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A PRELIMINARY EVALUATION OF THE USE OF
HIGH-TEMPERATURE PROCESS HEAT
AS PART OF A TOTAL NUCLEAR-ENERGY SOURCE

by

L. J. Gordon and J. F. Marchaterre

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

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Reactor Engineering Division

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*Aerojet-General Corporation, Sacramento, California

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A PRELIMINARY EVALUATION OF THE USE OF HIGH-TEMPERATURE PROCESS HEAT AS PART OF A TOTAL NUCLEAR-ENERGY SOURCE

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ABSTRACT

A preliminary study of the use of high-temperature (1500-3000°F) process heat as part of a multipurpose complex was carried out. The conclusions of the study indicate that in addition to conventional electric power generation, nuclear energy might be useful in

- (1) Alumina and aluminum production.
- (2) Cement production as part of a complex.
- (3) Calcining and/or sintering ores such as taconite.

The main factor that could make high-temperature, nuclear, process heat attractive is the potential of developing specially designed multipurpose reactors. The multipurpose reactor appears to be a possible way in which high-temperature process heat could be economically supplied.

Most uses of high-temperature process heat that appear attractive would necessitate the development of heat exchangers to heat air to 2200-2700°F. The magnitude of this development effort must be evaluated.

I. INTRODUCTION

In terms of long-range energy applications, continuous attention must be given to the use of nuclear energy in the process and metallurgical industries. Although a large fraction of our energy consumption in the future will be nonelectrical, almost no progress has been made to satisfy these demands with nuclear sources. This study had two objectives: to review the industrial potential for nonelectrical utilization of nuclear energy as affected by recent technological and economic progress, and to explore new reactor concepts that may enhance the promise for competitive, nonelectrical application of nuclear energy.

Recent advances in nuclear-reactor technology for rocket applications and for the 710 and UHTREX reactor programs have indicated that the high-temperatures gas streams of 2000-2700°F can be produced at reasonable core lifetimes. It is natural, therefore, to consider possible uses of such high-temperature gas streams as heat sources for industrial processing. Use of nuclear energy in combined electric power-water desalination plants is currently receiving much attention, and it is interesting to see how a possible high-temperature capability adds to the overall usefulness of nuclear power. Accordingly, a preliminary study has been made of the use of nuclear energy, especially at high temperatures (1500-3000°F) in the following United States industries:

Iron-ore reduction and pelletizing

Alumina and aluminum production

Cement production

Fertilizer production

Petrochemical processing.

Preliminary conclusions indicate that in addition to conventional electric power generation, nuclear energy could be useful in:

(1) Alumina and aluminum production when used as a total energy source at an ore site, although the use of high-temperature process, specifically in alumina calcining, will be small compared to electric power.

(2) Cement production, using air as heating medium, either as part of a large nuclear-powered complex such as an electricity generating-sea water desalinization plant, or as a mobile plant operating in newly developing areas.

(3) Calcining and/or sintering ores (e.g., taconite) at mine sites, using air as a heating medium in very large-scale operations ($\geq 5,000,000$ tons/year).

In many cases in which nuclear energy appears to be useful because of competitive energy costs, an additional economic incentive comes from freedom of site location; i.e., by eliminating the need to transport large quantities of raw materials to sources of fossil fuels or to hydroelectric power; or by eliminating the need to ship fossil fuel to processing sites. This siting advantage is particularly valuable in the aluminum industry, where the ores average about 25% metal, as contrasted with the iron industry; where the ores, with the exception of low-grade ores such as taconite, range from 50 to 70% metal. One reason why nuclear energy does not appear useful in the fertilizer and petrochemical industries is that these industries require large, cheap sources of hydrocarbons, not merely as fuel but as

basic raw materials. Similarly, iron-ore reduction requires either carbon or hydrogen as a reductant, which must also be obtained from cheap, raw materials. For these industries, it is difficult to conceive of a situation, at least in the near future, in which a raw material will be cheap enough for use in the process and not also cheap enough to be used as fuel. Nuclear electricity would have to be very inexpensive to produce electrolytic hydrogen for ammonia production or iron-ore reduction as long as supplies of coal and natural gas last.

Nuclear energy will probably be used in multipurpose plants. If and when high-temperature, nuclear, process heat is used, it will undoubtedly also be economical to produce electricity and low-temperature process steam at the same location. The relative balance between high-, moderate-, and low-temperature heat produced at any site will, of course, be dictated by the economics of the local situation. Whatever the balance, however, the need for development of a large, economic, nuclear reactor capable of delivering part of its energy at temperatures in the 1500-3000°F range seems to be clearly indicated; and the technology for such development appears to be at hand.

In the more distant future, nuclear energy may supply most of the world's energy needs. Projections of coal, petroleum, and gas reserves and consumption are always hazardous, but current estimates indicate that some basic realignment of energy usage, particularly with respect to natural gas, can probably be expected before the end of the century. At such time, it will become necessary for nuclear reactors to supply high-temperature heat. Otherwise, high-temperature chemical processes will have to use electrical energy--an inherently thermodynamically inefficient process. Otherwise, allowing that nuclear reactors will be able to produce gas streams at least as hot as those possible with direct firing of fossil fuels, there is little likelihood that nuclear energy will bring about any changes in basic chemical or metallurgical processes. Nuclear reactors (like fossil fuels) are simply a source of heat, and the chemical and economic factors that determine the choice of processes will not be markedly changed by the source of the heat. Even in the complete absence of hydrocarbon sources, electrolysis of water to produce hydrogen can supply a large portion of needed raw materials and chemical reducing agents. From there on, however, the chemical process steps will be more or less unchanged from those of today.

A matter interrelated with use of nuclear energy for high-temperature processing is the development of high-temperature, corrosion-resistant, heat exchangers. For example, cement production and ore pelletizing presently use direct-firing techniques. If these processes are to be carried out with nuclear-heated air, problems relating to contamination of the product will undoubtedly require use of a primary reactor loop and heat exchange to secondary air, thus necessitating development of very large heat exchangers

able to withstand corrosion by air at 2200 to 2700°F. Although difficult, such heat exchangers probably can be built.

This report represents the first phase of a study of high-temperature, process-heat applications. The second phase will deal with reactor design and economics. The technology and economics of the various processes considered in this study are discussed in the following paragraphs.

II. ALUMINA AND ALUMINUM PRODUCTION

The use of nuclear energy in the production of alumina and aluminum appears to be an attractive possibility. Large quantities of electricity are required in the refining of the metal, and approximately 4 tons of bauxite are required to produce 1 ton of aluminum. The freedom of site location given by nuclear energy could allow an electric power plant to be built near an ore site and thereby result in sizable transportation economy.

A. Production Processes

Alumina (Al_2O_3) is produced almost exclusively from bauxite by the Bayer process, except in the USSR, where adequate supplies of metal-grade bauxite are not easily available. There, alumina is produced on a large scale from nepheline (NaAlSiO_4).

Over 90% of all the alumina produced is used for the production of aluminum, mainly by the Hall electrolytic process.

B. Alumina via the Bayer Process

The Bayer process for the production of alumina is applicable only to bauxite processing. Bauxite consists essentially of hydrated alumina ($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ or $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$) and iron and silicon oxides (Fe_2O_3 and SiO_2). The process is based on the fact that the solubility of aluminum oxide in caustic soda varies with temperature and with soda concentration. After extraction of the aluminum from the ore as soluble NaAlO_2 , the impurities are left as a "red mud" containing Fe_2O_3 and NaAlSiO_4 . Silica content of the ore thereby causes a loss of both NaOH and Al_2O_3 , and if this loss is high, the red mud is often later reworked. The solution of NaAlO_2 and NaOH is then diluted, cooled, and seeded to precipitate $\text{Al}(\text{OH})_3$. A large amount of low-temperature process heat is required to concentrate the NaOH solution for recycle, and high-temperature heat is needed for a final calcining step to convert $\text{Al}(\text{OH})_3$ to Al_2O_3 . Variations in the process, due to differences in the degree of hydration of the alumina originally in the ore, consist mainly in temperatures at which the bauxite is digested with NaOH .

In the United States, the small amount of domestic bauxite available is processed mostly by a combination lime-soda sinter and Bayer process. Although the cost of production by this process is higher than the conventional Bayer process using low silica ores, the saving in transportation costs by the use of domestic bauxite makes the process economical.

Table I shows the raw-material requirements for alumina production in both the Bayer and lime-soda sinter processes.

TABLE I. Requirements per Net ton of Alumina¹

Bauxite Type:	Process Used		
	Bayer	Bayer	Lime-Soda Sinter Combination
	A	B	C
<u>Raw Materials</u>			
Bauxite (net tons dry)	2.0	3.0	2.2
Soda ash (net tons)	0.08	0.40	0.12
Lime (net tons)	0.06	0.30	0.10
Limestone (net tons)	-	-	0.70
Natural gas (1000 ft ³)	9.0	10.0	23.0
<u>Bauxite Quality</u>			
Percent SiO ₂	3	13	13
Percent Al ₂ O ₃	55	50	50
<u>Expected Recovery</u>			
Percentage of bauxite	50	33	45
Percent of Al ₂ O ₃	91	66	90

A. Bauxite containing 3% silica and 55% alumina.

B and C. Bauxite containing 13% silica and 50% alumina.

A point to note from Table I is that the lime-soda sinter process used with low-grade domestic ores uses a larger quantity of natural gas (heating fuel) than the Bayer process. This could be an important economic factor in the use of nuclear energy at a domestic site.

C. Alumina via Other Processes

1. Sintering Process

Various processes have been devised for the production of alumina by calcining bauxite with sodium carbonate (soda ash), calcium carbonate (limestone), barium carbonate, or sodium sulfate. These processes produce a soluble alkaline aluminate, which may be precipitated as in the Bayer process. Although these processes have not been quite competitive with the Bayer process, they are all reasonably economic and should be re-evaluated in conjunction with any detailed analysis of the use of nuclear energy in the aluminum industry.

2. Production of Alumina from Clay

The Bureau of Mines has published several reports on the production of alumina from clay.²⁻⁵ These reports are cost evaluations of a variety of processes. Two of the most attractive processes, from a cost

standpoint, appeared to be the hydrochloric acid-caustic purification process and the isopropyl ether extraction process. In the HCl process, calcined clay is leached with 20% HCl to form AlCl_3 . The impure chloride solution is filtered to remove the solid residue containing silica and other undissolved materials. The solution is concentrated by evaporation, precipitating aluminum and iron chlorides. These chlorides are calcined at 1000°F to produce alumina in a soluble condition. This crude alumina is then purified by a modified Bayer process. The alumina cost breakdown⁴ is shown in Table II.

TABLE II. Estimated Annual Operating Cost for the Caustic Purification Process (350,000 tons of alumina)⁴

	Annual Cost	Cost per ton of Alumina
<u>Direct Cost</u>		
<u>Raw Materials</u>		
Raw clay @ \$1/ton	\$ 1,782,200	\$ 5.09
Hydrochloric acid, 18° Be, @ \$28/ton	2,587,200	7.39
Sodium hydroxide (50%), @ \$38/ton	1,170,400	3.34
Total	\$ 5,539,800	\$15.82
<u>Utilities</u>		
Electric power @ 0.5¢/kW-hr	\$ 334,700	\$.96
Steam, 100-psig, @ 50¢/1000 lb	1,178,800	3.37
Water, cooling @ 2¢/1000 gal	242,800	.69
Water, process @ 10¢/1000 gal	159,200	.46
Water, raw @ 1¢/1000 gal	3,100	.01
Natural gas @ 2.5¢/therm	2,727,100	7.79
Compressed air @ 1¢/1000 ft ³	8,500	.02
Total	\$ 4,654,200	\$13.30
<u>Direct Labor</u>		
Labor @ \$2.30/hr	\$ 2,353,700	\$ 6.72
Supervision, 15% of labor	353,100	1.01
Total	\$ 2,706,800	\$ 7.73
Plant maintenance, 6% of installed equipment cost	\$ 3,103,200	\$ 8.87
Operating supplies, 15% of plant maintenance	465,500	1.33
Total direct cost	\$16,469,500	\$47.05
Indirect cost, 50% of direct labor and maintenance	\$ 2,905,000	\$ 8.30
<u>Fixed Cost</u>		
Taxes and insurance, 2% of total plant cost	\$ 1,793,600	\$ 5.12
Depreciation, 5% of fixed capital cost	4,663,400	13.32
Total operating cost	\$25,831,500	\$73.79

In the isopropyl ether extraction process, dehydrated clay is leached with 20% HCl to form AlCl_3 . The impure solution is filtered and concentrated, and isopropyl ether is then used to extract the iron chloride. The aluminum chloride is then crystallized as $\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$ in evaporators and then decomposed and calcined in rotary kilns. A cost breakdown is shown in Table III.

TABLE III. Estimated Annual Operating Cost for the Isopropyl Ether Extraction Process (350,000 tons of alumina)⁴

	Annual Cost	Cost per ton of Alumina
<u>Direct Cost</u>		
<u>Raw Materials</u>		
Clay @ \$1/ton	\$ 1,694,000	\$ 4.84
Hydrochloric acid, 18° Be, @ \$28/ton	2,381,400	6.80
Isopropyl ether @ \$99/ton	34,700	.10
Total	\$ 4,110,100	\$11.74
<u>Utilities</u>		
Electric power @ 0.5¢/kW-hr	\$ 203,900	\$.58
Steam, 100-psig @ 50¢/1000 lb	3,003,000	8.58
Water, cooling @ 2¢/1000 gal	438,000	1.25
Water, process @ 10¢/1000 gal	33,300	.10
Water, raw @ 1¢/1000 gal	2,700	.01
Natural gas @ 2.5¢/therm	2,414,000	6.90
Total	\$ 6,094,900	\$17.42
<u>Direct Labor</u>		
Labor @ \$2.30/hr	\$ 1,655,300	\$ 4.73
Supervision, 15% of labor	248,300	.71
Total	\$ 1,903,600	\$ 5.44
Plant maintenance, 6% of installed equipment cost	\$ 2,530,300	\$ 7.23
Operating supplies, 15% of plant maintenance	379,500	1.08
Total direct cost	\$15,018,400	\$42.91
Indirect cost, 50% of direct labor and maintenance	\$ 2,217,000	\$ 6.33
<u>Fixed Cost</u>		
Taxes and insurance, 2% of total plant cost	\$ 1,541,500	\$ 4.40
Depreciation, 5% of fixed capital cost	4,008,000	11.45
Total operating cost	\$22,784,900	\$65.09

The production of aluminum from clay could be of further interest because of the expanding production of aluminum and the limited reserves of domestic bauxite. Furthermore, use of a total-energy-source nuclear reactor could shift the economic balances.

D. Electrolytic Reduction by the Hall Process

Most of the world's supply of aluminum is produced by the Hall process-electrolytic reduction of alumina dissolved in fused cryolite ($\text{AlF}_3 \cdot 3\text{NaF}$). Processes other than the Hall process have been tried throughout the years, but have been only partially successful.

The difficulty of winning aluminum from Al_2O_3 is best shown by thermodynamics. Figures 1 and 2 give the enthalpy and free-energy changes of various aluminum reactions. Enthalpy is the amount of heat that must be supplied; a negative free energy gives the tendency for the reaction to proceed spontaneously. Note that Al_2O_3 cannot be reduced by hydrogen at any temperature. At temperatures near 2000°K , Al_2O_3 can be reduced by carbon but only to Al_4C_3 , which must be further treated to obtain aluminum. At higher temperatures, Al_4C_3 no longer forms, but the aluminum boils and the metal vapor cannot be separated from CO.

Fig. 1. Enthalpy of Aluminum Reactions

Fig. 2. Free Energy of Aluminum Reactions

Al_2O_3 can be reduced at temperatures below the boiling point of the metal only by a combination of carbon plus nitrogen to yield AlN , which can then be decomposed by using heat and vacuum. This process has not been economical, however, as the heat of reaction had to be supplied electrically. Hence, the process had no advantage over the Hall electrolytic process.

In the Hall process, a solution of Al_2O_3 in molten cryolite ($\text{AlF}_3 \cdot 3\text{NaF}$) is electrolyzed by means of carbon anodes. The reaction is carried out at 900-1000°C and approximates

Currents of up to 100,000 Amp per cell are used. Cells, which require about 5 V each, are connected in series in a potline of up to 800 V. Energy consumption is about 9 kW-hr/lb of aluminum. The cost of the carbon anodes that are consumed is a significant part of the overall cost.

Aluminum is refined either electrolytically or by a chloride process. In the latter, impure aluminum (generally containing FeAl_3 and/or Al_4C_3) is reacted with AlCl_3 to form $\text{AlCl}(\text{v})$. Upon cooling, the latter compound disproportionates to $\text{AlCl}_3 + 2\text{Al}$. Energetics for this reaction are also given in Figs. 1 and 2.

A typical breakdown of raw material requirements for 1 lb of aluminum by the Hall process is

1.9 lb of alumina

0.7 lb of carbon electrodes

8.0-9.0 kW-hr of electric power

0.023 lb of cryolite

0.029 lb of AlF_3 .

E. Energy Requirements for Aluminum Production

The thermal requirements for the production of alumina from bauxite by the Bayer process are split almost evenly between the low-temperature (i.e., 100-150 psig) steam and the high-temperature calcining heat requiring air at 2000-2300°F. Approximately 5×10^6 Btu/ton of alumina produced are required for each step. Although this amounts to 20×10^6 Btu/ton of aluminum metal, the largest energy requirement is in the electrolytic reduction step, which requires ≈ 9 kW-hr/lb of aluminum.

The following would be the approximate energy requirements for a large (300,000-ton/year) aluminum-producing complex:

Low-temperature process steam	100 MWt
High-temperature process heat	100 MWt
Electrical energy	630 MWe.

The energy requirements are primarily electrical, but in a large aluminum-producing complex the thermal requirements would not be insignificant. Approximately twice the above amount of process heat is required for processing of high-silica domestic ores.

F. Aluminum Production and Economics

Aluminum production in the United States reached 2.55 million tons in 1964, and is growing at the rate of about 10%/year. Thus, the 300,000-ton/year plant used in the preceding illustration represents about one year's growth for the United States aluminum industry and is about equivalent in size to the Aluminum Company of Canada, Ltd., plant at Kitimat, British Columbia.

Approximately 85% of the bauxite used for the production of aluminum and alumina in the United States is imported. Forty-nine percent of the ore is Jamaican type (from Jamaica, Haiti, and the Dominican Republic), and 36% is from Surinam and British Guiana. Since it is desirable to keep transportation costs to a minimum, owing to the requirement of about 2 tons of bauxite to produce 1 ton of alumina, domestic bauxite is processed at or near the mine site.

Imported ore is usually shipped directly to the United States because of high fuel costs at the mine site. Thus, a large part of the alumina production is located at Gulf Coast sites, where inexpensive fuel is available and where low-cost water transportation is available for the bauxite.

After alumina is produced, the emphasis is on obtaining low-cost electrical power for the reduction process. Hence, the alumina is shipped to the reduction plant. Historically, the electrolytic reduction of aluminum grew because of the available low-cost hydroelectric power, first in the central United States and then later in the Pacific Northwest. But the limited supply of this power has caused aluminum reduction plants to be operated with fossil fuels, both in the central United States and on the Gulf Coast. Table IV shows the breakdown of aluminum-reduction costs.

Power costs quoted from Reference 6 may be somewhat high, since quoted power costs for a new electric-generating plant built by Alcoa were 3.5 mills.

TABLE IV. Example of Estimated Aluminum-reduction Cost for a 60,000-ton/year Plant Using Power Costs Comparable to That from TVA⁶

	Cost, ¢/lb
Power: 9 kW-hr @ 4.25 mills/kW-hr	3.83
Alumina: 1.91 lb @ 3.7¢/lb (includes plant amortization, interest, and profit)	7.07
Cryolite and aluminum fluoride: 0.05 lb @ 15¢/lb	0.75
Labor: 0.008 man-hr/lb @ \$3.00/hr (including overhead)	2.40
Repair and maintenance material (including potlinings)	1.00
Electrodes: 0.6 lb @ 2.5¢/lb	1.50
Miscellaneous plant costs	0.95
Indirect overhead	0.50
Total operating costs	18.00
Amortization, interest, and profit	6.00
Freight to market	1.00
Delivered price of aluminum pig	25.00

The actual economic choice of a plant location depends on many factors including power costs, bauxite transportation costs, alumina transportation costs, and the cost of delivering the aluminum pig from the reduction plant to market. These freight costs are difficult to evaluate because there is no open market for alumina in the United States. Handling costs at three separate points can significantly affect costs. Published non-United States figures give some indication of bauxite transportation costs. Bracewell¹ gives the following figures for the difference between c.i.f. and f.o.b. costs for the following:

Sarawak to Japan $\approx$ \$17/ton of aluminum

France to England $\approx$ \$13/ton of aluminum.

The 1963 prices⁷ for dried bauxite (60% Al_2O_3 , 6% SiO_2 , $1\frac{1}{4}\%$ Fe) are given as the following:

\$ 7.25/long ton	F.O.B. vessels, British Guiana
\$13.95/long ton	F.O.B. cars, Atlantic ports
\$17.15/long ton	Average delivered value at alumina plants.

Thus total transportation costs could be as high as \$45/ton or 2.3¢/lb of aluminum. If freight to market is added, this could bring the total to 3.2¢/lb of aluminum.

G. Use of Nuclear Energy

Aside from the directly competitive energy-cost balance, the freedom of site location given by nuclear energy could provide a strong incentive for its use. If it is assumed that 3.5-mill power is presently competitive, then the allowable power cost, as a function of saving in transportation cost, is illustrated as follows:

Saving in Transportation Cost, ¢/lb of aluminum	Allowable Power Cost, mills/kW-hr
0.5	4.05
1.0	4.61
1.5	5.16
2.0	5.72

Because of the large reduction in weight from bauxite to aluminum, a mine-site application of a total energy source might be attractive. Whether or not the high-temperature heat is supplied by a reactor, there appear to be advantages to providing the electrical energy and steam for the Bayer process from a single energy source. Obvious, practical difficulties in providing power backup at an isolated site might dictate smaller units at higher power costs. Also, even though the high total tonnage is reduced, handling costs of aluminum pig, as contrasted to bauxite, would reduce the freight savings. An alternate possibility is the seacoast location of the aluminum complex with short, low-cost, water transportation of bauxite to the plant and aluminum to market.

III. IRON-ORE REDUCTION AND PELLETIZING

Because of the enormous size of the industry and of the amount of energy consumed, it is important to investigate the possibility of using nuclear energy for iron-ore reduction. Nuclear energy can be used for:

- (1) Iron-ore reduction by means of well-established hydrogen-reduction processes.
- (2) Ore pelletizing at large mine-site plants.

The use of nuclear energy for a reduction process has two economic drawbacks. One is that the steel companies have large investments in coal-consuming blast furnaces, which must not be idled, and which are constantly being improved in efficiency. Therefore, hydrogen processes with or without nuclear energy will not be readily adopted. The other is that to be economically competitive, the hydrogen processes must use cheap hydrogen made from either coal or natural gas. Given the need for some source of raw material, it is difficult to conceive of a situation in which more of the same raw material could not be used as a cheap fuel.

On the other hand, ore pelletizing could provide a use for nuclear energy, as the process does not require a reductant. Here air would be the heating medium, just as in nuclear-powered cement plants discussed in Section IV below. Present-day mine-site plants, which are several times as large as any existing cement plants, are probably large enough to warrant nuclear installations.

To provide a base for possible economic analyses, the following brief discussion of current technology is presented.

A. Blast-furnace Technology

Most iron ore is presently reduced by coke in a blast furnace. In these units, iron ore is reduced in a sort of two-step process:

The reaction goes to completion with respect to iron, but the exit gas composition is essentially determined by the equilibrium constant of Reaction (1). The net useful reaction in a blast furnace is approximately

The endothermic heat of Reaction (3) is 121 kcal. This heat of reaction is supplied by burning additional coke to the stoichiometry determined by

the iron equilibrium,

From Eqs. (3) and (4) it is calculated that for 1 ton of iron, about 430 lb of carbon are needed for reduction, and 480 lb of carbon are needed to supply the heat of reduction. In practice, up to twice the sum of these amounts (as coke) is used in blast furnaces. The additional fuel is needed to supply heat for drying the ore, for endothermic reactions taking place in the slag, to make up the net sensible heat of the exit streams, and for other losses.

Coke rather than coal is used in a blast furnace both for cleanliness and because the hardness of coke is needed to provide a burden that will move smoothly through the furnace. The blast furnace is basically inefficient, both in its incomplete use of fuel (burning to CO rather than CO₂) and its need for high-cost coke (\$15-20/ton) rather than low-cost coal (\$4-6/ton). Over the years, however, the economy of blast furnaces has been constantly improved by oxygen enrichment of the blast, which cut down the fuel requirements, by supplanting part of the coke with cheap fuels such as powdered coal, natural gas, oil, etc., and by the use of preprepared, low-slag ores. Still, the blast furnace remains a basically inefficient device, which provides the impetus for development of other reduction processes.

References 8, 9, and 10 provide further information on the subject of blast furnaces.

About the only way nuclear energy might be useful with a blast furnace is by preheating the air entering the furnace. Currently this is done by burning top gas with air and transferring the combustion heat to the blast air via regenerative stoves or pebble-bed heaters. The mixture of CO and CO₂, produced as in Eq. (3), when burned with air,

has a heat of combustion of 135 kcal. This is slightly greater than the endothermic heat of Reaction (3) and is a large share of the total heat requirement of the furnace. If nuclear preheat were used, it would be only to provide heat beyond that available from combustion of top gas. It is difficult to estimate just how much heat would be needed, but it is doubtful if any one blast furnace would have a heating requirement large enough to make a nuclear reactor economical.

B. Hydrogen Reduction Processes

Hydrogen is about as effective a reducing agent as CO. The reaction

for which the endothermic heat of reaction is 36 kcal. Assuming that no gas is purged, the overall reaction of Fig. 1, including the CH_4^* reforming, is

The endothermic heat of this reaction is 75 kcal, and if nuclear energy were used in the process, it would be to supply this net heat.

Without using nuclear energy, however, consider the economics of a pure combustion cycle. If purged hydrogen is burned and the heat is returned to the system, and additional CH_4 is burned with air to provide the remaining heat of reaction, the overall reaction of a combustion cycle would be

For Reaction (10) to have a zero heat of reaction, X need only be 0.39. This says that the total amount of natural gas needed in a no-heat-loss system would only be 39% greater than the minimum amount needed for ore reduction. Practically, excess steam is generally used to prevent cooling in the CH_4 reforming step, so that some heat is lost as uncondensed steam. But with respect to using nuclear energy to supply the net heat, it is difficult to conceive of a situation in which the CH_4 would be cheap enough to allow production of hydrogen, and yet not cheap enough so that even an equal amount could not be burned competitively with nuclear energy.

C. Electrolytic Hydrogen

Nuclear energy could conceivably be used for iron-ore reduction via a hydrogen-reduction process if hydrogen could be made electrolytically from water cheaply enough. In some geographically-remote situation, the saving on cost of coal or natural gas might offset a higher hydrogen-production cost. However, the cost of electrolytic hydrogen is strongly dependent on the byproduct value of oxygen, and therefore there must also be a need for large quantities of oxygen at the remote site. An economic evaluation is complex, but one can get an idea of the costs from the following discussion. Assume that:

- (1) Electrolytic hydrogen requires 120 kW-hr/1000 ft³.
- (2) Steam reforming of CH_4 requires 400 ft³ of CH_4 per 1000 ft³ of hydrogen.
- (3) Ore reduction requires 19,000 ft³ of hydrogen per ton of iron.

From these values, and assuming comparable hydrogen plant costs, the allowable costs of electrolytic hydrogen are summarized in Table V.

*Hydrogen may also be made by partial combustion of natural gas rather than by steam reforming, or from coal, air, and water, although these processes introduce a nitrogen-separation problem.

Present-day prices on natural gas are as follows:

15-20¢/1000 ft³ at fields;

25-30¢/1000 ft³ delivered to large-scale users;

50¢-\$1.50/1000 ft³ delivered to small-scale users.

TABLE V. Allowable Costs of Electrolytic Hydrogen

CH ₄ cost, ¢/1000 ft ³	15	20	30	30	60	90
Oxygen value, ¢/1000 ft ³	10	10	10	20	20	20
CH ₄ cost, ¢/1000 ft ³ of hydrogen	6	8	12	12	24	36
Oxygen value, ¢/1000 ft ³ of hydrogen	5	5	5	10	10	10
Allowable electrolytic hydrogen value, ¢/1000 ft ³	11	13	17	22	34	46
Allowable electrical cost, ¢/kW-hr	0.09	0.11	0.14	0.19	0.28	0.38
Hydrogen cost, in \$/ton of iron, based on raw-materials cost or electrical cost only	1.14	1.52	2.28	2.28	4.56	6.84

These numbers indicate that electrolytic hydrogen must be very cheap to compete with hydrogen from natural gas. Nuclear-electricity costs have been projected to be as low as 2 to 4 mills/kW-hr but only for very large plants.

Taking some representative numbers on plant size, assume a hydrogen-reduction plant produces 500 tons of iron per hour (350,000 tons/month vs U. S. production of 12,000,000 tons/month). For electrolytic hydrogen production, this would require

$$500 \text{ tons Fe/hr} \times 19,000 \text{ ft}^3 \text{ H}_2/\text{ton Fe} \times 120 \text{ kW-hr}/1000 \text{ ft}^3 \text{ H}_2 = 1,140,000 \text{ kW.}$$

Nuclear electricity costs might be as low as 3-4 mills/kW-hr for this size plant, but the oxygen byproduct production would be 212 tons of oxygen per hour (which is a large quantity of oxygen). Given this low electricity cost and no outlet for such quantities of oxygen, one might find straightforward, electric-furnace reduction of iron ore more economical. Any use of electrolytic hydrogen must find a use for byproduct oxygen; only a small fraction of this quantity could be used in oxygen steel-making. One advantage of nuclear heat in the hydrogen-reduction process is a simplification of heat-exchanger problems since the heat exchanger does not have to handle combustion products.

D. Hydrogen from Direct Decomposition of Water

The main reason that electrolytic hydrogen is so costly is that electric energy is obtained from heat at a low thermodynamic efficiency (approximately 30%). If water could be directly decomposed by heat, and the products efficiently separated, it might be possible that hydrogen could

be produced cheaper from water than from coal or natural gas. Unfortunately, direct decomposition of water and separation of products are not technically feasible. Equilibrium constants of the reaction

are as follows:

<u>T°K</u>	<u>T°R</u>	<u>K</u>
2000	3600	0.0003
3000	5400	0.05
4000	7200	0.6
5000	9000	3

These data indicate that straightforward, thermal decomposition of water, let alone the separation of the products, is unlikely at a reasonable temperature. It is doubtful if any material can be found to withstand the attack of a mixture of water, hydrogen, and oxygen vapors at temperatures much above 2000°K.

As an alternate to direct decomposition of water, one might investigate the possibility of the following two-step process:

This type of approach might be carried out in a pebble-bed reactor with the MO_X being the pebbles, but environmental problems here will be hardly less severe than for direct decomposition of water. Although unlikely, some process of this type just might make the use of nuclear energy for hydrogen production economical.

E. Iron-ore Pelletizing

The throughput, and hence the economic efficiency, of a conventional blast furnace can be markedly improved if the burden (ore plus coke) is closely sized. This allows a higher gas velocity to be used in the furnace without causing excessive pressure drop and carryover of fines. Many techniques have been used to obtain the desired burden, one of which is to use closely-sized ore pellets. For example, taconite ore, after being concentrated, is formed into green pellets with binder and water, and the pellets are dried and heat-hardened at temperatures above 2000°F. The hardening is done by direct firing, and although the contact with combustion products results in a slight increase in the oxidation state of the ore,

the slight increase in the oxygen content of the ore is of little importance in the blast furnacc.

Pelletizing plants range upward in size from 5,000,000 tons/year, and heat requirements range from 1 to 2 million Btu/ton. Assuming a large plant of 10,000,000 tons/year, with a heat requirement of 1 million Btu/ton, the thermal power requirement is found to be 385 MW. A nuclear power plant to provide this amount of heating to an air stream at 2200°F might be interesting. It might also be interesting to combine this plant with an electricity-generating plant to power electric reducing furnaces. These furnaces are generally small compared to blast furnaces and would hardly use the output of a 10,000,000-ton/year pelletizing plant. But if sufficient units were installed to consume, say, 100 to 200 MW, a power plant of 700 to 1000 MW could be built. A detailed economic analysis of a nuclear-powered pelletizing plant, in possible conjunction with electric power generation, appears to be warranted.

IV. CEMENT PRODUCTION

One of the largest energy-consuming processes in the world is cement production. Cement is made by mixing limestone and sand-clay mix, heating the mixture in a rotary kiln to produce a clinker, and then grinding the clinker to powder. The heating is done by direct firing at temperatures around 2700°F. In 1963, 361 million barrels of cement, each weighing 376 lb, were made in the United States. Coal, oil, and natural gas were burned to supply the required heat, averaging 1.2 million Btu/barrel. With a total energy consumption of 4.3×10^{14} Btu/year, it seems worthwhile to investigate the use of nuclear energy for cement production.

A. Cement Technology

An average composition of Portland cement¹⁴ is

64% CaO
 21% SiO₂
 6% Al₂O₃
 3% Fe₂O₃
 2% MgO
 1% Alkali
 2% SO₂.

Most of the energy consumed in making cement goes into the decomposition reaction,

A large part of the remainder of the energy goes into evaporating free moisture and water of hydration from the various ingredients. About 600 lb of raw materials are used to produce a 376-lb barrel of cement. Other raw materials used in making cement are: shale, marl, marble-quarry waste, gypsum, sand, blast-furnace slag, low-grade bauxite, and Bayer-process red mud. Special cements are made for many purposes. For example, ilmenite (TiO₂·Fe₂O₃) is used to provide a high-density cement for nuclear shielding.

In considering the use of nuclear energy to make cement, it is apparent that air heated by a reactor would be as effective as combustion products in producing a clinker. There is no chemical reaction between cement ingredients and combustion products of air. The only technological factor involved in using nuclear energy is in the development of a heat exchanger for the transfer of heat from the primary reactor stream to air. Obviously one would not carry the hot stream far from the source, but installation of one or more kilns around a reactor should not present a problem.

The questions in the use of nuclear energy for cement production, then, are primarily economic. How much will the high-temperature reactor and heat exchanger cost, and can cement be produced in a large enough scale to warrant use of a nuclear reactor? The first question can only be answered after detailed analysis, but as discussed below, there is good indication that, when part of a multipurpose reactor, a high-temperature section can be made reasonably economical.

The scale of the cement industry is given in Table VI.

TABLE VI. Estimated 1963 Capacity of Cement Plants

Capacity, million barrels/year	Number of Plants in U. S.	Percent of Total Capacity
Less than 1	8	1.3
1 to 2	55	17.3
2 to 3	64	32.3
3 to 4	31	21.2
4 to 5	12	10.5
5 and over	11	17.4

Some plants have a capacity of more than 10 million barrels/year, and one plant planned for the United States will have a single kiln capable of producing 7 million barrels/year.¹⁵

Cement is always produced near places of consumption. Most cement is shipped by truck in bulk from mill to market. A lesser amount is shipped by rail, and in the coastal and Great Lakes regions, some is shipped by water. Barges having a capacity of up to 90,000 barrels are used.

The largest cement-producing states in 1963 were:

California	46,100,000 barrels;
Pennsylvania	38,400,000 barrels;
Texas	29,200,000 barrels;
Michigan	24,200,000 barrels.

The production of cement in the larger, cement-producing countries is summarized in Table VII. Although cement production is temporarily in overcapacity in the United States today, Table VII indicates that a nuclear-heated cement plant with a capacity of 10 or 20 million barrels would not have a disruptive influence on world production. Assuming operation for 7600 hr/year, the power equivalent of a large plant would be

10 million barrels/year	= 463 MWt;
20 million barrels/year	= 925 MWt.

Nuclear power plants of this size might be economical, and certainly thermal units of this size as part of a multipurpose complex of, say, 4000-5000 MWt total, are worth investigating.

TABLE VII. Production of Cement in
Larger Cement-producing Countries

Country	Production, million barrels/year		
	1954-58 Average	1960	1963
United States	361	391	436
West Germany	108	146	171
U.S.S.R.	151	267	358
France	68	83	104
Italy	65	94	130
China	37	79	53
India	30	46	55
Japan	76	132	172

B. Portable Cement Plant

One possible application might be a portable, nuclear-heated, cement plant. Such a plant could be moved to, for example, a large hydroelectric-dam construction site and be used until construction is complete. The plant could also have an electricity generation unit, etc. Many ramifications of this concept have to be considered. The basic plant size would be quite small, of the order of 100,000-200,000 barrels/year.

V. FERTILIZER PRODUCTION

Many discussions of the use of nuclear energy point out nitrogen and phosphate fertilizer production as present large energy users, but it is difficult to see how future production of fertilizer can use direct nuclear heating to any large extent in the United States. Nitrogen fixation and making phosphate rocks soluble are not inherently energy-consuming processes, and given coal and sulfur, chemists have been exceedingly clever in carrying out these processes economically at low temperatures. Some energy is consumed in certain steps, principally the phosphate area, of fertilizer production, and it might be economical to use direct nuclear heating for these if carried out as part of some larger United States processing complex. But it appears fairly certain that calcining phosphate will not become a major user of thermal energy in this country.

To prepare a background for economic studies in the use of nuclear energy for fertilizer production, the following outline and comments on current practice are presented.

A. Nitrogen Fixation

The three main useful constituents of fertilizers are nitrogen, phosphorus, and potassium. The form in which these are applied to the soil is dependent on mostly economic factors, but also to some extent on soil needs for minor constituents and on pH control. Fertilizers are rated by their weight fractions of:

Nitrogen as total nitrogen;

Phosphorus as available P_2O_5 ;

Potassium as soluble K_2O .

The nitrogen content of fertilizers today is derived almost entirely from NH_3 . This is applied to the soil as liquid NH_3 , as ammonium salts of other needed constituents, or as NH_4NO_3 . This latter is made from NH_3 and HNO_3 , while the HNO_3 is itself usually derived from NH_3 . The only major variation in production of NH_3 is in the production of the hydrogen from which the NH_3 is synthesized. The natural sources of fixed nitrogen, such as Chilean nitrate, are no longer of major importance in the United States.

Although NH_3 can be obtained in a variety of ways, including distillation of coal, most NH_3 is obtained by direct synthesis as follows:

*Heat quantities are for gram molar quantities of the reaction as written. A negative value of Q means that heat is released; i.e., the process is exothermic.

Hydrogen for this process can be obtained in different ways, but it is primarily obtained from coal and water, from natural gas, or as a by-product in petrochemical processing. Key reactions in the production of hydrogen from coal are:

Reaction (12) is the primary gasification step. Reaction (14) is carried out catalytically to increase the hydrogen yield. The sum of Reactions (12), (13), and (14) is

Although the actual processes are not as simple or direct as indicated by these equations, essentially sufficient coal is burned as in Reaction (15) to supply the endothermic heat of Reaction (16) plus any heat losses.

Similarly, for the production of hydrogen from natural gas (CH_4), the overall reaction is

where X is sufficient to provide an overall, net heat release. In some cases, the burning of the methane with air is devised so as to leave the hydrogen and nitrogen from the air in proper proportions for direct NH_3 synthesis. Furthermore, CO_2 is often recovered as a valuable chemical.

In view of the simplicity and energy economy of these processes for making hydrogen and NH_3 , it is difficult to see how nuclear energy could be used economically for NH_3 production unless carbonaceous matter were in very short supply. In the latter case, one might use nuclear energy to crack CH_4 as in one or another of the following energy-consuming reactions:

In these cases, the products other than hydrogen are also valuable. Energy requirements of this sort of processing, however, could not be charged to nitrogen fixation.

Some hydrogen is obtained as a byproduct in the chlorine caustic soda electrolytic process,

but the amount is small compared to that used in NH_3 production.

In some special cases, hydrogen is made from electrolysis of water. Although the electrolysis process itself is reasonably efficient (2.0 V vs a theoretical voltage of 1.2 V), the energy requirement here is an order of magnitude greater than for the coal-natural gas methods.

Use of high-temperature heat or direct nuclear processes for decomposing water and separating the products does not appear technically feasible at present.

Nitric acid is made by catalytic oxidation of NH_3 . The reaction may be carried out in steps or directly but in any case the overall useful reaction is

Combining Reactions (11), (17) (with $X = 1/2$), and (22), yields

Again, it is difficult to see how nuclear energy can provide any economic advantage over this very exothermic process as long as natural gas (or coal) is available. Direct thermal, nuclear fixation or electric arc of nitrogen via

can be accomplished if necessary, but only at extreme sacrifice of thermodynamic efficiency. However, if electrical energy is inexpensive enough, favorable economics could result.

B. Phosphate Fertilizers

Phosphorus is in plentiful supply throughout the United States and certain other parts of the world in the form of phosphate rock. The

phosphorus-bearing mineral of such rock is apatite,

where X = Cl, F, OH, or any combination thereof, and is usually fluorapatite where X = F. Although phosphate rock may be and sometimes is ground and applied directly to the soil, the material is essentially insoluble so that the phosphorus becomes available to plants only over long periods of time. Fertilizer manufacture therefore is primarily a conversion of rock to more soluble phosphates.

The process generally used in the United States for obtaining soluble phosphates from rock is treatment with sulfuric acid. Shreve¹⁴ gives the reaction as

This reaction takes place slowly with a small heat release. The product, which is a mixture of phosphate and sulfate, is called superphosphate. Most of the sulfuric acid production of the United States is used in making superphosphate. Energy consumption occurs only in the handling and crushing operations, in the drying of the rock after washing and beneficiation, and in drying of the final product. Temperatures up to 1400°F may be used in the drying steps. Other acids (e.g., nitric, hydrochloric, or phosphoric acid) may be used for treating the rock. In the latter case, the product is triple superphosphate,

There are two energy-consuming processes for producing soluble phosphates. The first process uses carbon to reduce the P_2O_5 content of phosphate rock to elemental phosphorus in either a blast furnace or an electric furnace. The second energy-consuming process makes a low-grade fertilizer by a calcining operation.

The carbon-reduction processes are basically different from that used for iron and other similar metal-ore reductions. For phosphorus, carbon, which is a stronger reducing agent than CO, must be the reductant; therefore, the rock is briquetted with carbon before entering the furnace. SiO_2 is used as a flux, yielding $\text{CaO} \cdot \text{SiO}_2$ slag. The phosphorus vapor produced is collected and burned to pure P_2O_5 , which is later converted into a variety of phosphorus compounds. The phosphorus is always burned to P_2O_5 so as to utilize the heat of combustion.

Although one might investigate using nuclear energy, for example, to provide electric power for a furnace at the mining site, it must be

realized that if the CO and phosphorus produced are both burned to recover heat, the net energy consumption of the process is not very large; i.e., it is considerably less than for winning of a metal from an ore. Furthermore, since it is necessary to use carbon in the reduction, and if it were necessary to bring in coal to the mine site, it might well be better to bring in sulfur or some other acid-producing material for the nonenergy-consuming acid route.

The use of high-temperature heat obtained from a nuclear reactor would be most interesting in application to direct thermal (nonreducing) production of soluble phosphates from rock. Depending on the exact composition of the rock, and on the availability of other raw materials, the fluorine content (the part that makes the phosphate insoluble) of the rock can be removed by high-temperature calcining. If silica is used as the solubilizing reagent, the reaction, which must be carried out in presence of $\text{H}_2\text{O}(\text{v})$, would approximate

Other reagents which may be used in thermal processes are

In these cases, the fluorine may or may not be removed, but a soluble product is formed. Reactions are carried out almost exactly as in cement production, and temperatures used are about 2600°F. Although pilot-plant work in this area has been done by using hydrocarbon-fuel combustion gases as the heating medium, undoubtedly air heated by a nuclear power plant would be equally satisfactory.

Phosphate fertilizers made by the thermal process probably would not warrant building a nuclear power plant for a facility producing only the phosphate. The product would probably not gain wide acceptance in the United States where industry and agriculture are geared to preparing and using more concentrated fertilizers. Production from a single facility would, therefore, never be large. But, the thermal fertilizer might be made in conjunction with a nuclear cement plant where a large part of both processes uses similar or identical equipment and a single nuclear reactor, also producing electricity. The advantages of a cement-fertilizer-electric power complex for newly-developing countries are obvious.

C. Potash

Although potassium fertilizer is rated in terms of its equivalent potash (K_2O) content, almost any soluble potassium salt may be used.

In the United States, most of the fertilizer used is muriate of potash (KCl), which is obtained from the natural mixture of silvite (KCl) and halite (NaCl) called sylvinite. There seems to be no need for nuclear energy here.

D. Summary

There does not appear to be any large use for high-temperature process heat in fertilizer production. While it is possible to produce low-quality fertilizers by the thermal process, these fertilizers would probably not go in wide acceptance in the United States. Their production as part of a larger complex in a newly-developing nation may have application.

If nuclear electricity can be made cheap enough, both nitrogen fixation and phosphate production can be carried out electrically, but both of these will require extremely low electrical costs to be competitive.

VI. PETROCHEMICAL PROCESSING

A. General

A question often proposed is whether it makes economic sense to use nuclear energy for organic chemical processing in order to conserve natural sources of hydrocarbon raw materials, or merely to lower processing costs. There is no doubt that the processing can be accomplished by means of nuclear energy, as all but a few conventional organic reactions can be carried out at moderate temperatures, which can be produced by nuclear reactors. Analysis shows, however, that the use of nuclear energy does not make sense at present simply because the entire petrochemical industry would require only one or two reactors of a size considered to be economical for this sort of thing. Even in the future, the prospect for the use of nuclear energy for petrochemical processing does not seem good because the energy requirement for shifting carbon-hydrogen bonds is not very large. Therefore, for most processes, only a small additional amount of raw material needs to be burned with air to supply the needed energy. The case, however, might be improved by making a dual-purpose, electrical generating-chemical processing plant. This dual-purpose plant could not only provide a cost saving due to size, but might provide increased thermodynamic efficiency through the combining of functions. Paradoxically, the only process that might use nuclear energy in a single-purpose plant is coal- or oil-shale gasification. This is the only type of process that could be carried out in a central location to an extent where plant size would be large enough to take advantage of large-plant cost savings. In this case, the central plant would produce a basic feedstock, which could be distributed and processed elsewhere. If current projections¹⁶ of domestic natural-gas consumption and reserves are true, then this type of system could be used in conjunction with the currently-existing gas-distribution system at a time when natural-gas reserves become depleted.

B. Petrochemical Industry

The U. S. Bureau of Mines reports that in 1963, U. S. demand for crude petroleum was 3,180,030,000 barrels (42 gal) of which approximately 5% went for nonenergy-producing uses. Of this amount, 91,756,000 barrels were used as petrochemical feedstock. Additional stocks for chemical processing were obtained from natural gas and coal. The amounts of basic materials produced for the plastics and rubber and chemical industries are a few billion pounds per year for each basic material, and the total consumption is several tens of billions of pounds per year.

Table VIII lists typical energy-consuming processes in basic petrochemical production.

TABLE VIII. Typical Energy-consuming Processes in Basic Petrochemical Production

Reaction	Heat of Reaction, kcal/g-mole	Product Formed, g	Heat of Reaction, Btu/lb	Thermal power, MW, to Produce 10^9 lb/year ⁽⁵⁾
$\text{CH}_4^{(1)} + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2^{(2)}$	59.8	34.0	3160	122
$2\text{CH}_4 \rightarrow \text{C}_2\text{H}_2 + 3\text{H}_2$	90.0	32.0	5060	194
$2\text{CH}_4 \rightarrow \text{C}_2\text{H}_4 + 2\text{H}_2$	48.3	32.0	2720	105
$\frac{2}{n}(-\text{CH}_2-)_n^{(3)} \rightarrow \text{C}_2\text{H}_2 + \text{H}_2$	66.2	28.0	4270	164
$\frac{2}{n}(-\text{CH}_2-)_n \rightarrow \text{C}_2\text{H}_4$	24.5	28.0	1580	61
$\text{CH}_4 \rightarrow \text{C}^{(4)} + \text{H}_2$	17.9	16.0	2080	80
$\frac{1}{n}(-\text{CH}_2-)_n \rightarrow \text{C} + \text{H}_2$	6.0	14.0	770	30

(1) Natural gas.

(2) Synthesis gas.

(3) Petroleum.

(4) Carbon black.

(5) Based on 7600 hr/year.

The mixture of CO and hydrogen, called synthesis gas, can be converted to methanol, ammonia, and various other chemicals. C_2H_2 and C_2H_4 are building blocks for synthetic plastics. Carbon black is used extensively in tires. A 1000-MWt reactor would produce more than an equivalent of the total U. S. production of any of these basic materials. One would probably need a tenfold increase in consumption of petrochemicals before the use of nuclear energy for processing would appear warranted.

VII. MULTIPURPOSE PLANTS

The previous discussion and the discussions presented elsewhere have shown that in the near future nuclear energy could be valuable in

1. Integrated plant aluminum production
2. Iron-ore pelletizing
3. Cement production
4. Electricity production
5. Water desalinization.

It also has been established elsewhere, that within reasonable limits, the larger a nuclear plant, the more economical it becomes. Consider, therefore, what processes might best be combined in multipurpose plants to take advantage of large-plant cost savings.

Important factors in individual or multipurpose industrial-plant selection are nearness to raw materials, nearness to population centers (i.e., places of consumption), and nearness to cheap sources of energy and water when needed. Most of the advantage in using nuclear energy for the first two processes listed above comes from locating a nuclear power plant at the ore site (which is usually remote from population centers) to eliminate cost of shipping either large quantities of fuel or materials. Conversely, the main advantage of nuclear electricity, at least with the present-day, more or less equal, nuclear-vs-fossil-fuel cost picture, comes from locating the generating plant near population centers to eliminate transmission costs. Raw materials for cement are found almost anywhere, and current practice is to minimize shipping costs by locating cement plants near population centers. Finally, sea-water desalinization makes sense only for population centers near the sea. Although one can probably make a case for combining any or all of the listed processes in multipurpose nuclear plants, it is readily apparent that, based on geographical considerations, only certain combinations make economic sense.

A. Cement, Electricity, Desalinization Complex

One interesting combination of the five processes listed above seems to be that of cement, electricity, and water desalinization. If secondary processes, such as lime and magnesium production, are also included in the complex, some interesting tie-ins are provided.

Much of the magnesium produced in the United States is obtained from sea water. In this process, the magnesium is first precipitated as $\text{Mg}(\text{OH})_2$ by adding either lime (CaO) or dead burned dolomite ($\text{CaO} \cdot \text{MgO}$):

The $\text{Mg}(\text{OH})_2$ is then treated with HCl to produce MgCl_2 , which is electrolyzed to yield magnesium metal plus chlorine. The chlorine produced in the magnesium cells is reconverted to HCl and recycled. Lime and dead burned dolomite are produced from limestone and dolomite in kilns similar to cement kilns. Tables IX and X present the composition of sea water and the average composition of dolomite limestone.

TABLE IX. Concentration of Salts in Sea Water of 1.024-g/cm Density

	Concentration, g/liter
NaCl	27.319
MgCl_2	4.176
MgSO_4	1.668
MgBr_2	0.076
CaSO_4	1.268
$\text{Ca}(\text{HCO}_3)_2$	0.178
K_2SO_4	0.869
B_2O_3	0.029
SiO_2	0.008
Fe and Al as R_2O_3	0.022

TABLE X. Composition of Typical Dolomitic Limestone

	Composition, w/o
CO_2	30-45
SiO_2	1-5
Fe_2O_3	0-2
Al_2O_3	0-5
CaO	35-45
MgO	10-25
$\text{Na}_2\text{O} + \text{K}_2\text{O}$	0-3

Fig. 4. Mass and Energy Balance for Representative, Multipurpose, Nuclear-processing Complex for Production of Lime, Cement, Magnesium, Electricity, and Fresh Water

It was readily apparent how the magnesium and lime processes fit into the scheme of a cement-producing, water-desalinization plant. Figure 4 gives a rough estimate of the power requirements involved in a reasonable-sized plant making the discussed products. The cement, lime, and magnesium plant sizes shown are all representative of larger-sized plants actually in operation today, and the output of the complex is small compared to total U. S. production of all commodities except magnesium. Figure 4 shows the magnesium plant drawing the brine after the fresh-water plant, but some more favorable combined process, including the use of other minerals, could certainly be worked out. An estimate of the yearly value of the various product streams is as follows:

1000 MWe @ 3 mills/kW-hr:	\$22 million;
10 million barrels cement @ \$3.00/barrel:	30 million;
30,000 tons magnesium @ 35¢/lb:	21 million;
200,000 tons lime @ \$13/ton:	2.6 million;
Fresh water, 30¢ to \$1.00/1000 gal:	3 to 10 million.

Whether a plant of this type makes economic sense, with or without the secondary magnesium-and-lime processes, is entirely dependent on the cost of production of the high-temperature heat, and on how much extra (if any) transporting of cement and lime raw materials to the central site is needed. Only a detailed economic and process study can determine the feasibility of a multipurpose plant.

B. Aluminum-from-Clay Complex

Another process that might fit in well with an electricity-cement-desalinization complex would be one of the aluminum-from-clay processes discussed previously. Extraction of Al_2O_3 from clay requires considerably more of both steam heat and calcining heat than does the Bayer process. Although, therefore, less economical than the Bayer process alone, use of waste steam from electricity generation, plus high-temperature heat from a multipurpose nuclear reactor, might make the extraction process attractive.

Figure 5 presents a representative power balance for a multipurpose complex taking reasonable-sized electricity and cement plants, and including the estimated requirements for the isopropyl ether alumina extraction plant of Reference 4. The total, high-temperature, direct heat is 557 MW, vs 5600 MWt supplied to the turbines. A detailed economic analysis of this scheme, both with and without the desalinization portion, should prove profitable.

Fig. 5

Mass and Energy Balance for Representative, Multipurpose, Nuclear-processing Complex for Production of Cement, Aluminum, Electricity, and Fresh Water

C. Other Possible Combinations

Table XI and the accompanying notes discuss other possible multi-purpose nuclear-plant combinations.

TABLE XI. Other Possible Multipurpose Nuclear-plant Combinations

	Bauxite to Aluminum	Iron-ore Pelletizing	Cement Production	Electric Power Generation
Iron-ore Pelletizing	Note a	-	-	-
Cement Production	Note a	Note b	-	-
Electric Power Generation	Note c	Note d	Note e	-
Saline Water Conversion	Note f	Note g	Note e	Note e

Notes

a. Extracting alumina from bauxite leaves an $\text{Fe}_2\text{O}_3 \cdot \text{SiO}_2$ material, which can be used either in cement or as an iron ore. Currently, aluminum quantities are small compared to iron and cement, so that the amount of byproduct is relatively small. Furthermore, since shipping from alumina plants to points where other products are made is costly, the iron-bearing material is dumped at present. The byproduct of an aluminum operation per se would probably never be useful in the other industries, but if ore sites containing workable quantities of both bauxite and iron ore were found, a nuclear-powered complex providing high-temperature, pellet-hardening heat plus electrical energy might be interesting.

b. Iron-ore pelletizing is not now being practiced at places near enough to consumer centers to make cement production and shipment economical. However, the combination is not out of the question, and if the production of high-temperature nuclear heat became cheap enough in large sites, it should be considered.

c. The point of a nuclear-powered, integrated aluminum plant is that it could be located near an ore site. The outlet for additional quantities of electricity would be small.

d. Again, as in Note c, the outlet for electricity, other than a captive outlet such as an electric furnace, would probably be small.

e. This combination is discussed in detail in Section VII-A above.

f. An integrated aluminum plant might be located where fresh water was scarce. The large amount of waste heat from the electric power generation might make sea-water evaporation economical, and one might even combine the desalinization with the Bayer process. In the latter case, high-temperature steam might be extracted for concentrating caustic solution. Then lower-temperature steam could be extracted from there to evaporate sea water in successive stages. Sea-water conversion, however, would probably be limited to captive use.

g. There is little possibility that any large-scale iron processing would be located in a water-scarce area.

D. Processing of Other Minerals

Some consideration was given to including processing of other metals, e.g. titanium, copper, etc., in a nuclear complex, but in all cases either the size of the industry or the amount of heat required was too small to warrant consideration. Table XII presents some summary data on the size and dollar value of various United States mineral products.

TABLE XII. Selected Data on 1963 U. S. Production of Basic Materials⁷

Materials	U. S. Consumption or Production, tons/year	Average Price	Value	Principal Means of Production and Approximate Energy Consumption
Iron and steel	170,000,000	\$66/ton	\$11,220,000,000	Reduction with coke, 1200 lb coke/ton metal
Aluminum	2,313,000	22.6¢/lb	1,040,000,000	Electrolytic reduction, 9 kW-hr/lb
Magnesium	75,845	35.25¢/lb	53,200,000	Electrolytic reduction, 8 kW-hr/lb
Titanium	8,900	\$1.50/lb	26,700,000	One lb magnesium reduces TiCl ₄ to yield approximately one lb titanium
Copper	1,200,000	31¢/lb	745,000,000	Various smelting processes, 1-4 million Btu/ton
Cement	68,000,000	\$3.23/bbl	1,170,000,000	Calcining with various fuels, 6 million Btu/ton
Sulfur	6,700,000	\$23/ton	154,000,000	Mined
Common salt	31,000,000	\$5.97/ton	185,000,000	Mined
Phosphate rock	19,800,000	\$7.04/ton	139,700,000	Mined, converted to P ₂ O ₅ by various means

Note from Table XII that the United States phosphate-rock industry is rather sizable, but one realizes that most of the rock is converted to fertilizer by nonthermal processes. As stated in the foregoing discussion on fertilizer, there is little likelihood that calcining of phosphate rock will reach any large proportions in this country, but such processing should always be considered in planning a multipurpose, nuclear complex.

VIII. REACTORS FOR HIGH-TEMPERATURE, PROCESS HEAT

The one factor that makes high-temperature, nuclear-energy processing appear attractive is the potential development of specially designed multipurpose reactors. Just as current studies on the economics of the use of nuclear energy for production of electricity and desalinization of sea water point out definite advantages coming from both the combining of processes and from increased plant size, there appears to be the same sort of advantages in obtaining high-temperature energy from a large reactor also producing steam for production of electricity. As large as the United States mineral industry is, there are still few, if any, cases in which a single industry in any one location would be big enough to require a high-temperature energy source large enough for a nuclear plant to be economical; therefore the combining of processes in a single plant is more or less obvious. A more important point, however, is that if the unit producing high-temperature heat is combined within a reactor with a unit also producing high-temperature heat for conventional steam generation, some valuable design and construction economics are provided. In this sense, the reactor will be truly multipurpose.

The results of the survey indicate that high-temperature, process-heat uses are too small to take advantages of the cost savings inherent in large sizes. It thus appears that high-temperature heat must be produced as part of a reactor that also provides the other energy requirements. Since the cost of a reactor that produces all of its energy at high temperature may well outweigh the increased thermodynamic efficiency at temperatures above 1800°F, the most attractive way of supplying this energy appears to be with a high-temperature, reactor loop.

A simple schematic diagram of this type of system is shown in Fig. 6. In this system, consider the reactor to be of a conventional type with a

Fig. 6
Multipurpose Reactor
Schematic Diagram

separate high-temperature section, which provides the fraction of heat required at high temperature. The low-temperature process heat required can be supplied by steam extracted from the turbine. The preliminary survey has indicated several possible complexes that could use such a reactor system. The major unanswered question is whether such a use would be economical. In terms of long-range energy resources, the authors feel that this is the type of system that should eventually be considered.

In the shorter term, assuming the technology to build such a system, the economics may appear favorable. Studies of desalinization plants¹⁷ in the size range of 3220 to 3500 MWt indicate that heat costs for reactor steam will range from ≈ 19 to $26\text{¢}/10^6$ Btu for state or federal financing and from ≈ 30 to $38\text{¢}/10^6$ Btu for public-utility financing. These costs probably represent the lower limit of cost associated with the production of high-temperature heat from a reactor loop in reactors of this size. The costs assignable to the high-temperature portion of the system will certainly raise these figures. What these costs will actually be can only be determined by detailed study. However, it seems reasonable to suppose that they might remain competitive for some applications.

Several approaches can be taken to the design of a reactor of this type, depending on the relative fraction of high-temperature heat required and the reactor type desired. Such a system could be considered for almost any reactor type, but the need for penetrations in the reactor vessel to carry the high-temperature stream would make a low-pressure system desirable. Also, long-range fuel economy and the relative freedom of material choice would seem to make a fast reactor desirable. If the fraction of high-temperature heat desired is not too large, then the high-temperature region could be confined to the blanket area. This would be desirable from a reactor economic standpoint, since for a large reactor there should be a lesser importance of blanket structure on the breeding ratio.

Current technology being developed for both graphite and refractory metal fuel elements, as part of the nuclear rocket program, the high-temperature materials program, and reactor experiment programs such as UHTREX and the 710 Reactor, gives every indication that a reactor core or blanket section could produce the high-temperature gas streams of interest.

The major unanswered question in the use of a system of this type is heat-exchanger construction. One conclusion of the process survey is that if nuclear, high-temperature, process heat is to be useful in a variety of processes, it must be able to heat air to 2000-2700°F. The construction of large heat exchangers to do this will be a formidable development job. Once the heat-exchange operation has been accomplished, the conducting of high-temperature air to the process can be handled by standard techniques.

The coolant for the high-temperature portion of the reactor would be an inert gas, and the primary side of the heat exchanger can be constructed of refractory metals. The major development area is the secondary side of the exchanger, where materials must have long life in an oxidizing atmosphere.

IX. CONCLUSIONS AND RECOMMENDATIONS

The results of this preliminary survey indicate the following possible significant uses of large, multipurpose reactors, which produce high-temperature heat:

- (1) Alumina and aluminum production
- (2) Cement production as part of a larger complex
- (3) Calcining and sintering ores such as taconite.

These systems appear to be attractive enough to continue the study of applications and to study the types of reactor designs that would be useful for high-temperature process heat and evaluating whether they could be economically competitive. The main factor that can make high-temperature, nuclear, process heat attractive is the potential of developing specially-designed, multipurpose reactors. In terms of long-range energy applications, attention must be given to the means by which high-temperature process heat can be used. Economics will always be important, and the multipurpose reactor appears to be a way of economically supplying high-temperature process heat.

Most uses of high-temperature process heat that appear attractive would necessitate the development of large heat exchangers capable of heating air to 2200-2700°F. The magnitude of this development effort should be evaluated.

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