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It has been estimated that the energy consumed in the production of all fertilizer products in the United States (roughly 45,000,000 tons of products) amounts to somewhat less than 3% of the total energy consumed in this country. This could be considered to be an almost negligible amount until the actual quantities in the United States alone are considered, i.e., an estimated 1.9 quadrillion Btu (1.9×10^{15}) for fertilizer production out of a gross consumption of about 75 quadrillion Btu (75×10^{15})/year (12). World production of fertilizers outside the United States increases this energy consumption by another 8 to 10 quadrillion Btu/year. Clearly, the magnitude of energy consumption by the fertilizer industry warrants a detailed energy evaluation of the processes involved and of both near-term and far-term (10-year) possibilities of reducing these requirements by substitution of fuel or feedstocks, processes or other products to increase energy efficiencies.

This evaluation of the energy requirements of the fertilizer industry was made under the sponsorship of the International Bank for Reconstruction and Development (Industrial Projects Department).

The fertilizer processes described have been chosen as representing the most widely adopted processes for the production of available nitrogen, phosphorus, and potash, the three primary plant nutrients. A brief description of each process is included to identify the major energy-consuming unit operations within each process.

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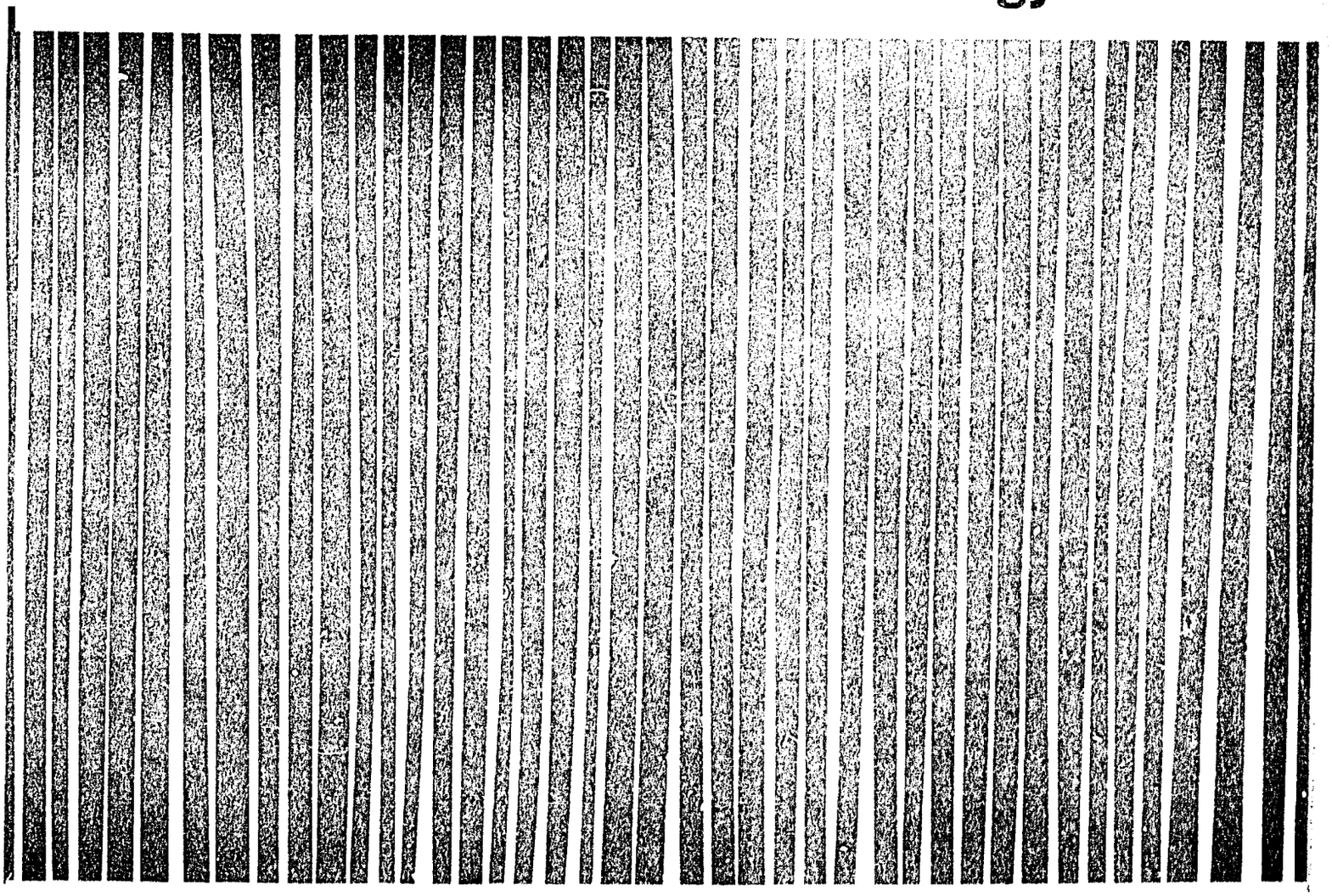

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Estimates used in this publication are based on January 1974 costs. Tremendous escalations have occurred since. For example, a 1,000-ton-per-day ammonia plant (battery limits) that cost $28 million in January increased to $40 million by July and to about $50 million by late 1974.

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RSSA TVA 01-74

Prepared by

G. M. Blouin

National Fertilizer Development Center, Muscle Shoals, Alabama 35660

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INTRODUCTION

It has been estimated that the energy consumed in the production of all fertilizer products in the United States (roughly 45,000,000 tons of products) amounts to somewhat less than 3% of the total energy consumed in this country (3, 4). This could be considered to be an almost negligible amount until the actual quantities in the United States alone are considered, i.e., an estimated 1.9 quadrillion Btu (1.9×10^{15}) for fertilizer production out of a gross consumption of about 75 quadrillion Btu (75×10^{15})/year (12). World production of fertilizers outside the United States increases this energy consumption by another 8 to 10 quadrillion Btu/year. Clearly, the magnitude of energy consumption by the fertilizer industry warrants a detailed energy evaluation of the processes involved and of both near-term and far-term (10-year) possibilities of reducing these requirements by substitution of fuel or feedstocks, processes or other products to increase energy efficiencies.

This evaluation of the energy requirements of the fertilizer industry was made under the sponsorship of the International Bank for Reconstruction and Development (Industrial Projects Department).

REPRESENTATIVE FERTILIZER PROCESSES

The fertilizer processes described below have been chosen as representing the most widely adopted processes for the production of available nitrogen, phosphorus, and potash, the three primary plant nutrients. A brief description of each process is included to identify the major energy-consuming unit operations within each process.

The "base case" is the condition of capital investments and operating costs estimated to exist in the United States in January 1974. One ground-rule of the sponsoring agency was to omit calculations of returns on capital investment; therefore, only estimated production costs are given.

Experience factors that are normally used by TVA in translating known U.S. costs to those of the average developing country (DC) invariably result in significantly higher investment costs and, therefore, in higher capitalization charges against a given process in the DCs. Operating costs cannot be generalized, but normally, fuel and electrical energy charges are higher. Labor costs are often nearly the same as those in the United States because, although hourly wages are much lower, the number of operating personnel is invariably higher often by government decree.

Plant investment factors normally used by TVA to adjust U.S. costs to the average DC conditions are as follows:

Battery limits (BL) investment, DC	= U.S. x 1.25
Auxiliary facilities, DC	= BL (DC) x 0.25
Support facilities, DC	= BL (DC) x 0.25

The sum of the items above usually represents a viable DC capital investment for an operational plant. However, it appears to be the practice of many DC governments to make a showplace of an industrial development by building a complete township with all appurtenances. This can lead to "plant investments" of double the above factors. It is felt that this should be avoided in evaluating the economics of the plant complex itself.

In the cost estimates given in this report, the fact that a given cost is expressed to the nearest cent should not be regarded as being significant. As is usual in estimates of this type, the accuracy is of the order of ±10%; however, valid comparisons of one process with another can still be drawn because errors introduced in the estimating procedure tend to be in the same direction.

AMMONIA

General Process Description

At least 90% of the world supply of fertilizer nitrogen is derived from the fixation of atmospheric nitrogen with process hydrogen as anhydrous ammonia (NH_3) in the ammonia synthesis process. Ammonia has a nitrogen content of 82.5%. The four major steps (greatly simplified here) in ammonia synthesis are: (1) Catalytic, high-temperature reaction of water (steam) with a light hydrocarbon, such as methane, followed by addition of air to supply nitrogen; or, a noncatalytic reaction with carbon (coal or oil) at high temperature and moderate pressure, with steam and less than theoretical quantities of oxygen or oxygen-enriched air to yield a "synthesis" gas mixture of hydrogen, nitrogen, and carbon monoxide; (2) the catalytic, high-temperature reaction of the carbon monoxide with additional steam to yield more hydrogen plus carbon

dioxide; (3) removal of the carbon dioxide and other impurities from the synthesis gas; and (4) catalytic, high-temperature, high-pressure reaction of the hydrogen and nitrogen to yield ammonia.

The last three steps are common to all commercial ammonia processes except when pure hydrogen is available (say, by electrolysis of water) in which case only the actual ammonia synthesis step is required. It is the first step, the production of process hydrogen, that has the widest latitude of process variations and requires by far the greatest portion of the total energy input to the process. The commercially significant variations used throughout the world are (in order of world capacities) as follows:

1. Catalytic reforming (reaction) of natural gas with steam over a supported nickel catalyst at about 750° to 800°C.
2. Catalytic reforming of straight-run naphthas (130°-150°C final boiling point) with steam over a promoted nickel catalyst at about 800°C.
3. Partial oxidation (oxygen-deficient burning) of crude or heavy fuel oil with oxygen, or oxygen-enriched air in the presence of steam at about 1400°C; in addition to the oils, nearly any liquid or gaseous hydrocarbon may be used; nitrogen is supplied from a liquid air plant.
4. Partial oxidation of coal a modification of process (3) above, which should more properly be called coal gasification, even as applied to ammonia production; in modern processes, steam and oxygen (liquid air plant) are used to gasify the coal at 1000° to 1700°C, yielding raw gases high in carbon monoxide (yields additional hydrogen after shift conversion), hydrogen, and in some cases methane. Nitrogen is also supplied from the liquid air plant.

Other sources of hydrogen for ammonia There are a number of miscellaneous sources of hydrogen, some that can be utilized with much less expensive clean-up procedures than those involved in the major processes mentioned above. These sources are: (1) coke-oven gas, (2) petroleum refinery gas, and (3) residual gas from the production of acetylene, ethylene, or chlorine. The coke-oven gas does require extensive cleanup. These gases are in each case regarded as byproducts and the only cost assigned to the ammonia plant would be that of gas purification. However, it is only in isolated cases that the gas production is of sufficiently large volume to render the scale of ammonia production economical. Only 6% of the U.S. ammonia production is from these sources principally coke-oven and refinery gases.

Importance of Fuel/Feedstock to Ammonia Production

Although this report is primarily concerned with the effects of the shortage of petroleum and its derivatives, natural gas, in similar short supply or nonexistent in nearly all industrial nations, will be treated in the same manner because of its inseparable connection with the petroleum industry, both in production and pricing structure.

The production of ammonia from some of the various feedstocks discussed previously requires the following equivalent energy inputs as combined fuel and feedstock (1, 13).

Process	Fuel/feedstock	Energy consumption Btu x 10^6/mt NH_3
Reforming	Natural gas	34.5
Reforming	Naphtha	37
Partial oxidation	Fuel oil	38
Partial oxidation	Coal	45 (minimum)

Range, energy consumption/mt N = 42 to 55 Btu x 10^6

Thus, ammonia synthesis is a highly energy-intensive process, not only in terms of the heat energy (fuel) required, but also because of the inherent economic requirement that the same fuel be used as the chemical process feed.

Near-Term Potential for Substitution of Other Fuels or Feedstocks for Current Ones

Direct substitution of fuel or feedstocks—Nearly all of the existing world capacity for ammonia production is based on natural gas, naphtha, and fuel oil, in that order. A small but growing capacity based on coal exists. The degree of flexibility in substituting feedstocks is indicated in the following tabulation.

	Design feedstock			
	Natural gas reforming	Naphtha reforming	Partial oxidation Fuel oil[a]	Partial oxidation Coal
Substitute feedstocks[b]	None	Natural gas	Any gaseous or liquid hydrocarbon	Coke Charcoal Char Fuel oil[a]

[a]Or crude oil, depending upon overall economics.
[b]Substitution not entailing high capital expenditures for equipment changes and loss of at least 1 year of income during conversion.

The dilemma of world ammonia producers is simply that by far the greatest percentage of world capacity today is based on the scarcest feedstocks natural gas and naphtha utilizing the least flexible process designs. Conversion of existing gas- or naphtha-based plants to even oil-based, partial-oxidation plants would require an additional capital investment essentially equal to the original cost of the reforming plant, taking into account the cost of removal of the existing reforming section of the plant, the inflationary trends, and the loss of income for about a year. Conversion to coal would increase the total capital investment in the

plant to about 2.5 times the original. For these reasons, there appears to be little chance of any significant near-term conversion of existing facilities to more plentiful, cheaper feedstocks, petroleum-based or otherwise.

On a worldwide basis, with political considerations aside, the only practical near-term expediency for fulfilling the growing demand—and the even greater need, based on recommended usage—for nitrogen is to concentrate on a coordinated and expeditious effort to complete current projects for ammonia production and shipping capacity in and from those areas (Mideast, Southeast Asia, North Africa, Venezuela, Canada, etc.) where natural gas is currently being flared in tremendous quantities and for liquified natural gas (LNG) production in and shipping from these same areas.

This admittedly is a contingency operation, with the ammonia export capacity ideally going to those developing nations with high population growth rates, but without indigenous feedstocks or nitrogen capabilities, and the gas export capacity going to industrialized nations with large NH_3 capacities, but with dwindling gas or naphtha resources.

However, the key words are "coordinated and expeditious." This form of international cooperation is probably a utopian ideal. Already there is a specter of near-term nitrogen overcapacity in the offing. TVA sources have identified NH_3 projects under way or firmly committed that will, by 1978-79, add about 3.6 million tons of new capacity in Canada, about 2 million tons in the United States, and about 14 million tons in the remainder of the world. LNG projects are growing rapidly as well and may have, indirectly, an added impact on NH_3 capacity. About 8 major projects are in operation, another 8 in advanced stages and firmly committed, and 10 or more in the planning stage. This capacity will, of course, be required in the long term, but there could be an interim of serious short-term oversupply.

In the United States, where 94% of existing NH_3 capacity is based on natural gas, contingency actions should be taken to give nitrogen producers the highest industrial priority, both on intrastate and interstate gas, and to reverse the trend away from coal to gas for fuel-only usage by (a) relaxing antipollution requirements in many situations, and (b) equating natural gas costs to those of other fuels to minimize the incentive for gas usage as a fuel.

Indirect substitution of fuel or feedstocks With respect to substitution of fuel (heat) energy in NH_3 synthesis, it is technically feasible in the gas and naphtha reforming processes only to substitute another fuel for that portion of the total feedstock input that is consumed in the high-temperature endothermic catalytic reforming reaction, the synthesis gas purification step, and the compression of the synthesis gas to synthesis pressure. Of the approximately 35-million Btu/ton NH_3 total input in a large natural gas reforming plant (gas turbing compressors) about 14-million Btu/ton, or 40%, is consumed as fuel. Theoretically, the use of a more plentiful, cheaper material as fuel would be more economical, and would conserve the scarcer hydrocarbon feedstock.

However, the only practical, alternate fuel that is not petroleum related is coal. The problems involved in the short-haul availability, in-plant logistics, and reformer reworking or replacement, coupled with stack gas handling (antipollution), are formidable even in the United States, where some Midwest plants are located in coal-producing areas. Nevertheless, although the economics cannot be generalized, those existing NH_3 plants located in coal-producing areas should consider this alternative. The necessary adaptations could be considered as near- to midterm capability.

Much of the above discussion may seem to have departed from the primary objective of this report—to define methods of petroleum-based fuel and feedstock conservation in the ammonia industry. However, the current worldwide shortage of nitrogen fertilizers (including, certainly, the United States) cannot be divorced from the same situation in the petroleum-based energy supply, so a discussion of the most efficient use of the available energy in this area appears to be pertinent.

The expendient approaches discussed above do not represent the optimum in economics or international financing. Those political areas with dwindling or nonexistent feedstocks still will be faced with the dilemma of high costs and high foreign exchange drains versus the growing and in many cases, desperate need for food energy for their growing populations. However, given the necessary food energy input, the increased productivity of those areas may, in many instances, significantly offset these economic drains.

Potential for Far-Term (10-Year) Ammonia Process Substitution

General consideration Given the restriction of proven process substitution for the far-term period, particularly on the scale of operation necessary to affect a meaningful reduction of consumption of petroleum-related feedstocks, there is little chance of full process substitution for ammonia synthesis in the 10-year period with which this report is concerned.

There are, however, two processes which would entirely eliminate carbon or hydrocarbon feedstocks and fuels in ammonia (hydrogen) synthesis. These are:

1. *Electrolysis of water (electrochemical)* Essentially only water, electrical energy, and nitrogen (from a nitrogen-only liquid air plant or scrubbed flue gas) are required. Unfortunately, the present-day electrolytic cells are so extremely costly that the capital

charges can be offset only by very low-cost electrical energy; it was estimated in 1969 (6) that with the best of present cell technology essentially zero electrical energy cost would be required to compete with natural gas at $0.50/1,000 feet^3. However, given the impetus of drastically increasing costs of gas and oil, and given about a fivefold increase in operating current density and a fourfold decrease in module cost, the electrolytic ammonia process could compete with carbon-based ammonia. This is highly unlikely to occur in the foreseeable future, particularly since the cost of electrical energy is also increasing steadily, but this approach should not be neglected. This process is used today in small installations where no carbon feedstock is available and electric energy costs are low (hydroelectric).

2. *Thermochemical dissociation of water*—This process is still in the laboratory stage and the lack of engineering data precludes an economic evaluation. However, estimated overall heat energy conversion efficiencies of up to 60% are significantly greater than current NH_3 synthesis processes (30%-40%), including electrolysis. The process involves the high-temperature (about 700°C) stepwise reaction of calcium bromide, water, and mercury bromide to yield hydrogen and oxygen. This process appears very promising, but is beyond the scope of this report in terms of probable development.
3. *Coal gasification*—The tremendous impact of a technologically and economically sound large-scale coal gasification process upon the economy and energy independence of the United States cannot be overemphasized. Sidestreams from such a process could certainly be adapted to ammonia production and could eliminate the predicted dependency of this nation on imported petroleum feedstocks and nitrogen. Statistics bear this out the United States Geological Survey estimates United States "reserves" at about 500 billion tons (1 trillion barrel oil equivalent; at least equal to proven world oil supply), with perhaps 500-1,000 billion tons of additional coal "resources" not quantified and minable under present conditions.

However, at this point in time, unfortunately, the confused overview of the technology itself and of the process economics, and, as importantly, the apparent lack of advanced (mechanized and automated) mining technology to deliver the raw material at tremendous annual volumes and at low costs renders the chances of fruition of this "process" by the mideighties very unlikely. A meaningful evaluation of ammonia production capability and costs in relation to this type of operation is, therefore, impossible at this point. It appears that an effort and expenditure akin to that of the Apollo space program would be required and justified—to bring on a really significant capacity of this type by 1985; most concede that even first-generation plants will not come on-stream in significant numbers before 1990-1995.[1]

4. *Partial oxidation of coal*—Thus, in the preceding sections, the very promising but as yet unproven process substitutions have been eliminated, until only one is left for the foreseeable decade ahead. This process—partial oxidation of coal—is not new by any means, as has been indicated in the section on General Process Description. It simply has not been developed to its full potential. It has, however, a better chance of implementation within the 10-year framework of this report than any other full feedstock substitution process. It involves the gasification process, preferably at the mine head, but in much smaller multiple units, specifically tailored to the ammonia synthesis plant itself. The economics are not as favorable as the potential economics of the conceptual 250 million ft^3/day gasification units (sufficient for about seven 1,000 tons/day ammonia plants) due to the smaller scale of operation, but the technology is thought to be advancing more rapidly. Indeed, three large (900 mt/day) low-grade coal units are nearing completion in India and will serve as pilot plants for those areas having proven reserves of coal, including the United States.

The coal-based operation has significant disadvantages as compared with gas or naphtha reforming. Higher original capital costs for the gasifiers, gas purification units, and liquid air plant; great variability in coal quality; high fuel (heat) losses; high steam requirements; higher labor costs; and limited capacity of individual gasifiers are some of the problems involved. However, in the past the greatest deterrent to erection of significant capacity has been the poor operating experience high down-time—with these units.

Nevertheless, there are many areas, particularly developing areas, that have no other feedstock/fuels except coal, and the incentives are great to pursue this route—the greatest is the tremendous reduction of foreign exchange capital required to meet growing agricultural nitrogen demands when compared with the alternatives of importing ammonia (or N products) or importing the feedstocks. The drive toward minimizing or eliminating national dependence upon others for this basic need is also a strong incentive.

Effect of energy shortage on plant investments of current ammonia processes—TVA sources have indicated

[1] Firm plans for the construction of at least two 250 million CFD coal-gasification units in New Mexico, U.S.A., by 1977-80 are being pursued; these, however, are not based on new-generation gasification units, but on a multiplicity of small but proven "partial-oxidation" units as described in Section D.

the early 1974 contract price for a gas-reforming NH_3 plant, U.S. Gulf Coast, has increased 40% over that of early 1973. A 1,000-ton/day unit was $20 million in 1973, but is now about $28 million, battery-limits basis. The shortages of all materials of construction and of transportation have been blamed on the current energy shortage. However, it is felt that a significant portion of this increase is due to the "sellers' market" in the fertilizer industry, including process equipment.

Effect of process substitution on plant design—If it is granted that partial oxidation of coal is the only practical far-term process "substitution" for conventional NH_3 processes, drastic changes in the design of the "front end" (synthesis gas production) of existing gas-reforming plants would be required. The two-stage gas reformer would be replaced with four to five gasifiers, the gas scrubbers would be doubled in number and size, and a liquid air plant would be added to supply oxygen and nitrogen.

Effect of far-term process substitution on plant investment—The inherent weakness of the coal partial-oxidation (gasification) has been its high capital cost. The small, multiple gasifiers; large CO_2 and sulfur removal systems; liquid air plant; and solids handling equipment increase the battery limits plant investment of this type plant to about twice that of a natural gas-reforming plant of the same capacity. The development of large, single train gasifiers would help this situation, but only to a modest extent.

Effect of far-term process substitution on ammonia production costs—Obviously, the high capitalization charges against the coal-based process and its low energy efficiency increase the production cost of the ammonia, as compared with that from a gas-reforming plant. At moderate equivalent energy costs (say, $0.50/million Btu) the coal-based production cost will exceed that of natural gas by about 70%. The only way in which coal can be competitive is by being available at a much lower unit energy cost.

Possibilities of Product Substitution

There is no possibility of near- or far-term (10 year) substitution of another form of fixed nitrogen for anhydrous ammonia on any commercial scale.

The fact that ammonia prices have increased at least twofold in a year's time (to March 1974) has not in any way decreased the demand. World markets bring even higher prices than those in the United States. Fertilizer investments are regarded by farmers as yielding the greatest return of any input to their operation. In early 1973, ammonia f.o.b. plant prices in the United States were $42/mt which represented low, if any, profit in the buyers' market. Current prices (early 1974) are $100-$110/mt with spot prices in excess of $130. Still, there is a firm pressure for greater quantities. These price increases are in part due to intrinsic production cost increases, but a large part is due to the sellers' market situation. Fertilizer production is again a profitable business after a number of profitless years.

Economic Factors in the Production of Synthetic Ammonia

Estimated ammonia plant investments (U.S. Gulf Coast basis) for 600 and 1,000 mt/day capacity–January 1974 basis–are given below. Plant investment for a 1,000 short ton/day complex consisting of the battery limits synthesis plant; auxiliary utilities facilities; support facilities, such as office buildings, shops; and product storage is given in the following tabulation:

	Investment $ million (1,000 mt/day plant)			
			Partial oxidation	
Investment item	Gas reforming	Naphtha reforming	Oil	Coal
Battery limits NH_3	28.0	32.0	37.0	56.0
Site preparation	1.0	1.0	1.0	1.5
Auxiliary facilities[a]	4.2	4.8	5.7	8.4
Support facilities[a]	4.2	4.8	5.7	7.6
Subtotal	37.4	42.6	49.4	73.5
Product storage[b]	2.0	2.0	2.0	2.0
Total complex investment[c]	**39.4**	**44.6**	**51.4**	**75.5**

[a]Estimated at 15% of battery limits investment.
[b]Refrigerated, atmospheric storage, 15,000 mt capacity.
[c]Does not include land, or special facilities such as marine facilities.

Similar investment data are given below for 600 mt/day plants.

	Investment $ million (600 mt/day plant)			
			Partial oxidation	
	Gas reforming	Naphtha reforming	Oil	Coal
Battery limits, U.S.	20.0	23.0	26.5	40.0
Site preparation	1.0	1.0	1.0	1.5
Auxiliary facilities[a]	3.0	3.5	4.0	6.0
Support facilities[a]	3.0	3.5	4.0	6.0
Subtotal	27.0	31.0	35.5	53.5
Product storage[b]	2.0	2.0	2.0	2.0
Total complex investment[c]	**29.0**	**33.0**	**37.5**	**55.5**

[a]Estimated at 15% of battery limits investment.
[b]Refrigerated, atmospheric storage, 15,000 mt capacity.
[c]Does not include land, or special facilities such as marine facilities.

The estimated production costs for ammonia produced in 600 mt/day plants based on natural gas, naphtha, crude or fuel oil, and coal are given in tables 1, 3, 5, and 7. Similar tables 2, 4, 6, and 8 are given for the 1,000 mt/day

Table 1. Ammonia production costs, natural gas feedstock (600 mt/day)

Plant capacity, 600 mt/day, 198,000 mt/year; Plant investment $29.0 million

	Units	No. units/mt product	Price/unit $	Production costs, $/mt, at indicated cost of feedstock 0.30	0.60	0.90
Materials						
Feedstock, natural	1,000 ft³	23.1	0.30	6.95		
gas (900 Btu/standard ft³)			0.60		13.90	
			0.90			20.80
Intermediates, catalysts, chemicals	–	–	–	0.60	0.60	0.60
Maintenance (2.5% plant investment)				3.66	3.66	3.66
Fuel, power, other						
Natural gas, fuel	1,000 ft³	15.4	0.30	4.61		
			0.60		9.25	
			0.90			13.80
Electric energy	kWh	33.0	0.02	0.66	0.66	0.66
Cooling water	1,000 gal	55.0	0.02	1.10	1.10	1.10
Boiler feedwater	1,000 gal	0.6	0.50	0.30	0.30	0.30
Labor						
Production	Man-hrs	0.20	5.00	1.00	1.00	1.00
Maintenance (2.5% plant investment)				3.66	3.66	3.66
Supervision	Man-hrs	0.10	5.00	0.50	0.50	0.50
Administrative	Man-hrs	0.10	5.00	0.50	0.50	0.50
Sales expense	Fixed	–	–	4.00	4.00	4.00
General expenses	Fixed	–	–	1.00	1.00	1.00
Capital charges						
12.7% plant investment[a]				18.60	18.60	18.60
Subtotal				47.14	58.73	70.18
8%, ½ working capital[b]				0.35	0.48	0.62
Total production cost, $/mt				**47.49**	**59.21**	**70.80**

[a]Sum of 6.7% (15 yrs) depreciation, 2% taxes and insurance, 8% (½ plant cost) interest.
[b]Working capital = 30 days' value of raw materials plus 90 days' value of subtotal production cost.

Table 2. Ammonia production costs, natural gas feedstock (1,000 mt/day)

Plant capacity, 1,000 mt/day, 330,000 mt/year; Plant investment $39.4 million

	Units	No. units/mt product	Price/unit $	Production costs, $/mt, at indicated cost of feedstock 0.30	0.60	0.90
Materials						
Feedstock, natural	1,000 ft³	23.1	0.30	6.95		
gas (900 Btu/standard ft³)			0.60		13.90	
			0.90			20.80
Intermediates, catalysts, chemicals	–	–	–	0.60	0.60	0.60
Maintenance (2.5% plant investment)				2.98	2.98	2.98
Fuel, power, other						
Natural gas, fuel	1,000 ft³	15.4	0.30	4.61		
			0.60		9.25	
			0.90			13.80
Electric energy	kWh	33.0	0.02	0.66	0.66	0.66
Cooling water	1,000 gal	55.0	0.02	1.10	1.10	1.10
Boiler feedwater	1,000 gal	0.6	0.50	0.30	0.30	0.30
Labor						
Production	Man-hrs	0.12	5.00	0.60	0.60	0.60
Maintenance (2.5% plant investment)				2.98	2.98	2.98
Supervision	Man-hrs	0.06	5.00	0.30	0.30	0.30
Administrative	Man-hrs	0.06	5.00	0.30	0.30	0.30
Sales expense	Fixed	–	–	4.00	4.00	4.00
General expenses	Fixed	–	–	1.00	1.00	1.00
Capital charges						
12.7% plant investment[a]				15.15	15.15	15.15
Subtotal				41.53	53.12	64.57
8%, ½ working capital[b]				0.50	0.63	0.77
Total production cost, $/mt				**42.03**	**54.75**	**65.34**

[a]Sum of 6.7% (15 yrs) depreciation, 2% taxes and insurance, 8% (½ plant cost) interest.
[b]Working capital = 30 days' value of raw materials plus 90 days' value of subtotal production cost.

Table 3. Ammonia production costs, naphtha feedstock (600 mt/day)

Plant capacity, 600 mt/day, 198,000 mt/year; Plant investment $33.0 million

	Units	No. units/mt product	Price/unit $	Production costs, $/mt, at indicated cost of feedstock 60	90	110
Materials						
Feedstock, naphtha	Mt	0.51	60.00	30.60		
(19,000 Btu/lb)			90.00		45.90	
			110.00			56.10
Intermediates, catalysts	–	--	–	0.80	0.80	0.80
Maintenance (2.5% plant investment)				4.17	4.17	4.17
Fuel, power, other						
Naphtha fuel	Mt	0.37	60.00	22.20		
			90.00		33.30	
			110.00			40.70
Electric energy	kWh	50.0	0.02	1.00	1.00	1.00
Cooling water	1,000 gal	72.0	0.02	1.44	1.44	1.44
Boiler feedwater	1,000 gal	0.5	0.50	0.25	0.25	0.25
Labor						
Production	Man-hrs	0.20	5.00	1.00	1.00	1.00
Maintenance (2.5% plant investment)				4.17	4.17	4.17
Supervision	Man-hrs	0.10	5.00	0.50	0.50	0.50
Administrative	Man-hrs	0.10	5.00	0.50	0.50	0.50
Sales expense	Fixed	–	–	4.00	4.00	4.00
General expenses	Fixed	–	–	1.00	1.00	1.00
Capital charges						
12.7% plant investment[a]				21.20	21.20	21.20
Subtotal				92.83	119.23	136.83
8%, ½ working capital[b]				0.66	1.00	1.34
Total production cost, $/mt				**93.49**	**120.23**	**138.17**

[a]Sum of 6.7% (15 yrs) depreciation, 2% taxes and insurance, 8% (½ plant cost) interest.
[b]Working capital = 30 days' value of raw materials plus 90 days' value of subtotal production cost.

Table 4. Ammonia production costs, naphtha feedstock (1,000 mt/day)

Plant capacity, 1,000 mt/day, 330,000 mt/year; Plant investment $44.6 million

	Units	No. units/mt product	Price/unit $	Production costs, $/mt, at indicated cost of feedstock 60	90	110
Materials						
Feedstock, naphtha	Mt	0.51	60.00	30.60		
(19,000 Btu/lb)			90.00		45.90	
			110.00			56.10
Intermediates, catalysts, chemicals	–	–	–	0.80	0.80	0.80
Maintenance (2.5% plant investment)				3.38	3.38	3.38
Fuel, power, other						
Naphtha fuel	Mt	0.37	60.00	22.20		
			90.00		33.30	
			110.00			40.70
Electric energy	kWh	50.0	0.02	1.00	1.00	1.00
Cooling water	1,000 gal	72.0	0.02	1.44	1.44	1.44
Broiler feedwater	1,000 gal	0.5	0.50	0.25	0.25	0.25
Labor						
Production	Man-hrs	0.13	5.00	0.65	0.65	0.65
Maintenance (2.5% plant investment)				3.38	3.38	3.38
Supervision	Man-hrs	0.07	5.00	0.35	0.35	0.35
Administrative	Man-hrs	0.06	5.00	0.30	0.30	0.30
Sales expense	Fixed	–	–	4.00	4.00	4.00
General expenses	Fixed	–	–	1.00	1.00	1.00
Capital charges						
12.7% plant investment[a]				17.15	17.15	17.15
Subtotal				86.50	112.90	130.50
8%, ½ working capital[b]				1.05	1.39	1.67
Total production cost, $/mt				**87.55**	**114.29**	**132.17**

[a]Sum of 6.7% (15 yrs) depreciation, 2% taxes and insurance, 8% (½ plant cost) interest.
[b]Working capital = 30 days' value of raw materials plus 90 days' value of subtotal production cost.

Table 5. Ammonia production costs, crude (fuel) oil feedstock (600 mt/day)

Plant capacity, 600 mt/day, 198,000 mt/year; Plant investment $37.5 million

	Units	No. units/mt product	Price/unit $	Production costs, $/mt, at indicated cost of feedstock 6	8	10
Materials						
Feedstock, crude	Bbls	3.65	6.00	21.90		
or fuel oil (17,500			8.00		29.20	
Btu/lb)			10.00			36.50
Intermediates/supplies (catalysts)				0.40	0.40	0.40
Maintenance (2.5% plant investment)				4.73	4.73	4.73
Fuel, power, other						
Crude oil–fuel	Bbls	2.62	6.00	15.70		
			8.00		20.90	
			10.00			26.20
Electric energy	kWh	50.0	0.02	1.00	1.00	1.00
Cooling water	1,000 gal	88.0	0.02	1.76	1.76	1.76
Boiler feedwater	1,000 gal	0.04	0.50	0.20	0.20	0.20
Labor						
Production	Man-hrs	0.27	5.00	1.35	1.35	1.35
Maintenance (2.5% plant investment)				4.73	4.73	4.73
Supervision	Man-hrs	0.135	5.00	0.67	0.67	0.67
Administrative	Man-hrs	0.135	5.00	0.67	0.67	0.67
Sales expense	Fixed	–	–	4.00	4.00	4.00
General expenses	Fixed	–	–	1.00	1.00	1.00
Capital charges						
12.7% plant investment[a]				25.10	25.10	25.10
Subtotal				83.21	95.71	108.31
8%, ½ working capital[b]				0.59	0.86	1.03
Total production cost, $/mt				**83.70**	**96.57**	**109.34**

[a]Sum of 6.7% (15 yrs) depreciation, 2% taxes and insurance, 8% (½ plant cost) interest.
[b]Working capital = 30 days' value of feedstock plus 90 days' value of subtotal production cost.

Table 6. Ammonia production costs, crude (fuel) oil feedstock (1,000 mt/day)

Plant capacity, 1,000 mt/day, 330,000 mt/year; Plant investment

	Units	No. units/mt product	Price/unit $	Production costs, $/mt, at indicated cost of feedstock 6	8	10
Materials						
Feedstock, crude	Bbls	3.65	6.00	21.90		
or fuel oil (17,500			8.00		29.20	
Btu/lb)			10.00			36.50
Intermediates/supplies (catalysts)				0.40	0.40	0.40
Maintenance (2.5% plant investment)				3.88	3.88	3.88
Fuel, power, other						
Crude oil–fuel	Bbls	2.62	6.00	15.70		
			8.00		20.90	
			10.00			26.20
Electric energy	kWh	50.0	0.02	1.00	1.00	1.00
Cooling water	1,000 gal	88.0	0.02	1.76	1.76	1.76
Boiler feedwater	1,000 gal	0.4	0.50	0.20	0.20	0.20
Labor						
Production	Man-hrs	0.16	5.00	0.80	0.80	0.80
Maintenance (2.5% plant investment)				3.88	3.88	3.88
Supervision	Man-hrs	0.08	5.00	0.40	0.40	0.40
Administrative	Man-hrs	0.08	5.00	0.40	0.40	0.40
Sales expense	Fixed	–	–	4.00	4.00	4.00
General expenses	Fixed	–	–	1.00	1.00	1.00
Capital charges						
12.7% plant investment[a]				19.75	19.75	19.75
Subtotal				75.07	87.57	100.17
8%, ½ working capital[b]				0.89	1.06	1.24
Total production cost, $/mt				**75.96**	**88.63**	**101.41**

[a]Sum of 6.7% (15 yrs) depreciation, 2% taxes and insurance, 8% (½ plant cost) interest.
[b]Working capital = 30 days' value of feedstock plus 90 days' value of subtotal production cost.

Table 7. Ammonia production costs, coal feedstock (600 mt/day)

Plant capacity, 600 mt/day, 198,000 mt/year; Plant investment $55.5 million

	Units	No. units/mt product	Price/unit $	Production costs, $/mt, at indicated cost of feedstock 10	20	30
Materials						
Feedstock, coal	Mt	1.15	10.00	11.50		
(11,400 LHV			20.00		23.00	
Btu/lb)			30.00			34.50
Intermediates, chemicals				0.40	0.40	0.40
Maintenance (2.5% plant investment)				6.95	6.95	6.95
Fuel, power, other						
Coal, fuel	Mt	1.05	10.00	10.50		
			20.00		21.00	
			30.00			31.50
Electric energy	kWh	150.0	0.02	3.00	3.00	3.00
Cooling water	1,000 gal	77.0	0.02	1.54	1.54	1.54
Boiler feedwater	1,000 gal	0.5	0.50	0.25	0.25	0.25
Labor						
Production	Man-hrs	0.53	5.00	2.65	2.65	2.65
Maintenance (2.5% plant investment)				6.95	6.95	6.95
Supervision	Man-hrs	0.26	5.00	1.30	1.30	1.30
Administrative	Man-hrs	0.26	5.00	1.30	1.30	1.30
Sales expense	Fixed	–	–	4.00	4.00	4.00
General expenses	Fixed	–	–	1.50	1.50	1.50
Capital charges						
12.7% plant investment[a]				35.60	35.60	35.60
Subtotal				87.44	109.44	131.44
8%, ½ working capital[b]				0.57	0.83	1.09
Total production costs, $/mt				**88.01**	**110.27**	**132.53**

[a]Sum of 6.7% (15 yrs) depreciation, 2% taxes and insurance, 8% (½ plant cost) interest.
[b]Working capital = 30 days' value of raw materials plus 90 days' value subtotal production cost.

Table 8. Ammonia production costs, coal feedstock (1,000 mt/day)

Plant capacity, 1,000 mt/day, 330,000 mt/year; Plant investment $75.5 million

	Units	No. units/mt product	Price/unit $	Production costs, $/mt, at indicated cost of feedstock 10	20	30
Materials						
Feedstock, coal	Mt	1.15	10.00	11.50		
(11,400 LHV			20.00		23.00	
Btu/lb)			30.00			34.50
Intermediates, chemicals				0.40	0.40	0.40
Maintenance (2.5% plant investment)				5.70	5.70	5.70
Fuel, power, other						
Coal, fuel	Mt	1.05	10.00	10.50		
			20.00		21.00	
			30.00			31.50
Electric energy	kWh	150.0	0.02	3.00	3.00	3.00
Cooling water	1,000 gal	77.0	0.02	1.54	1.54	1.54
Boiler feedwater	1,000 gal	0.5	0.50	0.25	0.25	0.25
Labor						
Production	Man-hrs	0.32	5.00	1.60	1.60	1.60
Maintenance (2.5% plant investment)				5.70	5.70	5.70
Supervision	Man-hrs	0.16	5.00	0.80	0.80	0.80
Administrative	Man-hrs	0.16	5.00	0.80	0.80	0.80
Sales expense	Fixed	–	–	4.00	4.00	4.00
General expenses	Fixed	–	–	1.50	1.50	1.50
Capital charges						
12.7% plant investment[a]				29.00	29.00	29.00
Subtotal				76.29	98.29	120.29
8%, ½ working capital[b]				0.84	1.10	1.44
Total production costs, $/mt				**77.13**	**99.39**	**121.73**

[a]Sum of 6.7% (15 yrs) depreciation, 2% taxes and insurance, 8% (½ plant cost) interest.
[b]Working capital = 30 days' value of raw materials plus 90 days' value subtotal production cost.

plants. In each, a practical range of feedstock (fuel) costs is used. The minor inputs of heat (steam) or electrical energy are held constant at $0.50/thousand pounds and $0.02/kWh, respectively.

The results of the calculations in the tables are summarized in figure 1. To determine breakeven points for the various feedstocks, read across to the desired curves at a given production cost (ordinate) and pick off the breakeven feedstock costs on the corresponding cost scales (abscissa). For example, at a production cost of $70.00/mt, coal at about $6.50/mt breaks even with natural gas at about $1.04/1,000 feet^3.

UREA

Urea is rapidly becoming the greatest single source of solid nitrogen fertilizer in the world; in 1967, urea production was about 19% of total nitrogen production, but in 1973 it was about 30% of the total N. Its high analysis (46% N), satisfactory physical properties, and its lack of fire and explosion hazards (as compared to ammonium nitrate) are the reasons for this growing demand.

General Process Descriptions

All commercial process variations utilize the overall reaction of liquid anhydrous ammonia (NH_3) and gaseous carbon dioxide (CO_2) to yield urea [$CO(NH_2)_2$].

$$2NH_3(\text{liquid}) + CO_2(\text{gas}) \xrightarrow[\text{heat}]{\text{pressure}} CO(NH_2)_2(\text{solid}) + H_2O\uparrow$$

This is an oversimplification of the chemical reaction steps involved, but is sufficient for this purpose. Both reactants are obtained from the adjacent ammonia plant (see "Ammonia"); thus, the urea plant operation is dependent upon that of the ammonia plant.

The reaction is endothermic and requires the input of thermal energy to produce the solid called prills. The reaction is favored by high pressure and high temperature; commercial processes today operate in the range of 2,000 to 4,000 psig and 190° to 205°C, depending upon the economics of individual process variation involved. Compression of the reactants and recycle streams to high pressure also requires a high input of thermal and electrical energy.

The reaction above does not go to completion, i.e., only 60%-70% of the ammonia and carbon dioxide are converted to urea in a single pass. As a result, the unreacted NH_3 and CO_2 must be separated, at low pressure, from the reactor effluent solution (prior to evaporation of the water of reaction to yield the solid) and recycled (by recompression or pumping) to the reactor. It is this requirement that adds to the cost and complexity of the process.

The total recycle of the unreacted raw materials within the urea plant can be avoided, but only by the erection of another, dependent, NH_3-consuming plant, such as an ammonium nitrate unit. Because of this interdependence of these plants, few producers elect this alternative; nearly all modern installations accept the interdependence of the ammonia and urea plants (because it cannot be avoided except at a significant cost of NH_3 and CO_2 storage), but utilize the total recycle urea plant to avoid a three-plant chain. It is even feasible to integrate the urea and ammonia plants in such a way as to, in effect, purify the ammonia synthesis gas by scrubbing out the CO_2 with ammonia and recycle solution in a urea "prereactor" and pumping the resulting solution up to urea synthesis pressure. Significant energy savings are possible, but such a large, delicately balanced system is difficult to maintain in stable condition. No such units are known to be in operation.

Importance of Fuel and Feedstock Energy to the Urea Process

The energy input to some of the conventional urea processes is as follows.

	Energy, Btu x 10^6/mt urea			
Process	NH_3 energy equivalent	Equivalent electrical	Steam	Total
Total solution recycle	20.7	0.56	2.5	23.8
CO_2 or NH_3 stripping	20.7	0.45	1.7	22.9
Heat recycle[a]	20.7	0.56	1.2	22.5
Hot gas recycle[b]	20.7	0.04[c]	0.3[d]	21.0
Average energy consumption, Btu x 10^6/mt plant nutrient = 49.0				

[a]Two small units in operation.
[b]Unproven but theoretically sound.
[c]No cooling water pumping or solution pumping.
[d]Estimated net (import of 2,800 lbs 400 psig superheated steam export 2,800 lbs 150 psig steam).

Urea process designers have long recognized the need to strive for maximum energy efficiency. The above processes are in order of decreasing world capacity as well as decreasing energy consumption. The heat recycle process is being demonstrated in two small plants—operating results are not yet public. The hot gas recycle process is merely a drawing board design, but appears to be sound. It cannot be pilot-planted because the centrifugal hot-gas compressor cannot operate in less than a 1,500 tons/day urea plant—an expensive pilot plant. The "net" steam requirement is valid only if a use for the medium pressure export steam exists in the complex.

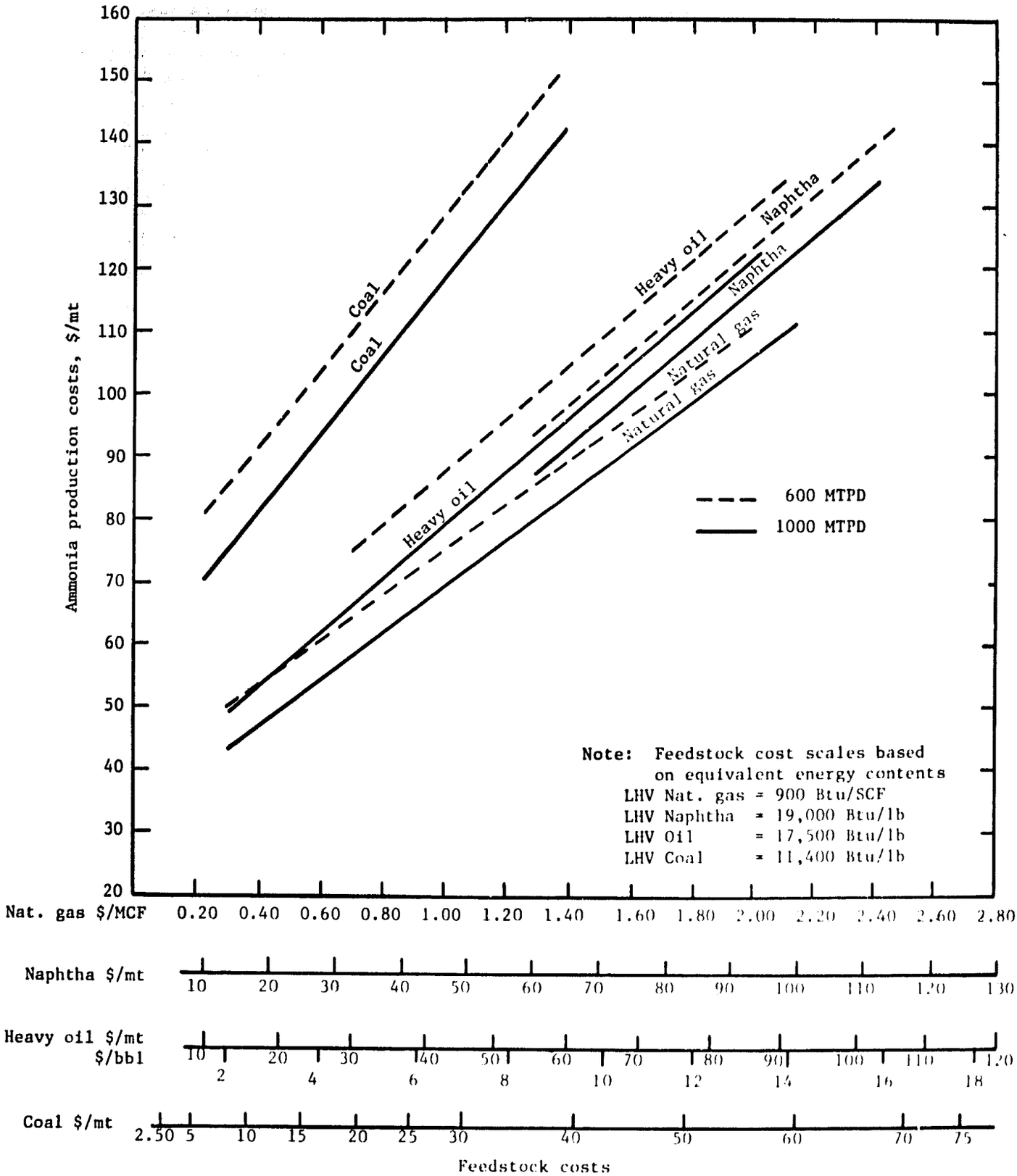

Figure 1. Ammonia production costs versus feedstock costs

Near-Term Potential for Substitution of Other Feedstock or Fuels for Present Ones

There is no known large scale commercial process for the production of urea from feedstocks other than ammonia and carbon dioxide.

The heat energy input to the urea plant is invariably from the same source as that to the ammonia plant in order to simplify in-plant logistics. However, considering the urea plant itself, the primary source of energy is not critical from the technical viewpoint, since it is delivered to the synthesis system as steam from an external steam generator that could be fired with any available fuel.

Potential for Far-Term (10-Year) Urea Process Substitution

General considerations—There is no known process that might be available later, even given the impetus of intensive research over the far term, to eliminate, or even reduce the carbon oxide requirement for the synthesis of urea.

It is conceivable that carbon monoxide, rather than carbon dioxide, could be utilized in urea synthesis, thus increasing the potential sources of byproduct carbon oxides. However, the process, which has been pilot-planted, involves the reaction of stoichiometric quantities of carbon monoxide, sulfur, and ammonia to yield urea (at lower temperature and pressures than now practical) plus byproduct hydrogen sulfide. The estimated high cost of regenerating the sulfur from the H_2S is a stumbling block to this process and it does not eliminate the need for the carbon oxide.

Although it has already been indicated that production of hydrogen for ammonia synthesis by electrolytic or thermochemical decomposition of water is projected well beyond the time framework of this report, it should be pointed out that when this era approaches, a carbon oxide (CO_2 or CO) will have to be deliberately produced for urea synthesis, since the byproduct CO_2 normally associated with NH_3 production will be lacking. The oxygen resulting from the water decomposition could be used in a CO_2 generator using any available form of carbon.

Impact of high energy costs on current urea plant investments—Like ammonia plant investments, the costs of urea synthesis plants have risen sharply since January 1973; first-quarter 1974 contracts were increased by about 40% over early 1973 costs. These drastic cost increases, however, are thought to be limited to the very heavy, high pressure, alloy steel construction of NH_3 and urea plant equipment and may also reflect the effects of the present sellers' market in process equipment.

Effect of process substitution on urea process equipment design—Since there is little chance of a practical substitute urea process in the 10-year period of this report, a detailed discussion of design changes is not pertinent.

On the other hand, the speculative processes mentioned previously, i.e., hot-gas recycle and carbon monoxide-ammonia-sulfur reaction, would have significant effects on equipment design. The hot-gas recycle process would substitute a single large steam turbine recycle gas-compressor for the troublesome hot carbonate solution recycle pumps required in present units, and would effect, theoretically, a higher energy efficiency.

The ammonia-sulfur-carbon monoxide reaction achieves a higher degree of single-pass conversion of ammonia to urea at much lower pressures and temperatures, thus decreasing the high costs that are inherent in high-pressure process equipment.

Effect of process substitution on urea plant capital investments—Unfortunately, the speculative processes mentioned in the previous section have not progressed to a point where equipment costs can be estimated reliably. The same may be said of production costs and potential process problems.

Possibilities of Product Substitution

General comments—Urea is, of course, only one of several forms of nitrogen fertilizers, all of which are equally effective on an applied-nitrogen basis. Because of its high nitrogen content (46% N) and inherently low processing costs, urea generally may be delivered more cheaply on a nitrogen basis than the other common solid nitrogen products, such as ammonium nitrate (33% N), ammonium sulfate (21% N), or ammonium chloride (26% N). In short-haul situations, ammonium sulfate and chloride, which are generally byproducts of coking, caprolactum, and soda processes, may be less expensive applied to the soil, and should be used in these situations.

Strictly from the standpoint of energy consumption, the use of the byproduct nitrogen fertilizers would be far better than that of the synthetic urea or ammonium nitrate, discounting even the significantly higher transport energy costs of the former. However, it would be impossible to supply the required amounts of N in these forms—less than 20% of the world supply of N is from these byproduct sources. Of the two principal nitrogen products—urea and ammonium nitrate—urea is the most economical and does not consume a significantly greater amount of energy in production than ammonium nitrate.

The direct application of liquid ammonia to the growing crops is a practical—and widely used—substitute for urea and other solid fertilizers in the United States. The incremental energy requirement for production of the solid is thus eliminated. In the United States, nearly 40% of the total fertilizer nitrogen application is in the form of liquid NH_3. This percentage is far lower in the rest of the world.

but is growing in those areas where large farms are the norm. The special high pressure equipment required for its application greatly restricts its use for direct application in the usual developing country that is typified by very small farms. However, a concerted effort at training and equipment adaptation for this usage could result in significant savings in nitrogen fertilizer energy requirements.

Effect of higher costs on demand in the United States—Prices of urea have increased from about $85/mt in early 1973 to $90-$100/ton in late 1973 to $140-$165/mt in early 1974; spot prices in excess of $220 have been reported. Yet there is no decrease in demand and inventories built up in 1972-73 are virtually depleted.

Economic Factors in the Production of Urea

In this section, the operating costs of the most efficient of the proven processes, *i.e.*, total recycle, ammonia-stripping, will be considered. Since the greatest energy input by far is that equivalent to the ammonia input, the cost of the input ammonia will be regarded as the variable input, with the relatively lower inputs of heat and electrical energy being held constant.

Urea plant investment (U.S. Gulf Coast basis), 1,000 and 1,600 mt/day capacity—January 1974 basis—The plant investments for 1,000 mt/day and 1,600 mt/day urea plants (part of an ammonia-urea complex), including the battery limits synthesis plant, auxiliary utilities facilities, support facilities, and product storage, are shown below.

Investment item	Investment cost, $ million 1,000 mt/day	1,600 mt/day
Battery limits, urea	17.5	23.6
Site preparations	0.5	0.5
Auxiliary facilities[a]	2.6	3.5
Support facilities[a]	2.6	3.5
Subtotal	23.2	31.1
Bulk, dehumidified storage[b]	1.8	2.8
Bagged storage[c]	0.4	0.7
	25.4	**34.6**

[a]Estimated at 15% of battery limits investment.
[b]110,000 tons and 175,000 tons @ $16/ton.
[c]27,500 tons and 44,000 tons @ $15/ton.

Estimated production costs—The estimated production costs for the two urea plants, utilizing ammonia input costs of $50, $80, and $110, which are equivalent to natural gas costs of $0.50, $1.30, and $2.10/1,000 feet^3, respectively, are given in tables 9 and 10. The results are summarized in figure 2.

PHOSPHATE FERTILIZER PRODUCTION

About 95% of the world phosphate fertilizer production is based on mined phosphate deposits—phosphate rock of

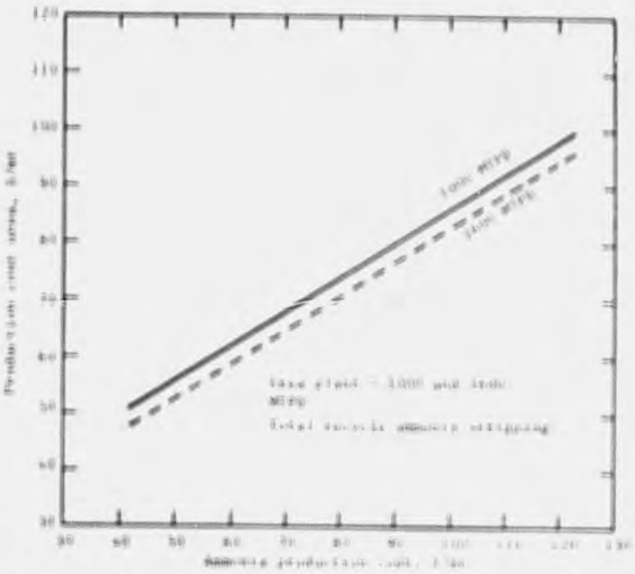

Figure 2. Effect of ammonia production cost on production cost of urea

various types. Small amounts of cave deposits of guano are "mined" and even smaller, more insignificant amounts of phosphates are derived from other phosphatic materials. Traditionally, the plant nutrient content of phosphatic fertilizers has been expressed as percent phosphorus pentoxide (P_2O_5).

General Description of Processing Sequences

Phosphate rock is mined, usually in open pit mining operations, and is concentrated or beneficiated by crushing, followed by hydroseparation and/or flotation to remove impurities. The rock is then reacted with an acid—most often with sulfuric acid (or with phosphoric acid derived from the sulfuric acid reaction), or, to a much lesser extent, with nitric or hydrochloric acids to convert the phosphate to a form readily available to crops.

The more important reaction products from the rock are as follows:

With sulfuric acid	With phosphoric acid
Ordinary superphosphate (solid)	Concentrated superphosphate (solid)
Phosphoric acid (liquid)	

In the United States, ammonium phosphates, principally diammonium phosphate (DAP), constitute about 50% of the total phosphate fertilizer output. For this reason it has been singled out in this report for an energy evaluation.

The production of DAP consists of three phases:

1. Production of concentrated (93%) sulfuric acid (H_2SO_4) from sulfur.
2. Reaction of H_2SO_4 and phosphate rock to yield phosphoric acid (about 30% P_2O_5) and by-product

Table 9. Production costs of urea, variable NH_3 costs (1,000 mt/day)

Plant capacity, 1,000 mt/day, 330,000 mt/year; Plant investment $25.4 million

	Units	No. units/ton	Price/unit $	Production cost, $/st at indicated NH_3 cost 50	80	110
Materials						
Raw materials	Ton	0.6	50.00[a]	30.00		
NH_3			80.00[a]		48.00	
			110.00[a]			66.00
CO_2	Ton	0.77	0.00	0.00	0.00	0.00
Intermediates, supplies, chemicals				0.20	0.20	0.20
Maintenance (2.5% plant investment)				1.92	1.92	1.92
Fuel, power, other						
Natural gas, fuel	1,000 ft³	0.07	0.50	0.04	0.04	0.04
Electrical, purchased	kWh	120.0	0.02	2.40	2.40	2.40
Cooling water	1,000 gal	5.0	0.02	0.30	0.30	0.30
Boiler feedwater	1,000 lbs	0.5	0.50	0.25	0.25	0.25
Labor						
Operating	Man-hrs	0.26	5.00	1.30	1.30	1.30
Maintenance (2.5% plant investment)				1.92	1.92	1.92
Supervision	Man-hrs	0.13	5.00	0.65	0.65	0.65
Administrative	Man-hrs	0.13	5.00	0.65	0.65	0.65
Sales expense	Fixed		4.00	4.00	4.00	4.00
General expense	Fixed		1.00	1.00	1.00	1.00
Capital charges						
12.7% plant investment[c]				10.10	10.10	10.10
Subtotal				54.73	72.73	90.73
8%, ½ working capital[b]				0.69	0.95	1.21
Total production cost, $/ton				**55.32**	**73.68**	**91.94**

[a]Excluding sales expense.
[b]Working capital = 30 days' value of raw materials plus 90 days' value of subtotal production cost.
[c]See tables 1-8.

Table 10. Production costs of urea, variable NH_3 costs (1,600 mt/day)

Plant capacity, 1,600 mt/day, 528,000 mt/year; Plant investment $34.6 million

	Units	No. units/ton	Price/unit $	Production cost, $/st at indicated NH_3 cost 50	80	110
Materials						
Raw materials	Mt	0.6	50.00[a]	30.00		
NH_3			80.00[a]		48.00	
			110.00[a]			66.00
CO_2	Mt	0.77	0.00	0.00	0.00	0.00
Intermediates, supplies, chemicals				0.20	0.20	0.20
Maintenance (2.5% plant investment)				1.64	1.64	1.64
Fuel, power, other						
Natural gas, fuel	1,000 ft³	0.07	0.50	0.04	0.04	0.04
Electrical, purchased	kWh	120.0	0.02	2.40	2.40	2.40
Cooling water	1,000 gal	15.0	0.02	0.30	0.30	0.30
Boiler feedwater	1,000 lbs	0.5	0.50	0.25	0.25	0.25
Labor						
Operating	Man-hrs	0.16	5.00	0.80	0.80	0.80
Maintenance (2.5% plant investment)				1.64	1.64	1.64
Supervision	Man-hrs	0.08	5.00	0.40	0.40	0.40
Administrative	Man-hrs	0.08	5.00	0.40	0.40	0.40
Sales expense	Fixed		4.00	4.00	4.00	4.00
General expense	Fixed		1.00	1.00	1.00	1.00
Capital charges						
12.7% plant investment[c]				8.30	8.30	8.30
Subtotal				51.37	69.37	87.37
8%, ½ working capital[b]				1.05	1.30	1.55
Total production cost, $/ton				**52.42**	**70.67**	**88.92**

[a]Excluding sales expense.
[b]Working capital = 3 days' value of raw materials plus 90 days' value of subtotal production cost.
[c]See tables 1-8.

calcium sulfate, which is removed by filtration and discarded; the phosphoric acid is generally concentrated to 40%-54% P_2O_5 acid.

3. Reaction of ammonia and phosphoric acid to yield solid, granular DAP; 40% P_2O_5 acid is generally used in an acid-DAP complex at the phosphate rock mine, whereas 54% acid is used for shipment to a DAP plant elsewhere.

For the purposes of this report, the three operations will be regarded as a single system, and the overall energy requirements will be discussed on this basis.

Importance of Energy Input to Conventional Process (Diammonium Phosphate 18-46-0)

The overall energy requirements for the production of 18-46-0 grade DAP have been estimated (4) to be

Unit operation	Btu x 10^6 per mt DAP	% of total
Sulfur mining, storage (Frasch)	4.0	29.0
Sulfuric acid production	0.1	0.7
Phosphate rock preparation	0.4	2.9
Phosphoric acid production*	0.3	2.2
NH3 equivalent energy (raw material input)	8.4	60.9
Ammoniation and granulation	0.1	0.7
Product drying	0.5	3.6
Total energy input Btu x 10^6/mt DAP	**100.0**	**100.0**

*Not even the heat energy available from the sulfuric acid plant

Since DAP is primarily a phosphatic fertilizer, calculation of the energy requirement per mt of P_2O_5 as DAP involves deleting that energy associated with the nitrogen content of the material, namely, 8.4 x 10^6 Btu, leaving 5.4 x 10^6 Btu/mt DAP, or 11.8 x 10^6 Btu/mt P_2O_5, as the proportionate energy input for that nutrient. This compares to about 42 x 10^6 Btu/mt N as ammonia. Obviously, phosphate production is not as energy intensive as is nitrogen production; nevertheless, the energy input for phosphates is significant and far-term reductions would be of major importance to the fertilizer industry.

Near Term Potential Substitution of Less Scarce Fuel/Feedstocks in DAP Production

Like nitrogen producers, phosphate producers have pushed the development of the phosphatic materials toward minimization of production costs and toward increases in grade (plant nutrient content) for the purpose of decreasing the transportation and field distribution costs of the nutrients so as to achieve the lowest cost per unit of nutrient delivered to the field. They have been well aware of the effects of overall energy inputs in these efforts. For this reason, the production of ordinary and concentrated superphosphates, both of which are in effect likewise produced by the reaction of rock and sulfuric acid, are declining in demand, even though the production energy requirement is somewhat lower (10-11 million Btu/mt P_2O_5) than that of DAP. Their significantly lower grades (20% and 46% P_2O_5, respectively) and resulting higher distribution costs offset this advantage. The ammonium phosphate appear to be the ultimate for the near term.

Acidulation with byproduct hydrochloric acid (instead of sulfuric) is technically feasible and a few plants are in operation today. At first glance, the elimination of almost 30% of the input energy to DAP product by substituting byproduct HCl for H_2SO_4 would be a major accomplishment. Unfortunately, byproduct HCl is not plentiful and primary HCl is more costly in energy than H_2SO_4. Byproduct sulfuric acid is also very scarce.

There does not appear to be any possibility of significant near-term feedstock substitution for phosphate production.

Potential for Far-Term (10-Year) Ammonium Phosphate Process Substitution

General considerations. Phosphate rock is the one indispensable raw material for the production of phosphatic fertilizers. Worldwide production of phosphate rock reached nearly 95 million tons (about 30 million tons P_2O_5) in 1973. Known reserves are considered ample for several hundred years. New mines are being opened in Australia, Peru, and Angola. Although rock, as well as all other fertilizer raw materials, is in tight supply at present, it is believed that this will be a near-term situation until the new sources are opened and the transport segment responds to the demand for greater capacity.

Sulfur is the second key raw material in the production of phosphates, ammonium phosphates or otherwise. At present sulfur is in short supply on a worldwide basis.

The supply-demand situation is extremely complex and is beyond the scope of this report. However, it has been predicted (10, 14) that in the U.S., sulfur will be in short supply in the near-term (3-5 years), but as pollution abatement sulfur becomes available (recovery from sour gas, oil, and coal) in increasing quantities there may well be a surplus of virgin and recovered sulfur.

Though it is impossible to predict the potential quantity (estimates range from 4 to 20 million tons by 1985) and the time periods involved (estimates range from 1980 to 2000) for surplus sulfur from pollution abatement, it is a fact that abatement sulfur will be an important factor in phosphate fertilizer production. In fact, such fertilizer production may become a means of disposal of recovered (abatement) sulfur and, therefore, energy requirements for

phosphate production will be significantly lower than at present.

The point of the above discussion is to explain the conclusion that in spite of current sulfur supply problems, there is little incentive toward massive phosphate process substitution (such as electrothermal phosphate) in the next decade.

Impact of high energy costs on current plant investment — Undoubtedly the rising energy costs have increased the plant investment costs for sulfuric acid, phosphoric acid, and ammonium phosphate production units. However, the increases in these conventional liquid/solid handling plants are considerably lower than those mentioned previously for the heavy high-pressure ammonia and urea synthesis plants. Industry sources indicate an escalation of about 15% over 1972-74 for comparable plants. However, in the case of the sulfuric acid plants, an increase of at least 60% in investment costs has come about in the U.S.A. because of Occupational Safety and Health Administration and Environmental Protection Agency requirements.

Plant or process design changes — Since no basic process substitution for phosphate production is envisioned in the far-term period, a discussion of process design changes is not pertinent.

However, there are some unit-operation modifications that can effect energy requirements, but could not properly be discussed in the near-term potential because the present generation of phosphoric acid and ammonium phosphate could not economically convert to the "new" technology in the near-term. The changes should be regarded as modifications to existing technology rather than process substitution.

The modifications and the estimated energy savings are indicated below.

Modification	Energy reduction Btu x 10^6/mt DAP
Wet handling, grinding, and feeding of rock to phosphoric acid process	0.36
Hemihydrate modification for phosphoric acid (50%-54% P_2O_5 without steam evaporation)	1.86
Direct ammonium polyphosphate process (no drying required)	0.47
Total saving to ammonium phosphate process	**2.40**

However, the major item, the reduction of evaporative concentration requirements in the hemihydrate process, would result in an actual reduction in total energy usage only if an economic use for the export steam from the sulfuric acid plant—normally used for phosphoric acid concentration—could be found elsewhere. The energy economics of the combination of modifications would be fully utilized in those relatively few instances (presently) where byproduct or recovered sulfuric acid is utilized (the heat of combustion of elemental sulfur thus is not available).

Effect of process substitution (or modification) on plant investment costs — The effects of the modifications listed above on plant investment costs are estimated as follows:

1. Phosphoric acid production
   a. Wet receipt, handling, and grinding of phosphate rock. It has been estimated (9) that this modification would reduce the plant investment of large phosphoric acid plants by 13%, compared with dry grinding.
   b. Hemihydrate process—capital investment would be essentially the same as the conventional dihydrate acid plant investment.
   c. Direct ammonium polyphosphate process modification would decrease plant investments by about 25%, compared with the DAP plant alone.

Thus, incorporation of all three modifications would result in a decrease in the ammonium phosphate complex investment cost of about 20%.

Effect of process substitution (or modification) on production costs — Estimates of changes in production costs of ammonium phosphate due to incorporation of the three modifications discussed in the previous section are as follows:

1. Wet grinding of rock and the hemihydrate process would decrease production costs by about 2%.
2. The direct ammonium polyphosphate process would not significantly change overall production costs (nutrient basis).

Potential Product Substitution

In previous sections, it has been indicated that several possible product substitutes for the ammonium phosphates are feasible and are, in fact, in use today. The primary objective of many of these processes is to eliminate sulfur—the highest energy consumer in conventional phosphate processing—as a raw material. However, the limitations of these processes, as touched on in the general considerations and near-term potential for feedstock substitution, still apply to the far-term potential for product substitution. The electrothermal phosphorus-phosphoric acid process—which is a current, viable process for low volume, high value, high purity products—does not appear to have any greater potential than electrolytic production of hydrogen for ammonia production (see "Ammonia"), and for the same reasons—the very high capital investments and extremely high energy consumption (about 2.5 times that of wet-process acid). It is concluded that phosphate production will rely on sulfur, virgin and recovered, until that era when electrical energy from fast breeder or fusion reactors is the lowest cost source of all energy forms.

Mention should be made here of a well-known class of phosphatic fertilizers called nitric phosphates; nitric acid, rather than sulfuric acid, is the phosphate rock acidulating agent. When considered as a phosphate production process, nitric phosphate requires about 3 times the energy input, per unit of P_2O_5, as does diammonium phosphate. The excess energy input is, of course, recovered, but it is in the form of low-grade ammonium nitrate (about 4.5 tons per ton P_2O_5). Because of the decreasing popularity of ammonium nitrate in favor of the much higher grade urea, the complexity of the nitric phosphate processes, and the relative inflexibility of the product grades, no further details of the nitric phosphates will be given.

Economic Factors in the Production of Phosphate Fertilizers – Diammonium Phosphate

Frasch sulfur production costs – The production costs of Frasch sulfur vary widely from one mine location to another. An average estimate of production costs are given in table 11.

The data indicate that the Frasch process is sensitive to fuel costs; about 8.3 million Btu of heat energy is required per metric ton of sulfur.

Capital costs of "mines" and terminals vary so widely that it is possible only to give a hypothetical average. It is felt that a discussion and demonstration of the effects of such variables as deposit size, number of wells per deposit and resulting life of the deposit, the porosity of the geological formation and the resulting water-sulfur ratio, the effect of age on deposit recoveries, etc., are beyond the scope of this report. Hence, table 11 contains estimated costs of a single new (1974) hypothetical Frasch mine (7). Capital costs do not include exploration or land. An appropriate optional cost royalty is included in lieu of land costs.

The high production costs of Frasch sulfur, of which fuel is but one high-cost item, explains why recovered (sour gas) sulfur is displacing mined sulfur. Although presently only about 20% of total sulfur produced in the U.S. is recovered sulfur, in the Western world, over 50% of total sulfur production is now in the form of recovered sulfur (vs 25% in 1960).

As in other segments of the fertilizer industry, the pressure of demand and of increased operating costs due to energy shortages have significantly increased the costs of production and price of phosphatic fertilizers. In the U.S., phosphate rock export prices have increased from \$9-\$13/mt in 1972 to \$22-\$33/mt (depending upon grade) in early 1974. Domestic prices are \$5-\$6 lower. Spot prices in excess of \$40 from African sources have been reported. Sulfur has increased from \$12/ton in 1972 to \$38/ton in 1974. However, higher energy costs have not created such dramatic cost increases, per se. The demand has created a sellers' market in which prices are not entirely related to production costs.

Estimated production cost of sulfuric acid – The production costs of sulfuric acid from Frasch sulfur are known to be relatively sensitive to energy inputs. Therefore, in tables 12 and 13, the input variable is the market price of sulfur over a practical range. In the fertilizer industry, sulfur is normally shipped to the phosphate producing area (there are some exceptions); therefore, as indicated, estimated market prices, rather than captive costs, are used in this estimate.

As noted in the section, "Impact of High Energy Costs on Current Plant Investments," the investment costs of new sulfuric acid plants has increased in the U.S. by about 60% because of drastic antipollution equipment costs. The estimated plant investments for 1,000 and 1,500 mt/day units are as follows:

Item	Estimated plant investment \$ million (1974)	
	1,000 mt/day	1,500 mt/day
Battery limits, U.S.	3.3	4.2
EPA/OSHA requirements	2.0	2.5
Auxiliary and support facilities	1.0	1.5
Total	**6.3**	**8.6**

The results in tables 12 and 13 indicate that because of the high cost of the raw materials (variables) in the sulfuric acid process, the effect of plant capacity on production cost is small, less than one dollar per ton.

Estimated production costs of phosphate rock – The estimated production costs for a new mine, say in South Florida, having a capacity of 2.7 million mt/year and costing \$100 million for the mining lights, mine, beneficiation plant, storage, and rail handling system are given in table 14.

The narrow range of costs (\$10 to \$11) caused by tripling the power cost from \$0.01 kWh to \$0.03 kWh indicates that the mining-beneficiation operation is not sensitive to energy input. If fuel costs had been varied from \$0.40/1,000 feet^3 to \$1.60/1,000 feet^3, the production cost would have been changed only ± \$0.12/mt.

Present production costs of beneficiated rock from old mines are of the order of \$8 to \$10/mt; therefore, at present, reasonable returns on a present-value capital investment basis are being realized in contrast to the 1969-1971 period, when rock sold for \$6 to \$8/mt, probably a breakeven level, or lower.

As in the case of Frasch sulfur, mining costs at various locations are so highly variable that the calculated effect of mine capacity on cost is highly suspect. The data in table 14 is hypothetical – for this reason, no other "size" of mine is considered.

Table 11. Production cost of Frasch sulfur

Mine capacity, 1,000 mt/day, 350,000 mt/year; Terminal investment $7.8 million

	Units	No. units/mt product	Price/unit $	Production cost, $/mt at indicated fuel cost 0.40	1.00	1.60
Materials						
Maintenance				0.30	0.30	0.30
Supplies, chemicals				0.10	0.10	0.10
Fuel, power, other						
Natural gas, fuel	1,000 ft³	9.2	0.40	3.68		
			1.00		9.20	
			1.60			14.70
Electric energy	kWh	40.0	0.02	0.80	0.80	0.80
Water	1,000 gal	4.0	0.02	0.08	0.08	0.08
Boiler feedwater	1,000 gal	1.0	0.50	0.50	0.50	0.50
Labor						
Operating				1.20	1.20	1.20
Maintenance				0.30	0.30	0.30
Supervision				0.60	0.60	0.60
Administrative				0.60	0.60	0.60
Sales expense				0.50	0.50	0.50
Well costs[a]				3.20	3.20	3.20
General expense (fixed)				0.25	0.25	0.25
Depletion tax				1.50	1.50	1.50
Capital charges						
12.7% plant investment[b]				2.83	2.83	2.83
Subtotal				16.44	21.96	27.46
8%, ½ working capital[b]				0.14	0.22	0.30
Estimated royalties (lieu of land costs)				5.00	5.00	5.00
Total production costs, $/mt				**21.58**	**27.18**	**32.76**

[a]Wells are short-lived and must be moved on the average of once a year; this becomes an operating cost.
[b]See tables 1-8.

Table 12. Estimated production costs of sulfuric acid (1,000 mt/day)

Plant capacity, 1,000 mt/day, 330,000 mt/year; Plant investment $6.3 million

	Units	No. units/mt product	Price/unit $	Production cost, $/mt at indicated sulfur cost 20	40	60
Materials						
Raw materials						
Sulfur	Mt	0.34	20.00	6.80		
			40.00		13.60	
			60.00			20.40
Intermediates, supplies, chemicals				0.30	0.30	0.30
Maintenance (2.5% plant investment)				0.48	0.48	0.48
Fuel, power, other	kWh	11.0	0.02	0.22	0.22	0.22
Electric energy	kWh	11.0	0.02	0.22	0.22	0.22
Cooling water	1,000 gal	6.8	0.02	0.14	0.14	0.14
Boiler feedwater	1,000 gal	0.33	0.50	0.16	0.16	0.16
Steam export	1,000 lbs	2.00	0.50	(1.00)	(1.00)	(1.00)
Labor						
Operating	Man-hrs	0.06	5.00	0.20	0.20	0.20
Maintenance (2.5% plant investment)				0.48	0.48	0.48
Supervision		0.03	5.00	0.15	0.15	0.15
Administrative	Man-hrs	0.03	5.00	0.15	0.15	0.15
Sales expense (none, captive use)				0.50	0.60	0.70
General expense				0.50	0.50	0.50
Capital charges						
12.7% plant investment[a]				2.43	2.43	2.43
Subtotal				11.24	18.04	24.84
8%, ½ working capital[a]				0.10	0.20	0.20
Total production cost				**11.34**	**18.24**	**25.14**

[a]See tables 1-8.

Table 13. Estimated production costs of sulfuric acid (1,500 mt/day)

Plant capacity, 1,500 mt/day, 500,000 mt/year; Plant investment $8.6 million

	Units	No. units/mt product	Price/unit $	Production cost, $/mt at indicated sulfur cost 20	40	60
Materials						
Raw materials						
Sulfur	Mt	0.34	20.00	6.80		
			40.00		13.60	
			60.00			20.40
Intermediates, supplies, chemicals				0.30	0.30	0.30
Maintenance (2.5% plant investment)				0.43	0.43	0.43
Fuel, power, other						
Electric energy	kWh	11.0	0.02	0.02	0.22	0.22
Cooling water	1,000 gal	6.8	0.02	0.14	0.14	0.14
Boiler feedwater	1,000 gal	0.33	0.50	0.16	0.16	0.16
Steam export	1,000 lbs	2.00	0.50	(1.00)	(1.00)	(1.00)
Labor						
Operating	Man-hrs	0.04	5.00	0.20	0.20	0.20
Maintenance (2.5% plant investment)				0.43	0.43	0.43
Supervision	Man-hrs	0.02	5.00	0.10	0.10	0.10
Administrative	Man-hrs	0.02	5.00	0.10	0.10	0.10
Sales expense (none, captive use)				0.50	0.60	0.70
General expense				0.50	0.50	0.50
Capital charges						
12.7% plant investment[a]				2.18	2.18	2.18
Subtotal				10.79	17.69	24.59
8% interest, ½ working capital[a]				0.15	0.25	0.35
Total production cost				**10.94**	**17.94**	**24.94**

[a]See tables 1-8.

Table 14. Estimated production costs for mining and beneficiating phosphate rock (new mine 1974)

Mine capacity, 8,000 mt/day, 2,700,000 mt/year; Total capital investment $100 million

	Units	No. units/mt product	Price/unit $	Est. production costs, $/mt at indicated power cost 0.01	0.02	0.02
Materials						
Supplies				0.70	0.70	0.70
Explosives	Costs obtained from mine data			0.03	0.03	0.03
Maintenance				0.92	0.92	0.92
Fuel, power, other						
Natural gas, fuel	1,000 ft³	1.7	0.60	1.02	1.02	1.02
Electric energy	kWh	50.0	0.01	0.50		
			0.02		1.00	
			0.03			1.50
Process water	1,000 gal	10.0	0.02	0.20	0.20	0.20
Labor						
Production	Man-hrs	0.20	5.00	1.00	1.00	1.00
Maintenance	Man-hrs	0.18	5.00	0.92	0.92	0.92
Supervision	Man-hrs	0.02	5.00	0.10	0.10	0.10
Administrative	Man-hrs	0.03	5.00	0.15	0.15	0.15
Sales expense	Man-hrs	0.06	5.00	0.30	0.30	0.30
General expense				0.25	0.25	0.25
Capital charges						
12.7% plant investment[a]				4.70	4.70	4.70
Subtotal				11.29	11.79	12.29
8%, ½ working capital[a]				0.11	0.11	0.11
Total production cost, $/mt				**11.40**	**11.90**	**12.40**

[a]See tables 1-8

Estimated production costs of wet-process phosphoric acid—As indicated in a previous section, two modifications to the widely used dihydrate process could result in significant energy savings to the production of wet-process acid. A comparison of production costs of the conventional and modified processes are given in tables 15, 16, 17, and 18. Because of uncertainties in establishing the transfer cost for the phosphatic rock feed to these acid processes, variable values ($15-$35/mt) were used.

Plant investments for the two processes are given in the following tabulation:

Process	Estimated investment cost, $ million: 400 mt/day P_2O_5	600 mt/day P_2O_5
Conventional, battery limits		
dry grinding, storage, concentration to 54% P_2O_5	10.3	12.8
Auxiliary and support facilities	3.1	3.8
Total	**13.4**	**16.6**
Modified wet grinding, hemihydrate process	10.9	13.6
Auxiliary and support facilities	3.3	4.1
Total	**14.2**	**17.7**

The required heat energy input to the production of wet-process acid as steam from the sulfuric acid plant is about 1.8 million Btu/ton of P_2O_5 (as 54% acid) in the conventional process. In the hemihydrate process, no heat energy input is required. The results of the estimates are summarized in figure 3. The data indicate that raw material costs overshadow capital charges, so the processes are not extremely sensitive to plant capacity changes.

Estimated production costs of diammonium phosphate and ammonium polyphosphate—As indicated previously, the use of the TVA direct ammonium polyphosphate (APP) process could result in a saving of about 1 million Btu/mt of P_2O_5, as compared with the conventional TVA diammonium phosphate process. Cost estimates are given for both processes in tables 19, 20, 21, and 22.

The costs are based on estimated 1974 plant investment costs as follows:

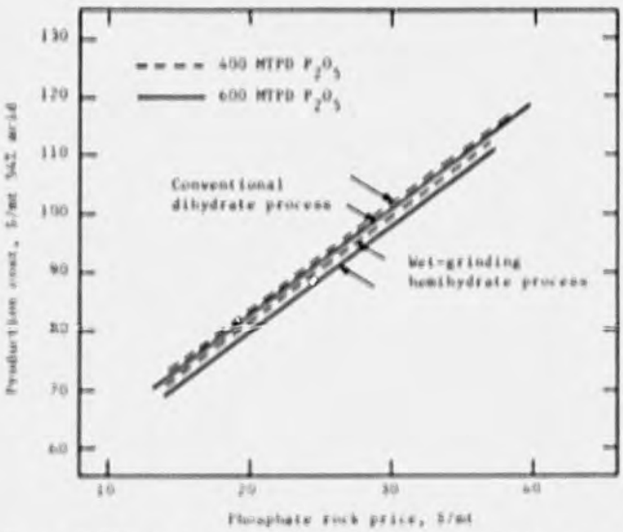

Figure 3. Effect of phosphate rock price on production cost of wet-process phosphoric acid

Comparisons of the estimated DAP production costs (tables 19 and 20) with those of APP (tables 21 and 22) show that in comparable plants, the costs per ton of DAP product (18-46-0) are about 5% to 15% cheaper than the costs per ton of APP product (12-57-0). However, the following cost comparisons, made on the basis of plant nutrient contents, demonstrate the effects of the differences in product grades (nutrient contents) and $N:P_2O_5$ ratios:

	Production costs, $[a]: DAP	APP
Cost, $/mt product	103	116
Cost, $/mt P_2O_5	224	204
Cost, $/mt plant nutrient ($N + P_2O_5$)	161	168

[a]Based on wet-process acid at $90/mt in 600 mt/day plants (tables 20 and 22).

The cost relationships are thus dependent upon the basis used; the most practical basis is cost per ton of total plant nutrient. It is, therefore, concluded that although the APP process results in a significant reduction in energy

Process	Investment, $ million: DAP, mt/day 400 P_2O_5 870 DAP	DAP, mt/day 600 P_2O_5 1,300 DAP	APP, mt/day 400 P_2O_5 700 APP	APP, mt/day 600 P_2O_5 1,050 APP
Granulation, battery limits, U.S.	2.30	2.75	1.80	2.15
Auxiliary and support facilities (30%)	0.70	0.83	0.54	0.65
Product storage				
Bulk (¼ annual)	0.72	1.10	0.54	0.83
Bagged (1/12 annual)	0.24	0.34	0.18	0.25
	3.96	**5.02**	**3.06**	**3.88**

Table 15. Estimated production costs of the conventional dihydrate wet process phosphoric acid process (400 mt/day)

Plant capacity, 400 mt/day P_2O_5, 132,000 mt/year P_2O_5; Plant investment $13.4 million

	Units	No. units/mt P_2O_5	Price/unit $	Production costs, $/mt P_2O_5 at indicated cost of phosphate rock 15	25	35
Materials						
Unground rock, 32% P_2O_5	Mt	3.38	15.00	51.00		
			25.00		84.50	
			35.00			118.00
Sulfuric acid, 100%	Mt	2.75	17.94	49.50	49.50	49.50
Chemicals				0.50	0.50	0.50
Maintenance (2.5% plant investment)				2.54	2.54	2.54
Fuel, power, other						
Steam (H_2SO_4 plant)	1,000 lbs	2.0	0.50	1.00	1.00	1.00
Cooling water	1,000 gal	5.5	0.02	0.11	0.11	0.11
Electric energy	kWh	120.0	0.02	2.40	2.40	2.40
Labor						
Operating	Man-hrs	0.27	5.00	1.35	1.35	1.35
Maintenance (2.5% plant investment)				2.54	2.54	2.54
Supervision	Man-hrs	0.13	5.00	0.65	0.65	0.65
Administrative	Man-hrs	0.13	5.00	0.65	0.65	0.65
Sales expense	Fixed			5.00	5.00	5.00
General expense	Fixed			1.00	1.00	1.00
Capital charges						
12.7% plant investment[a]				12.90	12.90	12.90
Subtotal				131.14	164.64	198.14
8%, ½ working capital[a]				1.86	2.33	2.68
Total production cost, $/mt P_2O_5				**133.00**	**166.97**	**200.82**
$/mt acid (54% P_2O_5)				**71.82**	**90.16**	**108.44**

[a]See tables 1-8.

Table 16. Estimated production costs of the conventional dihydrate wet process phosphoric acid process (600 mt/day)

Plant capacity, 600 mt/day P_2O_5, 204,000 mt/year P_2O_5; Plant investment $16.6 million

	Units	No. units/mt P_2O_5	Price/unit $	Production costs, $/mt P_2O_5 at indicated cost of phosphate rock 15	25	35
Materials						
Unground rock, 32% P_2O_5	Mt	3.38	15.00	51.00		
			25.00		84.50	
			35.00			118.00
Sulfuric acid, 100%	Mt	2.75	17.94	49.50	49.50	49.50
Chemicals				0.50	0.50	0.50
Maintenance (2.5% plant investment)				2.50	2.50	2.50
Fuel, power, other						
Steam (H_2SO_4 plant)	1,000 lbs	2.0	0.50	1.00	1.00	1.00
Cooling water	1,000 gal	5.5	0.02	0.11	0.11	0.11
Electric energy	kWh	120.0	0.02	2.40	2.40	2.40
Labor						
Operating	Man-hrs	0.18	5.00	0.90	0.90	0.90
Maintenance (2.5% plant investment)				2.04	2.04	2.04
Supervision	Man-hrs	0.09	5.00	0.45	0.45	0.45
Administrative	Man-hrs	0.09	5.00	0.45	0.45	0.45
Sales expense	Fixed			5.00	5.00	5.00
General expense	Fixed			1.00	1.00	1.00
Capital charges						
12.7% plant investment[a]				10.30	10.30	10.30
Subtotal				126.69	160.19	193.69
8%, ½ working capital[a]				1.80	2.25	2.80
Total production cost, $/mt P_2O_5				**128.49**	**162.44**	**196.49**
$/mt acid (54% P_2O_5)				**69.38**	**87.72**	**106.10**

[a]See tables 1-8.

Table 17. Estimated production costs of the wet-grinding hemihydrate wet process phosphoric acid process (400 mt/day)

Plant capacity, 400 mt/day P_2O_5, 132,000 mt/year P_2O_5 (as 54% P_2O_5 acid); Plant investment $14.2 million

	Units	No. units/mt product	Price/unit $	Production costs, $/mt P_2O_5 at indicated cost of phosphate rock 15	25	35
Materials						
Unground rock, 32% P_2O_5	Mt	3.38	15.00	51.00		
			25.00		84.50	
			35.00			118.00
Sulfuric acid, 100%	Mt	2.75	17.94	49.50	49.50	49.50
Chemicals				0.50	0.50	0.50
Maintenance (2.5% plant investment)				2.68	2.68	2.68
Fuel, power, other						
Cooling water	1,000 gal	28.0	0.02	0.56	0.56	0.56
Electric energy	kWh	95.0	0.02	1.90	1.90	1.90
Labor						
Operating	Man-hrs	0.27	5.00	1.35	1.35	1.35
Maintenance (2.5% plant investment)				2.68	2.68	2.68
Supervision	Man-hrs	0.13	5.00	0.65	0.65	0.65
Administrative	Man-hrs	0.13	5.00	0.65	0.65	0.65
Sales expense	Fixed			5.00	5.00	5.00
General expense	Fixed			1.00	1.00	1.00
Capital charges						
12.7% plant investment[a]				13.70	13.70	13.70
Subtotal				131.09	164.59	198.09
8%, ½ working capital[a]				1.77	2.25	2.68
Total production cost, $/mt P_2O_5				**132.86**	**166.84**	**200.77**
$/mt acid (54% P_2O_5)				**71.90**	**90.00**	**108.50**

[a]See tables 1-8.

Table 18. Estimated production costs of the wet-grinding hemihydrate wet process phosphoric acid process (600 mt/day)

Plant capacity, 600 mt/day P_2O_5, 204,000 mt/year P_2O_5 (as 54% P_2O_5 acid); Plant investment $17.7 million

	Units	No. units/mt product	Price/unit $	Production costs, $/mt P_2O_5 at indicated cost of phosphate rock 15	25	35
Materials						
Unground rock, 32% P_2O_5	Mt	3.38	15.00	51.00		
			25.00		84.50	
			35.00			118.00
Sulfuric acid, 100%	Mt	2.75	17.94	49.50	49.50	49.50
Chemicals				0.50	0.50	0.50
Maintenance, 2.5% plant investment				2.24	2.24	2.24
Fuel, power, other						
Cooling water	1,000 gal	28.0	0.02	0.56	0.56	0.56
Electric energy	kWh	95.0	0.02	1.90	1.90	1.90
Labor						
Operating	Man-hrs	0.18	5.00	0.90	0.90	0.90
Maintenance (2.5% plant investment)				2.24	2.24	2.24
Supervision	Man-hrs	0.09	5.00	0.45	0.45	0.45
Administrative	Man-hrs	0.09	5.00	0.45	0.45	0.45
Sales expense	Fixed			5.00	5.00	5.00
General expense	Fixed			1.00	1.00	1.00
Capital charges						
12.7% plant investment[a]				11.05	11.05	11.05
Subtotal				126.79	160.29	193.79
8%, ½ working capital[a]				1.72	2.20	2.68
Total production cost, $/mt P_2O_5				**128.51**	**162.49**	**196.47**
$/mt acid (54% P_2O_5)				**69.40**	**87.70**	**106.00**

[a]See tables 1-8.

Table 19. Estimated production costs for diammonium phosphate (18-46-0) (800 mt/day)

Plant capacity, 800 mt/day, 287,000 mt/year; Plant investment $3.96 million

	Units	No. units/mt product	Price/unit $	Production costs, $/mt at indicated cost, W-P acid 70	90	110
Materials						
Ammonia	Mt	0.23	55.00[a]	12.65	12.65	12.65
W-P acid (54% P_2O_5)	Mt	0.87	70.00[b]	60.80		
			90.00[b]		78.40	
			110.00[b]			95.80
Maintenance (2.5% plant investment)				0.34	0.34	0.34
Fuel, power, other						
Fuel oil (drying)	Gal	3.3	0.20	0.66	0.66	0.66
Electric energy	kWh	22.0	0.02	0.44	0.44	0.44
Fuel oil (steam gen.)	Gal	4.4	0.20	0.88	0.88	0.88
Labor						
Production	Man-hrs	0.18	5.00	0.90	0.90	0.90
Maintenance (2.5% plant investment)				0.34	0.34	0.34
Supervision	Man-hrs	0.09	5.00	0.45	0.45	0.45
Administrative	Man-hrs	0.09	5.00	0.45	0.45	0.45
Sales expense	Fixed			4.00	4.00	4.00
General expense	Fixed			1.00	1.00	1.00
Capital charges						
12.7% plant investment[c]				1.75	1.75	1.75
Subtotal				84.66	102.26	119.66
8%, ½ working capital[c]				1.19	1.44	1.70
Total production cost, $/mt 18-46-0				**85.85**	**103.70**	**121.36**

[a]Produced from natural gas at $0.60 1,000 ft^3.
[b]At sulfur cost of $40/mt; 40% acid would be used if acid is produced at the same complex—costs would be slightly lower.
[c]See tables 1-8.

Table 20. Estimated production costs for diammonium phosphate (18-46-0) (1,300 mt/day)

Plant capacity, 1,300 mt/day, 430,000 mt/year; Plant investment $5.0 million

	Units	No. units/mt product	Price/unit $	Production costs, $/mt at indicated cost, W-P acid 70	90	110
Materials						
Ammonia	Mt	0.23	55.00[a]	12.65	12.65	12.65
W-P acid (54% P_2O_3)	Mt	0.87	70.00[b]	60.80		
			90.00[b]		78.40	
			110.00[b]			95.80
Maintenance (2.5% plant investment)				0.29	0.29	0.29
Fuel, power, other						
Fuel oil (drying)	Gal	3.3	0.20	0.66	0.66	0.66
Electric energy	kWh	22.0	0.02	0.44	0.44	0.44
Fuel oil (steam gen.)	Gal	4.4	0.20	0.88	0.88	0.88
Labor						
Production	Man-hrs	0.12	5.00	0.60	0.60	0.60
Maintenance (2.5% plant investment)				0.29	0.29	0.29
Supervision	Man-hrs	0.06	5.00	0.30	0.30	0.30
Administrative	Man-hrs	0.06	5.00	0.30	0.30	0.30
Sales expense	Fixed			4.00	4.00	4.00
General expense	Fixed			1.00	1.00	1.00
Capital charges						
12.7% plant investment[c]				1.48	1.48	1.48
Subtotal				83.69	101.29	118.69
8%, ½ working capital[c]				1.12	1.36	1.62
Total production cost, $/mt 18-46-0				**84.81**	**102.65**	**120.31**

[a]Produced from natural gas at $0.60 1,000 ft^3.
[b]At sulfur cost of $40/mt; 40% acid would be used if acid is produced at the same complex—costs would be slightly lower.
[c]See tables 1-8.

Table 21. Estimated production costs for direct process ammonium polyphosphate (12-57-0) (700 mt/day)

Plant capacity, 700 mt/day, 231,000 mt/year; Plant investment $3.1 million

	Units	No. units/mt product	Price/unit $	Production costs, $/mt at indicated cost, W-P acid 70	90	110
Materials						
Ammonia	Mt	0.15	55.00[a]	8.25	8.25	8.25
W-P acid (54% P_2O_5)	Mt	1.07	70.00[b]	75.00		
			90.00[b]		96.50	
			110.00[b]			117.50
Maintenance (2.5% plant investment)				0.35	0.35	0.35
Fuel, power, other						
Fuel oil (steam gen.)	Gal	4.4	0.20	0.88	0.88	0.88
Electric energy	kWh	25.0	0.02	0.50	0.50	0.50
Labor						
Production	Man-hrs	0.20	5.00	1.00	1.00	1.00
Maintenance (2.5% plant investment)				0.35	0.35	0.35
Supervision	Man-hrs	0.10	5.00	0.50	0.50	0.50
Administrative	Man-hrs	0.10	5.00	0.50	0.50	0.50
Sales expense	Fixed			4.00	4.00	4.00
General expense	Fixed			1.00	1.00	1.00
Capital charges						
12.7% plant investment[c]				1.79	1.79	1.79
Subtotal				94.12	115.62	136.62
8%, ½ working capital[c]				1.40	1.72	2.04
Total production cost, 12-57-0				**95.52**	**117.34**	**138.66**

[a]Produced from natural gas at $0.60 1,000 ft³.
[b]At sulfur cost of $40/mt.
[c]See tables 1-8.

Table 22. Estimated production costs for direct process ammonium polyphosphate (12-57-0) (1,050 mt/day)

Plant capacity, 1,050 mt/day, 346,000 mt/year; Plant investment $3.9 million

	Units	No. units/mt product	Price/unit $	Production costs, $/mt at indicated cost, W-P acid 70	90	110
Materials						
Ammonia	Mt	0.15	55.00[a]	8.25	8.25	8.25
W-P acid (54% P_2O_5)	Mt	1.07	70.00[b]	75.00		
			90.00[b]		96.50	
			110.00[b]			117.50
Maintenance (2.5% plant investment)				0.30	0.30	0.30
Fuel, power, other						
Fuel oil (steam gen.)	Gal	4.4	0.20	0.88	0.88	0.88
Electric energy	kWh	25.0	0.02	0.50	0.50	0.50
Labor						
Production	Man-hrs	0.14	5.00	0.70	0.70	0.70
Maintenance (2.5% plant investment)				0.30	0.30	0.30
Supervision	Man-hrs	0.07	5.00	0.35	0.35	0.35
Administrative	Man-hrs	0.07	5.00	0.35	0.35	0.35
Sales expense	Fixed			4.00	4.00	4.00
General expense	Fixed			1.00	1.00	1.00
Capital charges						
12.7% plant investment[c]				1.50	1.50	1.50
Subtotal				93.13	114.63	135.63
8%, ½ working capital[c]				1.38	1.70	2.02
Total production cost, 12-57-0				**94.51**	**116.33**	**137.65**

[a]Produced from natural gas at $0.60 1,000 ft³.
[b]At sulfur cost of $40/mt.
[c]See tables 1-8.

consumption, its production cost per metric ton of plant nutrient is slightly higher than that of DAP. However, this difference would probably be offset by the somewhat lower distribution costs of APP because of its higher grade.

POTASH FERTILIZER PRODUCTION

Nearly all of the estimated 32 million tons of potash fertilizer produced throughout the world in 1972-73 was derived from the minerals potassium chloride and, to a much less extent, potassium sulfate. Both minerals for the most part (90%) are recovered by deep mining operations. Traditionally, the term "potash" has come to mean the mineral, potassium chloride, though officially potash means potassium oxide (K_2O), the measure of the potassium content of the ore or a fertilizer.

General Description of Production Processes

Unlike phosphate ore, which generally requires both a raw ore beneficiation process and a chemical alteration process before it is usable, potash requires only the ore mining and beneficiation process. It is used as produced from beneficiation, and is invariably mixed with nitrogen and/or phosphate fertilizer compounds.

The potash (KCl) ore is mined by two methods

1. Conventional shaft and tunneling (90% of total)
2. Solution mining—pumping hot unsaturated brine down on borehole, through ore deposit, and up a second borehole; the mineral is thus dissolved out of the deposit (10% of total)

Production economics have, in many instances, dictated that the potash (KCl) mineral be separated by a process called "flotation," when the raw ore is mined by conventional methods. In this beneficiation process, the raw ore is crushed to a previously determined optimum particle size range (average about 14 mesh in U.S. deposits, but only 4 mesh in Canadian deposits). By the addition of very small quantities of the proper chemicals, the KCl crystals thus "unlocked" from the gangue can be made to float to the top of an open tank in which air is bubbling through a slurry of the crushed minerals passing through the tank. The gangue flows out through the underflow.

In the solution mining process, the saturated brine emerging from the "mine" outlet borehole is cooled and concentrated in vacuum crystallizers, which crystallizes the KCl, leaving the impurities, predominantly common salt, in solution.

Importance of Fuel and Feedstock to the Conventional Process

Estimates (5) of energy consumption in the mining and beneficiation (including storage) of potassium chloride are as follows:

	Btu × 10^6/mt of potash	
	Solution mining	Shaft mining
Mining	6.8	2.2
Beneficiation and storage	5.6 (crystallization)	1.0 (flotation)
	12.4	3.2

It would appear that conventional shaft mining has a great energy advantage over solution mining. However, it is claimed that the original investment, in terms of energy and capital, for mine development is much greater for the shaft mine than for the well-type solution mine, although data are contradictory in this respect. In addition, much deeper deposits can be reached by solution mining, and in some instances, shaft mining is impossible because of geological considerations. On the other hand, the operational savings in energy for shaft mining plus flotation beneficiation is great. For example, in 10 years of operation at $\frac{2}{3} \times 10^6$ mt of ore per year, an operational saving of 180 million Btu (value, $90 million @ $0.50/1,000 feet^3 gas) could be achieved by this combination, as compared with solution mining plus crystallization. It is possible that this operational energy savings might more than offset the reported higher costs of shaft mine development. Because of these considerations, each deposit must be very carefully evaluated before the decision is made as to which type of mining is to be followed.

Near Term Potential for Substitution of Less Scarce Fuel or Feedstocks for Current Ones

In the U.S. and Canada, most of the fuel energy consumed in the mining and beneficiation of potash appears to be derived from natural gas, primarily because by chance, that is the nearest and cheapest fuel in the producing areas. Since only fuel usage is involved, any other cheaper, more readily available fuel could be used. However, the near term conversion to coal, which would be neither cheaper nor more readily available in most cases, but would pose no technical problems, merely for conservation of natural gas or fuel oil would be impractical because of logistics as well as economics. Again, as in the case of natural gas for ammonia production, potash (as well as sulfur and phosphate) producers should be given the highest priority, in view of their vital role in food production.

Far Term Potential for Potash Process Substitution Using Another Feedstock

General considerations—As in the case of phosphatic fertilizers, potassium salts (primarily KCl and K_2SO_4) are the key "feedstock" to the production of available potash. There is no substitute for the potassium required by

growing crops. There is no other practical source that can produce the required amount of K_2O in the foreseeable future. Fortunately, as in the case of phosphate ore, the proven reserves of mineable potash is in excess of 50,000 million tons of K_2O (not ore), which should be sufficient for hundreds of years. We could turn to the seas and natural brine lakes (Dead Sea, Searles Lake, Great Salt Lake, Caspian Sea, etc.), but this is far in the future for high production rates via solar or thermonuclear energy. It is conceivable that in the era of solar and nuclear energy, recovery of potash and other minerals from the seas may become a byproduct of tremendous desalination projects, in which case conventional mining might become uneconomical.

Impact of higher energy costs on current plant investment costs — Since no new mine developments have been publicized, it is not possible to give realistic plant investment data. In fact, it is very difficult to obtain realistic cost data on old mining developments. It is estimated, however, that the plant investments would follow the general increases indicated by current indices such as the *Chemical Engineering Plant Cost Index*, which shows a general chemical process industry plant cost increase of about 7% since early 1973.

Plant design changes in process substitution — Since there does not appear to be any possibility of substitution of a different process for the current mining and beneficiation of potash ore, comments in this section are not pertinent.

Possibilities for Product Substitution

There are several other potassium salts (K_2SO_4, KNO_3, KOH, K_3PO_4, etc.) that are as agronomically effective as potassium chloride, but none that can be produced in the quantities required, nor as cheaply, both cost- and energy-wise, as the chloride. There appears to be no chance of significant substitution for this product within the time period of this report.

Like all other fertilizer materials, potash has risen in costs since the fall of 1973. Prices in the U.S. in late 1973 were about $51 to $54/mt (KCl); by March 1974, the range was $59 to $61. Note that this was a relatively modest 28% increase, as compared to twofold increases in nitrogen and phosphate. The potash increase is more nearly indicative of energy cost increases, because the demand for potash is not as firm in relation to supply as for the other plant nutrients and prices have remained relatively low.

Economic Factors in the Production of Potash

As previously indicated, potassium chloride (KCl) provides about 90% of the potash fertilizer requirements throughout the world. Also, it is used as produced in the beneficiated form, generally mixed in granulation or bulk blended products containing the other primary nutrients. Other potassium salts such as potassium sulfate or potassium nitrate are produced in relatively small quantities (about 10% of the total), so they will not be treated in the report.

This section, then, will deal with the only important operation in potash production, namely, the mining and beneficiation of potassium chloride. Cost data are scarce, so no attempt has been made to estimate the economical effects of mine capacity. Many of the developed mines, particularly in Canada, are thought to have mineable deposits that should last 50 years or more, so actual amortization charges should be small. However, accounting procedures vary widely and book amortization rates may be much higher than those used in this section.

Estimated production costs of potassium chloride by shaft mining and flotation beneficiation — The overall known capital cost of a Canadian shaft mine producing about 1.0 million mt of K_2O (as beneficiated ore, 61%) year are updated to 1978 and are broken down by estimation as follows:

	Capital investment, $ million
Mine shaft, tunnels and equipment	52.5
Flotation plant	44.0
Total	**96.5**

Tables 23 and 24 are summarizations of production cost data from several sources (2, 3, 4, 11) and must be accepted as order of magnitude figures.

The total mining costs (table 23) do not appear to be affected by any single operating cost, with the exception of capital charges ($11.10/mt). The royalty charge is estimated on the basis of those published for sulfur, which is about 35% of the other production costs.

The estimated production costs for beneficiation by flotation are given in table 24. The beneficiation costs are more strongly affected by raw ore (mining) costs than fuel or power costs.

Estimated production costs of potassium chloride by solution mining and crystallization — There does not appear to be any reliable information on capital investment and production costs (mining only) of potash by the solution mining process. Two operators in Canada claim both lower capital costs and production costs by this method, and it appears to be a reasonable assumption that well drilling should be much cheaper than shaft excavation. Yet, published total capital costs (mining plus beneficiation) for both types of processes indicate much higher capital costs for the solution mine approach, about 50% to 60% higher.

On the other hand, beneficiation cost data are available; for this reason, the raw ore will be assigned variable costs and only the beneficiation costs will be estimated. This estimate is given in table 25.

Table 23. Estimated shaft mining production costs

Capacity: 12,000 mt/day ore (26% K2O), 4,500,000 mt/year ore (26% K2O); Mine investment $52.5 million

	Unit	No. units/mt ore	Price/unit $	Production cost $/mt ore
Materials				0.20
Fuel, power, other				
Electrical	kWh	12.0	0.012	0.20
Fuel oil	Gal	1.0	0.20	0.20
Labor				
Operating				0.25
Maintenance				0.22
Supervision				0.12
Administrative				0.12
General expense				0.10
Capital charges				
2% ins and maintnce				0.25
5% depreciation (20 years)				0.58
8% interest (1/2 mine investment)[a]				0.47
Subtotal				2.14
8% interest (1/2 working capital)[a]				0.025
Royalties (est.)				1.00
Total production cost, $/mt ore				**4.19**

[a]See table 18.

Table 24. Estimated costs of beneficiation by the flotation process

Plant capacity: 6,000 mt/day (85% potash), 2,000,000 mt/year (85% potash); Refinery investment $48 million

	Unit	No. units/mt product	Price/unit	Production cost, $/mt potash, at indicated power cost 0.03	0.02	0.02
Materials						
Raw materials						
Raw ore	Mt	2.30	8.10	5.70	5.70	5.70
Chemicals	lb	0.50	0.50	0.50	0.50	0.50
Supplies				0.20	0.20	0.20
Maintenance (2.5% plant investment)				0.55	0.55	0.55
Fuel, power, other						
Natural gas, fuel	1,000 ft³	0.88	0.030	0.26	0.26	0.26
Electric	kWh	110.0	0.01	1.10		
			0.012		2.20	
			0.02			3.30
Process water	1,000 gal	10.0	0.012	0.20	0.20	0.20
Labor						
Operating	Man-hr	0.12	7.00	0.80	0.80	0.80
Maintenance (2.5% plant investment)				0.55	0.55	0.55
Supervision	Man-hr	0.08	7.00	0.60	0.60	0.60
Administrative	Man-hr	0.08	7.00	0.60	0.60	0.60
Sales expense	Fixed			0.50	0.50	0.50
General expense	Fixed			0.50	0.50	0.50
Capital charges						
12.5% plant investment[a]				2.80	2.80	2.80
Subtotal				14.10	15.20	20.30
8% interest working capital[a]				0.20	0.21	0.22
Total production cost, $/mt potash				**14.30**	**15.47**	**20.58**
$/mt K2O				**30.80**	**32.30**	**36.30**

[a]See table 18.

Table 25. Estimated costs of beneficiation by the crystallization process

Plant capacity: 6,000 mt/day 62% potash; 2,000,000 mt/day 62% potash; Refinery investment $68 million

	Units	No. units/mt product	Price/unit	Production cost, $/mt potash, at indicated ore cost: 3	5	7
Materials						
Raw material						
Raw ore	Mt	2.3	3.00	6.90		
			5.00		11.50	
			7.00			16.10
Chemicals	LS	0.5	0.80	0.40	0.40	0.40
Supplies				0.20	0.20	0.20
Maintenance (2.5% plant investment)				0.65	0.65	0.65
Fuel, power, other						
Natural gas fuel	1,000 ft^3[a]	5.5	0.60	3.30	3.30	3.30
Electric	kWh	77.0	0.02	1.54	1.54	1.54
Process water	1,000 gal	2.4	0.02	0.05	0.05	0.05
Labor						
Operating	Man/hr	0.15	5.00	0.80	0.80	0.80
Maintenance (2.5% plant investment)				0.65	0.65	0.65
Supervision	Man/hr	0.08	5.00	0.40	0.40	0.40
Administrative	Man/hr	0.08	5.00	0.40	0.40	0.40
Sales expense	Fixed			0.50	0.50	0.50
General expense	Fixed			0.50	0.50	0.50
Capital charges						
12.7% plant investment[b]				8.32	8.32	8.32
Subtotal				21.00	25.60	30.21
8%, ½ working capital[b]				0.25	0.32	0.37
Total production cost, $/mt potash				**21.25**	**25.93**	**30.58**
$/mt K_2O				**36.30**	**43.80**	**49.30**

[a]See table 15.

It is obvious from the detailed costs that beneficiation by the crystallization process is more energy intensive than by the flotation process. The effect of varying the natural gas fuel costs are given in the following tabulation, using a fixed raw ore cost of $5/mt.

Gas cost $/1,000 ft^3[a]	Production cost, $/mt beneficiated ore
0.30	19.60
0.60	21.26
0.90	22.90

Comparison of beneficiation costs by the two methods, crystallization and flotation, indicates that at comparable mining costs, the former process is higher in cost by about $8/mt of beneficiated ore because of the higher fuel requirement and the higher capitalization costs. Obviously, to be competitive, the solution mining (only) costs must be nearly $2/mt lower than that of shaft mining. This seems unlikely in view of the high energy requirements of the solution mining process. However, solution mines do have the advantage of being operable at much greater depths and in geological formations that rule out shaft mining, advantages that may come into play as the more accessible deposits are mined out.

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