>2</sup>/g and 38 m<sup>2</sup>/g, respectively), but they are not highly reactive. In these examples most of the surface area is attributed to the clay particles (iron and aluminum compounds) in the rocks.

Table 4. Particle Size and Surface Area Data for Selected Phosphate Rocks Used in SAB-PAPR Studies

Phosphate Rock Source	Particle Size		Average Particle Size	Median Particle Size	Surface Area
	Passing 100-Mesh	Passing 200-Mesh			
	..... (%) .....		( $\mu$ m)	( $\mu$ m)	(m <sup>2</sup> /g)
Central Florida (U.S.A.)	99	95	14	25	13
Huila (Colombia)	93	89	12	24	6
Kodjari (Burkina Faso)	97	80	20	42	15
Media Luna (Colombia)	92	77	12	28	6
Mussoorie (India)	92	77	14	32	2
Pesca (Colombia)	100	97	7	9	8
Tilemsi Valley (Mali)	100	96	13	6	38
Utah (U.S.A.)	91	77	28	63	3

## Degree of Acidulation

Degree of acidulation, expressed as a percentage, refers to the amount of acid actually used compared with the stoichiometric quantity of acid required to fully acidulate a particular phosphate rock to SSP. The theoretical effect of degree of acidulation (assuming pure fluorapatite) on the amount of water-soluble P<sub>2</sub>O<sub>5</sub> in sulfuric and phosphoric acid-acidulated products is shown in Figure 2. These data show a linear relationship between the theoretical water-soluble P<sub>2</sub>O<sub>5</sub> and the acidulation degree for sulfuric acid acidulation and a nonlinear relationship for phosphoric acid acidulation.

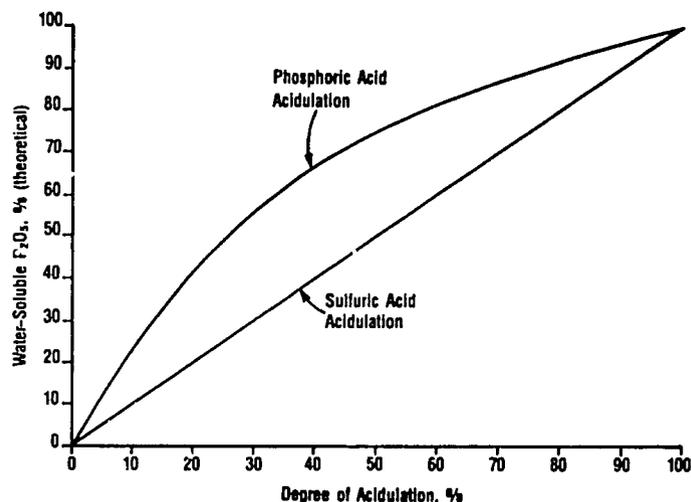


Figure 2. Theoretical Effect of Degree of Acidulation on Water-Soluble P<sub>2</sub>O<sub>5</sub> in Acidulated Phosphate Rock.

## Acidulation Efficiency

To facilitate a comparison between different acidulations of the same or different phosphate rocks, the term "acidulation efficiency" is used. This term describes the effectiveness of the acidulation process in converting the phosphate in the rock to water-soluble and NAC-soluble forms of P<sub>2</sub>O<sub>5</sub>, when compared with the theoretical conversion expected from the intended acidulation degree.

Since the stoichiometric amount of sulfuric acid required for the total acidulation of a phosphate rock is based on the conversion of the P<sub>2</sub>O<sub>5</sub> to the water-soluble form (MCP), the acidulation efficiency is calculated on the basis of the level of water-soluble P<sub>2</sub>O<sub>5</sub> obtained in the product. In practice, however, a portion of the MCP usually reacts to form water-insoluble but NAC-soluble P<sub>2</sub>O<sub>5</sub> in the product.

Therefore, in this bulletin acidulation efficiency is expressed in two ways—on the basis of water-soluble P<sub>2</sub>O<sub>5</sub> and on the basis of available P<sub>2</sub>O<sub>5</sub> (NAC-soluble P<sub>2</sub>O<sub>5</sub>, including water-soluble fraction) in the product:

$$1. \text{ Water-soluble P}_2\text{O}_5 \text{ acidulation efficiency, \%} =$$

$$\frac{\text{Water-soluble P}_2\text{O}_5, \%}{\text{Total P}_2\text{O}_5 \text{ in product, \%}} \times \frac{\text{Actual degree of acidulation, \%}}{\text{Actual degree of acidulation, \%}} \times 100$$

$$2. \text{ Available P}_2\text{O}_5 \text{ acidulation efficiency, \%} =$$

$$\frac{\text{NAC-soluble P}_2\text{O}_5 + \text{water-soluble P}_2\text{O}_5, \%}{\text{Total P}_2\text{O}_5 \text{ in product, \%}} \times \frac{\text{Actual degree of acidulation, \%}}{\text{Actual degree of acidulation, \%}} \times 100$$

When these definitions are used, the water-soluble P<sub>2</sub>O<sub>5</sub> acidulation efficiency more closely describes the process performance based on the intended level of acidulation, and the

available  $P_2O_5$ , acidulation efficiency more appropriately describes the agronomic usefulness of the product. It should be noted that in the calculation of the available  $P_2O_5$ , acidu-

lation efficiency the NAC-soluble  $P_2O_5$  that may occur in the unacidulated rock was not considered in developing the equation.

## Status of Technology of SSP and SAB-PAPR

Since SSP has been produced in large quantities for about 140 years in many countries, a brief review of its technology is given. For a more complete review see *Superphosphate: Its History, Chemistry, and Manufacture* (18).

In the most common practice, production of SSP consisted of (1) mixing of ground phosphate rock with sulfuric acid, (2) denning, and (3) curing. After curing by pile storage for several weeks, the product was reclaimed from the pile and crushed to pass a 3- or 4-mm screen. Such product is known as ROP superphosphate and may be sold as such or used as an ingredient in mixed fertilizers. In the United States over 80% of the product was used to make mixed fertilizers (84% in 1951).

The major process variables in producing SSP included fineness of grinding of the rock, concentration of the sulfuric acid, acid-to-rock ratio, and rock composition. Usually the sulfuric acid was diluted to about 70%  $H_2SO_4$ , although in some cases concentrated acid, water, and rock were simultaneously added to the mixer. Typical acid-to-rock ratios were near 0.6 kg of  $H_2SO_4$  (100% basis) per kilogram of Florida rock. A wide variety of mixing devices, both batch and continuous, have been used. Their function is to mix the rock and acid quickly and thoroughly and to discharge the slurry-type mixture into the den while it is still semi-fluid.

A number of den designs have also been used, both batch and continuous. Continuous (mechanical) dens permitted retention times of 20 minutes to 2 hours; stationary (box- or pit-type) dens usually were operated at an average retention time of about 1 hour. The function of the den was to permit reactions to proceed to the point that the superphosphate was firm enough to be excavated by mechanical devices and conveyed to storage but still soft enough for easy excavation. (In some of the early plants, the den was a brick- or stone-lined rectangular pit, which was excavated manually with shovels.) Curing usually consisted merely of storage in piles for 3 weeks or more while chemical

reactions were reaching completion and the material was hardening.

Optional steps in SSP production were drying, granulation, and incorporation of additives such as potash salts, micronutrients, or conditioners. Superphosphate may be granulated either before or after curing. In some cases SSP is granulated without drying, and in other cases it is dried without granulation. Granulation before curing followed by partial drying (to permit curing reactions to continue) is another variation that is practiced in some plants.

Partial acidulation of phosphate rock or ground bones probably is as old as superphosphate. Gotthold Escher, a school headmaster in Moravia who is credited by some authorities with the invention of superphosphate in 1835, suggested "slightly to moisten bonemeal with a cheap and not too strong an acid" (18). Some subsequent producers of superphosphate probably underacidulated bones or phosphate rock for various reasons—ignorance, economy, or a belief that high solubility of  $P_2O_5$  was deleterious. The first recorded systematic, deliberate, and overt underacidulation of phosphate rock was in Finland in the late 1920s. The product was called "Kotka Phosphate" because it was produced in the city of Kotka in Finland. The process was based on the theory that a phosphate with less acid than fully acidulated superphosphate would be beneficial to acidic Finnish soils as well as more economical. At first the product was made by underacidulating phosphate rock; later it was made by mixing unacidulated rock with fully acidulated fresh superphosphate. Sauchelli, in his book published in 1960, states that Kotka superphosphate had been manufactured and sold for 30 years and gives a typical analysis of 26% total  $P_2O_5$ , 20%  $P_2O_5$  soluble in citric acid, and 13%-15% water-soluble  $P_2O_5$  (19). Later, PAPR was produced in other European countries and South Africa by various processes involving direct underacidulation or by mixing ground rock with fully acidulated SSP.

## PAPR Production Processes

Two basic PAPR production methods (processes) were evaluated by IFDC. In one commercially practiced process, an ROP product is made. The ROP product is usually semi-granular in appearance but still quite dusty. After curing for several days, this ROP material is usually granulated in a separate step to produce a straight or multinutrient (compound) granular product. An IFDC-developed process produces granular PAPR by single-step acidulation/granulation (SSAG)(6). In this process a closely sized, durable, and non-dusty granular product resembling granular SSP, TSP, or

DAP is produced in a single step without curing.

The SSAG process was initially developed in laboratory-scale batch and continuous test equipment using various phosphate rocks. The laboratory-scale test results obtained at a production rate of about 25 kg/h were generally confirmed in pilot plant-scale tests performed at production rates of 250-750 kg/h using two phosphate rock sources. The ROP process was also studied in pilot plant-scale equipment at a production rate of about 200 kg/h using two phosphate rocks. Throughout the course of development, a large

number of SAB-PAPR products were prepared for agronomic testing. A description of the two basic SAB-PAPR processes evaluated in IFDC pilot plant-scale equipment follows.

## Run-of-Pile SAB-PAPR

This process is relatively simple with respect to machinery and equipment (Figure 3). In the process ground phosphate rock, acid, and water (optional) are fed continuously into a mixer. This mixer (usually a pug mill type) is designed to provide thorough mixing of the phosphate rock and acid with a minimum of retention time (typically 30-60 seconds). A relatively short retention time during the mixing step is preferred to avoid excessive agglomeration, caking, and other material-handling problems. A certain amount of agglomeration (granulation) sometimes occurs in the mixer, but this is incidental to the major function of the unit—to obtain thorough mixing of the phosphate rock and acid. Batch-type mixing is not preferred because the acid and rock mixture tends to agglomerate and solidify too quickly to obtain good mixing and rapid discharge from the mixer.

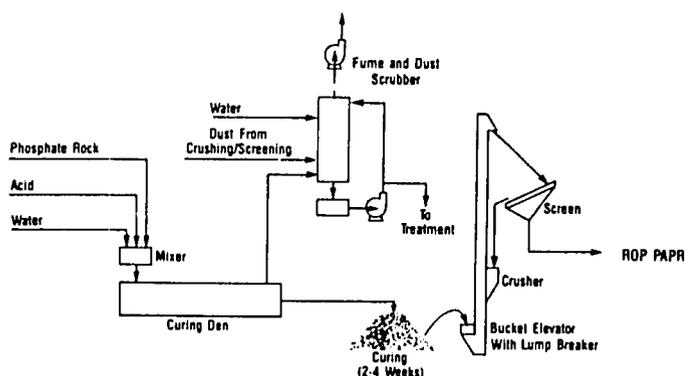


Figure 3. Run-of-Pile SAB-PAPR Process.

The phosphate rock, acid, and water are usually added to the mixer at the same point. However, depending upon the characteristics of the phosphate rock, degree of acidulation, and other process variables, the points of addition for rock, acid, and water may be manipulated to achieve optimum mixing and reaction. Likewise, the rotational speed of the mixer shafts and the orientation of the mixing paddles may be varied to achieve the desired retention time for optimum mixing and reaction.

In some cases adding other materials to the mixer (typically potassium chloride) may be desirable to improve the acidulation process (discussed later) or to provide additional nutrients in the product. Usually when potassium chloride is added, it is fed directly to the mixer without first being premixed with the phosphate rock.

In one variation of this process (batch-type denning process) simulated by IFDC in the laboratory and pilot plant, the material discharged from the mixer was stored for a

short time in a closed and ventilated chamber (curing den). The IFDC pilot-plant den had a capacity of about 1 mt, whereas the capacity of a commercial-scale unit usually ranges from 10 to 40 mt. After about 1 hour the material was excavated from the den and transferred to storage. This denning process was essentially the same as that used for the previously described production of ROP SSP. In some cases, depending upon the characteristics of the rock and degree of acidulation, it is possible to transfer the material directly from the mixer to storage without first denning. If denning is required, a continuous belt-type den can be used as an alternative to the previously described batch-type unit. After a period of storage, usually about 2 weeks, the ROP material is reclaimed and crushed to pass a nominal 4-mm screen before it is bagged or otherwise prepared for shipment. The particle size data for two ROP SAB-PAPR-50 products are shown in Table 5. These data indicate that the product is quite granular (about 55% retained on a 1.18-mm [14-mesh] screen). The semigranular characteristic of the ROP material is attributed to the lack of sufficient liquid phase (acid plus water) at a 50% level of acidulation to form a slurry. Instead of forming a typical SSP-type slurry that solidifies into a monolithic mass, the PAPR product discharged from the mixer is moist and relatively granular in appearance.

Dust and fumes (primarily fluorine gas) must be ventilated from the mixer, den (if used), conveyor system, and in some cases the product storage area. However, because of the relatively low levels of acidulation and the correspondingly small release of fluorine, it is unlikely that fume-scrubbing equipment normally used for the recovery of byproduct fluorine would be economical unless the recovered fluorine (fluosilicic acid) could be sold or used to replace a portion of the sulfuric acid fed to the process.

The ROP SAB-PAPR process may be operated in a single-step or two-step mode. With some phosphate rocks, especially at higher levels of acidulation, it may be desirable to perform the acidulation in two steps to obtain optimum conversion of the phosphate to the available form and to improve the physical properties of the product. With the two-step acidulation method, the phosphate rock and approximately one-half of the acid required for the intended degree of acidulation are fed to the process. The material is cured for several hours to several days before it is reclaimed and fed through the process a second time while the remainder of the acid is added. After the second pass through the process, the product is cured for an additional period (about 2 weeks) before it is bagged.

The need for crushing, screening, and other processing of the material between the acidulation steps, or of the cured SAB-PAPR product before bagging, is largely dependent upon the character of the phosphate rock and the degree of acidulation used. In general, lumping and caking of the SAB-PAPR product during curing tends to increase as the degree of acidulation is increased. This is especially true with the more unreactive rocks or with rocks that contain a low level of free carbonate.

Table 5. Physical Properties of Selected Granular and Run-of-Pile SAB-PAPR Products<sup>a</sup>

Phosphate Rock Source	Nominal Degree of Acidulation (%)	Free Moisture (%)	Particle Size Analysis, Cumulative % Retained on						Crushing Strength <sup>b</sup> (kg)	Abrasion Resistance <sup>c</sup> (% Degradation)	Moisture Absorption <sup>d</sup> (g/cm <sup>3</sup> )	Moisture Penetration <sup>d</sup>	Compatible With Urea <sup>e</sup>	
			Free Acid (%) (% P <sub>2</sub> O <sub>5</sub> Basis)	4-Mesh	6-Mesh	8-Mesh	10-Mesh	14-Mesh						20-Mesh
<b>Laboratory-Scale Production (Granular)</b>														
Central Florida (U.S.A.)	40	3.0	3.4	0.0	0.0	5.1	35.0	77.1	99.4	1.1	22	NA <sup>f</sup>	NA	NA
Huila (Colombia)	50	0.5	0.2	0.0	0.0	11.0	49.4	82.0	90.7	0.4	54	NA	NA	Yes
Kodjari (Burkina Faso)	45	0.8	0.9	0.0	0.2	27.7	91.7	99.6	99.9	1.2	27	NA	NA	Yes
Mussoorie (India) <sup>g</sup>	35	2.1	4.6	0.0	2.4	33.9	72.6	94.1	98.0	0.5	27	21	0	NA
Pare W (Niger)	50	0.6	0.2	0.0	0.0	10.2	65.6	94.0	99.2	0.8	33	NA	NA	Yes
Pare W (Niger)	25	0.2	0.1	0.0	0.2	24.0	57.0	88.5	98.7	0.5	54	NA	NA	Yes
Pesca (Colombia)	40	0.4	0.6	0.0	0.0	6.1	39.8	82.9	94.4	1.1	22	NA	NA	Yes
Sukulu Hills (Uganda)	50	2.5	1.0	NA	NA	NA	NA	NA	NA	3.2	NA	11	0	No
		(fresh)	(fresh)											(fresh)
		0.5	0.1	0.0	2.0	54.6	89.6	99.5	99.9					Yes
		(cured)	(cured)											(cured)
Tilemsi Valley (Mali)	30	1.4	0.1	0.0	0.0	19.1	76.2	98.5	99.9	1.0	NA	NA	NA	Yes
Hahotoe (Togo)	50	0.3	0.1	0.0	0.0	11.4	66.9	93.3	99.4	0.8	NA	NA	NA	Yes
Hahotoe (Togo)	25	0.6	0.2	0.0	0.4	10.5	67.6	95.3	99.2	1.1	NA	NA	NA	Yes
<b>Pilot Plant-Scale Production (Granular)</b>														
Central Florida (U.S.A.)	50	2.8	0.7	0.0	11.0	45.7	75.5	96.0	98.8	2.5	1.3	95	0	NA
Central Florida (U.S.A.)	40	1.6	0.3	0.0	16.3	67.6	92.4	99.6	99.7	3.0	NA	47	0	NA
Central Florida (U.S.A.)	30	1.7	0.3	0.0	17.7	70.4	91.7	99.0	99.3	2.8	NA	51	0	NA
Utah (U.S.A.)	50	1.3	0.2	0.0	16.0	52.7	78.1	96.6	97.9	2.1	1.4	18	0	Yes
Utah (U.S.A.)	40	2.6	0.6	0.0	13.9	53.3	82.5	98.9	99.3	1.9	1.7	NA	NA	No
Utah (U.S.A.)	30	0.9	0.2	0.0	16.4	56.0	85.0	98.4	99.0	1.7	NA	21	0	NA
<b>Pilot Plant-Scale Production (Run-of-Pile)</b>														
Central Florida (U.S.A.)	50	1.1	0.3	5.7	9.3	25.8	45.0	57.9	66.7	0.2	NA	NA	NA	NA
Kodjari (Burkina Faso)	50	1.1	0.1	0.0	0.1	21.0	40.9	55.2	64.3	0.8	NA	NA	NA	NA

a. All tests performed on cured product (1 month or more curing) unless otherwise noted.

b. Test performed on minus 7- plus 8-mesh particles.

c. Rotary drum/steel ball test method.

d. At 30°C and 80% relative humidity for 72 h.

e. SAB-PAPR/prilled urea mixture (1:1) at 30°C for a minimum of 72 h.

f. Data not available.

g. Run-of-mine phosphate rock.

## Granular SAB-PAPR

Granular SAB-PAPR can be produced either by granulating previously prepared ROP material in a separate step using steam/water, or it can be prepared directly by using the SSAG SAB-PAPR process developed by IFDC and shown in Figure 4. One producer in Germany also uses a compaction/granulation process to produce a granular product (usually containing some potassium) from an ROP material.

In the SSAG process, the phosphate rock, sulfuric acid, water, and recycle material are fed continuously to a granulator, usually a rotary drum-type unit. Recycle material fed to the granulator consists of the undersize fraction (from the screening operation described later) and usually a portion of the product. The amount of recycle material fed to the granulator may vary, depending upon the type of phosphate rock and other operating conditions. However, a rate equivalent to a recycle-to-product ratio of about 2 is usually

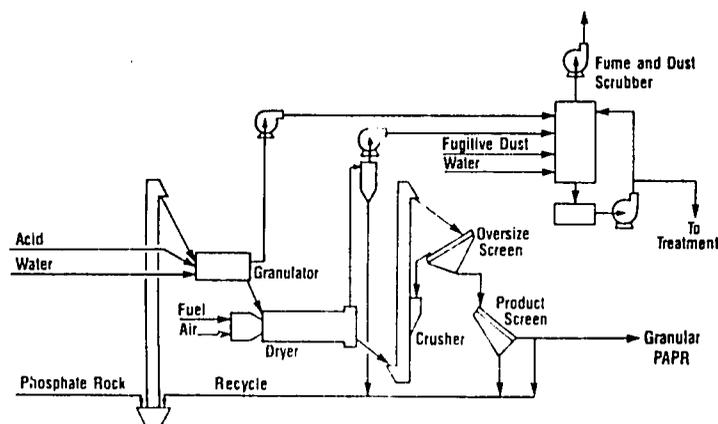


Figure 4. Single-Step Granular SAB-PAPR Process.

sufficient to maintain acceptable granulation. Sulfuric acid and water are sprayed (through separate systems) onto the

rolling bed of material in the granulator to obtain the desired level of acidulation and granulation, respectively. The retention time in the granulator required to obtain the optimum level of reaction and granulation varies, depending upon the phosphate rock composition and level of acidulation; however, it is normally in the range of about 5-8 minutes.

The moist, plastic material from the drum granulator is discharged into a rotary drum-type, cocurrent dryer. The temperature of the material discharged from the dryer is maintained at the desired level by controlling the temperature of the drying air. A dry-type dust collector is usually

used to partially clean the air before it is discharged into a wet scrubber to remove the fluorine and fine particulate.

The material from the dryer is screened to yield a product usually in the 1- to 4-mm size range. Oversize material from the screening unit is routed to a crusher. The material discharged from the crusher is recycled to the screen. As previously mentioned, the undersize material and usually a fraction of the product are returned to the granulator as recycle. It is usually unnecessary to treat the product with a conditioner to minimize caking; however, the addition of a small amount of oil may be useful as a dust suppressant, especially if the product is handled in bulk.

## Laboratory- and Pilot Plant-Scale Test Results

The usefulness of SAB-PAPR production technology (ROP or granular) can usually be determined by evaluating three major factors—(1) composition of the phosphate rock and its amenability to chemical processing, (2) cost of production especially with respect to the quantity of acid required to achieve an agronomically acceptable product, and (3) agronomic performance of the PAPR product compared with alternative phosphate sources. Several phosphate rocks were evaluated in the IFDC laboratory and pilot plant, as described in this bulletin, to gather information on these factors and to develop an objective criterion for determining on a case-by-case basis the technical and economic feasibility of SAB-PAPR technology as a phosphate processing alternative. The laboratory- and pilot plant-scale equipment used for these studies is shown in Figures 5 and 6, respectively.

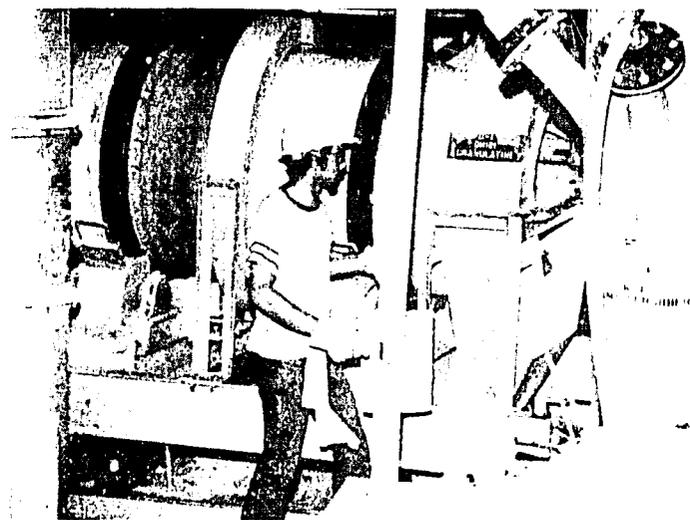


Figure 6. IFDC Pilot Plant-Scale SAB-PAPR Production Unit.

### Phosphate Rock Composition

The chemistry of phosphate rock acidulation is complex and not always clearly understood; therefore, it is difficult to judge with certainty how a particular phosphate rock will

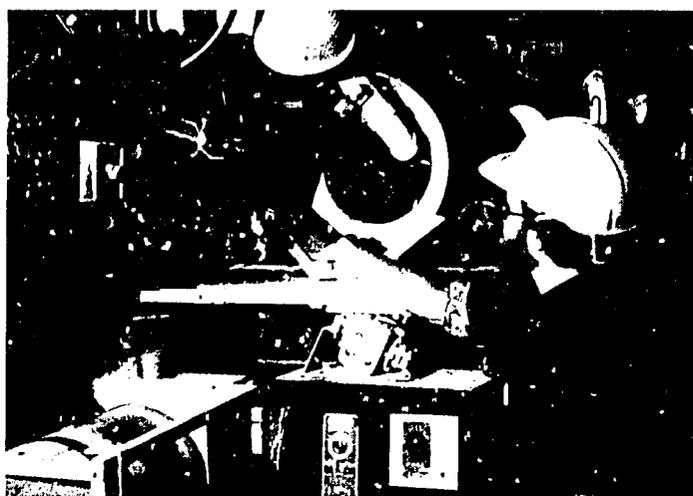
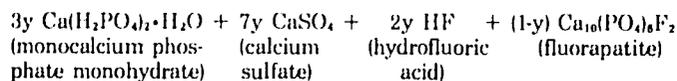
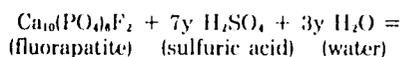


Figure 5. IFDC Laboratory-Scale Granular SAB-PAPR Production Unit.

behave when treated with acid. The chemical transformation of the phosphate minerals in a rock during and after initial acidulation is usually affected by competing and synergistic factors specific to each rock, including texture, surface area and porosity, and the presence of associated compounds of calcium, iron, aluminum, magnesium, fluorine, and sulfur. Thus, acidulation chemistry is sometimes unpredictable because these associated compounds may participate to some degree in the acidulation reactions and subsequent reactions that occur during product curing and storage. Furthermore, the influence of some of these physical and chemical factors can be altered by controlling critical process parameters, including the reaction temperature profile, retention time, rate of reaction, and level of moisture. However, since fluorapatite is usually the major constituent of phosphate rock, the simplified equation for its reaction with sulfuric acid to form SSP or SAB-PAPR may be written as follows:



In this equation the term  $y$  represents the degree of acidulation—for example, 100% acidulation (production of SSP) corresponds to a  $y$  value of 1.0, and a  $y$  value of 0.5 refers to a 50% acidulated PAPR. As previously stated, the role of nonfluorapatite components in the phosphate rock may significantly alter the above reaction chemistry. For this reason a relatively large number of phosphate rocks were studied (Table 2) to characterize the SAB-PAPR process chemistry and to develop meaningful estimates of the expected technical, economic, and agronomic performance of a given SAB-PAPR product.

An important attribute of PAPR technology is that a phosphate rock may be suitable for SAB-PAPR processing even though it is unsuitable for full acidulation to SSP. The Kodjari deposit in Burkina Faso is an example of a rock well suited for SAB-PAPR processing. This sedimentary-type rock is very unreactive and contains relatively high levels of silica, iron, and aluminum. Acidulation of this rock beyond about 50% results in a paste-like material that is very difficult to handle. The nonporous and therefore relatively low surface area of the apatite component of this rock makes it difficult to achieve good contact and complete reaction between the phosphate mineral and the acid; thus, the rock is difficult to fully acidulate. As previously mentioned, the relatively high surface area of the Kodjari rock (about 15 m<sup>2</sup>/g) is caused by clay minerals in the rock, not by the apatite. Extra fine grinding of such a rock to achieve a higher level of reactivity is not practical because it contains a large amount of abrasive silica (about 25%). Also, the iron and aluminum, while not adversely affecting the physical properties of the product, tend to react slowly during curing to form insoluble phosphate compounds that have the net effect of decreasing the efficiency of the acidulation reaction.

Many phosphate rocks, especially those that are not highly weathered, contain high levels of calcium and magnesium carbonate. High carbonate levels adversely affect SSP and SAB-PAPR production in two ways—first, the carbonate preferentially reacts with the acid during acidulation, increasing the amount of acid required to achieve the desired level of acidulation, and second, the acid/carbonate reaction releases carbon dioxide gas which usually causes undesirable frothing during the reaction and weakening of the granules if the SSAG-PAPR process is used. Stepwise reaction of such high-carbonate rocks (those containing more than about 4% CO<sub>2</sub>) lessens the adverse physical processing problems, but it does not avoid the problem of excessive consumption of acid.

The relatively unreactive rocks can usually be acidulated to a level of only about 30%-60% while still yielding a product that is sufficiently low in free acid to avoid excessive stickiness or hardening during processing and storage. In most cases a higher level of acidulation can be obtained if the ROP-PAPR process is used because more time is available for the acidulation reactions to reach completion during the curing step. The maximum degree of acidulation that could be expected for several phosphate rocks in the SSAG and ROP PAPR processes is shown in Table 6.

### Effect of Process Variables

The chemical and physical characteristics of the phosphate rock have a major influence on the performance of the SAB-PAPR process (ROP or SSAG) and the quality of the product. However, some process conditions (variables) also have a significant influence. The most important process variables identified in the IFDC laboratory- and pilot plant-scale

Table 6. Maximum Degree of Acidulation Predicted for Various Phosphate Rocks—Run-of-Pile and Single-Step Granular SAB-PAPR Processes

Rock Source	Typical Analysis		Relative Reactivity <sup>a</sup>	Predicted Degree of Acidulation	
	Total P <sub>2</sub> O <sub>5</sub>	NAC-Soluble P <sub>2</sub> O <sub>5</sub>		Run-of-Pile Process	Single-Step Granular Process
	..... (%) .....			..... (%) .....	
Central Florida (U.S.A.)	31.0	4.2	Medium	100	60
El-Hassa (Jordan)	30.4	4.5	Medium	100	60
Hahotoe (Togo)	35.9	3.0	Medium	100	60
Huila (Colombia)	20.7	3.5	Medium	100	30
Kodjari (Burkina Faso)	25.3	1.9	Low	60	40
Meda Luna (Colombia)	30.0	2.3	Low	100	70
Mussoorie (India)—Concentrate	25.0	0.4	Low	100	50
Mussoorie (India)—Run-of-Mine	18.6	1.0	Low	100	35
Parc W (Niger)	28.5	2.6	Low	100	60
Pesca (Colombia)	19.5	3.3	Medium	100	30
Sukulu Hills (Uganda)	37.9	2.7	Low	100	60
Tahoua (Niger)	27.9	2.5	Low	60	40
Tilemsi Valley (Mali)	26.2	4.2	Medium	70	50
Utah (U.S.A.)	30.2	2.4	Low	100	50

a. Relative reactivity criteria: NAC-soluble P<sub>2</sub>O<sub>5</sub>, 0%-2.9%—Low.  
 NAC-soluble P<sub>2</sub>O<sub>5</sub>, 3.0%-4.9%—Medium.  
 NAC-soluble P<sub>2</sub>O<sub>5</sub>, 5.0% and above—High.

studies were (1) degree of acidulation, (2) concentration of acid, (3) process temperature profile, and (4) retention time.

IFDC's laboratory- and pilot plant-scale evaluations indicate that the chemistry of phosphate rock acidulation is not always predictable. This lack of predictability is presumed to be due to variations in the chemical and physical characteristics of the rocks and the specific SAB-PAPR processing conditions (degree of acidulation, temperature, and retention time). The characteristics of the final product may also vary as a result of curing reactions during storage. For these reasons the laboratory- and pilot plant-scale test data shown

in Table 7 and the product characteristics (Tables 3 and 5) vary quite widely from one rock to another. Also, test results using the same rock may vary considerably from one test to another, as the process conditions are changed. Therefore, specific test work is required to determine the performance of a rock sample and to quantify the effect of the major process variables on the quality of the final product.

Although there is a significant variation in the data available, the general effect of the most significant process variables can be summarized as follows.

Table 7. Pilot Plant-Scale Operating Data--Run-of-Pile and Granular SAB-PAPR

Phosphate Rock Source	Run-of-Pile Process		Single-Step Granular Process			
	Central Florida	Burkina Faso (Kodjari)	Utah		Central Florida	
	200	200	250	234	246	256
Production Rate, kg/h	200	200	250	234	246	256
Degree of acidulation, %	50	51	50	39	51	53
Acid concentration, % H <sub>2</sub> SO <sub>4</sub>	69	69	73	92	74	95
Phosphate rock feed rate, kg/h	140	155	180	180	175	180
Dilute sulfuric acid feed rate, kg/h	62	49	71	44	71	60
Water feed rate, kg/h	25	19	46	47	76	70
Recycle feed rate, kg/h	-	-	195	216	497	490
Recycle/product ratio, kg/kg	-	-	0.8	0.9	2.0	1.9
Temperature of recycle, °C	-	-	48	48	49	48
Particle size of recycle:						
Oversize (plus 6-mesh), %	-	-	0.1	0.0	6.6	6.8
Product (minus 6- plus 14-mesh), %	-	-	7.4	7.4	49.6	64.3
Fines (minus 14-mesh), %	-	-	92.5	92.6	43.8	28.9
Retention time in mixer or granulator, min	2	2	12.7	14.8	8.6	8.6
Moisture in mixer or granulator discharge, %	15.3	10.5	4.1	4.8	6.6	5.7
Mixer or granulator discharge temperature, °C	64	66	52	50	51	58
Dryer air discharge temperature, °C	-	-	76	76	75	76
Airflow through dryer (outlet conditions), m <sup>3</sup> /h	-	-	3,300	1,800	3,100	3,100
Temperature of material discharged from dryer, °C	-	-	68	63	66	67
Curing time in den, min	50	73	-	-	-	-
Temperature of material removed from den, °C	63	77	-	-	-	-
Total dust collected, kg/mt of product	-	-	72	28	74	52
Composition of product after 7-day curing:						
Total P <sub>2</sub> O <sub>5</sub> , % dry basis	22.7	20.1	22.9	24.6	22.7	22.7
Water-soluble P <sub>2</sub> O <sub>5</sub> , % dry basis	10.9	2.7	10.2	9.4	9.1	10.9
NAC-soluble P <sub>2</sub> O <sub>5</sub> , % dry basis <sup>a</sup>	3.5	4.6	2.2	2.3	4.0	3.3
Free acid (as P <sub>2</sub> O <sub>5</sub> ), % dry basis	2.9	0.9	0.2	0.4	0.6	0.5
F, % dry basis	NA <sup>b</sup>	NA	2.1	2.3	2.4	1.8
Ca, % dry basis	21.9	18.3	21.7	20.2	22.2	23.6
SO <sub>4</sub> , % dry basis	20.3	13.9	22.8	22.6	21.8	25.3
Free H <sub>2</sub> O, %	7.9	4.8	1.2	2.6	2.5	2.6
Water-soluble P <sub>2</sub> O <sub>5</sub> acidulation efficiency, %	95	27	90	99	79	90
Available P <sub>2</sub> O <sub>5</sub> acidulation efficiency, %	126	72	109	123	113	118
Composition of product after 21-day curing:						
Total P <sub>2</sub> O <sub>5</sub> , % dry basis	20.9	19.8	22.5	24.0	21.9	22.6
Water-soluble P <sub>2</sub> O <sub>5</sub> , % dry basis	9.5	1.2	11.1	8.7	9.6	10.9
NAC-soluble P <sub>2</sub> O <sub>5</sub> , % dry basis <sup>a</sup>	3.7	5.9	1.8	2.7	4.2	3.8
Free acid (as P <sub>2</sub> O <sub>5</sub> ), % dry basis	0.3	0.1	0.2	0.6	0.7	0.5
F, % dry basis	NA	NA	2.2	2.4	2.5	2.5
Ca, % dry basis	21.9	18.4	23.7	26.4	21.6	22.1
SO <sub>4</sub> , % dry basis	24.6	15.2	25.9	25.5	23.3	23.0
Free H <sub>2</sub> O, %	1.1	1.1	1.3	2.6	2.8	2.7
Water-soluble P <sub>2</sub> O <sub>5</sub> acidulation efficiency, %	90	12	99	93	86	91
Available P <sub>2</sub> O <sub>5</sub> acidulation efficiency, %	126	70	115	122	124	122
Crushing strength, kg/granule	NA	NA	2.3	1.9	2.3	3.0

a. Does not include water-soluble fraction.

b. Not available.

**Degree of Acidulation**—An increase in the degree of acidulation usually results in a higher proportion of the available  $P_2O_5$  in the product being in the water-soluble form. Acidulation efficiency (Table 7) appears to be unrelated to the degree of acidulation. Acidulation efficiency apparently is influenced to a greater extent by the combined effect of the phosphate rock composition, reactivity, and other process variables.

**Concentration of Acid**—The acidulation reaction is very exothermic (about 90 kcal/kg of fluorapatite reacted with sulfuric acid), and an increase in temperature is usually accompanied by an increase in the rate of reaction. However, with some phosphate rocks, especially those that are less reactive, a higher level of acidulation can be obtained if the temperature is decreased and the rate of reaction is slowed to minimize surface reactions and facilitate deeper penetration of the acid into the phosphate rock matrix. For this reason, when an unreactive phosphate rock is processed, improved results are usually obtained if the acid is diluted and cooled in a separate step before it is reacted with the rock.

Laboratory-scale tests using Kodjari (Burkina Faso) phosphate rock, which is relatively unreactive and contains a high level of iron and aluminum, show that a dilute acid (60%-75%) is more effective than a more concentrated acid in decreasing the precipitation of reaction products on the surface of the phosphate rock particles. This surface precipitation of reaction products partially blocks or blinds the rock and leads to incomplete reaction, excess free acid, and a sticky, unmanageable product. Furthermore, the unreacted acid in the product tends to slowly react with the iron and aluminum impurities during storage to form a number of insoluble (unavailable) phosphate compounds. When a more reactive rock (for example, central Florida) was used in the pilot plant, the higher acid concentration (95%) resulted in a slightly higher acidulation efficiency when measured in terms of water-soluble  $P_2O_5$ . However, when a less reactive (Utah) rock was used, a slightly higher acidulation efficiency (water-soluble  $P_2O_5$  basis after curing 21-days), was obtained with a dilute (73%) acid.

An optimum balance between the concentration of the acid, the reactivity of the phosphate rock, and the quantity of moisture (liquid phase) that can be tolerated must be determined for each phosphate rock and desired level of acidulation. In general, a sulfuric acid concentration of 60%-75% is desired for acidulating the less reactive rocks, and an acid concentration of 75%-93% is more appropriate for the more reactive rocks.

**Process Temperature Profile**—As indicated from the above discussion, it is difficult to separate the influence of temperature and rate of reaction when evaluating the SAB-PAPR process. When a less reactive phosphate rock such as Kodjari (Burkina Faso) is processed, a high temperature during the initial period of reaction and during subsequent drying (assuming the SSAG process) usually causes a decline in the amount of water- and NAC-soluble  $P_2O_5$  in the finished product.

Part of this adverse effect on the solubility of  $P_2O_5$  in the

finished product is related to the previously described blinding and to the high free acid which leads to the undesired iron/aluminum reactions during curing. These reactions are caused in part by the high temperature of the PAPR material resulting from the combined effect of a high acid concentration and rate of reaction. The temperature of the material that is maintained during the drying step can also adversely affect the level of water-soluble  $P_2O_5$  (MCP) in the finished product. Laboratory-scale results indicate that the reversion of water-soluble  $P_2O_5$  to NAC-soluble and insoluble compounds is minimized if the temperature of the material during drying does not exceed 120°C, 100°C being the preferred maximum temperature. The reversion reactions were also found to be influenced by retention time during drying. The laboratory data indicate that the retention time during drying at the 100° - 120°C level should not exceed 30 minutes to ensure a minimum loss of water-soluble  $P_2O_5$ .

Pilot-plant tests were performed at drying temperatures of 66° - 93°C. Within this range, and with a rock of medium reactivity (central Florida) and one of low reactivity (Utah), the amount of water-soluble  $P_2O_5$  in the product generally increased as the drying temperature was increased. However, the maximum drying temperature that could be maintained without causing a significant decline in the level of water-soluble  $P_2O_5$  was not determined. In the design of an SAB-PAPR process for a particular rock, the maximum allowable drying temperature should be determined and used. This will ensure that the dryer (the most costly item of equipment in the process) is properly sized and that it is operated at the optimum level to obtain the required product characteristics.

**Retention Time**—The acidulation reaction, although initially quite rapid, requires considerable time to approach completion. For example, in the production of fully acidulated ROP SSP, a reaction or "curing" period of 10-30 days is usually required for optimum utilization of the acid and conversion of the phosphate to the available form. In the SSAG process used to produce a 50% acidulated product in the pilot plant, a minimum retention time of about 4 minutes was required for the initial rock/acid reaction in the granulator when a phosphate rock of medium reactivity (central Florida) is used. An additional 12 minutes was required for drying (curing) in the rotary drum-type dryer. The retention time in the process equipment (granulator and dryer) is based on the mass flow of material through the equipment. Therefore, the maximum production rate that can be achieved in a given plant is determined by the retention time required for the particular phosphate rock after taking into account the required recycle-to-product ratio (total flow of material through the process equipment). In general, for a given acidulation level the retention time required to achieve optimum operation of the plant and conversion of the  $P_2O_5$  to an available form increases as the reactivity of the rock decreases. A diagram of the effect of retention time in the pilot-plant granulator on the quality of the operation and product when a rock of medium reaction (central Florida) was used is shown in Figure 7.

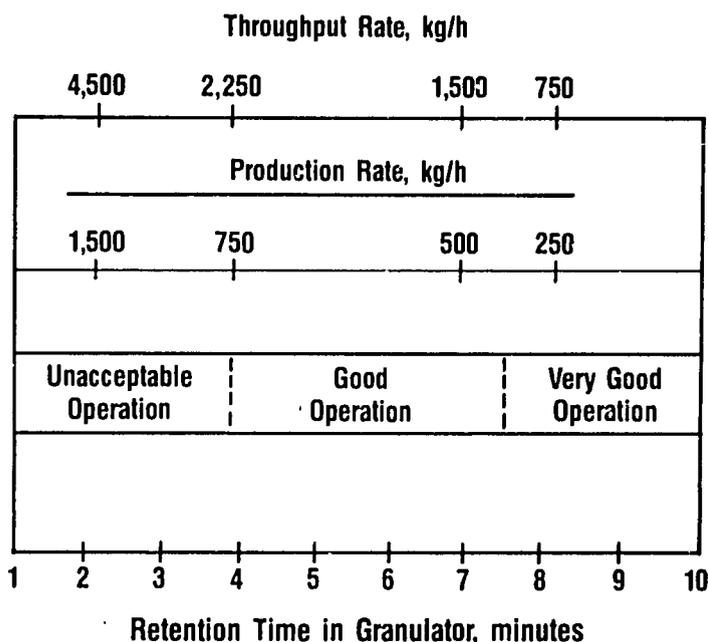
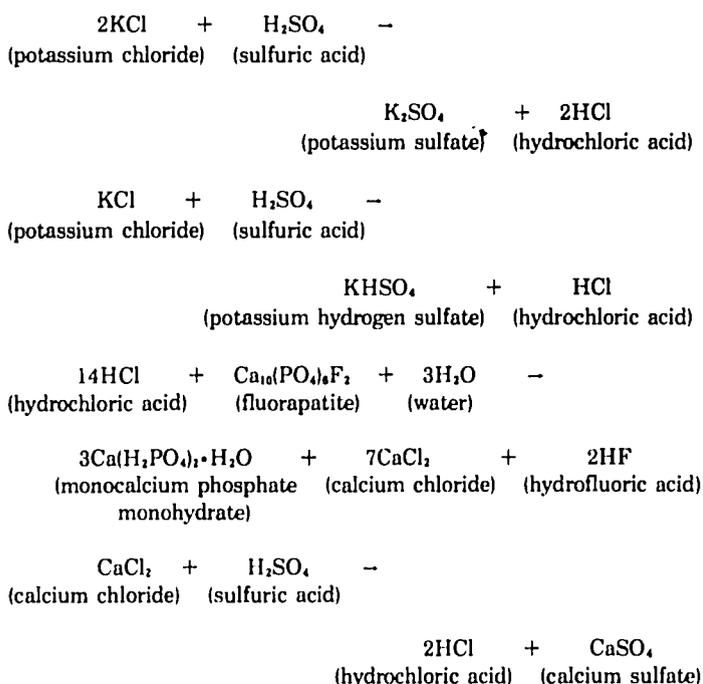


Figure 7. Effect of Retention Time (production rate) on Plant Operation and Product Quality—Single-Step Granular SAB-PAPR Process.

**Potassium Chloride Additive**—With some relatively unreactive rocks, the addition of a small amount of potassium chloride or sodium chloride (about 3%-10%) to the acidulation reaction usually increases its efficiency. The increase in efficiency is presumed to be due to the formation of hydrochloric acid which attacks the rock more aggressively than does straight sulfuric acid according to the following reactions.



Addition of potassium chloride is particularly advantageous when there is an agronomic need for potassium.

However, the presence of chloride may lead to increased corrosion of process equipment.

**Particle Size**—During the course of developing the SAB-PAPR processing technology, no tests were made specifically to evaluate the effect of the particle size of the phosphate rock on the performance of the process or the quality of the product. However, in several laboratory-scale tests using Hahotoe (Togo) and Pesca (Colombia) phosphate rocks (rocks considered low in reactivity), it was observed that relatively coarse material (65%-89% passing 100-mesh and less than 50% passing 200-mesh) was difficult to process. The 30%-50% acidulated rock was extremely sticky and could not be properly granulated or dried because of an excessive amount of unreacted acid. When the rocks were more finely ground (at least 80% passing 200-mesh), the problems of stickiness and high levels of unreacted acid were largely eliminated.

Furthermore, in pilot plant-scale SSAG tests using the relatively unreactive Utah rock, the granular product was weak (this led to an excessively high recycle-to-product ratio) when a relatively coarse (45% passing 200-mesh) material was used. However, when the rock was more finely ground (77% passing 200-mesh), the strength of the product improved and operation was routine at a recycle-to-product ratio of about 1.

**Effect of Curing**—Reactions during curing (aging) of superphosphate-type products often affect the  $\text{P}_2\text{O}_5$  solubility. When ROP-SSP is produced from relatively high-grade, low-impurity phosphate rock, curing of the moist material for a period of about 1-4 weeks increases the solubility of the  $\text{P}_2\text{O}_5$ . Aging of granular SAB-PAPR products made by IFDC had a variable effect on the final water- and NAC-soluble  $\text{P}_2\text{O}_5$  in the products.

The data in Table 8 show that even though the granular products were essentially dry, a significant reversion of water-soluble  $\text{P}_2\text{O}_5$  to NAC-soluble or insoluble  $\text{P}_2\text{O}_5$  occurred in those products containing a relatively large quantity of iron and aluminum impurities. For example, with the Tilemsi Valley (Mali) product, the water-soluble  $\text{P}_2\text{O}_5$  declined about 60% and the NAC-soluble  $\text{P}_2\text{O}_5$  increased about 19% with aging. Likewise, the Kodjari (Burkina Faso) product declined about 49% in water solubility and increased about 80% in NAC-soluble  $\text{P}_2\text{O}_5$ . In these two cases, the available  $\text{P}_2\text{O}_5$  (water- plus NAC-soluble fractions) declined about 27% and 8%, respectively, as a result of aging.

The products made from central Florida (U.S.A.), El-Hassa (Jordan), and Huila (Colombia) rocks were not significantly affected by aging, presumably because of their relatively low level of iron and aluminum impurities.

Although some samples were analyzed after 12-months' aging, most of the reversion occurred within 2-4 weeks after production.

Table 8. Effect of Curing (Aging) on P<sub>2</sub>O<sub>5</sub> Solubility—Granular SAB-PAPR Products Made by IFDC<sup>a</sup>

SAB-PAPR Product	Degree of Acidulation	P <sub>2</sub> O <sub>5</sub>				Free Acid (as P <sub>2</sub> O <sub>5</sub> )	Free Water	Fe <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>
		Total	Water-Soluble	NAC-Soluble <sup>b</sup>	Available				
(%)									
Central Florida (U.S.A.)								1.3	1.1
Fresh	50	23.6	11.2	3.1	14.3	0.6	1.8		
Aged	50	23.4	11.9	3.8	15.7	0.8	1.2		
El-Hassa (Jordan)								0.44	0.21
Fresh	30	26.1	7.9	3.1	11.0	1.5	4.2		
Aged	30	26.2	7.5	3.1	10.6	0.1	0.7		
Kodjari (Burkina Faso)								3.1	4.0
Fresh	50	18.0	6.5	3.0	9.5	NA <sup>c</sup>	NA		
Aged	50	18.3	3.3	5.4	8.7	<0.1	2.0		
Tilemsi Valley (Mali)								6.3	2.5
Fresh	30	22.7	6.6	4.8	11.4	2.1	3.8		
Aged	30	23.1	2.6	5.7	8.3	<0.1	2.2		
Tahoua (Niger)								10.3	2.1
Aged 1 day	50	22.6	6.5	2.9	9.4	1.1	1.3		
Aged 1 week	50	22.4	6.6	3.3	9.9	0.9	1.8		
Aged 1 month	50	22.8	5.9	3.7	9.6	0.3	1.9		
Aged 3 months	50	22.4	4.7	4.0	8.7	0.1	NA		
Aged 6 months	50	22.3	4.5	5.1	9.6	<0.1	1.6		

a. Unless otherwise noted, fresh samples were analyzed on day of production. Aged samples were analyzed 3 weeks to 12 months following production, depending upon sample.

b. Does not include water-soluble P<sub>2</sub>O<sub>5</sub> fraction.

c. Not analyzed.

## Product Physical Properties

The granular SAB-PAPR products produced in laboratory-scale equipment generally exhibit less strength than those prepared in the pilot plant (Table 5). The increased strength of the granules produced in the pilot plant (about 3 kg/granule in the pilot plant compared with about 1 kg/granule in the laboratory) is attributed to the greater compaction forces that are imparted to granules in the larger size equipment. As previously mentioned, the strength of the granules is also improved if the rock does not contain excessive amounts of carbonates. When the carbonate level is high (in excess of about 4% CO<sub>2</sub>), the granules are relatively porous and weak. This can be seen by comparing products made from low-carbonate (central Florida) and high-carbonate (Huila and Mussoorie) phosphate rocks. A crushing strength of at least 2 kg/granule is usually needed to avoid excessive degradation during handling and storage. Conventional granular products, such as SSP, TSP, and DAP, usually have crushing strengths of 2-5 kg/granule, depending upon the process and raw material compositions.

The amount of water used during granulation also tends to have an effect on granule strength. When water evaporates from a granule during the drying step, the structure of the granule may become quite porous and this may cause the granule to become relatively weak. However, in some cases the adverse effect of high porosity may be offset by strong salt bridging on the surface of the granule caused by the migration of a salt solution from the core of the granule to the surface during drying.

Unlike SSP and TSP, most of the granular SAB-PAPR

products tested were fairly compatible with urea (Table 5). This improved compatibility may make it possible to prepare (bulk blend) multinutrient (NPK) mixtures using urea—usually the most abundant and economic source of nitrogen fertilizer. The reason for the incompatibility of SAB-PAPR made from Sukula Hills (Uganda) phosphate rock is not fully understood, but it is presumed to be related to the relatively high level of free acid and moisture in the freshly made product. A “cured” sample (5 months old) of the same product having a low level of free acid and free water showed good compatibility with urea. Also, two mixtures of urea and cured SAB-PAPR prepared from Utah phosphate rock showed differences in compatibility. One sample, containing 1.3% free water, remained in good condition while the other sample, containing 2.6% free water, became wet and sticky after 6 days of storage at 30°C. The free acid (P<sub>2</sub>O<sub>5</sub> basis) in both samples was low (0.6% or less). Although these tests are preliminary and long-term storage data with mixtures of urea and SAB-PAPR are not available, it is likely that it will be feasible to mix SAB-PAPR with urea and avoid unwanted reactions that cause wetting and caking provided the SAB-PAPR contains very low levels of free water and free acid.

The 50% acidulated ROP products made from central Florida (U.S.A.) and Kodjari (Burkina Faso) rocks were quite granular. After it was reclaimed from the curing pile and crushed (milled) to remove the large lumps, about 50% of the material was between 4- and 14-mesh and the granules were relatively hard (Table 5). In some cases such a semi-granular product may be an acceptable alternative to the more costly granular product.

# Commercial-Scale Practices and Potential

The rate of commercial utilization of SAB-PAPR technology is increasing. However, largely because of market preferences and unattractive economics caused by the relatively small scale of operation required in many developing countries, this production technology is not expected to significantly replace the traditional, more soluble phosphate products. Some exceptions to this global prediction are described.

## Europe

Commercial-scale production of SAB-PAPR was begun in Finland in about 1930 and in Germany in the mid-1960s and now is established to a limited extent in those countries as well as in France—a total production of about 400,000 mtpy is estimated (20). The European firms prepare an ROP material that is subsequently granulated (after an appropriate period of curing) either alone or in combination with nitrogen and/or potassium salts. A steam/water granulation process is most commonly used, but a pressure-roll compaction/granulation process is also used. The choice of the granulation method used is more closely related to the cost of fuel and electricity than to the technical merits of either process. For example, if fuel (for drying with steam/water granulation) is relatively expensive compared with electricity (for pressure-roll compaction), compaction/granulation may be preferred.

## Latin America

Economic reasons are most often cited when explaining the recent rapid expansion of SAB-PAPR production in Brazil—nearly 200,000 mt was reportedly produced by about 20 companies in 1983 (21). The government's mandate to maximize the utilization of indigenous phosphate resources (primarily of igneous origin) coupled with the desire to decrease acid consumption (importation of sulfur) catalyzed this rapid growth which began in about 1982.

Most of the SAB-PAPR processing methods used in Brazil are similar to those used in Europe—an ROP material is usually produced by use of a typical continuous, belt-type den superphosphate process; one plant, however, uses a single-step acidulation/granulation process similar to the SSAG process developed by IFDC. After being cured (for a few days to several weeks), the ROP material is reclaimed

from storage and granulated using steam and water. The simplicity of using the existing SSP and TSP processing equipment for producing SAB-PAPR further explain Brazil's rapid adoption of this technology. The intermediate and long-term agronomic and economic impact of this shift away from the highly soluble phosphate fertilizer (SSP and TSP) must still be determined.

Extensive agronomic testing of SAB-PAPR product made from a number of indigenous and imported phosphate rock sources has been under way since about 1978 in Colombia. Favorable results (discussed later) may lead to the construction of SAB-PAPR production facilities in Colombia. Unlike Brazil, Colombia would most likely install new production units because they do not have a large existing superphosphate industry. This would make it possible to install the SAB-PAPR process that is best suited for the specific characteristics of the indigenous phosphate rock and the needs of the market. A preference for the granular SAB-PAPR product over the ROP variation is expected

## Africa and Asia

**West Africa**—The potential for the adoption of SAB-PAPR technology in the interior regions of West Africa is quite high. However, despite the availability of numerous indigenous phosphate deposits, the relatively modest demand for fertilizer and the small scale of operation consequently required are expected to increase the cost of locally produced phosphate fertilizers (including SAB-PAPR) to a level that is not economic.

**India**—The situation in India is similar in many ways to that in West Africa. Certain cost reductions may be achievable through economy of scale and improvements in the technology and the physical distribution system. However, it is expected that government mandates, similar to those instituted in Brazil, will be needed to catalyze the adoption of this technology.

**Israel**—Israel, a longtime producer and exporter of phosphate fertilizers, is reported to have begun commercial production of SAB-PAPR in 1984 (22). This product—along with its predecessors, granular phosphate rock and TSP—is expected to find its way into the export market, principally in Europe. This PAPR product is expected to replace a portion of the thermally altered phosphate fertilizers produced in Europe, which require large amounts of energy.

## Production Economics

The production economics, including capital investment requirements, were estimated for several phosphate processing schemes, including ground phosphate rock (GPR), SSP, and SAB-PAPR. A description of the processing schemes

and the production capacities used for comparing the economics of SAB-PAPR with conventional processing alternatives are shown in Table 9.

Table 9. Process Schemes and Capacities Used for Comparing Economics of SAB-PAPR Processing Alternatives

	Scheme I (Ground Phosphate Rock)	Scheme II (ROP SSP)	Scheme III (ROP SSP Followed by Granulation)	Scheme IV (ROP SAB-PAPR)	Scheme V (ROP SAB-PAPR Followed by Granulation)	Scheme VI (Single-Step Granular SAB-PAPR)	Scheme VII (Single-Step Granular SAB-PAPR Using Purchased Acid)
	(capacity, mtpd <sup>a</sup> )						
<b>Required Production Units</b>							
Phosphate rock grinding product (30% P <sub>2</sub> O <sub>5</sub> )	200	200	200	200	200	200	200
P <sub>2</sub> O <sub>5</sub>	60	60	60	60	60 <sub>b</sub>	60 <sub>b</sub>	60
Sulfuric acid (100% H <sub>2</sub> SO <sub>4</sub> )	-	112 <sup>b</sup>	112 <sup>b</sup>	56 <sup>b</sup>	56 <sup>b</sup>	56 <sup>b</sup>	<sup>c</sup>
SAB-PAPR (50% acidulation) product (22% total P <sub>2</sub> O <sub>5</sub> )	-	-	-	270	270	270	270
P <sub>2</sub> O <sub>5</sub>	-	-	-	60	60	60	60
SSP (100% acidulation) product (19% total P <sub>2</sub> O <sub>5</sub> )	-	315	315	-	-	-	-
P <sub>2</sub> O <sub>5</sub>	-	60	60	-	-	-	-

a. Indicated capacities assume 100% utilization and negligible losses.

b. Based on 0.56 mt 100% acid/mt rock for 100% sulfuric acid acidulation.

c. Purchased sulfuric acid must be equivalent to 56 mtpd of 100% acid. Actual acid concentration may be as low as 75% or as high as 98% H<sub>2</sub>SO<sub>4</sub>.

## Basic Premises and Assumptions

These estimates are intended to describe the relative differences in the fixed-capital investment and production costs for a number of phosphate fertilizer processing schemes and therefore make it possible to objectively assess the economic merits of the SAB-PAPR processing alternatives. Investment estimates are given for three basic SAB-PAPR processing schemes, including phosphate rock grinding, sulfuric acid production, storage, and related items. A scheme assuming purchased sulfuric acid is also included. In all cases a plant location in a developing country is assumed for estimating the required capital investment and production cost. The capacity of each production unit is based on a rock-grinding capacity of 200 mtpd of a rock containing 30% P<sub>2</sub>O<sub>5</sub> (60 mtpd P<sub>2</sub>O<sub>5</sub>). Other premises and assumptions used in preparing these estimates are shown in Appendix A.

The cost estimates in this bulletin are presented in such a way that they can be easily adjusted to fit local conditions. By using these cost estimates as a reference, it is possible to make relatively accurate site-specific investment and production cost estimates after considering such site-specific factors as (1) cost of process equipment; (2) local construction costs; (3) cost of raw materials; (4) cost of labor, supervision, fuel, and finance charges; and (5) expected capacity utilization.

## Investment and Production Cost Estimates

A summary of the capital investment and production cost estimates for the various processing schemes used to com-

pare the SAB-PAPR production alternatives is shown in Table 10. A detailed description of the estimates for each scheme is given in Tables 11-18. The estimated cost of the major SSP and SAB-PAPR equipment items and the total fixed-investment components for each processing scheme are shown in Appendix A.

**Investment Cost Estimates**—These estimates (Table 11) show that the SSAG process scheme using purchased sulfuric acid (Scheme VII) is the least costly of the SAB-PAPR processing alternatives involving granulation (about US \$15.6 million). The ROP SAB-PAPR process followed by granulation and the SSAG process (including production of sulfuric acid) require essentially the same total capital investment (about US \$18.9 million) while the ROP SAB-PAPR process (Scheme IV) requires the least investment (about US \$13.4 million compared with about US \$18.9 million for the granular SAB-PAPR variation). All the schemes include rock grinding, and the SSP and SAB-PAPR schemes (except Scheme VII) include the production of sulfuric acid. The ROP SSP and the granular SSP alternatives (Schemes II and III, including rock grinding) cost approximately US \$3.5 million more than the equivalent SAB-PAPR processing units. This increased investment is due primarily to the cost of a larger sulfuric acid unit. In all cases the cost for the battery limits process plant units for the three granular SAB-PAPR schemes is less than 25% of the total capital investment (15.5%, 18.9%, and 23.0% for Scheme V, VI, and VII, respectively).

**Production Cost Estimates**—Of the granular SAB-PAPR alternatives (Table 10), the SSAG process (Scheme VI, including the production of sulfuric acid) shows the lowest production cost (about US \$105/mt product or about US \$478/mt P<sub>2</sub>O<sub>5</sub>). The SSAG process, based on purchased sulfuric acid (Scheme VII), is indicated as the most costly

**Table 10. Summary of Investment and Production Cost Estimates Used For Comparing SAB-PAPR Processing Alternatives<sup>a</sup>**

	Scheme I (Ground Phosphate Rock)	Scheme II (ROP SSP)	Scheme III (ROP SSP Followed by Granulation)	Scheme IV (ROP SAB-PAPR)	Scheme V (ROP SAB-PAPR Followed by Granulation)	Scheme VI (Single-Step Granular SAB-PAPR)	Scheme VII (Single-Step Granular SAB-PAPR Using Purchased Acid)
Plant capacity, mtpd							
Product	200	315	315	270	270	270	270
P <sub>2</sub> O <sub>5</sub>	60	60	60	60	60	60	60
P <sub>2</sub> O <sub>5</sub> content of product, %	30	19	19	22	22	22	22
Capital investment	(US \$ x 1 million)						
Fixed investment	4.3	14.4	19.6	11.6	16.6	17.2	13.6
Working capital	0.7	2.4	2.9	1.8	2.3	1.7	2.0
<b>Total Capital Investment</b>	<b>5.0</b>	<b>16.8</b>	<b>22.5</b>	<b>13.4</b>	<b>18.9</b>	<b>18.9</b>	<b>15.6</b>
Production cost	(US \$/mt)						
Raw material	25.8	40.9	40.9	33.5	33.5	33.5	56.0
Variable conversion	15.8	18.2	27.6	17.8	26.9	24.1	24.7
Fixed conversion	18.7	35.8	47.6	34.3	47.7	47.6	38.1
<b>Total Production Cost</b>							
Product basis	60.3	94.9	116.1	85.6	108.1	105.2	118.8
P <sub>2</sub> O <sub>5</sub> basis	201.0	499.5	611.1	389.1	491.4	478.2	540.0

a. Values may vary slightly due to rounding when compared with detailed estimates.

**Table 11. Total Capital Investment Estimates Used for Comparing SAB-PAPR Processing Alternatives<sup>a</sup>**

	Scheme I (Ground Phosphate Rock)	Scheme II (ROP SSP)	Scheme III (ROP SSP Followed by Granulation)	Scheme IV (ROP SAB-PAPR)	Scheme V (ROP SAB-PAPR Followed by Granulation)	Scheme VI (Single-Step Granular SAB-PAPR)	Scheme VII (Single-Step Granular SAB-PAPR Using Purchased Acid)
Plant capacity, mtpd							
Product	200	315	315	270	270	270	270
P <sub>2</sub> O <sub>5</sub>	60	60	60	60	60	60	60
P <sub>2</sub> O <sub>5</sub> content of product, %	30	19	19	22	22	22	22
Direct plant cost	(US \$ x 1 million)						
Phosphate rock grinding unit <sup>b</sup>	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Sulfuric acid unit <sup>b</sup>	-	2.30	2.30	1.50	1.50	1.50	-
SSP or SAB-PAPR unit <sup>c</sup>	-	0.79	3.20	0.72	2.94	3.57	3.57
Raw material and product storage and handling facilities <sup>d</sup>	0.75	1.80	1.80	1.50	1.50	1.10	1.45
Utility facilities <sup>e</sup>	0.25	1.00	1.20	0.80	1.10	1.10	0.50
General service facilities <sup>e</sup>	0.25	0.60	0.70	0.50	0.60	0.60	0.50
<b>Total Direct Plant Cost</b>	<b>2.45</b>	<b>7.69</b>	<b>10.40</b>	<b>6.22</b>	<b>8.84</b>	<b>9.07</b>	<b>7.22</b>
Other costs							
Engineering and supervision	0.37	1.15	1.56	0.93	1.33	1.36	1.08
Construction overhead and expenses	0.25	0.77	1.04	0.62	0.88	0.91	0.72
Contractor's fee <sup>f</sup>	0.25	0.77	1.04	0.62	0.88	0.91	0.72
Subtotal	0.86	2.69	3.64	2.18	3.09	3.17	2.53
<b>Total Plant Cost</b>	<b>3.31</b>	<b>10.38</b>	<b>14.04</b>	<b>8.40</b>	<b>11.93</b>	<b>12.24</b>	<b>9.75</b>
Spare parts <sup>f</sup>	0.09	0.32	0.47	0.25	0.40	0.44	0.32
Preoperational and startup expenses <sup>f</sup>	0.13	0.48	0.71	0.38	0.61	0.66	0.47
Project management services <sup>f</sup>	0.17	0.52	0.70	0.42	0.60	0.61	0.49
Contingencies <sup>f</sup>	0.33	1.04	1.40	0.84	1.19	1.22	0.97
Interest during construction <sup>f</sup>	0.28	1.66	2.25	1.34	1.92	1.97	1.56
<b>Total Fixed Investment</b>	<b>4.30</b>	<b>14.39</b>	<b>19.58</b>	<b>11.63</b>	<b>16.65</b>	<b>17.16</b>	<b>13.56</b>
Working capital <sup>f</sup>	0.69	2.36	2.86	1.80	2.27	1.74	1.99
<b>Total Capital Investment</b>	<b>4.99</b>	<b>16.75</b>	<b>22.44</b>	<b>13.43</b>	<b>18.92</b>	<b>18.90</b>	<b>15.55</b>

a. Totals may vary slightly due to rounding.

b. Based on vendor estimates and IFDC cost files.

c. Refer to Appendix Tables A-1 and A-2.

d. Refer to Appendix A for capacity and unit cost.

e. Based on engineering and construction estimates for similar projects.

f. Refer to Appendix A for cost estimating factors.

Table 12. Production Cost Estimate—Scheme I, Ground Phosphate Rock

Basis: 1. Total plant cost—US \$3.31 million  
 2. Total fixed investment—US \$4.30 million  
 3. Working capital—US \$0.69 million  
 4. Total capital investment—US \$4.99 million  
 5. Annual production—66,000 mt of 30% P<sub>2</sub>O<sub>5</sub> ground rock

Item	Basis	Cost US \$/mt
Raw material cost		
Unground rock (30% P <sub>2</sub> O <sub>5</sub> )	1.03 mt @ US \$25/mt	25.8
Variable-conversion cost		
Electricity	25 kWh @ US \$0.1/kWh	2.5
Diesel oil (mobile equipment)	0.092 mt @ US \$400/mt	0.8
Miscellaneous supplies	-	0.5
Bags	20 bags @ US \$0.6 each	12.0
Subtotal		15.8
Fixed-conversion cost		
Operating personnel	Appendix Table A-3	1.8
Administration and general overhead	100% personnel cost	1.8
Maintenance materials and labor	5% of US \$3.31 million/year	2.5
Insurance and taxes	1% of US \$3.31 million/year	0.5
Fixed-capital recovery	16.3% of US \$4.30 million/year	10.6
Interest on working capital	14% of US \$0.69 million/year	1.5
Subtotal		18.7
TOTAL PRODUCTION COST <sup>a</sup>		
Product basis		60.5
P <sub>2</sub> O <sub>5</sub> basis		201.0

a. At 100% capacity utilization and including bagging.

Table 13. Production Cost Estimate—Scheme II, Run-of-Pile Single Superphosphate

Basis: 1. Total plant cost—US \$10.38 million  
 2. Total fixed investment—US \$14.39 million  
 3. Working capital—US \$2.36 million  
 4. Total capital investment—US \$16.75 million  
 5. Annual production—103,950 mt of 19% P<sub>2</sub>O<sub>5</sub> product

Item	Basis	Cost US \$/mt
Raw material cost		
Unground rock (30% P <sub>2</sub> O <sub>5</sub> )	0.66 mt @ US \$25/mt	16.5
Sulfur	0.122 mt @ US \$200/mt	24.4
Subtotal		40.9
Variable-conversion cost		
Electricity	23 kWh @ US \$0.1/kWh	2.3
Water	1.4 m <sup>3</sup> @ US \$0.5/m <sup>3</sup>	0.7
Diesel oil (mobile equipment)	0.003 mt @ US \$400/mt	1.2
Catalyst, chemicals and miscellaneous supplies	-	2.0
Bags	20 bags @ US \$0.6 each	12.0
Subtotal		18.2
Fixed-conversion cost		
Operating personnel	Appendix Table A-3	2.0
Administration and general overhead	100% personnel cost	2.0
Maintenance materials and labor	5% of US \$10.39 million/year	5.0
Insurance and taxes	1% of US \$10.38 million/year	1.0
Fixed-capital recovery	16.3% of US \$14.39 million/year	22.6
Interest on working capital	14% of US \$2.36 million/year	3.2
Subtotal		35.8
TOTAL PRODUCTION COST <sup>a</sup>		
Product basis		94.9
P <sub>2</sub> O <sub>5</sub> basis		499.5

a. At 100% capacity utilization and including bagging.

**Table 14. Production Cost Estimate—Scheme III, Run-of-Pile Single Superphosphate Followed by Granulation**

Item	Basis	Cost US \$/mt
<b>Basis:</b> 1. Total plant cost—US \$14.04 million		
2. Total fixed investment—US \$19.58 million		
3. Working capital—US \$2.86 million		
4. Total capital investment—US \$22.44 million		
5. Annual production—103,950 mt of 19% P <sub>2</sub> O <sub>5</sub> product		
Raw material cost		
Unground rock (30% P <sub>2</sub> O <sub>5</sub> )	0.66 mt @ US \$25/mt	16.5
Sulfur	0.122 mt @ US \$200/mt	24.4
Subtotal		40.9
Variable-conversion cost		
Electricity	90 kWh @ US \$0.1/kWh	9.0
Water	1.6 m <sup>3</sup> @ US \$0.5/m <sup>3</sup>	0.8
Fuel oil	0.006 mt @ US \$350/mt	2.1
Diesel oil (mobile equipment)	0.003 mt @ US \$400/mt	1.2
Catalyst, chemicals and miscellaneous supplies	-	2.5
Bags	20 bags @ US \$0.6 each	12.0
Subtotal		27.6
Fixed-conversion cost		
Operating personnel	Appendix Table A-3	2.5
Administration and general overhead	100% personnel cost	2.5
Maintenance materials and labor	5% of US \$14.04 million/year	6.8
Insurance and taxes	1% of US \$14.04 million/year	1.3
Fixed-capital recovery	16.3% of US \$19.58 million/year	30.7
Interest on working capital	14% of US \$2.86 million/year	3.8
Subtotal		47.6
<b>TOTAL PRODUCTION COST<sup>a</sup></b>		
Product basis		116.1
P <sub>2</sub> O <sub>5</sub> basis		611.1

a. At 100% capacity utilization and including bagging.

**Table 15. Production Cost Estimate—Scheme IV, Run-of-Pile SAB-PAPR**

Item	Basis	Cost US \$/mt
<b>Basis:</b> 1. Total plant cost—US \$8.40 million		
2. Total fixed investment—US \$11.63 million		
3. Working capital—US \$1.80 million		
4. Total capital investment—US \$13.43 million		
5. Annual production—89,100 mt of 22% P <sub>2</sub> O <sub>5</sub> product		
Raw material cost		
Unground rock (30% P <sub>2</sub> O <sub>5</sub> )	0.77 mt @ US \$25/mt	19.3
Sulfur	0.071 mt @ US \$200/mt	14.2
Subtotal		33.5
Variable-conversion cost		
Electricity	27 kWh @ US \$0.1/kWh	2.7
Water	0.8 m <sup>3</sup> @ US \$0.5/m <sup>3</sup>	0.4
Diesel oil (mobile equipment)	0.002 mt @ US \$400/mt	1.2
Catalyst, chemicals and miscellaneous supplies	-	1.5
Bags	20 bags @ US \$0.6 each	12.0
Subtotal		17.8
Fixed-conversion cost		
Operating personnel	Appendix Table A-3	2.3
Administration and general overhead	100% personnel cost	2.3
Maintenance materials and labor	5% of US \$8.40 million/year	4.7
Insurance and taxes	1% of US \$8.40 million/year	0.9
Fixed-capital recovery	16.3% of US \$11.63 million/year	21.3
Interest on working capital	14% of US \$1.80 million/year	2.8
Subtotal		34.3
<b>TOTAL PRODUCTION COST<sup>a</sup></b>		
Product basis		85.6
P <sub>2</sub> O <sub>5</sub> basis		389.1

a. At 100% capacity utilization and including bagging.

Table 16. Production Cost Estimate—Scheme V, Run-of-Pile SAB-PAPR Followed by Granulation

Item	Basis	Cost US \$/mt
<b>Basis:</b> 1. Total plant cost—US \$11.93 million		
2. Total fixed investment—US \$16.65 million		
3. Working capital—US \$2.27 million		
4. Total capital investment—US \$18.92 million		
5. Annual production—89,100 mt of 22% P <sub>2</sub> O <sub>5</sub> product		
<b>Raw material cost</b>		
Unground rock (30% P <sub>2</sub> O <sub>5</sub> )	0.77 mt @ US \$25/mt	19.3
Sulfur	0.071 mt @ US \$200/mt	14.2
<b>Subtotal</b>		<b>33.5</b>
<b>Variable-conversion cost</b>		
Electricity	80 kWh @ US \$0.1/kWh	8.0
Water	1.0 m <sup>3</sup> @ US \$0.5/m <sup>3</sup>	0.5
Fuel oil	0.009 mt @ US \$350/mt	3.2
Diesel oil (mobile equipment)	0.003 mt @ US \$400/mt	1.2
Catalyst, chemicals and miscellaneous supplies	-	2.0
Bags	20 bags @ US \$0.6 each	12.0
<b>Subtotal</b>		<b>26.9</b>
<b>Fixed-conversion cost</b>		
Operating personnel	Appendix Table A-3	2.8
Administration and general overhead	100% personnel cost	2.8
Maintenance materials and labor	5% of US \$11.93 million/year	6.7
Insurance and taxes	1% of US \$11.93 million/year	1.3
Fixed-capital recovery	16.3% of US \$16.65 million/year	30.5
Interest on working capital	14% of US \$2.27 million/year	3.6
<b>Subtotal</b>		<b>47.7</b>
<b>TOTAL PRODUCTION COST<sup>a</sup></b>		
Product basis		108.1
P <sub>2</sub> O <sub>5</sub> basis		491.4

a. At 100% capacity utilization and including bagging.

Table 17. Production Cost Estimate—Scheme VI, Single-Step Granular SAB-PAPR

Item	Basis	Cost US \$/mt
<b>Basis:</b> 1. Total plant cost—US \$12.24 million		
2. Total fixed investment—US \$17.16 million		
3. Working capital—US \$1.74 million		
4. Total capital investment—US \$18.90 million		
5. Annual production—89,100 mt of 22% P <sub>2</sub> O <sub>5</sub> product		
<b>Raw material cost</b>		
Unground rock (30% P <sub>2</sub> O <sub>5</sub> )	0.77 mt @ US \$25/mt	19.3
Sulfur	0.071 mt @ US \$200/mt	14.2
<b>Subtotal</b>		<b>33.5</b>
<b>Variable-conversion cost</b>		
Electricity	70.6 kWh @ US \$0.1/kWh	7.0
Water	1.0 m <sup>3</sup> @ US \$0.5/m <sup>3</sup>	0.5
Fuel oil	0.005 mt @ US \$350/mt	1.8
Diesel oil (mobile equipment)	0.002 mt @ US \$400/mt	0.8
Catalyst, chemicals and miscellaneous supplies	-	2.0
Bags	20 bags @ US \$0.6 each	12.0
<b>Subtotal</b>		<b>24.1</b>
<b>Fixed-conversion cost</b>		
Operating personnel	Appendix Table A-3	2.6
Administration and general overhead	100% personnel cost	2.6
Maintenance materials and labor	5% of US \$12.24 million/year	6.9
Insurance and taxes	1% of US \$12.24 million/year	1.4
Fixed-capital recovery	16.3% of US \$17.16 million/year	31.4
Interest on working capital	14% of US \$1.74 million/year	2.7
<b>Subtotal</b>		<b>47.6</b>
<b>TOTAL PRODUCTION COST<sup>a</sup></b>		
Product basis		105.2
P <sub>2</sub> O <sub>5</sub> basis		478.2

a. At 100% capacity utilization and including bagging.

**Table 18. Production Cost Estimate—Scheme VII, Single-Step Granular SAB-PAPR Using Purchased Sulfuric Acid**

- Basis:** 1. Total plant cost—US \$9.75 million  
 2. Total fixed investment—US \$13.56 million  
 3. Working capital—US \$1.99 million  
 4. Total capital investment—US \$15.55 million  
 5. Annual production—89,100 mt of 22% P<sub>2</sub>O<sub>5</sub> product

Item	Basis	Cost US \$/mt
Raw material cost		
Unground rock (30% P <sub>2</sub> O <sub>5</sub> )	0.77 mt @ US \$25/mt	19.3
Sulfuric acid (100% basis)	0.216 mt @ US \$170/mt	36.7
Subtotal		56.0
Variable-conversion cost		
Electricity	60 kWh @ US \$0.1/kWh	6.0
Water	0.5 m <sup>3</sup> @ US \$0.5/m <sup>3</sup>	0.3
Fuel oil	0.013 mt @ US \$350/mt	4.6
Diesel oil (mobile equipment)	0.002 mt @ US \$400/mt	0.8
Catalyst, chemicals and miscellaneous supplies	-	1.0
Bags	20 bags @ US \$0.6 each	12.0
Subtotal		24.7
Fixed-conversion cost		
Operating personnel	Appendix Table A-3	1.8
Administration and general overhead	100% personnel cost	1.8
Maintenance materials and labor	5% of US \$9.75 million/year	5.5
Insurance and taxes	1% of US \$9.75 million/year	1.1
Fixed-capital recovery	16.3% of US \$13.56 million/year	24.8
Interest on working capital	14% of US \$1.99 million/year	3.1
Subtotal		38.1
<b>TOTAL PRODUCTION COST<sup>a</sup></b>		
Product basis		118.8
P <sub>2</sub> O <sub>5</sub> basis		540.0

a. At 100% capacity utilization and including bagging.

(about US \$119/mt product or about US \$540/mt P<sub>2</sub>O<sub>5</sub>). The least expensive SAB-PAPR alternative is the ROP SAB-PAPR process (Scheme IV)—about US \$86/mt product or about US \$389/mt P<sub>2</sub>O<sub>5</sub>. For comparison, the ROP and granular SSP alternatives were evaluated. A production cost of about US \$500/mt P<sub>2</sub>O<sub>5</sub> for ROP SSP and about US \$611/mt P<sub>2</sub>O<sub>5</sub> for granular SSP is indicated. The major reason for the increased cost of SSP compared with SAB-PAPR is the cost of additional sulfuric acid (sulfur). Also, when expressed in terms of total P<sub>2</sub>O<sub>5</sub>, the PAPR product has the added benefit of a higher P<sub>2</sub>O<sub>5</sub> content (22% P<sub>2</sub>O<sub>5</sub> compared with 19% for SSP).

### Factors Affecting SAB-PAPR Production Costs

The cost of producing SAB-PAPR, as with most other fertilizers, is influenced by several factors. A discussion of the most important factors identified as a result of these technical/economic studies follows.

**Effect of Fixed-Capital Investment**—Except for the cost of raw materials, the largest single production cost component for the SAB-PAPR processing schemes described in this bulletin is fixed-capital recovery (21%-30% of total production cost). This component is heavily influenced by the plant investment and the cost of money (interest or expected return on equity). The effect of fixed-capital investment on production cost (at 100% capacity utilization), including bagging, for the SSAG process (Scheme VI) compared with granular SSP (Scheme III) is shown in Figure 8. The production of sulfuric acid is included in both schemes. This figure can also be used to estimate the impact of plant location on production cost (location factor) by comparing the base-case fixed investment used in this bulletin with the actual investment expected in the specific location.

**Effect of Capacity Utilization**—The previously mentioned production costs were based on 100% capacity utilization. The effect of decreasing capacity utilization of the SSAG unit (Scheme VI) and the granular SSP unit (Scheme III) below the 100% level on the expected production cost

Basis: 100% Capacity Utilization is Equivalent to 270 mtpd 50% acidulated SAB-PAPR and 315 mtpd SSP. Costs of Producing Sulfuric Acid and Bagging Are Included. Fixed-Capital Investment—US \$17.2 Million SAB-PAPR (Scheme VI); US \$19.6 Million Granular SSP (Scheme III).

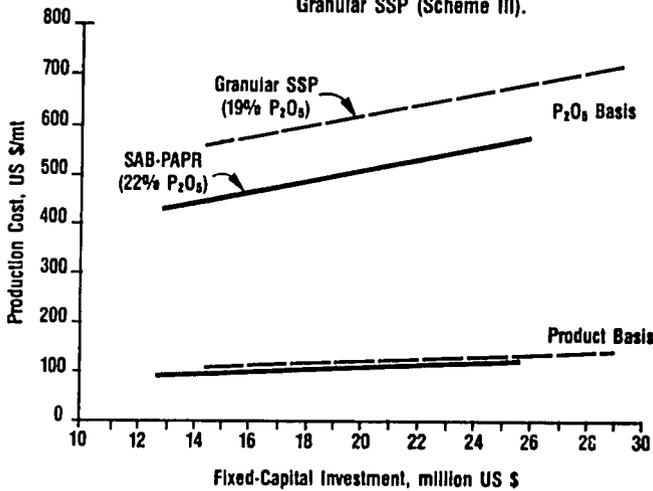


Figure 8. Effect of Fixed-Capital Investment on Production Cost—Single-Step Granular SAB-PAPR Process (Scheme VI) Compared With Granular SSP (Scheme III).

Basis: 100% Capacity Utilization is Equivalent to 270 mtpd 50% Acidulated SAB-PAPR and 315 mtpd SSP. Costs of Producing Sulfuric Acid and Bagging Are Included.

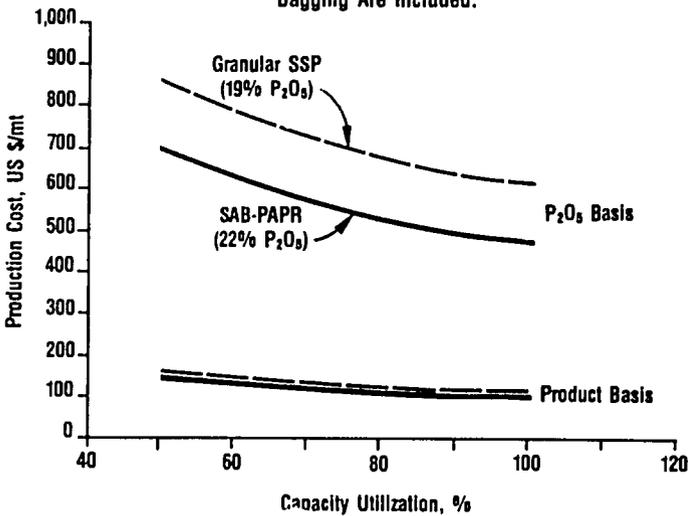


Figure 9. Effect of Capacity Utilization on Production Cost—Single-Step Granular SAB-PAPR Process (Scheme VI) Compared With Granular SSP (Scheme III).

including the production of sulfuric acid and bagging) is shown in Figure 9. A similar adverse effect on the production cost would also occur with the other processing schemes.

**Effect of Degree of Acidulation**—For the example illustrated in Figure 10 (Scheme VI, including production of sulfuric acid), the cost of production will increase if the acidulation level is increased above the base-case level of

Basis: A 50% Degree of Acidulation Corresponds to 270 mtpd of 22% Total P<sub>2</sub>O<sub>5</sub> Product and 0.071 mt Sulfur/mt Product. Sulfur is priced at US \$200/mt. Costs of Producing Sulfuric Acid and Bagging Are Included.

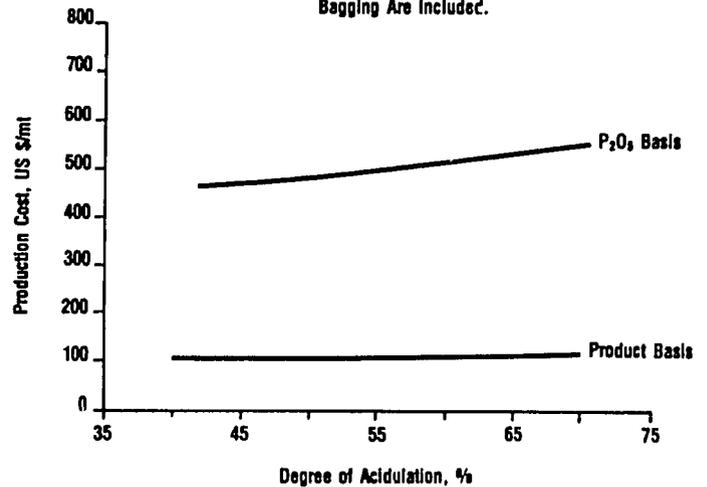


Figure 10. Effect of Degree of Acidulation on Production Cost—Single-Step Granular SAB-PAPR Process (Scheme VI).

50%. This occurs not only because more sulfuric acid is required per metric ton of product but also because the overall production rate must be decreased below the base-case production rate of 270 mtpd of 50% acidulated product (less rock will be used) since the capacity of the sulfuric acid plant cannot be significantly increased. When the acidulation level is decreased below the base-case value of 50%, the rock-grinding capacity becomes a limiting factor and the production of sulfuric acid and finished product must also be decreased accordingly. The result of this is a slight decrease in production cost (compared with the base-case level of 50% acidulation) because the sulfuric acid saving more than offsets the other cost increases due to the slightly decreased capacity utilization. For example, at a 30% level of acidulation, about 250 mtpd of product would be produced compared with 270 mtpd at the 50% (base-case) level of acidulation. Also, since the total P<sub>2</sub>O<sub>5</sub> content of the SAB-PAPR product declines as the degree of acidulation is increased, the cost of production, when expressed in terms of total P<sub>2</sub>O<sub>5</sub>, also increases with the degree of acidulation.

**Effect of Raw Material Cost**—The impact of the cost of sulfur and unground phosphate rock on the cost of production of SAB-PAPR compared with granular SSP is shown in Figures 11 and 12, respectively. The effect of using purchased sulfuric acid is shown in Figure 13. These data show that the production cost of a SAB-PAPR processing alternative based on the use of purchased sulfuric acid (Scheme VII, for example) will be affected the most by changes in the cost of sulfur or sulfuric acid. Although the cost of unground phosphate rock is significant with respect to production cost, its impact is less pronounced.

Basis: 50% Acidulated SAB-PAPR.  
 0.071 mt Sulfur/mt SAB-PAPR; 0.122 mt Sulfur/mt SSP.  
 Costs of Producing Sulfuric Acid and Bagging Are Included.

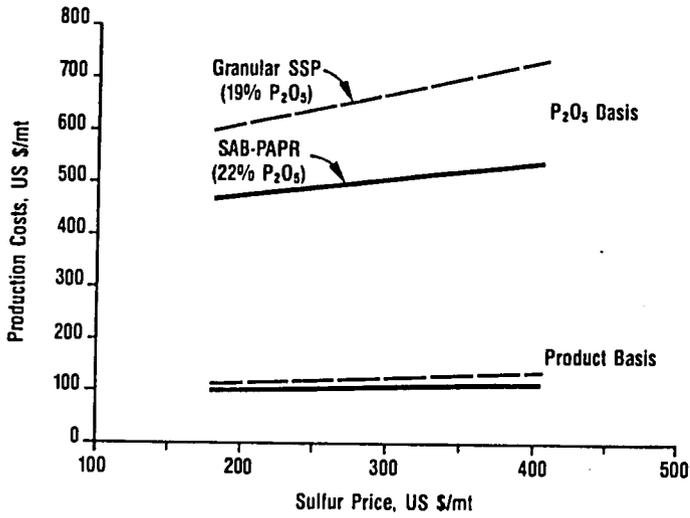


Figure 11. Effect of Cost of Sulfur on Production Cost—Single-Step Granular SAB-PAPR Process (Scheme VI) Compared With Granular SSP (Scheme III).

Basis: 50% Acidulated SAB-PAPR Using 0.216 mt Acid/mt Product.  
 Production Cost Includes Bagging.

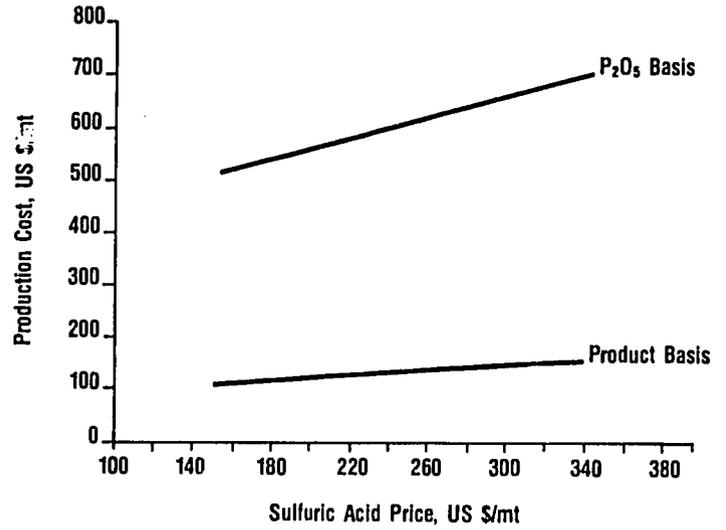


Figure 13. Effect of Cost of Sulfuric Acid on Production Cost—Single-Step Granular SAB-PAPR Process Using Purchased Sulfuric Acid (Scheme VII).

Basis: 50% Acidulated SAB-PAPR.  
 0.77 mt Phosphate Rock/mt SAB-PAPR.  
 0.66 mt Phosphate Rock/mt SSP.  
 Costs of Producing Sulfuric Acid and Bagging Are Included.

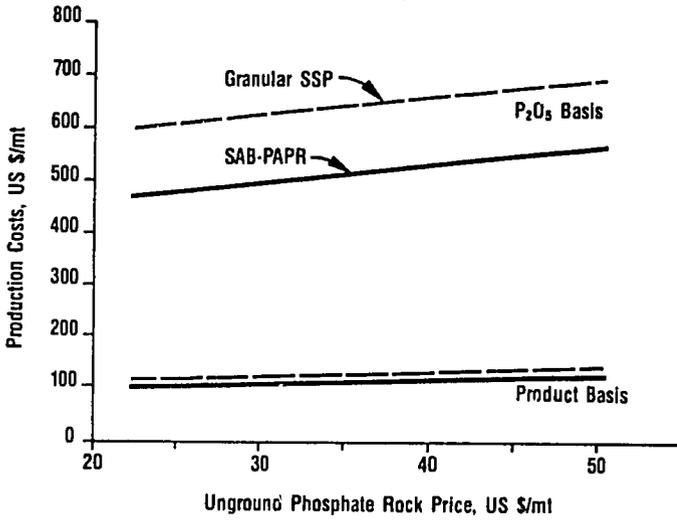


Figure 12. Effect of Cost of Unground Phosphate Rock on Production Cost—Single-Step Granular SAB-PAPR Process (Scheme VI) Compared With Granular SSP (Scheme III).

## Agronomic Performance

Phosphorus is absorbed by plants as  $\text{H}_2\text{PO}_4^{1-}$  and  $\text{HPO}_4^{2-}$  ions present in the soil solution. Without the use of phosphorus-containing fertilizers, replenishment of the soil solution with the phosphorus-containing ions depends upon the release of phosphorus from compounds native to the soil such as apatite, iron or aluminum phosphates, or phosphates combined with the clay and organic fractions of the soil. The degree to which the concentration of  $\text{H}_2\text{PO}_4^{1-}$  and/or  $\text{HPO}_4^{2-}$  is altered in the soil solution depends upon the solubility of the phosphate and the pH of the soil.

Conventional types of phosphate fertilizers are generally classified into the following three groups with respect to solubility:

- Group 1. Those in which the phosphorus is mostly soluble in water (for example, SSP, TSP, DAP, and monoammonium phosphate [MAP]).
- Group 2. Those containing phosphorus that is moderately soluble in water but highly soluble in an NAC solution (for example, ammoniated superphosphates and some nitrophosphate-type fertilizers).
- Group 3. Those in which the phosphorus is not readily soluble in water but quite soluble in an NAC solution (for example, dicalcium phosphate, thermally altered phosphates, and basic slag).

Unacidulated phosphate rock falls into a fourth category in which the phosphorus is not soluble in water and only sparingly soluble in an NAC solution.

The solubility of a fertilizer directly influences the quantity of plant-available phosphorus that will be released from the fertilizer at any given time after its application. The phosphorus in the fertilizers belonging to Group 1 can be expected to enter into the soil solution almost immediately following application. For those fertilizers in Group 2, 30%-50% of the phosphorus usually will immediately enter into the soil solution, and the remainder will enter over a period of several weeks to several months. In the case of the fertilizers in Group 3, only a small portion of the phosphorus will enter into the soil solution immediately, but nearly all of it will become available through the course of the growing season of the crop.

Since phosphate rocks contain virtually no water-soluble phosphorus and variable amounts of NAC-soluble phosphorus, depending upon the origin and composition of the predominant phosphorus-containing mineral, they dissolve in acid environments at a rate related to their NAC solubility (reactivity). Therefore, untreated phosphate rocks provide phosphorus to the soil solution in a slow but continuous manner with the rate of release determined by the rock's reactivity (solubility) and the characteristics of the soil. The phosphorus extracted from phosphate rock by an NAC solution is not a finite meas-

ure of the quantity of available phosphorus in the rock (the case with most conventional chemically processed phosphate fertilizers). Instead, repeated NAC extractions of a phosphate rock sample will cause the incremental release of a portion of the phosphorus in the rock. This release of phosphorus can be used to index the expected rate of rock (phosphorus) dissolution.

Partially acidulated phosphate rock products such as SAB-PAPR combine some of the solubility characteristics of all the phosphate fertilizers described above. Since SAB-PAPR is the product of the acidulation of phosphate rock with less sulfuric acid than is required for the production of a fully acidulated material (SSP), it contains variable quantities of water-soluble, NAC-soluble, and NAC-insoluble phosphorus, depending upon the reactivity of the phosphate rock, the quantity of acid used, the impurities in the rock, and the process conditions. The water-soluble portion, therefore, provides an immediate source of phosphorus for entry into the soil solution, and the unacidulated portion of the SAB-PAPR behaves in a manner similar to that of the phosphate rock from which it was produced.

When MCP (the principal water-soluble phosphate component in SSP, TSP, and SAB-PAPR) hydrolyzes in the soil, the soil near the fertilizer becomes quite acid (pH usually less than 2). This high acidity is transitory but can cause rapid dissolution of the otherwise insoluble and unreactive iron and aluminum compounds in the soil. If this occurs, these solubilized compounds may react with soluble phosphorus and render it unavailable to the crop. The usually good performance of SAB-PAPR (compared with conventional sources of phosphate such as SSP and TSP) in such soils is attributed in part to the neutralizing effect of the unacidulated phosphate rock contained in SAB-PAPR. The net result is that the localized acidity caused by the hydrolysis of MCP is quickly neutralized, the dissolution of iron and aluminum is slowed, and more phosphorus is apt to remain in the soil solution for immediate use by the crop. Furthermore, the unreacted phosphate rock in the SAB-PAPR also offers a residual source of phosphorus as it gradually dissolves in the soil. The conditions under which the SAB-PAPR would be expected to be the most effective are summarized:

1. SAB-PAPR would be expected to provide the maximum amount of plant-available phosphorus when applied to acid soils. In all soils the water- and NAC-soluble  $\text{P}_2\text{O}_5$  portions would be immediately available to promote rapid development of the crop, but only in acid soils would the unacidulated portion of the rock be expected to contribute plant-available phosphorus in any significant quantity.
2. Although SAB-PAPR would be expected to show high effectiveness when applied to acid soils with low phosphorus-fixation capacities, its efficiency relative to more soluble phosphate fertilizers would be maximized

in acid soils with high phosphorus-fixation capacities (for example, soils high in iron and aluminum oxides and hydroxides).

- The increase in agronomic effectiveness of a SAB-PAPR product above that of an unacidulated phosphate rock will often be most pronounced when the reactivity of the phosphate rock is low. This is because highly reactive phosphate rocks applied to acid soils may already be very effective. In those cases, the minimal increase in effectiveness due to the additional soluble phosphorus may not justify the additional expense of partial acidulation. This is illustrated in Table 19 which shows the high effectiveness of a very reactive unacidulated phosphate rock (Sechura deposit in Peru) when compared with TSP in a greenhouse experiment using several Colombian soils. This table also illustrates the improvement of a less reactive rock (Pesca deposit in Colombia) when it was converted to SAB-PAPR and applied to soils exhibiting relatively high pH values and phosphorus-fixation capacities.

Table 19. Influence of Soil Characteristics on Agronomic Effectiveness of Phosphate Rock and SAB-PAPR

Soil	Soil Characteristics			Relative Agronomic Effectiveness <sup>c</sup>		
	pH	Available Native P <sup>a</sup> (ppm)	P Fixation <sup>b</sup> (%)	Phosphate Rock		Pesca
				Sechura	Pesca	SAB-PAPR
<b>Ultisols</b>						
Amazonas	4.55	3.22	20.2	106	87	88
Quilichao	4.30	1.08	40.1	102	88	80
Caucasia	4.85	1.49	30.4	93	37	65
<b>Oxisols</b>						
Gaviotas	4.25	1.83	33.5	115	74	75
Carimagua	4.65	2.43	32.3	108	91	85
La Libertad	4.60	2.35	33.9	107	70	80
<b>Andepts</b>						
Unidad 10	5.50	3.95	41.2	59	0	59
El Refugio	5.30	0.42	72.1	88	16	77

a. Bray I test method.

b. Method as described by Fassbender and Igue (23).

c. Based on dry-matter production of grass (*Brachiaria decumbens*) relative to TSP.

Source: IFDC/CIAT collaborative research (1).

Another factor that usually enhances the agronomic performance of the SAB-PAPR product is the relationship between phosphorus and sulfur. In most SAB-PAPR products this relationship closely matches the crop's nutritional demand for both of these elements. Sulfur deficiencies are becoming apparent in phosphorus-deficient tropical regions because of the widespread use of essentially sulfur-free phosphate fertilizers such as TSP and DAP. The SAB-PAPR product is usually an adequate source of sulfur because the quantity of sulfur required

to overcome the deficiency is generally far less than the amount of sulfur provided by a fully acidulated product (SSP) if the SSP is applied at the level required to meet the phosphorus requirement. The beneficial effect of the sulfur component of SAB-PAPR was observed in a number of locations. One such example is illustrated in Figure 14. In this experiment, performed at Ikare, Nigeria, the superior performance of SAB-PAPR and SSP compared with DAP and NPK (15-15-15) was attributed to the addition of nutrient sulfur as well as phosphorus.

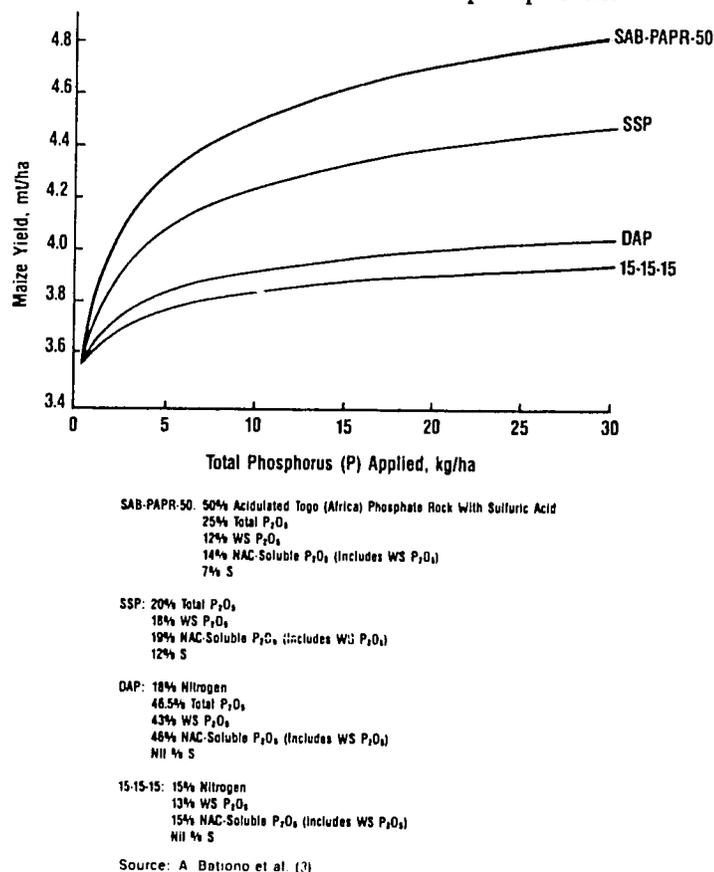
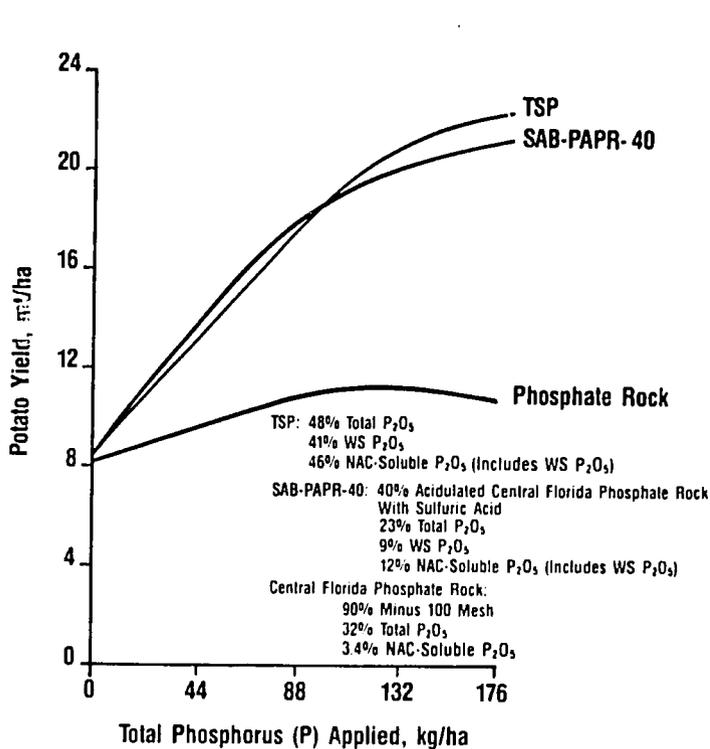


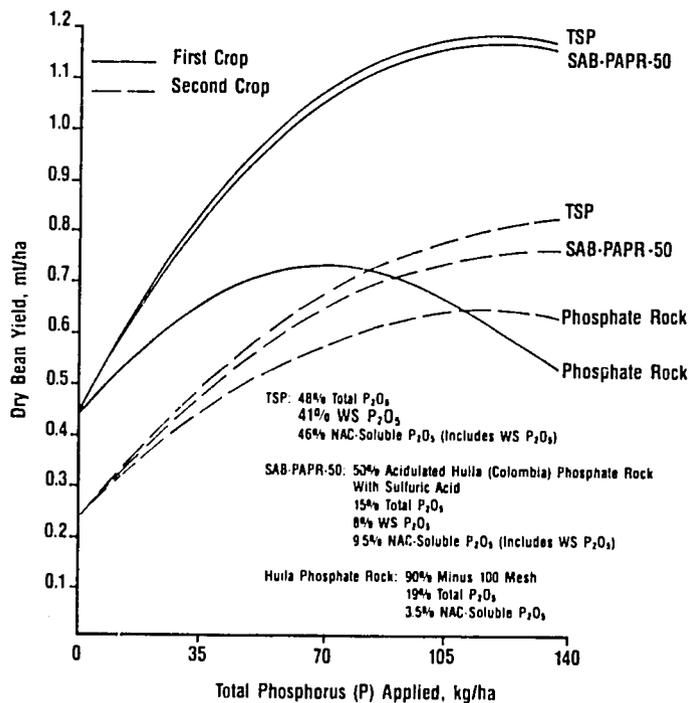
Figure 14. Effect of Phosphorus and Sulfur on Yield of Maize—Subhumid Africa.

Extensive field investigations into the agronomic effectiveness of SAB-PAPR have been performed during the past 10 years under a wide range of tropical conditions in Latin America, Africa, and Asia. These experiments have been conducted both in research experiment stations and under the constraints encountered at the farm level. Typical crop responses to SAB-PAPR on phosphorus-deficient acid soils are illustrated in Figures 15-20. It can be seen from these data that SAB-PAPR, especially when acidulated to a level of about 50%, was found to be usually as effective as TSP or SSP over a wide range of soil and cropping combinations. Likewise, it can be observed that this high degree of effectiveness was obtained even during the first cropping period following application of SAB-PAPR fertilizer. In contrast, during this first cropping period, the rocks from which the SAB-PAPR products were produced—unacidulated rocks of low to medium reactivity—contributed little phosphorus to the soil solution.



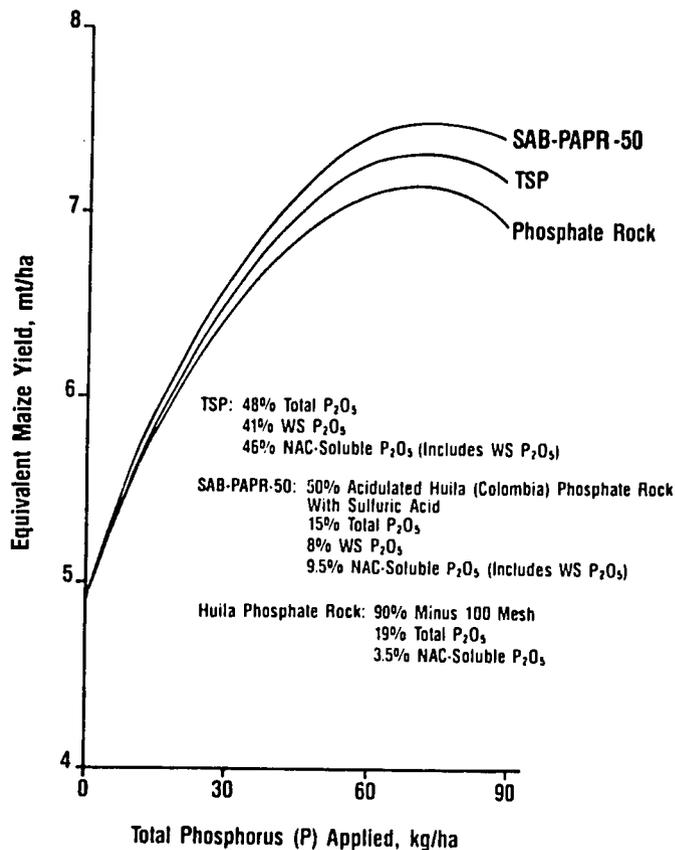
Source: IFDC/INIAP collaborative research (1).

Figure 15. Effect of Phosphorus Source on Yield of Potatoes—Ecuador.



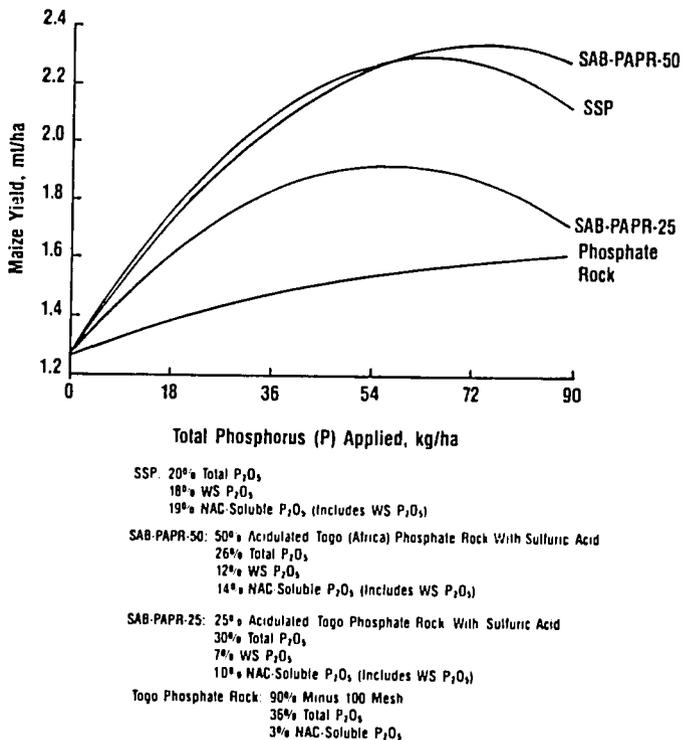
Source: L. A. Leon (2).

Figure 16. Effect of Phosphorus Source on Yield of Two Crops of Beans—Colombia.



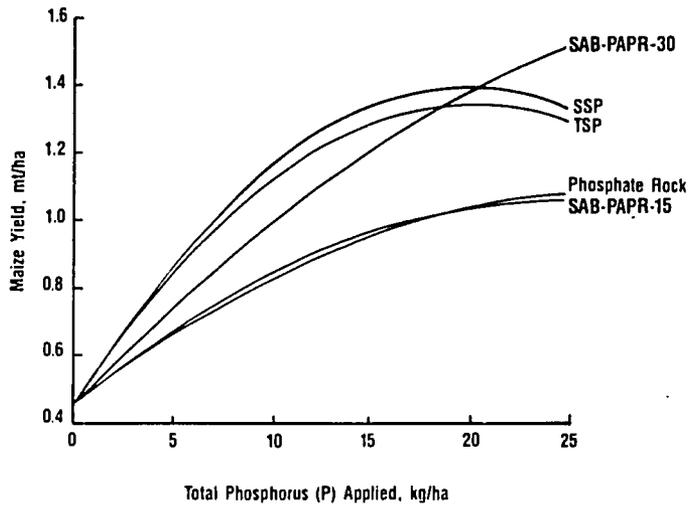
Source: L. A. Leon (2).

Figure 17. Effect of Phosphorus Source on Yield of Intercropped Maize and Beans—Colombia.



Source: A. Batlono et al. (3).

Figure 18. Effect of Phosphorus Source on Yield of Maize—Humid Africa.



TSP: 48% Total  $P_2O_5$   
41% WS  $P_2O_5$   
46% NAC-Soluble  $P_2O_5$  (Includes WS  $P_2O_5$ )

SSP: 20% Total  $P_2O_5$   
18% WS  $P_2O_5$   
19% NAC-Soluble  $P_2O_5$  (Includes WS  $P_2O_5$ )

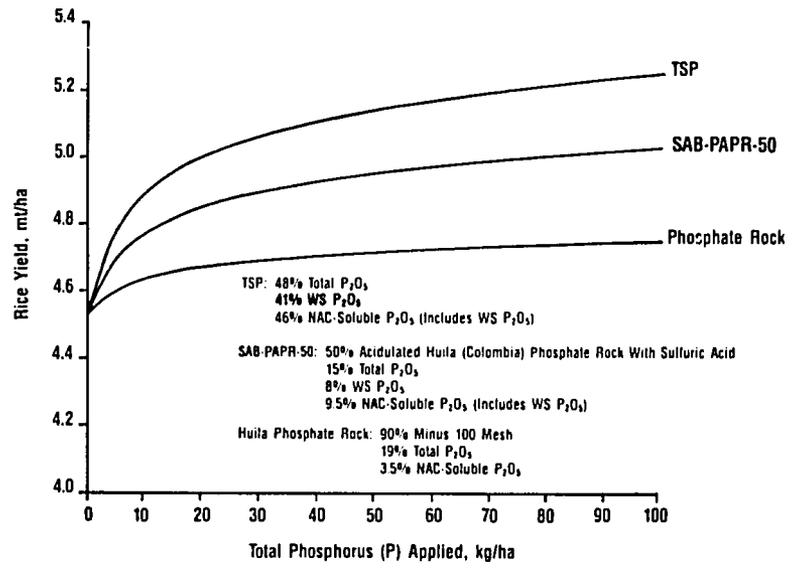
SAB-PAPR-30: 30% Acidulated Tilemsi Valley (Mali) Phosphate Rock With Sulfuric Acid  
23% Total  $P_2O_5$   
6% WS  $P_2O_5$   
11% NAC-Soluble  $P_2O_5$  (Includes WS  $P_2O_5$ )

SAB-PAPR-15: 15% Acidulated Tilemsi Valley Phosphate Rock With Sulfuric Acid  
25% Total  $P_2O_5$   
2.5% WS  $P_2O_5$   
7.5% NAC-Soluble  $P_2O_5$  (Includes WS  $P_2O_5$ )

Tilemsi Valley Phosphate Rock: 90% Minus 200 Mesh  
26% Total  $P_2O_5$   
4% NAC-Soluble  $P_2O_5$

Source: A. Battono et al. (3).

Figure 19. Effect of Phosphorus Source on Yield of Maize—Semi-arid Africa.



Source: L. A. Leon (2).

Figure 20. Effect of Phosphorus Source on Yield of Rainfed Upland Rice—Colombia.

## References

1. Hammond, L. L., and L. A. León. 1983. "Agronomic Effectiveness of Natural and Altered Phosphate Rocks From Latin America," *Proceedings*, Third International Congress on Phosphorus Compounds, October 4-6, Brussels, Belgium.
2. León, L. A. 1984. "On-Farm Suitability of Indigenous Phosphate Products," unpublished.
3. Bationo, A., S. K. Mughogho, and A. U. Mokwunye. 1985. "Agronomic Evaluation of Phosphate Fertilizer Alternatives in Sub-Saharan Africa," Paper presented at the Symposium on the Management of Nitrogen and Phosphorus Fertilizers in Sub-Saharan Africa, Lome, Togo, March 25-28.
4. Sudjadi, M., J. Prawirasumantri, and B. Palmer. 1985. "Response of Upland Rice to Applied Phosphorus and Lime on a Typic Paleudult," unpublished.
5. Hagin, J. 1985. "Partially Acidulated Phosphate Rock, A Review," Technion, Israel Institute of Technology, Haifa, Israel, June.
6. Carmon, S., and A. H. Roy. February 27, 1985. "Single-Step Acidulation and Granulation Process for Selective Acidulation of Apatite in Phosphate Rocks," Patent Application, Serial No. 706368.
7. International Fertilizer Industry Association Limited. 1984. "Raw Materials Committee Meeting, Palm Springs, September 20-21, 1984, Volume III, Phosphate Rock," Paris, France.
8. Louis, P. L. 1985. "Outlook for Raw Materials Supply and Demand," International Fertilizer Industry Association Limited, Paris, France.
9. The British Sulphur Corporation Limited. 1985. "World Statistics Fertilizer Products," June.
10. Kanwar, J. S., and M. S. Mudahar. 1983. *Fertilizer Sulfur and Food Production*, Executive Brief, IFDC Bulletin T-27, International Fertilizer Development Center, Muscle Shoals, Alabama 35662.
11. *Solutions* 24(6), November/December, 1980. "Tracking Down Sulfur Deficiencies—A Tricky Business".
12. The Association of Official Analytical Chemists (AOAC). 1984. "Official Methods of Analysis, Method 2.044-2.047."
13. Official Journal of the European Communities. 1977. Vol. 20, No. L213, Method 3.1.3.
14. Official Journal of the European Communities. 1977. Vol. 20, No. L213, Method 3.1.2.
15. Hill, W. L., and K. C. Beeson. 1936. *Journal Association Official Agricultural Chemists* 19:328-338.
16. Tennessee Valley Authority. 1972. "A Revised Laboratory Reactivity Scale for Evaluating Phosphate Rocks for Direct Application," Bulletin Y-43, Muscle Shoals, Alabama 35660.
17. McClellan, G. H., and F. J. Klem. 1977. "Phosphate Rock Characterization," IN FAI/IFDC *Fertiliser Seminar, 1977, Trends in Consumption and Production*, Proceedings, Tech II/2, pp. 1-18.
18. U.S. Department of Agriculture and Tennessee Valley Authority. 1964. "Superphosphate: Its History, Chemistry, and Manufacture," U.S. Government Printing Office, Washington, D.C. 20402.
19. Sauchelli, Vincent (Ed.). 1960. *Chemistry and Technology of Fertilizers*, Reinhold Publishing Corporation, New York, New York.
20. International Fertilizer Development Center. 1985. IFDC Industry Survey, unpublished.
21. Associacao Nacional Para Difusao de Adubos e Corretivos Agricolas (ANDA). 1984. Unpublished data, Sao Paulo SP, Brazil.
22. *Green Markets*. 1984. McGraw-Hill, Volume 8, Number 36, September 10.
23. Fassbender, H. W., and Y. K. Igue. 1967. "Comparacion de Metodos Radiometricos y Colorimetricos en Estudios Sobre Retencion y Transformacion de Fosfatos en Suelo," *Turialba* 17:284-287.

# Appendix A

## Premises and Assumptions and Related Data Used for Investment and Production Cost Estimates

1. Investment cost estimates are based on mid-1985 costs in a developing country where these costs are similar to those of a U.S. Gulf Coast plant location.
2. The investment cost estimates do not include allowances for land, infrastructure, and facilities located outside the plant site boundary.
3. The SAB-PAPR and SSP process plant battery limits are defined to include the process plant building and related facilities beginning with the raw material feed system and ending with the conveyor belt used to transfer the product to the bulk storage and/or bagging facilities.
4. The auxiliary and support facilities include storage and handling facilities for raw materials, in-process curing, bulk and bagged products, utility facilities (including steam, electricity, and water supply), and general service facilities (including site development, laboratory, maintenance facilities, and administration buildings).
5. The investment cost estimates do not include allowances for escalation during construction.
6. Engineering and supervision are equivalent to 15% of total direct plant cost.
7. Construction overhead and expenses are equivalent to 10% of total direct plant cost.
8. Contractor's fee is equivalent to 10% of total direct plant cost.
9. The cost of spare parts is based on 6% of the direct plant cost for process units and utility facilities.
10. Preoperational and startup expenses are based on 9% of the direct plant cost for process units and utility facilities.
11. Project management services are based on 5% of the total plant cost.
12. Contingency cost is based on 10% of total plant cost.
13. Interest during construction of the SAB-PAPR and SSP plants (Schemes II- VII) is equivalent to 13% of total fixed investment. This value is calculated using a 14% annual interest rate and a 2-year period of construction with 40% of the funds disbursed during the first year and the remainder disbursed during the second year. A factor of 7% is used for the phosphate rock grinding plant (Scheme I), which is based on a 14% annual interest rate and a 1-year period of construction.
14. Raw material and product storage capacities and unit costs are based on 100% capacity utilization:
  - Phosphate rock (coarse concentrate)—2.5 months outdoor storage (cost included in general service facilities)
  - Sulfur—2.5 months outdoor storage (cost included in general service facilities)
  - Sulfuric acid (Scheme VII only)—2.5 months storage (US \$240/mt)
  - Bulk product—1 month indoor storage for granular products; 2 months for ROP products to allow for curing (US \$50/mt)
  - Bagged finished product—15 days indoor storage (US \$80/mt)
15. Delivered raw material and utility prices are assumed as follows:
 

Phosphate rock (coarse concentrate, 30% P <sub>2</sub> O <sub>5</sub> ), US \$/mt	25.00
Sulfur, US \$/mt	200.00
Sulfuric acid, US \$/mt H <sub>2</sub> SO <sub>4</sub>	170.00
Electricity, US \$/kWh	0.10
Natural gas, US \$/million kcal	16.00
Fuel oil, US \$/mt (9.6 million kcal/mt)	350.00
Diesel oil, US \$/mt (10 million kcal/mt)	400.00
Water, US \$/m <sup>3</sup> or mt	0.50
Bags, US \$/bag (50-kg)	0.60
16. Personnel costs (operating labor and supervision) are based on typical staffing and costs in developing countries (Table A-3).
17. Administrative and general overhead expenses are equivalent to 100% of operating labor and supervision costs.
18. Annual costs for maintenance materials, labor, and contract services are based on 5% of the total plant cost.
19. Annual costs for insurance and taxes are based on 1% of the total plant cost.
20. Annual interest on working capital is based on 14% of the working capital.
21. Working capital estimates include allowances for the following:
  - 50-day inventory of raw materials at delivered cost
  - 20-day inventory of bulk product (40 days for ROP products) and 10-day inventory of bagged product at total production cost.
  - Cash is equivalent to 30 days of conversion cost.
22. Fixed-capital recovery is equivalent to 16.3% of the total fixed investment. This capital recovery factor corresponds to an annual interest rate of 14% and a 15-year amortization period (plant life). The capital recovery factor (16.3%) covers depreciation and interest (or return on investment).
23. The production cost estimates are based on a capacity utilization of 100% with the annual capacity rating corresponding to 330 days operation at the daily rated capacity.

Appendix Table A-1. Estimated Cost of Major Process Equipment Items—SSP and SAB-PAPR Processing Schemes<sup>a</sup>

	Scheme II (ROP SSP)	Scheme III (ROP SSP Followed by Granulation)	Scheme IV (ROP SAB-PAPR)	Scheme V (ROP SAB-PAPR Followed by Granulation)	Scheme VI or VII (Single-Step Granular SAB-PAPR)
Plant capacity, mtpd	315	315	270	270	270
Equipment Item	(US \$ x 1,000)				
Primary lump breaker	-	8 <sup>b</sup>	-	8 <sup>b</sup>	-
Raw material bucket elevator	24	46 <sup>b</sup>	24	46 <sup>b</sup>	24
Raw material surge hopper and feed system, including dust collector	35	70 <sup>b</sup>	35	55 <sup>b</sup>	35
Acid surge tank	12	12	12	12	12
Pug mill mixer	30	30	25	25	-
Belt-type curing len	74	74	74	74	-
Rotary drum granulator	-	180	-	160	200
Rotary dryer with combustion system	-	420 <sup>c</sup>	-	420 <sup>c</sup>	700 <sup>c</sup>
Screen feed bucket elevator	-	40	-	35	44
Oversize and product screens	-	55	-	50	60
Oversize crushers	-	15	-	10	20
Fluid bed-type product cooler	-	100	-	100	100
Cyclone-type dust collectors	-	120	-	120	180
Dust and fluorine scrubber	35	85	25	75	100
Exhaust fans	30	80	30	75	125
In-process conveyors	60	100	60	80	100
ROP product reclaiming and mill- ing system, including dust collector	70	70	55	55	-
<b>Total Process Equipment Cost</b>	<b>370</b>	<b>1,510</b>	<b>340</b>	<b>1,400</b>	<b>1,700</b>

a. Includes delivery.

b. Includes two systems; one for phosphate rock and one for reclaimed ROP SSP or SAB-PAPR.

c. Dryer for Scheme III and Scheme V is 2 m in diameter and 12 m long; dryer for Scheme VI and Scheme VII is 3.7 m in diameter and 18.5 m long.

Appendix Table A-2. Direct Plant Cost Data for SSP and SAB-PAPR Processing Units

	Scheme II (ROP SSP)	Scheme III (ROP SSP Followed by Granulation)	Scheme IV (ROP SAB-PAPR)	Scheme V (ROP SAB-PAPR Followed by Granulation)	Scheme VI (Single-Step Granular SAB-PAPR)	Scheme VII (Single-Step Granular SAB-PAPR Using Purchased Acid)
	(US \$ x 1,000)					
Process equipment <sup>a</sup>	370	1,510	340	1,400	1,700	1,700
Equipment installation <sup>b</sup>	150	620	135	560	680	680
Chutes, ducts, and piping <sup>b</sup>	40	150	35	140	170	170
Instrumentation <sup>b</sup>	20	80	20	70	90	90
Electrical <sup>b</sup>	60	230	50	210	250	250
Process plant building <sup>b</sup>	150	620	140	560	680	680
<b>Total Direct Plant Cost</b>	<b>790</b>	<b>3,210</b>	<b>720</b>	<b>2,940</b>	<b>3,570</b>	<b>3,570</b>

a. Refer to Appendix Table A-1.

b. Based on vendor and IFDC cost-estimating data for similar process units.

**Appendix Table A-3. Estimated Workforce Requirements and Labor Costs for Various SAB-PAPR and SSP Processing Schemes**

Position	Annual Salary <sup>a</sup> (US \$)	Scheme I (Ground Phosphate Rock)	Scheme II (ROP SSP)	Scheme III (ROP SSP Followed by Granulation)	Scheme IV (ROP SAB-PAPR)	Scheme V (ROP SAB-PAPR Followed by Granulation)	Scheme VI (Single-Step Granular SAB-PAPR)	Scheme VII (Single-Step Granular SAB-PAPR Using Purchased Acid)
		(number required)						
Superintendent	15,000	1	1	1	1	1	1	1
Shift supervisor	10,000	4	4	4	4	4	4	4
Foreman	5,000	4	8	8	8	8	8	4
Operator	3,000	12	28	44	28	44	36	24
Laborer	1,000	8	28	28	25	25	25	15
<b>Total</b>		<b>29</b>	<b>69</b>	<b>85</b>	<b>66</b>	<b>82</b>	<b>74</b>	<b>48</b>
<b>Total Annual Cost, US \$ x 1,000</b>		<b>119</b>	<b>207</b>	<b>255</b>	<b>204</b>	<b>252</b>	<b>228</b>	<b>162</b>

a. Estimated based on typical employee salaries and benefits in developing countries.