PHOSPHORUS RESOURCES, UTILIZATION, AND RELATED ENERGY EXPENDITURES

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ROBERT KIRK JOHNSON, SR.
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ABSTRACT

PHOSPHORUS RESOURCES, UTILIZATION, AND RELATED ENERGY EXPENDITURES

By

Robert Kirk Johnson, Sr.

Phosphate rock is the raw material for numerous industrial and agricultural applications. Reserves are being depleted steadily by increasing demand from a growing population. Reuse of phosphorus in wastewater could postpone depletion although related energy requirements are significantly higher.

Part I includes a cursory review of the biological significance of phosphorus and the geological characteristics of mineral rock phosphate deposits. Current data on reserves, production, consumption and market characteristics have been compiled for the world and the United States. Projections of consumption through the year 2000 were made and schedules of a range of depletion rates have been formulated. Phosphorus in wastewater has been identified by source and potential quantities available for reuse calculated.

Part II outlines energy expenditures of two alternative methods of phosphorus application. Energy requirements for fertilizer phosphates have been evaluated from the time of extraction through refinement, transport and application to the soil. Similarly, energy expenditures resulting from the use of municipal sewage effluent have been traced through collection, distribution and application to crops.

Robert Kirk Johnson, Sr.

It is concluded that application of effluent for the purpose of plant nutrition and prolonging resource life is not economically feasible at this time, within the framework of this analysis. The advent of alternative power sources, possibly nuclear, could make reuse schemes more favorable. Additionally, the relative importance given non-economic considerations, as abatement of environmental degradation and effective planning of resource exploitation, could influence evaluation of proposed recycling.

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By

Robert Kirk Johnson, Sr.

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INTRODUCTION

Phosphorus is one of the most important elements because of its irreplaceable function in biological processes and its relative scarcity in the biosphere. Phosphorus from large localized deposits is extracted and utilized in a myriad of industrial and agricultural processes. Man's careless pattern of use disperses phosphorus in the form of wastewater to surface waters, effectively rendering it to unavailable storage. The source of commercial phosphorus, phosphate rock, is diminishing at an undetermined rate. The most liberal estimates of the life of this resource place the date of depletion at several hundreds of years. This time period represents a very small segment of the natural cycle required for the formation of deposits the type of which are now being exploited.

It has been suggested that the reuse of phosphorus in waste could postpone depletion of reserves hundreds of years. One of the more popular schemes for reuse of the element includes the application of sewage treatment plant effluent to agricultural land by a variety of methods. A potentially significant obstruction to land application techniques is the amount of energy required for transmission of the liquid waste to the agricultural site from the treatment facility. The current status of fossil fuels in the United States and the

world and consequent higher energy costs will make power requirements an increasingly larger percentage of operational budgets.

In consideration of increased concern for the longevity of this essential, finite mineral resource, combined with inadequate knowledge of energy expenditures associated with alternative management schemes, the following hypothesis is advanced. Energy inputs required by reuse projects applying a unit of phosphorus contained in wastewater will be significantly higher than those requirements related to the application of an equivalent amount of phosphorus from manufactured fertilizers.

The approached to be taken in addressing this hypothesis is a theoretical comparison made to determine the relative energy requirements of the two basic alternatives for application of phosphorus. The first alternative to be evaluated will be the application of manufactured fertilizer, triple superphosphate, derived from mineral rock, proceeded by a second method applying effluent from sewage treatment facilities. A centrally-located farm in midwestern United States will be used as the recipient of phosphorus. Discussion will include methods of fertilizer manufacture, modes of transportation and systems of wastewater utilization. Energy expenditures will be compiled for operational activities, excluding requirements of capital equipment and installation.

Methodology

Biological significance and cycling of phosphorus in the natural environment will be evaluated. The location, quality and volume of world and United States reserves of rock phosphate will be compiled in detail from an extensive review of the literature. Phosphorus production and patterns of consumption shall be presented and projections to the year 2000 made. Schedules of reserve depletion will be formulated for the world and the United States.

Energy requirements will be evaluated for alternative methods of phosphorus application. Fertilizer manufacture and use will be traced from representative mines in the western fields and Florida through respective refining processes, modes of transportation and application by farm machinery. Conveyance of effluent from a treatment facility to regional delivery points, distribution to the farm and application by alternate techniques will be described. Data for total energy expenditures shall be compiled at the conclusion of respective sections.

PART I. PHOSPHORUS RESOURCES

1. BIOLOGY AND THE PHOSPHORUS CYCLE

1.1 Biological significance

Phosphorus is a universal constituent of protoplasm required for growth and reproduction in all forms of plants and animals. Phosphorus shares its importance with other elements (nitrogen, oxygen, hydrogen, carbon and sulfur) but differs in availability. Other elements of major biological significance are readily obtained where phosphorus is bound in mineral rock.

Phosphorus does not occur in elemental form. All phosphorus is in the form of soluble and insoluble phosphates which are found in the soil, freshwater and in the seas. Soluble orthophosphates are present in relatively small amounts, the concentration effectively controlled by solubilization processes and cations as calcium, iron and aluminum which are capable of forming highly insoluble orthophosphates. In plants and animals phosphorus occurs as orthophosphates, polyphosphates, ortho- and polyphosphate esters, phosphoproteins and complex nucleotides.[(1)]

Insoluble mineral phosphates constitute the majority of fixed phosphates in the soil and mineable rock deposits. These compounds can be biologically utilized over a number of years in many soil environs through activity of microorganisms, leaching by carbonate waters and other means. Although the earth's supply of phosphorus remains constant, the amount biologically available varys, at a rate which is a function of its turnover.

1.2 Phosphorus cycle

The phosphorus cycle is illustrated in Figure 1, which includes major natural and cultural pathways. The cyclical processes provide the basis for phosphorus concentration, biological utilization and eventual return to the sea. A portion of the earth's phosphorus is continually passing out of the mineral reserve into living substance and subsequently re-entering from living matter back to the mineral reserve. Solubilization and growth proceeded by deposition and decomposition provides the mechanism which assures an almost universal distribution of biologically available phosphorus over the surface of the earth.

The natural cycle of phosphorus occurs over extremely long periods of time, requiring millions of years for geologic uplift of depositions to complete the cycle. The portion of the sequence influenced by man, however, has effectively created a subcycle with a flow of phosphorus to non-available storage greater than the flow from non-available storage.(3)

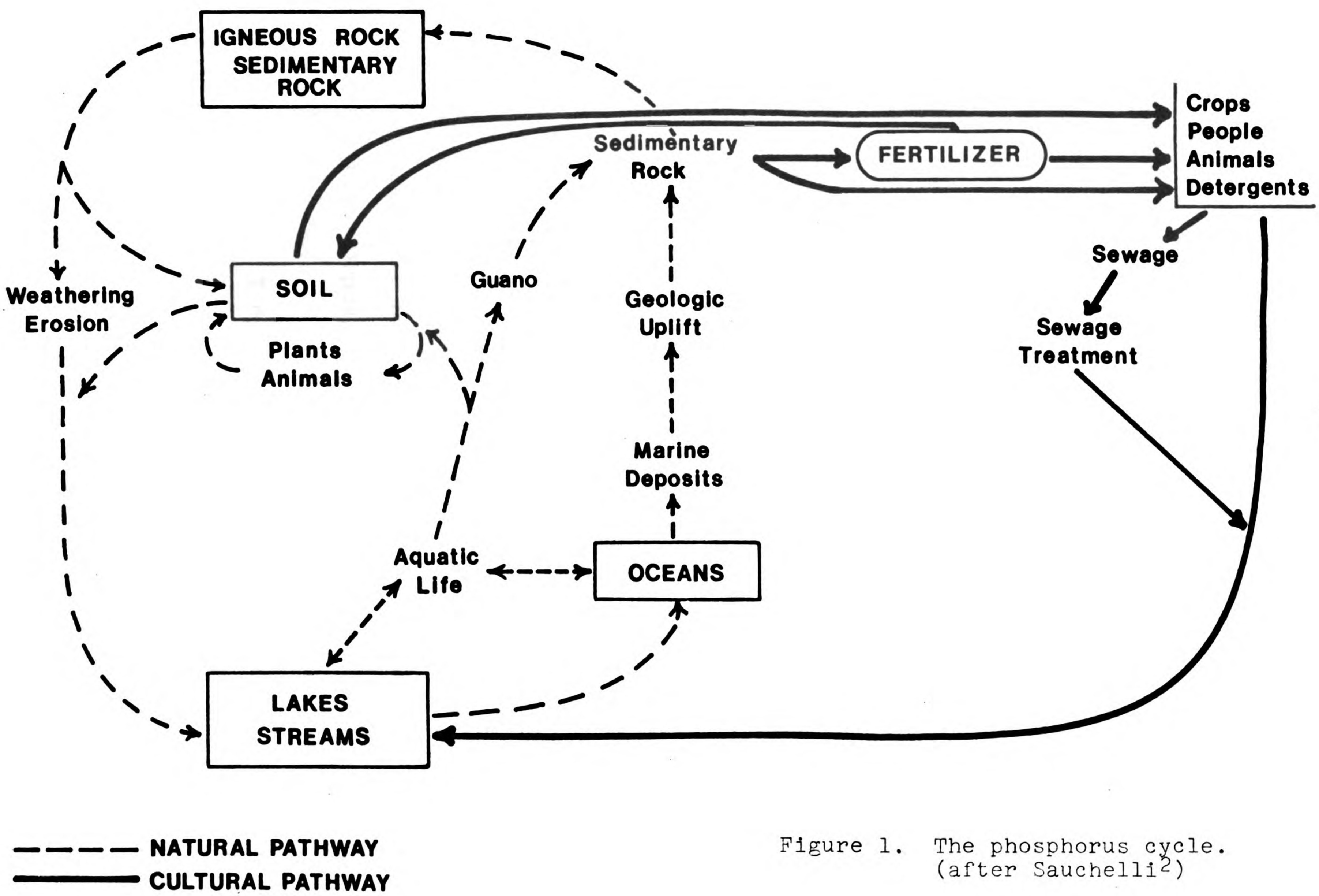


Figure 1. The phosphorus cycle.
(after Sauchelli[2])

2. GEOLOGY OF PHOSPHATE ROCK

Phosphate rock is generally considered to be any rock that contains one or more phosphatic minerals of sufficient purity and quantity to permit its commercial use as a source of phosphatic compounds or elemental phosphorus.[4] There are three general types of phosphate deposits, classified according to the process responsible for their primary localization:[5]

1. Apatite deposits of igneous origin
2. Guano and related deposits
3. Sedimentary phosphorites

2.1 Apatite deposits of igneous origin

Apatite deposits occur primarily as intrusive masses or sheets commonly associated with alkalic igneous rock complexes. Deep weathering may yield a phosphate-rich residuum at the surface during decomposition of calcite, dolomite, and other more soluble minerals. Some of the largest igneous deposits are found in the Kola Peninsula of the Soviet Union, in Eastern Uganda and in the Republic of South Africa. Their content may reach 36% P_2O_5 with average grades between 20 and 25% P_2O_5.[6]

The remainder of igneous apatite deposits are either less extensive or lower quality and consequently are of less economic importance. Low yield deposits are found in Virginia, Norway, and southern Ontario.

2.2 Guano and related deposits

Large accumulations of guano are formed primarily by seafowl with smaller quantitites deposited by bats and other cave-dwelling mammals and birds. Bat guano is most abundant in cave districts of temperate and tropical regions, however, accumulations are small with mining seldom greater than a few thousand tons.(7) Seafowl deposits are mainly confined to islands and coastal regions in low latitudes, the largest of which lie along the west coasts of lower California, South America, Africa, and islands near the equatorial currents. Many guano deposits were once several hundred thousand metric tons although most of the fossil accumulations are now depleted. Current production is very low, less than 0.01% of world phosphate rock production.(8)

Fresh seafowl droppings contain about 22% nitrogen and 4% P_2O_5. Decomposition proceeds rapidly and the relative phosphate content increases as the nitrogen and organic matter decreases. Modern guano contains about 10% P_2O_5 whereas leached guano contains 20-32% P_2O_5. In areas of rainfall the soluble phosphates are carried to underlying rocks where they may be deposited as cavity fillings or replacement. Through this process, phosphates from guano have accumulated over long periods of geologic time and formed significant deposits as those found on the island of Nauru in Oceania where original reserves of rock are estimated to have been 30 million metric tons of rock averaging about 39% P_2O_5.(3)

The mineralogy of phosphatized rock derived from guano depends on the composition of the host rock. Limestone as found in coral reefs results in apatite while silicate of volcanic origin yields aluminum or iron phosphates.

2.3 Sedimentary phosphorite and weathering derivatives

Most of the world's phosphate production comes from marine phosphorites. The richest and largest of these form at low latitudes in areas of ocean upwelling, chiefly along the west coast of continents or in large Mediteranian seas along the equatorial side of the basin. Lesser but significant concentrations form along the west sides of poleward-moving warm currents on the eastern coasts of continents.

Rock assemblage in the cold-current environment is the product of deposition on a shoaling bottom, over which shoreward moving waters are progressively warmed. The thickest accumulations of phosphorite form in areas of geosynclinal subsidence generally associated with carbonaceous shale. The phosphorite is typically carbonaceous and pelletal but nodules as well as skeletal material may be present in lesser quantities.

Individual beds are generally a few meters thick and often many kilometers wide containing up to 30% P_2O_5. Thicker and richer deposits may occur locally but are highly lenticular. Phosphorites deposited from upwelling are found in the Phosphoria Formation in Idaho and adjacent states, extensive deposits in western and northern Africa, and in the Middle-East.

Phosphate deposits formed in warm-current environments along the eastern coasts of continents generally consist of phosphatic limestone or sandstone and are less extensive and lower in quality than those formed from cold currents. Depositions derived from warm-current activity are found in the Bone Valley Formation of central Florida. The distribution of some deposits suggests estuarine deposition and may have resulted from processes of circulation and nutrient enrichment.[(9)]

Secondary processes have played a prominent role in concentrating the richest of the marine deposits. The highest grade beds in the Western Phosphoria Formation appear to have been extensively washed by marine currents and leached of carbonates and sulfides. Weathering in the cycle accounts for the formation of enriched residual and replacement deposits from phosphatic deposits not otherwise mineable. Tennessee "brown-rock" consists of present day residuum developed through decomposition of phosphatic limestone.[(10)]

3. PHOSPHATE ROCK RESERVES

3.1 World reserves

Phosphate rock occurs throughout the world and is mined extensively on every continent although three regions - the United States, the Soviet Union and North Africa - constitute over eight-tenths of the world's developed resources. These deposits have provided a dependable source of phosphate rock in past decades and will continue to supply foreseeable demand for the next few hundred years.

Table 1 contains a compilation of the world's known and potential deposits of phosphate rock, equivalent quantities of P_2O_5 and 1970 regional production statistics. The North African region possesses the largest reserves while North America produces the largest volume of rock. European reserves are almost exclusively found in Northeastern Russia. Total known and potential reserves of the world are nearly 160 billion metric tons of rock or about 43 billion metric tons P_2O_5 equivalent at an average assay of 26.9% P_2O_5.

Many deposits contain relatively insignificant amounts of phosphate rock. Recent discovery and exploitation of reserves, particularly in underdeveloped nations, has decreased dependency of smaller countries on major producers for raw phosphate materials. The three major producing regions have supplied the rest of the world with rock and phosphorus derivatives, specifically resource

TABLE 1

WORLD PHOSPHATE ROCK RESERVES AND 1970 PRODUCTION
(million metric tons)

	RESERVES					PRODUCTION (ref. 8)	
Location	Ref.	Rock	P_2O_5	Avg. Grade	Percent of Total P_2O_5	Rock	Percent of Total
WORLD		159,303	42,974	27.0	100.0	85.32	100.0
AFRICA		71,426	22,555	31.6	52.5	19.84	23.2
Algeria	6	2,791	831	30.0			
Angola	11:14	111	39	35.0			
Egypt, Arab Rep.	8, 11:11	745	223	30.0			
Mauritania	11:4	4	1	25.0			
Morocco	6	59,590	19,138	32.1			
Rhodesia	12	34	3	8.1			
Senegal	11:13	45	14	30.0			
South Africa, Rep.	11:12	363	22	6.0			
Spanish Sahara	11:4	1,179	360	30.5			
Tanganyika	12	9	2	20.0			
Togo, Rep.	11:2	45	16	36.6			
Tunisia	6	6,281	1,869	29.8			
Uganda	11:7, 12	229	37	16.3			
ASIA		8,134	2,027	24.9	4.7	5.76	6.8
China, P. Rep.	6	7,419	1,868	25.2			
Christmas Island	11:4	181	40	22.0			
India	8, 11:9	144	42	29.2			
Israel	11:8	7	2	27.0			
Japan	2	24	8	35.0			
Jordan	2	5	1	27.0			
Lebanon	11:1	5	1	25.0			
Syrian Arab Rep.	11:3	168	45	27.0			
Turkey	8	181	20	11.0			
OCEANIA		2,127	408	19.2	0.9	2.63	3.1
Australia	8	1,887	323	17.1			
Makatea Island	2	8	3	35.0+			
Ocean & Nauru Island	2	232	82	35.0+			
EUROPE		26,570	5,487	20.7	12.8	20.92	24.5
France & Poland	2	358	90	25.0			
U.S.S.R.	6	26,212	5,397	20.6			
NORTH AMERICA		49,499	12,033	24.3	28.0	35.29	41.4
Mexico	11:10	140	22	15.6			
United States	6	49,359	12,011	24.3			
SOUTH AMERICA		1,547	464	30.0	1.1	0.88	1.0
Brazil	11:6	120	22	18.3			
Columbia	11:8	5	1	20.0			
Peru	11:3	1,422	441	31.0			

deficient Europe and Japan which employ intensive agricultural practices.

3.2 United States reserves

Twenty-three states in the United States have reported phosphate rock deposits. Significant deposits are found in Florida, North Carolina, Tennessee, and the western mountain states (Idaho, Montana, Utah and Wyoming). The geographic locations of important commercial reserves are summarized in Figure 2. Current data on U. S. known and potential reserves and recent U. S. production statistics have been gathered in Table 2.

Florida reserves[14]

Florida's major deposits of phosphate rock are modular or pelletal conformations found in the Bone Valley Formation, located in the west-central portion of the state. The formation covers an area of about 6,700 square kilometers with the highest grade rock situated in the northern sector. A typical bed consists of a 6 meter thick overburden of quartz sand under which is a 2 meter leached zone containing 20-30% calcium-aluminum phosphate minerals. A 5 meter thick bed of matrix follows comprised of an unconsolidated mixture of one-third phosphate pellets, one-third sand and one-third clay and sand slimes. The pellets range in size from minute to 2.5 cm in diameter.

The deposits are fairly continuous in both grade and thickness over large areas although abrupt variations may occur locally. Overburden ranging from 3 to 6 meters must

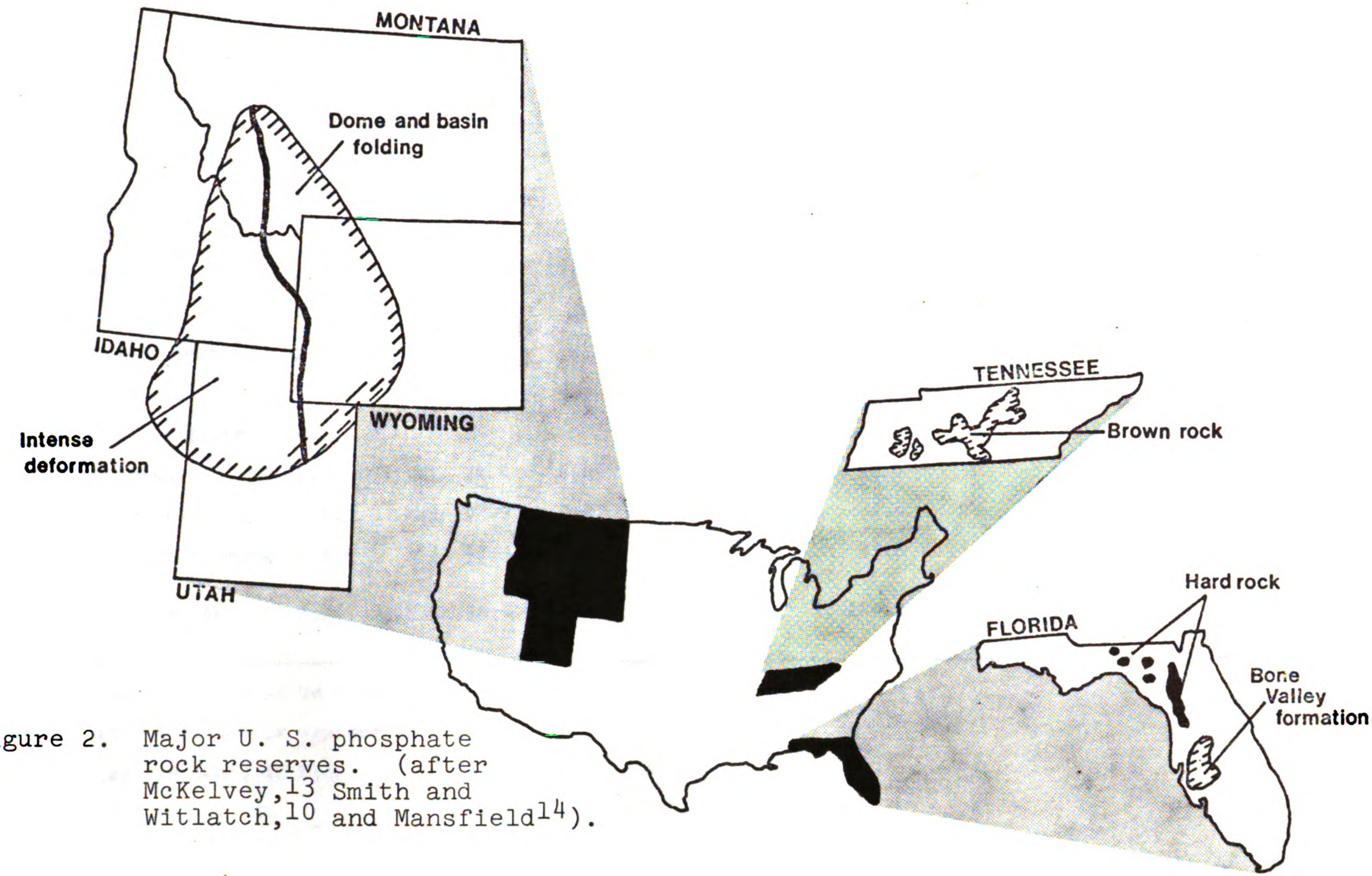


Figure 2. Major U. S. phosphate rock reserves. (after McKelvey,[13] Smith and Witlatch,[10] and Mansfield[14]).

TABLE 2

UNITED STATES PHOSPHATE ROCK RESERVES AND 1970 PRODUCTION
(million metric tons)

	RESERVES (ref. 6)							PRODUCTION (ref. 8)		
	KNOWN			POTENTIAL						
	Rock	P_2O_5	Grade	Rock	P_2O_5	Grade	Percent of Total P_2O_5	Rock	P_2O_5	Percent of Total P_2O_5
Alabama	---	---	---	na	na	na	----	(a)	(a)	(a)
Arkansas	---	---	---	18	5	22.9	----	---	---	---
California	na	na	na	na	na	na	----	(b)	(b)	(b)
Florida	2,041	654	32.1	23,582	4,985	21.1	41.5	28.24	9.06	82.8
Georgia	---	---	---	na	na	na	----	---	---	---
North Carolina	2,032	602	29.6	na	na	na	----	(c)	(c)	(c)
Tennessee	59	11	17.6	5,442	1,143	21.0	9.5	2.89	0.78	7.1
Western States:								4.03	1.10	10.1
Idaho	1,215	301	24.8	6,077	1,537	25.3	12.8			
Montana	998	229	22.9	1,270	312	24.5	2.6			
Utah-Wyoming	816	353	43.3	12,970	4,030	31.1	33.6			
U. S. TOTAL	7,161	2,150	30.0	49,359	12,012	24.3	100.0	35.16	10.94	100.0

(a) included in Tennessee

(b) included in Western States

(c) included in Florida

be removed in order to mine the matrix which is usually 3 to 10 meters thick. Areas presently mined are about 35 meters above sea level in flat terrain.

Florida's hard-rock deposits are located in the north-central area of the state. The rock is in a belt about 30 kilometers wide and 200 kilometers long aligned on an approximate north-south axis. The beds vary greatly in thickness, ranging from about one meter to over 30 meters in depth. The hard-rock is covered by an overburden of clay and sand which has been economically stripped to depths of greater than 20 meters. Mining in the area has been undertaken by as many as 70 operations although present production is limited.

Tennessee reserves[10]

Three types of phosphate rock are found in Tennessee formations - blue, white and brown rock. Blue rock consists of phosphate pellets cemented with calcium carbonate and white rock occurs as a heavy, massive material with a knurly structure, commonly found in thin beds. Neither of these have been extracted at significant levels in recent years.

Brown rock is composed of residual francolite pellets, quartz sand, and clay derived from the decomposition of limestone depositions of about 350 million years ago. The phosphate was originally deposited in shallow seas, later to be lifted gently and exposed by erosion. The brown rock often occurs as fillers lying between layers of limestone. This material covers a large irregular area traversing the center of the state in a north-south direction. The overburden in the brown rock fields runs from 0 to 15 meters thick, averaging about 2 meters, while the matrix ranges from 1.5 to 3.0 meters thick averaging about 2 meters.

Tennessee phosphate rock reserves are of relatively insignificant national importance. Commercial deposits are expected to be depleted in 10 to 20 years, although low grade deposits not currently considered as a reserve are available in the region.(6)

Western states' reserves(15)

The Rocky Mountain phosphate rock field is referred to as the Phosphoria Formation and covers an area of greater than 160,000 square kilometers in portions of Idaho, Montana, Wyoming and Utah. This field is one of the largest in the world and constitutes nearly 50% of U. S. reserves and greater than 10% of world reserves. The remote location and consequent high transportation costs prevented significant exploitation until the early 1950's.

Important reserves are the result of depositions of phosphatic material about 100 million years ago. From the time of its formation the strata has been greatly compressed, folded and uplifted resulting in beds that often dip at high angles, frequently greater than 45 degrees.

Rock of the Phosphoria Formation often occurs in the form of soft, weathered shales having a dark, somewhat oily appearance and a high carbon content. The highest grade rock (30-45% P_2O_5) is dense and usually appears partly modular, cemented together with finegrained carbonates.

The thickest beds of high assay rock lie in an area extending from the southeast corner of Idaho across the southwest tip of Wyoming. Most high grade deposits can be mined only by underground methods, however, there are a few rich outcroppings which are worked by surface mining in southeast Idaho and western Wyoming.

There are at present 33 phosphate rock mines in the United States operated by 28 mining concerns. The majority of the mines, 14, are in Florida while Tennessee and the western states have operations at 8 and 11 sites, respectively.[16]

4. PHOSPHATE ROCK PRODUCTION AND CONSUMPTION

4.1 World production and consumption

Phosphate rock is the primary raw material of the world's phosphorus and phosphate derivative industry, representing 94-96% of total phosphate production. Basic slag (a steel-making by-product from phosphoric iron ore) forms a secondary source contributing 4-6% of production. European usage of slag is higher than that of the world, constituting about 25% of phosphatic raw material for that region.(17) Worldwide distribution of phosphate rock by final use places fertilizer manufacturing as the greatest consumer at 85% of total production. The detergent and animal foodstuffs industries account for 8-9% and 6-7% of the total, respectively.

World phosphate rock production was relatively static from the establishment of the industry ca. 1910 until the late 1940's. In the 20 year period between 1950 and 1970, annual production increased more than 60 million metric tons, from 24 to 88 million metric tons.(8) The expansion of production has supplied the world with raw material for escalating fertilizer demand as well as a myriad of new uses. Prominent among these is sodium tripolyphosphate (STPP) used for detergent building. From the time of its inception as a laboratory curiosity in the late 1940's, STPP grew rapidly in a few years to the major industrial consumer of phosphorus and continues to consume 5-10% of total P_2O_5 production.[18]

Production of phosphate rock continues to increase although rates are substantially lower than those experienced in the early 1960's (Figure 3). Foreign exchange shortages, world political unrest, less-than-anticipated purchases by international agencies and inclement weather reducing agricultural production in some areas has restricted consumption and created a surplus of production capacity. In 1969-1970, the world installed capacity of phosphate rock production was approxiately 90 million metric tons annually. However, the industry utilized only about 75% of capacity and a surplus of about 18 million metric tons was realized by the industry worldwide.[17]

The distribution of rock phosphate and phosphatic fertilizer production, consumption, and international movement is represented in Figure 4. Three major producing areas shown - North and Central America, North Africa, and the Soviet Union - constitute nearly 90% of the world's rock phosphate production. Exportation of rock is undertaken by less developed countries while more technically advanced nations export moderate amounts of intermediary and finished phosphorus products (primarily acid phosphates) as well as rock.

Many regions of the world employing intensive, technologically advanced agricultural practices are also deficient in rock phosphate reserves, specifically Western and Eastern Europe and Japan, all of which are heavy importers of rock. Exports and imports are roughly aligned according to

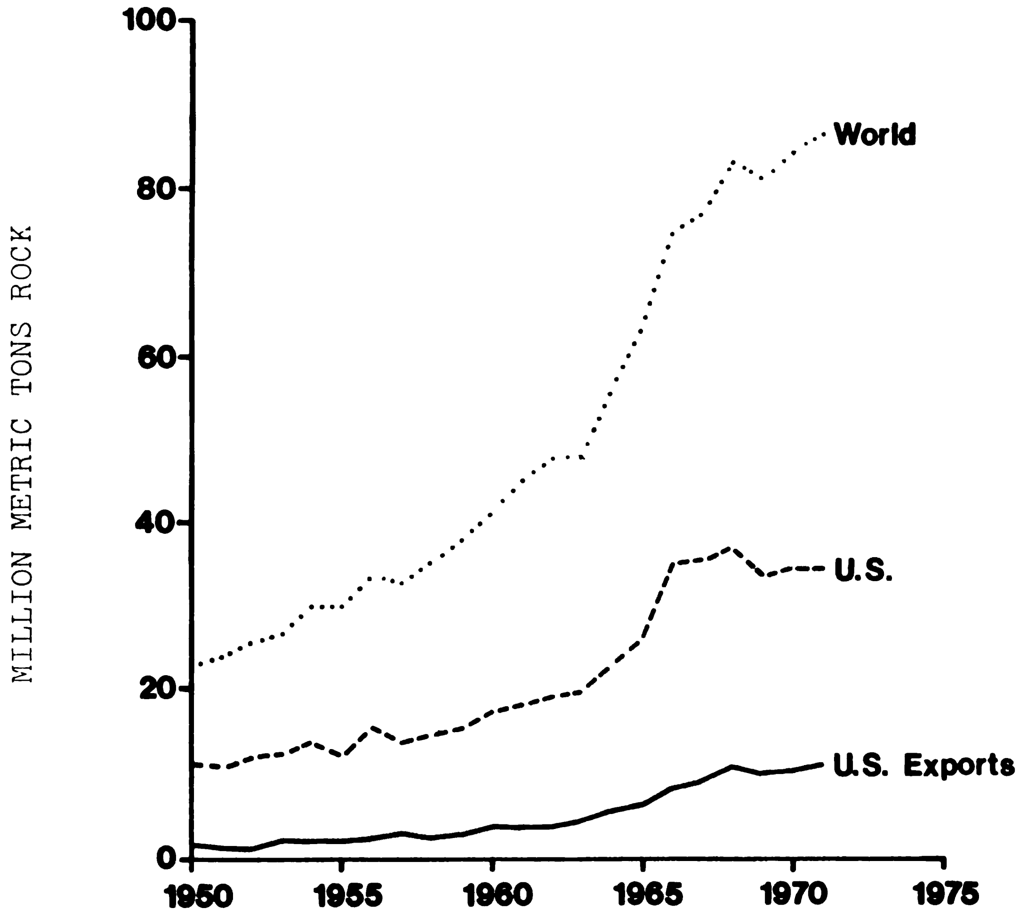


Figure 3. World and U. S. phosphate rock production. (from Harre[16])

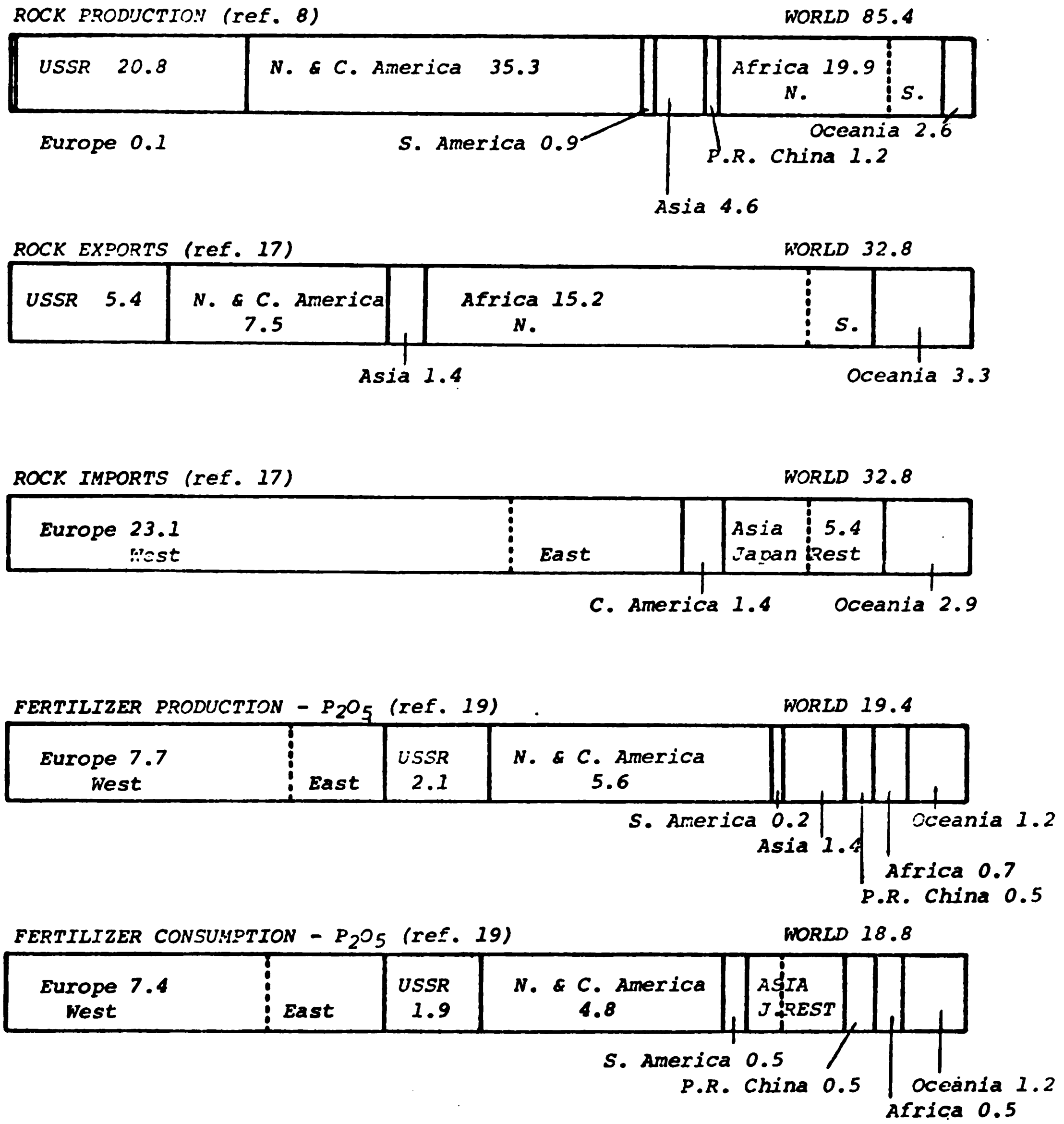


Figure 4. World phosphate rock and fertilizer production, consumption and trade, 1971. (million metric tons)

conventional free world-Communist bloc delineations; the United States exports to non-Communist nations; nearly 75% of exports from the Soviet Union are destined for Eastern Europe; North Africa exports to all major importers.[17] Despite its essential nature, phosphate rock is a low-priced commodity and competition in world and domestic markets is strong in spite of rising costs experienced by the entire industry.[6]

Refinement of rock phosphate and phosphatic fertilizer production is extensively undertaken in North America and Europe where consumption nearly mirrors production. Countries employing less advanced agricultural techniques use corresponding lower amounts of manufactured phosphate fertilizers. The People's Republic of China has only recently begun to utilize small amounts of refined phosphorus in place of natural manures. While feeding one-quarter of the earth's population, China produces a little more than 2% of the world's phosphate rock (while possessing sizeable reserves), imports about 3% of the world's exports of rock, and produces and consumes about the same quantity of phosphatic fertilizers. As the earth's population continues to grow and the agricultural practices employed by countries like China and India become more sophisticated, world demand for raw fertilizer materials will increase sharply. If global predictions of population and income growth materialize, fertilizer production over the next 30 years must triple to satisfy food demands.[20]

4.2 United States production

Production of phosphate rock in the United States originated in South Carolina and Florida. Florida continues to produce the bulk of U. S. phosphates, as illustrated in Figure 5. Reserves are sizeable after many years of intensive production although not as large as those found in the Western States. Florida's proximity to low cost ocean shipping combined with the geologic nature of phosphate reserves permitting strip mining has enabled extensive development of that state's resources.

The Phosphoria Formation of the western states had not been exploited to any significant degree until the early 1950's. Located approximately 1,050 kilometers from the Pacific Ocean in mountainous terrain, movement of western phosphates has been restrained by high transportation costs. Western reserves are unlike those found in Florida and Tennessee in that less than 50% of obtainable rock may be surface mined, the balance of which must be mined underground further constraining development.(21)

The flow of phosphate materials from the mineral resource to major agricultural and industrial applications is illustrated in Figure 6. Phosphorus in mineral form is first concentrated and/or separated into several grades for marketing and distribution within the industry. Most rock does not result in an end product directly but passes through a variety of other forms first. Low grade rock, less than 30% P_2O_5, is predominently processed by thermal methods to elemental phosphorus. Rock containing greater

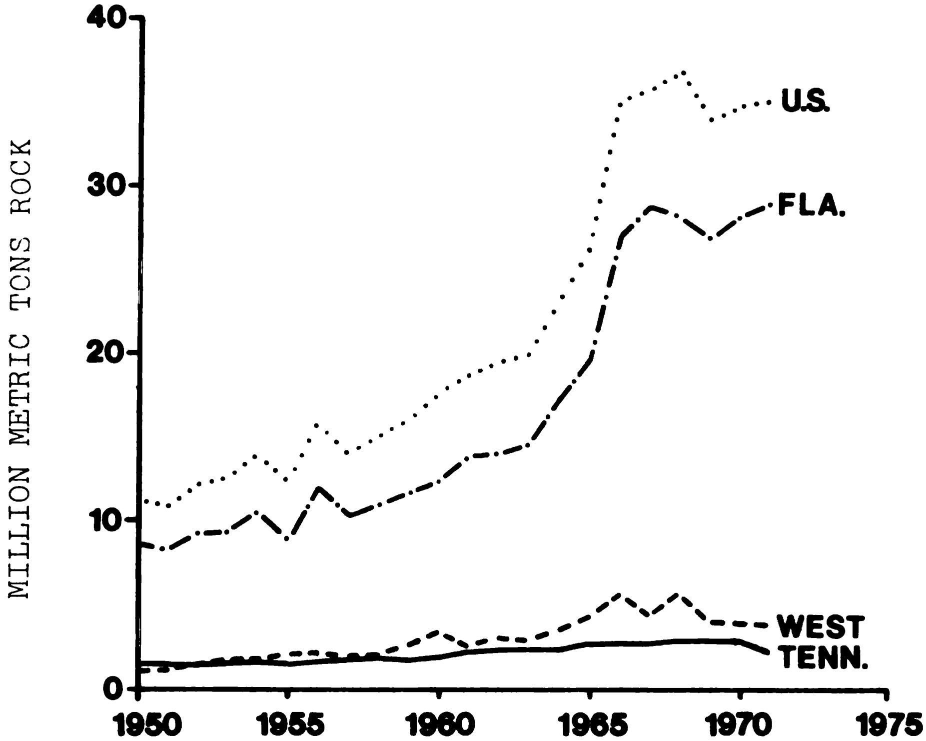
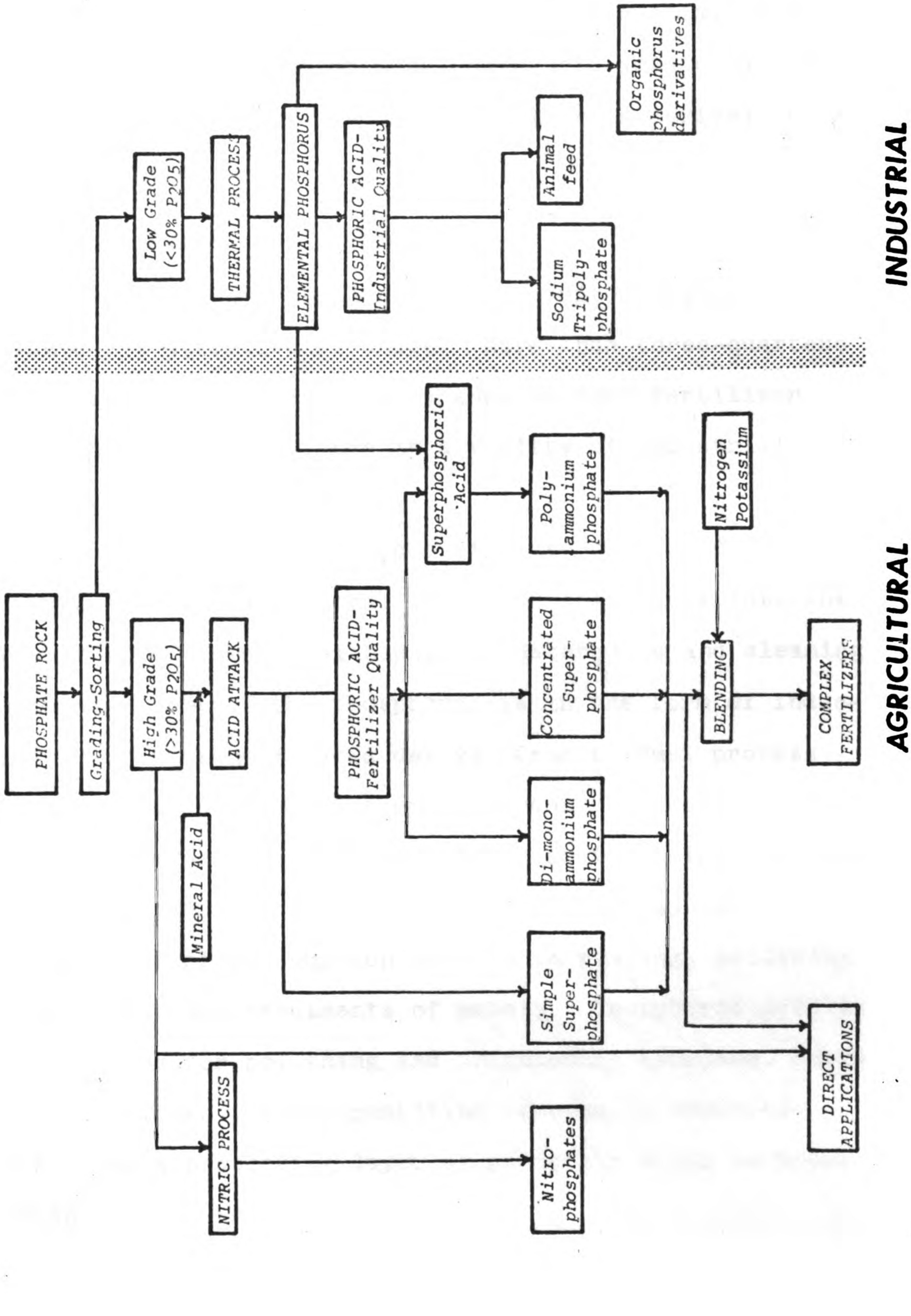


Figure 5. United States phosphate rock production. (from Harrel[6])

Figure 6. Flow of phosphatic materials in the U. S. phosphorus industry. (after Logue[18])


PHOSPHATE ROCK
Grading-Sorting
High Grade (>30% P2O5)
Low Grade (<30% P2O5)
THERMAL PROCESS
ELEMENTAL PHOSPHORUS
PHOSPHORIC ACID-Industrial Quality
Organic phosphorus derivatives
Animal feed
Sodium Tripoly-phosphate
INDUSTRIAL
Mineral Acid
ACID ATTACK
PHOSPHORIC ACID-Fertilizer Quality
Superphosphoric Acid
Poly-ammonium phosphate
Concentrated Super-phosphate
Di-mono-ammonium phosphate
Simple Super-phosphate
Nitrogen Potassium
BLENDING
COMPLEX FERTILIZERS
DIRECT APPLICATIONS
NITRIC PROCESS
Nitro-phosphates
AGRICULTURAL

than 30% P_2O_5 is refined by the "wet-process"; aciduation with a strong mineral acid, usually sulfuric acid. Most industrial applications utilize phosphoric acid obtained from the thermal process while fertilizer is derived chiefly from wet-process acid.

4.3 United States consumption

Consumption of phosphorus in the United States is dominated by agricultural usage. More than three-quarters of all phosphates refined are channeled into fertilizer production with the balance in a variety of industrial products, shown in Figure 7.

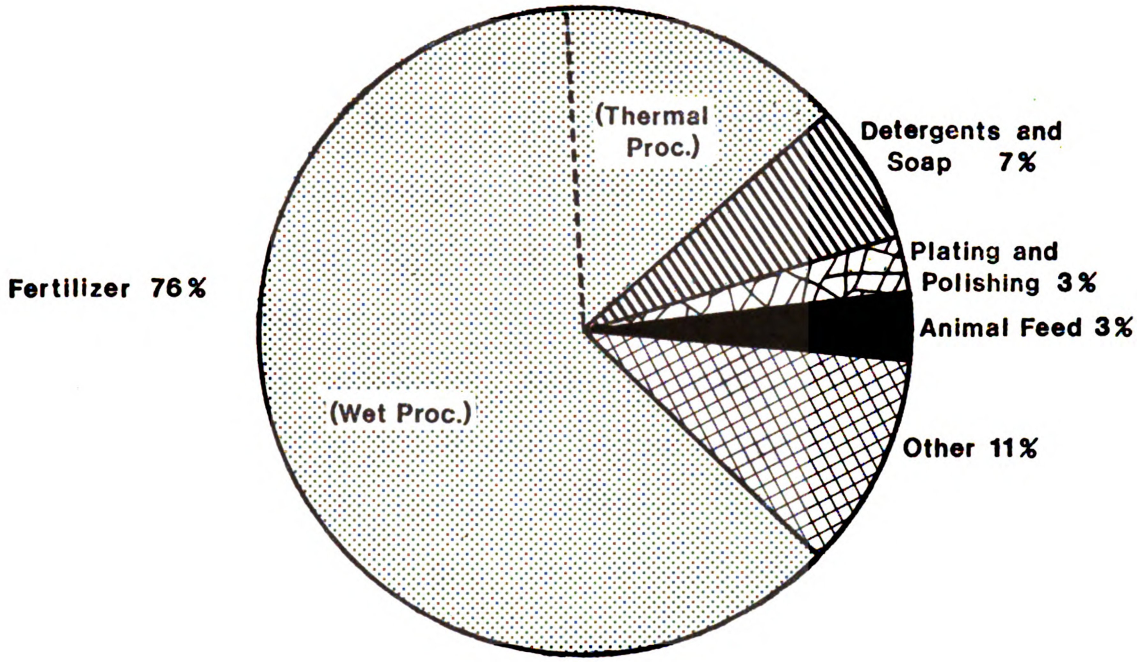
The largest industrial use of phosphorus is detergent building. About 7% of total rock production goes into the formulation of commercial household detergents and cleaning compounds. Most of the phosphorus is in the form of industrial grade phosphoric acid derived from thermal process elemental phosphorus with a small percentage from wet-process acid. The major detergent builder is sodium tripolyphosphate with lesser amounts of tetrasodium tripolyphosphate.

About 3% of consumption is used in plating, polishing and other surface treatments of metals. Phosphoric acid is used in baths for polishing and brightening aluminum, copper and their alloys. A phosphatizing process is employed which forms a protective layer of phosphate salts on metal surfaces.

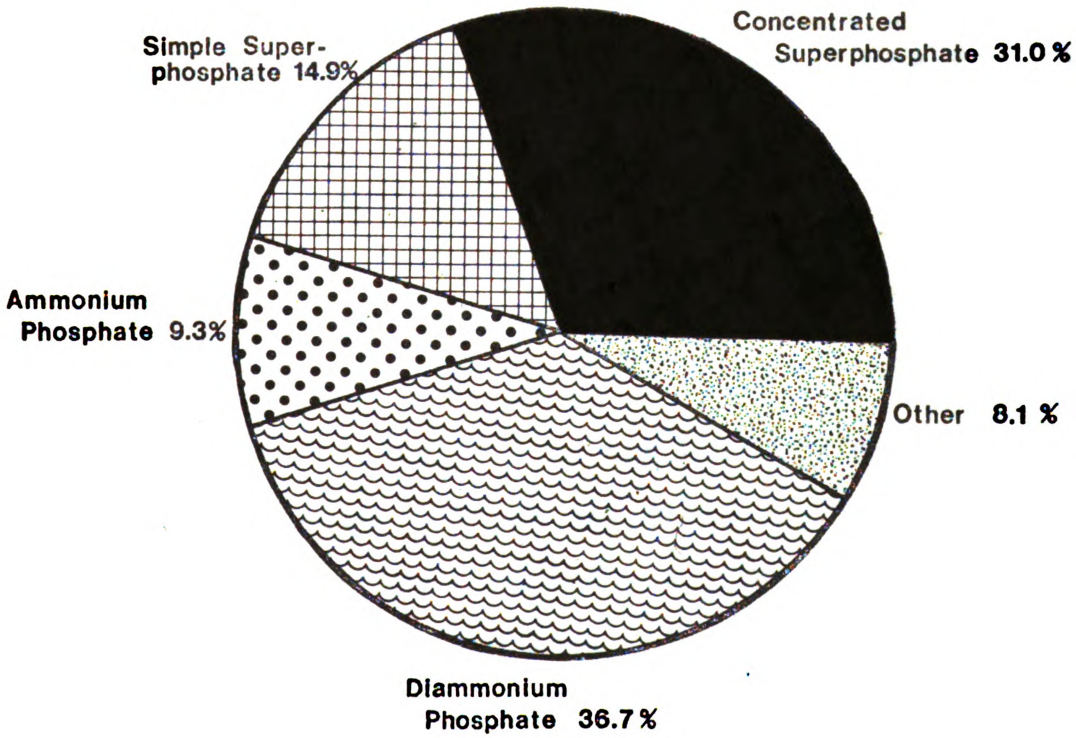
Another 3% of consumption is used in animal and fowl feed supplements. Animal malnutrition has been associated with phosphorus-deficient diets because of low nutrient

Figure 7. Distribution of phosphatic materials in the United States. (from Harre[16] and U.S.D.I., Minerals Yearbook, 1971[8]).

PHOSPHATE DISTRIBUTION



FERTILIZER DISTRIBUTION



levels in natural feed supplies. These supplements must possess very low fluorine levels which are derived from dicalcium phosphate prepared from thermal process phosphoric acid. The fluorine present in U. S. domestic rock prohibits its use for animal consumption. The resulting demand for defluorinated rock represents the only imports of phosphatic material into the United States.

The "other" or undistributed category includes a multitude of end products, all requiring small amounts of phosphorus. Among these are intermediary or finished phosphates for soft drinks, matches, water softening materials, insecticides, dentifrices, rat poison, and many others.

Three-quarters of all rock phosphate produced in the United States is consumed in the manufacture of fertilizer. Fertilizer production primarily involves conversion of rock to more soluble phosphorus compounds which may be effectively utilized by plants. The chemical process of solubilization of phosphate rock with acids is basic to the industry. Continued technological improvements have resulted in more economical production of higher analysis, better quality products.

Phosphoric acid (H_3PO_4) is the basis of phosphatic fertilizer production. It is the initial ingredient for superphosphates and ammonium phosphates and functions as an intermediate for liquid and solid mixed fertilizers. Table 3 contains an analysis of phosphoric acids and fertilizers which employ them as a primary input.

TABLE 3

PHOSPHATE FERTILIZERS

Form	Formula	PERCENT P_2O_5: Total	Available	% Water Soluble	PERCENT NITROGEN
Rock phosphate	$3Ca_3(PO_4)_2 \cdot CaF_2$	34	3-8	0	0
Phosphoric acid	H_3PO_4	54	54	100	0
Superphosphoric acid	H_3PO_4; $H_4P_2O_7$	76	76	100	0
Normal superphosphate	$CaH_4(PO_4)_2$	21	20	85	0
Concentrated super.	$CaH_4(PO_4)_2$	47	45	85	0
Triple super.	$CaH_4(PO_4)_2$	56	53	85	0
Ammonium phosphate	$NH_4H_2PO_4$	49	48	92	11
Diammonium phosphate	$(NH_4)_2HPO_4$	47	46	90	18

Source: Chirstenson, D. R., R. E. Lucas and E. C. Doll, 1972. Fertilizer Recommendations for Michigan. (ref. 22)

Conversion of rock into fertilizer material begins with a complex beneficiation process that involves wet screening, hydroseparation and concentration by flotation. Following beneficiation, the rock is converted to phosphoric acid by the "wet-process" or the thermal process.[23] Wet-process acid is produced by the action of sulfuric acid on ground beneficiated rock. The acid is then separated and concentrated. The thermal process reduces rock phosphate with coke in an electric-arc furnace resulting in a more pure acid but at considerably higher cost. Because of this cost factor, the ratio of wet-process acid to thermal process acid used in fertilizers is about four to one.

Superphosphate is a derivative of phosphoric acid which was first processed in England in the 1840's. The procedure consists of reacting sulfuric acid with phosphate rock to obtain phosphoric acid followed by aging or curing the mixture. The result is a dry porous material, "normal" superphosphate, $CaH_4(PO_4)_2$ or simply "super."[24] From its inception up to the 1950's, superphosphate was the major source of fertilizer phosphorus throughout the world. It proved to be an efficient, easily manufactured material with few problems associated with storage and application. Superphosphates have been consistantly regarded as the best of available phosphorus carriers over a wide range of soils, climatic conditions, and crop management practices.

Concentrated superphosphate is manufactured utilizing the same techniques employed to obtain superphosphate. However, orthophosphoric acid is used to aciduate phosphate rock in the place of sulfuric acid. The resulting compound contains more than double the available P_2O_5.[25] Concentrated superphosphate has figured predominately in fertilizer manufacture since ca. 1950 and reached the level of production nearly double that of simple superphosphate shown in Figure 7. The specific advantage realized with the use of concentrated superphosphate is the increased P_2O_5 content and subsequent reduction in transportation, handling, bagging, storage, etc.

Concentrated superphosphate can be further refined to produce triple superphosphate yielding 55-56% P_2O_5, presently a low volume fertilizer material. The same aciduation process is employed although triple superphosphoric acid (76-85% P_2O_5) is used.[26] Additional savings in transportation and handling may be realized.

Phosphate materials are combined with nitrogen to form a variety of mixed fertilizers. Forms receiving the greatest usage are ammonium phosphates, which include a sizeable number of fertilizers produced by ammoniation of phosphoric acid.[27] Ammonium phosphates may be formulated as a mono-ammonium or diammonium salt or mixtures of the two. They may be used for direct soil application or as an intermediate in mixed and blended fertilizers.

The chemical and fertilizer industries undertake continual research in development of new techniques and processes for phosphorus refinement and application. Many new fertilizer products experience low initial usage and are included in the "other" classification of Figure 7. A few recently developed fertilizers are as follows:[28]

- ammonium polyphosphate (15-60-0): produced from superphosphoric acid

- powdered monoammonium phosphates (11-48-0): produced from superphosphoric acid; one of the least expensive forms to transport

- ammonium phosphate-urea (18-45-0): produced from urea and concentrated phosphoric acid

- metal ammonium phosphate (8-40-0-14 mg): effective fertilizers with slow-release nitrogen; expensive

- potassium phosphates (0-56-36): high concentration of nutrients but difficult in manufacturing

5. CONSUMPTIVE PATTERNS AND FUTURE DEMAND FOR PHOSPHORUS

5.1 World population trends and agricultural production

The population of the earth in 1970 was slightly greater than 3.6 billion people, reflecting a worldwide annual increase of about 2% over past decades. The rate of growth is expected to slow to about 1.7% at the end of the century and the year 2000 is predicted to see nearly 6.5 billion inhabitants.[(29)] Less developed regions (much of Asia and Africa, Central and South America, and parts of Oceania) are more heavily populated than developed regions by a ratio of about 2.3 to 1. Accelerated growth is experienced by less developed areas which exhibit rates well above the world mean. Most of Asia is expected to increase at a rate of 2.5% or greater while Africa may exceed 3.0% by 2000. United Nations predictions estimate the ratio of people in less developed regions to developed regions to be even more lopsided in 2000, about 3.5 to 1.

To compound problems encountered with sheer numbers of people in underdeveloped countries, income levels and production of food is disproportionately low in relation to the rest of the world. Table 4 contains United Nations estimates of caloric and protein intake in "low-calorie" and "high-calorie" countries. To achieve FAO target consumption levels by the year 2000, the low-calorie regions would have to realize an annual increase in agricultural production of

TABLE 4

PER CAPITA DAILY FOOD SUPPLY, 1960 AND 2000

	Kilo-Calories	Animal Protein Grams
1. 1960		
Low-calorie countries	2,150	9
High-calorie countries	3,050	44
2. Target - Year 2000		
Low-calorie countries	2,450	21

Source: Food and Agriculture Organization of the United Nations. 1962. Population and Food Supply, Basic Study No. 7. (ref. 30)

about 3.3%. Livestock production would require a slightly higher growth rate to more than double animal protein intake.

To feed 6.5 billion people at current levels of consumption, food production will have to double by the year 2000. Numerous approaches have been put forth as panaceas for worldwide hunger, some valid, others not so plausible. Prominent among valid hypotheses are increasing the amount of land under cultivation and extensive use of fertilizers.[31] Bringing more land under cultivation holds some promise although the effect will be of consequential magnitude only in certain regions. There are approximately 32.5 million square kilometers of potentially arable land and another 32.5 million of potentially grazable land in the world with about 50% of each catagory utilized.[32] Europe tills nearly 90% of arable land, Asia greater than 80%, the Soviet Union and North America between 50 and 60%, while Africa, South America, and Australia have 20% or less under cultivation. Agricultural practices in past years have seen more extensive land use, particularly in the Far East. More than one-half of the increase in the world's cereal grain production in recent years has come from land expansion.(33) Africa, South America and Australia have the potential of realizing higher production levels by increasing agricultural land use. However, Asia, and to a lesser extent Europe, are severely constrained by current land-use patterns and must pursue other alternatives. The problem will be especially severe in Asia where 60% of the people are located and 88% of the land is used in agriculture. Therefore, a viable alternative for large areas of the world is employment of more intensive agricultural practices.

Increasing yield per unit of land holds potential in expanding the volume of agricultural production. High-protein, high-yeild varieties of grains, irrigation and greater use of fertilizers are a few of the methods available. Probably the most widely recommended means of increasing yield is through more intensive use of fertilizers, specifically phosphorus carriers. Production is straight forward, raw materials are procured with relative ease and the mechanics of effective application is well known. Barriers to implementation of high volume fertilizer usage exist in the massive scale which would be required. The world's phosphate industry does not have the capacity to supply the entire world with phosphatic fertilizers at the same level it supplies countries consuming great quantities. If India were to apply fertilizers at the same per capita rate as East or West Europe, the needs of that nation alone would be nearly 90% of the present world consumption.

5.2 World consumption and future demand

Soil enrichment and maintenance with phosphate fertilizers will serve an important function in future food production. The volume demanded is a function of a variety of variables, most notably population and agricultural practices of individual nations. Table 5 contains information on world population and agricultural consumption of phosphatic fertilizers for regions and selected countries in 1970. United Nations estimates of median population in the year 2000 are listed from which phosphatic fertilizer usage is projeted. Per capita consumption ranges from 0.47 to 63.05 kilograms annually with a world average of 5.62.

The United States consumes the largest quantity of any single nation although Oceania uses the greatest amount of P_2O_5 per capita. The Australian government has subsidized the use of fertilizer phosphates in a massive program to lessen dependence on sheep and wool production.(34) Land is being upgraded from sheep grazing to cattle grazing and crop land and diversification has been accomplished and maintained.

Areas employing intensive agronomic techniques generally consume greater than 10 kilograms per person annually. Regions of the world with relatively unsophisticated practices use much less; Asian agricultural consumption (excluding Japan) is

TABLE 5

WORLD POPULATION AND PHOSPHATE FERTILIZER CONSUMPTION, 1970 AND PREDICTIONS FOR THE YEAR 2000

(million persons; thousand metric tons P_2O_5)

Location	1970 Population (ref. 29)	1970 P_2O_5 Fertilizer Consumption (ref. 19)	1970 Per Capita P_2O_5 Fertilizer Consumption (kg)	2000 Population (ref. 29)	2000 P_2O_5 Fertilizer Consumption @ 1970 levels	2000 P_2O_5 Fertilizer Consumption @ 22.5 kg/person
WORLD	3,636	20,427	5.62	6,494	30,340	149,909
ASIA	2,056	2,496	1.21	3,778	4,571	85,005
P.R. of China	774	512	0.66	1,295	855	
India	555	420	0.76	1,063	808	
Pakistan (a)	137	65	0.47	295	139	
Indonesia	121	66	0.55	242	133	
Japan	104	697	6.70	159	1,065	
EUROPE	462	7,301	15.80	568	8,974	12,780
East	127	2,106	16.58	156	2,586	
West	335	5,195	15.51	398	6,173	
USSR	243	1,916	7.88	330	2,600	7,425
AFRICA	345	506	1.47	818	1,202	18,405
NORTH AMERICA	228	6,351	27.86	333	9,277	9,402
United States	206	5,950	28.88	305	8,808	
CENTRAL AMERICA	93	176	1.89	231	437	5,190
SOUTH AMERICA	190	483	2.54	422	1,072	9,495
OCEANIA	19	1,198	63.05	35	2,207	2,207

(a) includes Bangledesh

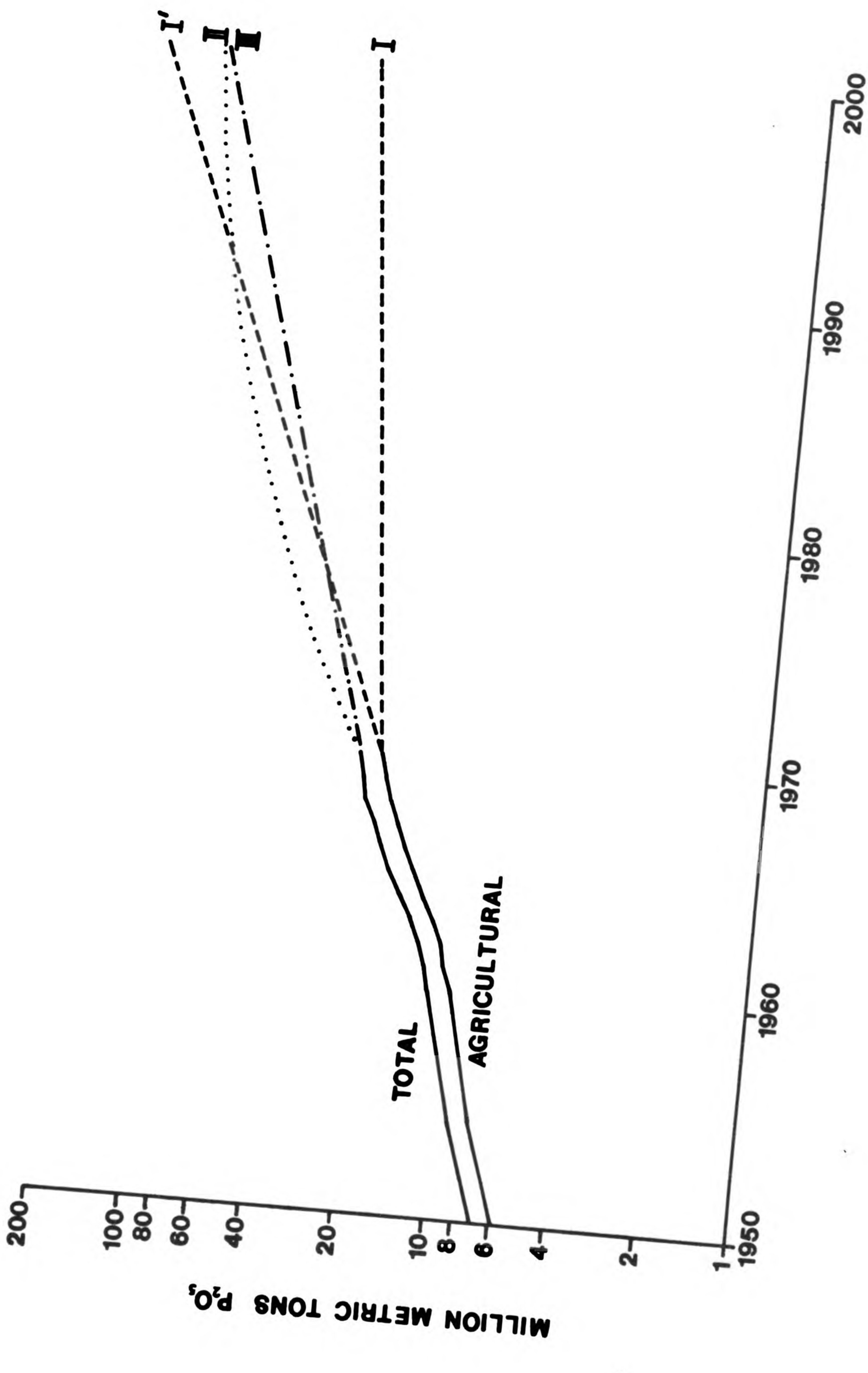
less than one kilogram per person annually.

The first set of predictions of phosphate consumption in the year 2000 from Table 5 is derived from 1970 per capita usage combined with population forecasts for 2000. Assuming a static condition in all variables except population, annual world consumption will increase more than 50% to about 30 million metric tons. From these projections, a viable lower limit can be established for future consumptive patterns up to the year 2000. These data are plotted in Figure 8 and designated "I".

A tentative upper limit can be formulated utilizing the same procedure. If all the less developed nations of the world applied phosphates at rates employed by more developed regions, consumption by the year 2000 would increase by a factor of ten. Assigning a figure of 22.5 kilograms per capita annual consumption (an approximate median of higher usage regions), the world's annual consumption would reach nearly 150 million metric tons P_2O_5. Regions with levels greater than 22.5 kilograms are held constant. These data are also plotted in Figure 8 and indicated by "I'". It is doubtful that the world would have the capability in the year 2000 to annually purchase, transport and distribute this quantity of fertilizer, equivalent to about 500 million metric tons of raw materials. However, the range defined by high and low projections creates realistic limits in which a more accurate future use pattern may be forecast.

Figure 8. World phosphate consumption, 1950-1970, projected consumption to 2000. (from Harre[16] and Table 5)

I & I': population based estimates, Table 5
II: OECD projection
III: U. S. Bureau of Mines projections


MILLION METRIC TONS P_2O_5
200
100
80
60
40
20
10
8
6
4
2
1
1950
1960
1970
1980
1990
2000
TOTAL
AGRICULTURAL

A number of national and international agencies monitor the phosphate rock and derivative industries of the world. The Organization of Economic Co-operation and Development (OECD), a "free-world" international association, has undertaken numerous analyses of phosphate rock reserves, phosphate fertilizer and world trade and consumption of these commodities. The Development Center of the OECD has predicted future use patterns utilizing a more comprehensive structure than population-based estimates made earlier.[17] Factors cited are:

1. estimates of installed capacity of regions for production of rock, fertilizers and industrial commodities
2. fertilizer capacities by manufacturing process; aciduation, thermal and nitrification
3. the rate of installation of future production facilities

A rate of growth is forecast for the 1970's based on extrapolation of historical data within the above constraints. Total annual world consumption will expand by 7.7% because of rapid increases in individual developing countries of about 20% and in the Soviet Union of about 11%. The balance of the century is expected to show an overall slowing of the trend caused by decreasing rates of increase in the United States and Europe as well as stabilizing use patterns in developing nations. Projection of OECD estimates puts consumptive levels in the year 2000 at about 100 million metric tons P_2O_5, about 15 kilograms per capita. This data is shown in Figure 8 and marked "II".

The United States Bureau of Mines is another organization which scrutinizes mineral commodities and formulates predictions of future consumptive patterns. Phosphate demand has been estimated by the Bureau on the basis of projected historical trends influenced by limitations of financing, transportation, distribution and utilization capabilities.[16] Continued growth at the rate of 6% experienced in the 1950's and 1960's would place 2000 annual consumption at about 125 million metric tons P_2O_5. Investigations cite the uncertainty of projections caused by problems of a technical, political or economic nature encountered by developing nations. Therefore, a lower growth rate of 4.2% has been formulated placing 2000 levels of consumption at about 98 million metric tons P_2O_5 or 15.7 kilograms per person. This trend is reflected in Figure 8, designated "III".

Additional activities by individual nations could significantly affect development of world phosphate consumption and shift projected curves. These items are by their nature uncertain and consequently are not numerically included in calculations of long-run demand. The distribution of phosphates under "free-market" conditions varies regionally. Present industrial use by the United States and other developed areas is as great as 25% while other regions consume a very low percentage in industry. (Table 6) Although different final production methods are utilized for agricultural and industrial phosphates, both draw on the same pool of resources and require the same initial transportation, extraction

TABLE 6

DISTRIBUTION OF PHOSPHORUS IN REGIONAL MARKETS

	Agriculture	Industry
North America	74.9	25.1
West Europe	78.1	21.9
Japan	84.4	15.6
East Europe	94.5	5.5
Oceania	97.2	2.8
Others	98.1	1.9
TOTAL	84.7	15.3

Source: Organization for Economic Co-operation and Development, 1972. Phosphate Rock and Phosphatic Fertilizers in the World. (ref. 17)

and beneficiation. Countries in which consumer demand is given greater recognition may experience competition for resources.

A consideration of greater potential impact is the possible, albeit unlikely, implementation of massive fertilizer programs in those countries with a very large population and very low present consumption levels. Evidence of such practices was shown earlier by the Australian government's phosphate fertilizer subsidy program. The People's Republic of China, India, Pakistan-Bangladesh and Indonesia collectively represent 43.7% of the world's people in 1970 and 44.6% of 2000 estimates. (Table 5) All of these nations consume less than one kilogram P_2O_5 per person annually in agriculture. One or more of these countries rapidly adopting intensive agricultural practices comparable to those of North American or Europe would cause a marked deviation in world consumptive patterns, severely affect the international price of raw fertilizer materials and place considerable stress on the production capabilities of the world phosphate industry.

5.3 United States consumption and future demand

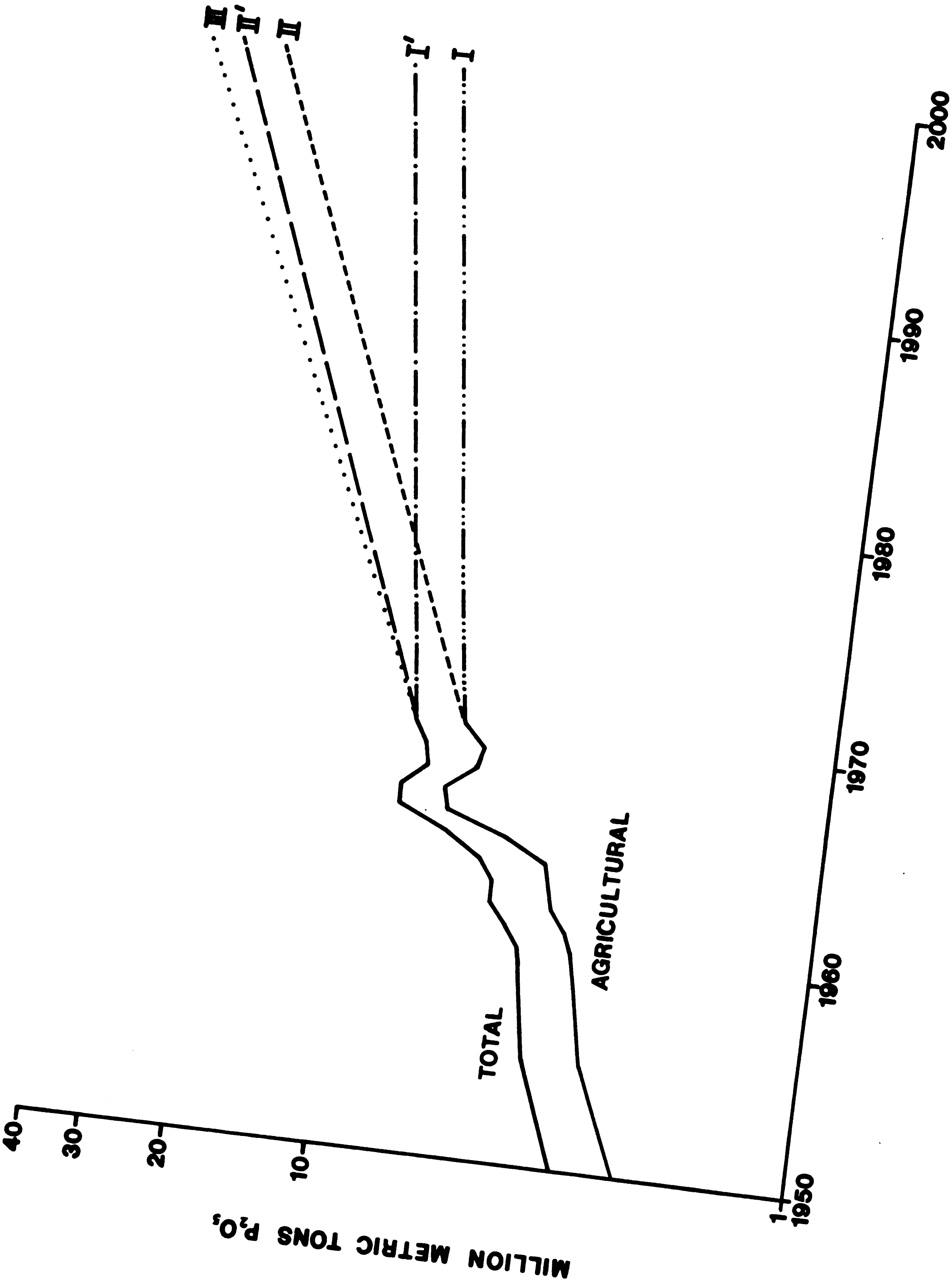
Consumption of phosphorus in the United States has evolved into a sophisticated, high volume operation. The pattern of use and diversity of end products is typical of developed nations of the world. The U. S. produces and consumes more phosphates than any other country and channels the greatest amount of phosphatic materials into industrial usage. (Figure 7 and Table 6) The structure of the industry as a whole is unique compared to most of the world in that it exhibits vertical integration, possessing sizeable reserves and facilities for utilization to the point of application.

Annual percentage increases in domestic consumption will be significantly lower than the rest of the world while absolute values will continue to be high. The potential role of the United States in supplying world demand for phosphatic fertilizers shifts projections upward by as much as 100%.

The U. S. population in 2000 is estimated at 305 million (Table 5). Combined with 1970 per capita consumption the resulting projections place agricultural and total annual consumption at 8.8 and 11.1 million metric tons, respectively. These data are plotted in Figure 9, designated "I" and "I'".

Figure 9. United States phosphate consumption, 1950-1970, projected consumption to 2000. (from U.S.D.I., Minerals Yearbook, 1971[8] and Table 5)

I & I': population based estimates
II & II': U. S. Bureau of Mines projections
III: U. S. Comm. on Population Growth and the American Future projections


MILLION METRIC TONS P2O5
40
30
20
10
1
1950
1960
1970
1980
1990
2000
TOTAL
AGRICULTURAL
III
II'
II
I'
I

Like the rest of the world, the key determinant of demand is population, although the effect is significantly greater in the United States. The mature U. S. industry precludes any implementation schemes which could double or triple consumption in a short period of time. Additionally, a greater share of total U. S. consumption is directed toward consumer oriented products, and involved in industrial processes, both of which are subject to population pressures and demand.

The Bureau of Mines has forecast growth of phosphate consumption to the year 2000, correlating population growth with fertilizers and detergents. Gross National Product is used as an indicator of demand for animal feed supplements and industrial uses other than detergents with technical and other contingencies included where applicable.[16] These data are summarized and presented in Table 7 and median values are illustrated in Figure 9 (II and II').

The 1970 per capita rate of 28.88 kilograms annually is expected to be maintained in future periods resulting in about 17 million metric tons P_2O_5 annually. The role of the U. S. in feeding the world's people now and in the balance of the century could possibly double demand to about 33 million metric tons.

Demand for detergents and soaps is also derived from population statistics. However, the use of phosphorus in these products is threatened by reduction or prohibition of use in relation to environmental degradation and could possibly result in demand dropping to zero by 2000. Therefore, a conservative maximum estimate of about one-half

TABLE 7

PREDICTED UNITED STATES DEMAND FOR PHOSPHORUS IN THE YEAR 2000
(million metric tons P_2O_5)

	Low	Median	High
Agricultural:			
Fertilizer	16.91	24.87	32.82
Industrial:			
Detergents and soaps	0.00	0.26	0.52
Plating and polishing	0.88	0.95	1.01
Animal feed	0.63	0.76	0.88
Other	3.79	3.91	4.03
TOTAL	22.21	30.75	39.26

Source: Lewis, R. W. 1970. Phosphorus, pp. 1139-1155. In Mineral Facts and Problems. U. S. Dept. of the Interior, Bureau of Mines, Circular 650. (ref. 6)

million metric tons P_2O_5 is offered in the event of feasible phosphate removal from sewage effluent.

There are no substitutes for phosphorus in animal feed and it is estimated that future demand will correspond with GNP growth, resulting in about 880,000 metric tons P_2O_5 annual consumption. Similarly, no technological shifts are foreseen for other industrial uses and demand is expected to increase to about 4.9 million metric tons P_2O_5 by 2000.

A final evaluation is offered which bases findings of mineral forecasts on comprehensive macroeconomic input-output relationships. In reports to the U. S. Commission on Population Growth and the American Future, considerable weight has been given to economic and technological aspects of phosphorus, production and use of commodities and domestic supplies.[35] Projections of phosphate demand are preceeded by reviews of population dynamics and United States participation in world trade. The conclusion reached places 2000 annual consumption at 26.7 million metric tons P_2O_5, illustrated in Figure 9 (III).

6. DEPLETION OF PHOSPHATE RESERVES

6.1 World reserves

Knowledge of phosphate rock reserves has increased regularly in the past 75 years. Estimates of known reserves in 1925 were 6.4 billion metric tons, which was increased to 16 billion in 1942.[36] In the early 1950's, the figure had risen to 43 billion metric tons[37] and further to 50 billion in the 1960's.[23] Compilation of current data contained in Table 1 establishes a current estimate of phosphate rock at 159 billion metric tons representing about 43 billion metric tons P_2O_5.

Phosphate rock has been regarded by many as a commodity with no end, in much the same manner other fund resources have been viewed and consequently mismanaged. Reports of phosphates depict reserves as vast, of infinite duration,[2] giving rise to no questions of depletion or problems,[38] and others employing similar adjectives. The time of depletion of phosphate reserves has been estimated to occur as rapidly as the year 2200,[39, 40] and as far distant as 1000 years.[41] Reserves are more than adequate to satisfy short-run demand for the next 200 years. However, a fund resource is by definition finite and the escalating pressure on phosphate resources may make depletion an eventuality in a relatively short period of time.

The actual date reserves will be exhausted is dependent upon the volume of materials consumed. Assuming the forecasts up to the year 2000 are credible, projections from that point have been made at various rates of growth for annual world consumption. Additional assumptions are required prior to formulation of the estimates:

1. Cumulative consumption for the period 1970-2000 will be about 1,823 million metric tons P_2O_5, thereby reducing reserves to 41,147 million metric tons P_2O_5.

2. Total reserves have been increased 15% to offset future discoveries, based on past exploration and potential unknown reserves in undeveloped regions of the world. The base figure is thereby adjusted to 47,319 million metric tons P_2O_5 in 2000.

3. Annual consumption for the base year is estimated at 100 million metric tons P_2O_5 from projections in Figure 8.

4. Capacity of the industry to mine and refine rock is sufficient to satisfy demand.

The combined result of the base data and assumptions is shown in Figure 10. The five curves plotted represent growth rates from zero to four percent per annum.

Figure 11 contains curves representing depletion of world phosphate rock reserves corresponding to individual growth rates in Figure 10. At zero rate of growth from the year 2000, the maximum length of time until reserves are exhausted is about 505 years, or until about 2475. The minimum time, derived from the four percent rate of increase, is about 105 years, or 2075. Neither of these appear plausible although values within the range give a more realistic estimate, possibly 0.5 to 1.5%, placing the date somewhere in the latter half of the 22nd century.

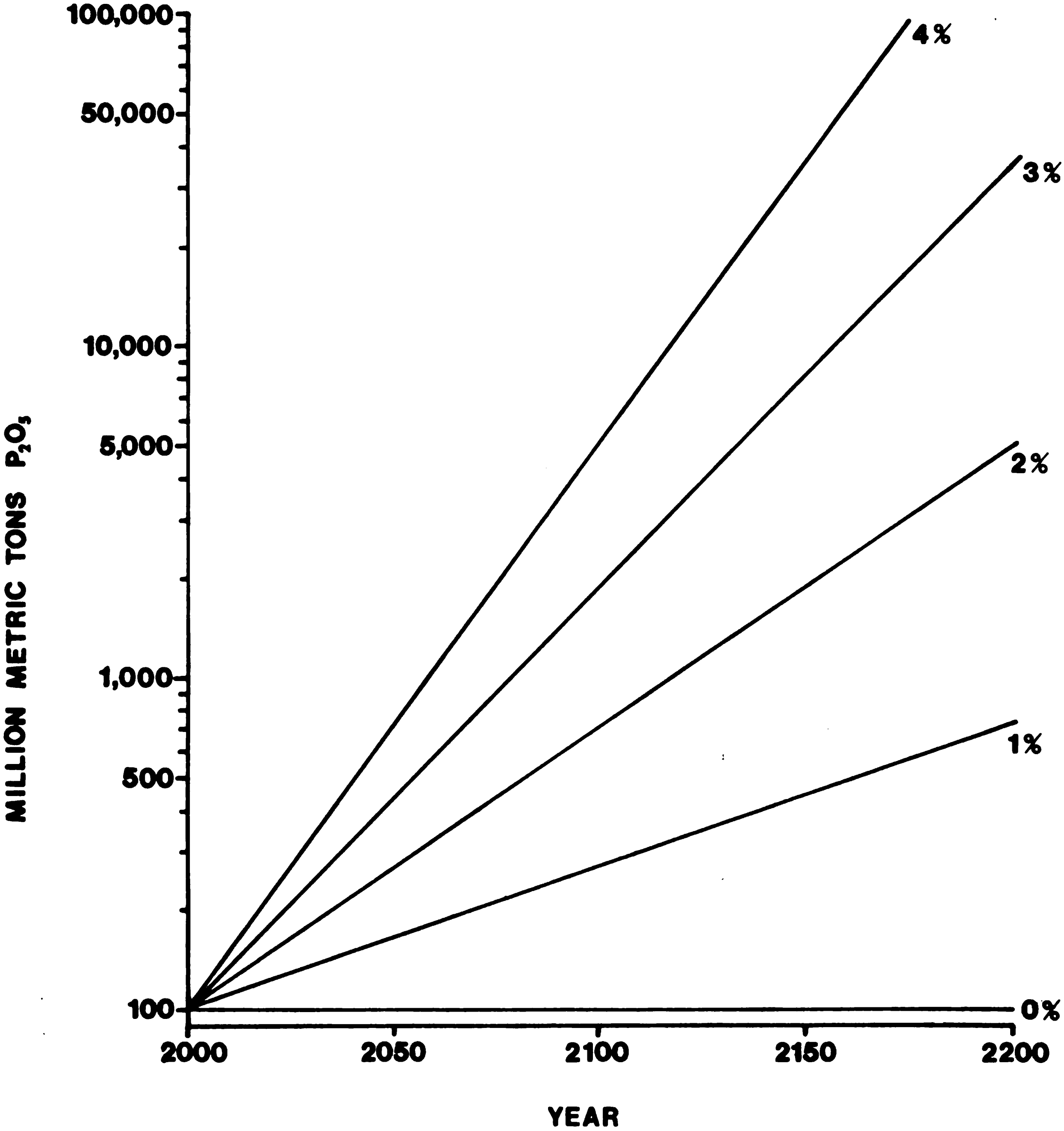


Figure 10. Projected rates of growth of world phosphate consumption.

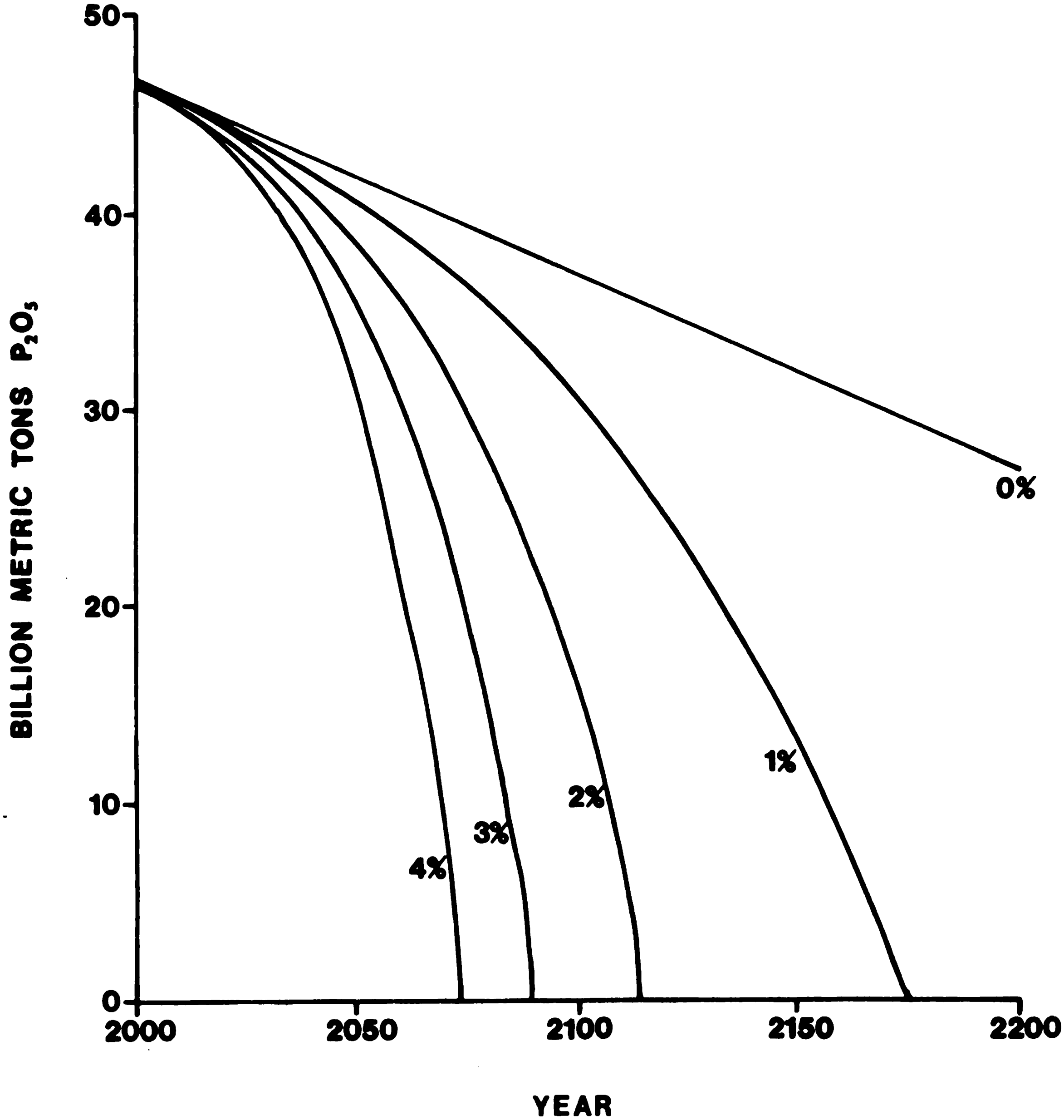


Figure 11. Schedule of depletion, world phosphate rock reserves.

6.2 United States reserves

Patterns of consumption are forecast from the year 2000 for the United States in the same manner utilized for world resources. Similarly, fundamental assumptions are made prior to derivation of estimates:

1. Cumulative demand for the period will be 517 million metric tons, reducing reserves to 11,494 million metric tons P_2O_5.

2. Total reserves are increased 15% to offset future discoveries, adjusting the base figure to 13,218 million metric tons P_2O_5.

3. Annual consumption in the base year is estimated at 27 million metric tons P_2O_5 from projections in Figure 9.

4. The industry will be capable of supplying demand.

Annual growth rates from zero to four percent are projected from base year 2000, shown in Figure 12. Figure 13 contains curves representing depletion of U. S. phosphate rock reserves corresponding to the various growth rates in Figure 12. At the zero percent rate, reserves could be expected to endure for another 520 years to about 2490 while the four percent rate would deplete reserves by about 2075, 105 years hence.

6.3 Contingencies

There are a number of issues surrounding phosphorus resources which confound smooth projection curves, both aggravating and enhancing the status of reserves. Phosphorus on the sea floor exists in the form of teeth, bones and nodules. Detrital material of this nature is remarkably common on the bottom, consisting of tricalcium phosphate containing about 34% P_2O_5.(42) Although they could not feasibly

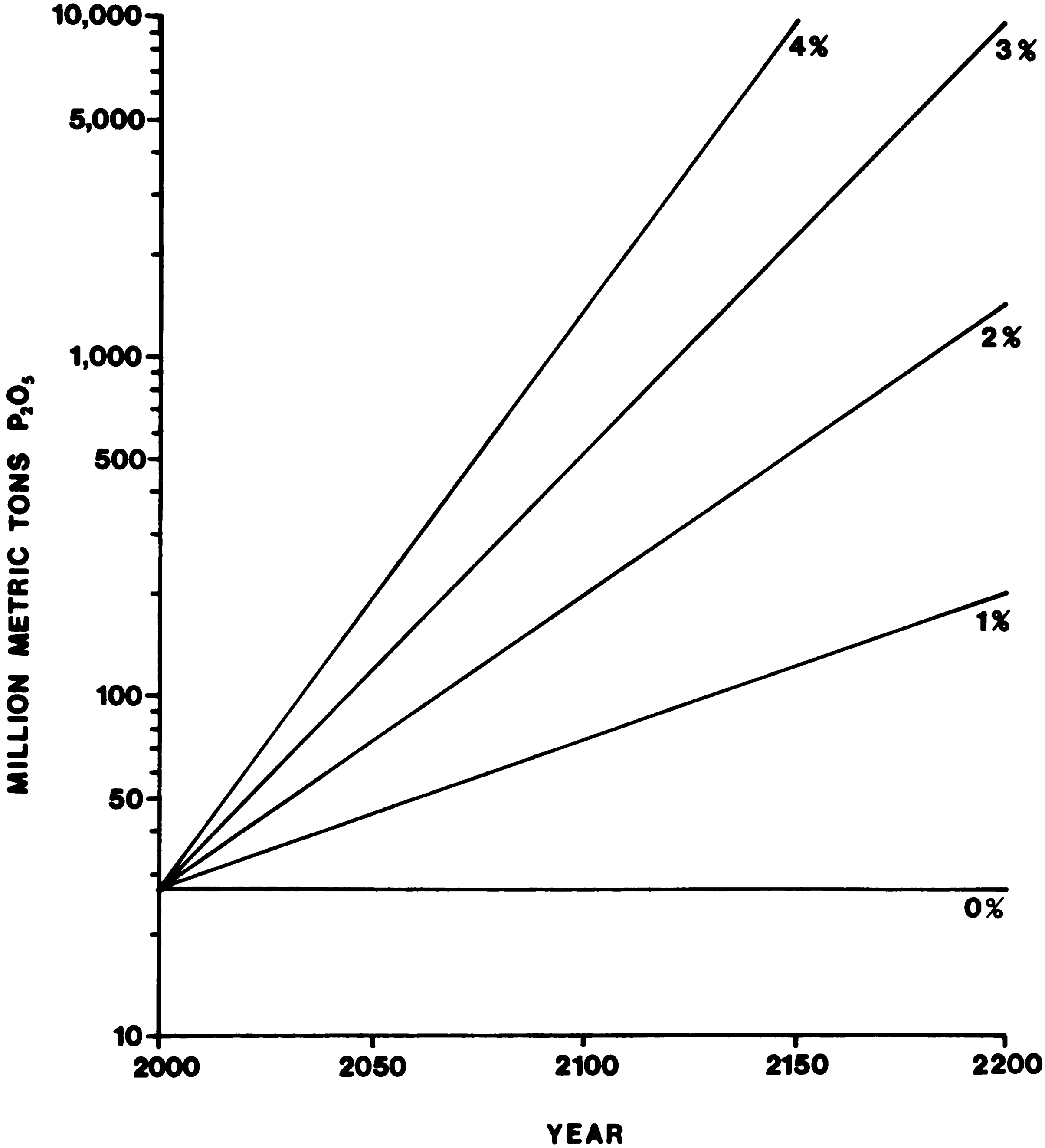


Figure 12. Projected rates of growth of United States phosphate consumption.

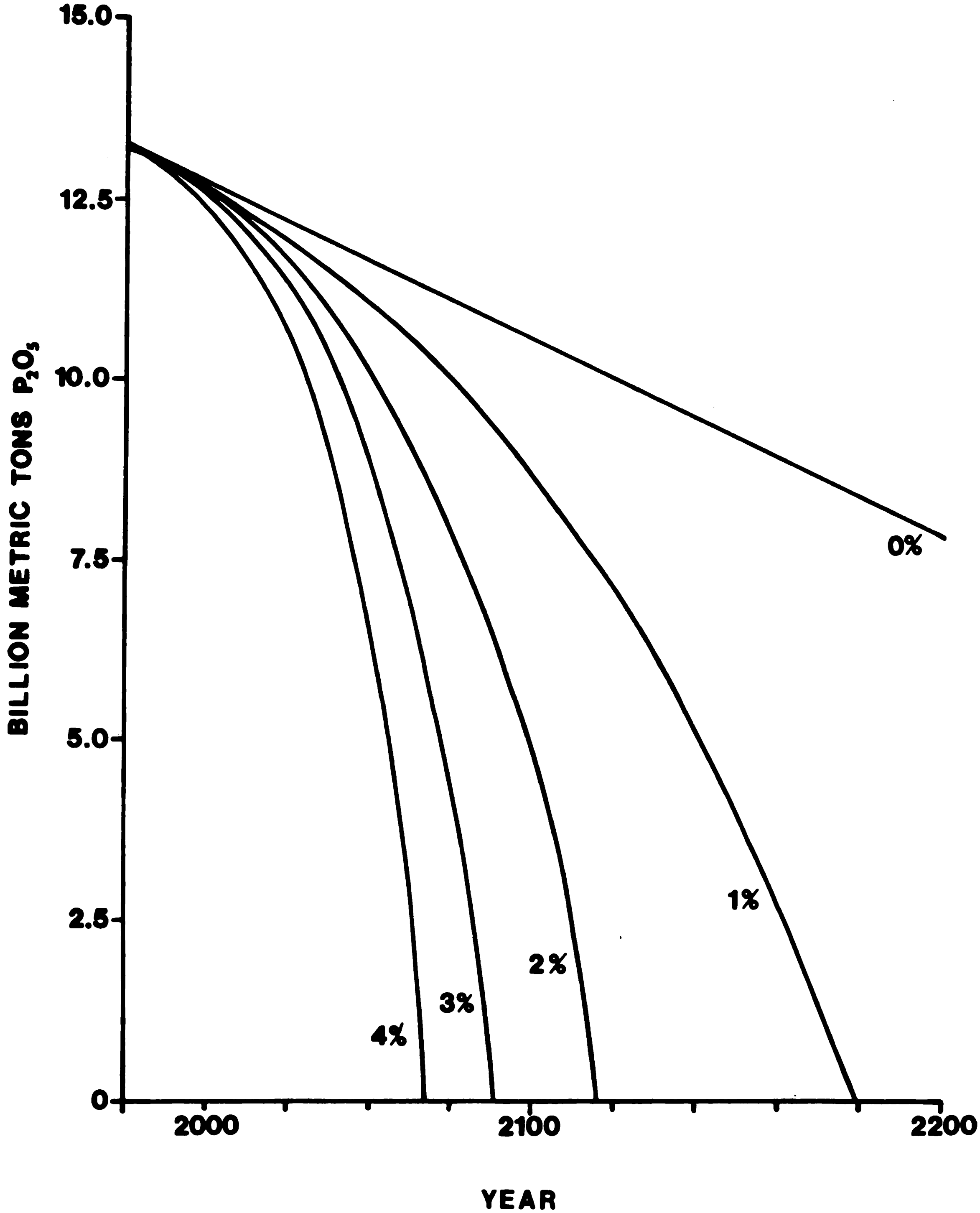


Figure 13. Schedule of depletion, United States phosphate rock reserves.

be mined alone, they could be recovered as a byproduct from any deep-sea mining operation. Phosphorite nodules are comprised of tricalcium fluorcarbonate phosphate which forms on sand, gravel and calcareous organic remains. The size varies from one millimeter up to one meter and generally consists of less than 30% P_2O_5.

Sea floor deposits of phosphate occur in areas where detritus and other sediment is excluded, usually by isolation on top of shallow banks or at the seaward edge of continental shelves.[43] Known deposits are found off Southern California, off Peru-Chile, off Southeastern United States and near the Republic of South Africa. Estimates of teeth and bones are not available and only elementary guesses have been made concerning ocean-bed deposits, placing U. S. reserves at a potential one billion tons of rock. These data are not included in reserve estimates offered earlier due to insufficient information concerning location, grade and feasibility of extraction.

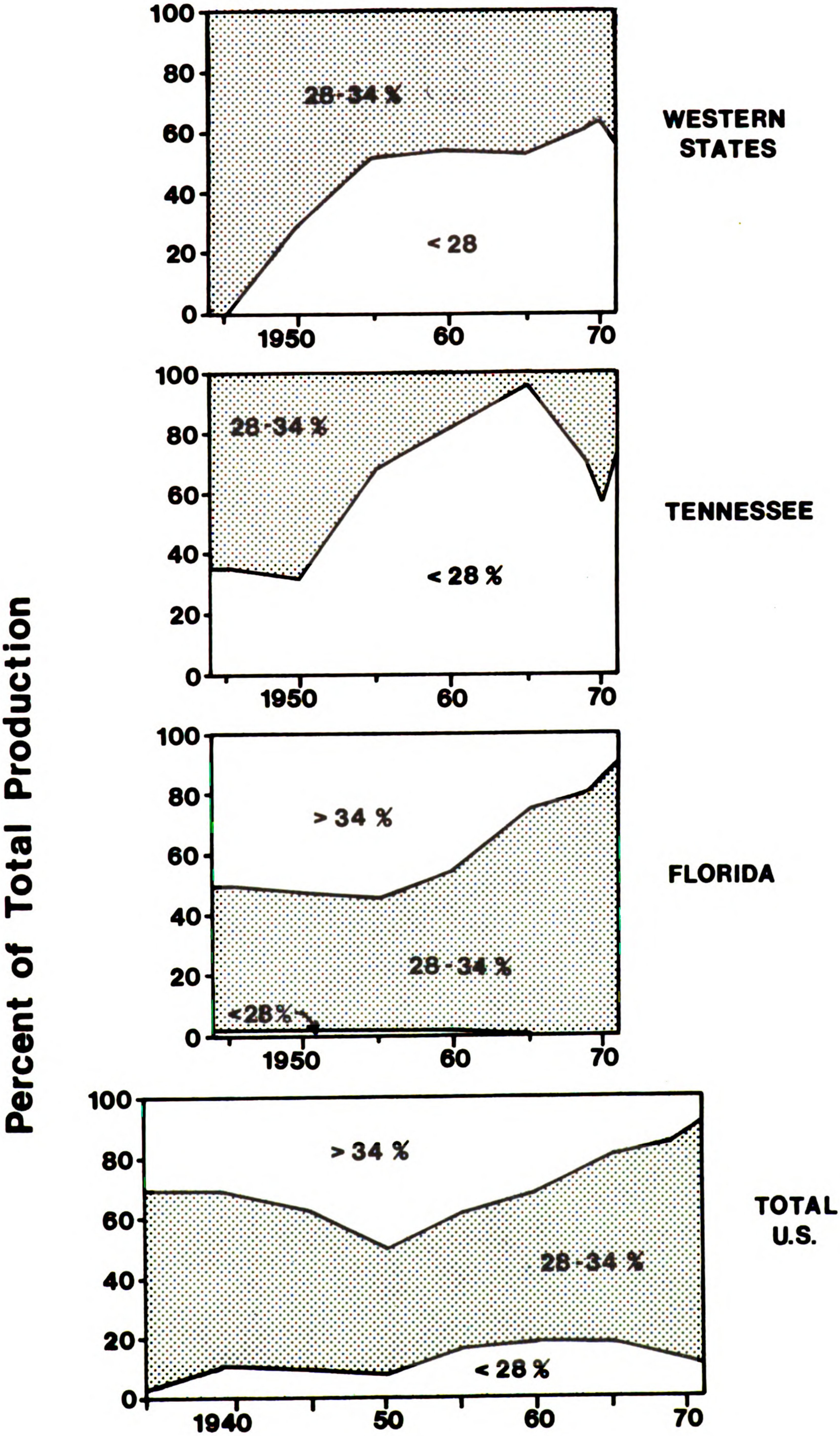
Other factors exist which do not affect the volume of known reserves and are not included in the framework of projections made to the year 2200. Rather they influence the economics of mining and refining procedures.

Florida has produced more than 80% of the United States' output of rock phosphate for domestic consumption and export markets for the entire history of the industry. This position of prominence was aided by proximity to low-cost bulk transportation via ocean vessels. Conversely, the Phosphoria Formation in the western states is approximately 1,050 kilometers inland from the nearest deep-water port. As the United States draws more heavily upon these reserves, inherent higher freight costs will be incurred.

Florida mines have similarly benefitted from the geology of the region's formation. The ratio of overburden to matrix is a prime determinant in the economic feasibility of a given mine. The ratio of Florida's mines is low, about 1:1 or 1:1.5, allowing exclusive use of open-cut mining. Much of the Western Phosphoria Formation, however, is contained in rugged mountains with much folding and intense deformation. Future extraction will necessitate underground mining with consequent increases in cost.[44] This factor should be a salient point in evaluating future exploitation of phosphate resources in the United States as nearly one-half of U. S. reserves are found in western deposits and about 35% of total U. S. production will require underground mining.

In addition to presence and accessibility of phosphates, the quality of rock produced is of significant importance. Mining in the United States has experienced an overall downward trend in the grade of rock extracted in the last 30 years. Figure 14 illustrates the ratio of grades of rock produced by each major center and the United States. The greatest percentage of high quality rock produced was in 1950 where the ratio of high:medium:low grade rock phosphate (>34%, 28-34%, <34% P_2O_5, respectively), is about 5:4:1. The ratio derived from recent production is about 1:8:1, reflecting a progressively lower percentage of high quality material available.

Figure 14. Relative quantities of high, medium, and low grade phosphate rock produced in the United States. (from U.S.D.I., Minerals Yearbook, 1971[8])


Percent of Total Production
100
80
60
40
20
0
28-34 %
< 28
1950
60
70
WESTERN STATES
28-34 %
< 28 %
TENNESSEE
> 34 %
28-34 %
<28%
FLORIDA
> 34 %
28-34 %
< 28 %
1940
50
TOTAL U.S.

Florida production typifies the condition of the industry. In the same time period, the ratio has progressed from about 5:5:0 in 1950 to 1:9:0 in 1971. The implications of the trend shown in Figure 14 are evident; less high grade rock is available for production, requiring greater amounts of all raw materials to furnish the same unit of finished phosphorus.

7. PHOSPHORUS REUSE

A final consideration which may affect resources is recycling of phosphorus presently classified as waste. The potential impact of recycled phosphatic materials is far-reaching; reducing surface water degradation brought about by current methods of disposal, altering consumptive use patterns of finished products in agricultural application and influencing levels of production of phosphate rock and depletion of reserves.

Natural and cultural pathways of the phosphorus cycle have been illustrated in Figure 1. Man's influence is in effect a short curcuit or sub-cycle of the natural process. The natural cycle requires millions of years from the time of deposition of materials to geologic uplife, completing the process and resulting in available formations. Man's current pattern of use, however, has shortened the cycle by dispersing phosphorus in low concentrations to available bodies of water. Continued unwise use of the resource will result in reducing most of the world's supply of phosphorus to a "non-available" status where recovery would require very high energy expenditures.(45)

Natural and cultural sources of phosphorus entering U. S. surface waters are contained in Table 8. The principle cultural sources are domestic sewage and runoff. These activities contribute more than 60% of all phosphorus discharged to surface waters or about 50% more than that of

TABLE 8

SOURCES OF PHOSPHORUS ENTERING U. S. SURFACE WATERS
(metric tons)

	Phosphorus	P_2O_5	Phosphate Rock Equivalent (a)	Percent of Total
NATURAL				
Rainfall	4,313	9,877		0.8
Aquatic Plants	24,289	55,622		4.3
Forest Land Runoff	188,410	431,459		33.7
TOTAL NATURAL	217,012	496,958		38.8
CULTURAL				
Sewage; human, food washing waste (b)	199,756	457,441	1,524,802	35.7
Runoff				
Urban land	8,626	19,754	65,845	1.6
Cultivated land	56,296	128,918	429,726	10.1
Animal feedlots	77,180	176,742	589,141	13.8
TOTAL CULTURAL	341,858	782,855	2,609,514	61.2
TOTAL ALL SOURCES	558,870	1,279,813		100.0

Source: Ferguson, F. A. A Nonmyopic Approach to the Problem of Excess Algal Growth. Environmental Science and Technology, Vol. 2, No. 3, March 1968. (ref. 46)
(a) average grade of rock = 30% P_2O_5
(b) 30% removal of phosphorus

the natural system. Domestic sewage represents the largest share of phosphorus discharged, 35.7% of the total.

The unfortunate consequence of massive flow of nutrients to lakes and streams is degradation of the receiving waters through accelerated aging or eutrophication. Eutrophication is a natural process which involves the biological productivity and consequent aging of natural bodies of water. The effects are the same, whether the process proceeds naturally or is hastened by activities of man. They include excess growth of algae and other plant life, depletion of dissolved oxygen, undesirable tastes and odors and a general lowering of aesthetic values.(47)

Carbon, nitrogen and phosphorus are generally considered to be limiting nutrients in aquatic productivity. While carbon and nitrogen have an atmospheric reservoir available to the aquatic environment, phosphorus is circulated almost exclusively by processes of erosion, sedimentation and biological activity.(48) Discharge of wastewater containing soluble phosphorus effectively creates a subcycle in the natural routine and increases the rate of aging in aquatic environs.

A 1971 survey of "problem lakes" conducted by the Wisconsin Water Resources Center specified 353 lakes in the United States which were reported to be in advanced eutrophic states with nuisance algal growth and/or aquatic vegetation.(49) Municipal sewage treatment plant effluent was recognized to be the cause in over 75% of those lakes evaluated. A summary of this facet of the study is as follows:

Number of eutrophic lakes receiving

municipal	194	5,328 square kilometers
feedlot discharge	14	299 square kilometers
other discharge	145	1,431 square kilometers
TOTAL	353	7,058 square kilometers

Domestic sewage is the best source available for manipulation and recycling via agricultural spray application. Phosphorus in sewage is derived primarily from human excrement and detergents. The fraction from human excreta varies with diet, usually 454-545 grams per person annually while the contribution from detergents is 1,362-1,589 grams.[50] Legislation by several state and local governments in the early 1970's now regulates levels of phosphorus in detergents and consequent input to receiving waters. The measures reduce the level of phosphorus in sewage although the increase in population served by municipal sewage treatment systems has negated the overall effect to a degree. During the period from the mid-1950's to the late 1960's, 40% of the increase of phosphorus resulted from an increase in the number of people discharging into municipal systems rather than greater phosphorus usage in personal products.[50]

Agriculture, the largest consumer of refined phosphatic materials, represents the most viable end use for phosphate in wastewater. Recycling on moderate scales has been practiced since the late 1800's. Many American and foreign projects utilize some combination of reclamation, reuse and recycling of wastewater. One well known project was initiated at Pennsylvania State University in 1963 in which secondary treatment plant effluent is sprayed on crop land and mixed hardwood and conifer woodlots. The results have been increased vegetation growth, prevention of discharge of pollutants to local receiving waters and contribution of high quality water to the local ground water supply.[51]

Muskegon, Michigan provides a second example of reuse schemes. A comprehensive plan utilizes the county's municipal and industrial wastes in a lagoon-irrigation system for growing crops on sandy soil normally considered non-agricultural land. Wastewater reuse has been used in this case for improvement of nutrient-deficient soils as well as waste disposal and elimination of effluent discharge into Lake Michigan.[52]

The average composition of municipal sewage and the effect of various treatment processes on phosphorus is listed in Table 9. The volume of phosphorus available for reuse is relatively unaffected by primary and secondary treatment processes although effluent from pond systems contains about one-half that of the other systems.

The phosphorus concentration of untreated sewage given in Table 9 is a range of 6 to 20 mg P/l. The estimated volume of domestic municipal wastewater generated annually in the United States is 29 billion cubic meters (175 million people served, 0.454 m^3 water/day, 365 days).[54, 55] The resulting range of phosphorus contained in the municipal sewage is 174,000 to 580,000 metric tons while equivalent values of P_2O_5 are 399,000 to 1,329,000 metric tons. These quantities represent 6.7-22.3% of P_2O_5 consumed as fertilizer in the United States during 1970 (Table 5).

TABLE 9

AVERAGE EFFLUENT CHARACTERISTICS OF VARIOUS TREATMENT FACILITIES

	Treatment	
	Primary (mg/l)	Secondary (mg/l)
Total Dissolved Solids	1,402	1,138
BOD	152	36
Total Nitrogen	37	21
Chlorides	461	200
Sulfate	180	300
Alkalinity	635	587
Sodium	329	239
Potassium	22	16
Calcium	96	75
Magnesium	34	45

Phosphorus	mg/l
Raw Sewage	6-20
Primary	11.0
Secondary	
Trickling filter	13.0
Activated sludge	12.9
Pond system	6.7

Source: Pound, C. E. and R. W. Crites, 1973. Characteristics of Municipal Effluents. (ref. 53)

The concentration of nutrients in industrial wastewater has been investigated by Vollenweider and found to contain from two to nine times as much phosphorus as that found in municipal sewage.[56] The highest levels are contained in wastewater from food processing operations as beet sugar processing, breweries, slaughterhouses and others. Concentrations range from 2 to 274 mg P/l with a mean value of approximately 54 mg P/l for the food industry as a whole. The volume of wastewater produced annually by food processing operations is about 4.5 billion cubic meters (205 million people, 19.8 m^3/person/year).[54] The corresponding values for phosphorus and P_2O_5 are 240,000 and 550,000 metric tons, respectively, which represents 9.2% of P_2O_5 consumption as fertilizer. Combined with estimates made for municipal sewage, the range now represents 15.9 to 31.6% of P_2O_5 consumption in agriculture and the equivalent of 8.7 to 17.2% of the rock phosphate produced in the United States in 1970.

Externalities associated with a nutrient reuse system are significant and numerous. Public health is an area of concern, both from potential ground water contamination and the affect of airborne pathogens. Soil and vegetation response requires monitoring as nearly all chemical elements are toxic at some concentration. Public acceptance may also influence the success of reuse programs because the private farmer is the final step in the process.

These and the many other factors unique to each general location and wastewater source are outweighed by the cost of application, particularly the operating cost incurred in transmission of effluent to the reuse site. For example, the additional operating cost to a system of 57,000 cubic meters per day capacity (15 MGD) pumping effluent 1.6 kilometers (1.0 miles) is about 50% of total treatment costs.[57] A significant portion of the cost increase, about 10%, is derived from power required to pump and distribute effluent throughout the system. One-half of power requirements is used in transmission to the site alone. As the distance from the treatment facility to the site increases, expenditures of energy increase at a considerably higher rate, constituting a much larger percentage of total cost. The implementation of large scale, long distance recycling programs will be inhibited by current high energy costs. Alternative energy sources, possibly nuclear power generation, could lower barriers and aid in promotion of effective reuse-recycling-reclamation efforts.

Part II is concerned with energy consumption of processes which contain as a final step the application of phosphorus on agricultural crops. Energy requirements are outlined from the point of mineral excavation to use on farm land. A similar framework is constructed for transmission of sewage treatment plant effluent to the farm via pipelines and irrigation equipment.

PART II. ENERGY CONSUMPTION

1. INTRODUCTION

In 1970 the United States utilized the equivalent to 20,000 billion kilowatt-hours of energy, 96% of which originated from fossil fuels.[58] Demand for energy has increased at an annual rate of about 4% from 1950 to 1970 and is expected to continue to increase to about double present consumption by the year 2000.[38] Demand for electricity, which represents about one-third of all fossil fuels consumed, is projected to quadruple in the same period.[59]

Pressure on finite resources of fossil fuel from escalating demand will result in rapid depletion. As stores decline, the costs of obtaining fuel from both foreign and domestic sources will rise rapidly. The net effect has resulted in a situation of increasing severity, frequently termed the "energy crisis."

Energy used in mining, the chemical industry and agriculture constitutes a significant portion of total U. S. requirements. Combined mining operations account for 10% of total industrial fossil fuel requirements and 7% of electricity generated while the chemical industry uses 25% of all industrial electricity.[38] Agriculture is an important consumer of liquid petroleum, about 10% of total United States usage, and about 3% of total electricity. Efficient power usage at this magnitude is crucial to both resources and profitability.

Those operations and processes which require large inputs of energy will become increasingly influenced by conditions of reduced supply, increased demand and consequent higher costs. Within this context, the use of fertilizers will be compared to the reuse of wastewater for plant nutrition. The comparison presented is a non-monetary evaluation of required energy to mine, refine, transport and apply a given unit of phosphate derived from mineral rock as opposed to obtaining the same quantity in wastewater from a municipal sewage treatment facility. Triple superphosphate, the fertilizer consumed in greatest quantity, is used in the example as the phosphorus-carrying fertilizer.

A mid-western farm situated 50 kilometers from Clinton, Iowa is presented as a typical recipient of plant nutrients from characteristic facilities in the United States. The location was chosen for a number of reasons, the first of which concerns transportation. Clinton is an equal straight-line distance, about 1800 km, from the center of the Florida phosphate producing region at Tampa and the center of the western region at Montpelier, Idaho. Clinton is also one of Iowa's major riverports on the Mississippi River, presenting a comparison of overland rail shipments and bulk shipments via water. The 50 km distance from Clinton to the hypothetical farm is assumed to represent normal movement of fertilizers from distribution centers to consumers. For wastewater reuse projects, Clinton has a population of about 38,000 people, capable of producing 6.3 million cubic meters of wastewater annually containing 38 to 126 metric tons of phosphorus equivalent to 87 to 289 metric tons P_2O_5.

The rate at which plant nutrients will be applied to the hypothetical farm is taken from U. S. Department of Agriculture recommendations which range from about 40 to 50 kilograms P_2O_5 per hectare (36-48 pounds/acre). Usage by general crop classification is as follows:(60)

close-growing (wheat, barley)	39.6 kg P_2O_5/ha
permanent pasture	43.9 kg P_2O_5/ha
hay	49.9 kg P_2O_5/ha
intertilled (corn, soy beans)	51.1 kg P_2O_5/ha

Phosphatic fertilizer usage is assumed to be 46 kg P_2O_5 per hectare. All processes evaluated culminate in application of nutrients to a ten-hectare plot of land, requiring a total of 460 kg or 0.46 metric ton P_2O_5 which equals the content of one metric ton of 46% P_2O_5 triple superphosphate. An equal amount of phosphorus derived from wastewater is applied to the same theoretical plot of land.

The segment of the example producing fertilizer from mineral phosphates begins with a survey of thee different types of phosphate mines; Western underground mining, Western surface strip mining and Florida strip mining. the manufacture of phosphoric acid, a basic component for triple superphosphate, is produced by the wet process or aciduation and the thermal process with electric furnaces. Production of triple superphosphate proceeds acid manufacture. Transport of raw and finished materials and the application of fertilizer to the soil constitutes the last step. A summary includes rock and fertilizer movement from the West and Florida, transported by alternate methods and applied in Iowa.

Phosphorus from wastewater is traced from the waste treatment discharge to the farm. Requisite steps in the process are collection and storage in lagoons, transfer to regional delivery points adjacent to farms and distribution to individual farms. Once on the site, application of the water is accomplished by a fixed-set irrigation system (underground piping) or by a center-pivot, portable system.

The comparison of alternative methods encompasses consumption of energy by established operations, excluding capital outlays. The power requirements of individual operations is discussed followed by summarization.

2. FERTILIZER MANUFACTURE

2.1 Phosphate rock mining

Extraction of mineral phosphate is undertaken by surface or strip mining and to a lesser extent by underground methods. Ore in Western deposits, characterized by Figure 15, is removed by both methods. Subsurface mining is employed where beds at greater depths permit while surface stripping is employed for shallower outcrops. Western mining is selective, removing high-grade ore for shipment and stockpiling low content rock for future use.

Rock from the Central Florida region differs from Western phosphates in that it is contained in a matrix of sand and clayey-sand. While Western phosphates require little or no treatment following extraction, almost all Florida rock is subjected to some form of ore dressing.(61) The ratio of waste to ore is about 30:1 in Western operations(62) where that of Florida mines is about 7:1.(63) However, waste from Western mines is removed by strippers prior to excavation of ore whereas more than one-half of the Florida mine waste must be treated with the phosphate rock. To obtain one unit of Western phosphate suitable for fertilizer manufacture, about 30 units of overburden and waste are removed. To obtain that same unit from Florida rock, 6.75 units of overburden and matrix must be excavated and three units hydraulically transported to a treatment facility. There it is

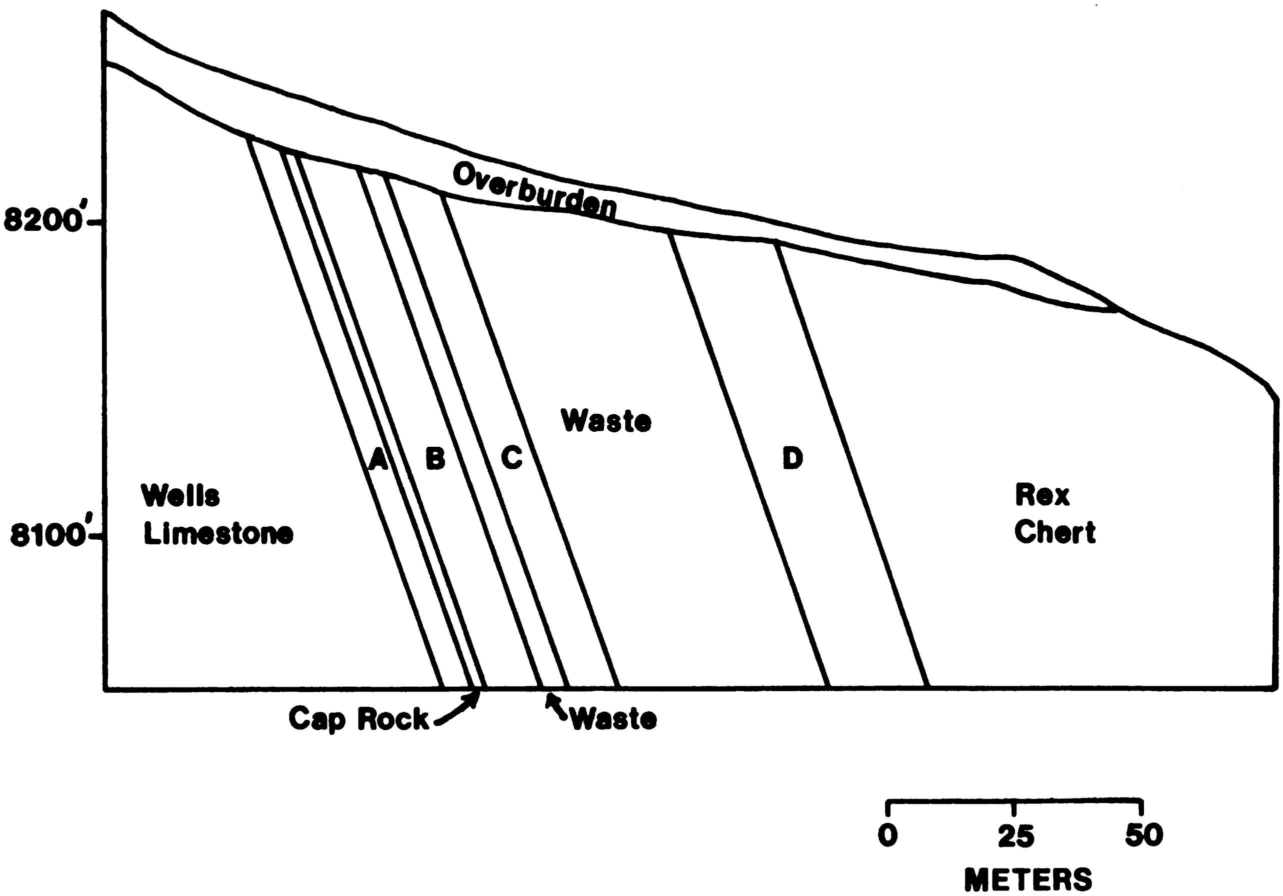


Figure 15. Typical section of the Phosphoria Formation in southeastern Idaho. (after Service and Popoff[15])

"A" Bed: +31% P_2O_5

"B" Bed: +27% P_2O_5

"C" Bed: +20% P_2O_5

"D" Bed: 18% P_2O_5, interbedded layers of high-grade phosphate and clay seams processed, concentrated to one unit, dried and stockpiled.

Estimates of energy consumption by the three mining techniques are represented in Table 10, followed by a brief explanation of each. Formulation of required inputs is difficult and economic evaluation of prospective mine sites are often accompanied by contingency factors as great as 25%. Generalizations are not applicable to Western phosphate deposits, even within a single region, because of intense deformation of phosphate-bearing strata. The following are examples of mine operations with estimates of power requirements as an indicator of approximate consumption.

Western strip mining

An investigation by the Bureau of Mines evaluated a stripping operation of phosphoria outcrop in Caribou County, Idaho.[62] Phosphatic shale was removed from the deposit and transported 2.4 kilometers by truck to a collection point. Drilling, blasting, ripping, stripping, loading and hauling required about 130 kwhr per metric ton of 31.5% P_2O_5 rock produced. The actual power consumed was about 3.9 kwhr per mt of material handled but 32 mt of waste for every ton of ore produced combined to give the value shown.

Western underground mining

Underground mining is distinguished from surface mining in a number of ways. Initially, the deposit must be developed, that is, shafts must be driven into the body of rock for ore removal. An example of an underground phosphate mine, the Arickeree Mine in Rich County, Utah, is shown in Figure 16.

TABLE 10

ENERGY REQUIREMENTS OF PHOSPHATE ROCK MINING OPERATIONS

	Ref.	Energy Source	kwhr/mt	Rock
Western Surface Mine				
stripping	62	oil	152.4	
		electric	5.6	
				158.0
haulage-ore	62	oil	157.4	
-waste		oil	10.3	
				167.7
TOTAL				325.7
Western Underground Mine				
extraction		electric		155.0
haulage-ore		oil	90.0	
-waste		oil	360.0	
				450.0
TOTAL				605.0
Florida Strip Mine				
stripping	64	electric		12.4
hydraulic transport-	65			
monitors		electric	14.5	
water supply		electric	2.4	
				16.9
beneficiation	62	oil	50.1	
		electric	50.7	
				100.8
drying	63	oil		344.5
conveying	66	electric		0.7
TOTAL				475.3

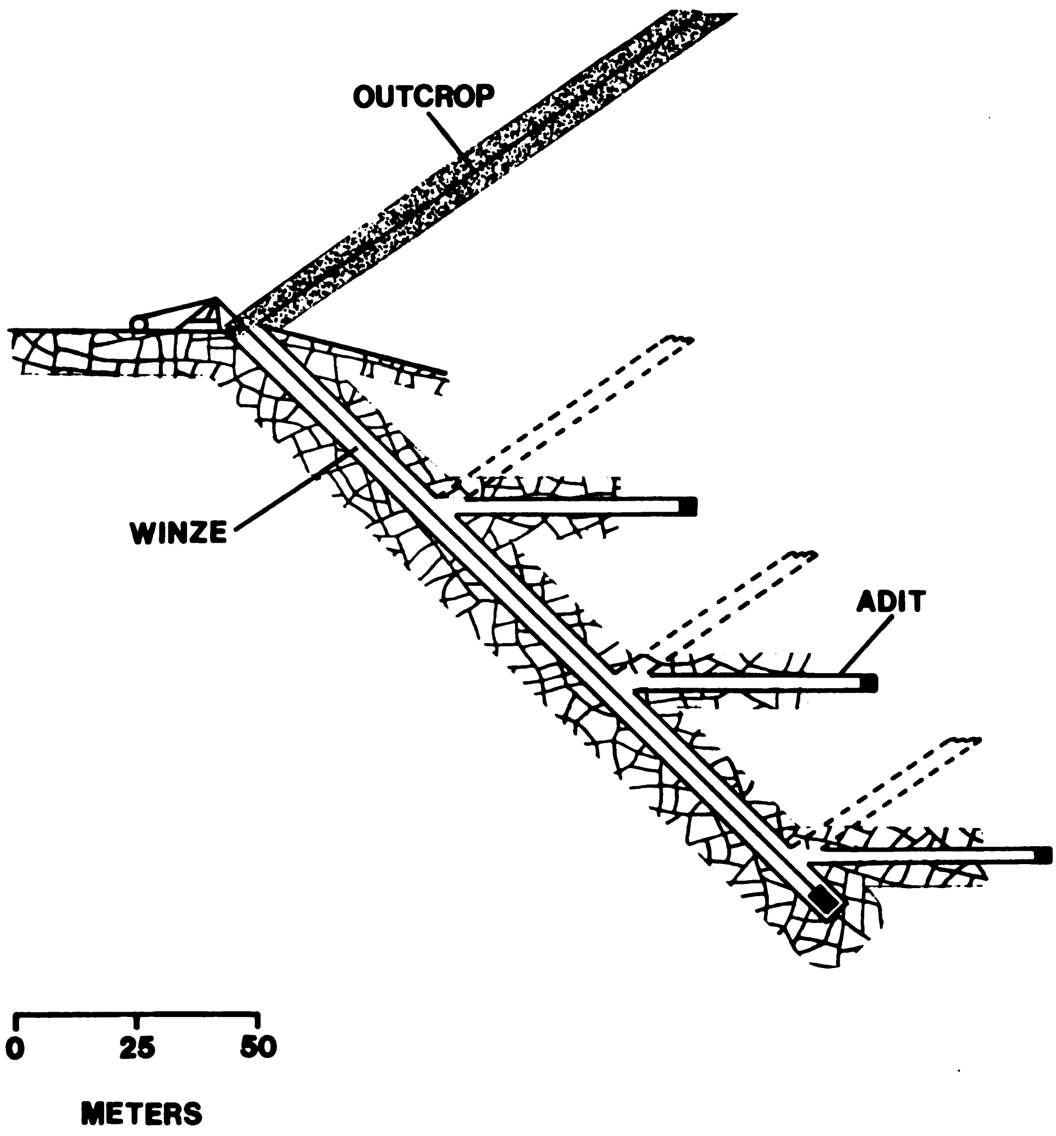


Figure 16. Section of inclined winze, Arickeree Phosphate Mine, Rich County, Utah. (after Wideman[67])

This location contains one inclined winze (main shaft) and three adits (horizontal shafts) which lead to the side of the mountain. Total length of these shafts is about 350 meters, each about 1.8 by 3.6 meters, resulting in 18,485 mt of waste material which was excavated prior to production of the first ton of rock phosphate. Following development, drifts were driven off the winze at 90 degrees into the phosphate deposit. Broken rock is hoisted from lower levels to the 100 level adit, moved out to the surface and transported by truck to a collection center.

Power requirements of underground mining operations are difficult to determine and often unavailable for specific minerals. Data regarding phosphate mines and related energy usage are incomplete and a series of underground mine examples are presented from which a reasonable approximation of required energy may be derived. Mines removing a variety of minerals in the western phosphate producing region are as follows:

Mine Example	Reference	Rock Type	kwhr/mt Rock Excavated
1	68	Variety	33.2
2	69	Granite	59.7
3	70	Granite	94.3
4	71	Sandstone	95.5
5 shaft	72	Sandstone-Siltstone	715.1
drift		Halite	480.7

The lowest value is an average of Western metal mines requiring little development. The highest is a vertical shaft lined with concrete for an atomic test in the New Mexico desert. Two of the examples, numbers 3 and 4, approximate the conditions of the Arickeree Mine in geologic nature and depth from which an estimate of 100 kwhr per mt is taken.

The development of the Arickeree Mine required an estimated 1.85 million kwhr, (18,485 mt @ 100 kwhr/mt). As the amount of ore removed increases, the initial cost of development is spread over the life of that particular mining operation and the total energy consumed per ton decreases. Therefore, the first 1000 mt of phosphate rock will require 1948.5 kwhr per mt, the second 1000 mt, 1024.3 kwhr per mt, and so on until the deposit is depleted. After about 35,000 mt of rock production the energy consumed per ton is equal to that of strip mining. Energy consumption is estimated to be about the same as that given for surface mining, or 155 kwhr per mt. A greater volume of waste material excavated and hauled from the underground mine is responsible for the disproportionate consumption of energy by the two western mines.

Florida strip mining

Mining in central Florida is simplified compared to that of the western states because of the geological nature of the area. The matrix of phosphatic materials averaging about 6 meters is located above the flat Hawthorne limestone formation of that region with an overburden of about 7.6 meters above the matrix.

Mining in the Bone Valley Formation is accomplished by what is commonly referred to as the "Florida phosphate mining procedure."[73] Stripping is undertaken by large electric walking draglines which first removes the overburden followed by excavation of the matrix. The matrix is put into a shallow sump where monitors direct jets of water at high pressure to break up lumps and create a slurry. The slurry is then pumped to processing plants at distances up to 12 kilometers. At the plant the matrix undergoes beneficiation, a series of processes where the material is washed, deslimed (removal of fine clay particles), sized and subjected to flotation (recovery of minute particles of phosphate). The concentrated rock is dried in oil-fired rotary-drum dryers and conveyed to stockpiles for shipment to phosphoric acid plants.

2.2 Phosphoric acid manufacture

Phosphate rock is a low-value, high-volume commodity and the location of phosphoric acid production facilities is primarily resource oriented. Nearly 70% of wet-process acid plants are located in close proximity to mines in Florida, North Carolina and Western States with an additional 14% located near Gulf of Mexico ports to take advantage of low-cost ocean transportation of Florida rock.[41] Thermal process acid plants are located in a similar manner with 87% of total production capacity adjacent to mines. Transportation of rock from stockpile to acid plants is usually done by conveyors which consume negligible amounts of energy, usually less than one kilowatt-hour per metric ton.[66]

Following receipt of raw phosphatic materials, the rock is ground and crushed to uniform size, sorted and classified. Power requirements for grinding and related operations is dependent on the type and condition of rock phosphate and the desired finished product. Consumption is generally 15 to 18 kwhr per mt.(74)

Wet-process phosphoric acid

Conversion of concentrated phosphate rock to phosphoric acid is accomplished by two general methods, the wet process and the thermal process. The production of wet-process acid involves aciduation of rock followed by agitation of the mixture and curing. In an operation characteristic of the industry, one metric ton of phosphate is produced as 85% phosphoric acid (H_3PO_4) containing 54% P_2O_5 and consuming 197.5 kwhr.(75) Raw material required is 3.08 mt of 31%-32% P_2O_5 rock and 2.30 mt 100% sulfuric acid (H_2SO_4). Sulfuric acid manufacture consumes approximately 8.8 kwhr per mt produced which contributes a total of 20.2 kwhr.(76) Recovery of phosphate from the rock is usually 93-95%. Low consumption of energy has contributed to the prominent position of wet-process acid in fertilizer manufacture.

Thermal-process phosphoric acid

Thermal-process acid begins with the production of elemental phosphorus in large electric furnaces proceeded by oxidation and conversion of the phosphorus to phosphoric acid. A typical facility employing three 44,000 kilowatt furnaces requires 6,586 kwhr to produce one metric ton of phosphate in 85% phosphoric acid containing 54% P_2O_5.[75] In this example, 9.88 mt of rock containing 11% P_2O_5 was used although any quantity of rock containing about 1.08 mt P_2O_5 can be used to produce a ton of acid. Recovery of phosphorus from the rock is generally 91-93%.

The greater power requirements of the thermal process has resulted in low consumption of that acid in the fertilizer industry. Production facilities are often located adjacent to low-cost energy sources as the Tennessee Valley Authority power plants in Tennessee and Alabama. The high quality of elemental phosphorus from furnace operations is best suited for industrial applications where most of the product is marketed. One distinct advantage to furnace production of phosphorus is that very low-grade ore may be used. Future production of phosphorus may require greater use of thermal installations.

Details of power consumption for both general phosphoric acid manufacturing processes are contained in Table 11.

2.3 Triple superphosphate manufacture

Production of triple superphosphate is comprised of the same basic processes used to produce phosphoric acid although phosphoric acid is used in the aciduation rather than sulfuric acid. Production follows a sequence of operations beginning with grinding of the phosphate rock.[26] The rock is then reacted with acid, mixed with mechanical agitators in large vats and fed into dryers. The resulting product is granular in form which is conveyed to curing piles

TABLE 11

ENERGY CONSUMPTION PER METRIC TON OF PHOSPHORIC ACID PRODUCED

WET-PROCESS:	
rock grinding, 3.08 mt @ 16.5 kwhr/mt	50.8 kwhr/mt
electricity	126.5
sulfuric acid manufacture, 2.3 mt @ 8.8 kwhr/mt	20.2
TOTAL energy consumption	197.5 kwhr/mt
THERMAL-PROCESS:	
rock grinding, 9.88 mt @ 16.5 kwhr/mt	163.0 kwhr/mt
electric furnace operation	6340.0
conversion (P_4 to H_3PO_4)	18.0
miscellaneous	65.0
TOTAL energy consumption	6586.0 kwhr/mt

where it remains for a period of days. The triple superphosphate is then shipped in bags or bulk to markets.

The production of one metric ton of triple superphosphate containing 46% P_2O_5 requires .65 mt of 85% phosphoric acid containing 54% P_2O_5 and .36 mt phosphate rock containing 31.5% P_2O_5. Related energy consumption is 128.6 kwhr per mt fertilizer, the bulk of which from fuel oil consumed in the drying operation.(76)

Detail of energy consumed by the production of one metric ton of 46% P_2O_5 triple superphosphate follows:

Triple superphosphate:

rock grinding, .36 mt @ 16.5 kwhr/mt	5.9 kwhr
electricity	7.7
dryers	115.0
	128.6 kwhr

2.4 Transportation and application

Transportation of fertilizer materials occurs between raw material sources and processing centers and from manufacturing plants to markets. As mentioned earlier, phosphoric acid manufacture is located near or at the site of phosphate rock production and transportation costs are negligible. Nearly 70% of U. S. sulfur and sulfuric acid production takes place in Texas and the mines and acid plants located in the coastal plain area supply the Florida industry with acid.(77) Northern Texas sulfur production provides acid for western states manufacture of fertilizer. The acid is transported to Tampa by ship from Galveston and by rail from northern Texas, near Amarillo, to the Montpelier, Idaho area. Finished triple superphosphate is shipped from Tampa to New Orleans by water and up the Mississippi River to Clinton, Iowa. Fertilizer from the western states moves by rail to Clinton. From Clinton, the triple superphosphate is moved by truck to farm locations. Pertinent transportation information including fuel consumption and equivalent energy consumption for individual shipments is included in Table 12.

The rate of phosphatic fertilizer application is variable, depending on soil type, moisture content, crops and other factors. Intertilled crops like corn are generally fertilized at the time of planting and again, later in the growing season. Close-growing crops as wheat and barley are fertilized once at or before planting. An average of 140 liters of fuel per hectare are consumed by tractors and similar equipment for farming operations in each growing season.[80] An estimated 7% of consumption, or 10 liters, may be attributed to average fertilizing operations, representing about 96.8 kwhr per hectare fertilized or 968 kwhr for a ten hectare farm. It is assumed that average power usage given is sufficient to apply one metric ton of 46% P_2O_5 triple superphosphate over one growing season.

2.5 Summary

The manufacture, transport and application of triple superphosphate fertilizer is combined and summarized in Table 13. The majority of energy consumed in both examples is by mining operations. Application of fertilizer is next with about one-third of total consumption for each situation.

TABLE 12

MOVEMENT OF RAW AND FINISHED FERTILIZER MATERIALS AND RELATED ENERGY CONSUMPTION

From	To	Commodity	Distance km	Mode of Transport	Fuel Consumed l/mt-km (1)	Fuel Consumed per mt	Energy Value kwhr/l (2)	kwhr/mt
Galveston	Tampa	Sul. acid	1223	water	.00708	8.66	11.59*	100.36
Amarillo	Montpelier	Sul. acid	1167	rail	.00496	5.79	11.59	67.09
Tampa	Clinton	Triple super	1495	water	.00708	10.59	11.59	122.68
Montpelier	Clinton	triple super	1802	rail	.00496	8.94	11.59	103.59
Clinton	Farm	triple super	50	truck	.04478	2.24	9.88**	22.12

Source: (1) Hay, W. W. 1961. Transportation Engineering. (ref. 78)

(2) Handbook of Chemistry and Physics. 1972. (ref. 79)

* diesel fuel

** gasoline

TABLE 13

ENERGY REQUIRED TO MANUFACTURE, TRANSPORT AND APPLY ONE METRIC TON OF 46% P_2O_5 TRIPLE SUPERPHOSPHATE

	FLORIDA				WESTERN STATES			
	Quantity mt	kwhr/mt	kwhr	% of Total	Quantity mt	kwhr/mt	kwhr	% of Total
ROCK PRODUCTION								
Phosphoric acid	3.08	475.3	1463.9	45.2	3.08	325.7	1003.2	38.2
Triple super	0.36	475.3	171.1	5.3	0.36	325.7	117.3	4.5
PHOSPHORIC ACID MANUFACTURE	0.65	197.5	128.4	4.0	0.65	197.5	128.4	4.9
TRIPLE SUPER. MANUFACTURE	1.00	128.6	128.6	4.0	1.00	128.6	128.6	4.9
TRANSPORTATION								
Sulfuric acid	2.30	100.4	230.9	7.1	2.30	67.1	154.3	5.9
Triple super.	1.00	144.8	144.8	4.5	1.00	125.7	125.7	4.8
APPLICATION	1.00	968.0	968.0	29.9	1.00	968.0	968.0	36.8
TOTAL			3235.7	100.0			2625.5	100.0

Transportation is also significant, requiring more than 10% of energy in both examples. The operation creating the greatest variance between Florida and western facilities is the production of rock. Florida rock requires greater treatment and consequently consumes greater quantities of energy.

3. WASTEWATER REUSE

3.1 Reuse systems

Two basic methods are employed in application of liquid wastes to soils, high-rate systems and low-rate systems.[81] Both systems apply wastewater intermittently, alternating application with resting or drying periods. High-rate systems apply large quantities of liquid, from a few meters to several meters per week. Basins containing several meters of water are preferred but furrows or large-capacity sprinklers can be used on land with uneven contour. Infiltration and drying periods are usually several weeks.

Low-rate systems apply 2.5-5.0 cm per week usually with sprinkler or spray irrigation equipment although furrows or borders are used if the topography of the site is favorable. Duration of application is generally a few hours each day or every few days. The quality of renovated wastewater is highest with low-volume systems employing spray or sprinkler techniques.

The majority of application systems are spray or sprinkler irrigation which has the greatest range of suitable soil types and has proven effective in agricultural operations.[82] Over 300 U. S. communities practice the use of wastewater with some irrigation technique.

Wastewater reuse projects consist of several basic elements. Requesite components are a source of wastewater, storage compounds, means of conveying liquids, methods of land application and often facilities which collect renovated water. The flow of wastewater and processes within the system are illustrated in Figure 17. Individual projects may reorder the sequence of components from that shown but basic processes required for operation will exist in most.

The operational framework of Figure 17 is representative of a system of wastewater reuse offered for Clinton, Iowa for comparison of fertilizer and sewage treatment plant effluent as alternative sources of plant nutrition. Each segment of the project will be discussed and related energy consumption given. Findings are summarized and applied to the example of a farm 50 km from Clinton.

3.2 Conveyance systems

Liquids are transferred by gravity flow pipelines or by pipe under pressure, determined in part by the topography of the land being traversed. Pressure lines employ very large pump stations at the beginning of the line while gravity flow is used with lift pumps at frequent intervals. Examples of both are contained in Table 14. These data and much of that to follow is taken from proposed treatment systems formulated for the U. S. Army Corps of Engineers in conjunction with regional wastewater management studies done for southeastern Michigan.[83]

The proposed Clinton, Iowa waste reuse example beings at the point where secondary effluent is discharged from an existing treatment facility. The liquid waste is transferred to storage lagoons adjacent to the plant. The water is then

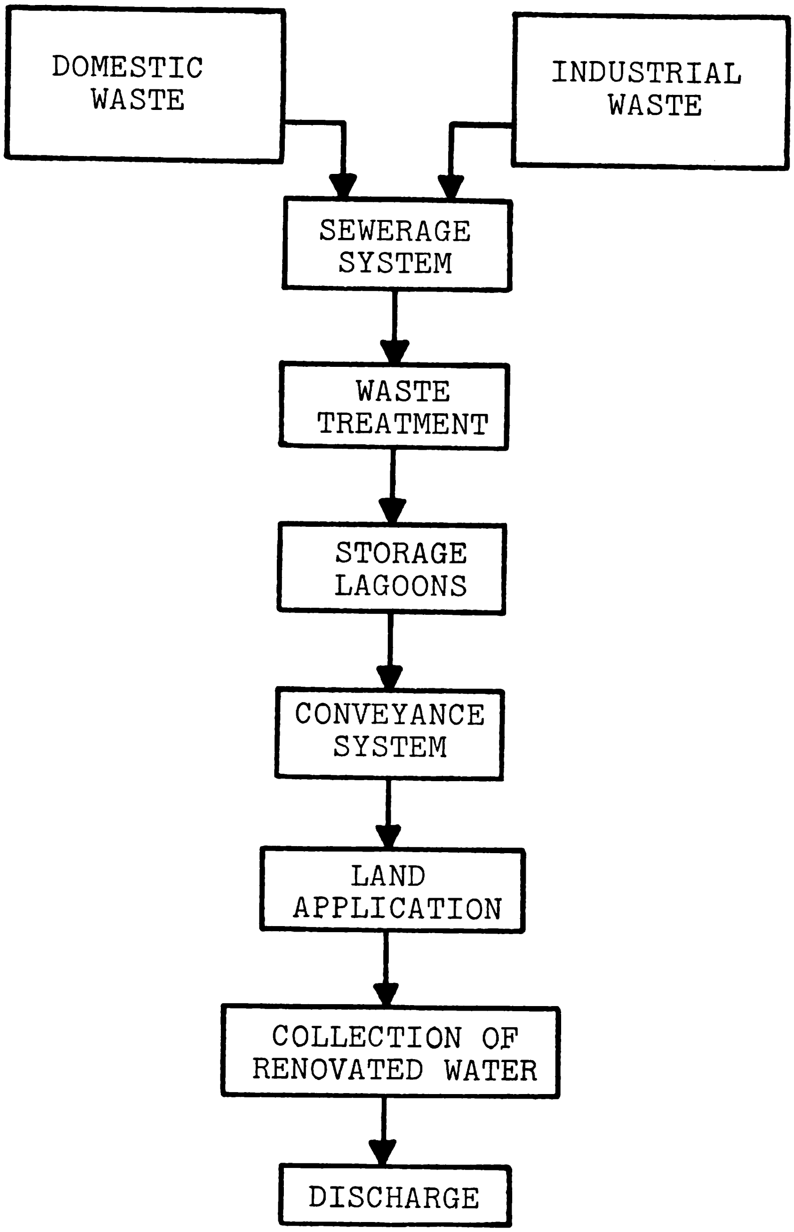


Figure 17. Flow of wastewater in reuse systems.

TABLE 14

EXAMPLES OF ALTERNATIVE EFFLUENT CONVEYANCE SYSTEMS
AND RELATED ENERGY CONSUMPTION

Type System	Length km (miles)	Daily Flow mcm* (mg)	Pump Stations	Total hp	hp/km	kwhr/mcm/km
1. Gravity	44.4 (27.6)	.023 (6)	13	754	17.0	7,605
2. Gravity	15.1 (9.4)	.045 (12)	3	345	22.8	9,330
3. Forced	117.9 (73.3)	1.139 (301)	1	97,700	828.7	13,011
4. Forced	19.5 (12.1)	.254 (67)	1	4,100	210.3	14,869

* million cubic meters (million gallons)

Source: Bauer Engineering, Inc. 1972. Lagoon Treatment and Conveyance Systems, Southeastern Michigan Wastewater Management. (ref. 83) transmitted 50 km to a regional delivery point near individual land application sites.

The southeastern Michigan locations of the systems in Table 14 are not dissimilar to the flat plains of eastern Iowa where Clinton is situated. Approximate averages of 8,470 and 13,940 kwhr/million cubic meters/km are taken for gravity and pressure systems, respectively, and will be presented in the summary.

3.3 Land application

Several techniques are employed for application of wastewater to the soil. Spray or sprinkler irrigation is the method receiving the greatest use in agriculture while other methods, as furrow and border surface irrigation are less popular. Spray operations utilize a variety of equipment, one of which is the fixed-set sprinkler system using a permanent underground distribution network. The major advantages of a fixed system is its adaptability to any crop or soil type, low labor costs and low application rates.(84) An inherent disadvantage is the capital expense for required underground pipelines.

A second type of spray applicator is the center-pivot system, a self-propelled lateral supported by wheeled towers. The rig irrigates a circular area with laterals up to 400 meters in length. The primary advantage of this method is low cost, generally 20% of a fixed-set to irrigate the same space. Disadvantages are higher labor costs and lack of adaptability to irregular-shaped or uneven fields.

Table 15 contains energy requirements for the operation of two center-pivot systems and a fixed-set system. The center-pivot rig is driven by small electric motors on the wheeled tower, consuming 10% of total requirements. The fixed-set consumes the greatest amount of energy because of the pressure system. These data are also represented in the summary.

TABLE 15

ENERGY CONSUMPTION OF SELECTED IRRIGATION EQUIPMENT

System	kwhr/mcm*	
Center-pivot		
76% coverage		
pump station	182,430	
irrigation rigs	18,243	
		200,673
91% coverage		
pump station	243,241	
irrigation rigs	30,404	
		273,645
Fixed-set		
pump station		374,416

* million cubic meters

Source: Dow Engineering, Inc. 1972. Irrigation and Collection Facilities for Southeastern Michigan Wastewater Management Program. (ref. 85)

3.4 Collection systems

The final energy consuming component of a wastewater reuse project is the collection of renovated wastewater. Drainage is often required for maintenance of aerobic conditions, which is determined by the characteristics of the individual site, as poorly drained soils or a high water table.[84] The tile drain also serves to collect the renovated water for further reuse or discharge to adjacent streams. It is assumed that the hypothetical farm in Iowa will require a collection system.

A series of gravity-flow underground laterals collect the percolate which is lifted by low-head pumps and discharged into open canals and directed to its final use. Power requirements are 50,386 kwhr/million cubic meters.[85]

3.5 Summary

The comparison of alternative systems of plant nutrition culminates in the application of .46 mt P_2O_5 to the soil. For fertilizer, this represents the amount of P_2O_5 contained in one metric ton of 46% P_2O_5 triple superphosphate, which would be applied to ten hectares of farmland, approximating normal usage. The volume of water required to obtain the same amount of phosphorus is variable, dependent upon the concentration of phosphorus in the wastewater. The range of phosphorus in treated secondary effluent is 6.7-13.0 mg P/l or 15.3-29.8 mg P_2O_5/l (Table 9). If the available wastewater contained 6.7 mg P/l, the required volume of water to obtain .46 mt P_2O_5 would be 30,412 cubic meters.

Less would be required for the upper range of 13.0 mg P/l, or 15,516 cubic meters.

Table 16 contains components of a reuse project with energy consumption appropriate to the volume of water required to obtain .46 mt P_2O_5, given upper and lower limits of phosphorus concentrations. The greatest quantity of energy consumed is in the conveyance of wastewater which is directly proportional to the distance pumped. The lower portion of Table 16 combines alternative systems to obtain four possible combinations. The lowest value utilizes gravity flow of effluent with center-pivot irrigation while the highest value uses pressure mains and a fixed-set system of irrigation.

TABLE 16

ENERGY REQUIRED TO CONVEY AND APPLY .46 METRIC TON OF P_2O_5 CONTAINED IN WASTEWATER IN A THEORETICAL REUSE PROJECT FOR CLINTON, IOWA

	6.7 mg P/1 15.3 mg P_2O_5/1 30,412 cubic meters	13.0 mg P/1 29.8 mg P_2O_5/1 15,516 cubic meters
CONVEYANCE		
Gravity 8,570 kwhr/mcm*/km @ 50 km = 428,500 kwhr/mcm*	13,032 kwhr	6,649 kwhr
Pressure 13,940 kwhr/mcm*/km @ 50 km = 697,000 kwhr/mcm*	21,197 kwhr	10,815 kwhr
IRRIGATION		
Center-pivot 200,673 kwhr/mcm*	6,103 kwhr	3,114 kwhr
Fixed-set 374,416 kwhr/mcm*	11,387 kwhr	5,809 kwhr
COLLECTION		
50,386 kwhr/mcm*	1,532 kwhr	782 kwhr
Gravity -- Center-pivot -- Collection	20,667 kwhr	10,545 kwhr
Gravity -- Fixed-set -- Collection	25,951 kwhr	13,240 kwhr
Pressure -- Center-pivot -- Collection	28,832 kwhr	14,711 kwhr
Pressure -- Fixed-set -- Collection	34,116 kwhr	17,406 kwhr

*million cubic meters

4. SUMMARY AND CONCLUSIONS

Phosphorus is one of the most important elements required for life because of its relative scarcity in the natural environment and the irreplaceable function it serves in plant nutrition. Large localized deposits of phosphate bearing rock are exploited to supplement soils in agricultural production. Man's activities have removed phosphorus from the earth, used it in a myriad of processes and disposed of much of it to available surface waters where recovery would require very high energy expenditures. Man has effectively created a sub-cycle of the natural phosphorus cycle requiring millions of years for completion.

Phosphorus consumption

Phosphorus has many applications in industry and agriculture with fertilizer manufacture representing 75 to 98% of requriements for individual nations. World population estimates for the year 2000 indicate an increase of about 80% to approximately 6.5 billion people. Food production facilities will be heavily taxed to provide enough food, even at subsistence levels. Phosphatic fertilizer is seen as one important input for increasing the yield of agricultural cropland.

Forecasts of phosphorus consumption for the year 2000 indicate a 500% increase in world demand while that of the

United States is expected to increase by about 400% in the same period.

Phosphorus reserves

Phosphate reserves have been historically regarded as providing an endless supply and have experienced little or no resource conservation or planned exploitation. A 40-year trend in U. S. mine production indicates decreasing phosphorus content in ore removed. United States reserves, particularly those found in the western states, are increasingly less accessible and will require greater amounts of energy to remove and process the contained phosphate.

Schedules of depletion have been formulated based on population growth, patterns of consumption, potential future demand and other factors. World reserves are predicted to endure for 105 to 505 years while United States reserves reflect a slightly broader range of 105 to 520 years. A plausible date of depletion is estimated to occur for both in the latter half of the 22nd century, assuming present patterns of consumption continue.

Phosphorus reuse and related energy consumption

An alternative to the use of mined and refined phosphorus is recycling of phosphorus which has been used and disposed of as waste. A maximum estimate of 1.9 billion metric tons P_2O_5 representing more than 30% of P_2O_5 consumed in fertilizers is discharged annually in the United States in municipal and industrial wastewater.

Application of phosphorus in wastewater for plant nutrition encounters many barriers, the most significant of which is the large amount of energy required. Reuse projects implemented in a period of time experiencing rapid depletion of fossil fuel reserves and consequent scarcity will realize abnormally high operating costs derived from the purchase of energy.

The comparison made of alternative systems of supplemental plant nutrition reflects a significant variation between energy requirements associated with phosphatic fertilizer usage and wastewater reuse. Energy consumed by application of a given unit of phosphorus contained in wastewater was four to ten times greater than an equivalent amount contained in manufactured fertilizer. These data, summarized from preceeding sections, are as follows:

Fertilizer manufacture, transportation and application		
Florida phosphates	3,235.7	kwhr/mt
Western states phosphates	2,625.5	kwhr/mt
Wastewater reuse		
gravity flow, center-pivot system		
P conc. 6.7 mgP/l	20,667	kwhr/mt
P conc. 13.0 mgP/l	10,545	kwhr/mt
Pressure flow, fixed-set system		
P conc. 6.7 mgP/l	34,116	kwhr/mt
P conc. 13.0 mgP/l	17,406	kwhr/mt

Transmission of the large volume of water carrying minute concentrations of phosphorus consumed the greatest amount of energy. Total power requirements are influenced greatly by the distance from the source of the wastewater to the site of application and the concentration of phosphorus in available wastewaters.

Total cost evaluation

This analysis has compared alternative methods of supplemental plant nutrition, internalizing requisite components of each system. Evaluation has been confined to a single input to agricultural production, albeit a very important one, and the sources from which it may be derived. Utilization of phosphorus contained in waste material has been presented as a substitute for rapidly diminishing rock phosphate reserves, requiring a significantly higher expenditure of energy. The unfavorable status of wastewater reuse for obtaining phosphorus which has been shown in this paper reflects a singular analysis of one segment of a situation requiring more comprehensive evaluation.

Other salient factors should be considered in an encompassing total-cost accounting of material recycling, including both resources and wastewater. Readily accessible reserves of phosphate rock are undergoing rapid depletion which will cause higher levels of energy usage to extract and process remaining supplies. Other plant nutrients, each requiring large amounts of energy for commercial preparation, are available for agricultural use via land application of municipal sewage effluent. The net result of comprehensive assessment of these and other contributing factors will be to enhance the economic position of wastewater reuse. Analyses similar to that given phosphorus are necessary for each segment in a total-cost evaluation.

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