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ORNL-4290
UC-80 – Reactor Technology

NUCLEAR ENERGY CENTERS
INDUSTRIAL AND AGRO-INDUSTRIAL COMPLEXES

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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NOVEMBER 1968

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
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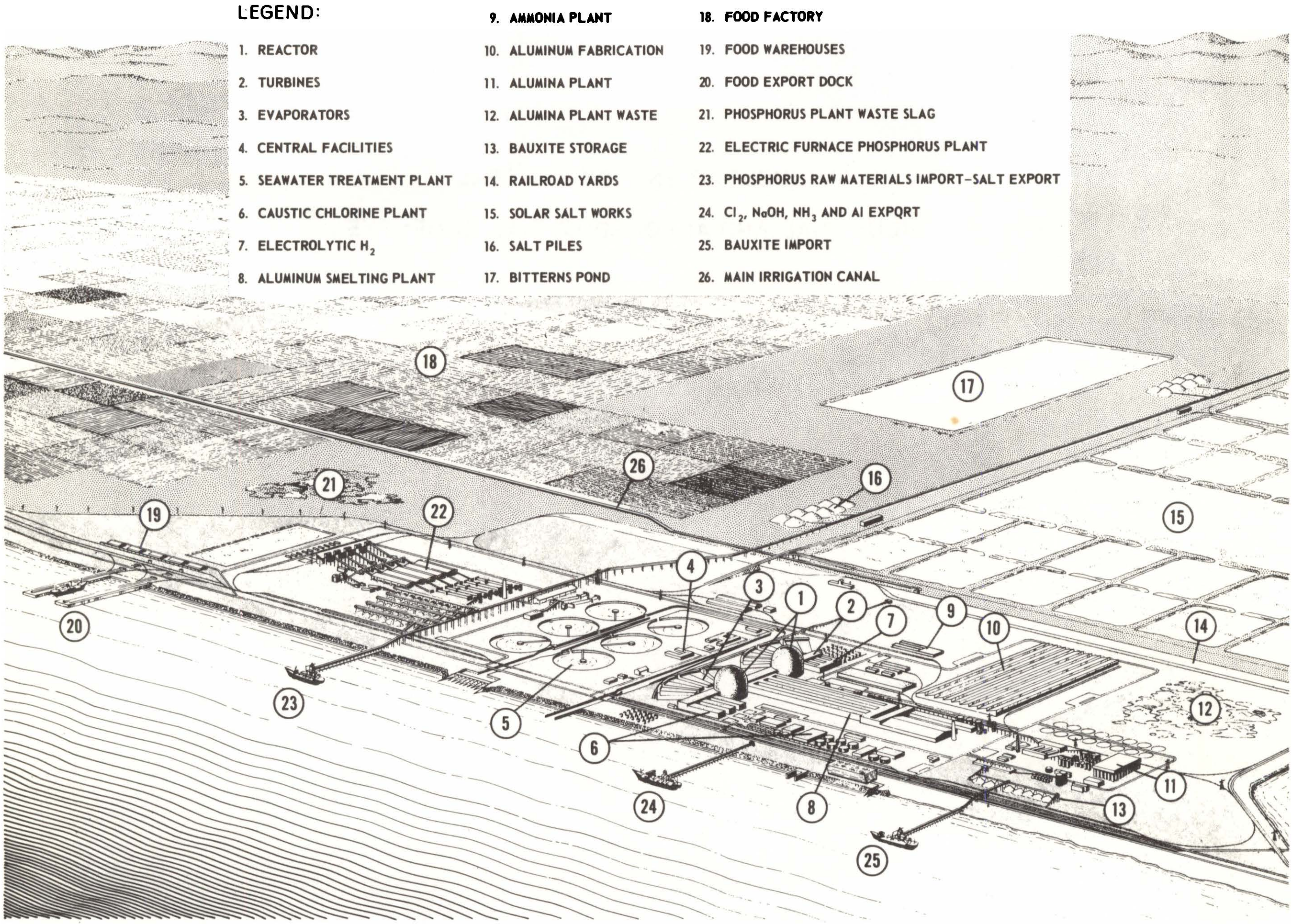
U. S. ATOMIC ENERGY COMMISSION

ORNL-DWG 67-10608A



Nuclear-Powered Agro-Industrial Complex

An artist's conception of an agro-industrial complex stretching along the shore of a coastal desert. It produces and consumes 2000 Mw of electricity and 1,000,000,000 gal of fresh water per day, employing two large reactors for the energy source. It includes a 300,000-acre farm, irrigated with water from a seawater evaporator, and industrial plants to produce aluminum sheet and bar stock, electric furnace phosphorus, caustic-chlorine by brine electrolysis, and ammonia from electrolytic hydrogen. Associated facilities include a solar salt works, a railroad marshaling yard, an artificial harbor, and docks for import of raw materials and export of food and industrial products. Not shown are a town and other living quarters for about 100,000 persons.

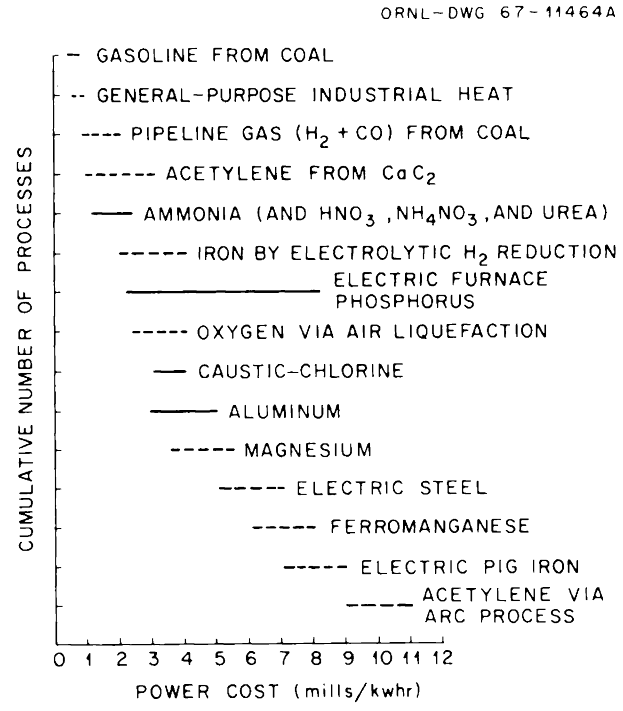
PREFATORY NOTE

Alvin M. Weinberg, Director
Oak Ridge National Laboratory

I have written a preface to this study on nuclear-powered industrial and agro-industrial complexes for several reasons:

First, I wish to stress the importance of the findings of the study. Combining the outputs of energy-intensive industrial processes, and clustering the plants around a nuclear reactor, is not a new idea. However, prior to this study, no really systematic analysis of such a complex had been made. Though the economics of such centers depends sensitively upon the prices that the industrial products can command, I find it most encouraging that even with fairly conservative assumptions substantial internal rates of return can be achieved in such nuclear-powered complexes.

Second, the study gives added incentive to the development of extremely low-cost energy sources. The demand for energy for chemical processing is decidedly elastic. If power can be produced at *much less* than the 3 mills or so per kilowatt-hour that TVA estimates for Browns Ferry No. 3, then we may see chemical processes increasingly substitute energy for other raw materials. To take an extreme example, power at 1 mill could play an important role in the liquefaction of coal. If these extremely low costs of energy are ever achieved, the demand for energy could be expected to rise dramatically, as indicated in a semiquantitative manner in the adjoining illustration. In a sense then, this study provides a strong incentive for the long-term development of the most advanced nuclear breeders – reactors that it is hoped can supply energy at much less than 3 mills/kwhr.



Elasticity of the Demand for Power.

Third, though industrial complexes of the general type described here are not fundamentally new, the combination of these with highly rationalized agriculture based on desalted water is a new and very interesting idea. The relative emphasis to be placed on the agricultural and the industrial aspects of the energy center was a matter to which the study group gave serious thought. The balance which finally emerged represents a careful weighing of the views of the agricultural and industrial experts who participated in the work. In any case the agricultural and industrial elements of the study are well separated and documented so that those more interested in the one or the other, or in the combination, can readily find what they need.

A study such as this, with its rather general approach, is not intended to prove that a nuclear-powered energy complex in a specific location ought or ought not to be built. Such judgment must come only after a very detailed examination of a specific site that takes into account all local and regional economic and political factors. I am pleased that several specific site studies are now under way, and we hope that at least some of these detailed studies will lead to actual construction of nuclear-powered energy centers.

In conclusion, I want to thank all the people who worked so diligently in preparing the study. Particular thanks go to Professor E. A. Mason, who headed the study during his stay in Oak Ridge in the summer of 1967; to John Michel, Deputy Director of the study; to Commissioner James T. Ramey, who provided strong support for performing the study; and to R. P. Hammond, whose ideas have formed the basis for much of this study.

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References

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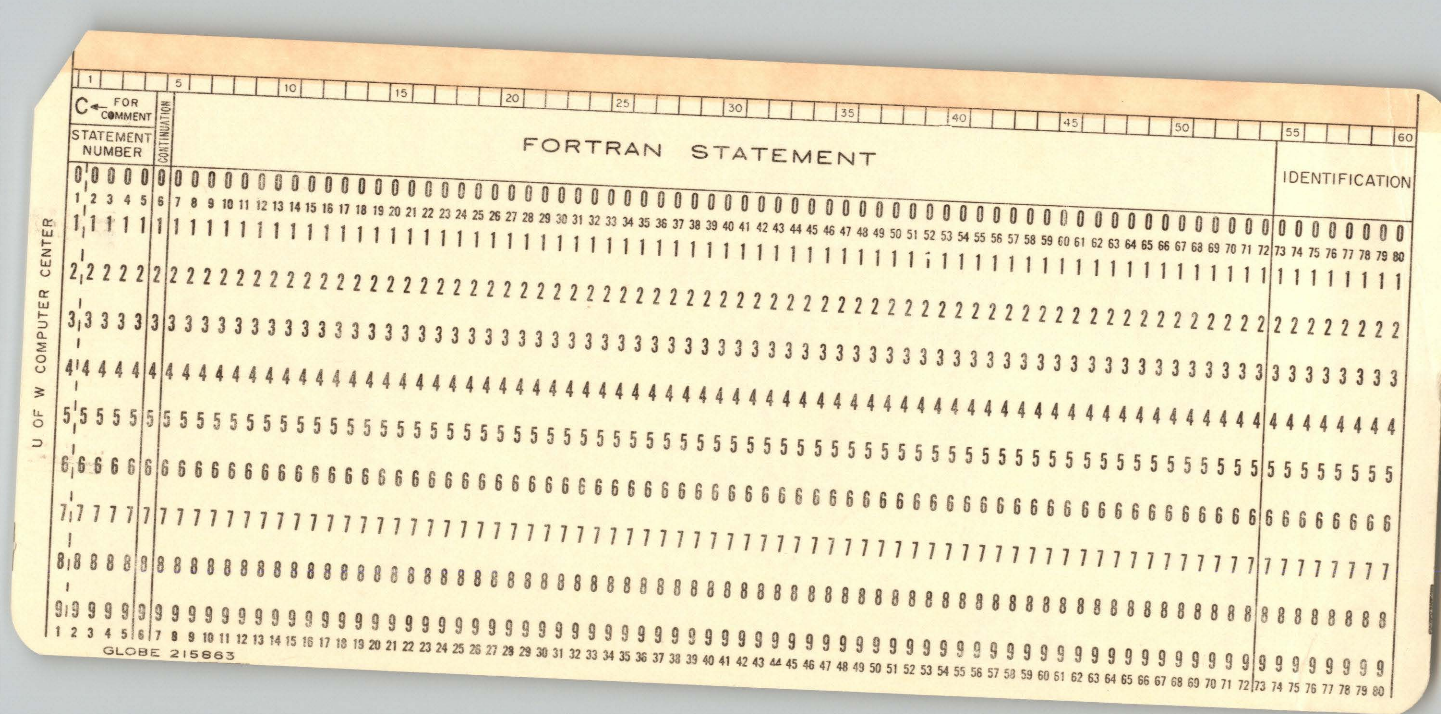

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NUCLEAR ENERGY CENTERS: INDUSTRIAL AND AGRO-INDUSTRIAL COMPLEXES

1. INTRODUCTION

In June 1967 the Oak Ridge National Laboratory started a study of the technical and economic feasibility of "nuclear-powered industrial and agro-industrial complexes," primarily as an avenue to industrial, agricultural, and general economic advancement in developing countries. Such a complex, shown schematically in Fig. 1.1, might consist of a large nuclear reactor station producing both electricity and desalted water. The electricity would be consumed in adjacent industrial processes and for pumping water, while the desalted water could be used either for municipal and industrial purposes in an industrial complex or in an irrigated agricultural complex located in a coastal desert region.

There are many different forms that energy-centered complexes can take. Possible complexes might include only the reactor coupled with an energy-consuming industry or with pumping stations for lifting and transporting groundwater to agricultural irrigation projects and for general industrial and urban use. An example of the latter case is described in a companion report[1] as applied in an irrigation scheme using pumped groundwater for the Ganges Plain in India.

The recent report of the President's Science Advisory Committee on *The World Food Problem* provides much of the motivation for the present study. This report[2] concludes, in part:

1. "The scale, severity, and duration of the world food problem are so great that a *massive, long-range, innovative* effort unprecedented in human history will be required to master it."
2. "Food supply is directly related to agricultural development and, in turn, agricultural development and *overall economic development* are critically interdependent in the hungry countries."

The principal question set by the ORNL study team was: How and to what extent could the low-cost energy anticipated from nuclear reactors be used effectively to increase both industrial and agricultural production, with particular attention being given to applications in developing countries?

1.1 Background for the Study

A study of integrated nuclear agro-industrial complexes seemed appropriate at this time for several reasons. Starting in 1966 the nuclear reactor generating capacity sold to the utility industry in the United States had increased dramatically.[3] The cost of producing electricity from the largest of

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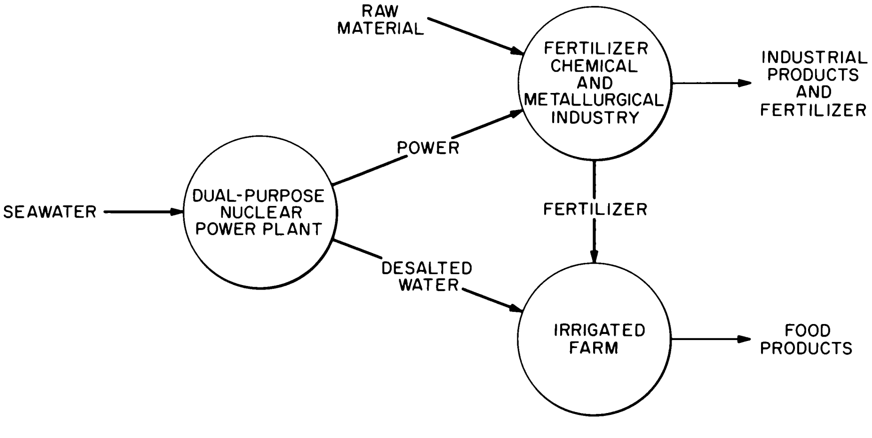

Fig. 1.1. Agro-Industrial Complex.

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[1] Perry R. Stout, *Potential Agricultural Production from Nuclear-Powered Agro-Industrial Complexes Designed for the Upper Indo-Gangetic Plain*, ORNL-4292 (to be published).

[2] *The World Food Problem*, A Report of the President's Science Advisory Committee, The White House, May 1967.

[3] U.S. AEC, Division of Operation Analysis and Forecasting, *Forecast of Growth of Nuclear Power*, WASH-1084 (December 1967).

these reactors has been estimated to be less than the alternative costs for producing electricity from fossil fuels in many regions of the United States.[4,5] Furthermore, developments now under way on advanced breeder reactors give prospects of further reductions in the costs of generating electricity.[6–8] Electricity is already an important "raw material" in the production of many chemicals and metals,[9] and the future availability of such low-cost power is likely to increase its role.[10,11] A preference for power-intensive processes should lead to changes in the technology which will, in turn, affect the economics of the chemical and metallurgical industries and in some cases eliminate the dependency on certain key raw materials. The importance of this is magnified by the mobility of nuclear energy since a nuclear reactor, unlike a hydro plant or even an oil- or coal-fired plant, can be built "anywhere" without suffering a significant fuel cost penalty. These developments open the possibility of underdeveloped countries that now lack fossil fuels becoming self-sufficient in energy and then in many heavy chemicals, including the basic fertilizers.

Coupling large advanced nuclear reactors with seawater evaporators incorporating an improved heat transfer surface suggests that it may be feasible to use desalted seawater in irrigation agriculture.[12] In these dual-purpose plants, high-temperature steam from the reactor is used for production of electricity in a turbine-generator; the exhaust steam is then used as the heat source in a seawater evaporator for the production of fresh water. The projected cost of water from such plants, though much less than what has been demonstrated so far, still is higher than most irrigation farmers usually pay although in many cases these prices are subsidized. It was recognized, however, that crop water requirements using distilled water may be less than generally had been believed to be the case. Its use in agriculture would nevertheless require intensive farm practices and skillful management.

Recent developments in both industrial and agricultural technologies further enhance the viability of such a complex. The electric furnace process for the production of phosphorus is of particular importance to developing countries that do not have sulfur,[13] especially in view of the recent rise in the price of sulfur.[14] Also of importance are the recent developments in water electrolysis, which could eliminate the need for natural gas or petroleum as a source for the hydrogen required in ammonia synthesis.[15] Inexpensive hydrogen will undoubtedly find other large industrial uses, such as reduction of iron ore to produce steel.

Recent advances have been made in agriculture, as evidenced by the new varieties of rust-resistant dwarf wheat and rice developed largely under the sponsorship of the Rockefeller and Ford Foundations. Under conditions of adequate fertilization and management, these varieties yield more than twice as much per acre as ordinary varieties. The water required to raise the grain needed to sustain an adult is much reduced by the use of these new crop types when coupled with efficient management practices.

These separate technologies, if judiciously combined, may provide developing countries a means of combating the imminent food shortages as well as providing a means of "leapfrogging" in their tech-

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[4] Tennessee Valley Authority, *Comparison of Coal-Fired and Nuclear Power Plants for the TVA System,* Chattanooga, Tenn., Office of Power, June 1966.

[5] G. L. Decker, W. B. Wilson, and W. B. Bigg, "Nuclear Energy for Industrial Heat and Power," *Chem. Eng. Progr.* **64**(3) (March 1968).

[6] Appendices to *An Assessment of Large Nuclear Power Sea Water Distillation Plants,* Annex A, Interagency Task Force, Office of Science and Technology, March 1964.

[7] J. A. Lane, "Economics of Nuclear Power," *Ann. Rev. Nucl. Sci.* **16** (1966).

[8] T. D. Anderson *et al., Technical and Economic Evaluation of Four Concepts of Large Nuclear Steam Generators with Thermal Ratings Up to 10,000 Mw* (ORNL report to be published).

[9] J. M. Holmes and J. W. Ullmann, *Survey of Process Applications in a Desalination Complex,* ORNL-TM-1561 (October 1966).

[10] R. E. Blanco *et al., An Economic Study of the Production of Ammonia Using Electricity from a Nuclear Desalination Reactor Complex,* ORNL-3882 (June 1966).

[11] Meyer Steinberg, *The Impact of Integrated Multipurpose Nuclear Plants on the Chemical and Metallurgical Process Industries. I. Electrochemonuclear Systems,* BNL-8754 (December 1964).

[12] R. P. Hammond, "Desalted Water for Agriculture," prepared for the International Conference on Water for Peace, paper No. P/384, May 23–31, 1967 (to be published).

[13] Currently, phosphatic fertilizers are primarily produced by treating phosphate rock with sulfuric acid.

[14] T. V. O'Hanlon, "The Great Sulfur Rush," *Fortune* **77**, 107 (March 1968).

[15] Allis-Chalmers, *Design Study of Hydrogen Production by Electrolysis,* ACSDS-0106643, vols. I and II (October 1966).

nological development. The advantages of combining these technologies into a single complex are twofold: first, the energy source can be larger than would otherwise be the case, and because of economics of scale the unit cost of power and therefore of each of the products is reduced; and second, by-products or waste products from one process can serve as raw material for adjoining processes.

Industrial complexes somewhat like the ones described in this study are by now well known in the world. One of the best examples is the petrochemical SASOL complex near Johannesburg, South Africa; others are located in Trombay, India, and Texas City, Texas. The complexes described here differ from these in two respects: agriculture, based on desalted water, is part of some of the complexes studied in this report; and nuclear energy, rather than coal or petroleum, is the fundamental raw material upon which these complexes are based. This existence of economically sound, integrated industrial complexes suggests to us that the idea of similar complexes based on nuclear energy is well worth serious further and detailed study.

1.2 Organization of the Work

In approaching the study, it was decided to begin with a survey of the component parts of an agro-industrial complex. Lists were prepared of many industrial and agricultural products, and it was quickly realized that many eliminations and choices could be made and technical interrelationships uncovered without reference to a particular locality. On the other hand the availability of labor, materials (including suitable land), and markets for end products are strongly affected by the locale, so that a compromise between specific and general studies had to be made.

The study therefore proceeded along two parallel lines: first, "building block" information on industrial processes and farm crops was developed, and, secondly and simultaneously, information concerning the geography, demography, and economics of several coastal desert regions of the world was obtained. More specifically the work fell into the following categories.

1. The basis or rationale for the assumed costs of power, steam, and desalted water. This was divided into two time reference periods: cost ranges expected from plants using current reactor and evaporator technology, and cost ranges projected or anticipated from plants using advanced breeder reactors and advanced evaporator concepts.

2. The effects of the cost of electricity upon the technologies and total costs of various chemicals, fertilizers, and metals which require large amounts of electricity in their production. This work included studies of the effect of integrating a number of these energy-intensive processes into various industrial (nonagricultural) complexes which would be served jointly by a nuclear-powered generating station.

3. The effects of the cost of water on the total production costs of a variety of selected crops. This work entailed the development of water-yield relationships, quantities and costs for fertilizer, labor, seed, etc., and the capital costs involved in developing coastal desert regions for growing these crops under year-round intensively managed farming. While the cost per unit of production of agricultural products remained as the focal point, emphasis was also placed on obtaining the maximum productivity of water.

4. The economics of combining a nuclear electric generating station, an industrial complex, and an agricultural complex into an agro-industrial complex.

5. The geographic factors, such as topography, soils, climate, mineral resources, economic factors, and shipping costs, which would influence the nature and feasibility of nuclear-powered agro-industrial complexes in various parts of the world. This included a preliminary review of the social implications and possible problems of implementation in developing countries.

1.3 Reporting the Results

The intent of this report is to describe the work performed, including a discussion of the rationale for the assumptions used, and to present the conclusions and recommendations for further work. Quantitative relationships have been included in the attached appendices to allow the reader to adjust the results for changes in assumptions in the manner of a "do-it-yourself kit." A separate summary report is being concurrently issued; more-detailed reports in several of the major subject areas will be published later, as follows:

Title of Report	Author	ORNL No.
1. Nuclear Energy Centers: Industrial and Agro-Industrial Complexes — Summary Report	Gale Young and J. W. Michel	4291
2. Potential Agricultural Production from Nuclear-Powered Agro-Industrial Complexes Designed for the Upper Indo-Gangetic Plain[a]	Perry Stout	4292
3. Data Obtained on Several Possible Locales for the Agro-Industrial Complex	T. Tamura and W. J. Young	4293
4. I. Steelmaking in an Agro-Industrial Complex	A. M. Squires	4294
II. Acetylene Production from Naphtha by Electric Arc and by Partial Combustion	W. E. Lobo	
5. Problems in Implementation of an Agro-Industrial Complex	J. A. Ritchey	4295
6. Tables for Computing Manufacturing Costs of Industrial Products in an Agro-Industrial Complex	H. E. Goeller	4296

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[a] Not prepared under auspices of the U.S. AEC but included in this series because of the close relationship to this project.

Perhaps it is desirable to mention what this study did not include. It was not intended to be a study *of* or *for* a particular country or region. Further, it could not be of sufficient depth to provide the basis for investment decisions; for example, no detailed market analyses or surveys of the adequacies of the countries' related infrastructures were conducted. In general, a *financial* analysis was not made nor was the nuclear-powered agro-industrial complex compared with other alternatives for achieving similar benefits. Finally, it should be recognized that the reason for not examining in this study an agriculture *only* complex based on desalted water was that single-purpose water-only plants have not yet been designed that will give water costs as low as those obtainable from the dual-purpose electricity/water plants.

1.4 Acknowledgments

During the summer of 1967 the Laboratory brought together a full-time study group staff of 16 engineers, economists, scientists, and agricultural experts under the direction of Professor E. A. Mason of the Massachusetts Institute of Technology. This staff was assisted by six consultants who worked on special topics, and by an advisory panel of 13 distinguished consultants from industry, government, and academic institutions. The panel met for three two-day review sessions during the summer. Experts from nine industrial organizations provided information concerning capital and operating costs for various industrial processes, while a large number of other contributors provided information on various other aspects of the project. The names and organizations of the participants are listed in Appendix 1A, and we wish to acknowledge their help.

2. SUMMARY

An intensive short-term study was made to evaluate the technical and economic feasibility of applying large nuclear energy centers for (1) the production of basic industrial products in the United States and in developing countries and (2) the production of both industrial and agricultural products using desalted water at coastal desert regions, primarily in developing countries of the world. This report describes the work performed in connection with this study, and the following summary section briefly discusses the most significant results in the main areas of work and presents the overall conclusions of the study. Detailed conclusions and recommendations are given in Chap. 9 of this report.

Two generalized models were used. In the first, the object was to determine the effect of various costs for electricity and water on the cost of production of industrial and agricultural products. Electricity and water were therefore considered to be purchased from outside the complex; the costs of the electricity, water, and raw materials required were varied parametrically over ranges selected to include conditions around the world.

In the second model, the object was to estimate the total investment, operating costs, income, and rate of return for integrated nuclear-powered industrial and agro-industrial complexes. Since the electricity and water required for production uses would be produced within the complex, the costs of electricity and water in this second model were not estimated directly, but rather all the capital and operating costs for producing these inputs were included in arriving at the total costs for operating the overall complex under consideration.

In both models, various levels of production capacity were considered. Two sets of economic conditions were employed – one for conditions in the United States and one for developing countries. These conditions primarily consisted of assumed sets of costs of plant construction, raw materials, and labor, and the sale prices of finished products. Uniform methods were adopted to allow for interest during construction, depreciation, working capital, etc., using a range for the cost of money from 2.5 to 20%. No allowances were specifically made for taxes, nor were marketing expenses, including transportation costs, provided for generally. All costs and incomes were estimated at the 1967 level, with no allowance for escalation.

Three types of economic analyses were made to indicate the profitability of the concepts considered in this study:

1. For industrial products – the maximum cost of electricity which would give the same manufacturing cost as obtained by using an alternative non-energy-intensive process.
2. For industry or agriculture – the maximum power cost or water cost which would give a production cost equal to the current selling price.
3. For industry or agriculture or for complexes involving each or both – an internal rate of return which represents the cost of money at which the present value of the manufacturing cost, including investment, equals the present value of the income from product sales.

Sufficient information is presented to enable other forms of analyses to be performed so that comparisons with other possible investment opportunities may be made, but such comparisons were not a part of this study.

2.1 Power and Water Technology and Cost Bases

The technology and the associated cost of production of power from a nuclear reactor and the cost of desalted seawater from evaporator plants were established for reference use throughout this report. Two time periods were considered: (1) 10 years in the future (designated "near-term"), using somewhat improved current technology consisting of light-water reactors with multistage flash evaporators, and (2) 20 years off (designated "far-term"), using the advanced technology of breeder reactors and combination vertical-tube and multistage flash evaporators. Cost estimates of equipment and operating expenses were prepared for each time period and for various methods of financing. Table 2.1 summarizes the basic power costs for United States conditions which were developed and used in this study.

It should be recognized that these costs are illustrative estimates only and that, particularly for the far-term breeder reactor, the costs should be considered with uncertainty limits of at least ±20%. For example, increasing the capital cost of a breeder reactor by 25% would increase the

Table 2.1. Power Costs for Large Multiple Reactor Stations, 3880 Mw (electrical)

Power costs in mills per kilowatt-hour; load factor = 90%. Numbers in parentheses represent primarily operating costs of overhead and maintenance, insurance, and fuel cycle.

Reactor Technology	Cost of Money			
	2.5%	5%	10%	20%
Near-term, light water	1.8(1.2)	2.1(1.3)	2.9(1.4)	4.8(1.6)
Far-term, advanced breeder	0.8(0.2)	1.2(0.3)	2.0(0.5)	4.3(1.1)

power cost (at 10% cost of money) to 2.4 mills/kwhr; simultaneously lowering the load factor to 0.8 would increase the power cost an additional 0.4 mill/kwhr.

For dual-purpose plants producing power and desalted seawater, no cost allocation for the two products was attempted; but incremental costs of adding additional capacity for each were obtained for several sizes of plants and for costs of money from $2\frac{1}{2}$ to 20%. For the near-term technology the incremental power cost varied from 0.8 to 3.8 mills/kwhr ($2\frac{1}{2}$ and 20% respectively), and the incremental cost of water varied from 12 to 49¢ per 1000 gal (also at $2\frac{1}{2}$ and 20% respectively). The corresponding figures for the far-term case were 0.3 to 3.3 mills/kwhr and 5 to 34¢ per 1000 gal.

2.2 Use of Power

A number of electricity-intensive processes were investigated to determine the effects of power cost on total manufacturing cost. This work involved the compilation of all the many cost components and their variation with the size of the production facility. Where possible, these processes were compared with a competing non-electricity-intensive process to determine the "break-even" power cost, that is, the cost of power at which the manufacturing costs by the two processes are equal. The two most important basic fertilizer materials, nitrogen (as ammonia) and phosphorus (as phosphoric acid), are in this category. Ammonia via water electrolysis was compared with ammonia via steam reforming of methane or naphtha, while phosphoric acid made by the electric furnace process was compared with phosphoric acid from the sulfuric acid acidulation of phosphate rock. Figure 2.1 shows these comparisons and illustrates the higher relative profitability of the electric furnace phosphorus process.

The manufacture of caustic and chlorine is normally done by brine electrolysis, and, unlike aluminum (see below), the raw material costs (salt) are usually quite low. For a cost of money of 10% and salt at $3 per ton, the production cost

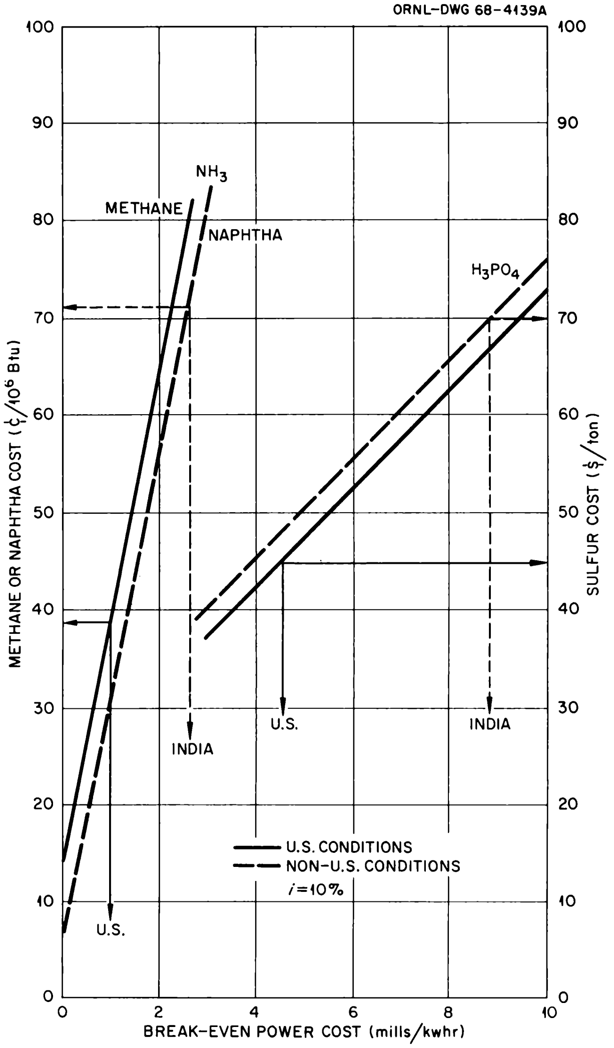

Fig. 2.1. Comparison of Ammonia via Water Electrolysis vs Ammonia via Steam Reforming of Methane or Naphtha and Comparison of Phosphoric Acid by the Electric Furnace Process vs Phosphoric Acid by the Sulfuric Acid Acidulation of Phosphate Rock.

for chlorine from a 1000-ton/day plant (assuming no credit for the coproduced caustic and allowing for all capital charges including a 10% return on investment) is as follows:

Power Cost (mills/kwhr)	Manufacturing Cost (dollars per ton of Cl_2)
2	33
4	40

For a chlorine selling price of \$50/ton (recent U.S., f.o.b.), reducing the power cost from 4 to 2 mills would result in an appreciable increase of profits. In developing countries where the coproduct, caustic, is more in demand and sells for as much as \$80/ton, the profitability is even greater. Caustic and chlorine (as hydrochloric acid) may be used either singly or together as a scale-preventative treatment for the seawater feed to an evaporator plant. Thus, electricity would in effect replace sulfur (as sulfuric acid) for treating seawater in evaporator plants.

The manufacture of aluminum was also evaluated in some detail. Since an alternative process is not available for this product, a geographical comparison was made. For example, low-cost (2 mills/kwhr) power at a hydro site 6000 miles from the raw materials was compared with a nuclear-powered site 1000 miles from the bauxite source. For this case a "break-even" power cost range of from $2\frac{1}{2}$ to about 6 mills/kwhr was obtained for a wide range of parameter values (e.g., cost of money from $2\frac{1}{2}$ to 20%, plant capacity from 60 to 685 tons/day, and bauxite costs from \$3 to \$14/ton). In this comparison, imported alumina at \$60 to \$77/ton was assumed to be the raw material for the aluminum plant at the hydro site.

Other processes that were examined, but in less detail than those mentioned above, were (1) chemicals from evaporator discharge brine, including salt (NaCl), potassium chloride, and magnesium; (2) iron and steel by hydrogen reduction; (3) acetylene from naphtha (or methane) using the electric arc process; and (4) cement and sulfuric acid from gypsum (obtained from seawater).

The industrial complex (a group of interrelated industries without an on-site power plant) was also evaluated by the break-even power cost method. ["Break-even" in this connection denotes the cost of power at which production cost, including all capital charges (at a given cost of money, i) just equals income from the sale of products.] For a United States location with i = 10%, the break-even power cost varied from about 4 to 6 mills/kwhr, depending on the product mix and the size of the complex. Two typical examples of the more than 70 cases evaluated are given in Table 2.2, indicating the effects of different product mixes, United States vs foreign location, and the influence of the cost of electricity on the attractiveness of the complex. The effect of the size of the complex and the cost of power on the rate of return is illustrated in Fig. 2.2 for a particular product mix under United States conditions.

In general, the selection of processes studied was limited to those requiring relatively large amounts of electricity. These were primarily basic products which would usually be further processed before use or be used as raw materials for other processes. However, to test the effect

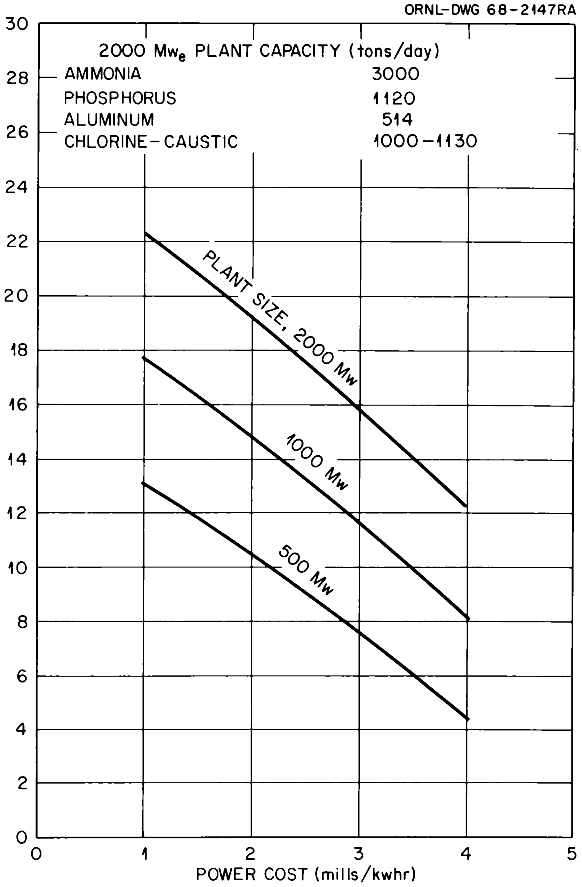

Fig. 2.2. Effect of Complex Size and Power Cost on Internal Rate of Return.

of manufacturing secondary products on the break-even power cost, the manufacturing costs for three fertilizer materials – urea, ammonium nitrate, and nitric phosphate – all made from ammonia – were computed. The overall profitability was appreciably increased by including the manufacture of these products in a complex.

A generalized comparison was made of the relative profitability of a large integrated industrial complex [2500 Mw (electrical)] with an equivalent industry made up of small plants dispersed throughout the country near the market or point of consumption. This comparison thus indicated the tradeoff between the savings in manufacturing cost, due to the low-cost power from a large captive power station along with size scaling and jointness advantages, and the increased transportation costs required to deliver the products to the markets. Table 2.3 summarizes this comparison for a non-U.S. case of shipping half the

Table 2.2. Two Typical 1000 Mw (electrical) Industrial Complexes

	U.S. Complex			Non-U.S. Complex		
Products (tons/day): Ammonia – 1500 Phosphorus – 560, as P_2O_5 Aluminum – 257 Caustic-chlorine – 500, of chlorine						
Total value of products $(10^6\$)$		129			172	
Power cost (mills/kwhr)	2	4	6	2	4	6
Production cost[a]	118	133	150	128	142	165
Break-even power cost (mills/kwhr)		3.3			7.0	
Total capital investment $(10^6\$)$		277			303	
Products (tons/day): Ammonia – 1630 Phosphorus – 800, as P_2O_5 Caustic-chlorine – 355, of chlorine						
Total value of products $(10^6\$)$		85			118	
Power cost (mills/kwhr)	2	4	6	2	4	6
Production cost $(10^6\$)$[a]	71	87	106	107	112	130
Break-even power cost (mills/kwhr)		3.6			4.6	
Total capital investment $(10^6\$)$		99			112	

[a] Capital charges computed for a 10% cost of money.

Table 2.3. Estimates of the Economic Advantages of a Large Integrated Industrial Complex

	Power Cost (mills/kwhr)	Product Manufacturing Cost (dollars/year)	Product Transport Cost (dollars/year)	Income from Sales (dollars/year)	Investment in Industry (dollars)	Direct Return on Investment (%)
		$\times 10^6$	$\times 10^6$	$\times 10^6$	$\times 10^6$	
Large complex	3	264	25	462	640	27
Small plants	3	296		462	960	17
	5	341		462	960	13

products from a large complex by rail 300 miles and half by sea 1000 miles and using a cost of money of 10%. Transportation costs for raw materials were not allowed for but would probably represent an additional advantage for the large complex at a seacoast location. As indicated in this table, a large complex could produce the same products (ammonia, phosphorus, aluminum, and caustic-chlorine) for two-thirds the investment and for considerably lower production cost. With the more probable value of 5 mills/kwhr for the small plant's power cost, over one-half of the difference in annual manufacturing costs may be attributed to the difference in the assumed power costs.

Several examples of a nuclear industrial complex were developed to illustrate the advantage of scaling the power source and jointly using other common facilities as well as using intermediate or waste products from one process by another. Rates of return were computed for a number of such complexes varying in size from 500 to 2100 Mw (electrical) for both United States and foreign conditions with different technologies and product mixes. As indicated in Table 2.4, rates of return varied from less than 5% to about 19%, the smallest value being obtained for a 500 Mw (electrical) United States case with current technology and the highest rate of return for the 2100 Mw (electrical) foreign advanced-technology case. Note the large increase in return for the 1000 Mw (electrical) LWR United States case when the product mix is tailored to a specific location.

Other uses of electric power which were included in some cases were: (1) power delivered by transmission lines to off-site load centers, (2) power used for pumping water within the evaporator plant and in the irrigation system, (3) auxiliary power for use within the complex, and (4) power for an associated town.

2.3 Use of Water

The production of distilled water was considered only for agro-industrial complexes located in remote coastal desert regions where the water was used primarily for irrigation. While water for general urban use could be produced in an industrial-only complex, this was not specifically considered in this study.

Water used for irrigation supplied primarily the evapotranspiration requirements of the crops. These requirements were estimated for ten crops, including grains, vegetables, oil crops, fruits, and fiber. Crop yields and their response to varying levels of water application were also estimated by a review of the available data and consultation with many experts. The yields assumed are those

Table 2.4. Comparison of Internal Rates of Return[a] for Several Nuclear-Industrial Complexes

	Product Mix I[b]		Product Mix II[b]	
	U.S.	Non-U.S.	U.S.	Non-U.S.
Reactor Type				
Light water	11.4	16.1	13.1	16.3
Fast breeder	12.9	16.8	14.9	17.3
Thermal breeder	14.1	18.0	16.5	19.1
Size (Light-Water Reactor)				
500 Mw (electrical)	4.5	9.7		
1000 Mw (electrical)	7.4	12.7		
2000 Mw (electrical)	11.4[c]	16.1		
Specific Location[d]				
1000 Mw (electrical) (LWR)	18.7[d]			

[a] The internal rate of return represents the maximum cost of money which may be used and just meet all expenses including return on investment, amortization, and interest during construction at this rate as well as the normal operating costs. Taxes and marketing expense are not included.

[b]

	Product Mix I	**Product Mix II**
Ammonia, tons/day	3000	3080
Phosphorus, tons/day	1120	1500
Aluminum, tons/day	514	
Caustic-chlorine, tons/day	1130/1000	2260/2000
Power, Mw (electrical)	2048	2026

[c] Increasing the reactor cost from $125/kw to $150/kw would reduce the rate of return by 0.6. Eliminating the production of NH$_3$ and thus decreasing the power consumption to ∼1000 Mw (electrical) increases the return by about 0.6.

[d] Tailored product mix for a Florida location near phosphate rock deposit: 1180 tons/day of phosphorus and 685 tons/day of aluminum ingot.

regularly obtained today by the top 20% of farmers on good irrigated land. The values adopted are shown in Table 2.5. In the context of a highly mechanized and intensively managed farm, the direct costs for each crop were compiled. These included the costs for labor, fertilizer and chemicals, seeds, storage, market preparation, etc. Current prices paid to farmers were obtained for each crop so that relationships between the return (above direct costs) and the price of water to the farmer could be obtained. Estimates were also made of the fixed costs, including the irrigation system, buildings, roads, equipment, and allowances for land reclamation and drainage facilities. It was then possible to estimate the relative profitability of producing various crops as a function of the price of water. For example, it was shown that some crops, such as tomatoes, citrus, and cotton, would have positive returns above direct costs with a water cost of 30¢/1000 gal or higher, while all other crops considered, with the exception of safflower, sorghum, and soybeans, could do so at 20¢/1000 gal.

The maximum water cost allowable so that the *total* production costs (direct plus fixed or capital expense) equal crop revenue, was obtained for several crops using a cost of money of 10%. For wheat this price was about 8¢/1000 gal, for peanuts, 12¢/1000 gal, and for potatoes greater than 35¢/1000 gal. These figures are quite sensitive to the assumed crop prices; for example, increasing the assumed price of wheat from 2.7¢/lb (paid to farmers in exporting countries) to 3.3¢/lb (delivered price to India) increases the maximum allowable cost for water to nearly 17¢/1000 gal.

Three types of cropping systems were evaluated: mixed crop, high profit, and high calorie production. All three obtained their irrigation water supply from a 1000-Mgd (million gallons per day) desalting plant at two levels of assumed water cost: 10 and 20¢/1000 gal. Table 2.6 summarizes these evaluations, and Fig. 2.3 indicates the effects of changes in the cost of water and in the crop price levels on the rate of return.

The two sets of crop prices used in Fig. 2.3 are (1) those paid to farmers in exporting countries, to

Table 2.5. Crop Water-Yield Relationships

Crop Type	Crop	Water Use		Fertilizer Applied per Acre (lb)		Yield (lb/acre)	Food Value (Cal/lb)	Efficiency of Water Use	
		Inches	Gallons per Acre	N	P_2O_5			Yield (lb/gal)	Gallons per 2500 Cal
			$\times 10^3$			$\times 10^3$	$\times 10^2$	$\times 10^3$	
Grain	Wheat	20	543	200	50	6.0	14.8	11.1	152
	Sorghum	27.6	749	150	80	8.0	15.1	10.7	154
Pulses	Peanuts	34.5	937	120	80	4.0	18.7	4.3	313
	Dry beans	20.6	559	70	70	3.0	15.4	5.4	302
Oil	Safflower	33.4	907	200	50	4.0	14.2	4.4	404
	Soybeans	33.4	907	100	50	3.6	18.3	4.0	343
Vegetables	Potatoes[a]	16	434	200	120[b]	48	2.79	111	81
	Tomatoes[a]	19	516	200	150	60	0.95	116	227
Citrus fruit	Oranges[a]	53.1	1442	180	30	44	1.31	30.5	628
Fiber	Cotton[a]	34.5	937	300	100	1.75 (lint) 2.8 (seed)		4.9 (total)	

[a] Due to marketing considerations, the acreages of these crops were restricted.

[b] 45 lb of K_2O was also applied.

Table 2.6. Summary of Farm Systems

	Pattern		
	Ten Crops	High Value	High Calorie
Farm size, thousands of acres	280	320	300
Percentage of water temporarily stored	18	26	24
Production			
Millions of tons per year	3.6	3.1	3.3
Billions of Calories per year	4080	4800	5680
Investment, millions of dollars	285	306	295
Operating costs, millions of dollars per year, at:			
10¢/1000 gal	115	102	92
20¢/1000 gal	148	135	125
Gross receipts at import prices, millions of dollars per year	206	195	182
Internal rate of return,[a] %, at:			
10¢/1000 gal	25	26	21
20¢/1000 gal	16	17	12
Millions of persons fed[b]	4.5	5.3	6.3
Protein per person fed, g/day	91	107	79
Water used per person fed, gpd	200	170	145
Investment per person fed, dollars	66	58	47
Operating cost per person fed, ¢/day, at:			
10¢/1000 gal	7.0	5.3	4.0
20¢/1000 gal	9.0	7.0	5.4

[a] Including all operating and overhead expenses, allowances for interest during construction, and all capital charges.

[b] 2500 Cal/day.

cover the case of entering world markets, and (2) an import price, to cover the case of internal consumption of the food. The use of set 2, which was 30% above set 1, significantly increased the profitability of the farm.

Another vital assumption made is that suitable crop varieties for the region will be available, which in some cases implies development programs including experimental farms and involving years of advance effort. In general, the uncertainties associated with agriculture appear somewhat greater than for the industrial enterprises.

2.4 Integration of Power and Water Production and Uses

Combining the nuclear reactor, turbine-generator, evaporator, industry, and farm into one large enterprise, a nuclear agro-industrial complex, necessitated the development of a physical model and an economic model. The physical model, partially depicted in the frontispiece, is based on use of a relatively flat coastal desert region and includes provision for all the required facilities to operate the complex including a town and small, family farm plots (not shown) for the farm employees and some of the industrial workers. This model also includes the required facilities for storage and shipping of all raw materials and products.

The economic analysis of the complex consisted in the itemization of capital expenditures, operating costs, and receipts from the sale of products. This was done for two levels of reactor/evaporator technology at several sizes for both United States and foreign cases. The internal rate of return was computed as a figure of merit for each case. Table

2.7 shows a condensed version of one of the many economic evaluations made and illustrates the difference between the application of near-term (light-water reactor and multistage flash evaporator) and far-term (advanced breeder reactor and vertical-tube evaporator) technologies for a non-U.S. location.

This table also illustrates the effects of several of the variables considered on the internal rate of return: (1) the effect of manufacturing secondary products (i.e., ammonium nitrate, urea, etc.) improves the return and (2) in the far-term case, bypassing 25% of the prime steam directly to the desalting plant and thereby reducing the electricity generation does not appreciably affect the return. Bypassing about 85% of the steam to provide only enough power to operate the desalting plant and the farm (no industrial power) decreased the internal rate of return for the far-term complex from 16.5 to 10.1% and for near-term technology from 14.6 to 7.4%.

For non-U.S. conditions the effects of size, industrial product mix, crop price level, and assumed capital and operating costs were varied to determine the sensitivity of the internal rate of return to variation in these parameters. Increasing the size of the complex from 525 Mw (electrical) industry/320 Mgd farm to 2100 Mw (electrical)/1280 Mgd gives an increase in the internal rate of return of about four percentage points. Eliminating the production of aluminum while increasing the production of caustic/chlorine and phosphorus decreased the internal rate of return by about one

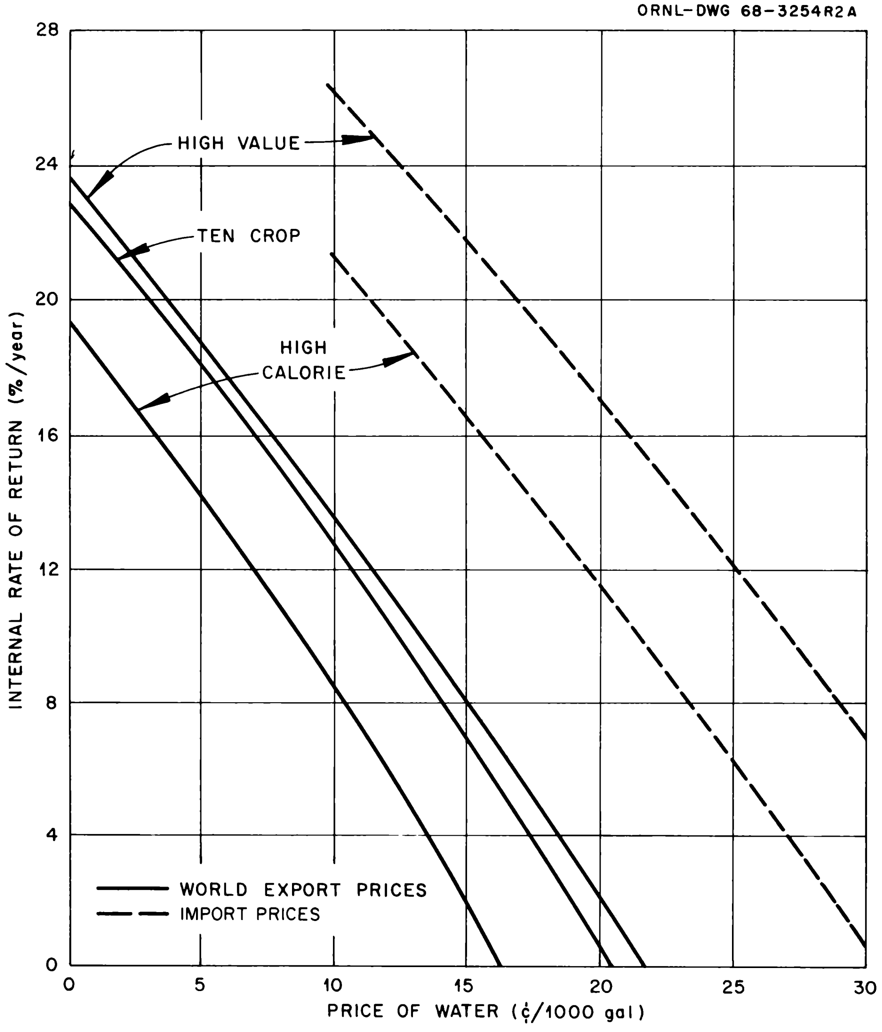

Fig. 2.3. Internal Rate of Return for the Three Farms as a Function of the Price of Water.

Table 2.7. Comparison of Technologies for Nuclear-Powered Agro-Industrial Complexes Producing Aluminum (685 Tons/Day), Ammonia (1740 Tons/Day), Phosphorus (765 Tons/Day), Caustic-Chlorine (1500 Tons/Day), and Food

Industrial power, 1585 Mw (electrical)

	Near-Term Technology		Far-Term Technology		
	Primary Products	Secondary Products, NH_3 Converted to Urea and Ammonium Nitrate[a]	Primary Products plus Grid[b]	Primary Products; No Grid; Steam Bypass[a,c]	Primary Products; No Industry; Steam Bypass[a,d]
Station size, Mw (thermal) (two reactors)	11,100		11,900	10,800	8820
Net electrical power, Mw (electrical)	2100		2900	1935	312
Desalted water, Mgd	1000		1000		
Farm size, acres	320,000		320,000		
Investment, millions of dollars					
Nuclear island	166		261	246	217
Turbine-generator plant	120		118	83	20
Grid tie	0		13	0	0
Evaporator plant	403		279		
Industrial complex	570	730	570		0
Farm	306		306		
Working capital	79	85	71	65	28
Harbor	35		35		30
Town	32		32		14
Fuel inventory	70		191	174	141
Total[e]	1781	1947	1876	1790	1035
Annual operating costs, millions of dollars					
Power and water plant	47		18	16	21
Industrial complex	133	152	133		
Farm	56		56		62
Total	236	255	207	205	83
Annual sales, millions of dollars					
Fissile material	7		16	15	11
Grid	0		20	0	0
Industrial products[f]	347	407	347		0
Farm products[f]	194		194		
Total	548	608	577	556	205
Income minus expenses, millions of dollars	312	353	370	351	122
Internal rate of return, %/year	14.6	16.1	16.5	16.4	10.1

[a] Only changes in numbers are listed; all other numbers are the same as listed under Primary Products.

[b] Due to higher initial steam conditions than obtained with the near-term case, more electricity is made; excess [~1000 Mw (electrical)] is sold to a grid at 3 mills/kwhr.

[c] Evaporator operated using some bypass of prime steam to achieve full water output of 1000 Mgd with no excess (grid) power produced.

[d] Only sufficient power is generated to operate reactor, evaporator, and farm; 85% steam bypass.

[e] Interest charges during construction not included in this total but are allowed for in computing the internal rate of return.

[f] Import price level used.

point. The use of export or world price levels for both the industrial and farm products decreased the return by about six points. Table 2.8 summarizes the sensitivity analysis by giving the amount of change required in the pertinent cost and income assumptions to cause a one percentage point change in the internal rate of return. Finally, the incremental rates of return for the addition of the food factory to nuclear-industrial complexes varied from 7 to 15%.

2.5 Applications

Five coastal desert regions around the world were studied as potential areas for the location of an agro-industrial complex. These were located in India (Kutch), southeastern Mediterranean (Sinai), Baja California, Peru (Sechura), and Western Australia. The individual localities were studied to test the sensitivity of the many assumptions made in relation to actual conditions existing in the world so that the breadth of the applicability of the agro-industrial complex could be estimated. The main locale parameters investigated were climate, soils, topography, physical resources, and transport facilities. In general, irrigation agriculture on the scale envisaged appeared feasible at all five locales, although more detailed information would be required before a realistic evaluation could be made. Also better resource surveys and market analyses would be required.

Table 2.8. Sensitivity Analysis: Changes Required to Give a One Percentage Point Change in the Internal Rate of Return for the Far-Term Complex with Grid

	Amount of Increment (dollars)	Percentage Change in Estimate
	$\times 10^6$	
Nuclear island cost	102	39
Evaporator cost	112	40
Industrial complex cost	108	19
Farm cost	121	40
Operating expenses	21	10
Sales		
Industrial products	21	6
Farm products	21	11

There appeared to be many possibilities for industrial applications both in the United States and overseas, particularly near large deposits of phosphate rock or bauxite.

A preliminary study of implementation problems as influenced by the social, political, and cultural environment was made. This study resulted mainly in the definition of a number of potential problem areas, and although some recommendations were made, no specific plan for implementation was developed.

2.6 Overall Conclusions

The main overall conclusions derived from this study project may be listed as follows:

1. Significant economic advantages appear possible by coupling an industrial complex with a large nuclear heat source as compared with equivalent (same producing capacity) dispersed smaller industry. The advantages are generally greater in developing countries than in the United States but are highly sensitive to the product mix selected and to local conditions which affect the cost of raw materials or other manufacturing costs. Industrial complexes based on a capacity requirement as small as 500 Mw (electrical) in some circumstances give internal rates of return of 10% or more.

The effect of advances in nuclear power technology, that is, use of breeder reactors, would significantly improve the internal rate of return. In the most striking example, the case of a particular nuclear-industrial complex in the United States, the substitution of a breeder reactor for a light-water reactor increased the rate of return from 13.1 to 16.5%, a 25% increase in the internal rate of return.

While this study did not consider nonnuclear energy sources, there may be some situations where fossil-fuel or hydro sources are preferred. In general, the concept of an integrated industrial or agro-industrial energy center is not dependent on the type of energy used, although the inherent characteristic of relative freedom of location is an important advantage for nuclear energy.

2. The use of coastal desert regions for producing a variety of agricultural products by irrigation with desalted water appears technically feasible and generally competitive with food produced on existing farms. The extra cost for the expensive water is at least partially offset by the

opportunity to conduct intensive year-round food-factory agriculture in favorable growing climates with many conditions under unusually good control. It appears that using year-round cropping patterns that might be employed on actual farms, the calorie requirement for a man can be met using less than 200 gal of water per day. For the high-calorie cropping pattern which also satisfies the minimum protein requirements,[1] sufficient food (2500 Cal/day) for one person could be *produced* for about 3¢/day with an initial investment of about $165 per person. These numbers are based on the incremental costs of adding an evaporator desalting plant and farm to a large agro-industrial complex. There were also several nonmonetary advantages identified for such a food factory located in coastal desert regions, for example: (1) the reliability of food production is increased since more of the production variables would be under control; (2) freedom from, in many cases, restrictive traditions or cultural practices so that the economic advantage of large-scale mechanized farming can be realized; (3) the internal requirement for an on-going agricultural research program could be expanded to benefit the country as a whole – the food factory could become a center for education, training, and research to also improve the conventional agriculture; and (4) unused or "waste" land could be made productive and valuable.

The food produced in off-site conventional agriculture which can be attributed to the application of the fertilizer made in the complex but surplus to the food factory requirements[2] could provide the minimum diet for 60 to 90 million people. The investment cost attributable to the required fertilizer production facilities, including the appropriate portion of the nuclear power plant (LWR), would be about $7 to $4 per person fed, and the operating cost would be 0.5 to 0.3¢ per person per day. The range for the number of persons fed is based on the range of the expected increase in grain yield per pound of applied plant nutrient as discussed in ref. 2 of Chap. 1 and assumes some simultaneous improvements in production practices.

3. Though it appeared that the above two conclusions were generally valid at the five locales studied, a much more detailed analysis of a locale using specific local data, including the prevailing financial costs, would be required before specific implementation of such a project could be attempted. This would include, in addition to actual soil, mineral resource, climatological, and labor surveys, a detailed marketing and logistic analysis as well as consideration of the many socio-political implications. Finally, the alternatives which may be available for achieving similar benefits would need to be evaluated to establish the best approach for actual implementation.

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[1] Quantity of protein is adequate but not the quality or the required protein spectrum.

[2] Up to 95% of the ammonia and 98% of the phosphorus produced would be shipped from the complex.

3. ECONOMIC GROUND RULES

3.1 Introduction

The results of economic analyses of various investment opportunities are highly dependent on the ground rules used in the evaluations. In order to obtain a valid comparison among the alternatives so that intelligent choices can be made, it is necessary to apply a uniform set of economic ground rules. The purpose of this section is to describe the economic models used and to define the appropriate rules used in this study.[1]

Two generalized models were used. In the first, the object was to determine the effect of various costs for electricity and water on the cost of production of industrial and agricultural products. Electricity and water were therefore considered to be purchased from outside the complex; the prices of the electricity, water, and raw materials required were varied parametrically over ranges selected to include conditions around the world.

In the second model the object was to estimate the total investment, operating costs, income, and rate of return for integrated nuclear-powered industrial and agro-industrial complexes. Since the electricity and water required for industrial and agricultural products would be produced within the complex, the costs of these items were not estimated directly, but rather all the capital and operating costs for producing these inputs were included in arriving at the total costs for operating the overall complex under consideration.

The main areas in which ground rules are required are as follows:

1. Cost of money, taxes
2. Replacement of investment
3. Interest during construction
4. Overseas construction and operations
5. Working capital
6. Risk and inflation
7. Marketing expense

In addition, it is necessary to establish methods for performing the economic analyses.

Three general types of economic comparisons are made in this report: (1) break-even power cost, comparing the production cost of an electric-intensive industrial process with that of a non-electric-intensive process; (2) break-even power cost with the sales price for industrial complexes; and (3) internal rate of return.[2] The break-even power cost comparisons are performed by increasing the price of electricity until the manufacturing cost of the electric-intensive process equals the manufacturing cost for the competing process or, in item 2, equals the sales price of the products. Chapter 5, "Industrial Processes," uses the first two methods in comparing individual processes and industrial complexes producing various product mixes. The internal rate of return is the cost of money at which a particular project will just break even, that is, the present value of expenses, including all capital charges, will just equal the present value of income from sale of products. This parameter is used in the evaluation of the relative merits of nuclear industrial and nuclear agro-industrial complexes in Chap. 7. This method is also used to evaluate the three farm systems as a function of water cost in Chap. 6 and to compare nominal 500, 1000, and 2000 Mw(electrical) industrial complexes as a function of power cost in Chap. 5.

Ordinarily, power plants and public utilities in general are evaluated at lower fixed charge rates than industry. This is primarily because the risk factor associated with utilities is lower, since the products they sell have assured markets. However, in this report, to simplify the economic evaluation of complexes, the risk factor was assumed to be the same for all components of a complex. This might tend to penalize the nuclear power station and water plant somewhat from the standpoint of their operation as a public utility. However, in the context of this report, the power and water plants are considered to be close-coupled to the industrial plants and farm and thus factors more in line with those of industry should probably be considered. The risk associated with farm production is usually very dependent on climatological conditions. Complete dependence on irrigation for water probably frees the farm of an agro-industrial complex from the greatest portion of its uncertainty, namely, rainfall. Under these conditions it is more reasonable to assume the same risk factors for industry and agriculture.

The industrial and farm products produced by the nuclear-powered complexes examined in this report were intended either to feed people or result in increased food production and in general to improve

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[1] A more complete explanation and worked examples are given in Appendix 3A.

[2] R. J. Reul, *Chem. Eng.* 9, 212 (1968).

the economic viability of a nation. With these purposes in mind, primary emphasis was placed on the production of basic fertilizer chemicals like ammonia and phosphorus and staple foods such as wheat and beans. Other basic industrial products considered were aluminum, caustic, and chlorine. Some high-value farm products such as cotton, tomatoes, and oranges were considered; however, the acreages allotted to their production were severely limited.

3.2 Cost of Money

To cover most situations that one might encounter in the real world, the cost of money is varied in this study over a range of 2.5 to 20%. Here, the cost of money is really a composite of two different factors: the going interest rate on borrowed money and the expected return on equity capital, both computed on the basis of a debt/equity ratio.

Another similar term which is used quite generally in the literature is the "fixed charge rate." This rate usually contains allowances for the cost of borrowed money, stock dividends and bond interest, depreciation (end-of-life replacement), federal, state, and local taxes, and insurance. In the context of this report, allowances have been separately provided for depreciation (in the form of a sinking-fund allowance) and nuclear liability insurance. Since taxes on income are a variable item throughout the world, they were not included in the economic analyses, and thus all returns are on a pre-tax basis. In the United States the effect of federal income taxes on overall complex economics may be estimated by assuming that the after-tax return is 58% of the pre-tax return on investment,[3] where the latter is defined as sales minus operating costs (including depreciation).

The tables listing detailed economic analyses of nuclear-industrial and agro-industrial complexes in Chap. 7 contain data listed as "net annual benefits" at four costs of money: 2.5, 5, 10, and 20%. These may be regarded as "profit," since they are the funds remaining after all expenses have been paid. Here expenses include operating costs, sinking-fund allowance on total plant cost (including interest charges during construction at the listed cost of money), and the cost of the total investment (sometimes called return on investment, ROI), all computed at their present values. Thus, to convert the economic data to a simple return on investment, as listed in many financial analyses, one may choose the net annual benefit corresponding to the desired cost of money and to this add the product of cost of money as a decimal fraction and total investment including interest during construction (usually listed in footnotes on tables), and then divide by the total investment. Expenses now include only operating costs and depreciation in the form of the sinking-fund allowance.

Specific depreciation allowances are not listed in the tabulated data for complexes because of the varying lifetimes assumed for different parts of the complex. Table 3.1 illustrates the effect of the

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[3] Based upon an analysis of the 1967 financial performance of 35 chemical and allied industries reported in *Chemical and Engineering News* (May 13, 1968).

Table 3.1. Total Fixed Charge Rates for Several Costs of Money and Assumed Lifetimes of 15 and 30 Years

Cost of Money (%/Year)	Sinking Fund Factor[a] (%/Year)		Total Fixed Charge Rate (%/Year)	
	15-Year Life	30-Year Life	15-Year Life	30-Year Life
2.5	5.6	2.3	8.1	4.8
5	4.6	1.5	9.6	6.5
10	3.1	0.6	13.1	10.6
20	1.4	0.1	21.4	20.1

[a] Assuming no salvage value.

sinking-fund allowance at several costs of money on the total annual fixed charge rate. The effect of different plant or equipment lifetime is shown using assumed lives of 15 and 30 years. The sinking-fund factor shown in the table assumes a salvage value of zero. However, in the economic analyses shown in Chap. 7, some salvage was assumed for most of the items, as shown in Table 3A.3 of Appendix 3A. Note that the sinking-fund factor exerts a smaller effect at the higher cost of money. The reason for this is that more money is accumulated annually at the higher interest rate, so that the deposit factor is decreased.

3.3 Replacement of Investment

Recovery or replacement of investment is a very broad term which conveys different meanings in different contexts; however, it does not mean that equipment or a plant will be duplicated at the end of its life. A broader understanding results if one considers that replacement is synonymous with displacement. Replacement then means that the present plant or piece of equipment will be displaced by a more economic one due to the beneficial results of continuing research and development programs.

3.3.1 Depreciation

In the value sense, depreciation refers to the loss caused by deterioration and obsolesence. However, in the accounting sense it refers to writing off unamortized cost over the useful lifetime of the equipment. The accountant prorates the cost of an asset (less any estimated salvage value when disposed of) against each year's earnings, and his mathematical model of distribution determines the effect of depreciation on each year's profits. The following is a list of some of the depreciation formulas in use:[4]

1. straight line: gives uniform depreciation,
2. sum-of-the-years digits: rapid depreciation in early years,
3. double-rate declining balance: rapid depreciation in early years,
4. sinking fund: rapid depreciation in late years.

All economic analyses in this report were analyzed using the sinking-fund formula,

$$\mathrm{SFDF} = \frac{i}{(1+i)^n - 1} , \qquad (1)$$

where

SFDF = sinking fund deposit factor,
i = cost of money as an annual interest rate,
n = investment lifetime (years).

Gross manufacturing costs for industrial "building block" processes and industrial complexes (without a nuclear power source) as reported in Chap. 5 were computed assuming that the salvage value of the investment was zero. The economic analyses of the farm (Chap. 6) and the nuclear industrial and nuclear agro-industrial complexes (Chap. 7) were calculated assuming salvage values as described in Table 3A.3, Appendix 3A.

3.3.2 Service Life and Interim Replacement

The service life assumed for all industrial plants was a uniform 15 years. This is conservative for an aluminum plant; however, for most of the other industrial processes, it appears to be quite reasonable. Other assumed service lives are listed in Table 3A.3, Appendix 3A.

Interim replacement parts for reactors and evaporators were calculated by determining the fraction of the investment represented by equipment having a shorter lifetime (15 years) than the overall plant (30 years). The sinking-fund factor was then computed on this basis, and monies were accumulated to take care of interim replacement.

3.4 Interest During Construction

In the economic appraisal of proposals, the concept of a construction period is arbitrary. All net receipts can be discounted to the initial year of construction of the project or to the initial year in which income is received or to any other year [Eq. (5), Appendix 3A]. The date of "initial operation" was chosen, for the purpose of economic appraisal, to correspond to the initial flow of income and not the date for startup of operation.

In this study, investment, income, and operating expenses are all considered end-of-year transactions. If various transactions are distributed throughout a year in the same manner (e.g., weekly or monthly),

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[4] G. A. Taylor, *Managerial and Engineering Economy*, D. Van Nostrand Company, Inc., 1964.

their sums would be translated to equivalent end-of-year amounts by a factor which depends only on the interest rate and the manner in which transactions are distributed. For such a case, the same factor multiplies all entries and balances out completely in the comparison of alternative proposals.

Income for the first year was taken the same as for subsequent years, except in the special case of delayed returns associated with specific items. When a project starts up, there will be delays in the initial flow of income because of the time required to produce and market the first set of goods. Production facilities that are relatively far from their markets will probably experience a somewhat greater delay than others. For the purpose of this analysis, this delay was not explicitly incorporated into the construction period, but some allowance may be assumed to have been included.

Construction periods assumed for economic analyses discussed in this report are listed in Table 3A.3 of Appendix 3A. In general, construction periods for non-United States locations are assumed to be one year longer than for their counterparts in the United States.

A more complete discussion of the computation of interest during construction is contained in Appendix 3A; Table 3A.2 in this appendix contains factors for calculating interest charges for various construction periods and interest rates.

3.5 Overseas Construction and Operations

The effect of location was considered in rationalizing costs for this study. Only very limited information is available on reactor power station costs for construction outside the United States, especially in developing countries; such information as is available is for systems of rather small capacity and hence high unit costs. Consequently, estimation of overseas costs had to be based on United States estimates.

Due to the advanced technologies involved, nuclear power stations constructed in developing countries will probably be based on non-indigenous design and fabrication of the principal reactor and turbogenerator components, although much of the erection and installation as well as many small components may be provided locally. The heavy equipment to be imported will cost more in the developing country than in the United States (or other supplying country) because of transportation costs. However, those items supplied indigenously may well cost less than in the United States due to lower labor costs.

To facilitate adaptation of United States cost estimates to overseas applications, a review was made of the individual cost items in cost estimates for several power stations, and all costs were separated into the two categories of "imported" and "indigenous" (from the point of view of a developing area) according to the nature of the item. The basis selected for deciding a probable source of supply was the state of industrialization of countries like India, the Philippines, and Israel. Information from two sources where comparative costs had been presented on a similar basis for non-United States nuclear power stations was also utilized.[5-7]

The cost assignment studies resulted in the expected indigenous components of cost ranging from about 32 to 50% of the total United States estimate. The Indian survey[7] has estimated that for fossil-fueled stations, the indigenous component for Indian conditions would be 33% in the 1967–71 period and 50% in 1971–76; the same report estimates that the indigenous component for nuclear plants (heavy-water reactors) should be 43% in 1965–71, rising to 58% in 1971–76. Considering the range of values obtained in this study, the capital costs (not including interest during construction) for United States construction were multiplied by 0.60 to obtain the imported component, which might be subject to transportation factors and payment in "hard" currencies, and by 0.40 to obtain the indigenous component, which might require modification to correct for use of local labor and currency.

In this study the capital costs of nuclear power stations were estimated by assuming that the cost of the imported components of the stations would be 1.2 times the United States cost for that portion of the plant, while the indigenous portion would (conservatively) cost the same as in the U.S. This implied that the estimated capital costs for nuclear power stations to be built outside the United States would be 12% greater than total costs in the United States ($1.12 = 0.6 \times 1.2 + 0.4 \times 1$).

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[5] *Preinvestment Study on Power, Including Power in Luzon Republic of the Philippines*, General Report, UNDP and IAEA Publication, chap. VI (November 1965).

[6] Rodolfo C. Sun, *Extrapolation of Cost Data from the Industrialized to Developing Countries*, Manila Electric Company.

[7] *Report of India Energy Survey of India Committee*, Government of India, New Delhi, India (1965).

All industrial and farm cost data for this report were obtained from United States manufacturers and vendors. To estimate these costs in non-United States countries, United States costs were extrapolated by separating the total investment into an imported portion and an indigenous portion. It was assumed that the imported portion would come from the United States, and thus additional transportation and handling charges would be incurred. However, it should be realized that many components might be available on the world market, probably at lower prices than comparable United States equipment. This introduced a factor of conservatism in our estimates of industrial and farm components. The indigenous portion of the investment would contain expenditures for labor and materials that usually would be less than in the United States. Here again, a conservative factor was introduced, since the assumption for this study was that the costs of indigenous components were the same as United States costs. Thus, costs for non-United States location were computed as the United States capital investment multiplied by the sum of two products,

$$P' = P[\,1.20A + 1.0(1 - A)\,] \;, \qquad (2)$$

where

P' = capital investment for non-United States location,

P = capital investment for United States location,

A = imported fraction of investment.

Various fractions of industrial plants were assumed as imported items, depending upon the product manufactured. Table 3.2 contains a listing of the indigenous fractions assumed. However, for the farm, a uniform fraction of 0.5 was assumed. This resulted in an overall 10% increase in the cost of the farm over its counterpart in the United States.

Other economic factors that must be considered in the operation of a non-United States complex are the cost of labor, the price and availability of raw materials, and the assumed price levels for products. With regard to industrial labor costs, $4.00 per man-hour was assumed for the United States, whereas 67¢/man-hour was used for non-United States locations. However, the efficiency of non-United States labor was assumed to be one-third of that of United States workers, and thus overall labor costs for industrial processes were one-half of their United States counterparts.

Farm labor in the United States is traditionally paid less than industrial labor. An average wage paid for farm labor in the United States was assumed to be $1.50 per man-hour, and, maintaining the ratio of 1/6 (67/400), non-United States farm wages were assumed to be 25¢/man-hour. These wages are quite low by American standards; however, in India, farm labor is currently paid at the rate of about 30¢/day.

Raw material prices depend upon availability and location with respect to the complex. Raw materials which are not indigenous are priced higher because of transportation costs. Table 5.9 contains the raw material price assumptions used in this study for United States and non-United States locations.

The level at which product prices are set is probably the most important single factor in determining the ultimate economic viability of any enterprise. Sales prices for the various products were fixed for this study after consultation with people in industry and various literature references. The prices listed in Tables 5.9 and 6.7 represent the best estimates of f.o.b. point of origin prices for the various commodities. Two levels of prices were chosen in the economic evaluations, an "export" price and an "import" price. Export prices were generally chosen so as to compete on the world market, whereas import prices represent value to a developing country as a replacement for

Table 3.2. Estimated Indigenous Fractions of the Investment Costs for Industrial Plants

Plant	Indigenous Fraction
Ammonia	0.50
Phosphorus	0.50
Aluminum	
Extraction	0.80
Smelting	0.60
Fabrication	0.60
Urea	0.27
Nitric acid	0.70
Nitric phosphate	0.70
Chlorine-caustic	0.40
Caustic concentrator	0.60

an imported product. In general, the import price is about 30% higher than the export price, and this increase represents transportation and handling costs.

An examination of the effect of concentrated large-scale production of fertilizer, chemicals, and metals on the selling prices of these products was not within the scope of this study. However, the need for a market survey was recognized as one of the most important items to consider in future studies of specific sites.

Table 3.3 illustrates the relative effect of maximum production of the basic chemicals from a complex on world, United States, and Indian markets. The effect of large production of ammonia and phosphorus on United States markets should not be ignored, especially with the present oversupply of nitrogen in the United States. With India serving as an example of an underdeveloped nation, it is readily evident that the assumed production figures are quite large; however, the anticipated demands are much greater than estimates of future production, and thus these products (especially fertilizer) should be easily absorbed by the economy. Considering that the time period envisioned for complexes containing maximum-size plants is at least ten years in the future, market perturbations in the United States should be minimal. The effect of this production on the economy of a developing nation might be gigantic, possibly resulting in a general improvement in the living standards of the country.

3.6 Working Capital

For all evaluations of gross manufacturing costs or economic analyses of complexes where the costs of power, water, and steam were used (Chaps. 5 and 6), working capital was calculated as the value of 60 days' production at gross manufacturing cost. For economic analyses of nuclear industrial and nuclear agro-industrial complexes where internal costs were not allocated, working capital was computed as the value associated with four months' operating costs for the entire complex.

3.7 Risk and Inflation

The usual method of incorporating risk allowances into an economic analysis involves probability estimations for different types of disasters.. The probability of natural disasters usually may be predicted on the basis of insurance rates; however, losses related to equipment or other production-oriented problems are quite specific and must be individually analyzed. The total cost of any disaster must be weighed against the annual cost of preventive measures needed to protect against it and the choice made on the basis of relative costs. Since very few investments are completely free of risk, the return (or interest rate) expected on venture capital is proportional to the risk involved.

Table 3.3. Maximum Complex Production as Percent of Total Production

Product	Maximum Assumed Production (tons/year)	Percent of Total Production					
		1967			1975		
		World	U.S.	India	World	U.S.	India
	$\times 10^6$						
Ammonia	1.07	4.5	20	170	1.7	11	33
Aluminum	0.25	3	6.3	200	2	4	51
Caustic soda	0.78	4	10.3	288	2.4	6.8	130
Chlorine	0.69	4	9.4	278	2.4	6.3	125
Phosphorus[a]	1.17	7	28	530	4.5	21	138

[a] As P_2O_5.

In comparing the relative economic benefits of alternate investment opportunities, the cost of money may be adjusted to account for any differences in risk. For example, location in a remote area may dictate the use of a higher cost of money since any unforeseen occurrence may be more costly in terms of lost production because of the time and difficulty involved if specialists or special parts are required to be brought in. Since it is a general study, this report does not attempt to quantify the various risks which inherently would be present for enterprises as large as those discussed. However, studies of specific locations should be cognizant of these factors in their economic appraisals.

Obsolescence of equipment and technology represents one element of risk. As a judgment factor, the service lives for the components of complexes discussed in this report were chosen to reflect possible obsolescence and unforeseen contingencies. A complete listing of the assumed service lives is included in Table 3A.3 of Appendix 3A. A specific allowance for risk is provided for the nuclear reactor with the inclusion of liability insurance in all economic analyses as discussed in Chap. 4 and Appendix 4A.

Inflation may be defined as the uniform increase with time in real costs and their equivalent in terms of the goods and services they will buy. If construction costs, operating costs, and income inflate uniformly and if the costs for alternatives are expressed in terms of the purchasing power of today's dollar, the effect of inflation on the economic analyses may be ignored. The assumption of uniform inflation was made for this report, and cost and price data were based on mid-1967 levels.

3.8 Marketing Expense

No allowances are provided for marketing expenses in any of the economic analyses discussed in the report. Normally, these expenses are passed on to the consumer in any case. The consumer, in the context of this study, is generally assumed to be a secondary manufacturing industry, since in most cases the products of the complex would be further processed before reaching individual consumers.

3.9 Methods Used for the Economic Analysis of a Nuclear-Powered Complex

The nuclear industrial complexes considered in this study consist of the power plant and the industries which utilize the power produced. Nuclear agro-industrial complexes include, in addition, a seawater desalination plant and an irrigated farm. The most equitable method of evaluation is the tabulation of capital investments, annual operating costs, and annual income from the sale of products. It excludes internal transactions such as the sale and purchase within the complex of electric power, steam, and desalted water or other byproducts. This avoids the problem of how to allocate to electric power and to water the cost of a dual-purpose reactor producing both products.

The accuracy of the analysis depends primarily on the cost and income estimates. In an attempt to include all costs, care was taken to include facilities such as a harbor, public utilities, and initial housing for the workers and their families and for service-industry personnel. Income was calculated from the sale of products at estimated prices which exclude cost of transportation from the complex.[8] The exception was for those examples in which electric power capacity was included not only for the needs of the complex but also for transmission and sale to other communities. This power was priced at its marginal production cost (including transmission cost), which would usually be considerably less than the cost of power from alternative smaller-sized local power plants. The possibility of providing such power is a potential benefit which depends on the costs and location of alternative supplies and which can be appraised at the time a complex is considered for a specific site.

3.10 Internal Rate of Return and the Discounted Overall Return

Nuclear industrial and nuclear agro-industrial complexes were evaluated and compared by evaluating their internal rates of return.

The internal rate of return is the equivalent level average annual earning rate of funds in use and may be specifically defined as "the interest rate at which a sum of money, equal to that invested in the proposed project, would have to be invested in an annuity fund in order for that fund to be able to make payments equal to, and at the same time as, the receipts from the proposed investment." It is computed by finding the interest rate at which the

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[8] Transportation costs were included in one comparative example; see chap. 5.

sum of the present worth of receipts exactly equals the sum of the present worth of all expenditures. Solution is by means of an iterative procedure described in Appendix 3A. Other names applied to the internal rate of return include true rate of return, discounted cash flow, and profitability index.[9] The advantage of this method of analysis is that it avoids stipulating an interest rate.

In choosing between several investment opportunities, it should be remembered that the alternative with the greatest rate of return may not have the greatest overall return, properly defined as the income over the life of the project less all expenses, including investment, discounted to its present worth through the use of the *appropriate* interest rate. The overall return, in millions of dollars per year, was calculated for various interest rates and listed as net annual benefits in Chap. 7. Choice of interest rate depends on the specific situation. The appropriate choice should assure that more attractive investment opportunities would not be precluded because of lack of investment funds. Numerical evaluations of overall return for some examples of nuclear-powered complexes are presented in Chap. 7. A detailed mathematical development of the procedure used for calculating the internal rate of return is given in Appendix 3A.

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[9] R. J. Reul, *Chem. Eng.* 9, 212 (1968).

4. RATIONALE FOR ESTIMATES OF POWER AND WATER COSTS

The principal justifying and motivating factors leading to this study are the low costs which have recently been estimated for electricity and desalted water produced using nuclear reactors now under construction or development. As evidenced by the number of reactor plants now in operation, under construction, or on order in the United States alone (48,000,000 kw in late 1967),[1] nuclear power has become competitive with fossil fuels under many conditions. Depending on plant size and financing charges, electricity production costs for nuclear stations in the range of 2.4 to 4 mills/kwhr have recently been announced for plants under construction in 1967.[2,3] Further, estimates for larger and more advanced reactor systems, including the breeder reactors now being developed, suggest that power costs may eventually be a factor of about 2 less than the estimated costs from the current generation of nuclear power plants.[4] Regarding the cost of producing desalted water from the oceans, recent estimates of the effects of developments in desalting technology now under investigation, when coupled with advanced reactors, indicate that for large plants desalted water costs of from 10¢ to 20¢/1000 gal should be attainable in the future.[5]

Projected energy and desalted water costs of these magnitudes are lower than previous estimates and were the basis for the suggestion that this study should investigate the possible effect of such reduced costs on large energy and water users, such as the electrochemical and metallurgical process industries and irrigation agriculture.[6–8]

Since many conditions – technologic, geographic, and economic – influence the costs of producing electricity and desalted water from nuclear energy at any given time and place, the effect of the cost of these two commodities was studied parametrically over reasonable ranges. The purpose of this section of the report is to present a consistent rationale for

1. justifying the ranges of power and water costs considered,
2. defining those combinations of size, technology, and economic conditions under which any of the selected costs might be expected to be realized, and
3. estimating capital and operating costs for use in the economic evaluation of nuclear-powered agro-industrial complexes.

4.1 Factors Considered in Estimating Power Costs

The principal factors which affect the cost of producing steam and electricity from nuclear energy are:

1. technology – reactor type, type of reactor fuel cycle, status of system development, and turbine system employed;
2. size – total energy produced and number of reactors per station;
3. place of construction – cost differentials for non-United States construction, time of construction and startup, and climate factors;
4. plant load factor – plant availability, scheduled and forced outages, and nature of load; and
5. financing – cost of money, amortization time (plant life), and taxes and insurance.

Some of these factors are briefly discussed below in terms of how they influenced the assumptions used in this study.

Two reference time periods representative of two levels of technology were assumed. These are

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[1] *The Nuclear Industry, 1967,* USAEC Division of Industrial Participation (1967).

[2] *Comparison of Coal-Fired and Nuclear Power Plants for the TVA System,* Office of Power, Tennessee Valley Authority, Chattanooga, Tenn. (June 1966).

[3] *Nucleonics Week,* p. 4 (Jan. 19, 1967).

[4] J. A. Lane, "Economics of Nuclear Power," *Ann. Rev. Nucl. Sci.* 16, 345–78 (1966).

[5] H. A. Sindt, I. Spiewak, and T. D. Anderson, "Costs of Power from Nuclear Desalting Plants," *Chem. Eng. Progr.* 63(4), 41–45 (1967).

[6] J. M. Holmes and J. W. Ullman, *Survey of Process Applications in a Desalination Complex,* ORNL-TM-1561 (October 1966).

[7] R. E. Blanco *et al.*, "Ammonia Costs and Electricity," *Chem. Eng. Progr.* 63(4), 46–50 (April 1967).

[8] R. P. Hammond, "Desalted Water for Agriculture," International Conference on Water for Peace, Washington, D.C., May 1967.

referred to as *near term* (NT) and *far term* (FT), which are defined as follows:

Near term refers to a level of technology that might be expected to be in commercial use in about ten years (i.e., 1977–78) and assumes the use of light-water reactors (LWR), either the boiling-water or pressurized-water type. Considering the time that follow-on development, design, evaluation, financing, procurement, and construction would involve before implementing any energy-producing–energy-consuming complex of the types considered in this 1967 study, the minimum time to reach full-scale operation was estimated to be about ten years (the time for construction of nuclear reactors in the United States is now five to six years). This permits an additional four to five years beyond 1967 designs (referred to as *present term*) for reactor development work before final reactor design selection and as much as seven to eight years of additional development and prototype work on desalting technology and industrial processes, depending on the construction times required. Estimates for power costs in the near term are therefore based on a survey of the costs for present-term reactors (i.e., reactors ordered in 1966 and early 1967 for startup in about 1971–73) plus an allowance for anticipated cost reductions due to four or five years of additional development work and experience.

In view of the present state of development and commercialization of various reactor types, the confidence level for estimates of energy costs for near-term applications based on light-water reactors was considered to be significantly greater than for any other reactor type. If and when developed to commercial level, the high-temperature gas-cooled and/or the heavy-water concepts may produce thermal and electrical energy at somewhat lower costs than the LWR's. However, the overall purpose of this study was to evaluate the impact of various energy and water costs on industrial and agricultural production. Rationales, or models, for estimating power and desalted water costs were developed to provide a reasonable basis for the required industrial and agricultural evaluations and were not intended to provide a comparison or evaluation of the various estimates and claims that have been made for different reactor concepts. Therefore, the required nuclear energy cost rationale for the near-term cases was derived from the costs for LWR's, which are commercially available in large sizes from a number of manufacturers.

Far term refers to the period approximately 20 to 25 years in the future, when reactor development programs already receiving significant effort may result in substantial further reductions in the cost of energy produced from nuclear fission. Since breeder reactors give promise of ultimately producing nuclear energy at lowest cost, the advanced breeder concepts now under active development were selected to provide the basis for the rationale of costs assumed for the far-term evaluations. The U.S. Atomic Energy Commission's program of development of breeder reactors is aimed at commercial availability by the middle 1980's, so that a time scale of about 20 years after 1967 was chosen as the basis for evaluation of far-term applications. This implies about 15 years from 1967 for development, prototype testing, and initial commercial operation prior to final selection of any concept evaluated in the far-term context of this study.

4.2 Estimated Energy Costs for Light-Water Reactors

In view of the greater amount of information available concerning cost projections for LWR's, the general model used in this study to rationalize projected energy costs will be discussed first using the LWR information. Subsequent sections will then discuss the quantitative changes introduced in the projected costs when the advanced breeder reactor concepts are considered. The rationale of costs for light-water reactors is based on a survey of information available during the summer of 1967.[2,3,9–12] This cost information was evaluated to identify and adjust for differences in the bases employed. Where differences in the resulting estimates still existed, average values were taken for use in this study.

Capital and operating costs change with time. The information presented here is based on con-

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[9] *Current Status and Future Technical and Economic Potential of Light Water Reactors*, Jackson Moreland and S. M. Stoller Associates, USAEC, New York Operations Office, WASH-1082 (December 1967).

[10] C. C. Burwell, ORNL, personal communication, July 1967.

[11] *General Electric Company Price Handbook*, sect. 8802, p. 10, Aug. 22, 1966.

[12] R. W. Lockhart, *Feasibility Study of Boiling Water Reactor Nuclear Steam Supply Systems with Capacities up to 10,000 MWt*, GECR-5155 (February 1967).

ditions in the spring and summer of 1967. The bases for the cost estimates used in this study are explained in some detail in this section and in Appendix 4A, so that the effect of future changes can be readily identified.

In many respects pressurized- and boiling-water reactors are very much alike, and thus the individual components of cost which make up the total costs of producing steam or electricity from these two reactor systems are usually quite similar. Capital cost breakdowns for several large LWR electricity-generating stations have been published.[2,3,11] In addition, a number of surveys of capital and generating costs for nuclear stations have also been made.[4,13] A 1967 engineering evaluation of the current status and future technical and economic potential of light-water reactors[9] provides a good summary of the design and costs for pressurized- and boiling-water reactor systems.

In addition to producing electricity, nuclear power stations can supply steam for process heating and seawater desalting purposes. Therefore, to facilitate estimating the capital and operating costs for such multipurpose stations, the power plants were considered to consist of three interrelated parts: namely, the nuclear island (N. I.), the turbogenerator island (T.I.), and the condenser island (C.I.). The nuclear island includes all facilities required to produce the prime steam and thus includes the reactor and its auxiliaries, a primary cooling system, and heat-exchanger-boilers. The turbogenerator island includes the facilities required to produce electricity and extraction steam from prime steam. The condenser island includes the facilities required to condense any steam emerging from the turbogenerator island which is not sent to process or desalting use.

This chapter briefly discusses the technique employed in this study for evaluating capital and total power costs for light water reactors. A summary of estimated power costs is also presented. Additional details are given in Appendix 4A.

4.2.1 Capital Costs

The capital investments in complete nuclear electric (single-purpose) generating stations vary widely,[4] but costs for a number of stations of about 1000 Mw(electrical) capacity in 1966 and 1967 fall in the range of $115 to $155/kw, including charges for interest during construction but not including cost of land.[3,9] A cost of $135/kw ± 15% for total investment (except land, fuel, and transmission facility) was therefore taken as representative of present-term capital costs (i.e., for reactors which might be ordered in early 1967 and reach commercial use in about 1972). The estimates of interest charges during construction (IDC) averaged 8% for United States installations in the sources used. When these charges are subtracted (so that the effect of varying IDC could be studied to allow for differences in the cost of money and time of construction from place to place), a base capital cost (not including IDC) of $124/kw(electrical) at 1000 Mw(electrical) capacity results.

The principal factors which were considered to change this base capital cost are increasing construction experience, technological improvements, plant size, the number of reactors per station, length of construction period, and location.

The effect of increasing construction experience was allowed for using the concept of a "learning curve." The recent evaluation of LWR's[9] suggests using a 90% learning curve; on this basis, costs are predicted to decrease 10% for each doubling of production experience. When coupled with projections for the growth of nuclear generating capacity in the United States alone, this procedure suggests possible reductions in the present-term capital costs of LWR's of 10% by 1977 (near term) and another 10% by 1987 (far term). In addition, improvements in LWR technology in the areas of pressure vessel, steam generator, and containment offer a potential saving estimated at $5.50/kw(electrical)[9] for the NT time period. Thus the total reduction in base capital costs assumed for near-term LWR's having a net capacity of 1000 Mw(electrical) is $18/kw(electrical).

The effect of size ("scale") on the capital cost of the nuclear island can be correlated over limited ranges in a fashion similar to many other industries by simple relationships of the type:

$$\text{Unit cost} = \text{base unit cost} \times (\text{capacity})^{-n} ,$$

where the scaling factor n varies between 0.30 and 0.44. Cost information from a number of sources[9–11,13] was found to give good agree-

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[13] *Power Supply for New England, 1973–1990* (preliminary), Ebasco Services Incorporated, New York (February 1967).

ment on the magnitude of the scaling factor over three capacity ranges (see Appendix 4A).

Jackson and Moreland[9] estimated the costs for nuclear reactor stations containing from one to four reactors each for reactors of 400, 600, 800, and 1000 Mw(electrical) capacity. These estimates and results of analyses made at ORNL[10] were used to estimate the costs of one- and two-reactor stations (Appendix 4A).

Considering the fact that prices for nuclear power plants have increased considerably during the period from mid-1967 to mid-1968, it seemed appropriate to place in perspective the capital costs used in this study as compared with recent industry experience. The total construction costs of a number of nuclear power plants (including IDC) exclusive of land, fuel, and transmission facility[14] are plotted in Fig. 4.1 as a function of their net power output. The majority of stations ordered before January 1967, represented as circles in Fig. 4.1, are expected to be in commercial operation by 1971–72. Those stations ordered after that date (triangles in Fig. 4.1) are expected to be in operation by 1973–74. The solid line indicates the capital costs of single-station light-water reactors at 10% cost of money based on the assumptions used in this study.

The shaded area shown in Fig. 4.1 contains 60% of those orders placed subsequent to January 1, 1967, apparently suggesting that prices have indeed escalated. However, the starred locations shown in the figure represent reactors located in the southeastern part of the United States, where unit costs appear to be considerably lower irrespective of the date of the order. Some possible reasons for the lower costs in this area may be (1) outdoor construction, (2) lower labor costs, and (3) availability of good cooling water. Many of the applications of an agro-industrial complex are intended to be in coastal desert areas of underdeveloped countries,

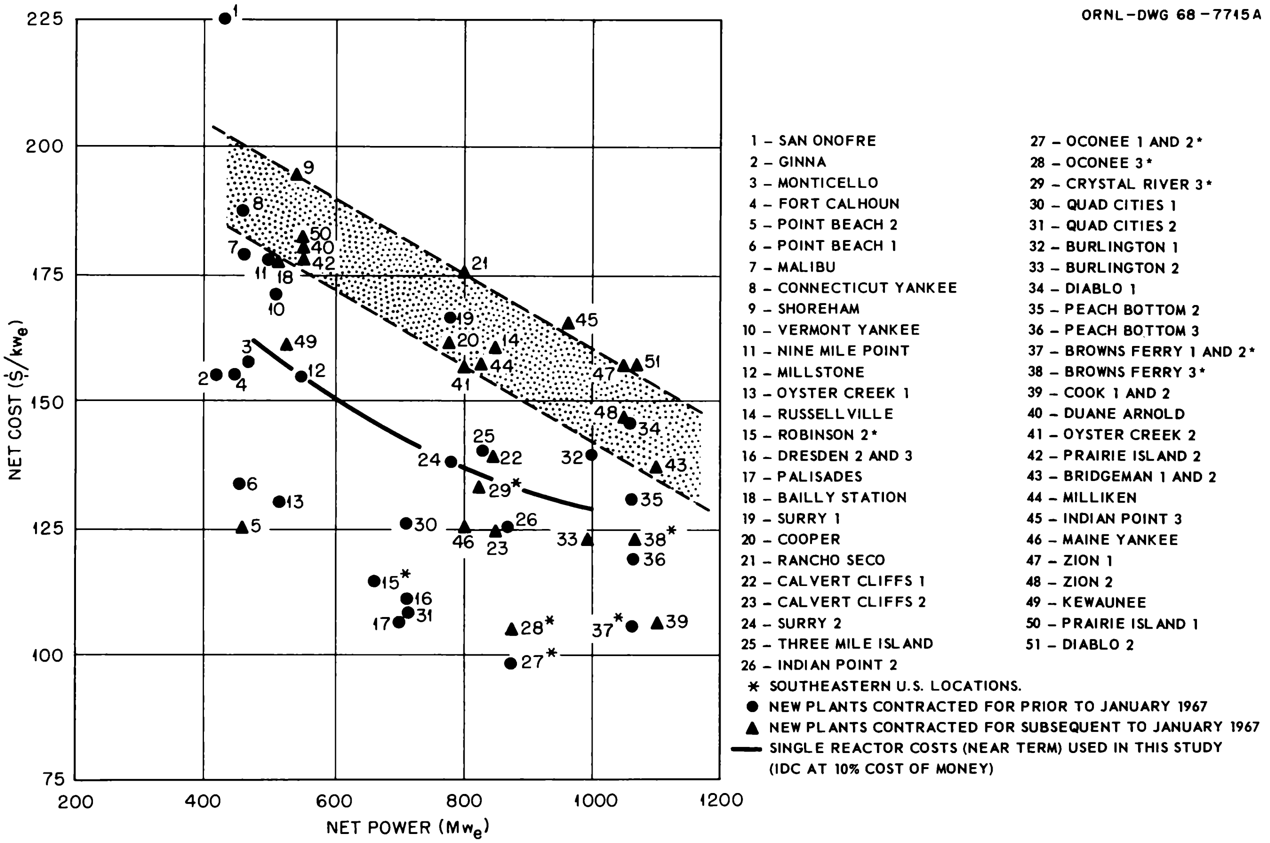

Fig. 4.1. Unit Costs of Central Station Nuclear Power Plants Operating, Under Construction, or on Order (Excluding Land, Fuel, and Transmission Facility).

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[14] "The Nuclear Industry, 1967," *Nuclear News* 11(1), 29–46 (January 1968).

and thus points 1 and 2 would be applicable in their construction.

In rationalizing costs for this study, the effect of location was considered. Only very limited information is available on reactor power station costs for construction outside the United States,[15,16] especially in developing countries, and this information is for systems of rather small capacity and hence high unit costs. To facilitate adaptation of United States cost estimates for application to non-United States locations, a review was made of the individual cost items in cost estimates for several power stations, and all costs were separated into the two categories of "imported" and "indigenous" (from the point of view of a developing area), according to the nature of the item. Factors were then applied to these two categories to reflect differences in cost between items which would be purchased with "hard currency" and imported vs those available locally (see Sect. 3.5).

4.2.2 Operating Costs

The principal operating costs for nuclear generating stations are fuel cycle costs, operating and maintenance costs, and insurance costs. In common with other comparative studies,[5,9,17] fuel cycle costs here are based on the steady-state operation of the reactor system (referred to as the equilibrium fuel cycle); the bases are consistent with other recent studies.[4,5,9,17,18] The annual costs for operation and maintenance, as well as nuclear liability and property damage insurance, were estimated and included. A detailed discussion of the bases and procedures used to estimate these costs is given in Appendix 4A.

4.2.3 Total Estimated Steam and Electricity Costs from LWR's

To show the effect of the different variables discussed above and in Appendix 4A, estimates of the total cost of producing prime steam and electricity from LWR's according to the rationale used in this study are given in Table 4.1 and Figs. 4.2 and 4.3 for a number of different cases.

The costs shown in Figs. 4.2 and 4.3 are based on the following factors:

Plant load factor	0.9 (7900 hr/year)
Thermal efficiency for LWR	34.2% gross, 32.6% net
Number of reactors per station	1 and 2
Size of single reactors	1500 to 10,000 Mw(thermal)
Cost of money	2.5, 5, 10, and 20%/year
Assumed plant life	30 years
Time of construction	4 years[a]

The concepts of industrial and agro-industrial complexes evaluated in this study would impose large, steady energy loads on the generating stations. Consequently, the load factor was considered to be greater than is normally the case for reactors that deliver their energy to electrical grids which have appreciable daily and seasonal load fluctuations.

Table 4.1 presents estimated capital costs and a breakdown of energy costs into the three main cost categories for near-term LWR's of 1100 and 3200 Mw(electrical) capacity and four values of the cost of money. Total costs for producing steam and electricity are shown in Fig. 4.2 as a function of station generating capacity and the cost of money. For the near-term cases shown in Table 4.1 and Fig. 4.2, annual fixed charges were calculated using the general model based on cost of money, time of construction, and plant life, as discussed in Chap. 3. To provide a comparison with published cost estimates for LWR's now under construction, costs were also estimated using the costs for present-term LWR's and fixed charge rates of 8 and 12%/year, which represent typical rates used in 1967 by publicly and privately financed utilities in the United States.

The near-term costs of electricity shown in Table 4.1 and Fig. 4.2 for a cost of money i of 10%/year lie between those estimated using the "public" and "private" financing conventions. Since nuclear power stations are capital intensive, varying the fixed charge rate has an important effect on the estimated costs for steam and electricity. The

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[15] *Report of India Energy Survey of India Committee*, Government of India, New Delhi (1955).

[16] *Pre Investment Study on Power Including Nuclear Power in Luzon Republic of the Philippines, General Report*, UNDP and IAEA Publication, chap. VI (November 1965).

[17] M. W. Rosenthal *et al.*, *A Comparative Evaluation of Advanced Converters*, ORNL-3686 (January 1965).

[18] *Technical and Economic Evaluation of Four Concepts of Large Nuclear Steam Generators with Thermal Ratings up to 10,000 MW*, ORNL-TM-2133, to be published.

[a] The time for construction of nuclear reactors in the United States is now five to six years.

Table 4.1. Estimated Costs of Electricity Production for Present-Term and Near-Term LWR Power Stations

	Present Term		Near Term							
Station size, Mw(thermal)	3400		3400				10,000			
Net power, Mw(electrical)	1100		1100				3260			
Number of reactors	1		1				2			
Cost of money, %/year			2.5	5	10	20	2.5	5	10	20
Fixed charge rate,[a] %/year	8	12	4.9	6.7	10.7	20.2	4.9	6.7	10.7	20.2
Capital cost,[b] dollars per kilowatt of net electrical capacity	135	143	111	115	124	142	97	101	108	124
Energy costs, mills/kwhr										
Capital charges	1.25	2.17	0.69	0.97	1.68	3.62	0.61	0.85	1.47	3.17
Operation, maintenance, and insurance[c,d]	0.26	0.26	0.26	0.26	0.26	0.26	0.20	0.20	0.20	0.20
Fuel cycle cost[d]	1.50	1.60	1.27	1.34	1.49	1.77	1.18	1.25	1.38	1.65
Total power cost[e]	3.0	4.0	2.2	2.6	3.4	5.7	2.0	2.3	3.1	5.0

[a] Fixed charge rates for near-term cases based on the cost of money and a 30-year life.

[b] Installed costs including interest charges during construction.

[c] Including nuclear liability and all-risk property damage insurance.

[d] See Appendix 4A for details.

[e] As discussed on pp. 25–27, these costs are somewhat lower than 1968 estimates of nuclear power costs.

estimated decrease in energy costs with increasing reactor size seems to become less important for reactors larger than about 6000 Mw(thermal) – about twice the size of the largest reactors being built in 1967 – using the assumptions of this report.

Reliability considerations will probably dictate the use of two or more reactors per station for large nuclear power stations, especially where it is not possible to tie in with an electrical grid of substantial capacity. Hence many of the complexes evaluated in this study presume the use of two reactors per station. Figure 4.3 shows that with capacities of about 3200 Mw(electrical), the steam and electricity costs for two-reactor stations are estimated to be about 5% more than for one-reactor stations and about 15% more for stations with capacities of about 1000 Mw(electrical).

Figure 4.3 also presents a comparison of the effects of varying LWR technology. At a cost of money of 10%/year, the far-term LWR technology gives an estimated decrease in energy costs of about 15% over near-term technology.

The upper three dashed curves in Fig. 4.4 show the sensitivity of the estimates of electricity costs to an increase in capital cost and a decrease in load factor for the LWR near-term case using two reactors per 10,000 Mw(thermal) station. At a cost of money of 10%, a 25% increase in initial capital cost would cause the power cost to increase by about 11%. Dropping the load factor from 0.9 to 0.8 would further increase the power cost to 3.7 mills/kwhr, for a combined increase of about 20%.

The overall range of estimated electricity costs from LWR's shown in these figures, considering the different costs of money, levels of technological development, and size and number of reactors per station, is from 2 to 6 mills/kwhr.

4.3 Estimated Energy Costs for Advanced Breeder Reactors

Estimations of the costs of producing electric power and steam from advanced breeder reactors were performed using the same general rules as discussed for light-water reactors except for thermal efficiencies, which are listed in Table 7A.1 of Appendix 7A. Two types of advanced breeder reactor (ABR) concepts were considered – liquid-metal fast breeder reactors (LMFBR) and molten-

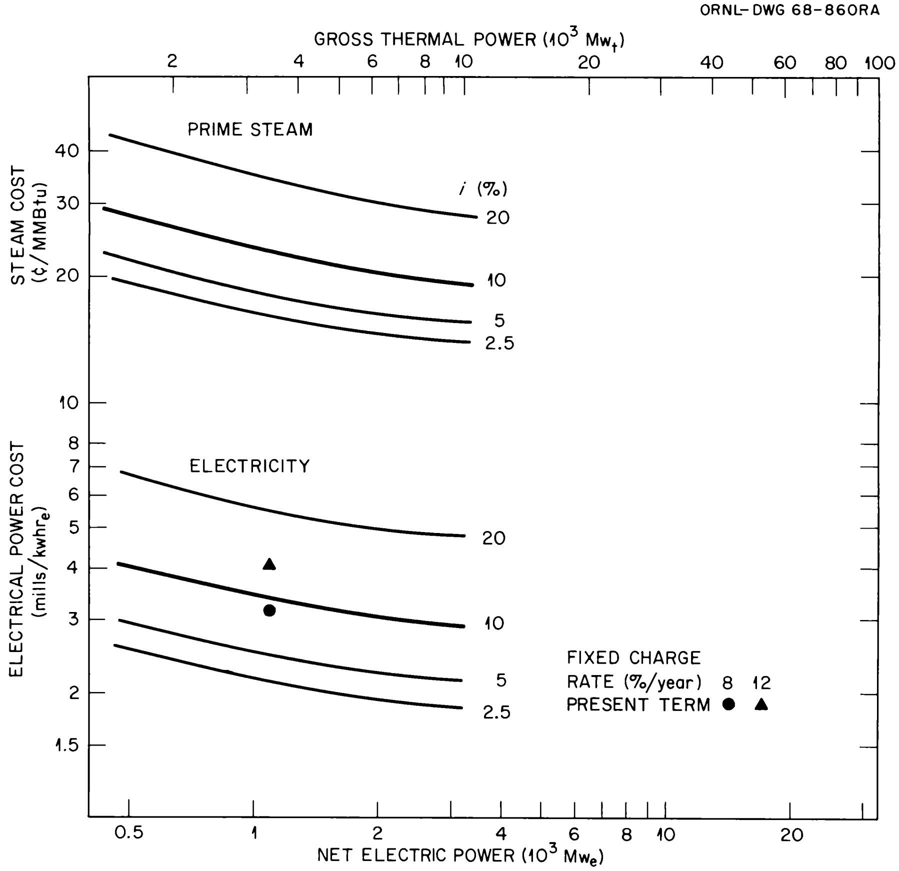

Fig. 4.2. Prime Steam and Electricity Costs for Near-Term LWR Under United States Conditions.

salt thermal breeder reactors (MSBR). Both of these concepts are in the early development stage. Experimental-size reactors have been operated successfully for both of these concepts; however, operating prototypes have not yet been constructed. The development program of the United States Atomic Energy Commission is aimed at commercial operation of advanced breeders by the late 1980's. Consequently, all cost estimates for such reactors are much more speculative than those for light-water reactors. These reactor concepts and the cost estimates which have been projected for them are considered here to indicate the range of potential reductions in nuclear power costs that may eventually result if these concepts are carried successfully to large commercial operations.

4.3.1 Capital Costs of Fast Breeder Reactor Power Stations

The costs for the large fast breeder reactors are based on an evaluation of a 10,000 Mw(thermal) sodium-cooled fast breeder concept performed by Argonne National Laboratory and Westinghouse Electric Corporation.[19] This report gives the plant design and fuel cycle cost bases which were used to obtain estimates for the capital and operating costs for this type of reactor. A detailed discussion of these bases and the cost factors[20] used in this study is given in Appendix 4A. The general values used are the same as for the LWR case except for the thermal efficiency, which was 41.2% gross and 38.8% net.

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[19] K. A. Hub *et al.*, *Feasibility Study of Nuclear Steam Supply System Using 10,000 MW Sodium-Cooled Breeder Reactor*, ANL-7183 (September 1966).

[20] T. D. Anderson and M. L. Myers, ORNL, personal communication (August 1967). (Memo to E. A. Mason, dated Aug. 28, 1967, "Capital and O & M Cost Data for Fast Breeder Reactors.")

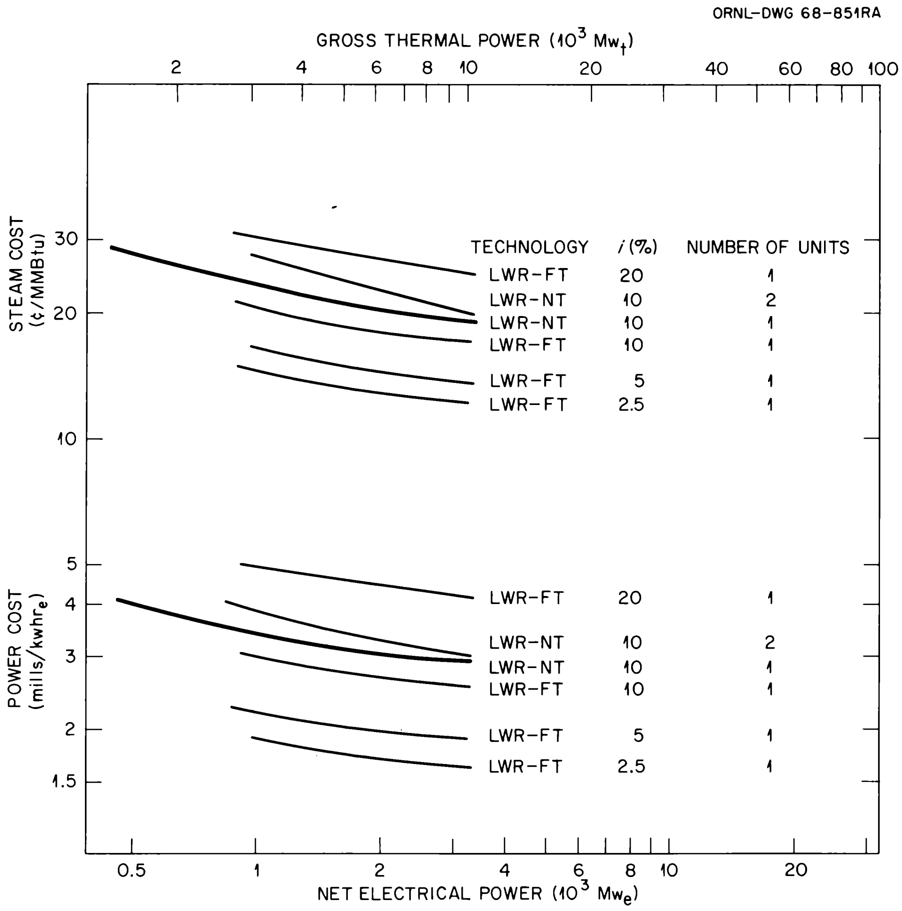

Fig. 4.3. Prime Steam and Electricity Cost for the LWR.

4.3.2 Estimated Cost of Electricity from Fast Breeder Reactors

From the data given in Appendix 4A, the cost of electricity produced by fast breeder reactors was computed for various costs of money and station sizes. The results given in Table 4.2 for a 10,000 Mw(thermal) LMFBR show costs ranging from less than 1 mill/ kwhr to more than 4 mills/kwhr and corresponding unit capital costs based on 1967 dollars ranging from \$99 to \$127 per kilowatt of electrical capacity.

The solid lines in Fig. 4.4 show the sensitivity of power costs for a 10,000 Mw(thermal) LMFBR station to changes in the base capital cost at various costs of money. For a cost of money of 10%, a 25% increase in capital cost results in a 14% increase in electricity cost, from 2.1 to 2.4 mills/kwhr. Decreasing the load factor from 0.9 to 0.8 results in an additional increase of 0.4 mill/kwhr for an overall 33% increase.

4.3.3 Capital Costs of Molten-Salt Breeder Power Stations

The capital cost estimates for the MSBR are based on an ORNL design for a 1000 Mw(electrical) reactor.[21] This reference design uses a four-module core arrangement. Cost data for larger plants were obtained by extrapolating the individual cost accounts of the reference design.[22] Detailed discussions of the bases and costs adopted are

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[21] P. R. Kasten, "Design and Performance Features of Molten-Salt Breeder Reactors," Oak Ridge National Laboratory, paper presented at 1967 ASME Annual Meeting, Nov. 12–17, 1967.

[22] T. D. Anderson, ORNL, personal communication, September 1967. (Memo to E. A. Mason, dated Sept. 18, 1967, "Molten Salt Breeder Reactor Cost Data.")

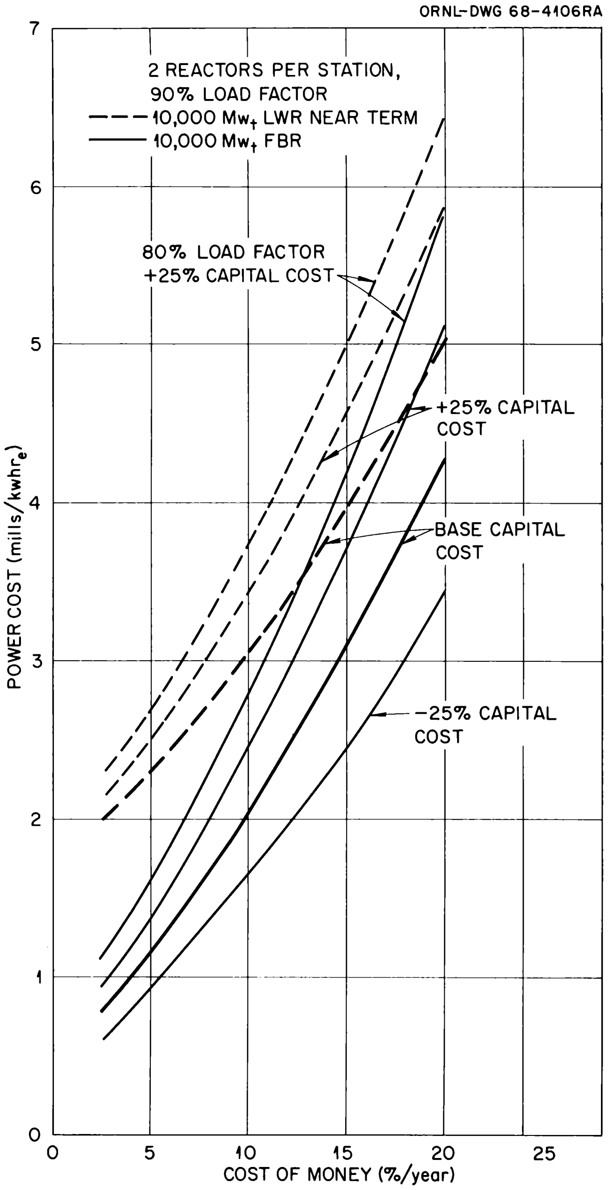

Fig. 4.4. Influence of Capital Cost and Plant Load Factor on the Cost of Power from a Large Nuclear Power Station.

given in Appendix 4A. Fuel cycle costs are also given in this appendix; the MSBR fuel cycle is significantly different from those associated with the solid-fueled reactors discussed previously. In particular, all fuel processing is done in an on-site plant, thus resulting in a stronger dependence of the fuel cycle costs on the reactor size.[18]

The thermal efficiency is taken as 47.5% gross and 45.1% net.

4.3.4 Estimated Cost of Electricity from Molten-Salt Breeder Reactors

The cost of electricity produced by molten-salt breeder reactors was computed for several costs of money and station sizes. The results for a station producing the same electric power output as the LMFBR shown in Table 4.2 are summarized in Table 4.3.

There is a large difference in fuel inventory between the two concepts of breeder reactors (step 6, Appendix 7B). The fuel cycle for the thermal breeder, having 40 to 50% less capital in fuel inventory (including fuel reprocessing plant), shows a lesser dependence on the cost of money. However, the capital costs assumed for the large thermal breeder are more speculative than those for the large fast breeder because they are the result of an extrapolation from a 1000 Mw(electrical) design.

4.4 Influence of Reactor Technology on Power Cost

The estimated effects of station size and cost of money on the cost of electricity generated by the two advanced breeder concepts are shown in Fig. 4.5. For comparison purposes the cost of electricity from light-water reactors based on near- and far-term technologies is also shown as a function of size at a cost of money of 10%/year. Note that at this cost of money the estimated electric power costs for the two advanced breeder reactors are about the same and about 24 to 34% lower than those for near-term light-water reactors but only 14 to 24% lower than those for far-term light-water reactors. Thus for large single-reactor nuclear power stations at a cost of money of 10%, the cost of electricity appears to decrease from 3 mills/kwhr for near-term technology to about 2 mills/kwhr when the advanced breeder reactors become available. Costs of money in excess of 10% appear to favor the thermal breeder because of its smaller fuel inventory and cheaper capital cost, while lower costs of money favor the fast breeder because of its cheaper fuel cycle, due primarily to the high breeding gain of plutonium.

Based on the results of these estimates of energy costs from light-water and advanced breeder reactors, a range of 1 to 8 mills/kwhr was used in the parametric studies of the effect of energy costs on energy-intensive industrial processes.

Table 4.2. Estimated Costs of Electricity Production for a Fast Breeder Reactor Power Station

Station size, 10,000 Mw(thermal)
Net power, 3880 Mw(electrical)

Number of reactors	2	2	2	1	2
Cost of money *i*, %/year	2.5	5	10	10	20
Capital cost,[a] dollars per kilowatt of net electrical capacity	99	103	110	100	127
Energy costs, mills/kwhr					
Capital charges[b]	0.62	0.87	1.50	1.34	3.23
Operation, maintenance, and insurance[c]	0.20	0.20	0.20	0.20	0.21
Fuel cycle	–(0.05)	0.08	0.34	0.34	0.86
Total power cost	0.8	1.1	2.0	1.9	4.3

[a] Installed costs, including interest during construction.
[b] Total fixed charge rates of 4.9, 6.7, 10.7, and 20.2%.
[c] Includes nuclear liability and all-risk property damage insurance.

Table 4.3. Estimated Costs of Electricity Production for a Molten-Salt Breeder Reactor Power Station

Station size, 8630 Mw(thermal)
Net power, 3880 Mw(electrical)
Number of reactors, 4

Cost of money *i*, %/year	2.5	5	10	20
Capital cost,[a] dollars per kilowatt of net electrical capacity	89	93	100	114
Energy costs, mills/kwhr				
Capital charges[b]	0.56	0.78	1.35	2.91
Operation, maintenance, and insurance[c]	0.18	0.18	0.18	0.19
Fuel cycle[d]	0.11	0.17	0.29	0.54
Total power costs	0.9	1.1	1.8	3.6

[a] Installed cost including interest during construction.
[b] Total fixed charge rates of 4.9, 6.7, 10.7, and 20.2%.
[c] Includes nuclear liability and all-risk property damage insurance.
[d] Includes capital charges on fuel reprocessing plant assuming a 20-year plant life.

4.5 Desalted Water Technology and Cost Rationale

Although a number of methods are available for producing fresh water from the sea, the method which currently appears to be most promising for large-scale applications is that based on evaporation. The two main types of evaporator design are multistage flash (MSF) and vertical-tube (VTE). The evaporator design concepts used in this study are assumed to be as presented in two ORNL reports.[23,24]

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[23] *Conceptual Design Study of a 250 Million Gallons per Day Multistage Flash Distillation Plant,* ORNL-3912 (February 1966).

[24] *Conceptual Design Study of a 250 Million Gallons per Day Vertical Tube Evaporator Desalination Plant,* ORNL-4260 (August 1968).

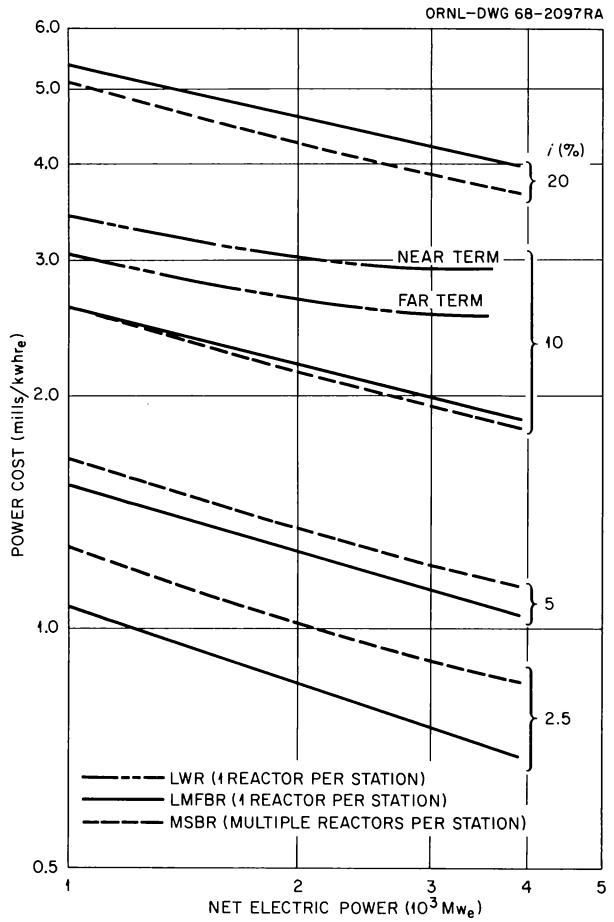

Fig. 4.5. Electricity Costs for Advanced Breeder Reactors.

4.5.1 Multistage Flash Evaporator

The multistage flash evaporator concept is shown schematically in Fig. 4.6. Seawater is first heated under sufficient pressure to prevent boiling and is then sent to the first stage of a multistage evaporator. Here the pressure is dropped slightly until boiling begins. A small portion of the water is vaporized (flashed), and the vapor, free of the dissolved salts, flows to a heat exchanger and is condensed by the incoming seawater, which in turn becomes heated. Both the fresh distilled water stream and the more concentrated and somewhat cooler salt water flow separately through restrictions (decreasing the pressure slightly) to the second stage. Here, both streams begin boiling, with a small fraction of each stream changing to vapor, which is again condensed by the cooler incoming seawater stream.

This process is repeated in many (~50) subsequent stages, where the pressure and temperature are gradually lowered until an economical approach to the inlet seawater temperature is reached. This evaporator arrangement provides for the efficient use of the initial heat source in that the quantity of water distilled may exceed by about 12 times the amount corresponding to the heat supplied. The amount of this regeneration, or heat reuse, is optimized by a balance between the cost of additional heat transfer surface and the cost of the heat saved.

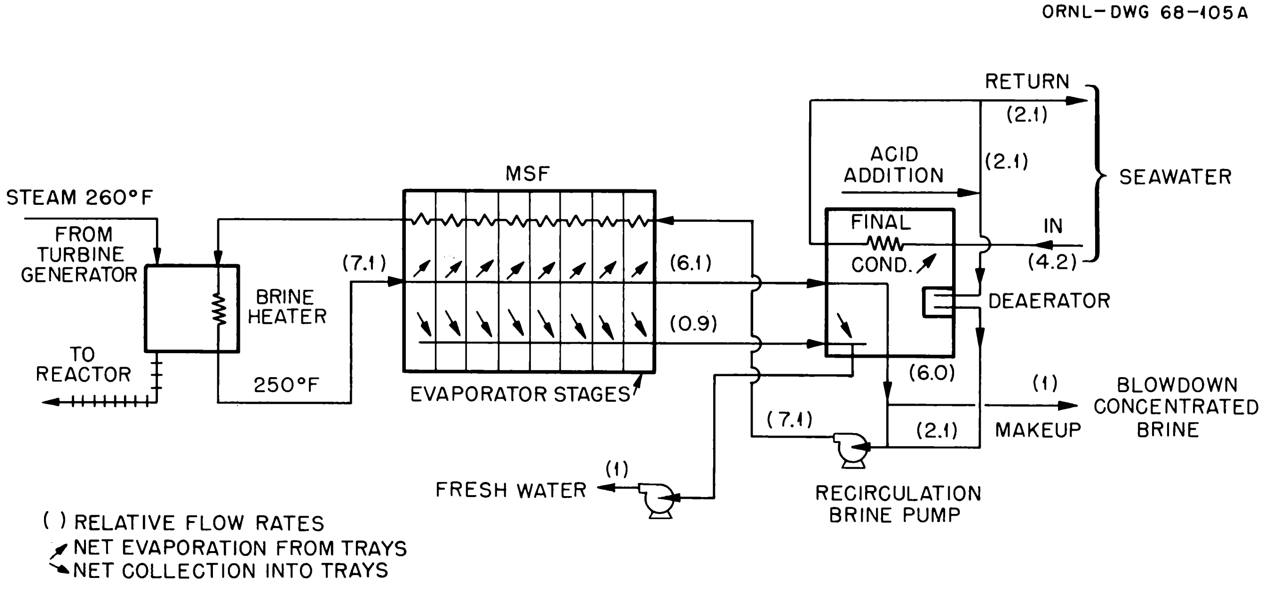

Fig. 4.6. Schematic Flow Diagram of MSF Evaporator.

A characteristic of the MSF design is that a large recycle flow of the brine is generally required to reduce the amount of seawater to be chemically treated, since the fraction of fresh water boiled off per pass through the evaporator is relatively small. In addition to the added pumping power required, the recycle flow causes a higher solids concentration (relative to a once-through system) in the brine which is in contact with the heating surface, so that careful attention must be given to the seawater chemical treatment method required to prevent scale formation.

The MSF design is currently in use in many parts of the world, including Cuba and Kuwait, and in the recent 2.5-Mgd (million gallons per day) plant at Key West, Florida. Current plans also call for its use in the 150-Mgd Metropolitan Water District plant at Los Angeles. This plant would make use of three evaporator trains of 50 Mgd each, with the first train scheduled for completion in the 1970's.

The primary extrapolation of MSF evaporator technology required for application in this study would be essentially one of size, since the maximum train size considered is 250 Mgd. The MSF evaporator technology has been adopted for the near-term application in this study, since it is felt that size extrapolations of this magnitude will be feasible by the late 1970's.

4.5.2 Vertical Tube Evaporator

The VTE design considered in this study[24] is based on a recently developed heat transfer surface, the double-fluted tube. This surface exhibits an improvement in overall heat transfer by a factor of 2 to 3 compared with smooth tubes. In this design, shown schematically in Fig. 4.7, about 75% of the input heat (steam from a nuclear power plant) is directed to the first vertical-tube effect. This steam condenses on the outside surface of the tubes, and the heat so given up causes the seawater flowing down the inside of the tubes to boil. This vapor then passes out of the tubes, through an entrainment separator, and is used as the heat source for the second vertical-tube effect, which is

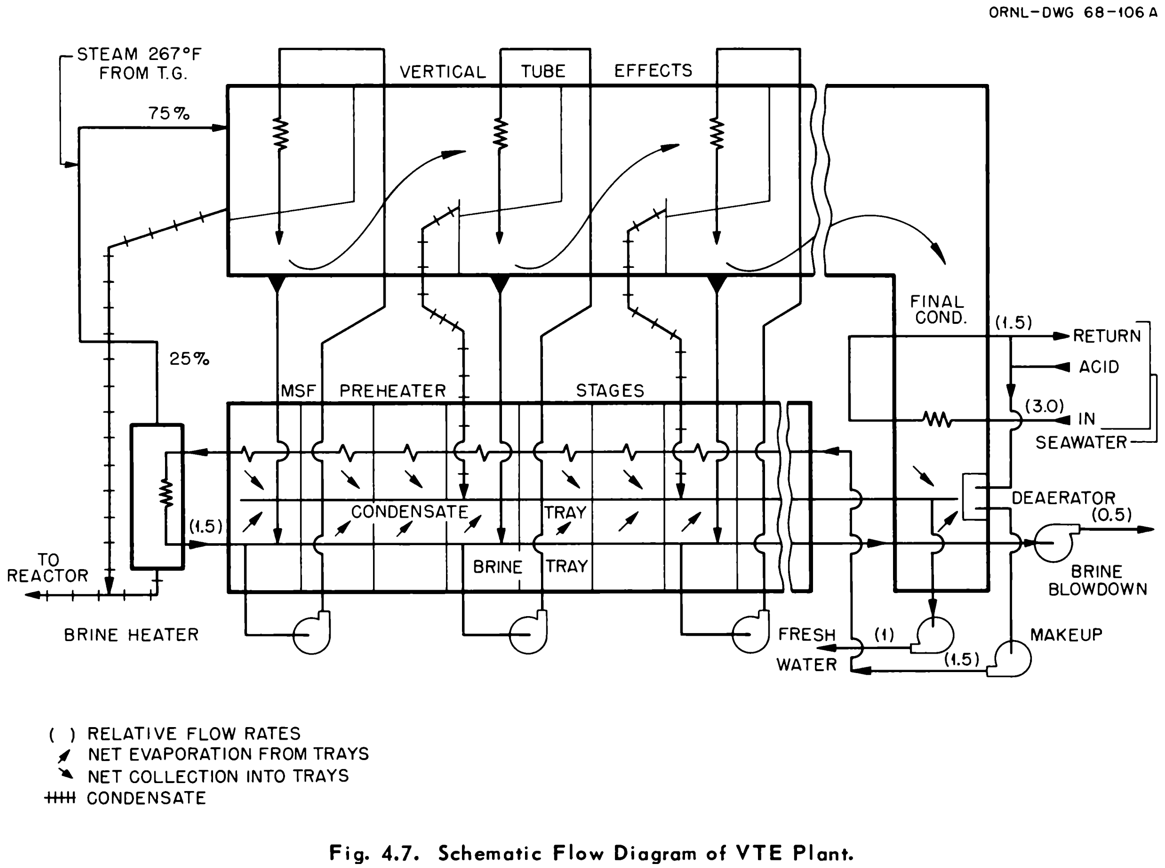

Fig. 4.7. Schematic Flow Diagram of VTE Plant.

at a lower pressure, so that the brine in this effect boils at the slightly lower temperature. The reject brine from each effect separates from the vapor and is returned to an appropriate stage of the MSF preheater section, described below. This process is repeated in 15 subsequent effects until a reasonable approach to the inlet seawater temperature is reached.

The remaining 25% of the input heat (steam from the reactor power plant) is used to provide the final stage of seawater preheating. The initial seawater preheating is carried out in an MSF evaporator integrally connected to, and operated in parallel with, the VTE. This MSF section produces about 20% of the product water.

The VTE design makes possible a once-through seawater flow circuit, thus eliminating brine recycling. This reduces the problem of scale formation and thus allows a higher maximum brine temperature and brine effluent concentration, as well as giving a lower pumping requirement (about one-half) than for the MSF design.

Vertical-tube evaporators using smooth tubes have been in operation for many years in the salt, paper, and chemical industries; the 1-Mgd seawater distillation plant built by the Office of Saline Water at Freeport, Texas, began operation in 1961. The particular combination of vertical-tube multieffect evaporators with fluted tubes and an MSF preheater as described is a relatively new concept, and the combination has not been demonstrated to date. Although the current experimental program, together with detailed design analyses, is quite encouraging, the concept has only been applied in the long-term applications of this study.

4.5.3 Auxiliary Facilities

Both types of evaporator plants require auxiliary facilities including (1) seawater intake and return, (2) seawater chemical treatment plant for scale control, (3) deaerator, and (4) product water treatment. The design concepts are assumed to be as presented in refs. 23 and 24. In addition to these facilities, evaporator brine and seawater pumping equipment is required. The amount of pumping power associated with the two evaporator concepts is given in Table 7A.1, Appendix 7A.

4.5.4 Design and Cost Parameters

The main variables which influence the evaporator design and cost and the values selected for the numerical comparisons in this study are as follows:

1. performance ratio, PR (pounds of water evaporated per 1000 Btu of input heat)–12 (reference value only; optimum value varies depending on other parameters);
2. maximum brine temperature – 250°F for MSF and 260°F for VTE;
3. seawater chemical treatment method – sulfuric acid or caustic/HCl;
4. brine effluent concentration ratio – 2.0 for MSF and 2.5 for VTE;
5. seawater temperature – 65°F;
6. train size – 50 to 250 Mgd; number – 2 to 5.

These parameters are discussed in Appendix 4A. Also given in the appendix are the major cost factors used, including evaporator capital costs, operation and maintenance costs, indirect capital charge factor, and interest during construction.

4.6 Designs of Dual-Purpose Plants and Resultant Water and Power Costs

With the commercially developed water-cooled nuclear reactors which provide steam at much higher temperatures (500–550°F) than can be utilized effectively in seawater evaporator plants, it is advantageous to first partially expand the steam through a turbine-generator (TG) unit for power production and then utilize the lower-temperature exhaust steam in the evaporator. This coupling gives lower costs for both power and water than would be obtained from separate plants for the production of either product. Although there are single-purpose water-only reactor concepts being developed which show promise of producing fresh water as cheaply as dual-purpose plants,[25,26]

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[25] R. P. Hammond *et al.*, *High Gain Breeders for Desalting or Power Using Unclad Metal Fuels*, ORNL-4202, to be published.

[26] T. D. Anderson *et al.*, "A Metallic Uranium Fueled PWR for Single-Purpose Desalting," *ANS/CNA Trans.* 11(1), 355 (1968); presented at the Annual Meeting, Toronto, Canada, June 10–13, 1968.

these were not considered in this study due to the preliminary nature of the work on low-temperature reactors.

4.6.1 Operating Modes

In the context of this report a dual-purpose plant consists of a nuclear reactor heat source providing steam which flows first through a back-pressure turbine-generator and then to a seawater evaporator plant. In some dual-purpose plant designs, part of the steam from the reactor may bypass the back-pressure turbine and enter the evaporator via a pressure-reducing valve.[27] In other designs, part of the steam from the reactor may be fed through a back-pressure turbine-generator to an evaporator, with the remainder fed through another turbine-generator to a condenser. There are other modes of operation possible which are essentially extensions or combinations of the above three modes, but these are not considered in this discussion. These operating modes are illustrated in Fig. 4.8, which shows, for a 500-Mgd water production rate and for certain design conditions, the reactor size required for plants with a net electrical output ranging from 500 to 2500 Mw. Steam bypass is required in parallel with a back-pressure turbine up to a power generation rate of 850 Mw, above which there is no bypass. A condensing turbine operating in parallel with the back-pressure turbine is added at 1000 Mw and increases in size from this point, proportionally, as the electricity production is increased.[28] In Fig. 4.8, the plant designs from 850 to 1000 Mw(electrical) are referred to as operating in the "back-pressure region." It may be noted that the optimum PR shown (computed by the ORNL ORCUP code)[27] is a constant 13.4 in the bypass region, drops to 11.6 in the back-pressure region, and then gradually decreases to 9.5 in the condensing turbine region. This figure then illustrates the flexibility available for selecting the amount of power which may be produced for a given size water plant; however, the best point of operation should be based on a detailed cost analysis but would normally be at the back-pressure condition.

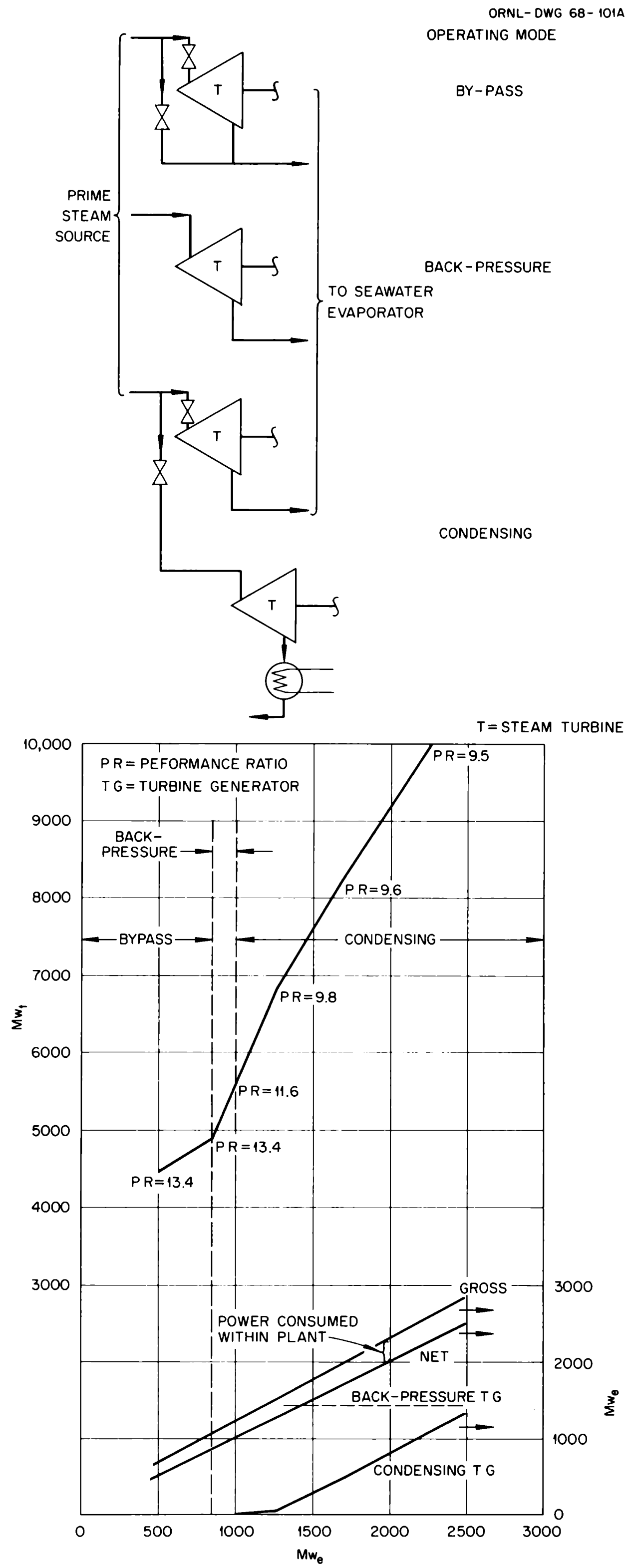

Fig. 4.8. Relationship Between Thermal and Electrical Megawatts for MSF Evaporator–LWR Dual-Purpose Plants Producing 500 Mgd.

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[27] O. M. Eissenberg and C. C. Burwell, *A Survey of Optimum Dual-Purpose Desalting Plants as a Function of Product Ratio Using Alternate Steam Supplies*, ORNL-TM-1659 (July 1967).

[28] In this example, the proportion of power produced by the condensing turbine is not significant except for plants designed with net electrical output over 1250 Mw.

4.6.2 Incremental Costs of Water and Power

For the case of incorporating a dual-purpose plant into a large agro-industrial complex, it would not usually be necessary to determine the actual unit costs for producing each of the two products, water and power. Arriving at such costs would involve an arbitrary allocation procedure for determining, for example, what fraction of the nuclear reactor capital and operating costs should be assigned to the water produced. Although this would be done for plants which sell these products, it was not required for this application, where the water and power are consumed within the complex.

To aid in the planning and design of a complex, it would be desirable to know the incremental costs for increasing (from some base) the quantity of water and power produced. Such information may be obtained by determining the total cost for building and operating dual-purpose plants of various sizes and relative amounts of water and power produced. In general, as the plant size becomes very large, the incremental unit cost approaches the average unit cost; and if the two products were sold at their incremental costs, the total production cost would be very nearly recovered. For the size of plants considered in this study the incremental costs for water and power are representative of their actual costs. These costs were developed for the two levels of technology: (1) near term[29] (~1977): light-water reactors (either pressurized water or boiling water) coupled with an MSF evaporator plant; and (2) far term (~1987): fast breeder reactor coupled with the VTE evaporator plant.

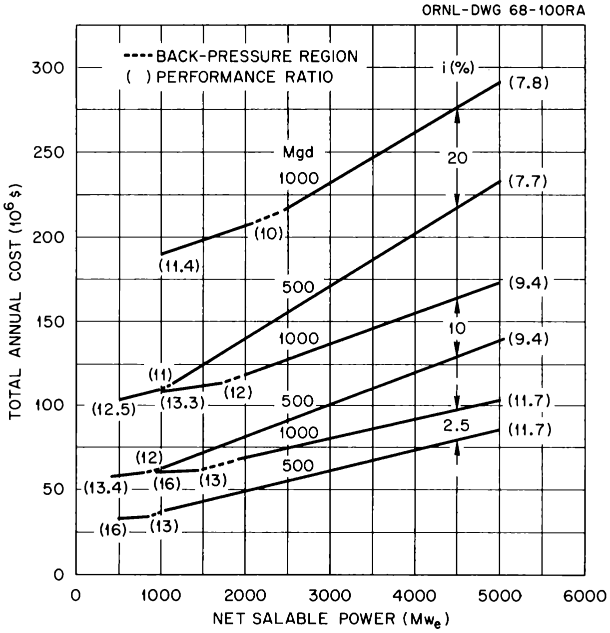

Fig. 4.9. Annual Cost of Operation for Dual-Purpose Plants Using an MSF Evaporator and a Light-Water Reactor.

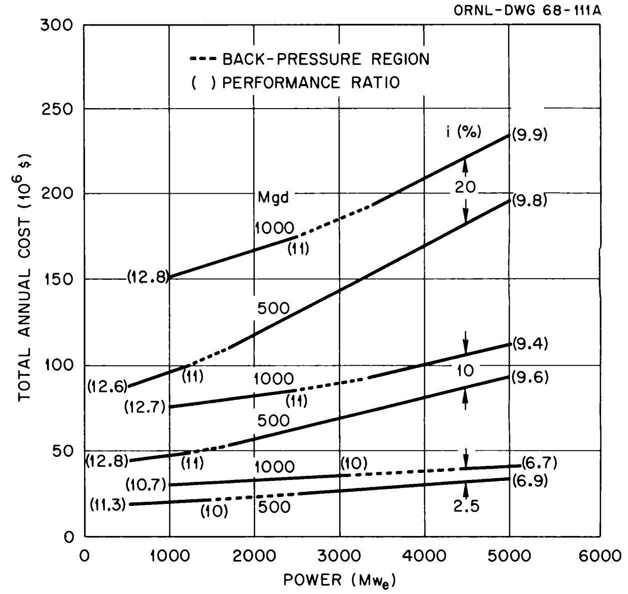

Fig. 4.10. Annual Cost of Operation for Dual-Purpose VTE-FBR.

The incremental costs may be computed from Figs. 4.9 and 4.10, which show for these two technologies the variation in total annual costs as a function of electricity and water production rates. The total annual costs include capital charges for return on investment, recovery of investment, and interest during construction, as well as the actual operating costs. The values for the amount of power shown on the horizontal axis represent power which is available for use outside of the plants; that is, power required within the water and power plants has been deducted. The incremental costs for power may be computed from the slopes of the lines shown in these figures and are given in Table 4.4. The corresponding numbers for the back-pressure region are omitted from the table, but they should be between the values for the other two regions. As indicated in this table, the range of incremental cost for power

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[29] The long construction period for a dual-purpose plant (~5 years) requires that a commitment be made by about 1972 for startup in 1977.

Table 4.4. Incremental Costs (mills/kwhr) for Power

Cost of Money (%)	Bypass Region		Condensing Region	
	MSF-LWR	VTE-FBR	MSF-LWR	VTE-FBR
2.5	0.8	0.3	1.6	0.4
10	1.2	1.0	2.4	1.5
20	1.9	2.0	3.8	3.3

is from 0.3 to 3.8 mills/kwhr. Although incremental water costs may be computed from these data for the bypass and condensing regions, it is of more interest to obtain a cost range for water in the back-pressure region as described below.

An approximate method for illustrating the range for the absolute cost of water as a function of technology and interest rate, two of the most important parameters, is shown in Fig. 4.11. An upper limit is obtained from the costs (capital and operating) of a single-purpose water-only plant using bypass throttling of the prime steam. Only sufficient electricity is generated to provide for the requirements of the evaporator and reactor plants. A lower limit may be obtained from the difference in total costs between a dual-purpose plant operating at the back-pressure point and a power-only plant producing the same amount of excess electricity as the dual-purpose plant.[30] The lower limit thus attributes all the mutual benefits of dual-purpose plants to the water production. While this technique indicates a maximum *range* of water costs of about 8¢ or 9¢/1000 gal, the usual allocated costs from a dual-purpose plant[31] would be expected to be only 1¢ or 2¢/1000 gal above the lower limit line.[32] Thus the range for the cost of water from 1000-Mgd plants, which would include the two technologies and costs of money from 2.5 to 20%, would be about 9¢ to 50¢/1000 gal.

Similar computations have been made for smaller-size plants to illustrate the effect of size scaling on the cost of water. At least down to 250-Mgd plants, the cost of water is not appreciably changed; at this size for the LWR-MSF dual-purpose plant the cost of water would increase by about 3.5¢/1000 gal (~15%) over the cost from a 1000-Mgd plant.

4.7 Method Adopted in Evaluation of Nuclear-Powered Complexes

Several simplifying approximations were adopted for use in the economic analyses of agro-industrial complexes based on dual-purpose nuclear power plants. These were that (1) one value, 12, would be used for the evaporator performance ratio and (2) operation would normally be at the back-pressure *point*; that is, all of the steam available from the back-pressure turbine would be utilized in the evaporator. It should be noted that a back-pressure *region* only exists if PR is optimized for each power level – for constant PR and a given water production rate the back-pressure condition is satisfied at only one power generation rate.

The optimum performance ratios shown in Figs. 4.9 and 4.10 indicate only a relatively small variation for the two technologies and the range of costs

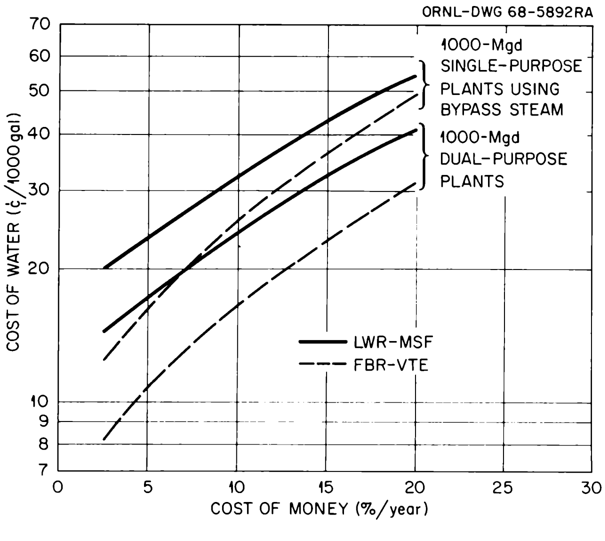

Fig. 4.11. Cost of Water from Single-Purpose (Steam Bypass) and Dual-Purpose Nuclear Desalting Plants Using Near-Term and Far-Term Technologies.

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[30] A simplifying assumption inherent in this illustration is that the evaporator performance ratio is fixed at 12; however, this was shown to be near the optimum value and has relatively little effect on the cost of water.

[31] C. C. Burwell and R. P. Hammond, *A Cost Allocation Procedure for Dual-Purpose Power-Desalting Plants*, ORNL-TM-1615; remarks prepared for the IAEA Panel on Costing Procedures for Nuclear Desalination, Vienna, Austria, Apr. 18–22, 1966.

[32] In practice it is doubtful if a water-only plant would be operated on bypass steam, since other plant concepts (e.g., vapor compression) would give lower water cost.

of money considered. A value of 12 was therefore selected for use in determining the cost of evaporators and the relative amounts of water and power produced. Since operation at the back-pressure point should give the lowest incremental costs of power and water, this operating mode was adopted generally throughout this study. Table 4.5 summarizes the parameters of dual-purpose plants for the various technologies considered and for operation at the back-pressure conditions.

Due to the time limitations of this study, it was not possible to arrive at an optimum plant size or an optimum water-to-power production ratio for any given complex considered because this involves a balance between incremental costs and incremental returns. The incremental return will depend on the use of the water and the power, that is, the value given to these products. In the concept of the agro-industrial complex, water and power are "intermediate products," and their use is well defined. The value of the water and power therefore depends on the value of the final agricultural and industrial products. Tentative values (sales prices) were assigned to these products, as discussed in Chaps. 5 and 6. No effort was made to determine a demand curve (price vs volume of sales) for each of the products, since such an investigation would require a detailed marketing study for the individual sites. Estimates of variation in returns (which depend on price) with output volume were left as a "missing link" in the generalized study but would certainly be an integral part of a detailed feasibility study.

The agro-industrial complex embodies, in part, a source-sink relationship; that is, the primary products will be consumed within the complex – water to a farm and/or to a city, and electricity to industry and/or a grid. As indicated in Table 4.5, however, size in itself can create some problems; for example, the MSBR operating in the back-pressure mode to produce 1000 Mgd of desalted water also produces about 4600 Mw of electricity, which would be difficult to consume in a developing country or, for a decade to come, in the United States. In this case it might be necessary to operate the evaporator partly with bypass steam.

In summary, estimates of incremental costs for water and power represent a basic step toward rational design of the size and character of the individual activities making up the complex and hence for the rational design of the complex as a whole. Once a design is formulated, its economic appraisal requires analysis of total rather than incremental values. This was carried out in the appraisal of industrial, agricultural, nuclear-industrial, and nuclear agro-industrial complexes, and the numerical results are included in Chap. 7.

Table 4.5. Dual-Purpose Plants Producing 1000 Mgd of Desalted Water

Technology	Steam Temperature (°F)		Turbine Cycle Efficiency (%)	Electrical Power to Evaporator (Mwe)[a]	Auxiliary Power for Reactor and TG (Mwe)	Salable Power (Mwe)
	To Turbine	To Evaporator				
LWR-MSF	540	260	21.4	345	142	1820
FBR-VTE	900	270	26.8	142	240	2724
MSBR-VTE	1000	270	37.4	142	286	4640

Technology	Required Reactor Power [Mw(thermal)]	Ratio of Water to Power, Mgd/ Mw(electrical)
LWR-MSF	10,780	0.55
FBR-VTE	11,590	0.37
MSBR-VTE	13,550	0.22

[a] Evaporator performance ratio constant and equal to 12.

5. INDUSTRIAL PROCESSES

5.1 Introduction

Electricity, steam, and water are basic to nearly all chemical manufacturing processes; therefore the opportunity to obtain these utilities at low cost should create exciting prospects for reducing the costs of manufacturing processes which make intensive use of them. The purpose of the industrial process study has been to determine which processes of interest are economically attractive with low-cost nuclear power and steam, and with low-cost water when the nuclear power plant has associated with it a desalination evaporator plant. A secondary aspect of the study has been to determine whether additional savings can be achieved by building and operating several different chemical and manufacturing plants at a single site where common-use facilities can be shared and intermediate or waste products from one process used by other processes.

5.2 Criteria for Process Selection

The criteria on which processes were selected for detailed study were based primarily on economic factors; however, much consideration was also given to the product needs and export potentials of developing nations.

- The first preference was given to processes in which a large fraction of the product cost is attributable to the cost of electrical power, steam, and/or water.
- Production of nitrogen and phosphorus fertilizers was also given high priority because of present and growing world food needs, particularly in the less industrially developed countries. Potassium fertilizers were also considered, but not as extensively as the other types.
- Similarly, the need for building materials such as iron and steel, aluminum, cement, and possibly plastics in developing nations and the need for basic chemicals such as caustic-chlorine and acetylene, which would be used by secondary industries throughout the country, were also considered.
- Products which can be produced from seawater were given special attention. In warm arid coastal regions, solar evaporation would probably be the main method used to further concentrate the brine from desalination-evaporator effluent, which is at least twice as concentrated as seawater. The main economic advantage here would be a significant saving in solar ponding costs over a similar operation that started with seawater. In the latter stages of bitterns evaporation, it might be more economic to use steam.
- Finally, the chemical needs of the desalting plant were considered, especially in connection with treating the seawater to prevent scaling of the evaporator heat transfer surfaces. Such treatment will be referred to throughout the report merely as seawater treatment.

5.3 Process Selections and Descriptions

Based on the above criteria the production costs for 17 chemical products were evaluated with the use of a digital computer. The first four production processes, those for making electrolytic hydrogen, electric furnace phosphorus, aluminum, and chlorine-caustic, are highly energy (electricity) intensive. The remaining 13 products either involve the production of the above products by alternative methods selected for economic comparison purposes or are secondary products; these are hydrogen from steam-naphtha reforming,[1] nitrogen by air liquefaction, ammonia, nitric acid, ammonium nitrate, urea, nitric phosphate, sulfuric acid, phosphoric acid by the acidulation of phosphate rock with sulfuric acid, alumina, salt, 50% caustic, and hydrochloric acid. A number of other products and processes were also studied, although less quantitatively and intensively. Included in this group are iron, steel, cement, magnesium, bromine, potassium chemicals, acetylene, and sulfuric acid from sources other than elemental sulfur.

In order to obtain a measure of the economic attractiveness of the processes being investigated for the different products, costs for highly energy-intensive processes were compared when possible with the costs for conventional nonelectrolytic methods, if available, of producing each product.

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[1] This method is more prevalent in non-U.S. locations, whereas steam-methane reforming is the process of choice in the U.S. The two reforming methods are compared in sect. 5.5.1.

These cost comparisons were done in detail, including parametric studies to indicate the most advantageous ways of reducing product costs. In other cases, where a competing process was not available, a geographic comparison was made on the basis of production in an area with cheap power but distant from the raw materials vs a location near the raw material source. An example of the application of the first evaluation method is the economic comparison of ammonia production using hydrogen from water electrolysis vs the conventional non-United States method of producing ammonia with hydrogen from steam-naphtha reforming. Another example is the production of phosphoric acid from elemental phosphorus produced in an electric furnace vs phosphoric acid production by the acidulation of phosphate rock with sulfuric acid. An example of the latter comparison is the production of aluminum from imported alumina with power at 2 mills/kwhr, such as is available in the northwest United States, vs production of both alumina and aluminum with power from an energy center located near a bauxite source.

5.3.1 Fertilizer Production

Detailed studies were made on the production of both fertilizer intermediates and a variety of conventional fertilizers. The fertilizer intermediates considered were hydrogen, from either the electrolysis of water or steam-naphtha reforming,[2] and nitrogen by air liquefaction, both for use in ammonia synthesis; nitric acid from the catalytic oxidation of ammonia; contact process sulfuric acid; electric furnace phosphorus by the reduction of phosphate rock with coke; and phosphoric acid from either the oxidation and hydrolysis of elemental phosphorus or the acidulation of phosphate rock with sulfuric acid. The conventional fertilizers studied include ammonia, ammonium nitrate obtained by the neutralization of nitric acid with ammonia, urea synthesized from ammonia and carbon dioxide, and nitric phosphate derived from the acidulation of phosphate rock with nitric acid. The production scheme for the above chemicals and fertilizers is shown in Fig. 5.1. The production of potassium chemicals and fertilizers is discussed in Section 5.3.3.

Hydrogen and Ammonia. — Ammonia is produced by the compression of a 3 to 1 mole ratio of hydrogen and nitrogen to about 2000 to 4000 psi, with the conversion occurring over a mixed-oxide catalyst. As noted above, several sources of hydrogen were considered. The base case involves the production of hydrogen (and oxygen) by the electrolysis of water in an advanced electrolytic cell developed on a laboratory scale by the Allis-Chalmers Company. The competitive process considered was the production of hydrogen by the widely used steam-naphtha reforming process. The use of naphtha, rather than methane, as a source of hydrogen in non-United States locations was considered because it is currently in excess in some developing countries or can be imported more economically than natural gas. An appreciable amount of hydrogen is produced in the electrolytic production of caustic and chlorine from brine; therefore, when this process was included in the industrial complex, this hydrogen was also assumed to be used in ammonia production, thereby reducing the water electrolysis requirements. In the case where HCl is used for seawater treatment, however, this source of hydrogen is not available. Other hydrogen sources considered were use of an advanced De Nora water electrolysis cell and use of an advanced high-temperature gas-phase electrolytic cell being developed by the General Electric Company. Partial oxidation of naphtha (or natural gas), shift reaction of steam and by-product carbon monoxide (from the electric furnace phosphorus process) to hydrogen and carbon dioxide, and production by the simultaneous oxidation and hydrolysis of phosphorus with steam were recognized as alternative hydrogen sources but were not studied.

Because of the emphasis in this report on the use of energy-intensive processes, particularly for water electrolysis to produce hydrogen (and oxygen), the principles of operation of the advanced De Nora and the experimental Allis-Chalmers and General Electric cells are briefly described below. It should be noted that none of these three cells is presently in commercial use and that present-day technology is limited to cells operating in the range of 100 to 200 amp/ft^2 and using power of 125 to 145 kwhr per thousand standard cubic feet of hydrogen ($\sim$9000 kwhr per ton of ammonia).

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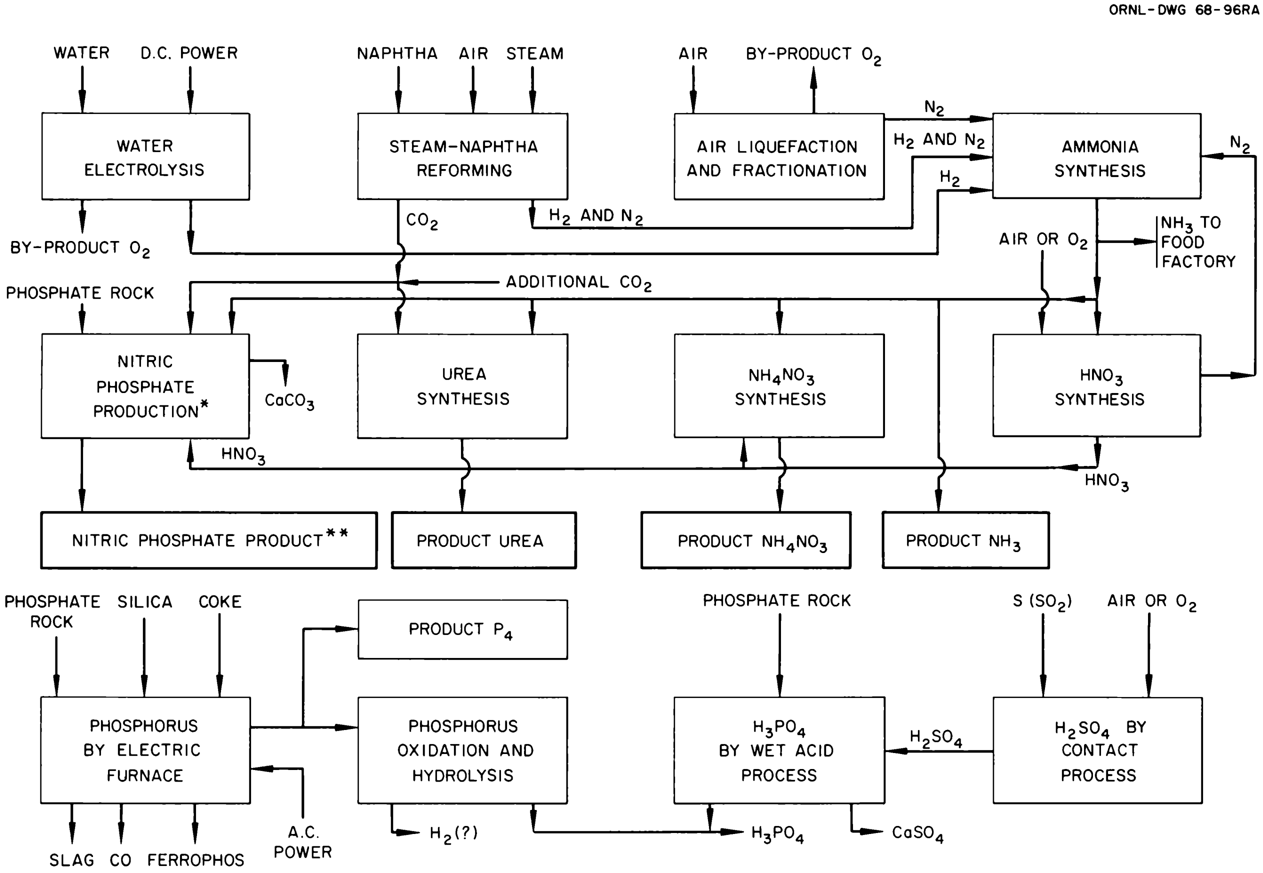
[2] Natural gas (methane) is the primary source in the U.S.; heavy stock from oil refineries and coal are being considered in India.



* NH_3 AND CO_2 ALSO REQUIRED BUT TOTALLY RECYCLED

** THIS PRODUCT HAS COMPOSITION 27-14-0 OR ALTERNATIVELY 23-23-0 PLUS NH_4NO_3 CO-PRODUCT

Fig. 5.1. Schematic Flowsheet for Production of Nitrogen and Phosphatic Fertilizer Intermediates and Finished Fertilizers.

The generation of hydrogen by water electrolysis is a relatively old process. However, recent concentrated research in the field of fuel cells has resulted in rapid strides in this area, and the resulting "spinoff" from this research has enhanced the economic position of hydrogen production by water electrolysis, which is the reverse of the fuel cell reaction. Our studies have incorporated three levels of technology in the field: an extension of present-day technology as represented by the De Nora cell, near-term technology represented by the Allis-Chalmers cell, and far-term technology represented by the General Electric high-temperature vapor-phase cell. Schematic diagrams of these three types of cells are shown in Figs. 5.2 to 5.4.

The De Nora cell (Fig. 5.2) operates at current densities up to 300 amp/ft^2 and at a temperature of 90°C. The products are generated at atmospheric pressure. This cell is restricted to lower current densities because formation and disengagement of product gas bubbles in the path of the current between the electrodes increases the internal resistance losses of the cell. The voids created by gas bubbles decrease the conductivity of the electrolyte. The manufacturer reports that he is ready to market this type of cell at the present time; however, none are presently in industrial use.

The Allis-Chalmers cell (Fig. 5.3) consists of two porous nickel electrodes separated by a thin asbestos membrane. The main advantage of this cell over the De Nora cell is the release of product gases from the back sides of the electrodes. Internal resistance losses are minimized, since the path of current through the electrolyte is not filled with voids. This permits operation at much higher current densities; 4000 amp/ft^2 has been achieved in laboratory studies. Cost optimization studies have indicated that 800 amp/ft^2 represents the most economic operating condition; this value is generally used throughout this study. The projected operating temperature of the cell is 120°C, and the product gases are generated at 300 psi. The cell has been operated in modules containing up to ten bipolar cells at a current density of 400 amp/ft^2 and temperatures up to 90°C. It requires further engineering development to verify the behavior of construction materials and to study the dynamics of full-size cell operation under the proposed operating conditions.

The General Electric vapor-phase electrolysis cell shown in Fig. 5.4 is a relatively new concept in water electrolysis. The cell is basically a solid-electrolyte cell which depends on the diffusion of oxygen ions through the solid electrolyte from the cathode to the anode at high temperatures – 1000 to 1100°C. Its main advantage is the lower reversible voltage (emf) required for electrolysis at these high temperatures. The solid electrolyte has a zirconia base and is doped with other oxides, such as yttria or ytterbia, which are conducting at high temperatures. The preferred composition at present is 8 to 10 mole % (13 to 14 wt %) yttrium oxide (Y_2O_3) in zirconium oxide (ZrO_2), although future cells may substitute ytterbium oxide (Yb_2O_3) for the Y_2O_3 because of improved conductivity. However, the Yb_2O_3 will probably be a more expensive raw material.

For electrodes the cell uses a nickel coating on the solid electrolyte as a cathode and a proprie-

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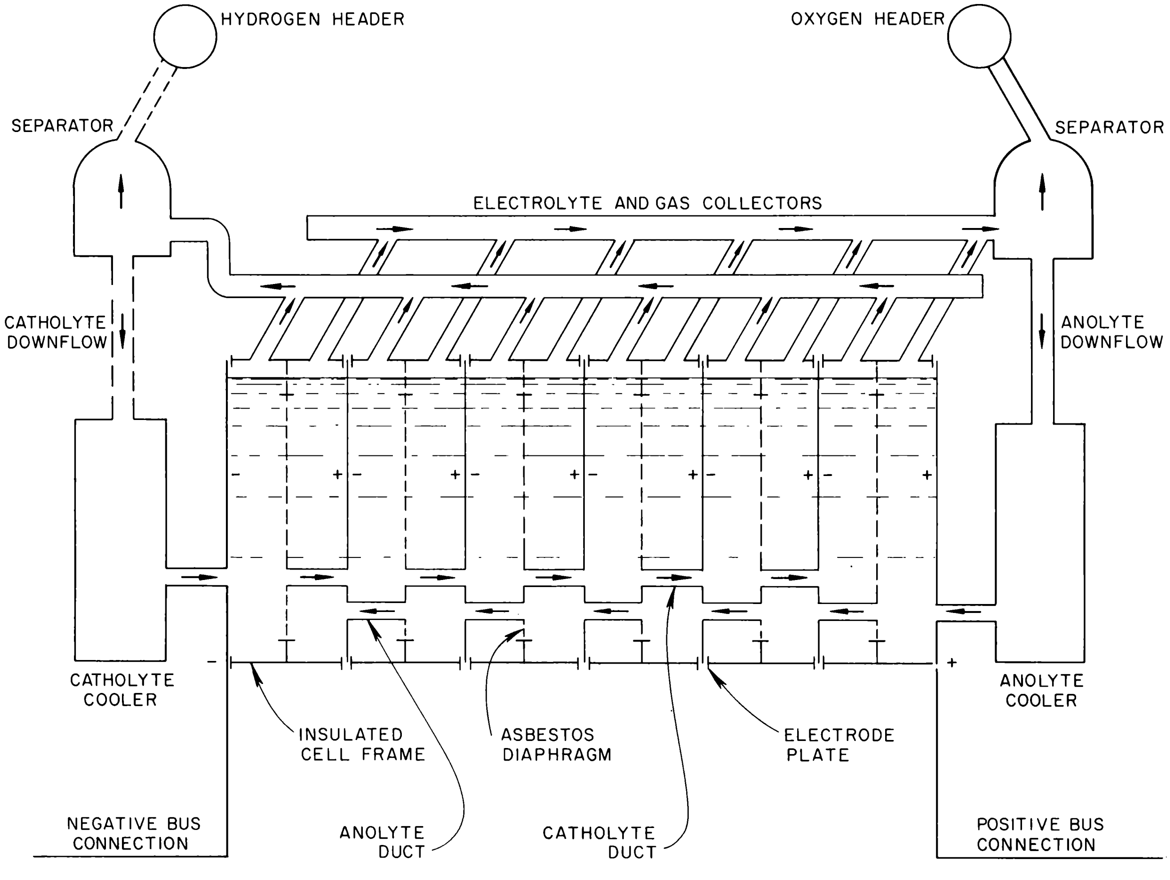

Fig. 5.2. Schematic Design of De Nora Bipolar Water Electrolysis Cell.

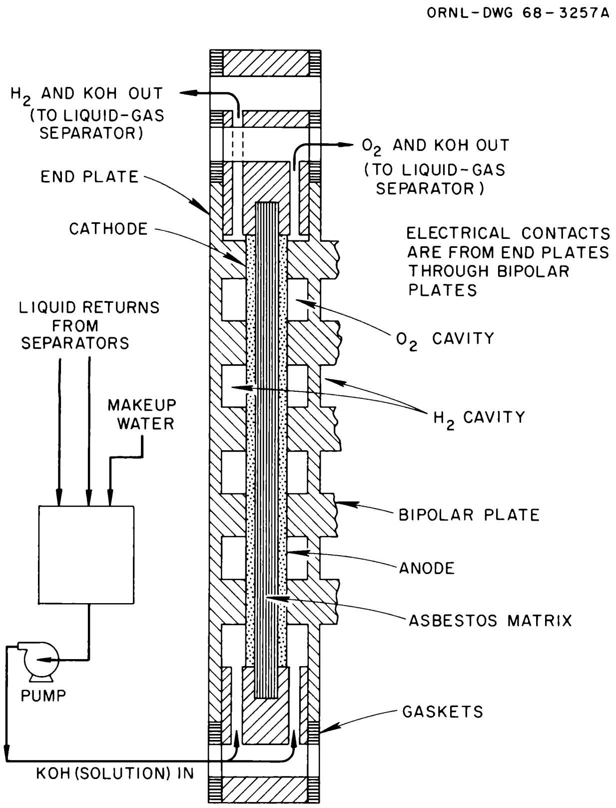

Fig. 5.3. Schematic Design of End Cell in Allis-Chalmers Bipolar Water Electrolysis Cell.

tary oxide coating as the anode. Reducing conditions must be maintained at all times on the cathode to prevent oxidation of the nickel coating. Therefore, in the electrolysis of H_2O, a small amount of hydrogen is introduced into the steam feed to maintain a reducing atmosphere. This requires that a small fraction (2%) of the cell product be recycled to the cell inlet, where it is mixed with the steam.

In operation, steam containing a small amount of recycle hydrogen ($H_2O/H_2 = 0.98/0.02$) is fed to the center tube at 100 to 500°C. It is heated by the gases flowing outside the center tube to somewhere near the operating temperature of 1000 to 1100°C. The steam flows into the outer tube, where it is electrolyzed, and leaves the tube as a mixture of hydrogen and steam ($H_2/H_2O = 0.98/0.02$). The steam must then be condensed and a small fraction of the hydrogen recycled to the feed.

The cell is in the very early stages of development, and only single cells have been operated in the laboratory. It has been operated at current densities up to 3500 amp/ft^2 and temperatures up to 1100°C. At this early stage, costs are highly speculative. Much laboratory research and development work is needed on the incorporation of individual cells into a modular design.

The primary nitrogen source for the production of ammonia using electrolytic hydrogen was air liquefaction and rectification, which also produces oxygen (partially or fully enriched) as a by-product. When hydrogen from steam-naphtha reforming was used, the nitrogen was obtained from the air added during the secondary reformer operations by cleaning up the reformer off-gases. When nitric acid is manufactured in the complex by burning ammonia in air, an alternative source of nitrogen is the nitric acid plant tail gas. The total nitrogen requirement for ammonia synthesis can be met by conversion of less than 10% of the produced ammonia to nitric acid. This alternative results in reduced capital costs of an ammonia plant using electrolytic hydrogen.

Ammonia-Based Fertilizers. – The ammonia produced can be sold directly or converted to secondary products in the complex. If the final fertilizers are to be used at an appreciable distance from the complex, transportation cost savings can be achieved by shipping the ammonia to outlying conversion plants, since ammonia contains 82% N.[3] The nitrogenous secondary products considered in this study were nitric acid, ammonium nitrate, and urea. Nitric acid is produced by oxidation of ammonia over a platinum catalyst followed by absorption of the nitrogen oxides in water. Ammonium nitrate is then produced by reacting the nitric acid with an equimolar amount of additional ammonia. Urea is manufactured by reacting ammonia and carbon dioxide under a pressure of about 3500 psig to produce ammonium carbamate, which is dehydrated to produce urea, $(NH_2)_2CO$. The ammonium nitrate and urea are both produced, initially, as aqueous solutions, which are then evaporated, prilled, mixed with a small amount of inert material, and distributed as bulk or bagged solid fertilizers.

The carbon dioxide for urea synthesis can be obtained from seawater treatment with sulfuric or hydrochloric acid or by the calcination of limestone, seashells, or the calcium carbonate pre-

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[3] Plans for transporting ammonia by pipeline in the central U.S. are now being implemented.

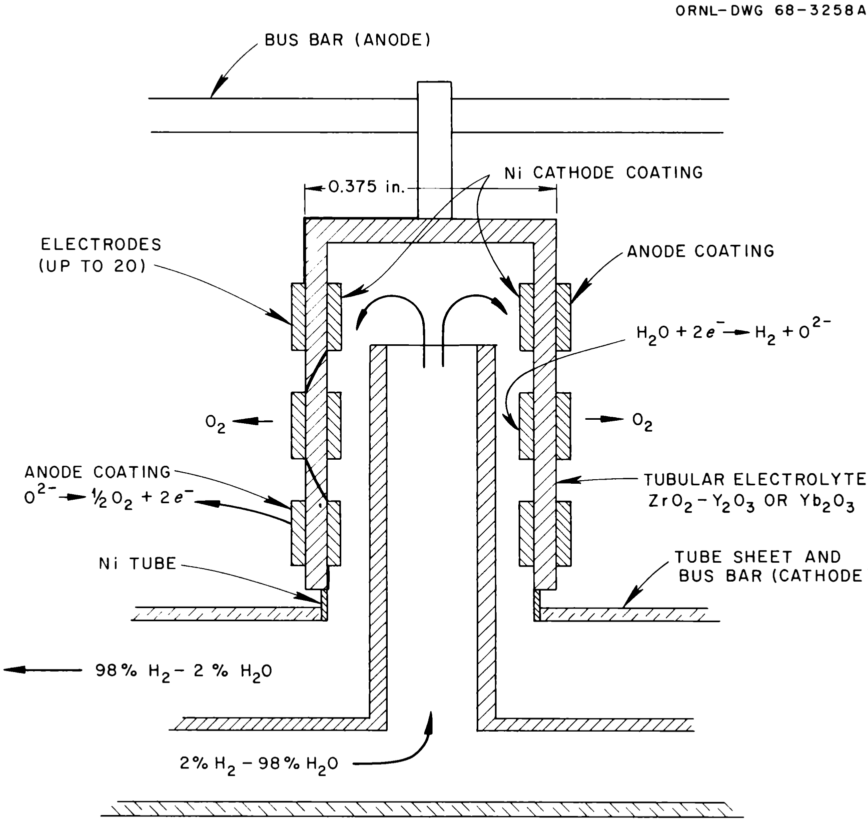

Fig. 5.4. Schematic Design of a Single Tube in Proposed General Electric Steam-Hydrogen Electrolysis Cell.

cipitated from seawater with caustic soda. Other sources include the aluminum smelting plant off-gases, which contain 70% CO_2, the shift conversion of steam and carbon monoxide (from the electric furnace phosphorus off-gases) to hydrogen and carbon dioxide, and the combustion of any carbonaceous material.

Phosphorus and Phosphatic Fertilizers. – Three methods for processing phosphate rock to produce fertilizers or fertilizer raw materials were studied. The first was the production of elemental phosphorus in an electric furnace. In this process the phosphate rock used may range from 23 to 25% P_2O_5. When the ore must be transported some distance, grades of 30 to 35% P_2O_5 are used. The ore is agglomerated by compaction, briquetting, or pelletizing and is then calcined or sintered. Silica for fluxing high-grade ore is supplied as sized silica gravel or rock from local sources. When the plant is located at the mine, siliceous phosphate matrix or tailing may be used by agglomerating it with the ore. The fuel for the kiln is supplied by using a portion of the carbon monoxide off-gas from the electric furnace. Next the agglomerated, calcined rock is mixed with dry coke and lump silica rock and is fed continuously to an electric furnace which is powered with 1000-v ac and uses baked carbon electrodes. In the furnace the phosphorus in the phosphate rock is reduced to elemental phosphorus, which is volatile at the furnace temperature. It then passes overhead with the carbon monoxide off-gas, from which it is condensed to liquid phosphorus in a spray condenser. Large amounts (>10 tons per ton of P_4) of calcium silicate slag and small amounts (~150 lb per ton of P_4) of ferrophosphorus are also produced as by-products in the furnace and are tapped off several times a day.

The elemental phosphorus can be shipped to off-site fertilizer plants or converted in the complex to phosphoric acid, phosphatic fertilizers, or mixed nitrogen-phosphate fertilizers. However, transportation of the product to the point of use as elemental phosphorus is highly attractive since it is equivalent to 229% P_2O_5 and can be shipped in mild-steel tank cars. One ton of phosphorus is equivalent in phosphorus content to 5 tons of triple superphosphate or 7 tons of high-grade phosphate rock. Conversion to phosphoric acid requires oxidation of the phosphorus with air or oxygen and hydrolysis of the resulting phosphorus pentoxide with water. Alternatively, oxidation and hydrolysis can be done concurrently with steam to produce hydrogen as a by-product.

The second method studied was the widely used wet acid process, based on the acidulation of phosphate rock with sulfuric acid, which produces phosphoric acid directly. The sulfuric acid was produced from sulfur dioxide, obtained by burning sulfur, by the contact process. In the wet acid process, high-grade phosphate rock is reacted with concentrated sulfuric acid to solubilize the phosphate content, which is recovered in the filtrate as phosphoric acid. The residual precipitate, a mixture of calcium sulfate and silica, is discarded.

The third method involves the acidulation of phosphate rock with nitric acid (followed by ammoniation and precipitation of calcium with carbon dioxide) to produce nitric phosphate fertilizer with a nominal composition of 27-14-0 (ref.4). Alternatively, the products from this process can be nitric phosphate with a composition of 23-23-0 and ammonium nitrate, in a ratio of approximately 3 to 2. In either case calcium carbonate is a by-product which can be calcined to produce nearly all the carbon dioxide required in the process. The nitric phosphate can be distributed either as bulk or bagged product.

5.3.2 Metals Production

Three studies on the production of metals (aluminum, iron and steel, and magnesium) were made. Aluminum was studied intensively; less thorough studies were made for iron and steel and for magnesium. The iron and steel study[5] was limited by the fact that although a number of alternatives to the conventional (blast furnace, coke oven, and basic oxygen furnace) steelmaking system have been tested, insufficient economic data are presently available on many of the alternatives to make complete comparisons. A rather complete survey of seven alternatives was made; however, the economic parts of the studies were limited to a comparison of approximate capital costs and electrode, fuel, and electricity costs. Production of magnesium was also studied quite extensively, and cost data have been accumulated. Unfortunately, receipt of these data was too late to permit the writing of a computer cost code and the evaluation of the various cost parameters. A schematic flowsheet for metals production is given in Fig. 5.5. In this flowsheet the starting material for magnesium production is anhydrous magnesium chloride, production of which is discussed in Sect. 5.3.3. The circled numbers on the iron and steel portion of the flowsheet indicate the route of the alternative systems.

Aluminum. – Production of alumina and aluminum was assumed to be by the Bayer and Hall processes, respectively, both of which are used, with minor variations, almost universally. A number of alternative processes are now under development by various aluminum companies, but none is yet in industrial use. It was further assumed that low-cost nuclear power would make competition from nonelectrolytic processes now under development less immediate.

In the Bayer process, bauxite is ground and reacted with aqueous caustic soda at elevated temperatures (~175°C) and pressures (~100 psig) to produce soluble sodium aluminate, which is filtered off. The solid waste, called "red mud," contains a mixture of iron, titanium, and silicon oxides plus small amounts of alumina and caustic soda. The alumina is precipitated from the sodium aluminate filtrate by seeding the cooled solution with fine alumina crystals and, occasionally, by sparging the solution with carbon dioxide. The precipitated alumina is recovered by filtration and washing and is finally calcined at 2000°F to remove combined water. The dry alumina is then fed to the Hall aluminum refining process, where it is dissolved in molten synthetic cryolite at 1000°F and electrolytically reduced to aluminum metal. The off-gas from the reduction cells is predominantly carbon dioxide, which may be useful in urea synthesis. As is customary in most aluminum plants, the plant also includes an anode manufacturing facility where the carbon anodes are

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[4] Standard designation for fertilizers, in which 27-14-0 means the above fertilizer contains 27% N, 14% P_2O_5, and 0% K_2O.

[5] Study prepared by A. M. Squires; complete report contained in ORNL-4294, part I (to be published).

made from petroleum coke, pitch, and anthracite coal. About ½ ton of anode is required to produce 1 ton of aluminum. The molten aluminum is finally tapped off several times a day and either cast into ingots or fed to an adjacent aluminum fabrication plant.

Iron and Steel. – Compared with the aluminum production method described above, iron and steel production systems are very complex and require a selection among a number of alternatives. This will be particularly true for developing countries, where the steel-producing capacity requirement is likely to be below the level at which blast furnaces and coke ovens are economic – a capacity in the order of several million tons of steel a year.

In our study, six "routes" to steel were compared with an advanced blast furnace technology. The routes are shown in Fig. 5.5 by the circled numbers. It was assumed first that in the blast furnace base case the new advances in blast furnace technology, made over the past ten years, will be carried to their logical maximum advantages and that some incipient innovations, such as the use of 27% oxygen rather than air as blast, will be fully implemented. Conversion to steel for the base system was assumed to be achieved by the use of existing or improved Linz-Donawitz (LD) basic oxygen furnaces, which are rapidly supplanting the open-hearth furnace both in the United States and overseas.

The various alternatives were divided into near-term, intermediate-term, and far-term systems for both iron and steel production. These probably represent general industrial acceptance in 10, 15, and 20 years respectively.

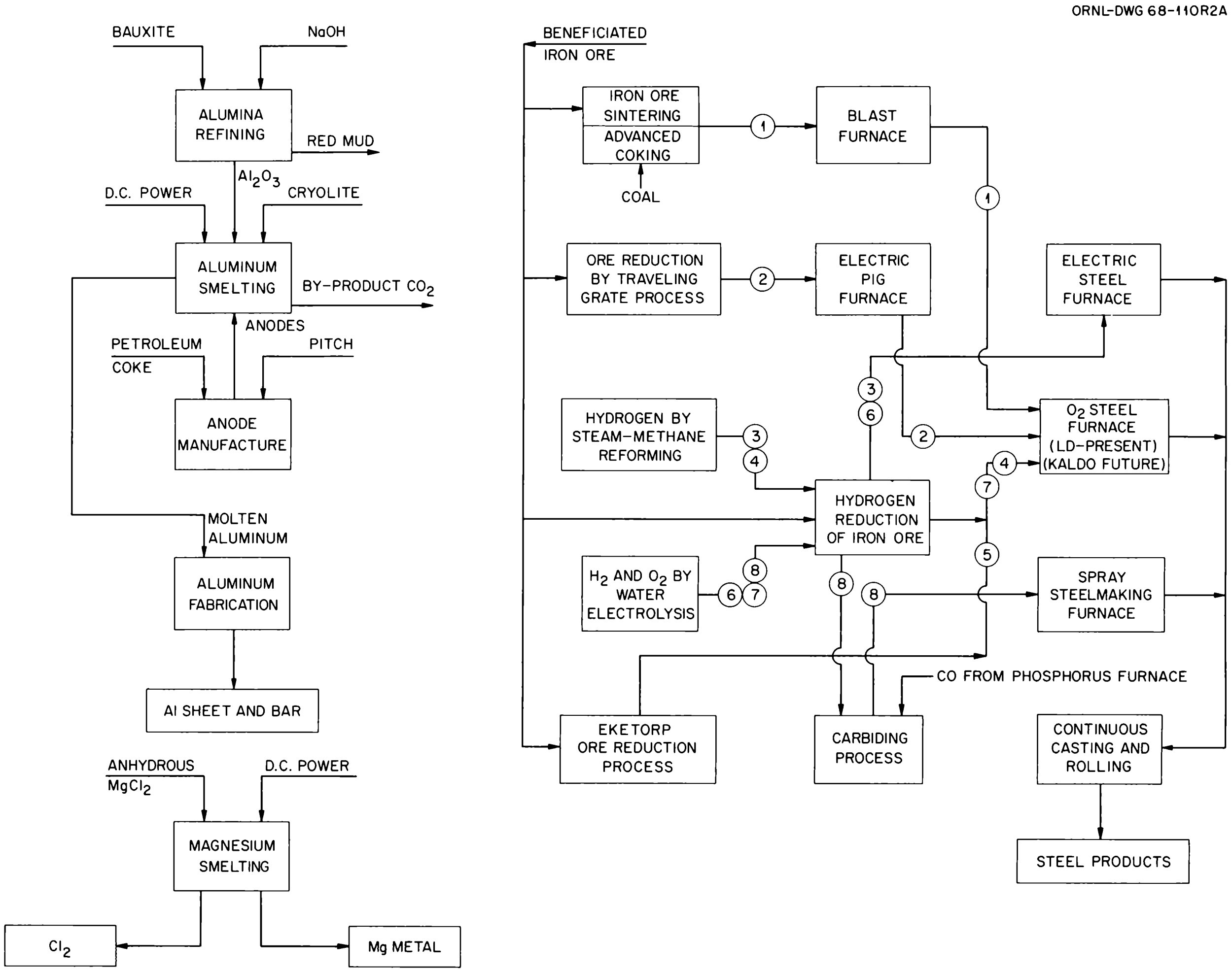

Fig. 5.5. Schematic Flowsheet for the Production of Aluminum, Magnesium, and Iron and Steel.

The near-term pig-iron production method was based on the use of a traveling-grate prereduction furnace developed at Battelle Memorial Institute[6] followed by an electric pig furnace. Both methods are now in limited use. The traveling-grate system was chosen over the various prereduction kiln methods because kiln-type operations provide poor heat and mass transfer.

The intermediate-term iron-making method chosen for study was the gaseous reduction processes[7] for iron ores in which the ore is reduced to powdered iron with hydrogen in a fluidized bed. These processes have been fully pilot planted and have been used on a small industrial scale by the Bethlehem Steel Company and by United States Steel Corporation. Production of hydrogen by both steam-methane reforming and water electrolysis was studied; the latter method has the advantage of simultaneously producing oxygen for subsequent use in steelmaking. An intermediate-term alternative to the hydrogen-reduction process, which was considered, was to only partially reduce the iron ore with hydrogen in a fluidized bed and to convert this product to a pig-iron powder by carbiding with carbon monoxide from the phosphorus-producing electric furnace.

As an example of a far-term iron-making system, the Eketorp furnace, now being pilot planted, was evaluated. In this process, ore is admitted to a spinning disk at the top of a furnace, drops as a curtain through a high-temperature reducing atmosphere, where it is reduced to metal, and falls into a pool of pig iron being sparged with fuel oil to produce the reducing gas stream above the pool.

The near-term steelmaking systems considered were an advanced version of the widely used LD oxygen furnace mentioned above and, alternatively, an advanced-type electric steel furnace. The intermediate-term method considered was use of an advanced Kaldo oxygen furnace which is presently in industrial use on a limited scale. The far-term system employed a spray steelmaking furnace presently being pilot planted in Great Britain by the British Iron and Steel Research Association (BISRA). In this process, molten pig iron is run through water-cooled nozzles in the top of a furnace where it is atomized with oxygen and converted to steel in a few milliseconds.

The six alternative overall iron and steel systems shown in Fig. 5.5 are various combinations of the iron- and steelmaking methods enumerated above. Since it was assumed that the steel produced by all the above processes would have about the same composition, only a single advanced method was considered for converting the molten steel to usable products. The method studied employed continuous casting and advanced rolling-mill practices. Providing a rolling mill with one or more continuous casting furnaces reduces the size and cost of the rolling mill by 50 to 65%.

Magnesium. – Magnesium metal and chlorine are produced by the fused-salt electrolysis of anhydrous magnesium chloride (see Sect. 5.3.3) at about 1400°F. With 92% pure $MgCl_2$, 4.4 tons of this salt is required to produce 1 ton of magnesium metal and 2.7 tons of chlorine. The cell feed should contain a minimum of sulfate (<0.05%) and boron (<0.002%) because these impurities are detrimental to electrolysis. On the other hand, diluent salts such as NaCl, $CaCl_2$, and KCl in approximately equal proportions are permissible up to a total of 8 to 10% of the cell feed composition. The cell bath should contain 5 to 25% $MgCl_2$, with the balance comprised of the above diluent salts, to achieve a high density. The electrical power requirement is 17,000 kwhr per ton of produced magnesium metal. The economics of magnesium metal production are reviewed, along with the costs of the recovery of chemicals from solar salt bitterns, in Appendix 5A.

5.3.3 Production of Chemicals from Seawater

The third general group of industrial chemical processes studied were those which would be associated with a seawater evaporation plant. These include:

1. seawater treatment with hydrochloric acid, caustic soda, or both to prevent scale formation on the evaporator heat transfer surfaces;
2. salt production by solar evaporation of the concentrated seawater evaporator effluent;
3. caustic and chlorine production by brine electrolysis for seawater treatment or sale;
4. processing of the bitterns from the solar salt works to recover magnesium chloride, magnesia,

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[6] McWane Cast Iron Pipe Co. is now building a traveling-grate prereduction plant at Mobile, Ala.

[7] The H-iron process, developed by Hydrocarbon Research, Inc., and Bethlehem Steel Co., and the Nu Iron process, developed by United States Steel Corp.

lime, gypsum, potassium chemicals, bromine, and sulfates, and possibly the production of cement and sulfuric acid.

This four-part system is shown in Fig. 5.6. In this study it was assumed that only part of the produced salt is used for caustic-chlorine production and that the remainder is sold. Although solar evaporation of the bitterns is shown, we believe that additional studies may show that evaporation using low-cost steam from the nuclear station may be more economical. Part or all of this system would very likely be included in any arid seaside complex which produced an appreciable amount of fresh water. Use of equimolar amounts of NaOH and HCl for seawater treatment appears less expensive than other methods, including the conventional H_2SO_4 method. When HCl or NaOH treatment alone is employed, the cost advantage is less obvious when the by-product caustic or chlorine has no market; however, if markets do exist, use of the latter methods can be even cheaper than the equimolar method. for example, in a non-United States complex, seawater treatment would employ HCl, and the by-product caustic, the product in demand, would be sold (see Fig. 5A.1, Appendix 5A).

Significant savings in solar ponding costs can be realized by further concentration of evaporator concentrate rather than starting with raw seawater. For an inland industrial complex the entire system would probably be omitted, with the possible exception of brine electrolysis using imported salt. The largest system considered involved solar evaporation of the equivalent of about 150 Mgd (million gallons per day) of raw seawater, which is about 6 to 10% (depending on the evaporator concentration ratio) of the effluent of the largest evaporators studied (1200 Mgd of fresh water); the capacity of this system is 5,000,000 tons of salt per year.

Solar salt and caustic-chlorine production will be discussed briefly below; use of hydrochloric acid and/or caustic soda seawater treatment and the recovery of chemicals from the solar salt works bitterns are also outlined below and are discussed in greater detail in Appendix 5A.

Solar Evaporation of Salt. – At an evaporator concentration ratio of 2, a seawater evaporator which produces 1000 Mgd of fresh water will reject a concentrated brine containing about 6% salt (NaCl) in the amount of 250,000 tons of salt per day or 85,000,000 tons/year. Therefore, where a market exists for salt (and/or for caustic-chlorine and seawater chemicals), it appears advisable to process part of this reject stream to recover the desired products, particularly since large savings in land and land improvement costs, which are an appreciable part of the salt production costs, can be achieved. For example, use of the concentrated brine in a 1,000,000-ton/year salt works reduces the land requirement from 40,000 to 24,000 acres, a saving of about 60%.

In ordinary solar salt production, raw seawater is passed through about ten successively smaller ponds, arranged in series, where the salt concentration is slowly built up to the saturation point. The saturated salt solution then flows or is pumped into crystallizing ponds, where approximately 75% of the salt is allowed to crystallize out along with a few percent of the $CaSO_4$ (1% $CaSO_4$ in the final salt). The crystallized salt is harvested, washed, dried, and stored for sale and/or for use in caustic-chlorine production. The bitterns, containing potassium, calcium, magnesium, sulfate, bromide, and other ions and about 25% of the original salt, are then drained off and either discarded or processed further for recovery of one or more of the above chemicals.

When the evaporator effluent is twice the raw seawater concentration, the first pond is eliminated; when it is three or four times the raw seawater concentration, one or two additional ponds may be eliminated respectively. About 11×10^9 gal of seawater is required to produce 1,000,000 tons of salt annually by solar evaporation. This amounts to less than 2% of the seawater fed to a nuclear desalination plant that produces 1000 Mgd of fresh water and concentrates seawater by a factor of 2.

Caustic and Chlorine Production. – In the manufacture of caustic and chlorine, salt is dissolved in fresh water to obtain a saturated brine, which is electrolyzed in a diaphragm cell to produce chlorine, hydrogen, and a caustic soda solution containing an equimolar amount of unelectrolyzed salt. The caustic-salt solution is evaporated to 50% NaOH for sale; during evaporation the salt is quantitatively precipitated, removed by filtration, and recycled to electrolysis.

Seawater Treatment. – Seawater treatment prior to fresh water production by evaporation includes (1) the removal of bicarbonate from the seawater

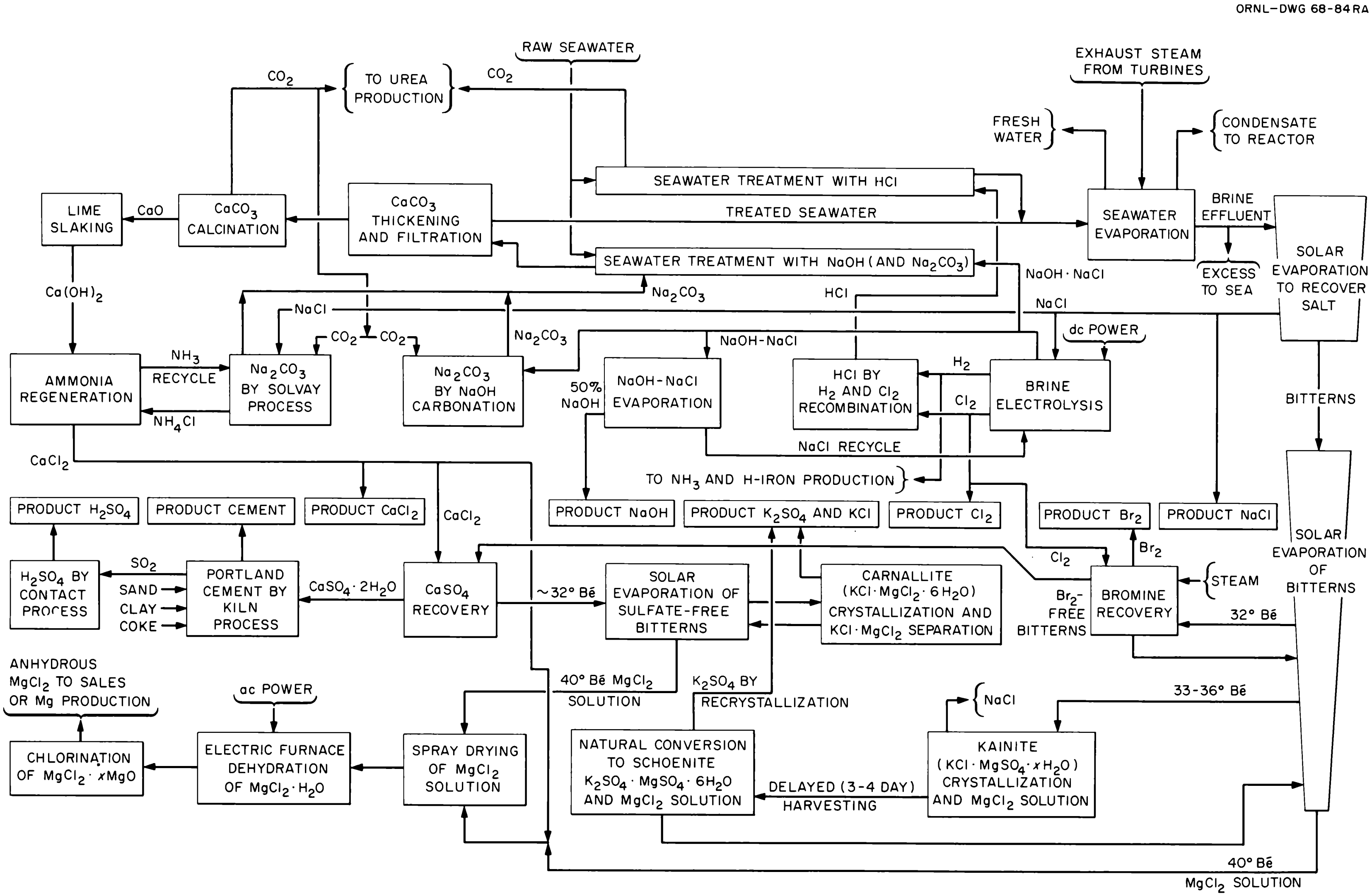

Fig. 5.6. Schematic Process Flowsheet for (1) HCl/NaOH Seawater Treatment, (2) Solar Salt Production, (3) Caustic-Chlorine Production, and (4) Recovery of Chemicals from Bitterns.

to prevent the formation of alkaline scale [$CaCO_3$, $Mg(OH)_2$] at evaporator temperatures of 170 to 180°F and (2) partial to complete removal of calcium to prevent the precipitation of calcium sulfate as anhydrite ($CaSO_4$) if evaporator temperatures of 260°F and above are desired.

At present the standard seawater treatment method involves the addition of sulfuric acid to completely remove the bicarbonate ion as carbon dioxide gas. Three newer methods have been proposed. The one recommended in this study is the use of hydrochloric acid and/or caustic soda; the former removes the bicarbonate ion alone without the addition of sulfate ion, whereas the latter removes all the bicarbonate and 23% of the calcium in the seawater. Use of equimolar amounts of hydrochloric acid and caustic results in minimum cost treatment for most conditions. The second method involves the use of the CO_2 suppression system, being developed at ORNL and elsewhere, and the third uses the lime-magnesium-carbonate (LMC) process developed by the W. R. Grace Chemical Company. The CO_2 suppression system removes all the CO_2 and up to 10% of the calcium; the LMC process removes all the CO_2 and about 70% of the calcium. Costs of these four methods are discussed and compared in detail in Appendix 5A.

With the HCl-NaOH seawater treatment method the hydrochloric acid is produced by recombination of hydrogen and chlorine from brine electrolysis. The caustic soda is added to the seawater as spent cell electrolyte containing equimolar concentrations of caustic soda and unelectrolyzed salt. The use of equimolar amounts of HCl and NaOH in seawater treatment consumes the total output of a caustic-chlorine plant (unless excess is made for sale). When more than 23% of the calcium in seawater must be removed, to attain evaporator temperatures above 295°F, caustic soda treatment must be augmented by the addition of soda ash (Na_2CO_3) produced either by the carbonation of caustic soda or by the Solvay process, which uses salt and ammonia (if it is not recycled) as its raw materials.

One further advantage of the HCl-NaOH seawater treatment system is that it permits a wide range in the amount of product caustic or chlorine available for sale. In the United States, where chlorine is the product in demand, seawater would be treated with caustic soda, whereas in most developing countries, where caustic soda is the more valuable product, hydrochloric acid treatment would be employed. A wide range of combinations of sales requirements can also be met.

Recovery of Chemicals from Solar Salt Bitterns. — The bitterns from a solar salt works constitute a rich source of potassium chloride or sulfate, magnesium chloride, and gypsum ($CaSO_4$). The magnesium chloride is the raw material for magnesium metal production, and the gypsum is a potential source of sulfuric acid and portland cement. Although the potassium salts are used in smaller quantities than nitrogenous and phosphatic fertilizers, they are nevertheless an important ingredient in modern-day agricultural practices. A full discussion of the methods used in the recovery of these products is given in Appendix 5A.

In order to provide an idea of the amounts of these products which are recoverable, the estimated daily recoveries of all products from a solar salt works with a capacity of 1,000,000 tons of salt per year are given in Table 5.1. Annual recoveries commensurate with solar salt works having capacities of 1,000,000, 2,000,000, and 4,000,000 tons of salt per year are also shown in the table.

5.3.4 Plastics Production

The last group of products considered for study was plastics, which are valuable in a developing country as building materials and as raw materials for secondary industries. It was originally intended that the production of a number of plastics be studied, but because of time limitations, efforts in this area were limited to a consideration of the production of some raw materials used in the plastics industry, namely, acetylene and ethylene produced from naphtha by the Hüls arc process or by partial oxidation.[8]

Acetylene has been conventionally produced by the action of water on calcium carbide produced in electric furnaces from limestone and coke. More recently, large-scale production from petroleum raw materials by partial oxidation with oxygen and by direct thermal pyrolysis has provided

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[8] This study made by W. E. Lobo, Consulting Chemical Engineer. Complete report contained in ORNL-4294, part II (to be published).

Table 5.1. Production Capacities for Salt and Bittern Chemicals

Product	Daily Capacity[a] (tons)	Annual Capacity (tons) for Pond Area[b] of —		
		24,000 Acres	48,000 Acres	96,000 Acres
Salt (NaCl)	3030	1,000,000[c]	2,000,000	4,000,000
Bromine	9	3,000	6,000	12,000
From Sulfate-Containing Bitterns Process				
Potassium sulfate	80	24,000	48,000	96,000
Magnesium				
As $MgCl_2$	169	51,000	102,000	204,000
As Mg metal	42	12,500	25,000	50,000
From Sulfate-Free Bitterns Process				
Portland cement	1400–1570[d]	460,000–520,000[d]	920,000–1,040,000[d]	1,840,000–2,080,000[d]
Sulfuric acid	260–300	85,000–100,000	170,000–200,000	340,000–400,000
Potassium chloride	82	27,000	54,000	108,000
Magnesium				
As $MgCl_2$	390	128,000	256,000	512,000
As Mg metal	94	31,000	62,000	124,000

[a] For annual salt production rate of 1,000,000 tons.

[b] At 2:1 concentration ratio.

[c] At 75% recovery, 1,000,000 tons of salt per year requires the evaporation of 1.1×10^{10} gal of raw seawater.

[d] Capacity in barrels of cement.

the raw material for petrochemical processes using acetylene as a base. When naphtha or heavier hydrocarbon fractions are used as the raw material, acetylene production is accompanied by the production of considerable amounts of ethylene.

The production of acetylene by the direct application of electrical energy was first commercialized at the plant of Chemische Werke Hüls, Germany, just before World War II; the feed stock for the electric arc was mainly methane and ethane from coal hydrogenation, later supplemented by natural gas. These processes can use a wide range of feed stocks, including vaporizable liquid hydrocarbons as well as gas. Acetylene is the main product, but ethylene can be made as a co-product by the introduction of naphtha prequench; hydrogen and carbon black are by-products.

The reported work in the literature with plasma cracking looks the most promising. Hydrogen plasma requires less energy than argon. Water vapor with hydrogen also gives good results. Naphtha requires less energy per unit of acetylene than methane does. The normally liquid feed stocks appear to be the most economical, particularly where use may be made of the other unsaturated products, such as ethylene and propylene. There is still great room for improvement both in yields and in energy consumption by further research and development. There seems to be no doubt that such processes would make fruitful development projects.

5.4 Acquisition and Development of Technical and Cost Data

A great deal of effort was expended by the study group, the numerous representatives from industry, and our consultants in developing good technical and cost data for all the processes studied. Material and heat balances were made for each process, based on realistic yields, losses, and utility requirements. Special studies were made on electrolytic cell current density in the case of water electrolysis, catalyst requirements for ammonia and nitric acid synthesis, the effect of phosphate rock assay, and a number of other special variables peculiar to particular processes.

Similar care was taken in the development of realistic costs for the various processes under economic conditions in the United States. Processing plant battery limit[9] capital investment costs (excluding working capital) were developed for each process at several capacities in order to determine appropriate cost scaling factors. Operating costs were developed as the sum of the costs of raw materials, utilities, operating and maintenance labor and supervision, plant overhead, special materials, and indirect costs (including recovery of investment, return on investment, and interest on working capital). Raw materials costs included, when necessary, shipping costs to the complex. Labor costs were derived from actual manpower requirements including fringe benefits times an average United States wage rate of $4.00 per hour. Overhead was uniformly taken as 60% of the total of operating and maintenance labor and supervision. Indirect costs did not specifically include insurance, local taxes, or corporate income taxes because these costs would be difficult to extrapolate later to non-United States conditions. Recovery of investment was computed by the sinking-fund allowance method assuming annual end-of-year payments for 15 years. Return on investment was determined on an annual basis at simple interest. In all building block and industrial complex cases, working capital was taken equal to 60 days total (direct and indirect) operating costs. Gross battery limit manufacturing costs were obtained as the sum of all prior costs plus the computed interest on working capital. By-product credits were not assumed in arriving at net manufacturing costs.

In the building block and industrial complex cost computations, all industrial plants were assumed to have a 15-year life and no end-of-life value. The 15-year life was chosen to reflect expected process obsolescence rather than the wearing out of equipment. The conversion of United States costs to non-United States conditions has already been discussed in Chap. 3.

5.4.1 Technical and Economic Parameters and Computer Codes

As noted previously the production of 17 products was studied intensively. The technical, and more particularly the economic, data obtained for these processes and products were sufficient to evaluate realistic manufacturing costs for a number of parameters, which will be enumerated and explained below. In order to make as complete an evaluation as possible in the limited time available, computer codes were developed and used to evaluate all reasonable sets of parameters. This section presents a summary of the parameters that were evaluated for the various products.

In nearly all cases these basic cost data (under United States conditions) were supplied by our consultants and the members of the cooperating companies listed in Appendix 1. We believe that the cost data are representative of the various industries studied but are not specific for a given company within the industry. Thus it is our opinion that the costs given here are realistic for plants of the capacities studied, since they were obtained from consultants and company representatives rather than from published sources.

For those readers who may wish to obtain a more detailed understanding of the computational methods used in our studies, a full review of the procedures, including a brief description of the computer codes, is presented in a companion report.[10] This report also provides numerous tables which will enable the reader to obtain, easily and quickly, any of the manufacturing costs (obtained in the computer runs) for any values of the parameters considered.

5.4.2 Summary of Parameters

The first parameter considered for the various processes was plant capacity. In general, a

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[9] Battery limit cost includes cost of production facility only and excludes off-site or support facility costs such as power plant; maintenance shops; administrative, fire, safety, health, and security needs; railroads; roads; water and sewage facilities; etc. These are discussed in detail in sect. 5.6.1

[10] H. E. Goeller, *Tables for Computing Manufacturing Costs of Industrial Products in an Agro-Industrial Complex*, ORNL-4296 (to be published).

lower limit was established for each product, based primarily on the capacity under today's technology below which it was found that product manufacturing costs would be too high to compete in the present or future markets. Similarly, the upper capacity limit was set at a value based on a developing country's capacity to consume a particular product in the future or to compete on the export market. In any one computer run, seven capacities can be compared, but in nearly all cases only four were evaluated (five were evaluated for solar salt).

The second parameter was utility (electricity, prime and exhaust steam, and process water) costs. The ranges for the various utility costs were established by examining nuclear reactor and desalination evaporator technologies; full discussion of the utilities cost rationale is given in Chap. 4 and in Appendix 4A. The computer codes used in the industrial studies can accept four costs for each utility per run. The electricity costs used in most calculations were 1, 2, 4, and 8 mills/kwhr. Comparable prime and exhaust steam cost sets used were 6, 16, 30, and 50¢ and 2, 6, 15, and 25¢/MMBtu (million Btu) respectively. The four base costs used for process water were 7, 12, 30, and 50¢/1000 gal. Single cost values were used for cooling water and fossil fuel; the values generally used were 2¢/1000 gal and 50¢/MMBtu respectively.

Another parameter studied was cost of money, expressed as an interest rate. The computer code can accept four interest rates during a single run; in all cases rates of 2.5, 5, 10, and 20%/year were used. This range was chosen to represent anticipated acceptable rates of return on investment both in the United States and overseas.

Raw materials costs for large bulk purchases were also a parameter in the computations; up to four values each were used for: naphtha for ammonia synthesis, sulfur for sulfuric acid manufacture, phosphate rock for phosphoric acid production (by both the electric furnace phosphorus and wet acid processes) and for nitric phosphate manufacture, bauxite for alumina and aluminum production, alumina (two values) for aluminum manufacture, and salt for caustic-chlorine production by brine electrolysis.

Several other parameters were used for specific processes; for example, four electrolytic cell current densities were used for water electrolysis in Allis-Chalmers cells and five for General Electric cells. Phosphate rock assay was also a variable, but use of a second assay required a second computer run.

In all calculations the final building block output was production cost per ton of product in terms of the previously enumerated parameters. Output for industrial complex computations was in annual product costs and values. The building block economic analyses were usually based on a comparison of production costs for each product under two conditions. In some cases (NH_3 and H_3PO_4) production by an advanced (preferably electrolytic) method was compared with production by the presently most-used technique. Where an alternative production method was not available (aluminum), an attempt was made to make a comparison on geographic or other grounds, as discussed in Sect. 5.3.

5.4.3 On-Stream Efficiency and Plant Reliability

In general, few industrial plants operate either absolutely continuously or at full capacity at all times. In order to take this into account in our analysis, an on-stream efficiency factor, based on experience in the various chemical and metallurgical industries studied, was used. The on-stream efficiency factor employed for ammonia and ammonia-derived fertilizer manufacture and for caustic-chlorine production was 0.95. For production of phosphoric acid both by the wet acid process and from electric furnace phosphorus, a factor of 0.93 was used. The factor for the solar salt works was 0.91. The aluminum production facility was assumed to have an on-stream efficiency factor of 1.00. In the industrial complexing calculations an overall average on-stream efficiency of 0.95 was employed.

With regard to reliability and the seriousness of shutdowns, there appears to be considerable variance from industry to industry. Water or brine electrolysis plants which produce hydrogen (and oxygen) and caustic-chlorine (and hydrogen), respectively, can be shut down either purposely or by a power outage with practically no ill effects. They can then be started back up in, at most, an hour. This characteristic permits such plants to utilize lower-cost off-peak or interruptable power very effectively. A brief study was made on the production of ammonia from off-peak power and will be discussed later. Ammonia plants cannot be readily shut down and restarted, because they operate at high pressure and intermediate temperature. Restarts take several hours, particularly if the equipment has cooled off and pressure has been lost following the shutdown.

Problems in electric furnace phosphorus operation and aluminum smelting are more severe because both of these processes operate at higher temperatures. When power to a phosphorus electric furnace is lost, the furnace and its contents start to cool down, the rate of cooling being a function of the size of furnace. A small furnace (30 tons/day) would have to be restarted in 24 hr to prevent solidification of the furnace contents, whereas a very large furnace (~300 tons/day) could probably be restarted readily after a power outage of several days. Once a furnace charge has solidified, restarting will take up to a day, being less for small furnaces. Considerable time-consuming rodding of the furnace charge to free the electrodes is required; since the furnaces are very rugged, a "freeze-up" does little damage, and the need for repair or replacement of equipment as the result of a shutdown is unlikely.

Much of what has been said for electric furnaces also applies to electrolytic aluminum smelting pots. Freeze-up times are shorter, and, because the pots are carbon lined, equipment damage is much more likely. Thus every effort is made to keep the power flowing to an aluminum pot line, and the extra costs for alternative sources of electrical power are generally considered justifiable. In the event of a power outage, extreme efforts are made to restore at least half power within 2 to 3 hr; this supplies enough power to be rotated among the various pots or pot lines to slow the cooling process. After 6 to 8 hr, power must be brought up to 75% of full power to make this technique effective, and after 16 to 24 hr, even this method is futile. Thus after a day at less than nearly full power the pot contents will freeze, and an expensive time-consuming period of 20 to 30 days is required to get the plant back in production. All the cryolite and aluminum must be removed and each pot inspected. About 10 to 15% of the pots must be relined because of damaged linings. An aluminum smelting plant normally contains about a 3 to 5% excess of smelting pots in order that a few can always be out of service to be relined; relining is required every one to two years.

Based on the above discussion it is our opinion that an ammonia plant using electrolytic hydrogen and a caustic-chlorine plant can be adequately run from a single power reactor. In the case of phosphorus-producing electric furnaces and particularly for an aluminum smelting plant, the reliability provided by dual power reactors or a single reactor tied to a large grid is very desirable.

5.5 Summary of Industrial Building Block Cost Results

This section presents typical results of the industrial building block cost studies. Two types of results are given: first the results which were obtained using a computer to evaluate manufacturing costs under conditions in the United States for hydrogen, ammonia, phosphorus, phosphoric acid, aluminum, salt, and caustic and chlorine, with their associated products; and second, the results of studies made in more general terms without the assistance of a computer on such products as magnesium, bromine, and potassium from seawater, iron and steel, and acetylene via the arc process and the partial oxidation process.

5.5.1 Computer-Derived Manufacturing Costs for Ammonia, Phosphoric Acid, Aluminum, and Caustic and Chlorine and Associated Products

In the processes studied, often only one of the major cost components is controlling in the overall production cost of a specific product. This trend is borne out in Figs. 5.7*a–d*, which show the cost contribution to the total production cost of raw materials, electricity, labor, other materials, and indirect (capital) costs vs power cost for four products: ammonia from electrolytic hydrogen, electric furnace phosphorus, aluminum ingot from the electrolytic reduction of alumina, and chlorine from brine electrolysis respectively. Figure 5.7*a* shows that even at low power costs, the cost of electricity is the major cost component in the production of ammonia from electrolytic hydrogen and that at high power costs (7 to 8 mills/kwhr) it overshadows all other costs. In Fig. 5.7*b* it is readily seen that in the production of electric furnace phosphorus the raw materials cost is controlling at all power costs. This is understandable since about 10 tons of phosphate rock and matrix are required to produce 1 ton of elemental phosphorus. For aluminum ingots, as shown in Fig. 5.7c, the plant capital cost is found to be overriding because of the high cost of aluminum smelting plants. Under appropriate conditions aluminum ingot can be produced for about $400.00 per ton; fabricated aluminum in simple shapes costs about $500.00 to $600.00 per ton to manufacture. Finally, as shown in Fig. 5.7*d*, no single cost component is controlling in caustic-chlorine production by electrolysis. Power cost is the major cost component above 6 mills/kwhr at 20% cost of money and above 3.3 mills/kwhr at 10% cost of money.

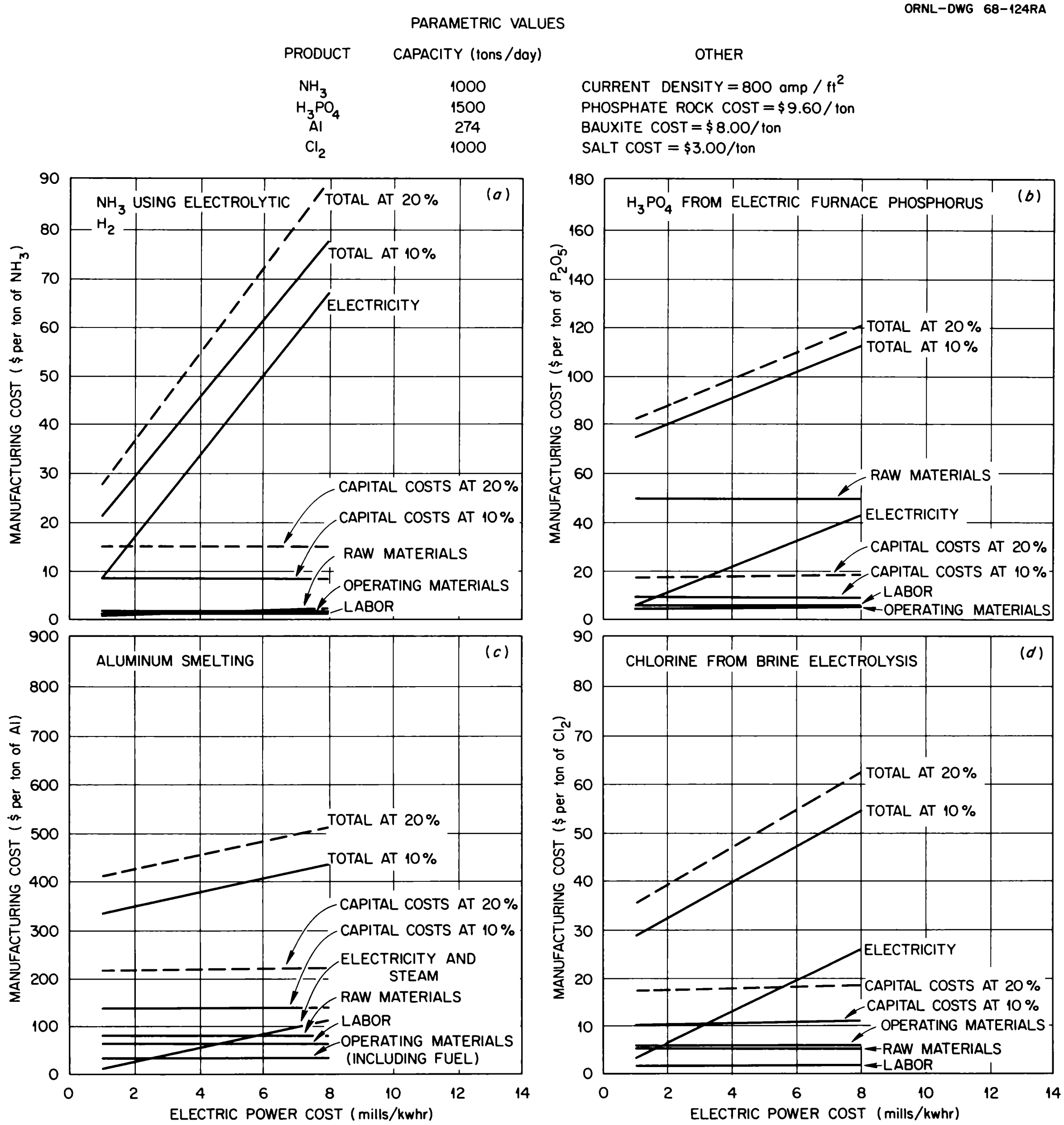

Fig. 5.7. Contributions of Various Cost Components to the Total Manufacturing Costs of (*a*) Ammonia, (*b*) Phosphoric Acid (as P_2O_5), (*c*) Aluminum, and (*d*) Chlorine at 10 and 20% Cost of Money.

Figure 5.8 shows the percent of the total manufacturing cost attributable to cost of electricity as a function of power cost for each of the above products and for 10% cost of money.

These conclusions will be even more apparent in the detailed cost analysis presentations for each of the various products, which will now be discussed in turn. In these discussions the values of the parameters studied for each product are tabulated in the section on that product.

Manufacturing Costs of Hydrogen and Ammonia. – This section provides a summary of the manufacturing costs of ammonia using hydrogen from both the electrolysis of water and steam-naphtha reforming. Naphtha, rather than natural gas, was used because it is presently more available in developing nations. Typical manufacturing costs of ammonia, nitric acid, ammonium nitrate, urea, and nitric phosphate, each using hydrogen from both sources, are also presented.

Three methods for the electrolysis of water, none of which are presently in commercial use, were studied: the first, the one for which the technology is most developed, involves the use of an advanced design De Nora diaphragm cell; the second, less developed but probably available for commercial use within ten years, employs a new type of Allis-Chalmers cell. The far-term alternative employs a new type of cell currently under development by the General Electric Company which electrolytically dissociates steam, containing a small amount of hydrogen, in the temperature range of 1000 to 1100°C. A more thorough discussion of the three cells is given in Sect. 5.3.1. Although the Allis-Chalmers cell was adopted as the standard for this study, enough cases were evaluated for the other two cells to provide hydrogen and ammonia manufacturing cost comparisons. Manufacturing costs for nitric acid, ammonium nitrate, urea, and nitric phosphate were based solely on the use of hydrogen from the Allis-Chalmers cell (and from steam-naphtha reforming).

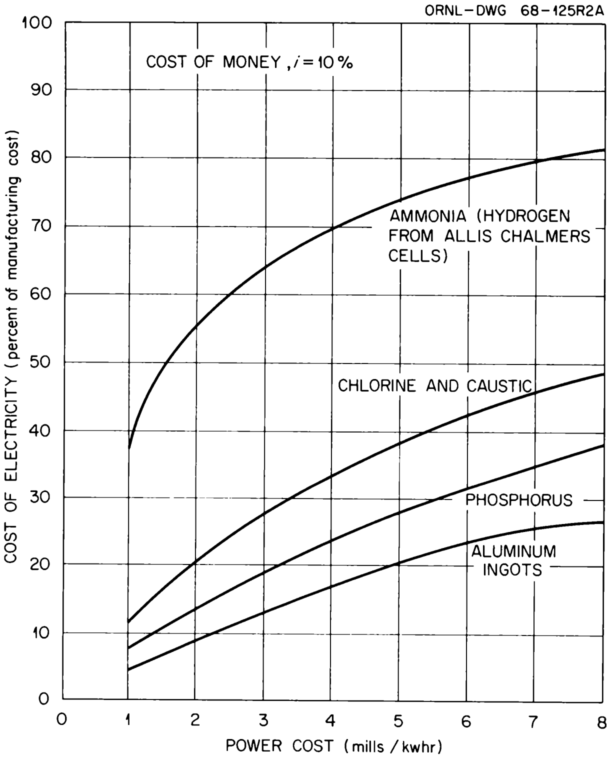

Fig. 5.8. Effect of Cost of Electricity vs Power Rate on Manufacturing Cost of Ammonia, Phosphoric Acid, Aluminum, and Chlorine.

In the computation of hydrogen (and ammonia) production costs, the values of the previously described variables which were used are as follows:

Interest rate (cost of money), %	2.5, 5, <u>10</u>, and 20
Plant capacity, tons of NH_3 per day	300, 600, <u>1000</u>, and 3000
Naphtha cost, dollars/ton	15, 22, <u>27</u>, and 35

For the case of the Allis-Chalmers cell the additional variable of current density was also evaluated at 400, <u>800</u>, 1200, and 1600 amp/ft^2. The De Nora cell was evaluated at a current density of 300 amp/ft^2 and a plant capacity of 1000 tons of ammonia per day. The General Electric cell was evaluated at a plant capacity of 1000 tons of ammonia per day and at current densities of 1750, 2500, 3500, 5000, and 7500 amp/ft^2. In addition, three General Electric cell module costs of \$25.00, \$50.00, and \$100.00 per square foot and three levels of internal resistance losses (cell types A, B, and C), which are a function of current density, were evaluated. In going from A to C it was assumed that resistance was decreased by providing thinner zirconia electrolyte sections and additives that lower the resistance of the zirconia. For example, ZrO_2-Yb_2O_3 has been found to have a lower resistance than ZrO_2-Y_2O_3. The final parameter, cell module cost, was given three values: \$100.00, \$50.00, and \$25.00 per square foot of electrode surface. General Electric's rationale for these costs is as follows: "It is estimated that cell modules can be produced at a cost of $100 per sq. ft. of cell area during early years of large-scale manufacture. With further manufacturing experience and improvements, it is reasonable to expect module cost to come down later to $50/sq. ft. and eventually to $25/sq. ft." In the economic calculations, only a limited number of the 27 possible combinations of the three parameters were evaluated; these included the type B cell at all unit cell costs and current densities (1750, 2500, 3500, 5000, and 7500 amp/ft^2) and the type C cell at a unit cost of $25.00 per square foot and all current densities. In addition the types A and C cells at unit costs of $50.00 and $100.00 per square foot were evaluated at a current density of 1750 amp/ft^2.

In addition, the costs of electricity, distilled water, and prime and exhaust steam were varied as follows:

Power cost, mills/kwhr	1, 2, 4, and 8
Distilled water cost, cents/1000 gal	7, 12, 30, and 50
Prime steam cost, cents/MMBtu	6, 15, 30, and 50
Exhaust steam cost, cents/MMBtu	2, 6, 15, and 25

In all calculations the variable utility costs were used as vertical sets; that is, 1-mill power was used with 7¢ water, 6¢ prime steam, and 2¢ exhaust steam, etc. Since these same values were used in computing production costs for all products they will not be retabulated in the discussions on other products.

The underlined values in the tabulations listed previously were used as standards of comparison in the typical example which follows. The 10% cost of money is generally in line with the existing private industrial opportunity rate of return after taxes in the United States. A 1000-ton/day ammonia plant is large, but several 1500-ton/day plants are presently in operation or under construction. A naphtha price of $27.00 per ton was chosen to reflect a price delivered about 2000 miles from a refinery in a developing nation. For example, naphtha currently sells in India for $26.00 to $36.00 per ton.[11]

With regard to the current densities assumed for the Allis-Chalmers cell, more development work is required in order to demonstrate long-term stability; however, a model of this cell has been run in the laboratory at ratings up to 4000 amp/ft^2 for 24 hr. The De Nora cell current density of 300 amp/ft^2 is twice that used in present operating units; however, recent advances indicate that the higher value can be obtained easily with newly designed cells. In the case of the General Electric high-temperature cell a single module (cell tube) has been successfully operated up to 3500 amp/ft^2. At this time, experiments have been done only with single modules.

Typical computed costs for ammonia using hydrogen both from the Allis-Chalmers cells and from steam-naphtha reforming are shown graphically in Fig. 5.9*a–d* for four variables: cost of money, plant capacity, naphtha cost, and current density respectively. Each plot shows gross manufacturing cost of ammonia vs power cost in mills per kilowatt-hour for the two alternative sources of hydrogen and indicates the electric power rates at which electrolytic hydrogen can compete with reformed hydrogen for the various economic variables considered. The underlined cost values previously discussed are the common values for the four graphs; for this case the break-even power rate is 2.7 mills/kwhr, and the gross manufacturing cost is $35.00 per ton of ammonia.

Figure 5.9*a* shows that the break-even power cost is relatively insensitive to the cost of money, since the break-even power cost varies only between 2.4 and 2.7 mills/kwhr as the interest rate is decreased from 20 to 2.5%. Plant capacity, as shown in Fig. 5.9*b*, is also a relatively insensitive variable, since the break-even power cost varies only between 2.4 and 2.8 mills/kwhr as the capacity decreases from 3000 to 300 tons of ammonia per day. Naphtha cost has a large effect on the break-even power cost, as shown in Fig. 5.9*c*, where the break-even cost varies from 1.3 to 3.4 mills/kwhr as naphtha cost is increased from $15.00 to $35.00 per ton. Finally, as shown in Fig. 5.9*d*, changes in current density have only a very minor effect on break-even cost, which varies between 2.4 and 2.5 mills/kwhr for the current density range 400 to 1600 amp/ft^2. Figure 5.10 presents the current density data in a different way; here ammonia manufacturing cost

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[11] Personal communication, Ministry of Petroleum and Chemicals, India.

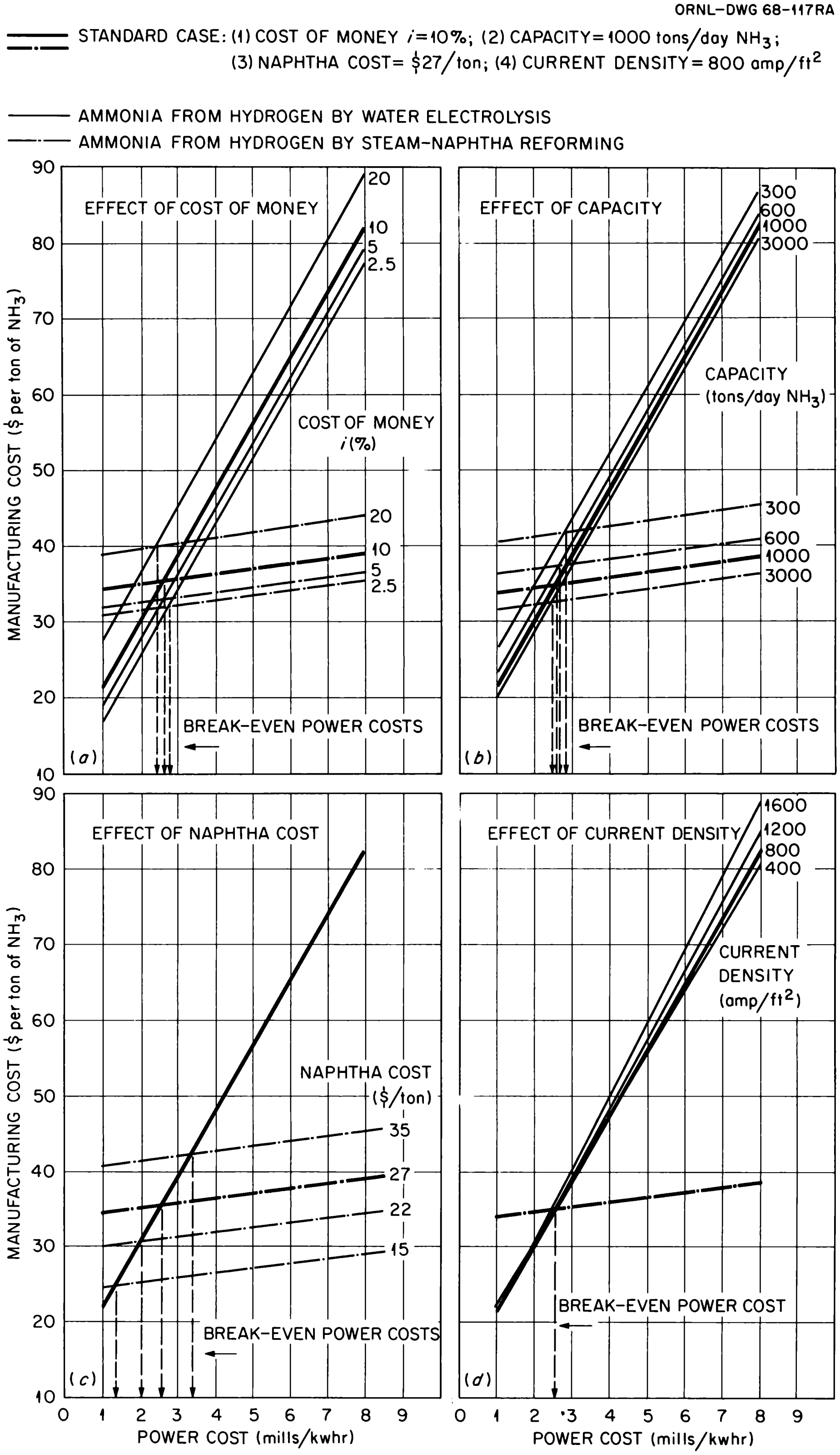

Fig. 5.9. Manufacturing and Break-Even Power Costs for Production of Ammonia.

is plotted against current density with cost of money and power cost as parameters. The graph shows that manufacturing costs using power at 1 and 2 mills/kwhr are relatively independent of current density and that at 4 mills/kwhr there is only a slight increase in cost at higher current densities. Although not shown in Fig. 5.10, this effect is somewhat more pronounced at 8 mills/kwhr. All but one of the curves go through a manufacturing cost minimum in the current density range of 400 to 1600 amp/ft^2. In general, these minima occur at lower current densities for lower costs of money and higher power rates.

Costs of hydrogen production using power at 1, 2, and 4 mills/kwhr are given for all cell types studied in Table 5.2 in cents per thousand standard cubic feet of hydrogen with and without $4.00 per ton oxygen credit; ammonia costs in dollars per ton of NH_3 are also given in Table 5.2 for hydrogen from the four cell types.

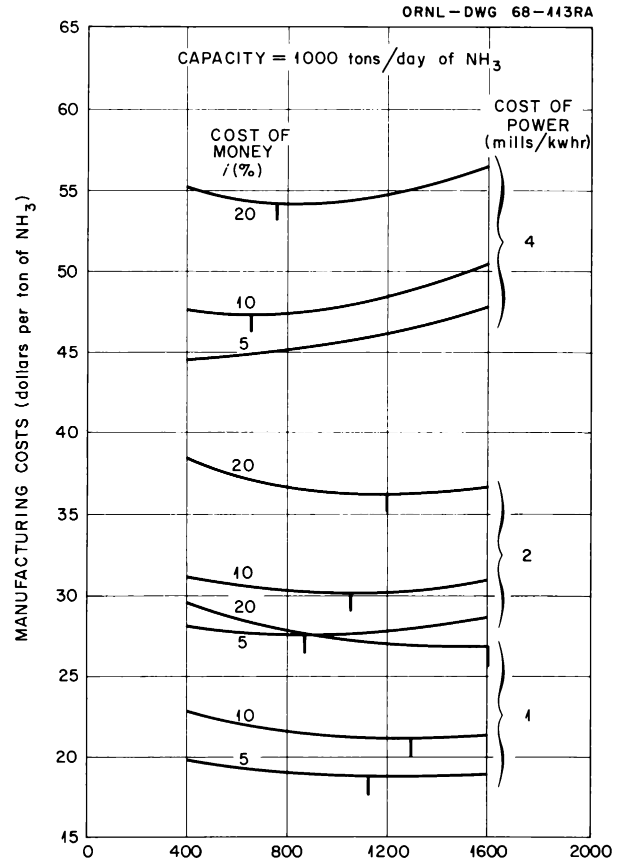

Fig. 5.10. Manufacturing Costs of Ammonia from Electrolytic Hydrogen as Functions of Current Density, Power Cost, and Cost of Money.

Figure 5.11*a* shows ammonia manufacturing costs as a function of power cost for present-day cells and for the three types of experimental cells. This comparison was made for a 1000-ton/day ammonia plant at a 10% cost of money. The costs of ammonia production from electrolytic hydrogen from the advanced De Nora, Allis-Chalmers, and General Electric cells (type A, $50.00 per square foot) are, within the accuracy of the estimates, about equal; they are about 45, 39, and 32% cheaper than present-day cells when power at costs of 1, 2, and 4 mills/kwhr, respectively, is available. However, if the type B and C General Electric cell characteristics are successfully developed, appreciable further savings, using a cell cost of $50.00 per square foot, appear to be achievable. The comparisons for the General Electric cells were made at a current density of 1750 amp/ft^2, the lowest density studied, and at a cell cost of $50.00 per square foot, the median value. A current density of 800 amp/ft^2, which was previously shown to be the most economic value, was used for the Allis-Chalmers cell in this comparison. The advanced De Nora cell assumed use of a current density of 300 amp/ft^2, the only value considered.

Figures 5.11*b* and c, for 10 and 20% cost of money, respectively, show the effect of current density and module material cost on ammonia manufacturing cost as a function of power cost for General Electric type B cell material.

Later information has indicated that further savings can be made with the General Electric cell if the oxygen atmosphere at the anode is replaced with a carbon monoxide atmosphere. Carbon monoxide serves to depolarize the anode by reacting with oxygen to produce CO_2, thus reducing the back emf at the anode. The benefits of this effect appear to be very attractive. For example, production of electrolytic hydrogen without benefit of an anode depolarizer, assuming use of the type B electrolyte configuration, requires an energy consumption of 90 kwhr of electricity per 1000 scf of hydrogen at a current density of 2000 amp/ft^2. With the use of a stoichiometric amount of carbon monoxide at the anode, the energy consumption may be reduced to 26 kwhr/Mscf. To put these numbers in perspective, the former is equivalent to a power cost of about $12 per ton of ammonia at an electricity cost of 2

Table 5.2. Hydrogen Manufacturing Costs for De Nora, Allis-Chalmers, and General Electric Electrolytic Cells

Cost of money, $i = 10\%$

A. Cost of Hydrogen

Plant Capacity (tons/day)	Type of Cell	Current Density (amp/ft^2)	H_2 Generation Pressure (psia)	Manufacturing Cost (cents/Mscf)[a]					
				Power Cost = 1 mill/kwhr		Power Cost = 2 mills/kwhr		Power Cost = 4 mills/kwhr	
				No O_2 Credit	With O_2 Credit[b]	No O_2 Credit	With O_2 Credit[b]	No O_2 Credit	With O_2 Credit[b]
162	Present	150	15	41	33	55	47	79	71
162	De Nora	300	15	25	17	37	29	57	49
162	Allis-Chalmers	800	300	23	15	35	27	53	45
162	GE[c]	1750	15	18	9	25	16	40	32

B. Cost of Ammonia

Plant Capacity (tons/day)	Type of Cell	Current Density (amp/ft^2)	H_2 Generation Pressure (psia)	Manufacturing Cost (dollars/ton)					
				Power Cost = 1 mill/kwhr		Power Cost = 2 mills/kwhr		Power Cost = 4 mills/kwhr	
				No O_2 Credit	With O_2 Credit[b]	No O_2 Credit	With O_2 Credit[b]	No O_2 Credit	With O_2 Credit[b]
1000	Present	150	15	40	34	51	45	73	65
1000	De Nora	300	15	24	18	33	28	51	43
1000	Allis-Chalmers	800	300	22	16	30	25	47	39
1000	GE[c]	1750	15	19	13	25	19	36	28

[a] Mscf = thousand standard cubic feet.

[b] At $4.00 per ton.

[c] Type C cell, module cost = $50.00 per square foot.

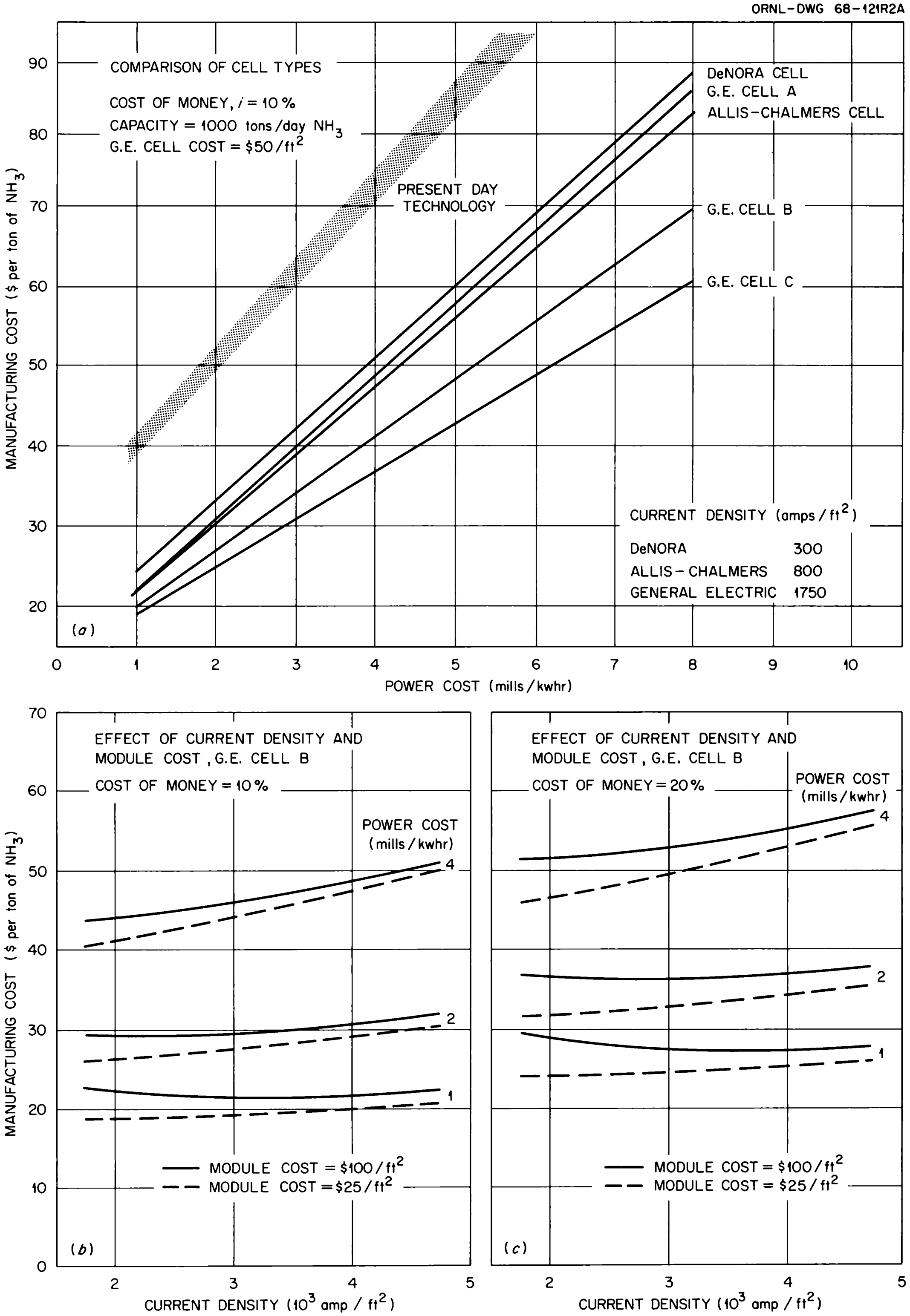

Fig. 5.11. Comparison of Water Electrolysis Cell Types for the Production of Hydrogen for Ammonia Synthesis.

mills/kwhr, while the latter is equivalent to about \$3.50 per ton of ammonia. An economic analysis of this latest development has not been completed at this time. However, it appears to place electrolytic ammonia in a much better competitive position compared with steam-methane reforming in the United States, although a cheap source of carbon monoxide is required.

Steam-methane reforming is now the most widely used process for the production of hydrogen for ammonia synthesis in the United States. This study did not incorporate an intensive study of this process for comparison with electrolytic hydrogen, because natural gas is usually not a major raw material present in developing countries. However, to provide some basic data for comparison on an equivalent basis, a few calculations were performed comparing steam-methane reforming ammonia plants in the United States with electrolytic hydrogen ammonia plants using Allis-Chalmers cells at a cost of money of 10%.

Table 5.2 indicates that ammonia using electrolytic hydrogen from an Allis-Chalmers cell with power at 2 mills/kwhr can be manufactured for \$30.00 per ton in a 1000-ton/day plant with no by-product oxygen credit assumed. Figure 5.12 indicates that a steam-methane reforming plant evaluated under identical conditions could pay as much as 67¢/MMBtu for natural gas and still manufacture ammonia for \$30.00 per ton. However, if one compares manufacturing costs for 300-ton/day plants, the break-even price of natural gas decreases to 52¢/MMBtu, illustrating the detrimental effect of scale on electrolytic ammonia plants as compared with its beneficial effect on reforming plants. If an oxygen credit of \$4.00 per ton is allowed, the above break-even natural gas prices are reduced by 18¢/MMBtu, thereby making electrolytic hydrogen much more competitive.

The shaded area on the left side of Fig. 5.12 outlines a range of prices of industrial natural gas typical of areas in the United States 1000 to 1500 miles (by pipeline) from the gas fields. It indicates that, for electrolytic hydrogen to compete with steam-methane reforming in these areas, the price of power must be in the range of 0.8 to 1.70 mills/kwhr, depending upon plant size (without oxygen credit). However, the price of natural gas in Texas is in the range of 22 to 29¢/MMBtu,[12] and here the competitive price of electric power should be in the range of 0.25 to 1.25 mills/kwhr. The possibility of attaining the latter power costs for a firm power load is remote; however, off-peak power from breeder reactors may achieve these costs if it is priced to recover only the direct operating costs of the nuclear power station (see Chap. 4).

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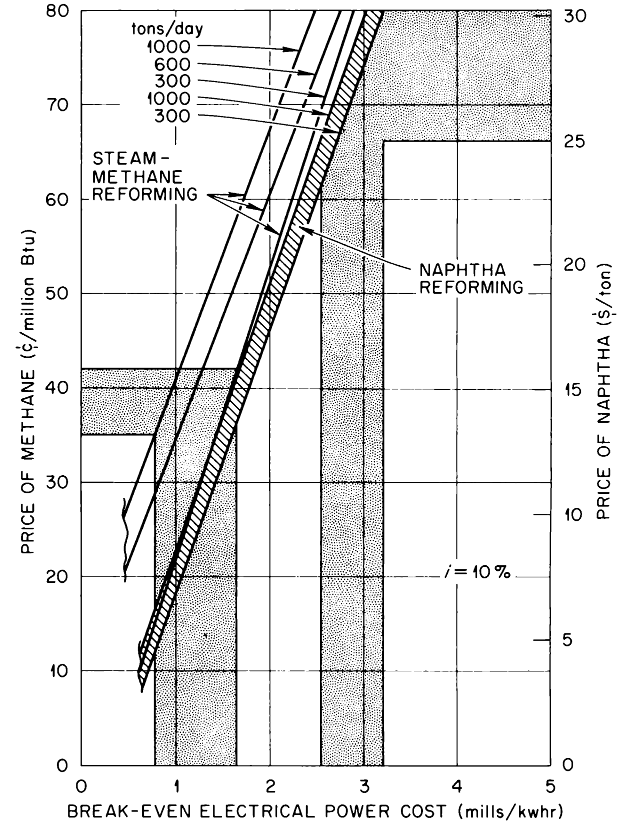

Fig. 5.12. Comparison of Steam-Methane and Steam-Naphtha Reforming with Electrolytic Hydrogen for Ammonia Production.

The ability to produce a synthesis gas from liquid feed material without the use of oxygen has been achieved in recent years. This advance has permitted steam-naphtha reforming to come of age. The manufacturing cost of ammonia by steam-naphtha reforming is somewhat higher than by steam-methane reforming because of higher capital costs and a more expensive raw material. Capital costs for the naphtha process average about 8% higher than costs for steam-methane.[13] Figure

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[12] H. C. Bauman, *Fundamentals of Cost Engineering in the Chemical Industry*, p. 238, Reinhold Publishing Corp., New York, 1964.

[13] Private communication from Chemico, Inc.

5.12 shows that naphtha at \$20.00 per ton is equivalent to natural gas at 53¢/MMBtu.

Naphtha, because of its bulk and the fact that it is a liquid, is costly to ship, and a price of \$20.00 can only be obtained at a refinery. The supply of naphtha in the United States is quite small because the largest output of our refineries is gasoline. European countries have relied more heavily on naphtha to supply their nitrogen fertilizer demands, but with the discovery of the natural gas fields under the North Sea this situation may change. India has very little natural gas and has relied almost exclusively on naphtha to provide fertilizer nitrogen. However, much of the naphtha is obtained from imported oil and, with the large quantities of fertilizer needed to supply India's needs, cannot be relied upon to meet the demand because of foreign exchange requirements. In India, refinery heavy stock and coal are being given much consideration as hydrogen sources.

The shaded band on the right side of Fig. 5.12 outlines a range of naphtha prices from \$25.00 to \$30.00 per ton. For these conditions and at a cost of money of 10%, ammonia obtained from electrolytic hydrogen could compete for power costs in the range of 2.6 to 3.2 mills/kwhr. These power costs can be obtained from large light-water reactors [>1500 Mw (electrical)] in the near term and for advanced design reactors at a cost of money of 10%/year (Chap. 4).

Ammonia Production Using Off-Peak Power. – In the event that the complex utilizes nonindustrial power on a daily part-time basis, as in the pumping of large quantities of water, off-peak power for industrial use may be available. To evaluate this possibility a study was made to determine the costs of producing ammonia assuming operation of the electrolytic hydrogen plant only during off-peak hours. Under normal 24 hr/day operation the water electrolysis cells were operated at a current density of 800 amp/ft^2. For off-peak periods of 12 to 24 hr, current density was adjusted to produce the needed amount of hydrogen; that is, for 16-hr operation, a current density of 1200 amp/ft^2 was used and for 12-hr operation 1600 amp/ft^2 was used, with the hydrogen plant sized to produce enough hydrogen for 600 tons/day of ammonia at 800 amp/ft^2. The maximum current density assumed was 1600 amp/ft^2, and thus for off-peak periods of less than 12 hr the electrolytic hydrogen facility was increased in size while maintaining operational current density at the maximum. The ammonia synthesis plant was sized to produce 600 tons/day and was assumed to operate continuously in all cases. For off-peak operation, during the part of the day when both plants were in operation, a portion of the hydrogen produced in Allis-Chalmers-type cells at 300 psig would be compressed from this pressure to 3000 psig and fed directly to the ammonia plant; the remainder would be compressed to 980 psig and stored underground in high-pressure 42-in. vanadium steel pipe.[14] When the electrolysis plant was idle, the ammonia plant would draw hydrogen from storage, decreasing the storage pressure from 980 to 300 psig. At the start of the drawdown period the ammonia plant feed compressors would operate from 980 to 3000 psig and at the end of the period, from 300 to 3000 psig.

The results of this study are summarized in Fig. 5.13 for off-peak operational periods of 6, 12, and 16 hr and with normal continuous operation shown for comparison. A plant life of 15 years and a cost of money of 10% were assumed. Compared with normal continuous operation using power at 3 mills/kwhr, constant ammonia manufacturing cost requires that off-peak power be available at 2.7, 2.3, or 1.1 mills/kwhr for operating periods of 16, 12, and 6 hr respectively.

This type of operation for electrolytic cells may be quite attractive since, with the electrolytic hydrogen plant designed to operate at 1600 amp/ft^2 and sized to operate at 800 amp/ft^2, it could serve as an electrical load-leveling device because the cells can operate at lower current densities with the advantage of decreased power usage. Unit power usage is increased by about 13% in going from 800 to 1600 amp/ft^2.

Production Costs of Ammonia-Derived Fertilizer. – Ammonia, whose manufacturing costs from both electrolytic hydrogen and reformed hydrogen were discussed in the previous section, can be used as a fertilizer directly. However, under current practices, the great bulk of the ammonia produced in the world is converted into a variety of solid fertilizers. In this section, typical results of computer code calculations on production costs of three of these – ammonium nitrate (NH_4NO_3), urea, and 27-14-0 nitric phosphate – are discussed; since nitric acid (HNO_3)

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[14] *Oil Gas J.*, p. 88 (Feb. 24, 1964).

also is used in the manufacture of NH_4NO_3 and nitric phosphate, its production cost is included.

Table 5.3 gives the four base capacities studied for each of these fertilizers and the percent of produced ammonia converted in each case. Figures 5.14*a–d* provide a comparison of production costs for each material from either electrolytic hydrogen or reformed hydrogen for power costs between 1 and 4 mills/kwhr. These graphs are for plants (at 10% cost of money) with capacities in the third capacity column of Table 5.3 (i.e., for 1067 tons of HNO_3 per day for NH_4NO_3, etc). A current density of 800 amp/ft^2 was assumed for electrolytic hydrogen production. Naphtha costs are a variable for the reformed hydrogen cases. In the case of nitric phosphate (Fig. 5.14*d*), phosphate rock costs of $5.50, $9.60, $17.00, and $24.00 per ton were used with naphtha costs of $15.00, $22.00, $27.00, and $35.00 per ton respectively. Curves are not given for the HNO_3 plant for nitric phosphate production; because of lowered capacity, compared with the HNO_3 plant for NH_4NO_3, all HNO_3 manufacturing costs for this case are about $0.75 higher than those shown in Fig. 5.14*a*.

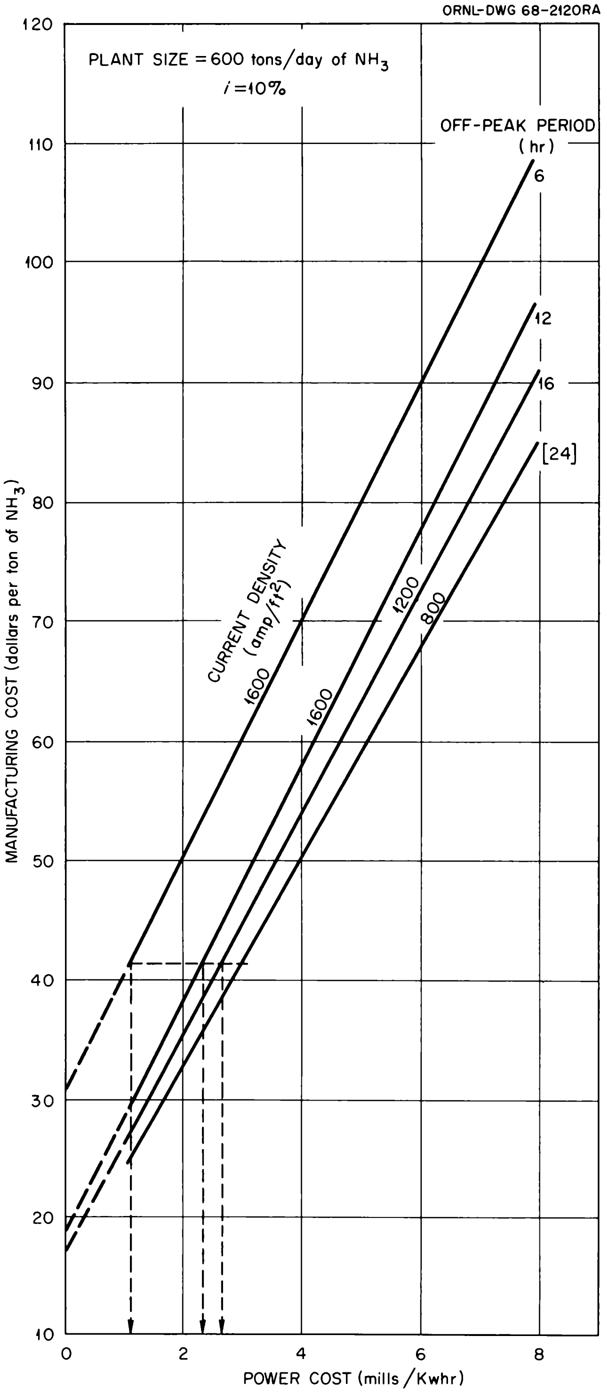

Fig. 5.13. Effect of Electrolytic Hydrogen Plant Off-Peak Operating Period on Production Cost of Ammonia Assuming Continuous Synthesis of Ammonia.

Figures 5.14*a–d* indicate that the break-even power costs for the production of each product using ammonia derived from electrolytic vs reformed hydrogen are about the same as for ammonia (Fig. 5.9c). This results from the fact that the secondary products use very little electricity compared with that needed for water electrolysis and that the secondary product production costs are small compared with those for water electrolysis and ammonia synthesis. As was shown

Table 5.3. Base Capacities for Ammonia-Derived Fertilizers

Product	Base Capacities[a] (tons per day)				Amount of NH_3 Converted (% of total produced)
HNO_3 for NH_4NO_3	320	640	1067	3200	30
NH_4NO_3[b]	400	800	1333	4000	59
Urea	300	600	1000	3000	58
HNO_3 for nitric phosphate	248	596	827	2480	23
Nitric phosphate[b]	450	900	1500	4500	52

[a] The corresponding base NH_3 production rates are given in sect. 5.5.1.

[b] Includes NH_3 used for HNO_3 production

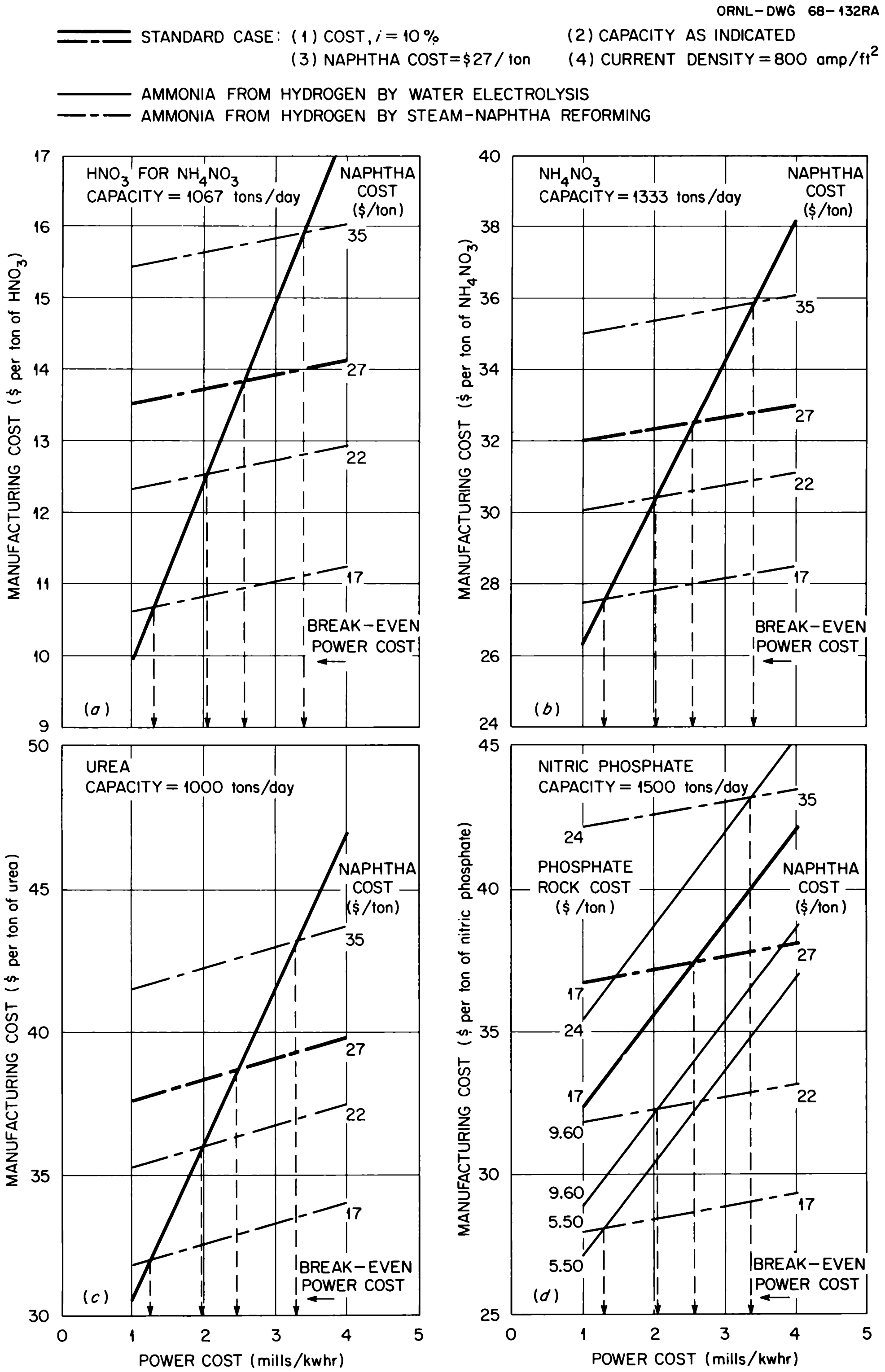

Fig. 5.14. Manufacturing Costs for Ammonia Derivatives.

in the preceding section on ammonia production costs, the effects of cost of money, plant capacity, and current densities for electrolytic hydrogen and ammonia production are much less significant than changes in power and raw material costs.

Phosphorus and Phosphoric Acid Manufacturing Cost. – The net manufacturing costs of producing phosphoric acid via both the electric furnace and wet acid methods were computed. In these computations the variables considered and their values were as follows:

Interest rate (cost of money), %	2.5, 5, 10, and 20
Plant capacity, tons of P_2O_5 per day	300, 600, 1500, and 3435
Phosphate rock cost, dollars/ton	5.50, 9.60, 17, and 24
Sulfur cost, dollars/ton	32, 50, 65, and 80

Variable utility costs are the same as those used for ammonia, given earlier in this section. All costs are based on United States conditions. The underlined values are the reference values used in the typical example which follows. The capacity of 1500 tons of P_2O_5 per day, although large by today's standards, will, we believe, be a reasonable size for either an electric furnace plant or a wet acid plant in ten years for either the United States or a large developing country such as India. The largest existing wet acid plant produces about 1000 tons of P_2O_5 per day, whereas the largest electric furnace process installation now under construction will have a capacity of about 600 tons of P_2O_5 per day. With the presently rising cost of sulfur, $50.00 per ton is rapidly being approached in many parts of the United States and has been surpassed in many developing countries; for example, sulfur in India currently sells for $60.00 to $80.00 per ton. Phosphate rock at $9.60 per ton is the present cost of Florida pebble rock delivered 1500 miles to a United States port by ocean freighter.

The power consumption, carbon requirements, and yield of phosphorus in the electric furnace process are sensitive to the raw materials analysis; changes in analysis can be accommodated in the computer code. The two analyses studied are given below:

	Composition (%)	
	Florida Rock	Indian Rock
P_2O_5	31.1	31.4
CaO	46.5	43.3
SiO_2	9.5	8.8
Fe_2O_3	1.7	9.3

The balance in each case consists of alumina, fluorine, and about 5% ignition loss. The Florida rock composition was used in all the basic calculations; a few comparison runs were made with the Indian rock analysis. Yields in the latter case were lower (and costs higher) because more of the phosphorus was lost to the production of by-product ferrophosphorus.

Typical computed costs results are shown graphically in Fig. 5.15*a–d* for the four variables interest rate, plant capacity, sulfur cost, and phosphate rock cost respectively. Each plot shows gross manufacturing cost of phosphoric acid vs power cost in mills per kilowatt-hour for the two alternative processes and indicates the power costs at which the furnace process can compete with the wet acid process. The underlined cost values previously discussed are the common values for the four graphs; for this case the break-even power rate is 5.4 mills/kwhr, and the gross manufacturing cost is $105.00 per ton of P_2O_5 as 54% phosphoric acid.

Figure 5.15*a* shows that the break-even power cost is relatively insensitive to interest rate and that it decreases from 5.7 to 5.1 mills/kwhr as the interest rate increases from 2.5 to 20%. Plant capacity, as shown in Fig. 5.15*b*, is also a relatively insensitive variable except at low capacities; at 300 tons/day of P_2O_5 the break-even cost is 4 mills/kwhr, whereas at higher capacities (600 to 3435 tons/day) the break-even cost varies only between 5.2 and 5.5 mills/kwhr. Sulfur cost has a large effect on the break-even power cost, as shown in Fig. 5.15*d*, where the break-even cost varies from 2 to 8 mills/kwhr as sulfur cost is increased from $32.00 to $65.00 per ton. With the current United States price of sulfur at $49.00 per ton, the furnace method can compete with the wet acid process if the cost of power is less than 3.6 mills/kwhr. Finally, as shown in Fig. 5.15c, changes in phosphate rock cost have only a minor effect on break-even cost, as expected, since the main advantage of the furnace process in this com-

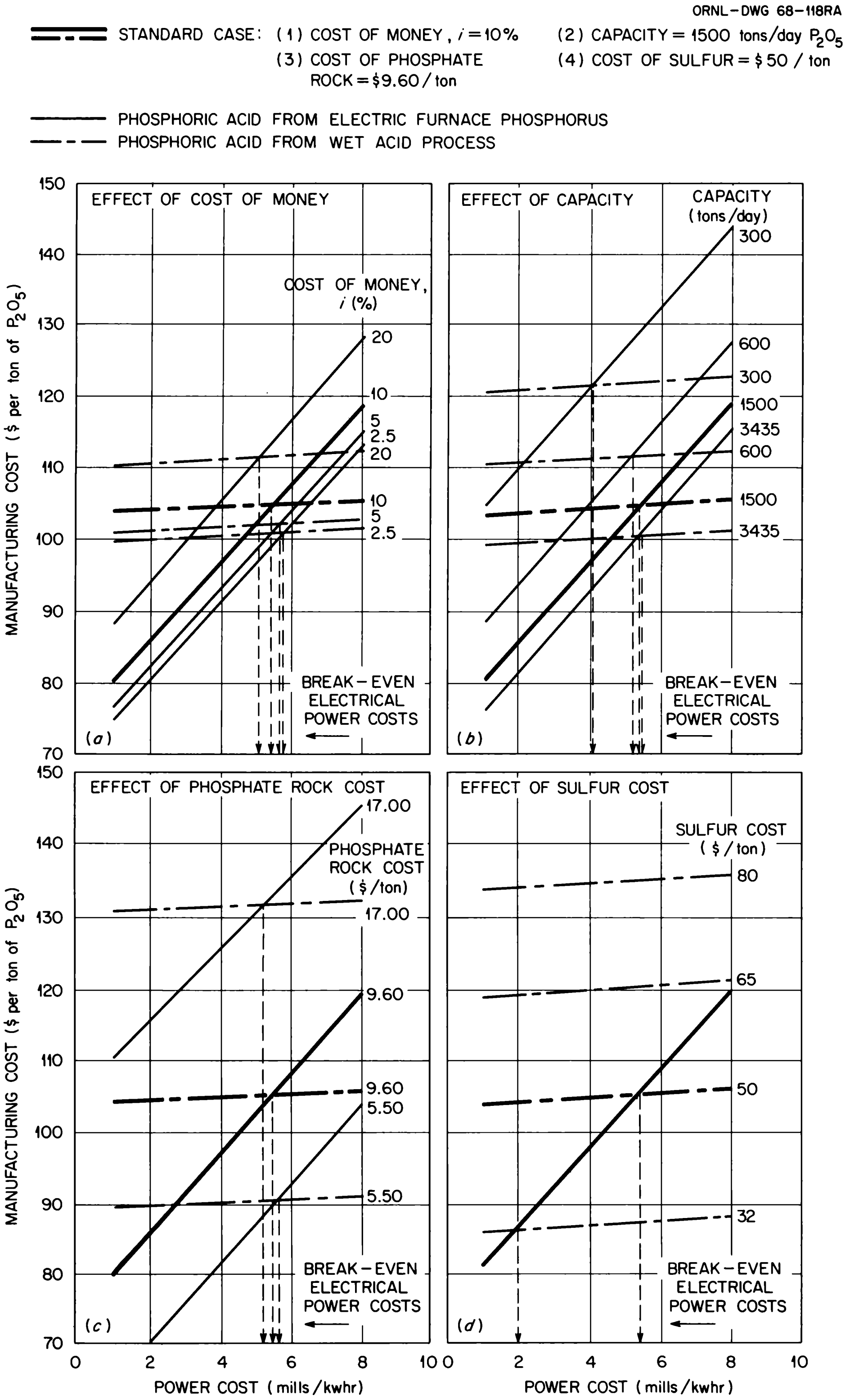

Fig. 5.15. Manufacturing and Break-Even Power Cost for Production of Phosphoric Acid.

parison is that it uses slightly less rock per ton of P_2O_5.

Aluminum Manufacturing Cost. – This section summarizes the studies made to determine the cost of producing aluminum from bauxite or imported alumina. Costs were computed in three steps: (1) production of calcined alumina; (2) production of molten aluminum, including the manufacture of the carbon anodes; and (3) fabrication of the molten aluminum to plate and bar.

Since the Bayer and Hall processes for the production of alumina and aluminum, respectively, have no competing processes in industrial use today, manufacturing costs were computed directly. In order to provide some sort of comparison, production of aluminum all the way from bauxite at varying bauxite and power costs was compared with the production of aluminum with power at 2 mills/kwhr from imported alumina, shipped 6000 miles, at $60.00 and $77.00 per ton. This is believed to be an increasingly good method of comparison since the latter case, which originally represented the aluminum industry practice in the northwestern United States and southwestern Canada, is becoming a much more widespread practice. The reason for this is the reduction in shipping costs made possible by shipment of alumina with approximately 1.5 to 2 times the aluminum content of bauxite. For example, bulk ocean shipping rates are given in Chap. 8 as 0.15 to 0.25¢/ton-mile. If alumina rather than bauxite is shipped 6000 miles (from Jamaica or Surinam to Seattle) a saving of about $10.00 per ton can be achieved.

The variables and their values used in the calculations were as follows:

Interest rate (cost of money), %	2.5, 5, 10, and 20
Plant capacity, tons/day	
Al_2O_3	120, 274, 548, and 1370
Al	60, 137, 274, and 685
Bauxite cost, dollars per ton of bauxite	3, 8, 11, and 14
Alumina cost, dollars per ton of Al_2O_3	60 and 77

Variable utility costs are the same as those used for ammonia, given earlier in this section. All costs are for United States conditions. The underlined values are the primary values used in the typical example which follows. The capacity of 274 tons/day (100,000 tons/year) of aluminum is about one-third of the world's largest existing aluminum plant and is relatively small for a highly developed country but very reasonable for a developing nation. Bauxite costs of $3.00 per ton are in line with costs at mines in Surinam, Jamaica, and elsewhere; costs of $8.00 per ton are typical of Jamaican ore delivered about 1000 miles to a refining plant on the United States Gulf Coast. Alumina costs of $60.00 to $77.00 per ton are typical of delivered Jamaican alumina costs in the Seattle, Washington, area.

Typical calculated costs are shown graphically in Figs. 5.16*a–d* for the four variables interest rate, plant capacity, bauxite cost, and alumina cost respectively. Each plot presents gross manufacturing cost of fabricated aluminum vs power cost in mills per kilowatt-hour and indicates the power costs at which locally produced aluminum can compete with aluminum produced in the northwestern United States with power at 2 mills/kwhr. Because only a single value (2 mills/kwhr) for power cost was considered for the northwestern United States cases, these cases appear as points on the four graphs. The underlined parametric values previously discussed are the common values for the four graphs; in this comparison the break-even power rate is 4.6 mills/kwhr, and gross manufacturing cost is $650.00 per ton of fabricated aluminum.

The break-even power rate is highly dependent on interest rate because of the large plant capital investment and decreases from 5.5 mills/kwhr at 2.5% to 2.9 mills/kwhr at a 20% interest rate, as shown in Fig. 5.16*a*. As shown in Fig. 5.16*b*, the break-even power cost is also sensitive, but to a lesser extent, on plant capacity; it varies from 3.3 to 5.1 mills/kwhr as the plant size is increased an order of magnitude from 60 to 685 tons of aluminum per day. Bauxite costs also have a fairly large effect on break-even power cost, as shown in Fig. 5.16*c*, where increasing the cost from $3.00 to $14.00 per ton of bauxite decreases the break-even power cost from 5.9 to 2.9 mills/kwhr. Finally, as shown in Fig. 5.16*d*, increasing the alumina cost from $60.00 to $77.00 per ton for the northwestern United States plant increases the break-even power cost for the local plant from 2.5 to 4.6 mills/kwhr.

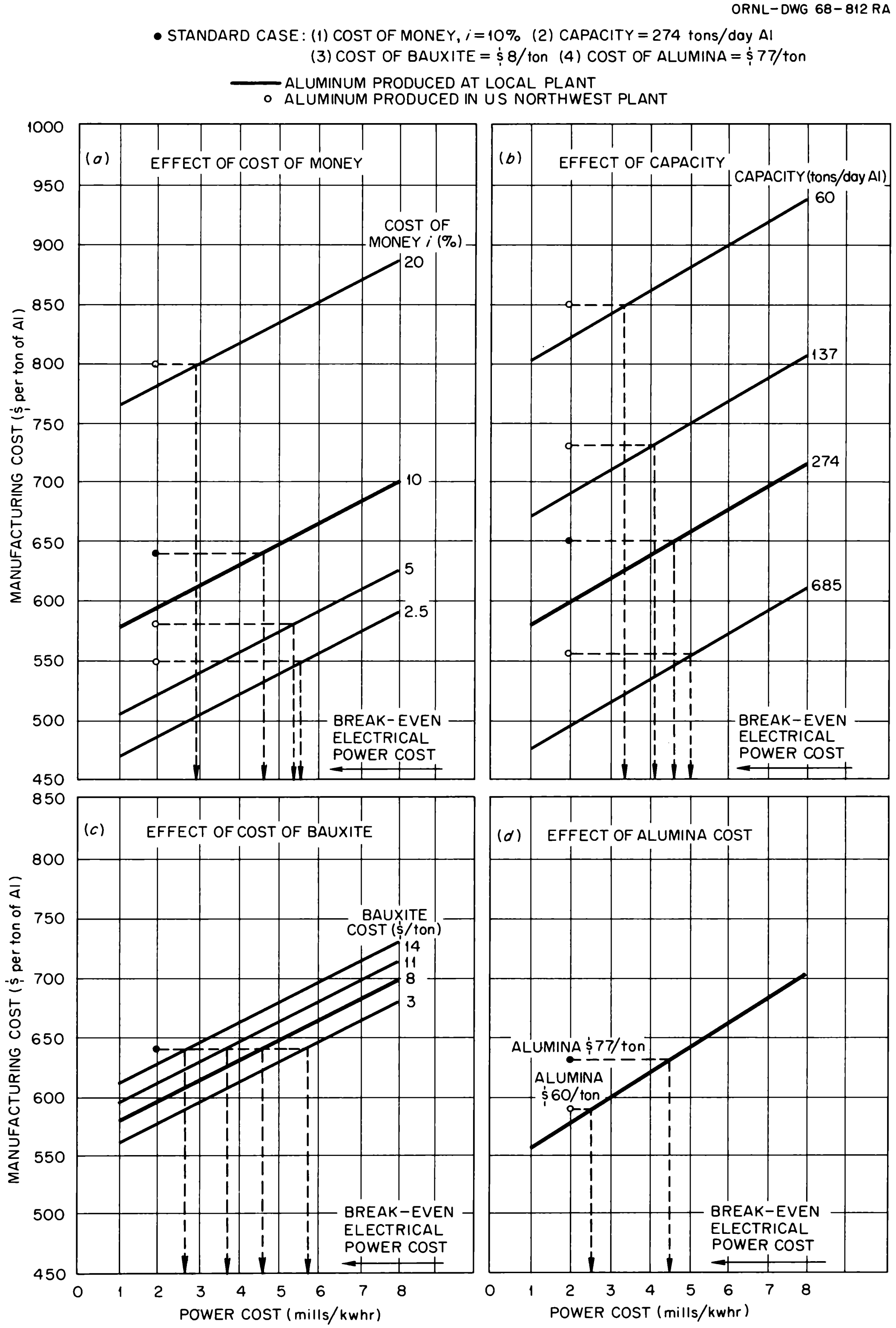

Fig. 5.16. Manufacturing and Break-Even Power Costs for the Production of Aluminum.

Solar Salt Manufacturing Costs. – One of the options which an agro-industrial complex located on an arid coast will have is the one of building a solar salt works to utilize at least part of the concentrated brine effluent from the seawater evaporator. Distinct savings in solar ponding costs can result from processing evaporator concentrate instead of regular seawater. In addition to producing salt for national use and export, the salt and its bitterns by-product are the source of a number of additional products. The salt itself can be used for the production of chlorine, caustic, hydrogen (for additional ammonia synthesis), hydrochloric acid, and sodium carbonate, and the bitterns are the raw material for the recovery of potassium fertilizers, anhydrous magnesium chloride, magnesium metal, and gypsum for sulfuric acid and cement manufacture. The caustic, sodium carbonate, and hydrochloric acid are materials which also provide for a totally internal system, if salt is recovered at the complex, of preevaporation seawater treatment. The economics of salt and caustic-chlorine production is discussed below; the costs of seawater treatment and recovery of other chemicals from solar salt bitterns are discussed both below and in Appendix 5A.

An arid coastal location provides warm temperatures and considerable sunlight, both prerequisites to efficient solar evaporation. The aridity of such an area also gives fair assurance of low population density, which is important because a solar salt works requires many square miles of land. Impervious ground, where available, is very desirable. The final general requirement, the need for very flat terrain, will depend on the topography of the particular area.

In this study for a non-United States solar salt installation, salt production capacities of 1,000,000 to 5,000,000 tons of salt per year were considered, which correspond approximately to 3,000 to 15,000 tons/day at a 91% load factor or onstream efficiency. One million tons per year is considered a large plant today, but for the future 5,000,000 tons is not unrealistic. For example, the National Bulk Carriers Corporation currently operates a 3,000,000-ton/year solar salt works in Baja California and plans to expand it to 5,000,000 tons/year around 1970 and ultimately to 10,000,000 tons/year.[15] At a salt capacity of 1,000,000 tons/year only 1.6% of the brine effluent from a 1000-Mgd seawater evaporator, operating at a concentration ratio[16] of 2, would be utilized by the solar salt works. At concentration ratios of 2.5, 3, and 4, the percentage of the brine effluent used would increase to 1.9, 2.1, and 2.4% respectively. At 5,000,000 tons/year a solar salt works would require slightly more than the total amount of brine effluent from a 100-Mgd seawater evaporator operating at an evaporation ratio of 3. The above data were obtained using the values: 3% NaCl in raw seawater and 75% recovery of salt.

With regard to the land requirements for solar salt plants, actual requirements will vary with the climatic conditions of the area under consideration. In general, for raw seawater, about 40,000 working acres are required per million annual tons of salt recovery at a 91% plant factor. When seawater evaporator effluent containing 6% NaCl (concentration ratio = 2) is the raw material to the salt works, this area is reduced to about 24,000 working acres per million annual tons; 9% NaCl (concentration ratio = 3) requires 16,000 working acres, and 12% NaCl (concentration ratio = 4) requires 12,000 working acres. This represents area reductions of 40, 60, and 70%, respectively, over the raw seawater case and can result in significant savings in solar ponding costs. For example, in Fig. 5.17*a*, for an interest charge of 10%, if $200.00 per acre is required for land and land improvement costs (dike construction, roads, pump houses, etc.), the use of seawater concentrated by a factor of 2 would result in a saving of $0.38 per ton of NaCl in solar ponding costs; at a concentration factor of 2.6, $0.50 per ton. These savings are 38 and 50% of the manufacturing cost of solar salt when the cost is $1.00 per ton. The cost of solar pond construction varies widely depending on the terrain of the land and other factors. For salt recovery from seawater, the cost may vary from $100.00 to $300.00 per acre. However, when recovering chemicals from concentrated brines like Great Salt Lake (ten times seawater concentration), it is possible to justify higher unit costs, such as $600.00 to $700.00 per acre.

The results of the computer calculations of solar salt production costs at a foreign plant are presented in Fig. 5.17*b* for costs of money, *i*, be-

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[15] Private communication, National Bulk Carriers Corporation, New York.

[16] Gallons of seawater evaporator feed per gallon of evaporator effluent.

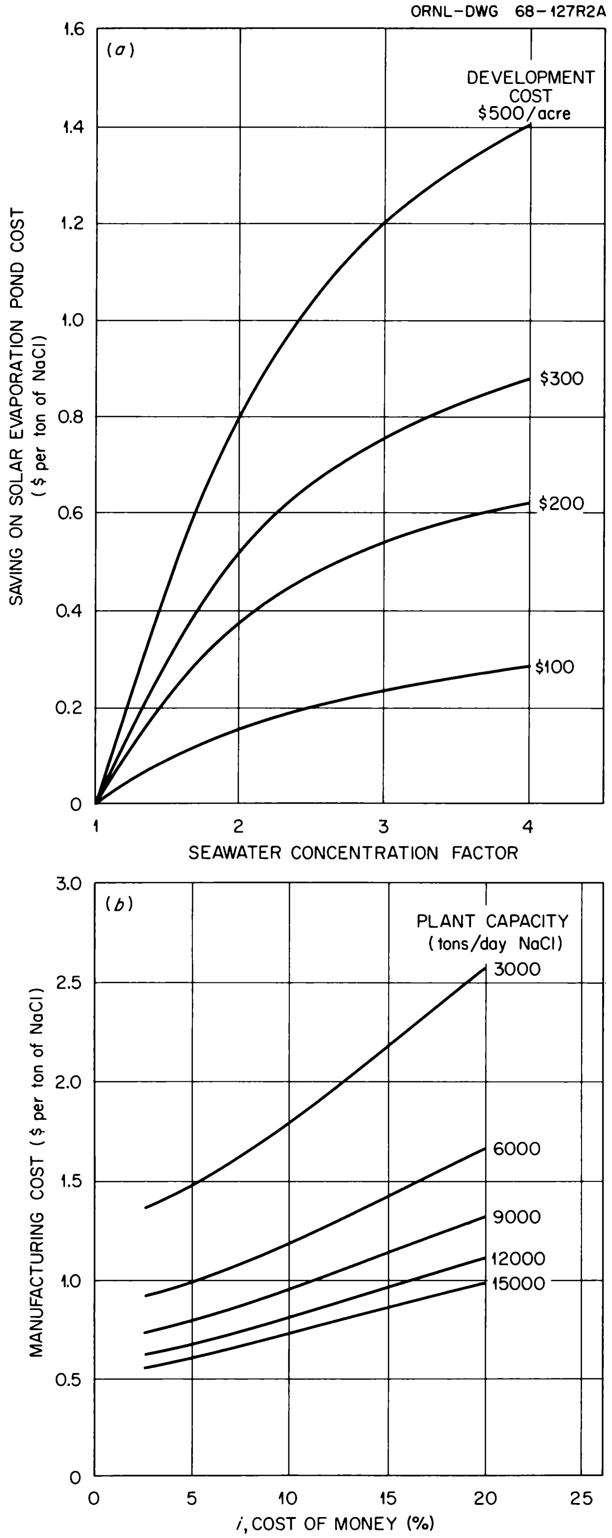

Fig. 5.17. (*a*) Savings in Solar Evaporation Pond Cost by Concentrating Seawater Prior to Solar Evaporation at a Cost of Money, $i = 10\%$; (*b*) Manufacturing Costs of Solar Salt.

tween 2.5 and 20% for the five base capacities noted earlier. The production costs vary, as shown, from $0.50 to $2.50 per ton of salt. Labor was costed at $0.67 per hour, but labor efficiency was assumed to be only one-third of that for a plant in the United States. It is significant that the median case of a 3,000,000-ton/year plant under 10% financing produces salt at slightly under $1.00 per ton, which is the cost of mined salt in the United States at the mine. Although not shown, there is a very slight variation of manufacturing cost with cost of electricity. The values given are for power at 2 mills/kwhr but apply almost exactly for 1 and 4 mills/kwhr as well. About 2¢/ton must be added when power cost is 8 mills/kwhr. The concentrated brine feed was given zero cost.

Caustic and Chlorine Manufacturing Costs. – The manufacturing costs of chlorine and caustic for a number of situations were computed. Since electrolysis of brine is the only really significant source of chlorine throughout the world, no other production method for chlorine was considered. In these calculations the variables and their values are as follows:

Interest rate, %	2.5, 5, <u>10</u>, and 20
Plant capacity, tons/day of Cl_2	300, 500, <u>1000</u>, and 2000
Salt cost, dollars/ton	1, <u>3</u>, 6, and 10

The underlined values are, as before, for the standard or reference case. Variable utility costs again are the same as those used for ammonia.

A capacity of 500 tons/day of chlorine is average by present United States standards, but in the future the average could be 1000 tons/day; the largest chlorine plant today has a capacity of 5000 tons/day. In most developing countries, a 1000-ton/day chlorine plant would be large. The $3.00 per ton cost of salt would be the cost when transportation is included to deliver the salt several thousand miles by ocean freighter; for example, $1.00 per ton solar salt made on the coast of India is sold at ports in Japan for $3.00 per ton.[17]

Typical computed costs are shown graphically in Fig. 5.18*a*–*c* for interest rate, plant capacity,

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[17] Private communication, U.N. Industrial Development Organization, September 1967.

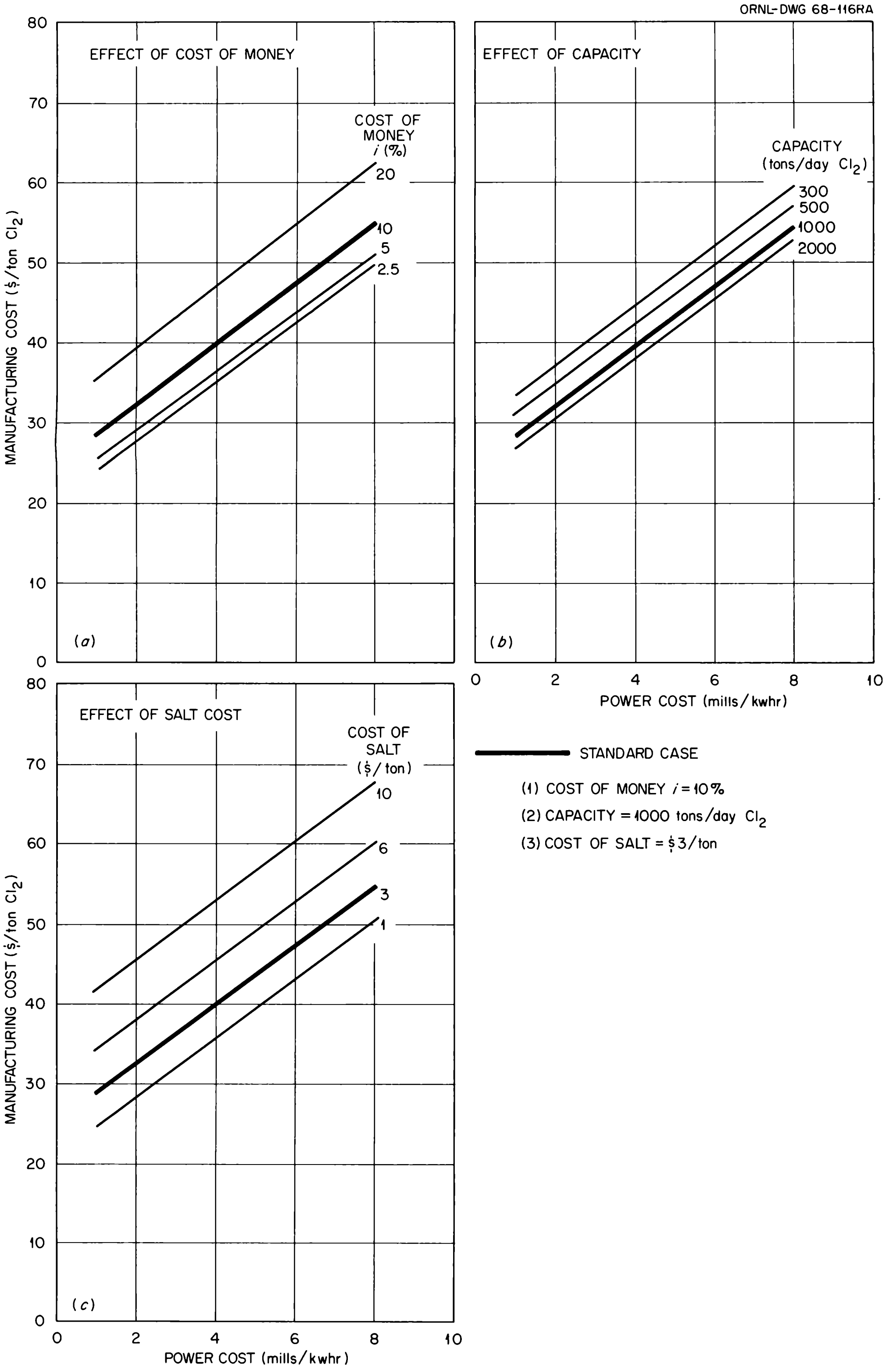

Fig. 5.18. Manufacturing Costs for Production of Chlorine.

and salt cost, respectively, as variables. Each plot shows the gross manufacturing cost of chlorine vs power cost in mills per kilowatt-hour. No break-even power costs are shown since no comparison with a competing process or situation was used. The heavy lines represent the standard case of 10% cost of money, 1000 tons of Cl_2 per day, and salt at $3.00 per ton.

Costs of Seawater Treatment. – A cost comparison of the four seawater treatment methods listed in Sect. 5.3.3 indicates that treatment with equimolar amounts of hydrochloric acid and caustic soda is generally the least expensive of all the alternatives (Sect. 5.3.3) and that treatment with sulfuric acid is the next most economical. The HCl-NaOH method is sensitive to power cost because it is based on the use of brine electrolysis, whereas use of sulfuric acid is almost completely insensitive to power cost. With power at 4 mills/kwhr the HCl-NaOH method is competitive with sulfuric acid produced from sulfur at $45.00 per ton, a very low price under present conditions. A full discussion of this subject is presented in Appendix 5A.

5.5.2 Building Block Cost Summary for Magnesium Chloride, Magnesium Metal, Potassium Fertilizers, Sulfuric Acid, Portland Cement, Iron, Steel, Acetylene, and Soda Ash

As previously indicated, production costs for a number of chemical products were determined in insufficient detail to make parametric computer studies; costs for these are summarized here. These products include anhydrous magnesium chloride, magnesium metal, potassium fertilizers, sulfuric acid, and portland cement from seawater; and iron, steel, acetylene, and soda ash. Sufficient data have been obtained for the production of seawater chemicals to do a computer cost analysis, which is planned for the near future.

Costs of Recovery of Chemicals from Solar Salt Bitterns. – The economics of the recovery of the seawater chemicals listed above and of the electrolytic reduction of anhydrous magnesium chloride to magnesium metal and chlorine was studied in considerable detail. Typical results of these studies are shown in Table 5.4 for 10% cost of money, a power rate of 4 mills/kwhr, and United States conditions. In addition, manufacturing costs for anhydrous magnesium chloride were also determined for the non-United States case. Typical present-day United States f.o.b. prices for the various products are also given.

For several of the products where high-temperature ($\geqq 2000°F$) heat is required, a comparison is made between the use of fossil fuels at 50¢/MMBtu and electric heating at 4 mills/kwhr.

As shown in Table 5.4 the cost of producing magnesium metal, using anhydrous magnesium chloride produced locally by fossil fuel heating, was found to be $360.00 per ton under United States conditions and 10% cost of money. Under the same conditions the cost of the magnesium metal smelting step alone was $290.00 per ton. The above results assumed no credit for the coproduced chlorine. When a $50.00 per ton credit is assumed, the two costs given above are reduced to $260.00 and $190.00 per ton of metal respectively. One of the advantages of magnesium metal production by this method is that it also produces chlorine (without caustic soda as a coproduct), which is normally in large demand in highly industrialized nations.

A more complete discussion on magnesium metal production costs and the economics of the recovery of chemicals from seawater is given in Appendix 5A.

Iron and Steel Production.[18] – The economics of the production of iron and steel is based on the eight processing schemes of Table 5.5. The iron and steel cost study was limited by the fact that, although a number of alternatives to the conventional (blast furnace, coke oven, basic oxygen furnace) steelmaking system have been tested, insufficient economic data are presently available on many of the alternatives to make complete comparisons. Thus the economic study was limited to a comparison of approximate capital costs and electrode, fuel, and electric power costs.

The conclusions of this study are summarized in Table 5.5. As noted in the table, the cost figures presented should be valid for the capacity range of 1,000,000 to 2,000,000 tons of steel per year, the capacity of interest to the larger developing countries. At these capacities, all the alternatives represent a capital investment 20 to 40% below the conventional method (blast-furnace–oxygen steelmaking). At higher capacities this

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[18] Iron and Steel Study prepared by A. M. Squires, CCNY.

advantage may well decrease or even disappear since the scaling factor for the massive conventional iron- and steelmaking equipment is less than the factor for most of the alternatives and because the need for duplication of equipment for conventional systems occurs at higher capacities.

Other conclusions which can be made in regard to capital costs among the various alternatives of Table 5.5 are that, from a capital-cost standpoint, electrolytic hydrogen is more expensive to use than hydrogen from steam-methane reforming for gaseous reduction of iron ore and that the electric furnace route to steel is less costly than oxygen steelmaking and the use of the traveling-grate prereduction–electric pig–oxygen steelmaking route. Coal, fluid fuel, and electrical energy requirements and the electrode carbon requirements for the various alternative processes are also given. Column A presents an optimistic estimate of the total energy and carbon costs at 30¢/MMBtu for fossil fuels and 2 mills/kwhr for electricity; column B gives a more conservative estimate based on 50¢/MMBtu for fuel and 3 mills/kwhr for power. These data indicate that the use of electrolytic hydrogen for the gaseous reduction of iron ore rather than hydrogen from reforming results in higher energy as well as higher capital costs. Conversely, the use of electric steel furnaces results in higher energy costs than required for oxygen furnaces, thereby compensating for the capital cost differences.

With regard to the Eketorp direct iron-making process, the capital costs appear to be in the same range with the oxygen steelmaking systems, but the energy costs are somewhat lower. For the hydrogen reduction process that employs electrolytic hydrogen, carbiding with carbon monoxide from a phosphorus-producing electric furnace or other source, and oxygen steelmaking, the capital costs are in line with systems using

Table 5.4. Typical Manufacturing Costs for Seawater Chemicals

Cost of money, i = 10%; power cost rate = 4 mills/kwhr

Product	Manufacturing Cost (dollars/ton)		Present United States (f.o.b.) Price (dollars/ton)
	United States	non-United States	
Potassium chloride	11		16
Potassium sulfate	17		25
Sulfuric acid and cement[a]			
Fossil fuel heating[b]	20[c,d]		
Electric heating	28[c,d]		
Anhydrous magnesium chloride			35
Fossil fuel heating[b]	22[d]	21	
Electric heating	37[d]	32	
Magnesium metal			700
Fossil fuel heating of $MgCl_2 \cdot 6H_2O$, no Cl_2 credit	360		
Including $50.00 per ton credit for Cl_2 co-product	260		

[a] Present U.S. (f.o.b.) prices for portland cement and sulfuric acid are $17.00 and $35.00 per ton respectively.

[b] Fossil fuel assumed to cost 50¢/MMBtu.

[c] Cost per co-ton.

[d] Break-even power cost for electric heating vs fossil fuel at 50¢/MMBtu is 1.8 mills/kwhr. At this power cost the manufacturing cost of anhydrous magnesium chloride is $21.00 per ton for U.S. conditions and $19.00 per ton for the non-U.S. case.

Table 5.5. Routes to Steel – Preliminary Evaluations for Grass-Roots Plants on the 1,000,000- to 2,000,000-ton/year Scale

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Scrap assumed to be unavailable

Processing Scheme	Capital Cost (dollars per ton per year)	Energy Requirements			Electrode Carbon (lb)	Cost of Energy and Carbon (dollars per ton of steel)	
		Coal (lb)[a]	Fluid Fuel (MMBtu)[b]	Electricity (kwhr)		Column A[c]	Column B[d]
Ore sintering + coking + blast furnace + oxygen	73	2175 (28.3)	1.5	30		9.00	14.99
Traveling-grate prereduction + electric pig furnace + oxygen	54	1600 (20.8)		980	8 at 15¢	9.40	14.50
Hydrogen from methane + H-iron + electric furnace	44		18.1	645	11 at 30¢	10.02	14.29
Hydrogen from methane + H-iron + oxygen (Kaldo)	52	320 (4.2)	18.1	190		7.07	11.72
Eketorp "direct" ironmaking	52?		17.0	180		5.46	9.04
Electrolytic hydrogen + H-iron + electric furnace	53			4480	11 at 30¢	12.26	16.74
Electrolytic hydrogen + H-iron + oxygen (Kaldo)	56	320 (4.2)		3930		9.12	13.89
Electrolytic hydrogen + H-iron + carbiding + oxygen (conceptual)	48?		6.0 (as CO)	2130		6.06	9.39

[a] Values in parentheses are in million Btu.

[b] Million British thermal units.

[c] Fossil fuel at 30¢/MMBtu and electricity at 2 mills/kwhr.

[d] Fossil fuel at 50¢/MMBtu and electricity at 3 mills/kwhr.

electric furnace steelmaking, and the energy costs are nearly as low as the Eketorp process requirements. Although not shown, use of hydrogen from reforming might result in even lower costs.

A second comparison was made for a fuel-rich country such as Kuwait, which might be unable to market all its natural gas production. In this case, as shown in Table 5.6 for three of the routes to steel, the costs for energy are drastically reduced. These cost advantages are probably not large enough to be decisive. Costs relating to supplies of both raw materials and labor could easily offset the energy-cost advantage. The inability of the fuel-rich country to market its natural gas is a reflection of the lack of local markets for all commodities – not merely gas – and probably also reflects an absence of people.

Finally, the argument that much of the steel production in the future in developing countries will result from the purchase and reclamation of scrap steel from advanced countries, as is done in industrialized Japan, appears invalid, since there is a strong trend in the highly industrialized, large steel-consuming nations to reprocess their own scrap.

It is our opinion that the results of this study on alternative routes to steel for developing countries as compared with the blast furnace technology appear sufficiently attractive to warrant further economic studies on the various alterna-

Table 5.6. Routes to Steel – Rough Evaluations for Grass-Roots Plants in a Fuel-Rich Country Unable to Market Natural Gas

Processing Scheme	Capital Cost (dollars per ton per year)	Energy Requirements			Electrode Carbon (lb)	Cost of Energy and Carbon (dollars per ton of steel)
		Petroleum Coke (lb)	Fluid Fuel (MMBtu)	Electricity (kwhr)		
Hydrogen from methane + H-iron + electric furnace	44		18.1 at 10¢	645 at 0.2¢	11 at 25¢	5.85
Hydrogen from methane + H-iron + oxygen (Kaldo)	52	170 (2.4[a] at 25¢)	18.1 at 10¢	190 at 0.2¢		2.79
Eketorp direct steelmaking	52?		20.0 at 10¢	180 at 0.2¢		2.36

[a] Million British thermal units (MMBtu).

tives, including the preparation of preliminary design studies by an architect-engineer, on the more attractive alternatives to firm up the costs. The process utilizing the hydrogen reduction of iron ore followed by fluid-bed carbiding with carbon monoxide appears sufficiently interesting to warrant at least some preliminary research and development.

Manufacturing Costs for Acetylene.[19] – A comparison was made of the production of acetylene from naphtha by the electric arc and "partial oxidation" processes. The assumed plant capacity (116.4 tons/day) is sufficient for the production of 250 tons of vinyl chloride per day by the conventional hydrogen chloride process.

A study of the various electrical processes led to the choice of the Orbach MHD hydrogen plasma process using a specific energy consumption of 2.75 kwhr per pound of acetylene produced, and a yield of 34.5 wt % on the naphtha charged. Using a naphtha feed value of about 1¢/lb (ex-refinery), forecast as a reasonable figure for India in the next five years, a 4-mill power cost, and a 40¢/MMBtu fuel gas credit, a figure of 5.1¢/lb is estimated as the cost of the acetylene produced. By lowering the power cost to 2.5 mills/kwhr and assuming some other favorable factors, the product cost can be lowered to 4.4¢/lb.

The SBA-Kellogg partial oxidation process has been taken as representative of the alternative route. A weight percent yield of 35% of acetylene can be expected when producing close to the minimum of ethylene, which is sent to tail gas. With the unit values assumed and including a fuel value of $0.40/MMBtu, the cost of acetylene comes out at 7.8¢/lb, nearly 50% higher than that shown for the arc process.

Where cheap power is available the arc process, and more particularly that using hydrogen plasma, producing high yields of high acetylene concentration gases, should thus be in a most favorable position; its further investigation and development are clearly warranted.

Soda Ash Manufacturing Costs. – When caustic is used for seawater treatment, 23% of the calcium precipitates as $CaCO_3$, and an evaporator temperature of 294°F is attainable. If higher temperatures are desirable, soda ash has to be added to precipitate more calcium. This is obtained either by the carbonation of caustic soda or by the Solvay process. The former method is not advisable in a non-United States location because the additional caustic requirement could create the problem of disposing of the co-product chlorine.

The Solvay process not only provides soda ash for seawater treatment but also provides calcium chloride for possible internal use within the complex, such as in gypsum recovery and the production of anhydrous magnesium chloride from seawater. The cost data in Table 5.7 are for a 1000-ton/day Na_2CO_3 plant.

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[19] Acetylene study made by W. E. Lobo, consulting chemical engineer.

Table 5.7. Cost Summary of Soda Ash Production by the Solvay Process

Capacity: 1000 tons of Na_2CO_3 per day

	Production Cost (dollars/ton) with Electric Power at –			
	1 mill/kwhr	2 mills/kwhr	4 mills/kwhr	8 mills/kwhr
Direct cost	18.00	18.40	19.20	20.50
Total manufacturing cost with cost of money, *i*, of:				
2.5%	27.10	27.50	28.30	29.60
5%	29.30	29.70	30.50	31.90
10%	34.10	34.50	35.40	36.80
20%	45.20	45.60	46.60	48.10

The capital cost of a 1000-ton/day Na_2CO_3 plant is $35 million;[20] the scaling factor is 0.82. All items of the operating cost will scale linearly except labor, which is about 0.68.

The market price for soda ash is currently $31.00 per ton f.o.b. producing plant, which according to Table 5.7 would be equivalent to a manufacturing cost that includes a 6% cost of money. In a developing nation like India, a soda ash plant could be justified provided the total manufacturing cost did not exceed $41.00 to $46.00 per ton of Na_2CO_3, allowing $10.00 to $15.00 per ton for the cost of shipping. This price range would probably be pretty firm. In general, there is no competition from caustic soda, because its demand typically is equal to or greater than its supply in a developing nation.

5.5.3 Summary of Building Block Results

Before proceeding to a discussion of the economics of industrial complexes it may be well, at this point, to summarize the cost results for the individual processes and products already presented in this section. First, it should be reemphasized that all costs are for battery limit plant situations and that the costs of off-site facilities are excluded; second, nearly all the results are for United States economic conditions during mid-1967.

Most of the preceding information concerned the four power-intensive products: ammonia from electrolytic hydrogen, electric furnace phosphorus, aluminum, and caustic-chlorine. First, it was shown (Fig. 5.7) that the controlling manufacturing costs for ammonia, phosphorus, and aluminum were for power, raw materials, and capital investment, respectively, and that for caustic-chlorine, cost of electricity was controlling at high power rates and capital costs at low power rates. The contribution of power cost to total manufacturing cost was shown (Fig. 5.8) to vary from 70% for ammonia to 14% for aluminum ingot when the power rate is 4 mills/kwhr.

The magnitudes of the various direct and indirect cost components and the overall manufacturing cost are shown in Table 5.8 for the major power-cost-intensive products and their precursors. The various costs are for the reference values of the several parameters studied, as listed on Figs. 5.9, 5.15, 5.16, and 5.18 for ammonia, phosphoric acid, aluminum, and chlorine, respectively, and at a power cost of 4 mills/kwhr.

In order to provide bases for production cost comparisons, the manufacture of ammonia from electrolytic hydrogen was compared with its synthesis from hydrogen obtained from steam-naphtha (or methane) reforming (Fig. 5.12), the production of phosphoric acid from electric furnace phosphorus was compared with its manufacture by the acidulation of phosphate rock with sulfuric acid (Fig. 5.15), and the production of fabricated aluminum from bauxite shipped about 1000 miles

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[20] Private communication, Diamond Alkali Co.

Table 5.8. Production Cost Summary for Major Products at Parametric Reference Values

	Ammonia		Phosphoric Acid[a]		Alumina from Bauxite	Aluminum		Caustic-Chlorine	
	From Electrolytic Hydrogen	From Reformed Naphtha	By Electric Furnace P	By Wet-Acid Process		(Ingot)	(Fabricated)	Chlorine	50% Caustic
Production costs, dollars/ton									
Raw materials	0	21.60	49.81	90.10	20.83	153.08[b]	382.50[c]	5.55	30.65[d]
Utilities[e]	33.62	3.64	21.99	1.30	7.85	56.66	13.40	13.25	1.58
Labor and Overhead	1.20	1.20	5.34	6.45	3.73	57.81	88.01	2.65	0.27
Supplies	1.68	2.14	3.74	2.23	3.82	13.97	27.25	5.57	0.30
Total direct costs	36.50	28.58	80.88	100.08	36.23	281.52	511.16	27.02	32.80
Recovery of investment	2.04	1.68	2.16	0.64	4.90	22.02	26.90	1.68	0.47
Return on investment	6.49	5.33	6.86	2.02	15.58	69.96	85.48	5.33	1.48
Interest on working capital	0.76	0.60	1.59	1.82	0.93	6.13	10.42	0.57	0.59
Total indirect costs	9.29	7.61	10.61	4.48	21.41	98.11	122.80	7.58	2.54
Conversion, P_4 to H_3PO_4			5.33						
Total manufacturing cost	45.79	36.19	96.82	104.56	57.64	379.63	633.96	34.60	35.34
Plant capacity, tons/day	1000	1000	1500	1500	548	274	274	1000	1130
Plant investment, 10^6 dollars	25.2	18.5	40.3	19.2	31.2	101.1	186.6	18.5	5.8

[a] As P_2O_5.

[b] Includes all costs of alumina refining.

[c] Includes all costs of alumina refining and aluminum smelting.

[d] Includes all costs of brine electrolysis.

[e] Power cost = 4 mills/kwhr.

by sea from a bauxite mine was compared with its manufacture using alumina shipped 6000 miles by sea to a plant where the power rate was 2 mills/kwhr (Fig. 5.16). In these comparisons break-even power cost was defined as that power rate for which manufacturing costs by the alternative methods were equal. Figure 5.19 summarizes the effect of the various parameters studied on the break-even power costs for the three products noted above and for caustic-chlorine (Fig. 5.18) at a production cost of \$40.00 to \$50.00 per ton of chlorine. For all products the parameters were cost of money, plant capacity, and raw materials costs. An additional parameter for ammonia was water-electrolysis cell current density for the experimental Allis-Chalmers cell chosen as the standard.

In Fig. 5.19 the abcissa is break-even power cost and the ordinate is without significance. For each product the effect on break-even power cost of each parameter taken alone is shown by a horizontal line; the limits for these parameters are given at each end of the line. The parameter is noted to the right of each line along with its units and value for the standard or reference case. The products are arranged downward by increasing break-even power cost or profitability. Figure 5.19 shows that the reference case break-even power cost for ammonia is 2.6 mills/kwhr and that the controlling parameter is naphtha cost for the steam-naphtha reforming process alternative. The break-even power cost for aluminum is 4.6 mills/kwhr, and here both capital and raw materials costs are highly significant. For phosphoric acid the mean break-even power cost is 5.3 mills/kwhr, and the cost of sulfur is the controlling parameter for the wet acid process alternative. Finally, the median power cost to produce chlorine at \$45.00 per ton is 5.6 mills/kwhr, and all parameters are significant.

Additional studies made on ammonia production included: (1) the use of steam-methane reforming in the United States as a source of hydrogen for ammonia synthesis (Fig. 5.12), (2) the use of advanced De Nora and General Electric as well as Allis-Chalmers water electrolysis cells (Fig. 5.11), and (3) the use of off-peak power for the production of electrolytic hydrogen for ammonia

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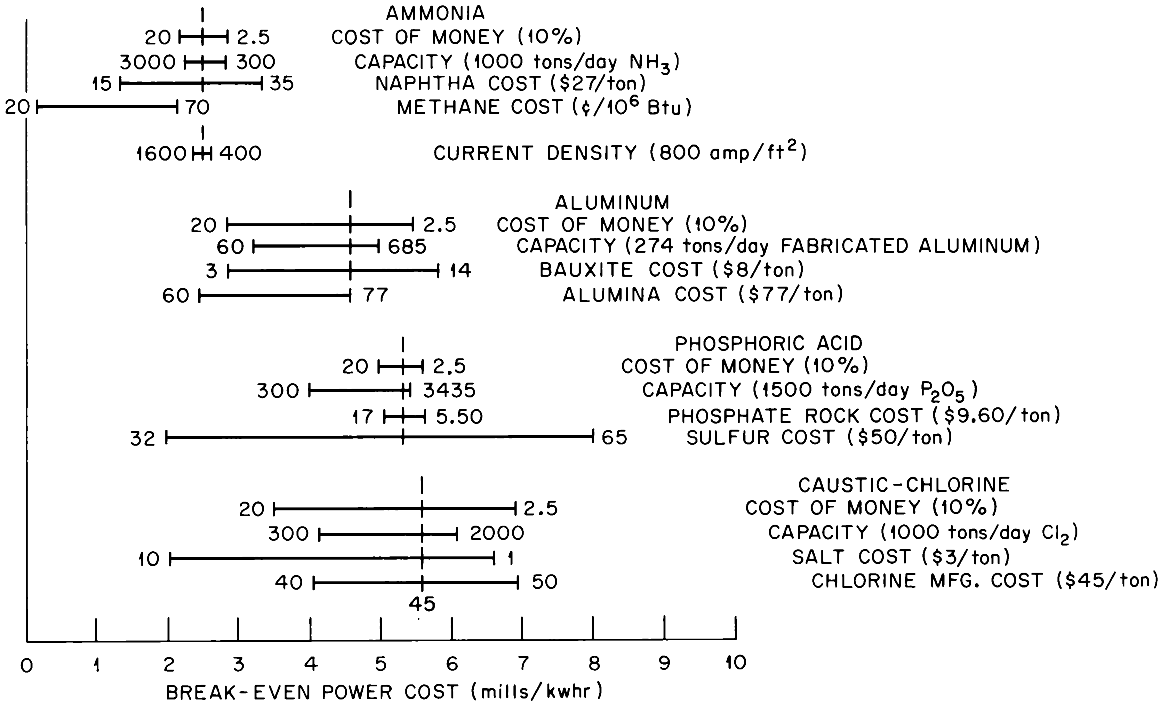

Fig. 5.19. Summary of Manufacturing Cost Results for Ammonia, Phosphoric Acid, Aluminum, and Caustic-Chlorine Production.

synthesis (Fig. 5.13). The steam-methane study showed that for areas in the United States where natural gas costs 35¢/MMBtu, the use of electrolytic hydrogen is competitive at a break-even power cost of 1.5 mills/kwhr. This compares with an average break-even power cost of 3 mills/kwhr for the use of steam-naphtha reforming (at $27.00 per ton of naphtha) in overseas installations. With regard to the three advanced water electrolysis cells, all three were found to be competitive (within 10%) and to be able to produce ammonia at a cost about 30% less than with presently used commercial cells. Further development of the General Electric cell, particularly the use of a carbon monoxide anode atmosphere if carbon monoxide is available elsewhere in the complex at no cost, is expected to result in large future savings. On the basis of the method studied for the exploitation of off-peak power, the power rate would have to be 2.6 or 2.3 mills/kwhr (compared with a rate for continuous service of 3 mills/kwhr) to break even for operational periods of 18 or 12 hr/day respectively. For operating 6 hr/day, the break-even off-peak power cost was 1.1 mills/kwhr.

Determination of production costs for ammonium nitrate, urea, and nitric phosphate fertilizers (Fig. 5.14) indicated that production of these secondary products, particularly nitric phosphate, was highly profitable.

In non-United States locations, where a large dual-purpose plant (nuclear reactor plus seawater evaporator) is much more apt to be installed than in the United States, the concentrated brine from the evaporator appears to be a very excellent source of salt and other seawater chemicals when markets exist for these products. At an evaporator concentration ratio of 2 the saving in land required over the use of raw seawater for solar salt production is about 40%. This amounts to about 40¢ per ton of salt, based on a land cost of $10.00 to $50.00 per acre plus a land improvement cost of $250.00 per acre. This represents a saving of about one-third in the cost of solar salt for a 2,000,000-ton/year salt works at 10% cost of money, which produces salt for $1.20 per ton when evaporator effluent is used.

Less extensive studies were made on the production costs of chemicals from the solar salt bitterns (potassium salts, magnesium chloride, magnesium metal, cement, and sulfuric acid) and of acetylene by the arc process and iron and steel. Since none of these were used in the complexing studies, they will not be discussed further.

5.6 Summary of Industrial Complexing Cost Parameters and Results

This section explains the techniques which were evolved in utilizing the industrial building block data to compute the costs for industrial complexes. Typical results obtained in the application of these techniques are also presented and analyzed. Results on calculations for nuclear-industrial and nuclear agro-industrial complexes are reported in Chap. 7.

5.6.1 Methods and Parameters Used in Industrial Complexing

This section explains the methods which were employed to utilize the building block data reviewed in Sect. 5.5 for the computation of costs for an industrial complex and includes discussions of off-site costs, integration of processes, and raw materials and product values used in complexing. Conversion of United States-based costs to conditions in a developing country was discussed in Chap. 3.

Off-Site Costs. – Manufacturing costs of products from the various industrial processes, for which typical values are given in a companion report,[21] are not gross manufacturing costs since they are based only on the capital investments required for battery-limits plants and thus lack necessary support (or off-site) facilities such as maintenance shops; administrative facilities; fire, safety, health, and security needs; railroads; roads; raw material unloading and product loading facilities; water distribution and sanitary facilities; etc. To provide for these support facilities, two functions giving fractional allowances for off-sites:

$$0.25/(10 \times \text{sum of battery limits plant costs in dollars} \times 10^{-6})^{0.097} \quad (1)$$

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[21] H. E. Goeller, *Tables for Computing Manufacturing Costs of Industrial Products in an Agro-Industrial Complex*, ORNL-4296 (to be published).

and

$$0.128/(\text{sum of battery limits plant costs in dollars} \times 10^{-6}/100)^{0.329} \quad (2)$$

were used. Function (1) gives complex support facilities as a percentage of total battery limits plant costs for total capital investments in the range of 10^5 to 10^8 dollars; function (2) applies to the range of 10^8 to 10^9 dollars. The use of these functions results in off-site capital costs of \$1.5 million for plant investments of 10^7 dollars, \$13 million at 10^8 dollars, and \$60 million at 10^9 dollars. These functions were used throughout to obtain the results presented in this section.

For complexes manufacturing aluminum, function (2) appears to allocate too much capital to off-site facilities, because plants associated with this process are highly capital intensive; therefore, for the nuclear industrial and nuclear agro-industrial complexes in Chap. 7 which include an aluminum plant, support facilities were allocated according to estimates provided by the R. M. Parsons Company of Los Angeles; these are discussed in Chap. 7.

The lifetime of all production plants in an industrial complex was assumed to be 15 years. This is somewhat conservative for the aluminum industry but quite reasonable for the other processes, considering factors leading to the obsolescence of certain processes.

Integration of Processes. – In addition to reduction of the total capital cost of the complex by the use of common support facilities, the integration of various industrial processes may lead to additional savings because the by-product or waste of one process may serve as the raw material for another. For example, a 2000-ton/day chlorine plant produces enough by-product hydrogen to supply a 300-ton/day ammonia plant. This could be used as an additional source of hydrogen for ammonia synthesis, or the size of the primary hydrogen supply could be reduced proportionately. Other examples are the use of nitric acid tail gases to supply nitrogen for an ammonia synthesis plant and the use of carbon dioxide from seawater (removal of CO_2 from seawater is necessary to prevent scaling of heat transfer surfaces in the evaporator plant; see Sect. 5.3) to provide raw material for the synthesis of urea. Benefits of integration of "building block" processes were utilized wherever possible when the capital costs of complexes were determined.

Raw Material and Product Values Used in Complexing. – Economic appraisal of possible benefits of an industrial complex requires realistic assumptions as to the cost of raw materials and the wholesale price of the products (f.o.b. plant). The values used in this study are based on consultations with industrial and government experts in this country and India and on various references. The values at mid-1967 assumed for this study are listed in Table 5.9.

Caustic in the United States and chlorine in developing countries are assumed to have no value because they are currently in oversupply. This is an oversimplification, however, because they do have some minimum "dumping" value. For complexes producing desalted water, caustic and chlorine (as hydrochloric acid) could be utilized to treat the incoming seawater to prevent scaling of heat transfer surfaces in the evaporator (see Sect. 5.3.3 and Appendix 5A).

The overall economics of a complex is very dependent on the assumed values shown in Table 5.9, and the values shown for foreign complexes are subject to change, depending upon specific locations, but are typical for a country such as India. The data shown for United States complexes represent, in our best judgment, meaningful f.o.b. plant prices for the products and materials as listed.

Conversion of United States-Based Costs to Foreign Conditions. – The factors applied to United States-based capital and operating costs, including manpower requirements and labor efficiencies, to obtain equivalent costs for application to plants in developing countries are derived and explained in Chap. 3.

5.6.2 Computer-Calculated Cost Results for Industrial Complexes

This section presents typical computer results from the 72 industrial complexes for which costs were determined. The computer handles seven product mixes at a time, but for either United States *or* non-United States conditions only; ten runs of seven complexes each were made using various combinations of the industrial building blocks previously discussed to determine the effects of the various parameters.

Table 5.9. Cost of Raw Materials and Wholesale Price (F.O.B. Plant) of Products for United States and Foreign Complexes

Raw Material	Cost (dollars/ton)		Product	Wholesale Price (dollars/ton)	
	U.S.	Foreign		U.S.	Foreign
Bauxite	8[a]	5.50[b]	Aluminum[c]	650	800
Phosphate rock	9.60[d]	19[e]	Ammonia	30	45
Silica gravel or rock	1[b]	1[b]	Phosphorus[f]	100	131[f]
Coke	17[b]	17[b]	Chlorine	50	[g]
Salt	3[b]	3[b]	Caustic	[g]	80
			Urea[h]	60	75
			Ammonium nitrate[h]	50	65
			Nitric phosphate[h]	60	80
			Solar salt		4

[a] Imported to seaport location from Surinam or Jamaica.

[b] Raw material obtained locally.

[c] Sheet, plate, and wire.

[d] Florida pebble shipped 1500 miles by sea; cost at mine \$3.00 to \$4.00.

[e] Florida or Morocco rock shipped about 6000 miles to a seaport location.

[f] Assumed product is elemental phosphorus; however, price is listed per ton of P_2O_5; price as elemental phosphorus is obtained by multiplying by 2.29.

[g] Chlorine assumed to have no value in developing nation; caustic assumed to have no value in U.S. (no caustic concentrator installed in U.S. chlorine plant).

[h] Bagged product; cost of bagging included in manufacturing cost.

One run of two complexes was also made to obtain additional data. The general results of the runs are presented in Table 5.10; however, interpretations are given later for only a few runs to indicate typical findings. Of the 72 runs completed, 14 were for complexes under United States conditions and 58 were for non-United States situations.

Table 5.10 presents an input summary of the industrial-only complexes evaluated. It includes the computer run number, whether the run was for United States or non-United States conditions or both, the products that were produced and their plant capacities, and the total industrial power required. The first order of breakdown in Table 5.10 is on the number and type of products produced; thus there are five sections: for one, two, three, or four products from energy-intensive processes, and for mixed fertilizers. Under the first group ammonia, phosphorus, aluminum, and chlorine, alone, are made at several capacities. The second group includes the manufacture of two product pairs, (1) ammonia and phosphorus and (2) phosphorus and aluminum, at several capacities and product ratios. The third group lists three-product mixes for all combinations of the four products; in most cases various product ratios are evaluated, and in some cases the total complex capacity, at a fixed product ratio, is varied. The fourth group provides for a variety of product ratios and product capacities for all four major products and includes four runs for determining incremental costs for each product by varying the capacity of each of the four products, one at a time. The mixed-fertilizer group includes the production of ammonia, phosphorus, and one or two mixed fertilizers at two different capacities. In one run aluminum production is substituted for phosphorus manufacture. The tabulated ammonia capacities in

Table 5.10. Summary of Input Data and Results for the Industrial-Only Complexes

Run No.		Products and Capacities (tons/day)				Total Electrical Power (Mw)	Total Capital Investment (dollars)		Annual Production Cost[a] (dollars)		Annual Value of Products (dollars)		Return on Investment[b] (%)	
U.S.	Non-U.S.	NH_3	P_4	Al	Cl_2[c]		U.S.	Non-U.S.	U.S.	Non-U.S.	U.S.	Non-U.S.	U.S.	Non-U.S.
							$\times 10^6$	$\times 10^6$	$\times 10^6$	$\times 10^6$	$\times 10^6$	$\times 10^6$		
						Single-Product Runs								
	R-7-1	300				105		11.7		5.5		4.7		3.4
	R-7-2	600				210		20.8		10.5		9.4		4.8
	R-11-1	1460				510		44		24.5		22.7		5.9
	R-6-1	2900				1013		79		48		45		6.2
	R-7-3a		66			34		10.4		8.4		6.7		0
	R-7-3		150			77		16.3		16.7		15.3		0.1
	R-SP-4		300			154		23.8		31		31		10
	R-11-2		975			500		62		96		99		115
	R-7-4			68.5		41		79		19.6		20		10.5
	R-7-5			137		82		133		34		40		14.5
	R-11-3			835		546		504		148		244		29
	R-7-6				400	55		14.8		6.1		12.5		53
						Two-Product Runs								
	R-5-7	666	1500			1001		114		158		163		14.4
	R-11-6	690	500			497		58		62		62		10
	R-5-6	1380	1000			995		105		121		123		11.9
	R-11-7	1075	250			504		55		44		42		6.4
	R-5-5	2150	500			1007		95		86		85		9
	R-11-5		575	342		518		296		128		158		20
R-3-7	R-2-7		1150	685		1037	467	502	204	217	251	317	20	30
	R-11-4		750	192		510		216		119		133		16.1
R-3-6	R-2-6		1500	384		1020	343	369	173	224	208	265	20	21
R-3-5	R-2-5		1500	685		1217	484	520	224	271	279	353	21.3	26
						Three-Product Runs								
R-1-2	R-4-2	2370	1500	685		2045	539	582	263	311	304	390	17.6	20
	R-12-5	770	375		500	506		69		60		66		18.6
R-1-3	R-4-3	3080	1500		2000	2016/2027[d]	187	218	174	223	184	263	15.4	28.5
	R-12-7	815	400		178	506		63		58		60		13.2
R-3-4	R-2-4	1630	800		355	1010/1012[d]	99	112	90	113	85	118	5	14.4
R-3-2	R-2-2	3260	1600		710	2020/2023[d]	177	200	173	221	170	236	8.3	17.5
	R-9-5	3180	1500		2000	2060		219		225		265		28.3
	R-9-6	3080	1600		2000	2077		222		233		274		28.5
	R-9-7	3080	1500		2100	2035		219		225		266		28.7
	R-6-7	1370		685	2000	1108		518		153		284		35.3
R-1-4	R-4-4	2060		342	1000	1029/1034[d]	310	341	114	119	120	163	11.9	23
R-1-6	R-4-6		1280	342	1000	1016/1021[d]	330	363	170	212	198	261	18.4	23.5
						Four-Product Runs								
R-1-7	R-4-7	310	595	685	2000	1033/1043[d]	479	527	193	216	247	328	21.2	31.3
	R-12-6	750	280	129	250	517		180		78		81		11.6
R-3-3	R-2-3	1500	560	257	500	1022/1024[d]	277	303	135	145	129	171	7.8	18.6
R-3-1	R-2-1	3000	1120	514	1000	2044/2048[d]	474	554	248	272	258	343	12.1	22.8
	R-12-4	475	375	171	500	515		213		95		111		17.5
R-1-5	R-4-5	950	750	342	1000	1026/1030[d]	328	360	148	175	167	222	15.8	23
R-1-1	R-4-1	1900	1500	685	2000	2052/2061[d]	560	616	278	329	334	445	20	28.7
	R-9-1	2000	1500	685	2000	2096		618		330		447		28.9
	R-9-2	1900	1600	685	2000	2113		612		338		445		29
	R-9-3	1900	1500	725	2000	2088		634		335		457		30
	R-9-4	1900	1500	685	2100	2070		618		330		449		29.3
	R-7-7	3000	1500	685	2000	2446		640		348		462	24.50	27.8

Table 5.10. (Continued)

Run No. Non-U.S.	Products and Capacities (tons/day)						Total Electrical Power (Mw)	Total Capital Investment (dollars)		Annual Production Cost[a] (dollars)		Annual Value of Products (dollars)		Return on Investment[b] (%)	
	NH_3	NH_4NO_3	Urea	Nitric Phosphate	P_4	Al		U.S.	Non-U.S.	U.S.	Non-U.S.	U.S.	Non-U.S.	U.S.	Non-U.S.
									$\times 10^6$		$\times 10^6$		$\times 10^6$		
							Mixed Fertilizer Runs								
R-6-2	2150	3210			500		1021		114		114		134		27.5
R-6-3	2150		1201		500		1014		109		93		105		21
R-5-2	2150		2407		500		1021		117		102		126		30.5
R-5-3	2150			4303	500		1019		119		121		181		59
R-5-4	2150			4303		430	1044		387		156		255		35.5
R-12-1	1075	1569	612		250		514		72		59		77		35
R-6-4	2150	3210	1201		500		1028		124		109		155		47
R-12-2	1075	1569		1022	250		511		74		65		89		42.5
R-6-5	2150	3210		1994	500		1022		127		119		179		57
R-12-3	1075		612	1022	250		512		71		59		75		32.5
R-6-6	2150		1201	1994	500		1024		121		111		149		41.5

[a] Power purchased at 4 mills/kwhr; interest on working capital, sinking fund (15-year plant life), and return on investment computed at 10% cost of money; interest during construction not included.

[b] Based on production cost from which the 10% ROI (see footnote a) was deducted.

[c] In U.S. cases only Cl_2 is sold; in non-U.S. cases only caustic is sold. Caustic production rate is 1.13 times listed Cl_2 production.

[d] Difference in power results from extra power requirement in non-U.S. complexes for evaporating cell liquor to 50% NaOH for sale.

this group indicate the total amount made and include the ammonia converted to ammonium nitrate, urea, and nitric phosphate. The phosphorus and nitric phosphate capacities are totally independent.

Table 5.10 also presents average-condition results for all of the United States and non-United States runs. The selected conditions were a power cost of 4 mills/kwhr and 10% cost of money. Values are given for total capital investment less interest during construction, the annual production cost, the value of products manufactured in the complex, and the return on investment.

In the following examples of industrial complexes the terms "capital investment," "operating (or production) costs," "value of product" (all on an annual basis), and "break-even power cost" are used frequently. Therefore it may be advisable to define each to avoid ambiguity and misunderstanding. The "capital costs" are total battery limit plant costs plus off-site facility costs, excluding interest during construction. "Production costs" are all direct operating costs plus the indirect costs associated with total capital investment, exclusive of interest during construction. The latter include return on investment, recovery of investment, and interest on working capital,[22] all at the specified costs of money. The "value of products" is computed as the summation of the annual production of products times the sale price (listed in Table 5.9). Finally, "break-even power cost" is that power cost in mills per kilowatt-hour at which production cost, including indirect costs at a specific cost of money, is equal to the value of the products. Thus the comparison of the break-even power costs of two complexes is a measure of their relative profitability.

In the following examples ammonia is assumed to be produced from electrolytic hydrogen, and elemental phosphorus by the electric furnace method.

Effect of Location and Aluminum Production. – Complete results are given for runs R-2-3, R-3-3, R-2-4, and R-3-4 in Figs. 5.20*a*–*d* to show the effects of a United States vs a non-United States location and the effect on a complex of including vs excluding an aluminum plant. Each figure is a plot of annual production cost as a function of

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[22] Working capital computed as the value of 60 days production at gross manufacturing cost.

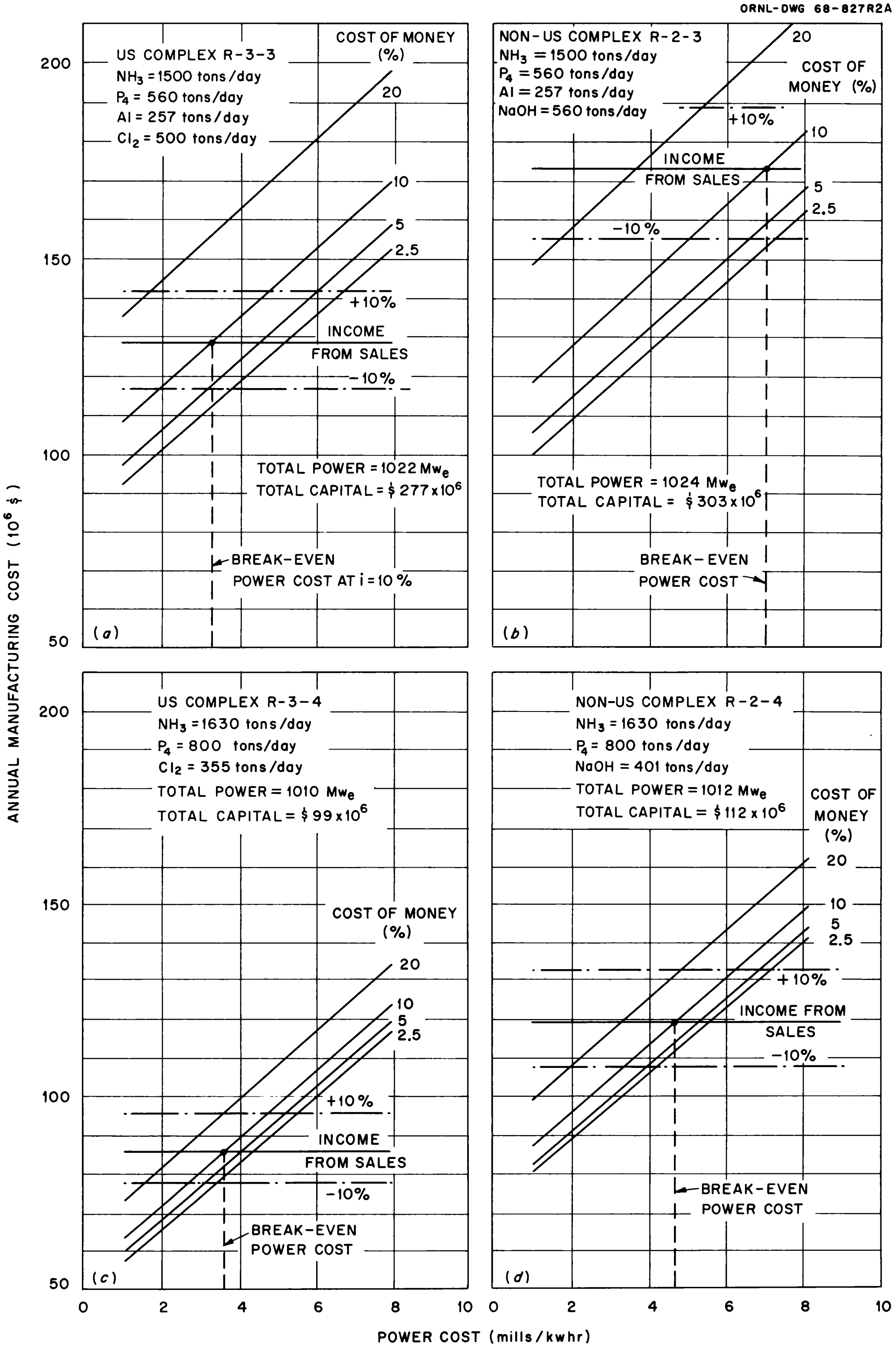

Fig. 5.20. Comparison of Annual Production Costs and Income from Sales for U.S. and Non-U.S. Complexes With and Without an Aluminum Plant.

power cost for the particular complex. The total product value is shown as a horizontal line, and the production costs, at 2.5, 5, 10, and 20% cost of money, are taken as parameters (as a set of four slanted lines). The intersections of the production cost lines with the product value line indicate the break-even power costs (shown only for $i = 10\%$).

In order to avoid the impression that income from sales and break-even power costs are absolute values, dashed horizontal lines are used to indicate sales values 10% less and 10% more than the base value. Although not shown, the break-even power costs will be correspondingly shifted.

Industrial complexes R-3-3 and R-2-3, for United States and non-United States conditions respectively, produce 1500 tons of ammonia per day, 560 of phosphorus, 257 of aluminum, 500 of chlorine, and 565 of caustic; complexes R-3-4 and R-2-4 produce 1630 tons/day of ammonia, 800 of phosphorus, 355 of chlorine, and 400 of caustic. Total capital investments for the four cases vary from \$99 to \$303 million. These complexes each require about 1000 Mw of electrical power; thus the capacities and power of these complexes are median values of all those studied.

Figure 5.20 shows that capital investment, production cost, and income from sales are all higher in the non-United States case. It also shows that the break-even power cost, a measure of profitability, is also higher. This occurs because the differences in value of products between United States and non-United States locations are greater than the capital and production cost differences. The effect of including vs excluding an aluminum plant in the complex is shown by the large differences in the indicated capital costs and in the larger spread of the production cost lines at different costs of money. It is interesting to note that there is little difference in the profitability with or without an aluminum plant in the United States case, but in the foreign case, as shown by the difference in break-even power costs, adding an aluminum plant to a complex is very profitable.

Effect of Total Capacity. – Figures 5.21*a–c* show the cost effects, on a non-United States complex with a fixed product ratio, of varying total capacity and power requirements. Runs R-12-6, R-2-3, and R-2-1 were chosen to show this effect. Complex R-2-3 uses 1024 Mw of electricity and produces 1500 tons/day of ammonia, 560 of phosphorus, 257 of aluminum, 500 of chlorine, and 565 of caustic; complex R-12-6 requires half this power and produces half the quantity of products, whereas complex R-2-1 has twice the power need and production capacity of complex R-2-3. In order to better illustrate the effect of these changes, the manufacturing cost scales on the three drawings are plotted in a 1:2:4 ratio for the three runs on the basis of increasing capacity. This comparison shows the effect of increased capacity, which is illustrated best by the break-even power cost (at 10% cost of money). For the small (512-Mw) complex, break-even occurs at a power cost of 6.4 mills/kwhr. Doubling the capacity of the small complex increases the break-even power cost to 7.1 mills/kwhr, and doubling again, to 8.0 mills/kwhr.

Figure 5.22 shows the same effect in a different manner for the same three complexes just described, but under United States conditions. In this figure power costs from 1 to 4 mills/kwhr are plotted against percent internal rate of return, which is defined in Chap. 3 and Appendix 3A. The data indicate that for any cost of power, doubling the power usage results in a 37 to 53% (at 3 mills/kwhr) increase in the rate of return and that for constant power usage a reduction of power cost of 1 mill/kwhr is worth about a 20 to 25% increase in the rate of return. The figure shows further that in the United States a 500-Mw complex producing the products shown has a break-even power cost of 2.2 mills/kwhr if a 10% internal rate of return is required and that a 1000-Mw complex would be rejected only if power cost is over 3.6 mills/kwhr. In general, increased ammonia production from electrolytic hydrogen decreased profitability.

Effect of Product Ratio. – The effect of changing product ratio is shown in Figs. 5.23*a–c* for a two-product complex at near constant total electric power usage. Complexes R-2-5, -6, and -7, each of which produces phosphorus and aluminum only, are used to demonstrate this effect. Only two products were used because of the masking effect of a third product. In run R-2-5 (Fig. 5.23*c*) phosphorus capacity is 1500 tons/day and aluminum output is 685 tons/day. In complex R-2-6 (Fig. 5.23*a*) the phosphorus capacity remains constant while the aluminum capacity is reduced to 384 tons/day; in complex R-2-7 (Fig. 5.23*b*) aluminum capacity is kept constant while

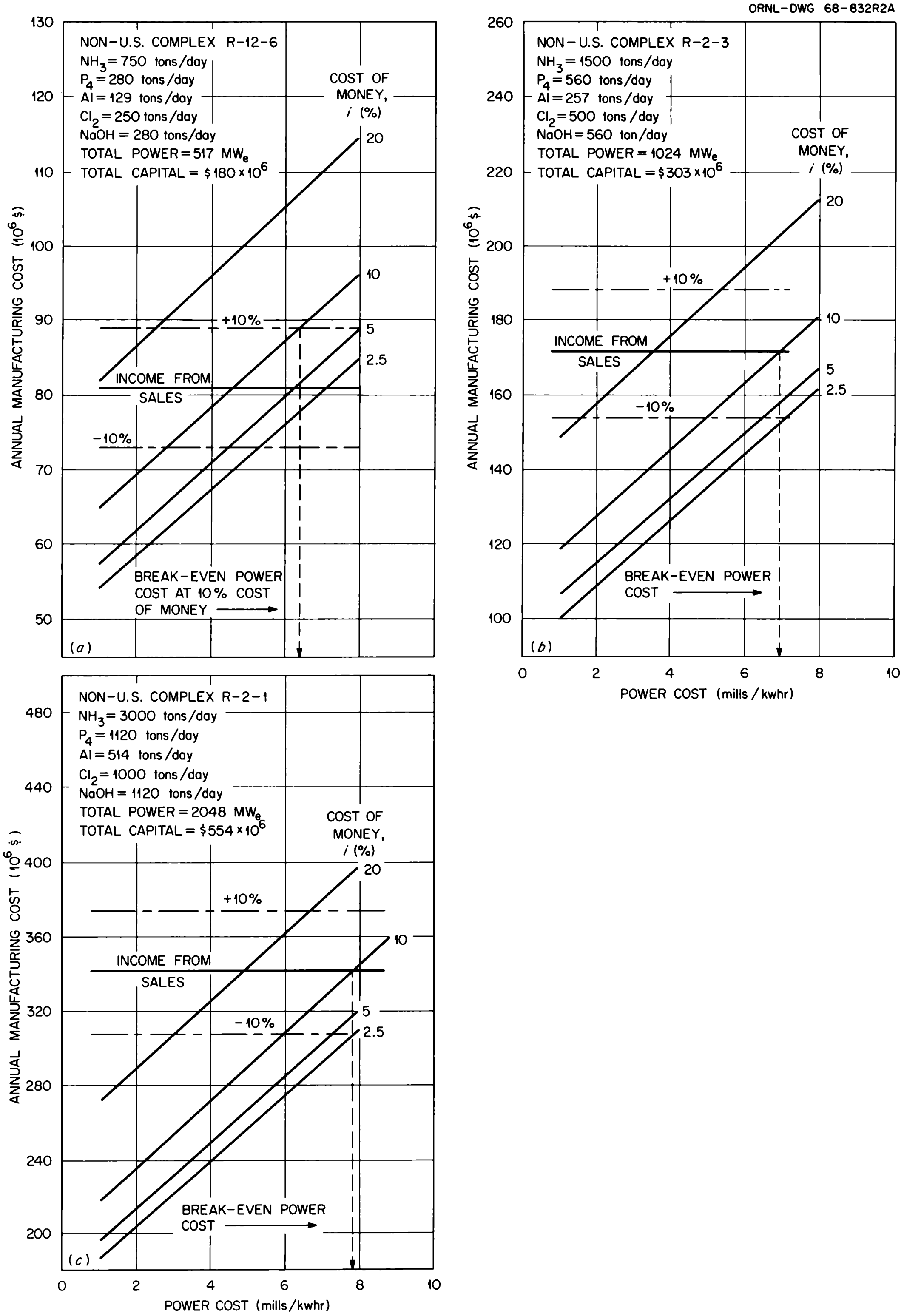

Fig. 5.21. Effect of Capacity at Constant Product Ratio on Annual Production Costs of a Typical Non-U.S. Industrial Complex.

the phosphorus output is reduced to 1150 tons/day. Complexes R-2-7 and R-2-6 require about 1025 Mw of electricity; complex R-2-5 uses 1217 Mw.

As seen in Figs. 5.23 the larger plant has the largest capital investment, production cost, and income from sales but is not the most profitable, since its break-even power cost is only 11.6 mills-kwhr, whereas the smaller plant producing the same amount of aluminum but less phosphorus has a break-even power cost of 12.5 mills/kwhr. The alternative smaller plant, producing the same amount of phosphorus but only half as much aluminum, is even less profitable, since its break-even power cost is only 9 mills/kwhr. It is interesting to note that for the two smaller plants, production costs, particularly at low costs of money, are nearly equal but that there is a large increase in annual sales for the plant producing the larger amount of aluminum.

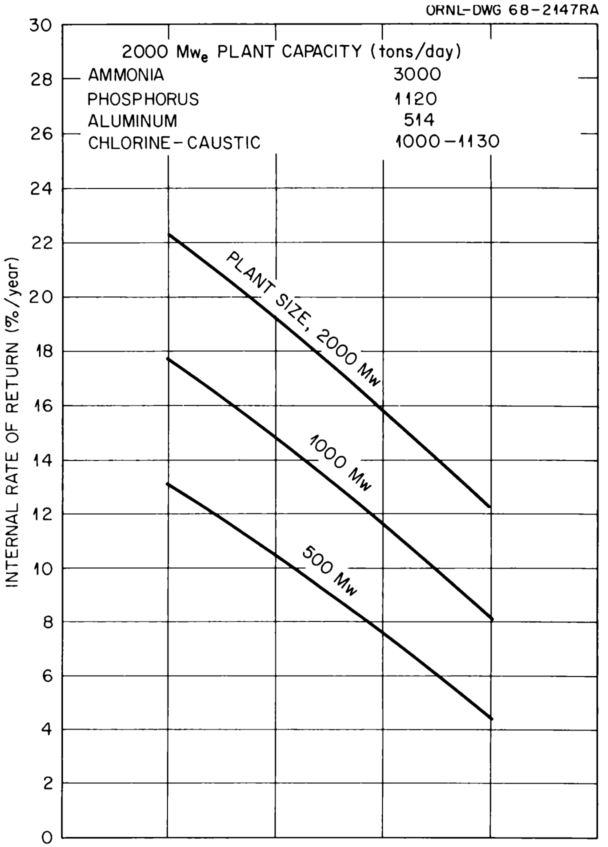

Fig. 5.22. Effect of Complex Size and Power Cost on Internal Rate of Return.

Effect of Conversion of Primary Products to Higher-Value Secondary Products. – In all the previous comparisons the products have been those produced from energy-intensive processes. Figures 5.24*a*–*d* show the effect on nominal 1000-Mw non-United States industrial complexes of converting part or all of these primary products into higher-value secondary products, in this case, ready-to-apply solid fertilizers. Figure 5.24*a* shows the cost advantage of converting all the produced ammonia into prilled ammonium nitrate. Complex R-6-1 (dashed lines) produces 2900 tons of ammonia per day, whereas complex P-5-1 (solid lines) produces the same amount but converts it completely to ammonium nitrate. Thus, by increasing the capital investment by $13 million (16.5%) and the operating cost by a factor of about 1.5 (for 1-mill/kwhr power, but less for higher power rates), the value of the salable product is tripled. This is reflected in the break-even power cost, which is increased from 3.7 to 11 mills/kwhr.

Figure 5.24*b* is a similar comparison, except that part of the total power is devoted to the production of 500 tons/day of elemental phosphorus; this reduces ammonia production to 2150 tons/day if total available power is kept at 1000 Mw. Complex R-5-5 produces only ammonia and phosphorus; complex R-6-2 has the same production, but two-thirds of the ammonia is converted into ammonium nitrate. The effect of adding the phosphorus production is shown by comparing the dashed lines in Fig. 5.24*b* with those of Fig. 5.24*a*. As seen, the capital investment is increased by $16 million (20%), and the operating cost (at 1 mill/kwhr power and 10% cost of money) is doubled, whereas the product value is increased by 80%. In this case the break-even power cost is increased from 3.8 to 6.2 mills/kwhr. When two-thirds of the ammonia is converted to ammonium nitrate (solid lines), the capital investment is increased by $19 million (20%) over complex R-5-5, and the operating cost is increased by 46%, but the value of product is increased by 55%. The break-even power cost rises from 6.2 mills for complex R-5-5 to 9.5 mills for complex R-6-2.

Figures 5.22*c* and 5.22*d* show that the conversion of ammonia to nitric acid for the acidulation of phosphate rock to produce nitric phosphate is quite profitable and that it is somewhat more profitable to produce aluminum rather than phosphorus as a third product, as shown by the in-

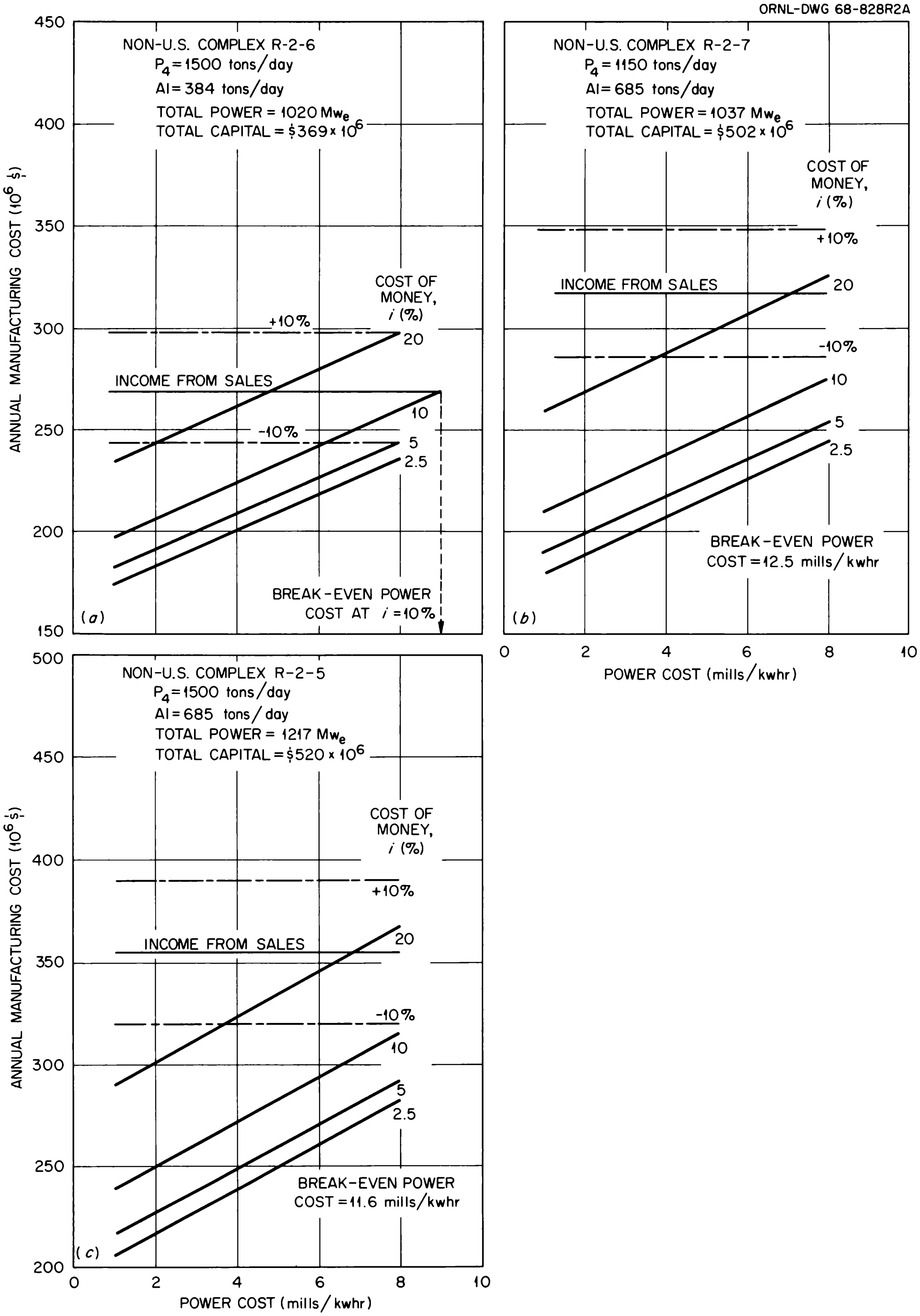

Fig. 5.23. Effect of Product Ratio on Annual Production Costs of a Typical Non-U.S. Industrial Complex Which Produces Elemental Phosphorus and Aluminum.

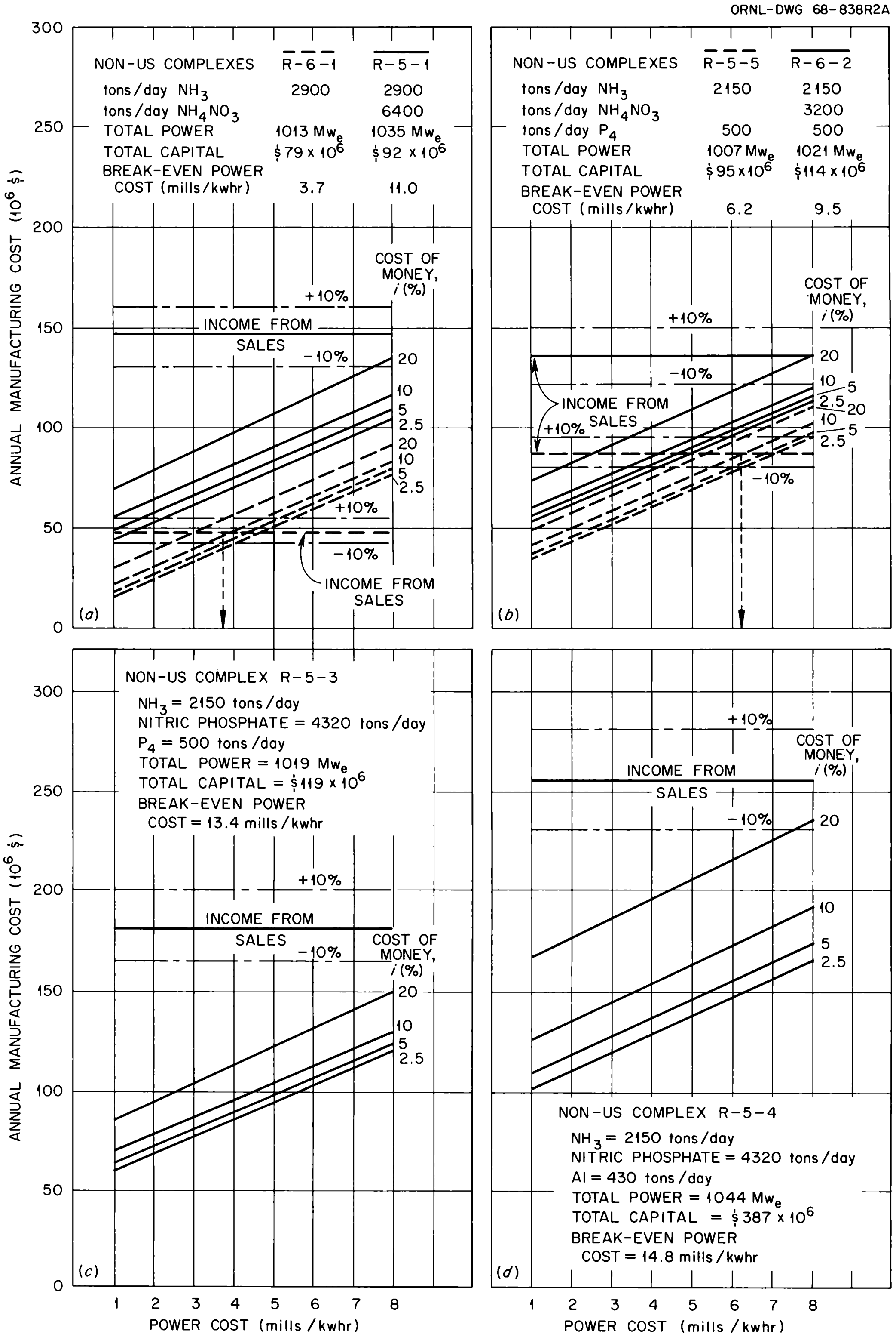

Fig. 5.24. Effect of Conversion of Primary Products to High-Value Secondary Products on Costs in a Non-U.S. Industrial Complex.

crease in break-even power cost from 13.4 to 14.8 mills/kwhr at 10% cost of money.

These illustrations show that conversion of electrochemical products into secondary products can be very profitable. However, it should be noted that the conversions used in these examples require very little power and could be done equally well nearer the consumer. Furthermore, shipping costs of ammonia and phosphorus to conversion plants near the consumer will be much less than shipping costs, for an equal distance, of the finished fertilizers.

Incremental Costs for Various Products. – As indicated earlier, a series of non-United States runs was made to determine incremental production costs for ammonia, phosphorus, aluminum, and chlorine. In 2000 Mw non-United States complex R-4-1, the standard for the first comparison, production rates are 1900, 1500, 685, and 2000 tons/day of the above products respectively. In complexes R-9-1, -2, -3, and -4, each of the above products, in the same order, produces an additional 100 tons/day of product (except for aluminum, in which the production increment is 40 tons/day). The power requirements for these four complexes are slightly increased, but in no case by more than 5%. A second series of incremental runs without any aluminum production was also made. In this case, non-United States complex R-4-3, which produces 3080 tons/day of ammonia, 1500 of phosphorus, and 2000 of chlorine and uses 2027 Mw of electricity, was used as a basis of comparison. In runs R-9-5, -6, and -7 the capacity of each product, in the same order, was increased by 100 tons/day. In this study chlorine was assigned a value of $40.00 per ton.

The results of this study are shown in Table 5.11. The base cost is the cost, for example, of ammonia production, including its share of off-site costs, divided by the annual tonnage of ammonia. The incremental manufacturing cost is the difference between the base and incremental production costs divided by the capacity increment. Actual savings as dollars per ton of product and as a percentage are given in the last two columns. The main inference which can be made from Table 5.11 is that for any existing industrial complex, expansions in aluminum or caustic-chlorine production will be more profitable than for ammonia or phosphorus.

Comparison of Dispersed Industry with a Large Complex. – In a developing country, capital is usually in short supply, and the concentration of a large capital investment in a single area is

Table 5.11. Incremental Manufacturing Costs for Several Products

Power cost, 2 mills/kwhr; *i* = 10%; foreign conditions; phosphate rock = $19.00 per ton, bauxite = $5.50 per ton, salt = $3.00 per ton

Product	Base Production Rate (tons/day)	Increment (tons/day)	Base Manufacturing Cost (dollars/ton)	Incremental Manufacturing Cost (dollars/ton)	Actual Savings	
					Dollars/ton	Percentage
			With Aluminum			
NH_3	1900	100	29.55	27.74	1.81	6.1
P_4	1500	100	114.02[a]	111.78[a]	2.24[a]	2.0
Al	685	40	464.52	374.81	89.71	19.3
Cl_2-NaOH	2000–2260	100–113	31.26[b]	24.77[b]	6.49[b]	20.0
			Without Aluminum			
NH_3	3080	100	29.80	27.92	1.88	6.3
P_4	1500	100	114.26[a]	112.66[a]	1.60[a]	1.1
Cl	2000–2260	100–113	31.83[b]	26.49[b]	5.34[b]	16.8

[a] Calculated per ton of contained P_2O_5.

[b] Per co-ton Cl_2-NaOH based on Cl_2 output.

usually discouraged. These countries would generally prefer to build a number of small plants dispersed throughout the country. In order to compare such a course of action with production of the same quantity of products at an industrial complex, a special study was made. The several small plants, located throughout the using area, would be expected to benefit from lower transportation costs to deliver their products to market. However, each small plant has associated with it various off-site or support facilities, and their small size requires that investment per ton of product be increased. The cost of industrial power available from the usual (small) sources would be much higher than could be obtained from a large power reactor associated with an industrial complex. Large size and the sharing of off-site facilities, resulting in reduction of capital investment per ton of product and the economics resulting from low-cost power, tend to offset the disadvantages of remoteness to markets.

To put the comparison of a large complex with a dispersed industry on a more concrete basis, the capital investment and operating costs as a function of power cost were obtained for non-United States complex R-7-7, consisting of a 3000-ton/day ammonia plant, a 1500-ton/day elemental phosphorus plant, a 685-ton/day aluminum plant (including fabrication into plate and wire), and a 2000-ton/day chlorine-caustic plant. They were compared with a dispersed industry with the same total product output but consisting of plants one-fifth the size of those listed above (non-United States complexes R-7-2, R-SP-4, R-7-5, and R-7-6 respectively).

To penalize the complex for its distance from the market,[23] transportation costs for shipping half the product by rail and half by sea or all the products by sea were added to the operating costs as shown in Fig. 5.25. No transportation

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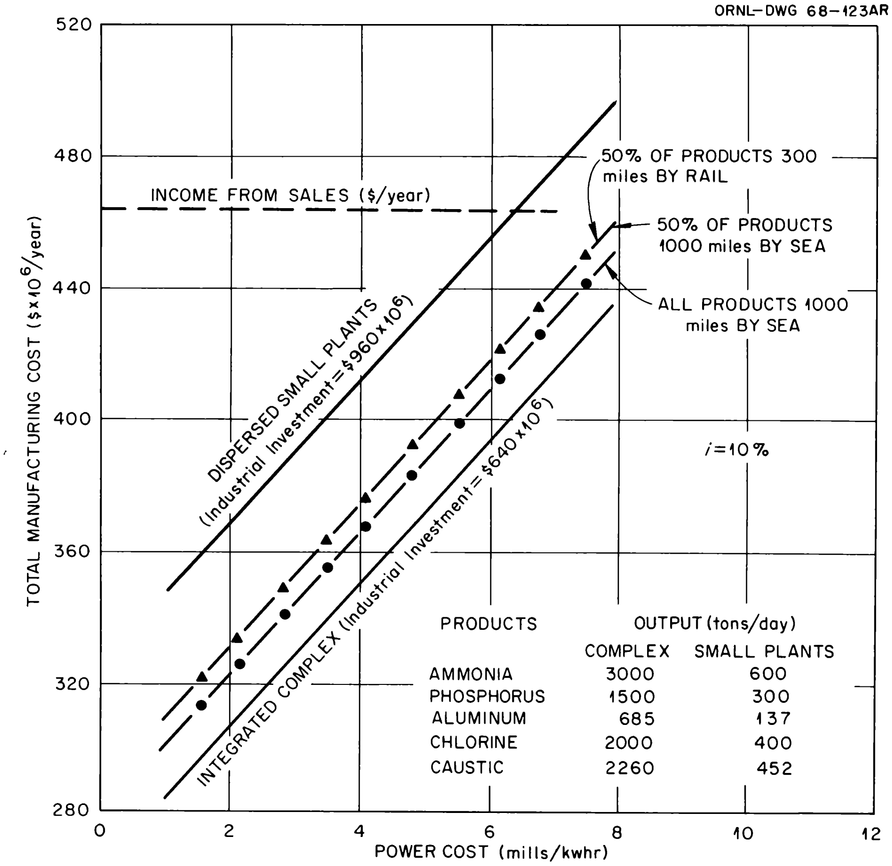
[23] Chapter 7 also discusses this general problem.



PRODUCTS	OUTPUT (tons/day) COMPLEX	OUTPUT (tons/day) SMALL PLANTS
AMMONIA	3000	600
PHOSPHORUS	1500	300
ALUMINUM	685	137
CHLORINE	2000	400
CAUSTIC	2260	452

Fig. 5.25. Small-Scale vs Large-Scale Production.

costs were assumed for the dispersed industry since it is assumed to be near the market. It was assumed that power for the complex can be obtained from a nuclear reactor for 4 mills/kwhr,[24] which is a reasonable assumption for this plant in a foreign location, and 6 mills was taken as an average industrial power rate for the dispersed industry; this is probably conservative. Under these conditions and assuming 50% of the products shipped 300 miles by rail and 50% shipped 1000 miles by sea, the operating costs of the complex are over $100 million less than those of the dispersed industry for a cost of money of 10%, and the investment in the large industrial complex is $320 million less than the total investment in the smaller dispersed industries. This appears to be a very attractive advantage for this complex, even though it is a highly concentrated investment.

Proper evaluation of the benefits of a large complex compared with a more dispersed industrialization for any given locale would require determination of many specific factors. Examples of these are:

1. a market survey for the type and amount of products which the market could be expected to absorb,
2. the likely locations for the complex and the smaller dispersed plants,
3. the modes and costs for transporting raw materials to the production units as well as the costs of transporting the final products to the actual markets,
4. manpower supply, prevailing labor rates, and other pertinent local factors.

Hence the example discussed here merely gives an approximate idea of the savings which might result from large-scale production.

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[24] This example allocates a cost to power, in contrast to previous examples where no allocating was performed.

6. AGRICULTURE

6.1 Introduction

The basic objectives of the agricultural section of this study were to:

1. obtain data on the potential yields and water requirements of a number of representative crops suitable for intensive irrigation agriculture in a coastal desert environment,
2. develop alternative cropping plans for an agricultural complex based on the above information,
3. evaluate the agronomic and economic feasibility of the above plans at varying levels of water cost and availability.

The procedure followed was to make and then evaluate plans for a generalized locale whose characteristics would represent a realistic and consistent set of parameters characteristic of a coastal desert, based on five specific sites examined. This approach had the advantage over the alternative, a more detailed study of a specific site, that it could be more effectively used to consider many different situations without being restricted by purely local features.

Thus the results obtained do not have specific application to any single country or location. Conditions vary so widely from one locality to another that detailed studies will be needed at each site to develop the locally optimum production system and to compare this concept of food and/or water production with alternative methods.

The study was concerned with developing the concept, selecting alternative layouts and production systems, and testing the agronomic and economic feasibility of the concept. Data were compiled to show how varying costs for irrigation water affected the cost of the food produced, and the economic returns from a large farm complex were compared assuming different yield and water requirement levels. Selected data are presented to assist in adapting the generalized concept to fit particular climatic and economic conditions and to show the significance of some of the major assumptions underlying the analysis.

The general assumptions, or ground rules, developed for this study are as follows:

1. The technology of agriculture refers to a date in the early 1980's. This does not imply the introduction of any new techniques or concepts not in use today; it merely assumes that by this date they will represent general practice instead of being confined to the more efficient farms as today. Continued progress in increasing the efficiency of water use, in increasing crop yields, and in developing crop varieties specially adapted to the specific locations should allow better results to be obtained than have been assumed here.

2. Systems of production, marketing, and distribution would be highly rationalized and efficient.

3. Although no specific form of organization and management was assumed, it must be very efficient. It could be a series of private firms or a large single organization. In some locations it might be more advantageous to start with a single firm or organization and change to smaller units as expertise develops among potential managers or owners.

4. Emphasis would be primarily on general food production, including a variety of such products as grain, vegetables, oil crops, and fruit crops. Although a specialized monoculture might be economically the most desirable production system at some locations, a general approach was adopted here because of the need to increase food production.

5. The study was not to include detailed social and political analyses. Such factors are vital and important, but they have reference to specific countries or sites. The scope of this study was limited to technical and economic feasibility, with the understanding that the other studies could be made later. Some social and political factors were considered as general concepts when time permitted.

6. Similarly, solutions to problems of marketing and distribution were not considered in depth, but should be studied for specific locations.

Before proceeding to details of the agricultural building blocks and complexes, it should be emphasized that the use of desalted water is not a simple solution to the complex world food problem. The many facets of this vital world concern cannot be solved by any single concept or technique. Solutions will require a wide variety of measures, including changes in national policies, general economic development, large capital expenditures in agriculture, higher levels of education and training, and the application of many forms of technology, organization, and managerial arrangements.

Water, however, is severely restricting production in some parts of the world,[1] and in many locations the cost of making it available is steadily rising with time. Use of desalted water for agriculture will become feasible as water costs continue to rise, as development lowers the cost of this alternative, and as agricultural technology allowing more efficient use of water develops. It is relevant at this stage to point out that the following section is equally applicable to desert agriculture based on high-quality water obtained from conventional but distant surface or subsurface sources.

6.2 The Agricultural Building Blocks

6.2.1 Crops Considered for Use in the Agricultural Complex

Ten crops were selected in this study for purposes of analysis and comparison from a wide variety of crop types, including grains, legumes, oil and fiber crops, and vegetables and fruit. The crops include some of the most important and widely grown food species and include a useful range of alternatives for efficiency in water use, sensitivity to water cost, and production of basic or high-quality diets. The number of crops considered was somewhat restricted by the time and availability of the necessary information, and undoubtedly a number of additional crops could be included with equal logic.

With the exception of the cotton crop, all the ten crops listed by type below are grown primarily for human food. Cotton was included because its fiber is a valuable raw material in many underdeveloped countries and the oil from cottonseed is a useful food product. It is a crop which lends itself to efficient irrigation.

Crop Type	Crops Selected
Grain	Wheat, sorghum
Vegetables	Tomatoes, potatoes
Oil crops	Safflower, soybeans
Fruit crops	Citrus
Fiber crops	Cotton
Pulses	Peanuts, dry beans

Many relatively similar crops might have been added to the list. For example, maize has production and utilization characteristics similar to grain sorghum; and some other vegetables use similar resources and have about the same season as tomatoes. Livestock agriculture was not included as a salient feature of the farm primarily due to time limitations of this study. Nevertheless, the large amount of agricultural by-products unsuitable for human consumption which will be available should allow the development of animal production as a relatively large secondary feature.

Crops to be considered at any specific site will vary according to specific conditions in different countries and locales, and the selection will also depend upon local demand and transportation facilities, proximity to markets, climate, and cost of water.

6.2.2 Water Requirements of Crops

The costs of water and irrigation equipment form a relatively large part of the operating and capital costs of the food factory. Hence the crop water requirements and irrigation system layout are critical features in the economic evaluation of the agricultural project.

Data are required on the total annual water requirement of the various crops considered, and their seasonal variation for these latter factors will determine the need for water storage installations. Details of the irrigation schedule within the cropping season are also important because they, to a large extent, determine the water storage capacity as well as the amount of irrigation equipment and labor needed.

The amount of water lost to the atmosphere by a crop from seeding to harvest is commonly referred to as its consumptive use. Consumptive use includes transpiration from within the leaves and evaporation from the soil and wetted foliage. This combined loss is also often referred to as evapotranspiration.

Consumptive use does not include deep percolation of water below the crop's rooting zone or evaporation losses which occur before the irrigation water reaches the crop. These two losses are included in the irrigation efficiency term, and, together with any changes in soil moisture storage and consumptive use, these three items constitute the total water requirements of the crop.

With an efficient irrigation system of the type envisaged, not operating during the hours of maximum

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[1] R. Revelle *et al.*, "Water and Land," p. 434 in *The World Food Problem*, vol. II, The White House, Washington, 1967.

evaporation loss, deep percolation forms the predominant part of the irrigation efficiency term.[2] An effective subsurface drainage system would permit the recovery and reuse of most of this percolated water, conservatively estimated at 10% of the total amount applied.

Consumptive use can be considered as governed by three factors. In order of importance these are (1) the climatologically determined evaporative demand, sometimes referred to as the potential evapotranspiration rate, (2) the amount of available soil water, which in an arid zone depends on the irrigation schedule, and (3) the crop and its particular growth stage.

The relationship of these factors is complex, dynamic, and not fully understood, so that it is impossible to calculate consumptive use theoretically. In practice it is necessary to determine consumptive use experimentally under field conditions. Such data are often empirically or semiempirically related to climatological measurements, so that the relationships found can be used to estimate consumptive use in other areas where only climatological measurements are available.

Ideally, measured values of consumptive use and crop yield obtained under a wide range of irrigation treatments are needed for each crop and locale examined in this study. Such a collection of data would allow an economic analysis to be made so that the optimum economic irrigation treatment[3] to be applied in each case could have been calculated. Unfortunately, this type of information, where yields are related to water use in production functions, is only available for very few crops, even in areas with developed irrigation farming. It is not known to what extent the relationships found there are applicable to other regions.

In the absence of experimental data on the economic or even agronomically optimum irrigation treatment, most climatological methods of estimating consumptive use have been based on measurements made under nonlimiting soil moisture conditions, that is, under conditions of potential evapotranspiration. Other climatological methods are based on correlations with measurements of consumptive use made in farmers' fields receiving commercial irrigation practice. It must be borne in mind that such practice may be far removed from the experimentally determined optimum treatment.

In addition to these limitations in the currently available data and methods of computing consumptive use of water by crops, there are other sources of error. Control methods of estimating crop water loss from measured changes in soil water content are such that an accuracy of 10% in consumptive use measurements for the period between two successive irrigations must be considered very satisfactory.[4] In many cases the climatological data needed for correlation with consumptive use measurements are themselves subject to considerable error, being calculated from other more easily or normally measured climatological parameters. This is particularly the case with the potentially accurate methods based on the radiation balance, which is itself rarely measured directly.

One further factor should be considered as being especially relevant to irrigation in desert locales. One effect of implementing an irrigation scheme on the scale envisaged in a desert region will be to modify the microclimate of the area, increasing the humidity of the air and decreasing its temperature and rate of movement. These changes will reduce the potential evapotranspiration rate and so reduce the water requirements below those calculated on the basis of the existing climatic data measured in the unmodified desert region.[5]

The size of this microclimate feedback effect depends on a number of factors, including the strength and constancy of the prevailing wind force and its direction with respect to the orientation of the irrigated area. An approximate estimate at one locale suggests that the size of the reduction will be between 5 and 15% of the total water requirement. The higher figure applies to the case of a farm layout in the form of a long narrow strip of irrigated land oriented parallel to the direction of the prevailing wind.

In the detailed cost estimates for the agricultural study the consumptive use was calculated by M. E. Jensen[6] on the basis of supplied climatological data

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[2] J. E. Christiansen and J. R. Davis, "Sprinkler Irrigation Systems," pp. 885–904 in *Irrigation of Agricultural Lands*, ed. by R. M. Hagan, H. R. Haise, and T. W. Edminister, Am. Soc. Agron., Madison, 1967.

[3] This is defined as that which gives the maximum returns based on current costs of water application, crop yield returns, and the relationship between these factors.

[4] C. B. Tanner, "Measurement of Evapotranspiration," *ibid.*, p. 536.

[5] D. A. De Vries, *J. Meteorol.* **16**, 256 (1959).

[6] Research Agricultural Engineer, Snake River Conservation Research Center, U.S.D.A., Kimberly, Idaho.

using his semiempirical energy balance equation.[7,8] In this method, potential evapotranspiration is calculated from the latent heat equivalent of the total solar radiation and mean air temperature. Consumptive use for each crop is calculated as a function of the stage of crop maturity and potential evapotranspiration. Each crop has its characteristic ratio – actual to potential evapotranspiration – curve from the time of sowing till harvest. Assuming that for each crop this curve is the same for different locales, it can be used to compute consumptive use from local measurements of solar radiation and mean air temperature. Since solar radiation measurements were not available for any of the locales examined in this study, they were estimated from cloud cover observations.[9]

Values of consumptive use were calculated in this way for ten different crops in the Sinai-Negev locale using the long-term average values measured at the El-Arish climatological station. The calculated values shown graphically in Fig. 6.1 also inindicate the approximate growing season for the

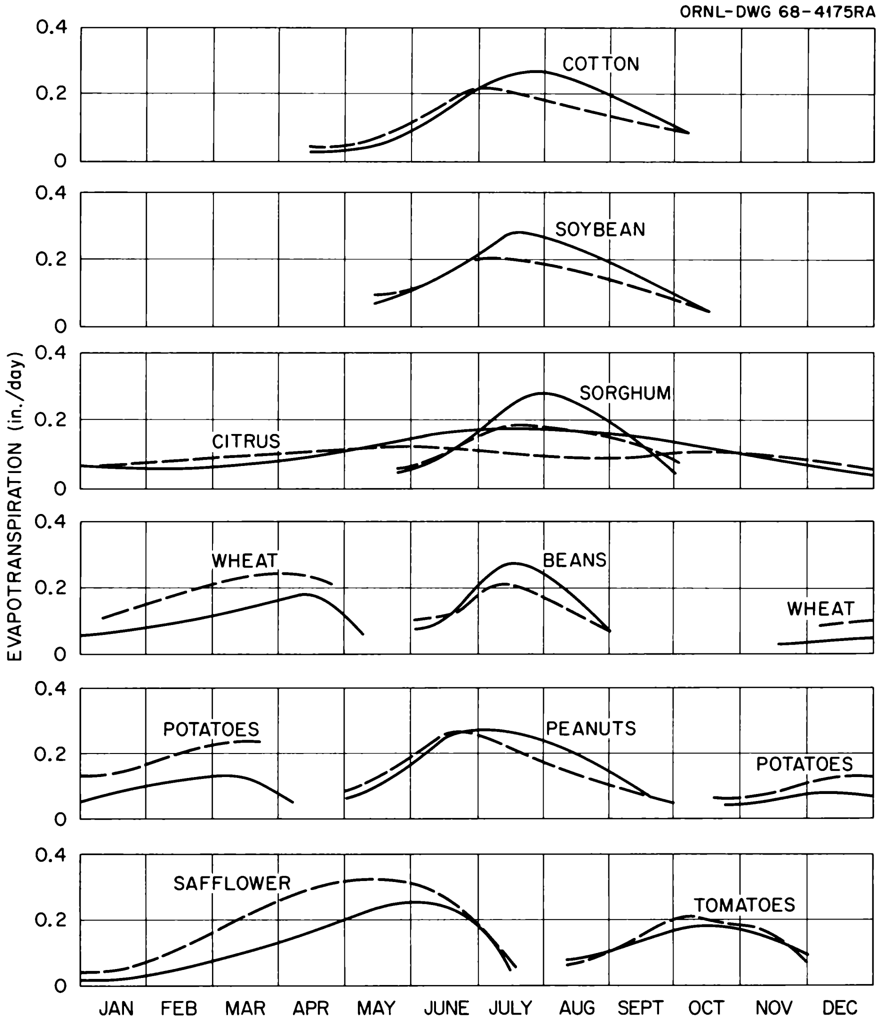

Fig. 6.1. Evapotranspiration of the Sinai-Negev (———) and Kutch (- - - - -) Locales.

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[7] M. E. Jensen and H. R. Haise, *Proc. Am. Soc. Civil Engrs., J. Irrigation Drainage Div.* **89**, 15 (1963).

[8] M. E. Jensen, *"Empirical Methods of Estimating or Predicting Evapotranspiration Using Radiation,"* pp. 49–53 in *Proceedings of Am. Soc. Agr. Eng. Conf. on Evapotranspiration and Its Role in Water Resources Management, Proc., Chicago, Ill., December 5–6, 1966.*

[9] M. I. Budyko, *The Heat Balance of the Earth's Surface*, pp. 28–33 (translated by Nina A. Stepanova), U.S. Dept. of Commerce, Washington, D.C., 1958.

selected crops. The values for citrus are based on mature, producing plantations. It can be seen that wheat, potatoes, and tomatoes have a late-summer–early-spring growing season, while all the other crops, with the exception of safflower and citrus, have a spring-summer growing season coinciding with the climatologically determined season of maximum water requirements.

The calculated values of consumptive use were adjusted to allow for a 20% water loss by deep percolation and sprinkler losses, that is, an irrigation efficiency of 80%. No allowance was made in the computations of total crop water requirements for possible reuse of deep percolation losses recovered by the drainage system or for the probable reduction in the estimated consumptive use caused by microclimate modification. Neither was any allowance made for the winter rainfall, which averages 3.8 in./year at this site. These three factors together could well reduce the estimated total water requirement by 20%. The considerable uncertainty in the basic calculations of total water requirements has already been pointed out.

The calculated values of crop water requirement at this locale were then compared with actual measured values of consumptive use of four crops growing in two settlements in the western Negev region of Israel, the northeastern section of this locale. The measured water losses were calculated from intensive soil water-content measurements made by the neutron scattering method in commercially managed fields efficiently irrigated according to the recommendations of the local extension service. These measurements are for 7- to 20-day periods between irrigations and were made during three consecutive years.[10]

In general, the results (Fig. 6.2) show a satisfactory agreement when the different time scales of the estimates and the measurements are borne in mind along with the fact that the estimates were based on climatological data from a coastal station some 80 miles from the irrigated fields.

The total water requirements for the ten crops at the Sinai-Negev locale are given in Table 6.1 for each month as well as for the season. These figures were used in the economic analysis of the cost of the various farm systems examined in the later part of this section.

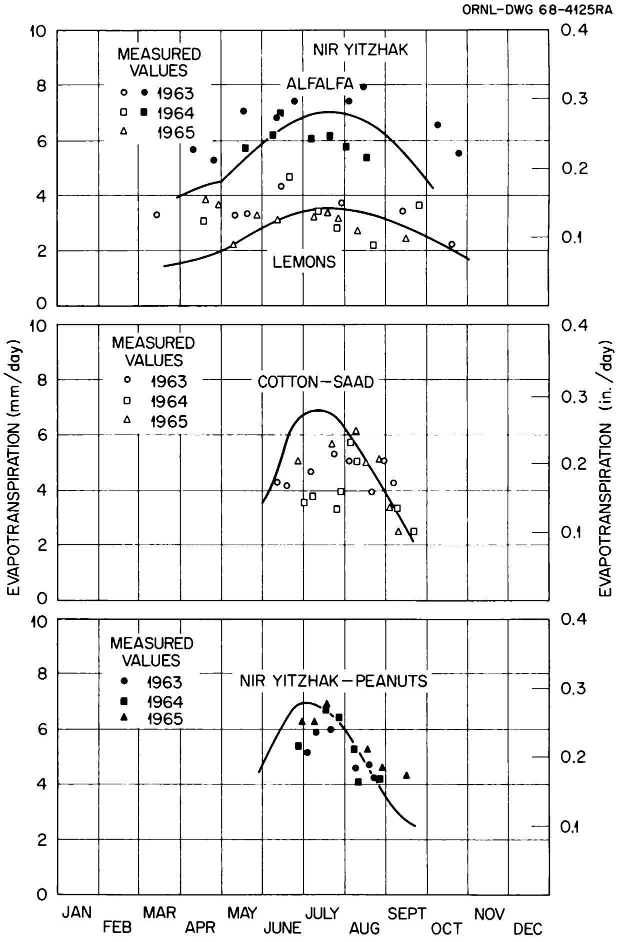

Fig. 6.2. Relationship Between Evapotranspiration Computed from Climatological Data and Measured Values at Two Sites in Southwest Israel.

Production functions relating yield to water application were used to calculate the optimum economic irrigation treatment at levels of yield and water requirement below the maximum. These functions were based on the analyzed results of water requirement experiments carried out in the region.[11]

The question now arises as to the differences in crop water requirements that can be expected at the other locales for which no experimental data are available to compare with the climatological estimates. Further details are given in Appendix 6A.

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[10] D. Goldberg and B. Gornat, *Further Studies on the Blaney and Criddle Formula, Final Research, Rehovot*, Project No. A10-SWC-11, Rehovot, Israel (November 1967).

[11] D. Yaron, *The Demand for Water by Israel Agriculture*, Faculty of Agriculture, Hebrew University, 1959.

Table 6.1. Monthly and Total Irrigation and Water Requirements, in Inches, Based on 80% Total Efficiency

Crop:	Cotton	Safflower	Peanuts	Soybean	Sorghum	Beans	Wheat	Potatoes	Tomato	Citrus
Planting date:	Apr. 15	Jan. 1	May 15	May 25	May 25	June 1	Nov. 15	Oct. 20	Aug. 10	
Harvest date:	Oct. 10	July 15	Oct. 10	Oct. 10	Sept. 30	Aug. 30	May 15	Mar. 20	Nov. 30	
Southeastern Mediterranean Locale										
Jan.		1.0					2.3	3.3		2.5
Feb.		2.0					3.4	4.2		2.5
Mar.		3.9					5.4	2.5		3.1
Apr.	0.4	6.1					6.1			3.7
May	1.7	9.3	1.6	1.6	0.3		0.7			5.2
June	5.6	9.0	6.8	6.1	3.9	4.5				6.3
July	10.6	2.3	10.6	10.6	9.5	9.8				6.7
Aug.	9.3		9.2	9.1	9.5	6.3			2.3	6.7
Sept.	6.0		5.4	5.2	4.5				5.5	5.6
Oct.	1.0		0.9	0.9				0.6	6.5	5.0
Nov.							0.7	2.6	4.8	3.3
Dec.							1.5	2.9		2.5
Total	34.6	33.6	34.5	33.5	27.7	20.6	20.1	16.1	19.1	53.1
Indian Locale										
Total	28.1	47.5	28.6	27.9	21.6	17.1	34.4	28.3	20.0	42.5

Some rather indirect information on this point can be found by a comparison with data of crop water requirements obtained from the main irrigation districts of the United States. These data[12–14] show a very wide range of figures for the same crop. In general, the water requirement values adopted for the Sinai-Negev locale in the economic analysis fall between the low and medium ranges of United States values.

Climatological estimates of crop water requirement were also made by Dr. Jensen for the Indian locale using the energy balance method previously described with long-term averages measured at the climatological station at Dwarka, Gujarat. The values for the individual crops are shown in Fig. 6.1, and totals for each crop are listed in Table 6.1. As in the Sinai-Negev locale, an 80% irrigation efficiency has been assumed; no allowance has been made for the midsummer monsoon rains, although they average 13.9 in./year. This is more than the potential evapotranspiration for the mid-June to mid-August period in which they fall.

It can be seen from Table 6.1 that the total seasonal water requirements estimated for most of the ten crops in the Indian locale are less than those in the Sinai-Negev locale. The mean total water requirements for all ten crops are, however, almost identical for the two locales, 29.9 in. at Dwarka and 29.2 in. at El-Arish.

Table 6.1 and Fig. 6.1 show considerable differences in the seasonal variation of the estimated crop water requirements at the two locales as well as in the total seasonal values. It was assumed in these calculations that the same sowing and harvest dates known to be appropriate for irrigated crops in the Sinai-Negev locale would also prove suitable for the Kutch region. In the case of the wheat crop, the sowing and harvest dates of which were precisely known at the Indian locale, this assumption was not fully justified. When the water requirement at Kutch was recalculated using the local cropping schedule, the value estimated was 25.6 in. instead of the 34.4 in. shown in Table 6.1. This example emphasizes both the importance of the cropping schedule in the determination of crop water requirement and the paucity of such data for most of the locales considered.

Supporting evidence for the estimates of crop water requirements is provided by an independent estimate of potential evapotranspiration at the Indian and Sinai-Negev locales. Penman's combined heat budget and aerodynamic equation[15] yielded monthly estimates of potential evapotranspiration that agreed within 10% with the values estimated by the climatological method used in this study.

6.2.3 Yield Potentials of Crops

Crop yields vary widely, even when grown under relatively controlled conditions. Much of this variation can be attributed to differences in climate, soil, and management. However, the effects of these factors and their interactions are so complex and little understood that it is not yet possible to describe them quantitatively. It is not, therefore, possible to calculate crop yields for any given set of growing conditions.

Yield data were required in this study for the economic evaluation of the various cropping schemes. The yields required were mean values which would be attainable in the early 1980's after an initial period of farm development.

In the absence of any reliable theoretical or even empirical method of calculating crop yields for a given locale, two methods of estimation could be used. First, the yield levels to be expected by the 1980's could be extrapolated from past records, assuming a continuation of the present rates of increase. Second, the judgment of crop specialists engaged in research and development could be utilized. In this study the latter method was used, and, for each crop, experts from the U.S. Department of Agriculture and from the agricultural colleges and experimental stations were asked to estimate the mean yields that are now being obtained on a regular basis by the "best" (i.e., top 20%) farmers in the different centers of production specializing in the various crops.

The estimated yields are considerably below present-day records but considerably above present-

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[12] L. J. Erie, O. F. French, and K. Harris, *Consumptive Use of Water by Crops in Arizona*, Technical Bulletin 169, A.E.S. Univ. of Arizona, Tucson, September 1965.

[13] S. A. Taylor, "Estimating Future Water Requirements of Crops," in *Water Requirements of Crops*, Special Publication SP-SW-0162, Amer. Soc. Ag. Engrs., St. Joseph, Michigan (January 1962).

[14] M. F. Blaney, *Determining Consumptive Use and Irrigation Water Requirements*, Technical Bulletin No. 1275, Agricultural Research Service, U.S.D.A. (December 1962).

[15] H. L. Penman, *Roy. Soc. London, Ser. A* **193**, 120–146 (1948).

day averages for irrigated farms in one arid region of western United States.

The spectacular yield increases obtained in this region during the last 20 years support the assumption that the estimated yield levels adopted here will be commonplace by the date suggested. Indeed, extrapolation of the average yield:time relationship occurring during the last 20 years for a number of important irrigated crops grown in Arizona gives average yields that are similar to, and in a number of cases even higher than, those adopted. These latter values, listed in Table 6.2, are the values used in the economic analysis.

In view of the importance of the yield level in the economic evaluation of the agricultural complex, some of the possible sources of overestimation will be outlined.

First, it has been assumed that all the crops will give high yields when grown together at a single locale, although the estimates were made for the different centers of production which are usually especially favorable for the specific crop grown there.

Second, the high yields were assumed to be attainable over the very large areas envisaged although, at present, they have only been obtained on rather limited areas where conditions approach the ideal.

Third, and perhaps most important, the effects of the occurrence of unusual and unfavorable climatic conditions such as high winds, heavy rains, and extreme spells of heat or cold have been ignored. Such an occurrence, which may reduce yields or interrupt essential farming operations, even once every ten years, could substantially reduce the average return. Abnormally heavy pest and disease infestation could have similar effects.

Similarly, the smaller but still important year-to-year variations in crop yield and water requirements, which occur even under the almost controlled conditions of irrigated desert agriculture, have not been considered.

Fourth, double cropping has been incorporated as a routine feature. This implies a high efficiency in farm operations, complete control of pests and diseases, and the availability of high-yielding short-season varieties for each crop and locale. This type of agriculture is at present not widely practiced with the crops considered but seems a likely near-term future development in large-scale desert agriculture.

Although the above points might suggest that the yield levels used are optimistic, it should be re-emphasized that they are in fact being regularly achieved now by the better farmers. Moreover, it is

Table 6.2. Crop Yields

Crop	Yield (cwt/acre)		
	Average Arizona Irrigated Farms[a]	Record	Estimated Level Adopted
Cotton, lint	9.0	25.0	17.5
Safflower	24.5	52	40
Tomatoes		1200	600
Peanuts			40
Soybeans	22.0	55	36
Sorghum	45.4	130	80
Dry beans	17.0	35	30
Wheat	39.4	120	60
Potatoes	250	1000	480
Citrus (oranges)		630	440

[a] Arizona Crop and Livestock Reporting Service, 1967.

reasonable to expect substantial increases in today's yields as a result of advances in agricultural technology that will surely occur in the next decade.

6.2.4 Water-Yield Relationships

The levels of yield so far considered have referred to those obtained with management techniques designed to provide the optimum environment for maximum production. Such a treatment, usually referred to as the optimum, ignores the price and cost relationship. Early irrigation experiments have shown[16] that when water is expensive relative to the value of the crop and the land, then the most profitable irrigation treatment is often that obtained by applying a quantity of water per unit area less than the maximum required by the physical environment. This is because, although such a treatment may reduce the yield, it reduces the water usage to a far greater extent. Thus, the water use efficiency or yield per unit water application is actually increased.[17]

In this study several alternative levels of water application were considered for the limited number of crops for which data were available. The water-yield relationship determined in Israel for three crops (cotton, grain sorghum, and peanuts)[11] was generalized and then used to calculate the water requirements and yields shown in Table 6.3 for three alternative water application levels. Level A represents the optimum agronomic treatment, while levels B and C represent increasing restrictions in the amounts of water application.

6.2.5 Productivity of Crops from Calorie and Protein Standpoint

One of the principal objectives of the establishment of the agricultural complex is the production of the maximum amount of human food. There are many ways of evaluating food products, one of which is to compare them on the basis of the number of calories or the amount of protein they contain.

It is generally considered that each person requires approximately 2500 kcal/day and 65 g of protein. The precise numbers are influenced by the amount of physical activity, climate, age, weight, sex, and other factors.[18] Information on the Calorie and protein content of each food product obtained from crops, based upon products as they are normally consumed, is given in Table 6.4. Peanuts, wheat, and sorghum have moderately high calorific values. In contrast, potatoes are considered low because of the high percentage of water, even though on a dry-weight basis they have a high starch content. Citrus fruit also has a high water content, and although it contains considerable sugar, it has a low calorie content on a total-weight basis.

Since one of the major objectives of the agricultural complex is to produce the maximum number of Calories for human consumption, a cropping system that maximizes the Calories produced is considered in a later part of this section.

6.2.6 Fertilizer Program

The fertilizer program for each crop grown in the agricultural complex will be determined by soil, previous crop, yield level, and other factors. Of the nearly two dozen elements known to be required for plant growth, it is probable that only nitrogen and phosphorus will be required initially in significant amounts as fertilizer. Desert soils are alkaline and inherently rich in potash. They usually contain moderate to abundant supplies of phosphorus and a minimum amount of nitrogen.

Since the cost of fertilizers forms a relatively small part of the total cost of crop production, it was not considered necessary to assess the actual amounts of fertilizer needed for the agricultural complex with the same accuracy as the crop water requirements. In the detailed cost estimates, the figures used for fertilizer requirement were supplied by R. Dennis[19] on the basis of the amounts used in the irrigated desert valleys of the southwestern United States under conditions of nonlimiting water applications. Initially, application rates of 300 lb or more of nitrogen per acre per year may be required to achieve maximum yields for a number of crops, such as wheat and sorghum, where irrigation is not limited. Yearly phosphate (P_2O_5) requirements may be as high as 150 lb/acre. Except possibly for potatoes, applications of potash will probably not be

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[16] J. A. Widstoe and L. A. Merrill, *Utah Agr. Coll. Exp. Sta. Bull.* 117, 69 (1912).

[17] G. Stanhill and Y. Vaadia, "Factors Affecting Plant Responses to Soil Water," p. 452 in *Irrigation of Agricultural Lands*, ed. by R. M. Hagan, H. R. Haise, and T. W. Edminister, Am. Soc. Agric., Madison, 1967.

[18] Grace A. Goldsmith *et. al.*, "Population and Nutritional Demands," p. 47 in *The World Food Problem*, vol. II, The White House, Washington, 1967.

[19] Consultant to Study Group and Agronomist, University of Arizona, Tucson.

required initially. With continued cropping over many years, potash fertilizer will probably also be needed for other crops.

Nitrogenous fertilizer will probably be most effective and efficient when applied in the irrigation water, since the greatest crop response to this element is usually obtained from frequent but small applications during the growing season. By contrast phosphate would normally be applied during seedbed preparation or at the time of the preplanting irrigation, since late applications of this element have very little influence on the yield.

For each crop and locale the optimum amount and combination of fertilizer as well as the best time and method of application would have to be determined experimentally.

Fertilizers will be available from the industrial area of the complex at relatively low cost, and no attempt has been made in this analysis to "optimize" their use from an economic standpoint. However, this would be desirable from the standpoint of operating such a complex even though water utilization and crop marketing are much more sensitive areas concerning profits. The assumed general fertilizer rates are shown in Table 6.5 for each crop.

6.2.7 Costs and Returns for Selected Crops

The general approach used here in evaluating costs and returns was to estimate costs of producing each crop for comparison with returns based on two levels of market prices. Two kinds of costs are im-

Table 6.3. Assumed Water-Yield Relationships

Crop	Water Application Level[a]	Water Requirement (acre-in./acre)	Yield (lb/acre)
Cotton	A	34.5	1,750[b]
	B	22.6	1,570[b]
	C	17.3	1,390[b]
Safflower	A	33.4	4,000
	B	25.0	3,500
	C	20.2	3,000
Tomatoes	A	19.0	60,000
Peanuts	A	34.5	4,000
	B	28.0	3,560
	C	24.1	3,100
Soybeans	A	33.4	3,600
Sorghum	A	27.6	8,000
	B	20.9	6,700
	C	17.3	5,340
Dry beans	A	20.6	3,000
Wheat	A	20.0	6,000
	B	16.7	5,200
	C	13.3	4,000
Potatoes	A	16.0	48,000
Citrus	A	53.1	44,000

[a] A – optimum agronomic treatment; B, C – water application restricted.

[b] Excluding weight of cottonseed harvested.

Table 6.4. Calorie and Protein Yield for the Ten Crops[a]

Crop[b]	Water Application Level	Calories			Protein		
		Per Pound	Per Acre	Per Acre-Inch of Water	Grams/Pound	Kilograms/Acre	Kilograms per Acre-Inch of Water
			$\times 10^3$	$\times 10^3$			
Safflower	A	1423	5,692	170.4	44.2	176.8	5.3
	B	1423	4,980	199.2	44.2	154.7	6.2
	C	1423	4,269	211.3	44.2	132.6	6.6
Tomatoes	A	95	5,700	300.0	4.5	270.0	14.2
Peanuts	A	1868	7,472	216.6	86.1	344.4	10.0
	B	1868	6,650	237.5	86.1	306.5	11.0
	C	1868	5,791	240.3	86.1	266.9	11.1
Soybeans	A	1828	6,580	197.0	154.7	556.9	16.7
Sorghum	A	1506	12,048	436.5	49.9	399.2	14.5
	B	1506	10,090	482.8	49.9	334.3	16.0
	C	1506	8,042	464.9	49.9	266.5	15.4
Dry beans	A	1538	9,228	448.0	101.2	607.2	29.5
Wheat	A	1479	8,874	443.7	46.3	277.8	13.9
	B	1479	7,691	460.5	46.3	240.8	14.4
	C	1479	5,916	448.1	46.3	185.2	13.9
Potatoes	A	279	13,392	837.0	7.7	369.6	23.1
Citrus	A	131	5,764	108.5	2.8	123.2	2.3

[a] The values for Calorie and protein content are taken from the U.S. Dept. of Agriculture, Agricultural Handbook No. 8, *Composition of Foods*, by B. K. Watt and A. L. Merrill, revised December 1963. The values for energy are in terms of the large calorie (kilocalorie) — the unit customarily used in nutrition studies. The values for both Calories and protein are the quantities contained in the edible portion of a pound as purchased.

[b] Cotton omitted because it is primarily a fiber crop.

portant in determining the best combination of crops to be grown and the best production systems: direct and indirect crop costs.

Direct crop costs are those farming expenses which arise directly from crop production. They include such items as fertilizer, labor, gasoline for tractors, and seed. Indirect costs are farming expenses of an "overhead" nature; taxes, building depreciation, insurance, and interest are examples. Indirect costs are an important component of total cost because of the large investment in developing the land for irrigation as well as in machinery and storage facilities.

Specific assumptions used as a basis for determining costs are as follows:

1. For the analysis given in this section, water is considered to be a direct crop cost and is charged a given price per gallon. For the reference analysis this cost is 10¢/1000 gal, or $33/acre-ft.
2. Eight-row machinery is used for basic tillage operations and, when appropriate, for harvesting.
3. A minimum number of tillage operations was assumed.

Table 6.5. **Fertilizer Applied per Year for the Agricultural Complex**

Crop	Pounds per Acre	
	N	P_2O_5
Cotton	300	100
Safflower	200	50
Tomatoes	200	150
Peanuts	120	80
Soybeans	100	50
Sorghum	150	80
Dry beans	70	70
Wheat	200	50
Potatoes[a]	200	120
Citrus	180	30

[a] Also requires 45 lb of K_2O per acre.

4. Labor is charged at 25¢/hr. While this is greater than the agricultural rates in many developing countries, as economic development takes place, wage rates for agriculture usually rise, causing a shift to more profitable enterprises.
5. Units common for the United States were used.
6. Costs were accounted for through the harvesting, cleaning, sorting, and storage stages. Storage facilities are available adjacent to the agricultural complex. Their costs were based on those now current in the United States, with some adjustments for wage rates and changing technology. These costs include labor and material. Since it was not possible to make detailed studies of these processes in the time available, they should be investigated later as a special study.
7. With the highly efficient production systems assumed, high levels of fertilizer applications were budgeted for as well as generous allowances (based on United States practice) for insect, disease, and weed control; the latter items were included under the heading "other chemicals."

The calculated direct costs for each crop were based on a number of cost studies (between five and ten for each crop) made in the United States, mostly in the Southwest.[20–23] The values used are shown in Table 6.6. It will be noted that for certain crops the cost of water when valued at 10¢/1000 gal forms a very high percentage of total direct costs. For example, water makes up more than 60% of the total direct cost of safflower, sorghum, wheat, soybean, and dry bean production. For these crops the level of profit is highly sensitive to the cost of water. For other crops, such as tomatoes, potatoes, and citrus, the cost of water makes up less than 20% of total direct cost, and profitability is therefore less sensitive to the cost of water.

6.2.8 Price Assumptions

Prices of agricultural products vary widely from month to month and from one country to another. Some countries have specific national policies designed to keep food costs low; for instance, prices are lower in exporting countries than in importing countries. Some of the crops considered here (such as wheat, which is a basic food, storable and easily transported) move in large volume in international trade. Other crops, such as tomatoes, can be stored only when processed, and international shipments are limited.

Prices of agricultural commodities moving in international trade were obtained from the United Nations and the U.S. Department of Agriculture for a period of years. Prices selected were those *paid to farmers.* For most crops the prices were those at a receiving station in the general area where the crop was produced or at a coastal shipping point. In the case of the tomato crop it was assumed that the fruit would be delivered to a processing plant. It was also assumed that certain other vegetables could be substituted for tomatoes to take advantage of markets or to more nearly meet the food needs of the local or national population. Forty percent of the citrus pro-

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[20] R. N. van Arsdall, *Labor Requirements, Machinery Investments and Annual Costs for the Production of Selected Field Crops in Illinois, 1965,* Report AE 4112, AES Univ. of Illinois, Urbana (1965).

[21] University of California, *Guide Lines to Production Costs and Practices,* Imperial County Crops, Agric. Exten. Services, El Centro, Circular No. 104 (no date).

[22] A. G. Nelson, *Costs and Returns for Major Field Crops in Central Arizona,* Tech. Bull. 174, AES Univ. of Arizona, Tucson (August 1965).

[23] J. S. Hill, J. S. Hillman, and P. L. Henderson, *Some Economic Aspects of the Arizona Citrus Industry,* Tech. Bull. 168, AES University of Arizona, Tucson (October 1965).

duction was assumed to be for the fresh fruit market and 60% for delivery to processing plants.

For this study two price levels are used. The reference price level reflects average prices over the last ten-year period in countries exporting the commodity or in countries with economic policies favoring low food prices. This set of prices is referred to as world market prices.

The second level is 30% above world market prices and reflects conditions where food is imported or where economic policies result in prices above world export levels.

This second level of 30% above world market prices is probably more appropriate for a country like India. FAO studies have shown that prices of agricultural commodities paid to farmers in India

Table 6.6. Direct Crop Cost per Acre for Ten Selected Crops

Dollars per crop per acre

Item	Cotton (Yield, 17.5 cwt)	Safflower (Yield, 40 cwt)	Tomatoes (Yield, 30 Tons)	Peanuts (Yield, 40 cwt)	Soybeans (Yield, 35 cwt)
Seed	3.00	4.20	2.50	28.00	3.97
Labor[a]	4.54	3.33	108.70	3.74	2.56
Machine operation	10.64	2.20	13.35	2.10	2.64
Fertilizer[b]	18.00	11.00	17.00	9.60	7.00
Other chemicals	28.80	3.00	128.60	25.90	3.00
Water[c]	94.88	91.85	52.25	94.88	91.85
Storage and marketing	70.00	2.24		10.40	1.98
Power[d]	9.67	9.36	5.32	9.67	9.36
Miscellaneous	18.09	10.25	26.87	14.22	9.91
Total	257.62	137.43	354.59	198.51	132.27

Item	Sorghum (Yield, 80 cwt)	Dry Beans (Yield, 30 cwt)	Wheat (Yield, 60 cwt)	Potatoes (Yield, 480 cwt)	Citrus (Yield, 440 cwt)
Seed	3.45	4.00	5.25	100.00	
Labor[a]	2.23	2.00	1.89	18.32	85.00
Machine operation	2.57	3.00	2.46	7.47	7.29
Fertilizer[b]	10.80	7.00	11.00	19.40	9.00
Other chemicals	4.00	2.50	3.00	30.00	116.50
Water[c]	75.90	56.70	55.00	44.00	146.03
Storage and marketing	4.80	4.70	3.30	228.40	233.20
Power[d]	7.73	5.77	5.60	4.48	14.88
Miscellaneous	9.95	7.50	7.73	48.43	59.28
Total	121.43	93.17	95.23	500.50	671.18

[a] Labor is charged at 25¢ /hr and excludes that involved in the storage and marketing processes.

[b] Fertilizer costs used are: N, 4¢ /lb; P_2O_5, 6¢ /lb; and K_2O, 7¢ /lb.

[c] Water is charged at 10¢ /1000 gal or $33/acre-ft and is at the A level of application from Table 6.4.

[d] For pumping water from the evaporator and charged at $0.005/kwhr.

have averaged considerably more than 30% above world market prices over the last five years and are likely to remain above this level in the foreseeable future in order to obtain desirable increases in domestic production. For example, the average wholesale price of wheat in Gujarat State during the last five years was twice the world market price level adopted here.

Price assumptions and calculated gross sales per year are shown in Table 6.7.

6.2.9 Effect of Water Cost on Returns

The calculated return above direct crop cost for each crop and level of water and yield is shown in Table 6.8 for world market prices and alternative water costs of 5, 10, 15, 20, and 25¢. This return is calculated as gross receipts minus direct crop costs and shows the income available to pay capital charges and other indirect costs.

With low-cost water, the high water application rates for each crop are found to be more profitable, but as water costs increase, a lower rate of water application per crop may be most profitable. When water is priced at 25¢/1000 gal, only cotton, tomatoes, potatoes, and citrus show significant returns above direct costs. These are all "high-value" crops whose water costs are a relatively small part of the total. When water is priced at 15¢/1000 gal,

Table 6.7. Crop Prices and Gross Receipts per Acre

Crop	Unit	Unit Price (dollars)		Water Application Level	Gross Receipts[a] (dollars/acre per year)
		World Market Price Level	30% Above World Market Price Level		
Cotton	Lint, hundredweight	22.00	28.60	A	452
	Seed, ton	48.00	62.40	B	406
				C	359
Safflower	Hundredweight	4.00	5.20	A	160
				B	140
				C	120
Tomatoes	Ton	24.00	31.20	A	720
Peanuts	Hundredweight	7.00	9.10	A	280
				B	249
				C	217
Soybeans	Bushel (60 lb)	2.90	3.77	A	174
Sorghum	Hundredweight	2.11	2.74	A	169
				B	142
				C	113
Dry beans	Hundredweight	6.00	7.80	A	130
Wheat	Bushel (60 lb)	1.60	2.08	A	160
				B	139
				C	107
Potatoes	Hundredweight	1.40	1.82	A	672
Citrus	Hundredweight	3.00	3.90	A	1320

[a] At world market price level.

wheat, dry beans, and peanuts are added to the list of crops with $40 or more return per acre above direct costs. With water at 10¢/1000 gal, sorghum and soybeans can also be added to the above list.

These relationships are shown graphically in Figs. 6.3 and 6.4. Safflower not only has lower returns than the other crops at low water costs, but the steep slope of the return per unit water cost relationship suggests that profits are highly sensitive to the price of water. Peanuts is another crop where returns are favorable at low water rates but very sensitive to higher costs for water.

Returns per acre-inch of water for each crop and water application level are shown in Table 6.9. An acre-inch of water only produces $1.53 return above direct crop cost for soybeans but $5.00 or more from cotton, tomatoes, potatoes, and citrus crops.

The relationship of cost to the two price levels is shown graphically for wheat and peanuts in Figs. 6.5 and 6.6. In this illustration indirect costs are assumed to be $150 per acre per year, or $75 for one crop, since it is assumed that two different crops can be grown on the same land in one year. The basis for the annual indirect charges is

Table 6.8. Return Above Direct Crop Costs per Acre for Selected Crops and Water-Yield Relationships with Varying Prices for Water

World Market Price Level

Crop	Water Application Level[a]	Acre-Inches of Water	Return (dollars) for Water Price (per 1000 gal) of —				
			5¢	10¢	15¢	20¢	25¢
Cotton	A	34.5	242	195	147	100	52
	B	22.6	226	195	164	133	102
	C	17.3	198	174	150	126	102
Safflower	A	33.4	68	23	–23	–69	–115
	B	25.0	65	30	–4	–39	–73
	C	20.2	54	26	–2	–30	–57
Tomatoes	A	19.0	392	365	339	313	287
Peanuts	A	34.5	129	82	34	–13	–61
	B	28.0	112	73	35	–4	–42
	C	24.1	88	55	22	–11	–44
Soybeans	A	33.4	88	42	–4	–50	–96
Sorghum	A	27.6	86	47	10	–28	–66
	B	20.9	72	43	15	–14	–43
	C	17.3	50	26	2	–21	–45
Dry beans	A	20.6	115	87	59	30	2
Wheat	A	20.0	92	65	37	10	–18
	B	16.7	81	58	35	12	–11
	C	13.3	59	41	23	5	–14
Potatoes	A	16.0	194	172	150	128	106
Citrus[b]	A	53.1	418	345	272	199	126

[a] Direct crop costs for water application levels B and C reflect lower water cost and, in addition, reductions in harvesting and other items associated with the reduced yield.

[b] Returns above direct crop costs are discounted at 10%/year to reflect initial year value of future income and expenses over the productive life of the orchard.

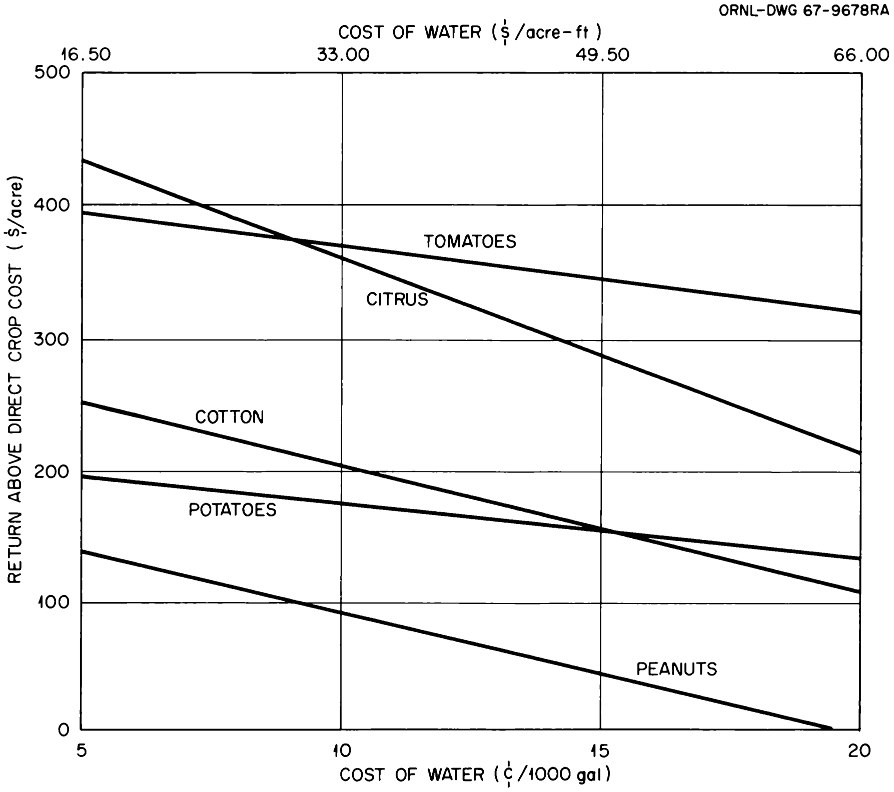

Fig. 6.3. Effect of Water Cost on Return per Acre at World Market Prices.

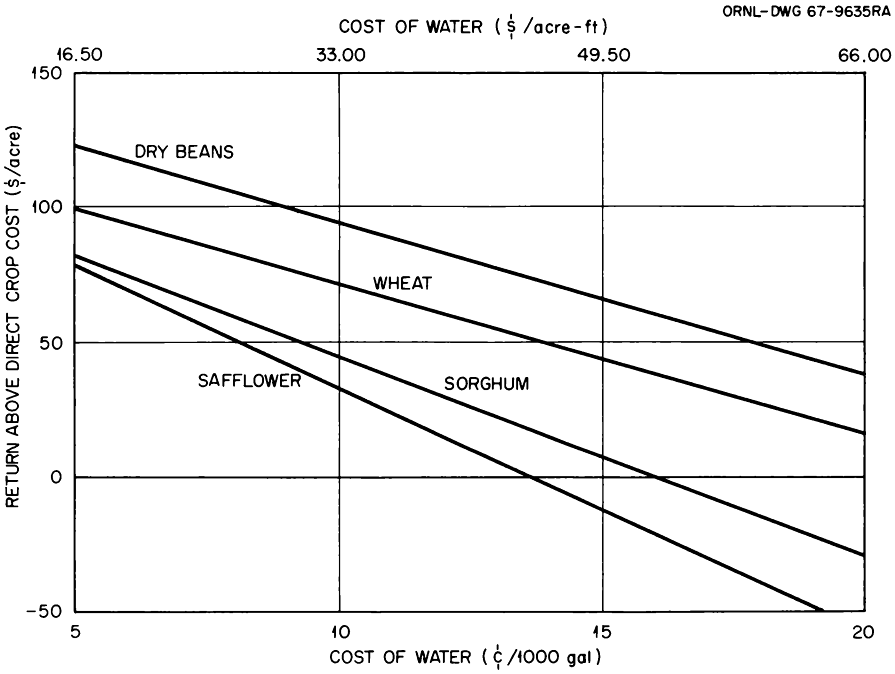

Fig. 6.4. Effect of Water Cost on Return per Acre at World Market Prices.

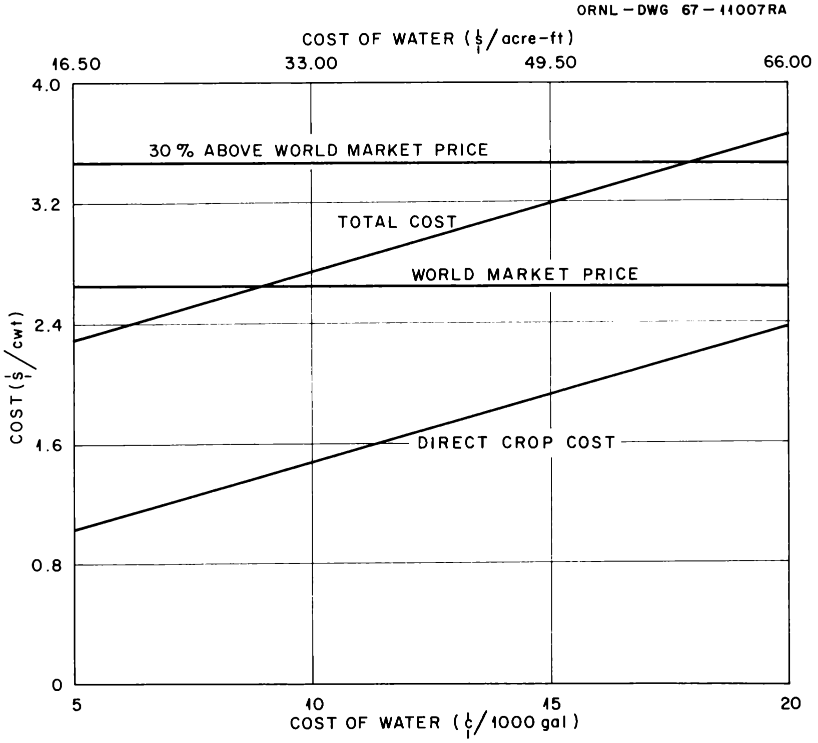

Fig. 6.5. Effect of Water Cost on Return per Hundredweight of Wheat Produced.

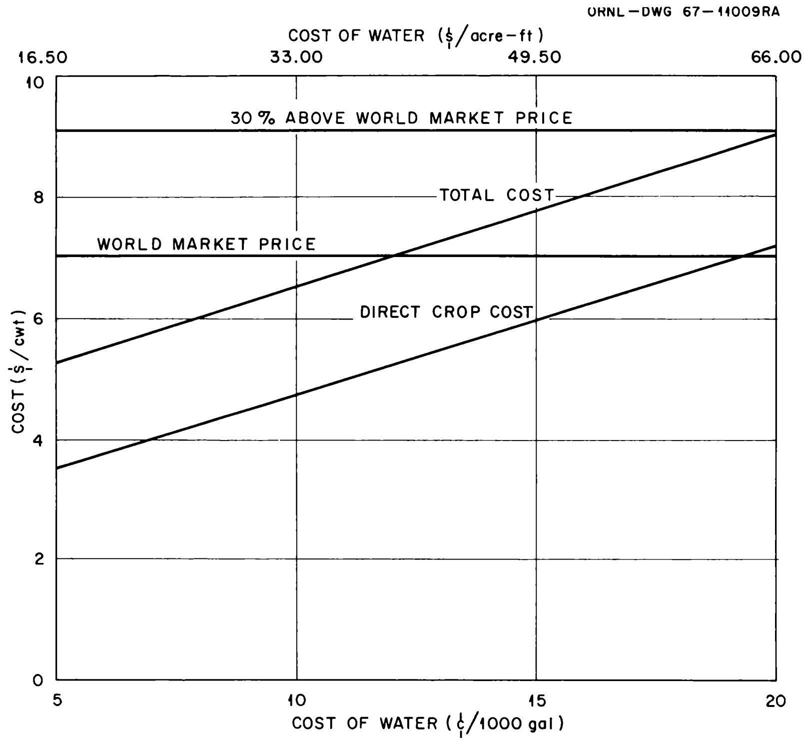

Fig. 6.6. Effect of Water Cost on Return per Hundredweight of Peanuts Produced.

presented later in this report and is based on a cost of money of 10%. The lower line is the direct crop cost per hundredweight. The total cost line reflects both direct crop costs and allocated indirect costs. The intersections of the total cost line with the price lines provide bench marks concerning break-even water costs. In the case of wheat, at world market price levels total direct costs are covered only when water costs less than about 8¢/1000 gal. The break-even cost rises to 17¢/1000 gal at the higher price levels occurring in Asia. For peanuts the break-even costs are considerably greater.

Table 6.9. Return Above Direct Crop Cost per Acre-Inch of Water[a]

Crop	Water Application Level	Dollars per Acre-Inch of Water
	Summer Period	
Cotton	A	5.60
	B	8.60
	C	10.10
Peanuts	A	2.40
	B	2.60
	C	2.30
Soybeans	A	1.30
Sorghum	A	1.60
	B	2.10
	C	1.50
Dry beans	A	4.20
	Winter Period	
Tomatoes	A	19.30
Wheat	A	3.30
	B	3.50
	C	3.10
Potatoes	A	10.70
	Perennial and Variable	
Citrus	A	6.50
Safflower	A	0.70
	B	1.20
	C	1.30

[a] Based on world market prices and 10¢/1000 gal for water.

The most profitable crop combination involves selection to maximize return above direct cost for the system as a whole and not necessarily to cover the *pro rata* share of all indirect costs for each crop separately. Frequently this involves using a resource for a crop in which the return obtained is less than the total cost but greater than the direct cost.

6.3 The Agricultural Complex

6.3.1 Cropping Systems

Three alternative cropping systems are discussed in this report. System 1 is a generalized production system where all ten crops are grown, system 2 is designed to maximize profit subject to various restraints, and system 3 is designed to maximize calorie yield subject to restraints. These three systems are more fully described in a later section.

6.3.2 Description of Farm Layout

The layout of the agricultural complex must be carefully designed to transmit and utilize water efficiently and yet provide the flexibility needed to produce a variety of crops under conditions of continual change. Changes in the economic environment, new technology, and changing demands for food products will require adaptability in the production system over the period of usefulness of the investment, and even from year to year.

The ultimate configuration and development of such a complex will be significantly influenced by the geomorphology of the area, such as the land gradient, natural drainage courses, and the availability of aquifers for water storage. Lacking full details on a specific site location, a number of simplifying assumptions have been made for the general conceptual layout.

In visualizing problems to be encountered in the development of the complex it is helpful to refer to Fig. 6.7, the conceptual layout. The output of the evaporators, about 1,000,000,000 gal of water per day, is pumped to the farmland through a trunk line, assuming a 200-ft lift to a canal bisecting the land area. From the canal the water is pumped through underground pipes to the fields, where a semiautomatic overhead sprinkler system distributes it to the crops. Since water requirements are much higher in the hot summer months than in the winter, provision is made for an extra acreage of land to be

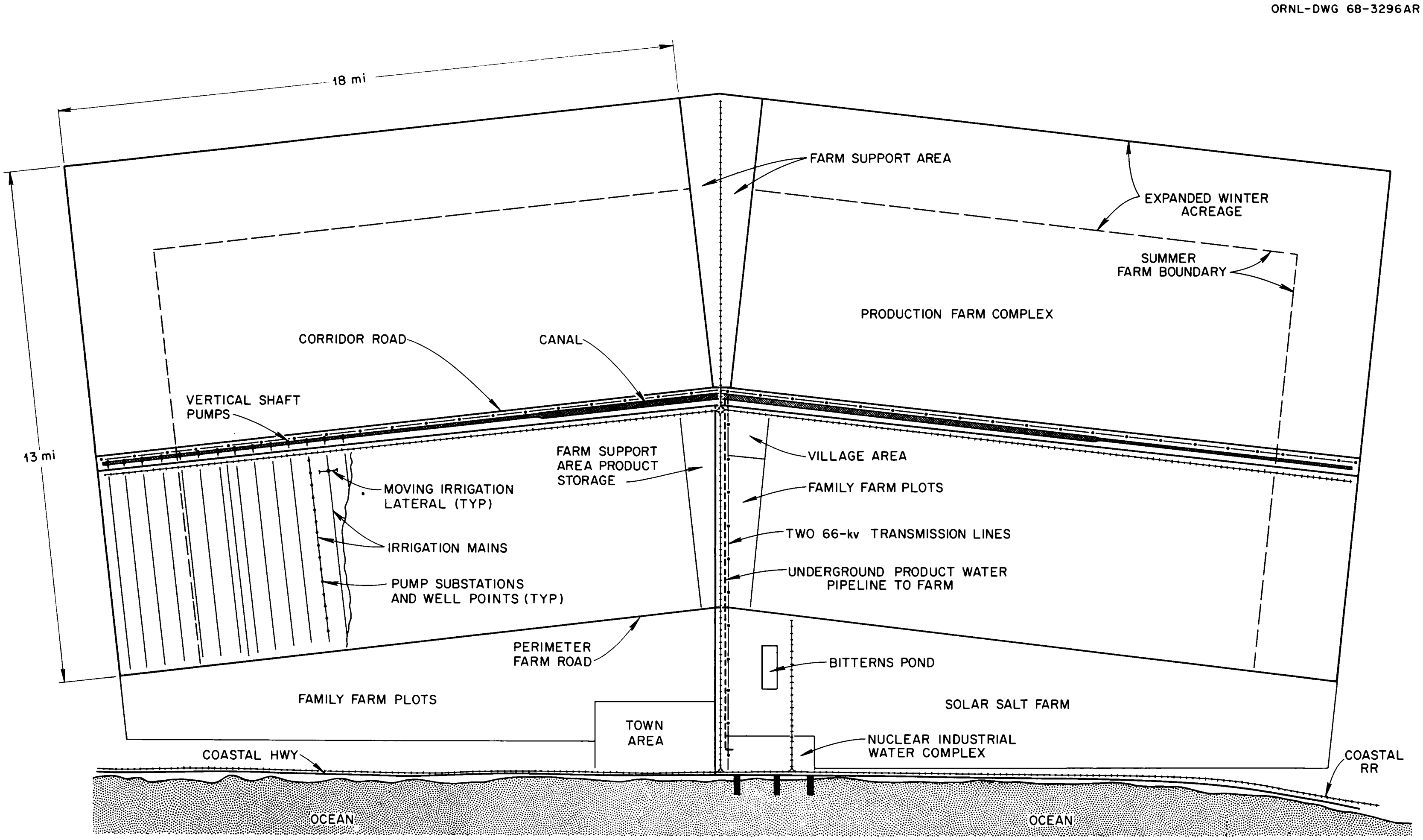

Fig. 6.7. Conceptual Plot Plan for Agro-Industrial Complex.

cropped in the winter months to utilize more evenly the constant amount of water available from the evaporators.

The opportunity is provided for storing water during slack periods for use during peak seasonal needs. Where hydrological conditions permit, water would be stored underground and repumped as needed. This system would probably require a lower investment than the construction of surface water storage facilities.

The land area for crop production varies from 280,000 to 320,000 acres in the three cropping systems considered. For the smaller area, this might be a plot approximately 36 miles long and 12.5 miles wide, equivalent to an area of 450 sq miles.

A wide variation in the nature of soils and topography at each locale can be expected as well as within each location. Hence the layout of the farm and the investment necessary to prepare land for efficient irrigation and machine operations will vary widely. In some situations a minimum of investment would be needed to cover only the cost of land smoothing. At other sites, high concentrations of sodium salts may require leaching, the soil texture may make expensive deep cultivation a necessity, or the topography may require a substantial investment in land leveling.

Structures needed include shops, machine storage, and storage facilities for crops produced. Processing facilities include a cotton gin and a vegetable canning plant. Several small villages would probably be developed adjacent to the irrigated area for the convenience of workers. It would be desirable also to have one or more areas of small plots equipped with irrigation water which could be owned and worked by families living in the area. This would be a way for workers in the industrial, agricultural, and support activities, or members of their families, to increase their standard of living with a part-time or supplemental activity.

6.3.3 Investment in Land and Its Preparation and Reclamation

The initial cost of obtaining ownership or use of land for the agricultural complex is highly speculative. In many desert areas there would be no sale price, since such areas are usually unproductive and unpopulated. In other situations there would be a cost, either because the land is controlled by individuals or organizations or because of the costs of relocating people living in the area. In any case it is assumed that the initial cost to obtain control over the land would be relatively low. It is possible, however, that once the economic feasibility of the agro-industrial complex has been demonstrated, suitable locations would increase in value, and any subsequent developments would involve higher costs for land purchase.

Costs of preparing the land for irrigation and agricultural use will also vary widely, depending on the specific state of the land. Often, desert areas located near the seacoast have accumulated large amounts of salt in the upper part of the soil horizon over a period of centuries. This situation is of particular concern when the ratio of sodium to calcium and other divalent salts is large. High concentrations of salts in the profile are harmful to plant growth and cause poor soil structure and slow water infiltration rates. When the salt concentration is high, reclamation of the land may be achieved by leaching the soil with salt-free water. In severe situations, application of gypsum and other soil amendments may also be needed.[24]

In California and certain other states where reclamation has been required, cost estimates for this operation average, per acre: (1) surface drainage canal, \$8; (2) subsoiling, \$8; (3) labor, \$2; (4) land leveling (touchup), \$8; and (5) nutrient replacement, \$9. An average of 3 acre-ft of water per acre is required for reclamation.[25]

If the cost of \$33 per acre-foot is assumed for the water that will be used for the leaching, the cost of water for leaching will be \$99. Under such an assumption the cost of land reclamation, similar to that claimed out in certain portions of the southern part of the San Joaquin Valley of California, would be \$134 per acre. Cost estimates for reclamation in the Imperial Valley of California range from \$50 to \$100 per acre.

The last increment of water applied for the leaching operation would remain in the soil and would be available to the plants. The amount of water remaining would depend on the texture of the soil and other factors, but would approximate ½ acre-ft/acre. If the cost of this water is not charged to leaching, the net charge for leaching as in the San Joaquin Valley of California would be \$118.5 per acre.

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[24] L. A. Richards (ed.), "Diagnosis and Improvement of Saline and Alkali Soils," *Agricultural Handbook No. 60*, U.S. Department of Agriculture, Washington, D.C., 1954.

[25] Personal communication from P. J. Koluvek, irrigation engineer, U.S.D.A., Imperial Valley, Calif.

While it will be very desirable to select a site for the agro-industrial complex that requires a minimum of land reclamation, estimates of the cost of reclamation have been made, should it be required. It is impossible to determine the cost for reclamation accurately until the physical-chemical status of the soil at the site selected has been established. The cost of reclamation might vary from zero to more than $150 per acre. A cost of $65 per acre was allowed for in this study.

Land leveling and land smoothing operations may need to be undertaken before crops are produced. Leveling commonly refers to the movement of soil from one location to another and requires heavy machinery. Land smoothing here refers to the preparation of an even field surface.

It is of interest here to consider the average cost of land development in several areas of the world. The cost of such development, including leveling of the soil so that it could be surface irrigated, was $40 per acre in the Imperial Valley and $58 per acre in Hawaii. Where no land leveling was required, development costs were $25 per acre in Australia and $20 per acre in Colorado.[26]

In this study it has been assumed that the cost of clearing, leveling, and smoothing the site will be $45 per acre. This figure was derived on the basis of the need to move about 250 yd^3 of earth at a cost of 16¢/yd^3. If land leveling is unnecessary the cost of land preparation will be $20 per acre.

Despite the fact that an efficient irrigation system delivering water of very low salt content is planned, the cost of providing drainage facilities has been included. This is because the history of arid zone agriculture throughout the world has shown that it is almost impossible to maintain permanent irrigation farming without artificial drainage.[27] In addition, most of the locales examined are subject to occasional heavy rains or the danger of flash floods from upland areas passing through the farm, and provision has to be made for the quick removal of such water.

Drainage costs vary widely from site to site according to soil properties and the existing natural drainage system. The costs adopted here are on the high side, but it should be borne in mind that some of the cost should be recoverable in the form of deep percolation and rainfall water collected for reuse.

The range in land and land preparation investment costs, together with the values used in this study, is given in Table 6.10. It will be noted that the costs per acre are less for the winter-only area than for the basic farm. This is justified on the grounds that single-crop agriculture requires less intensive land development than multiple cropping. It should also be possible to locate the additional winter acreage in an area where little land preparation would be needed.

6.3.4 Irrigation System

The sprinkler method of irrigation was selected for use in the agricultural complex as the most efficient method currently and commercially available. The possibility of some more efficient method of underground irrigation system being developed in the near future should be borne in mind, especially for some of the crops such as citrus. It is likely, however, that the cost of its installation and the complexity of its management will be greater than that for the sprinkler system. Conversely, while under favorable conditions the costs of furrow and border methods of irrigation are much less than the sprinkler system, they are also generally less efficient in water use and more difficult to control.

Sprinkler irrigation is adapted to a wide range of soil, climatic, and topographic conditions. It is well adapted to the soils and topography likely to be met with in the locales studied, and the small evaporation losses during sprinkling can be almost eliminated by restricting irrigation to the cooler and calmer part of the day. Water application can be controlled readily with sprinklers, so that the irrigation schedule can be adapted to the optimum treatment needed for each crop.[28]

Several types of irrigation systems using sprinklers are in general use. The system assumed here is based on the more recent large-scale schemes adopted in arid regions and has six major segments, as follows:

1. A main pumping station at the desalting plant to deliver the full capacity of the plant inland

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[26] R. Revelle *et al.*, "Water and Land," pp. 460–64 in *The World Food Problem*, vol. II, The White House, Washington, 1967.

[27] J. N. Luthin, "Drainage of Irrigated Lands," pp. 344–347 in *Drainage of Agricultural Lands*, ed. by J. N. Luthin, Am. Soc. Agron., Madison, 1957.

[28] J. E. Christiansen and J. R. Davis, "Sprinkler Irrigation Systems," pp. 885–904 in *Irrigation of Agricultural Lands*, ed. by R. M. Hagan, H. R. Haise, and T. W. Edminister, Am. Soc. Agron., Madison, 1967.

Table 6.10. Land and Land Preparation Investment Costs

Dollars per acre

Item	Typical Range (United States)	Values Used in This Study	
		Basic Farm	Extra Winter Area
Land purchase		10	10
Leaching	0–150	65	
Land leveling, clearing, and smoothing	18–76	45	20
Roads	15–50	30	20
Drainage system	100	110	0
Total	138–408	260	50

through the industrial area in a main trunk line to the main distribution canal.

2. A buried pipeline to carry the full capacity of the plant to the main canal. A trunk line about 15 ft in diameter would be required to carry 1,000,000,000 gal of water per day.
3. An open, concrete-lined canal carries one-half of the plant capacity from the trunk line in two directions. The added capital cost in covering this segment is not considered justified, as a preliminary estimate shows the evaporation losses would be negligible. This canal is oriented at an angle across the elevation contours to utilize gravity flow.
4. Pump stations are located every half mile along the main canal to supply water through the branch distribution lines to the lateral sprinklers at the desired pressure. These will also be used for pumping water stored underground during certain times of the year.
5. Buried pipe branch lines carry water in each direction from the main canal to the borders of the irrigated fields. The branch lines serve an area 1 mile wide and from 3 to 10 miles long. Water takeoff points are located along the branch for irrigation. It has been assumed that the branch lines required for the extra winter acreage could be laid above ground.
6. Sprinkler laterals receive water from branch lines and distribute it for irrigation. The laterals could be hand moved or tractor pulled, or, alternatively, one of the recently introduced semiautomatic self-propelled systems could be used. The latter system has laterals a quarter of a mile long and is equipped with pipe, traveling hose, and a sprinkler mechanism to irrigate an area 80 by 1300 ft at a rate of 0.6 in./hr. The whole system moves at a rate of 12 ft/hr powered by water pressure or electricity. Irrigation is limited to 16 hr/day, omitting the hours of maximum evaporative stress and wind velocity. This minimizes water losses during irrigation and increases the uniformity of water distribution at the price of a greater investment in irrigation equipment. However, the benefit of even small gains in irrigation efficiency appears to justify the cost of extra laterals. A total lift of 450 ft has been assumed for the entire system, based on a pressure at the sprinkler head of 50 psi and a land slope of 2 ft/mile from the coast.

6.3.5 Water Storage and Retrieval

Because the desalination plant will produce water at the same rate throughout the year whereas the crop water requirements vary seasonally by a factor of at least 6, some system of water storage is essential if the maximum use is to be made of water resources.

The cheapest method of water storage that could be envisaged would be underground in a suitable aquifer underlying the farm area. In such a storage system the water that was surplus to irrigation requirements during the winter would be pumped directly into the branch lines. From there it would be transferred into the aquifer via wellheads located along the branch lines or by the sprinkler system. During the periods of peak water demand in summer, this underground water would be pumped back into the branch lines for use in irrigation.

If the hydrology of the area was not suitable for underground water storage on the irrigated area, then considerable extra costs might be involved. The extra trunk line needed to carry the water from the desalination plant to an outside storage aquifer and back for summer use would cost approximately $1.92 million per mile. In addition, the size of the existing main trunk, canal, and branch line distribution system on the farm would have to be increased by 37%.

At other sites investigations might show that underground storage was not feasible. However, the alternative of constructing surface storage reservoirs would be very costly as well as wasteful in water. [Preliminary estimates of the capital cost of conventional water storage based on worldwide data collected by Clark[29] suggest that this would amount to approximately $10 million for the farming systems described later. To this sum, evaporation losses and extra pumping costs would have to be added.] Deep percolation losses from unlined reservoirs might be recoverable in certain locales, and in others intensive freshwater fish farming in the water storage areas might compensate for the high evaporation losses.

One way of reducing the need for water storage is to increase crop water consumption during the winter. This could be done most profitably by expanding the acreage of winter-only crops. These could include crops suitable for livestock production or specially drought-resistant crops which can be irrigated whenever water is available without reducing the yields.

The farming system envisaged here includes provision for both expanded acreages of winter crops and on-farm underground water storage. Without detailed on-site investigations at each locale, it is difficult to know to what extent the adoption of this system of water storage can be justified.[30] This aspect of the irrigation scheme is probably the most speculative part and should be given high priority in any further planning.

6.3.6 Irrigation Investments

The irrigation system investments for the three farming systems are shown in Table 6.11. In each case the total investment varies with the acreages and the peak water demand. Much of the cost is associated with the volume of water transmitted in the system. Thus the extra cost of providing water for an expanded winter acreage is considerably less than the average per acre cost for the irrigation system on the remainder of the farm. Average costs per acre range from $373 to $432.

6.3.7 Machinery and Equipment Inventory and Investment

The machinery and equipment inventory required for the agricultural complex has been prepared from a consideration of the individual requirements of all the crops. Some agricultural operations may be performed throughout the day, while others can be done only during a few hours of the day. Plowing of the soil, for example, and harvesting of some crops, such as potatoes, can continue throughout the entire day.

Table 6.11. Investment (in Millions of Dollars) in Irrigation System

Item	System 1,[a] 280,000 acres	System 2,[a] 320,000 acres	System 3,[a] 301,500 acres
Trunk lines	13.4	13.4	13.4
Lined canal	4.8	5.5	5.1
Branch lines	58.3	64.0	50.1
Well points	12.0	15.4	15.2
Pumping stations	17.6	18.7	12.9
Laterals	11.9	14.8	12.8
Electrical transmission	3.0	3.0	3.0
Total	121.0	134.8	112.5
Cost per acre (dollars)	432	421	373

[a] Three alternate farm systems were developed; see sect. 6.3.11.

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[29] C. Clark, *The Economics of Irrigation*, Pergamon, Oxford, 1967.

[30] Preliminary results from investigations at the Negev-Sinai locale are encouraging. Personal communication, S. Mandel, Center for Groundwater Research, Hebrew University, Jerusalem.

However, for certain crops, such as small grains, combining when the humidity is high is unsatisfactory and can only be carried out for 10 to 12 hr/day. The machinery plan has given consideration to each of the operations necessary in the growing and harvesting of all ten crops considered.

The number and cost of different items of farm machinery were itemized for system 1: A 15% downtime was assumed for each item, and an additional 10% has been added to current United States farm machinery prices to cover transportation and other costs likely to be encountered in moving the items to the site to be used for the complex. The cost of the machinery was estimated to be $28 million for system 1. About one-half of this is for tractors and trucks, 30% is for harvesting machines, and about 20% is for land preparation, planting, and miscellaneous tools.

The initial investment per acre for the 280,000-acre unit is $100. This same per acre investment was assumed for system 2. This investment is increased to $115 per acre for system 3 because all the land is utilized during both winter and summer.

6.3.8 Storage Facilities and Buildings

Storage facilities will be required for the food and fiber produced and for fuel, seed, insecticides, and other products used in the agricultural complex. Shelter must be provided for machinery, and shops are needed for repair and maintenance of equipment.

Estimated investment costs for storage and other buildings ranged from $61.5 million for system 3 to $82.7 million for system 1.

Storage facilities for potatoes include costs of storing a maximum of 90% of the crop under controlled temperature conditions. A maximum of 85% of other crops could be stored. Modern handling equipment for transferring commodities from trucks to storage and from storage to rail are included in these investment costs. The assumed capital costs are $1.82 per hundredweight for the controlled-temperature facilities for potatoes and $1.43 per hundredweight for grains and other food products. Time did not allow any investigations into the possibilities of food processing to reduce storage costs and enhance the value of the produce, although this aspect obviously merits considerable attention in any further planning. Such investments for processing food could be organized as a separate business, providing services on a contractual basis. Although they were not included in this analysis the availability of these processing services is assumed in the case of cotton ginning and tomato processing.

6.3.9 Agricultural Research Station and Experimental Farm

On-site research facilities with experimental fields would be essential to attain the production and efficiency levels assumed in the analysis. The experimental farm would be necessary for developing improved agricultural systems and testing alternative crops and cropping systems. In addition to routine work on water and fertilizer requirements and disease and pest control, a long-term research program aimed at increasing water use efficiency would be very desirable.

It is estimated that a staff of about ten professional agricultural scientists from various disciplines would be required. The total investment involved has been estimated at $1.0 million, itemized in Table 6.12.

6.3.10 Total Investment

The total investment in the agricultural complex varies from $295 million for systems 1 and 3 to $306 million for system 2. In terms of investment per acre the cost varies from $957 for system 2 to $1055 for system 1. The breakdown in per acre investment costs is shown in Table 6.13. In each case the investment in the irrigation system is the largest single cost.

Table 6.12. Investment and Operating Costs for a Research Station with a Professional Staff of Ten Investigators

Investment	
Laboratories and shops	$ 600,000
Greenhouses	100,000
Laboratory equipment	80,000
Field equipment	50,000
Land improvement and miscellaneous	170,000
Total	$1,000,000
Annual operating costs[a]	$350,000

[a] This does not include the cost of interest on investment or amortization charges.

Table 6.13. Total Investment (Dollars) per Acre of Land

Item	System 1, Mixed Crops	System 2, High Profit	System 3, High Calorie
Land and land improvement	200	208	260
Irrigation system	432	421	374
Farm machinery	100	100	115
Storage and buildings	319	225	227
Research station	4	3	3
Total cost per acre	1055	957	979

6.3.11 Production Systems

Three alternative production systems are discussed here to illustrate how a complete agricultural complex might be organized. The first is a mixed cropping system including all ten crops, the second is a high-profit system, and the third is a high-calorie production system.

Certain characteristics and assumptions are common to all three systems. Thus, 1,000,000,000 gal of water per day is available from the evaporating plant. At this plant there are 27 days of scheduled downtime for the evaporators during off-peak months, $13\frac{1}{2}$ days in May and $13\frac{1}{2}$ days in October. An additional ten days of unscheduled shutdown are prorated over the whole year. Minor water losses in transmission (approximately 3.5%), primarily from cracks in the lined canal, have been allowed for.

Water available would be as follows: 1,002,500 acre-ft from 328 days of operation, 35,500 acre-ft transmission losses per year, leaving 967,000 acre-ft available at field per year. The total cost of the water desalination plant is reflected as an assumed unit cost per acre-foot of water for the 1,002,500-acre-ft annual output. For some parts of the building-block analysis the assumed cost of the water is 10¢/1000 gal, or $33 per acre-foot. This basic price is, however, varied to show the effect of different prices on costs and returns.

The relatively constant supply of water coming from the evaporators and the marked seasonal differences in crop water requirements create a need for flexibility in water requirements and provision for storage in the water distribution system. This flexibility can be introduced by providing extra crop acreage in winter months and by varying crop varieties, planting dates, and the total amount of water applied per crop, and its distribution during the growing season. Such provisions for flexibility may involve higher costs or lower yields. Similarly there are a number of storage possibilities with differing capital and operating costs.

For this study, provision has been made for using extra land, particularly during winter months when per-acre water requirements are lower. Development costs for this extra acreage are lower than for the remainder of the farm. Since the total amount of water distributed does not change, some of the sprinkler laterals could be moved to this area.

Provision has also been made to store water underground to be repumped as needed. This involves additional investment and added costs for repumping as well as a water loss of 10%, the minimum needed to prevent seawater intrusion.

At any specific location and time, the market for a specific crop may require restraint in production. This frequently is the case for vegetables and fruits or other high-value crops. In other cases production may be limited by the ability to handle and distribute a perishable product. While the degree of production limitations will vary widely according to the objectives of the management, the time, and the place, several general restrictions were assumed for this study. Cotton was restricted to 40,000 acres, potatoes to 60,000 (except in system 1, where it is 90,000 acres), and citrus and tomatoes to 10,000 acres each.

System 1: Mixed Crops. – The crop combination for this farming system was hand calculated to provide a wide range of crops, minimum water storage requirements, and high-quality food. Although no single criterion was set for attainment, an attempt was made to utilize the maximum amount of water directly from the evaporation plant, and consideration was given to economic returns and food needs. Rotation requirements were taken into account to provide for two crops per year for the base acreage. All ten crops were grown at the high water requirement level.

A summary of land and water utilization, production, and gross sales for this system is shown in Tables 6.14 to 6.16. The receipts are in all cases based on world market prices. The system provides

Table 6.14. Land Use, Water Utilization, and Yields

Water application level A unless otherwise indicated

Crop	Acres		Yield per Acre	Water Requirement	
	Summer	Winter		Per Acre (acre-in.)	Total (acre-ft)
			System 1, Mixed Crops		
					$\times 10^3$
Cotton	40,000		17.5 cwt lint 1.4 tons seed	34.5	115.0
Safflower	10,000		40 cwt	33.4	27.8
Tomatoes		10,000	600 cwt	19.0	15.8
Peanuts	60,000		40 cwt	34.5	172.5
Soybeans	20,000		36 cwt	33.4	55.7
Sorghum	20,000		80 cwt	27.6	46.0
Dry beans	40,000		30 cwt	20.6	68.7
Wheat		170,000	60 cwt	20.0	283.2
Potatoes		90,000	480 cwt	16.0	120.0
Citrus	10,000	10,000	440 cwt	53.1	44.3
Total	200,000	280,000			949.0
			System 2, High Profit		
Cotton[a]	40,000		15.5 cwt lint 1.3 tons seed	22.6	75.3
Tomatoes		10,000	600 cwt	19.0	15.8
Dry beans	190,000		30 cwt	20.6	326.2
Wheat		240,000	60 cwt	20.0	400.1
Potatoes		60,000	480 cwt	16.0	80.0
Citrus	10,000	10,000	440 cwt	53.1	44.3
Total	240,000	320,000			941.7
			System 3, High Calorie		
Tomatoes		10,000	600 cwt	19.0	15.8
Sorghum[a]	295,600		67 cwt	20.9	514.9
Dry beans	5,900		30 cwt	20.6	10.1
Wheat[a]		231,500	52 cwt	16.7	322.2
Potatoes		60,000	480 cwt	16.0	80.0
Total	301,500	301,500			943.0

[a] Water application level B.

for both an expanded acreage in winter months (280,000 acres compared with 200,000 acres in the summer months) and a storage of water underground to be repumped in peak periods. A total of 175,000 acre-ft of water, or 18% of the water available, would be stored for use in spring and summer.

July would be the peak water use month, with requirements 185% of the water plant output. The water requirement is least in October and May. During these periods the plant could be shut down for several days for maintenance and repairs.

The two crops using the most water are wheat and peanuts, while wheat and potatoes occupy the most acreage and provide the most calories and the highest return above variable cost.

Table 6.15. Total Production and Gross Income

Water application level A unless otherwise indicated

Crop	Tons	Calories	Protein (metric tons)	Gross Receipts[a] (dollars)
System 1, Mixed Crops				
	× 10^3	× 10^9		× 10^6
Cotton	91			18.1
Safflower	20	57	1,800	1.6
Tomatoes	300	57	2,700	7.2
Peanuts	120	448	20,700	16.8
Soybeans	36	132	11,100	3.5
Sorghum	80	241	6,700	3.4
Dry beans	60	369	24,300	7.2
Wheat	510	1508	47,200	27.2
Potatoes	2160	1205	33,300	60.5
Citrus	220	58	1,200	13.2
Total	3597	4075	149,000	158.7
System 2, High Profit				
Cotton[b]	82			16.2
Tomatoes	300	57	2,700	7.2
Dry beans	285	1753	115,400	34.2
Wheat	719	2129	66,600	38.4
Potatoes	1440	803	22,200	40.3
Citrus	220	58	1,200	13.2
Total	3046	4800.0	208,100	149.5
System 3, High Calorie				
Tomatoes	300	57	2,700	7.2
Sorghum[b]	990	2982	98,800	41.8
Dry beans	9	54	3,600	1.1
Wheat[b]	602	1780	55,700	32.1
Potatoes	1440	804	22,200	40.3
Total	3341	5677	183,000	122.5

[a] Based on world export price level.

[b] Water application level B.

Table 6.16. Monthly Distribution of Water of Three Systems

Thousands of Acre-Feet per Month

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
System 1, Mixed Crops													
Crop water requirements	59	84	102	96	39	97	162	136	72	24	35	44	950
Water plant output	89	80	89	86	49	86	89	89	86	49	86	89	967
Water storage													
From storage		4	13	10		11	73	67					178
To storage	30				10				14	25	51	45	175
Cumulative[a]	149	150	132	122	131	120	47	0	13	35	81	122	
System 2, High Profit													
Crop water requirements	64	92	124	126	22	89	183	128	22	15	32	45	942
Water plant output	89	80	89	86	49	86	89	89	86	49	86	89	967
Water storage													
From storage		12	35	40		3	94	39					223
To storage	25				27				64	34	54	44	248
Cumulative[a]	199	187	152	112	136	133	39	0	38	89	137	177	
System 3, High Calorie													
Crop water requirements	53	76	100	99	18	75	181	181	87	9	27	38	944
Water plant output	89	80	89	86	49	86	89	89	86	49	86	89	967
Water storage													
From storage			11	13			92	92	1				209
To storage	36	4			31	11				40	59	51	232
Cumulative[a]	167	171	160	147	175	185	93	1	0	36	89	135	

[a] Includes 10% storage losses.

High Profit: System 2. – For the high-profit system the selection of crops, the acreage devoted to each (under the restraints previously discussed), the level of water used per crop, and the amount of extra winter land and repumped water were selected mathematically to maximize profits. A linear programming model was used, with the following major specifications and assumptions:

1. Maximum water available from the water plant is budgeted for in monthly periods. It can all be utilized for crop irrigation.
2. Water can be used for crop production after storage underground, being repumped as required. Each acre-foot of water used in this way bears an additional charge which includes loss of water during storage, power costs for repumping, and capital charges for the extra investment.
3. The base acreage can produce two crops per year. Additional winter acreage may be added to the production system if this is the most profitable alternative in relation to the annual total costs of this land. Such costs include capital charges, insurance, and maintenance for the land and its development and for the irrigation system.
4. Citrus acreage is limited to 10,000 acres, tomatoes to 10,000, potatoes to 60,000, and cotton to 40,000.
5. Subject to the above resources and restrictions, combinations of the ten crops and alternative rates of water per crop can be used to maximize return above variable cost.

The system developed (Tables 6.14 to 6.16) includes cotton at the medium rate of water application and tomatoes, dry beans, wheat, potatoes, and citrus at the higher rate. The acreages of the four high-value crops are the maximum allowed, with beans and wheat using the rest of the water. A total of 240,000 acres is required with two crops produced per year, and an additional 80,000 acres is used for wheat in winter months. About 77% of the water available is used for dry beans and wheat. These two crops also used a large proportion of the land.

About 26% of the water from the water plant is stored and repumped as needed. July is the month with the peak water requirement, double the amount available from the water plant. October has the lowest water requirement, followed by May.

High-Calorie Production: System 3. – The third system was designed to maximize calorie production. A linear programming model was used to help select the crops and water rates. Major resource quantities, restrictions, and assumptions in the model are as follows:

1. 967,000 acre-ft of water is available from the water plant, specified on a monthly basis.
2. All land is double cropped with no additional winter acreage.
3. Storage and repumping of water are minimized, given the requirements and production specified for the ten crops and alternative water rates.
4. Acreage limitations of specific crops were: citrus, 10,000; tomatoes, 10,000; potatoes, 60,000; and cotton, 40,000 acres.
5. Protein production must be at the rate of 65 g per 2400 Cal produced or higher, to be consistent with general diet requirements.
6. Subject to the above resources and restrictions, combinations of the ten crops and alternative water rates may be used to maximize calorie production.

The resulting system requires the use of 301,500 acres. Five crops were selected, including tomatoes and potatoes at the maximum acreage allowed. The largest acreages would be wheat and sorghum, while a small acreage of dry beans would be included to reduce storage of water to 24% of that available from the water plant. July and August were the peak water-use months, while October and May were the minimum-use months. Details concerning this system are given in Tables 6.14 to 6.16.

Annual Indirect Costs. – Annual indirect costs for the three systems are shown in Table 6.17 in terms of the whole complex and on a per acre basis. For this analysis 10% cost of money was assumed. The table shows the annual cost of the different types of investment and of various overhead items.

The total indirect costs vary from $148 to $158 per acre. While there is some variation for the three different systems, the general magnitude of costs can be seen with reference to the high-profit system 2. In this case the annual cost of the irrigation system is about $60 per acre per year. This includes charges for capital recovery and interest using the sinking fund method ($47.28 per year) and $9.08 for the other charges, which include maintenance of the system and a small allowance in lieu of insurance and taxes.

Table 6.17. Indirect Annual Costs for the Three Systems with an Annual Interest Rate of 10%

Item	System 1, Mixed Crop		System 2, High Profit		System 3, High Calorie	
	Dollars per Acre	Total $\$10^6$	Dollars per Acre	Total $\$10^6$	Dollars per Acre	Total $\$10^6$
Investment related						
Land and land development	24.90	7.0	25.80	8.2	32.00	9.6
Irrigation system	59.10	16.5	59.70	19.8	53.00	16.0
Farm machinery	14.20	4.0	14.20	4.5	16.30	4.9
Buildings and experiment station	36.80	10.3	26.20	8.4	26.60	8.0
Subtotal	135.00	37.8	125.90	40.90	127.90	38.5
System related						
Power — repumping from storage	1.30	0.4	1.6	0.5	1.60	0.5
Water loss	5.40	1.5	6.2	2.0	6.40	1.9
Management, interest on working capital, and miscellaneous	16.40	4.6	13.80	4.4	14.30	4.3
Subtotal	23.10	6.5	21.60	6.9	22.30	6.7
Total indirect annual cost	158.10	44.3	147.50	47.8	150.20	45.2
Dependent on interest rate		35.0		36.2		34.9
Other		9.3		11.6		10.3

Land and land development comes to about $26 per acre per year, including $21 for capital recovery and $1.50 for taxes. Similarly, indirect costs for buildings and the experiment station come to $26.20 per year, a substantial proportion of which is attributable to crop storage. The total annual indirect charge related to investments in the system is $125.90. Additional annual system related costs of $21.60 are made up of management costs, interest on operating capital, and small miscellaneous items which include water loss during storage. These items bring the total indirect costs to $147.50 per acre per year.

6.3.12 Comparison of the Three Systems

A summary of the three systems is shown in Table 6.18. It should be noted that there is a considerable difference in income and the quality and quantity of food produced.[31] More people could be fed on a minimum diet from the high-calorie system than from the high-profit system, but with a considerable sacrifice in profit. The high-calorie system would produce calories for 6.3 million persons (at 2500 Cal/day, excluding losses in storage, distribution, and processing) compared with 4.5 million persons for the mixed crop system and 5.3 million for the high-profit system.

Of the three, the high-profit system produces the most protein; however, this was not one of the criteria used for crop selection. All three systems

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[31] Attention was confined to edible protein and calories; protein quality and other essential nutritional requirements such as vitamins were not considered.

Table 6.18. Summary of the Three Systems

Water at 10¢/1000 gal

Item	System 1, Mixed Crops	System 2, High Profit	System 3, High Calorie
Land (acres)			
Summer	200,000	240,000	301,500
Winter	280,000	320,000	301,500
Crop utilizing largest acreage	Wheat	Wheat	Wheat
Crop utilizing most water	Wheat	Wheat	Sorghum
Water stored (percent of annual total water delivery)	18.1	25.6	24.0
Production (thousands of tons)	3600	3050	3340
Calories (billion)	4080	4800	5680
Protein (thousands of metric tons)	149	208	183
Millions of persons fed[a]	4.5	5.3	6.3
Protein per person fed (g/day)	91	107	79
Water used per person fed (gpd)	200	170	145
Investment			
Total (millions of dollars)	295	306	295
Per acre (dollars)	1055	957	979
Per person fed (dollars)	63	56	45
Gross receipts (millions of dollars) at world market prices	158.7	149.5	122.5
Direct crop costs (millions of dollars)	103.9	89.1	81.8
Return above direct crop cost[b]	51.8	57.4	40.7
Internal rate of return			
World export prices (%)	13	14	9
30% above world market prices (%)	26	26	19

[a] 2500 cal/day.

[b] Gross receipts minus direct crop costs and based on discounted returns (at 10%/year) from future income from citrus production.

meet the minimum nutritional criteria of total protein in relation to calorie production (60 to 70 g per person per day).

The high-profit plan (system 2) has the largest total investment but also the highest internal rate of return[32] at world market prices (a potential 14%). The return from the high-calorie system will just cover the full cost of production at a 9% cost of money.

At the higher price level of 30% above world market prices the internal rate of return increases to 26% for the high-profit system and 19% for the high-calorie system.

The relationship between the price of water and the internal rate of return is shown graphically in Fig. 6.8 for the world market and for the 30% above world market price levels.

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[32] See sect. 3.10 for explanation and discussion of the term and Table 3A.3 in Appendix 3A for economic factors used in the computations.

At world market prices and with an internal rate of return of 10%, the maximum cost of water could be approximately 9¢/1000 gal for the high-calorie system, about 13¢ for the mixed-crop system, and about 14¢ for the high-profit system. For the 30% higher price level the highest permissible water costs per thousand gallons are almost 22¢ for the high-calorie system and about 27¢ for the high-profit system.

Each of the three systems is a first approximation and could be improved by considering more alternative ways of using water and by refining the models and cost data. For example, all three systems have a four- or five-month consecutive period in the fall with water going into storage, when it is very likely that a crop could be found to utilize water profitably during this period.

Other systems could be developed with different criteria as objectives. For example, a maximum-calorie model could be developed with investment restrictions. Another model could specify limitations in foreign exchange or reflect greater incentives to utilize labor and would be useful in specific situations or for comparison with the three systems illustrated. For any given location a specific study would be required of the local situation, including climatic and soil factors, and supply and demand for capital, labor and different foods, before selecting crops and determining the acreages of each grown.

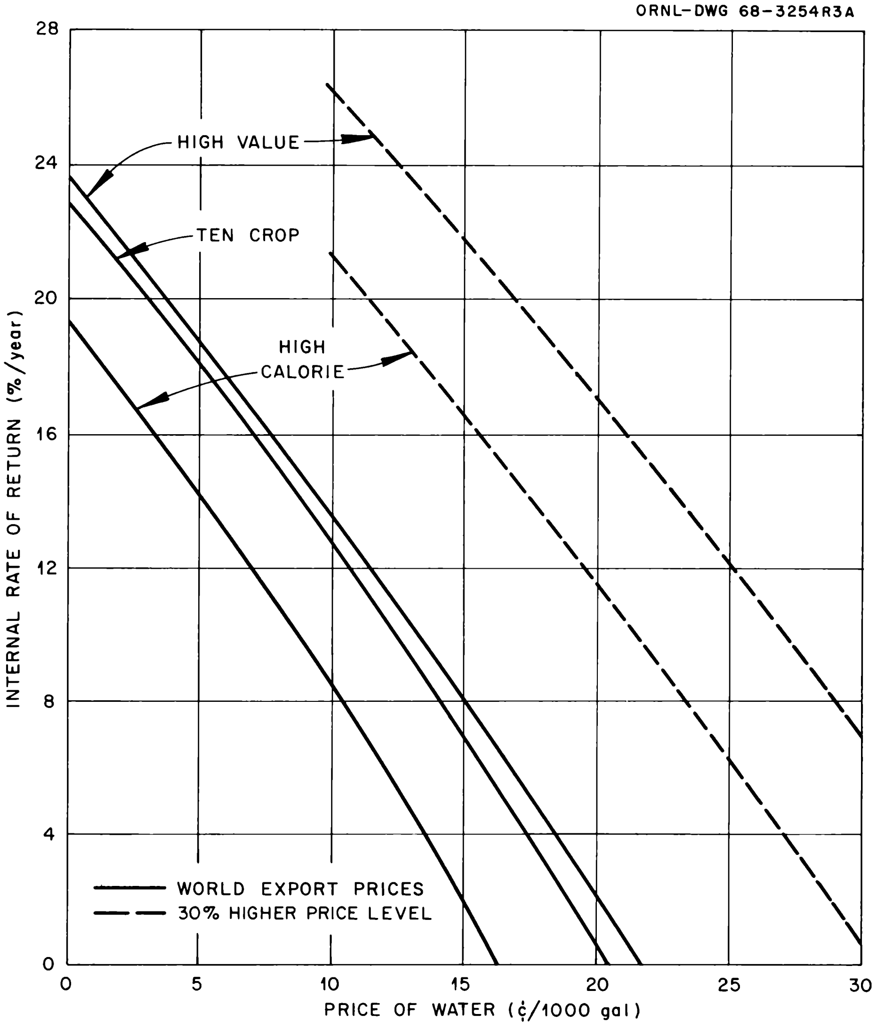

Fig. 6.8. Internal Rate of Return for the Three Cropping Systems as a Function of the Price of Water.

7. ECONOMIC ANALYSES OF NUCLEAR INDUSTRIAL AND NUCLEAR AGRO-INDUSTRIAL COMPLEXES

7.1 Introduction

The combination of a nuclear heat source and turbine generator with various industrial processes is termed a nuclear industrial complex. The combination of the above complex with a seawater desalting evaporator and a farm using the fresh water produced is defined as a nuclear agro-industrial complex. In the various economic analyses discussed in this section, the entire nuclear industrial or nuclear agro-industrial complex is considered as a single economic unit. Capital investments, operating costs, and all incomes were aggregated without any allocation of costs or incomes to the various components. This avoids the problem of cost income allocation within multipurpose plants, for example, dual-purpose desalination reactors producing power and water or brine electrolysis plants producing caustic and chlorine.

The purpose of this chapter of the report is the detailed presentation and discussion of results for the varied nuclear-powered complexes analyzed during the course of this study. For nuclear industrial complexes, comparisons are made on the basis of reactor technology, number of reactors per station, and power requirements for the complex; nominal 500, 1000, and 2000 Mw(electrical) sizes are discussed. In addition, for nuclear agro-industrial complexes, the effect of evaporator technology and the use of bypass steam for water production (eliminates the need for an associated industry to use power) are examined. Superimposed on these comparisons are the effects of United States vs foreign construction, variation in product mix, and two different product price levels; for non-United States complexes only, two price levels, representative of products produced for domestic sale or for export to the world market, were used.

7.2 Use of Building Block Information

Previous sections of the report have presented direct operating costs as a function of power cost for individual industrial processes and also the direct operating costs as a function of water costs for different agricultural crops. To these were added the indirect costs based on capital investment at various costs of money to obtain total manufacturing cost of the final product. These data have been labeled as "building block" information. This section describes the use of those data in arriving at an economic evaluation of a nuclear-powered complex.

7.2.1 Industrial Complexes

Operating cost data for nuclear industrial complexes are obtained by deducting the variable costs of power, water, and steam and the indirect costs associated with investment from the operating costs of the industrial complexes described in detail in a companion report.[1] Thus the only items included in the operating cost of the industrial portion of a complex for purposes of the economic analysis are costs of raw materials, maintenance materials, miscellaneous operating supplies, labor, and overhead.

Working capital for complexes is computed as the value of four months' operating costs for the entire complex, including the reactor. This is in contrast to the use of 60 days' operating costs at gross manufacturing cost for individual processes in Chap. 5, Industrial Processes. The reason for this difference is that power costs are not included as an operating cost in this section, while they are included in the industrial complexes and building block processes described in Chap. 5.

The costs of raw materials and the wholesale prices assumed for all products of nuclear-industrial complexes are listed in Table 5.9. These prices were used in all economic analyses of these complexes.

7.2.2 Agricultural Complexes

Agricultural crop building block operating cost data are summarized in Table 6.6. However, to determine the economics of nuclear agro-industrial complexes, it was necessary to deduct the variable costs associated with water and the cost of fertilize

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[1] H. E. Goeller, *Tables for Computing Manufacturing Costs of Industrial Products in an Agro-Industrial Complex*, ORNL-4296 (to be published).

nitrogen and P_2O_5 from the operating costs shown in the table. The total operating costs after these deductions are listed in No. 13 of Appendix 7B. The fertilizers needed for the farm are produced by the industrial complex and deducted from the annual sales according to crop acreage and crop usage as listed in Table 6.5.

Any chemicals needed by the nuclear agro-industrial complex and produced within the complex are deducted from the annual sales of the complex. For example, the treatment of seawater to prevent scaling of heat transfer surfaces in the evaporator requires the use of about 290,000 tons of chlorine per year (for 1000 Mgd of fresh water) using the hydrochloric acid scale-preventive process (see Sect. 5.3.3). If the complex produces these chemicals, the annual sales are reduced by this amount. In cases where the complex does not manufacture the chemical, it would be purchased from outside at the price listed in Table 5.9.

All discussions of the economics of nuclear agro-industrial complexes are based on the use of the high-profit farm (Chap. 6, Table 6.18). Crop acreages and capital costs are linearly scaled according to the water plant output assumed (water plant output needed for this farm in Chap. 6 is 1000 Mgd). The gross receipts and unit prices assumed for all crops are listed in Table 6.7.

7.3 Components of Nuclear Industrial and Nuclear Agro-Industrial Complexes

This section describes the methods used in determining capital costs and sizes of the various components of nuclear industrial and nuclear agro-industrial complexes. The sizing of the nuclear heat source is described briefly, with more complete details listed in Appendix 7A. Seawater treatment facilities and grid transmission lines and switchyards are discussed briefly. The items included in harbor improvement are listed. Allowance for a town is included only for nuclear agro-industrial complexes studied for non-United States locations.

7.3.1 Reactor and Evaporator Sizing and Costs

This section outlines the methodology involved in sizing the nuclear reactor and the evaporator to produce the power and water needed for a particular complex. A more complete discussion of the equations involved can be found in Appendix 7A. Load factors on reactors and evaporators are assumed to be 90%, and the nuclear heat source is sized to produce the peak load. This high load factor is justified, since a large power consumer is close coupled to the reactor, and the power demand is quite constant with time. However, grid power is assumed to have on-stream load factors of only 80%. The reactor is sized to produce the peak demand of the industries and farm (if included). Auxiliary reactor and turbine power, evaporator pumping power, and thermal efficiencies are tabulated for light-water reactors, liquid-metal fast breeder reactors, and molten-salt thermal breeder reactors in Table 7A.1.

For a nuclear industrial complex (no evaporator or farm), the computations are relatively straightforward, since the only input needed is the electrical power output and type of reactor. Fully condensing turbine generators are used with exhaust steam conditions of 92°F and 2 in. Hg absolute pressure. After determining reactor heat load in thermal megawatts [Appendix 7A, Eqs. (12) and (16)], the capital cost is determined using the cost data from Appendix 4A.

A nuclear agro-industrial complex requires the addition of an evaporator with its associated heat and power requirements and additional electric power needed to operate the farm irrigation system. Water and power are normally obtained at the optimum conditions, namely, full back-pressure operation of the turbine with no bypassing of prime steam. Under these conditions of operation, the electrical outputs of light-water and fast breeder reactors are somewhat different. To permit comparisons between reactor types, water output was maintained constant, turbines were operated under full back-pressure conditions, industrial power was maintained constant, and grid power was allowed to float to take up any difference in electrical power output between reactor types. To prevent sales of grid power from influencing the overall economics of a complex, this power was assumed to be sold at its incremental cost with an added factor for recovery of all production costs, including transmission. For light-water reactors the incremental cost of power with an added factor for recovery of all production costs, including an allowance for transmission, was estimated to be 3.4 mills/kwhr and for the advanced breeders, 2.0 mills/kwhr (see Chap. 4). These power prices will result in the complex not recovering all production costs at internal rates of return higher than about 10% (see Figs. 4.2 and 4.5). The economic effect of operating a nuclear agro-industrial complex under other than optimum conditions was evaluated by using some bypass steam in evaporator operation for some cases. This was done to eliminate the large block of grid power made necessary when a fast breeder powered evaporator operated with back-pressure steam produced the same amount of water as an evaporator powered by a light-water reactor.

Calculation of the total thermal load of the reactor for an agro-industrial complex requires as inputs the total water requirements in millions of gallons per day (Mgd), the type of evaporator technology [multistage flash (MSF) or vertical-tube (VTE) evaporators], the irrigation pumping power in megawatts (related to water requirements; see Appendix 7B, footnote 2), and the grid power. Water plant output, reactor steam conditions (type of reactor), and total electrical power requirements determine the needed mix of back-pressure and condensing turbines. Turbine-generator–condenser capital cost data (Appendix 4A) are broken down, with turbine-generator costs shown separate from condenser costs. This allows some latitude in the mix of back-pressure and condensing turbines.

Evaporator costs are based on two somewhat advanced technologies, multistage flash and multi-effect vertical-tube evaporators. Recent design changes in MSF evaporator plants, such as stacking brine trays vertically (up to eight levels) and constructing the evaporator shell of concrete, have resulted in considerable reduction in the capital costs of these plants. Other cost reductions were made by improvements in the heat recovery system. Capital costs of these evaporators range from 36¢ to 42¢/gpd (without interest during construction).

The VTE is a more advanced design than the MSF and less costly, with capital costs estimated to be 25¢ to 32¢/gpd. One of its main advantages over the MSF process is the reduction in auxiliary pumping. An MSF evaporator producing 500 Mgd of fresh water has a design power requirement of 172 Mw; a VTE of the same capacity would require only 71 Mw. One of the more notable improvements in the design is the use of double-fluted tubes in the evaporator tube bundles.

Operation and maintenance costs for reactor and turbine-generator–condenser islands are discussed in Appendix 4A. Reactor operation, maintenance, and nuclear insurance are computed as a function of the total thermal output (in megawatts) and the number of reactors per station. Operation and maintenance of the turbine-generator–condenser island is computed as a function of electric power output (in megawatts). Operation and maintenance costs of evaporators are determined as a function of the capital cost of the evaporator, as shown in Appendix 4A.

7.3.2 Seawater Chemical Treatment Costs

As discussed in Sect. 5.5.1 of Chap. 5, seawater chemical treatment costs are an important part of the production of desalted water by distillation. The factors involved in scale formation on evaporator tubes were discussed along with currently used and proposed methods of minimizing or preventing its formation. The method currently in use is the addition of sulfuric acid to raw seawater followed by deaeration to evolve carbon dioxide. Sulfuric acid seawater treatment is not included in the economic studies of nuclear agro-industrial complexes; however, costs and the amount of acid needed to treat seawater are discussed in Appendix 7B.

When a caustic-chlorine plant is included as a part of the complex, seawater used in the nuclear desalination plant can be pretreated with hydrochloric acid, caustic soda, or both (equimolar treatment). When hydrochloric acid treatment is specified in place of the traditional method of sulfuric acid addition, the only auxiliary equipment needed is a recombiner to make the acid from hydrogen and chlorine; when caustic treatment is specified, a clarification system is needed to separate and recover the calcium carbonate precipitate. It is estimated that these treatments permit maximum evaporator brine temperatures of 272 and 294°F respectively; however, the maximum evaporator temperature assumed for this report is 260°F. In equimolar treatment, hydrochloric acid is used to treat one-half of the seawater, and caustic soda is used for the balance. For this case, both a recombiner and a clarifier system are required, but only one-half of the size used for either all-acid or all-base treatment. The equimolar treatment allows estimated brine temperatures up to 283°F. In all cases the caustic concentrator is sized for the capacity of the caustic-chlorine plant, regardless of the amount of caustic used for seawater treatment. This is conservative, since capital is allocated for concentrating all the caustic, although the portion used in seawater treatment need not be concentrated. Sizing and costs of seawater treatment equipment needed for the various caustic-chlorine treatments are discussed in Appendix 7B.

7.3.3 Grid Connection Costs

To provide reliability when only one reactor is assumed, it was necessary to add the capital investments needed for the sale of power to a grid or for a grid-tie interconnection. The cost and explanation of facilities included are shown in Appendix 7B.

7.3.4 Harbor Costs

The costs of harbor facilities include harbor improvements and administration. In general, improvements include two- and four-position docks; dredging, assuming the presence of a bottom consisting of half sand and half rock; breakwater to shield the docks; and tanker mooring and submarine fuel lines. Harbor administration consists of an administration building, harbor fire station, and miscellaneous vessels. Raw material unloading and product loading facilities are included in the cost of off-site facilities for the complex. The costs associated with the above facilities are discussed more fully in Chap. 8.

7.3.5 Town

A town was provided only for nuclear agro-industrial complexes at non-United States locations. Details of size and capital investment are outlined in Appendix 7B.

7.3.6 Nuclear-Powered Complex Assembly Procedure

Appendix 7B is a step-by-step procedure outlining the items necessary to generate an analysis of a nuclear industrial or nuclear agro-industrial complex. Information is provided by reference to other sections, or equations are shown directly in the procedures.

7.4 Comparison of Results from Several Complexes

Results of economic analyses for different complexes are discussed in terms of internal rates of return and their net annual benefits at various costs of money (discussed in Chap. 3). This discussion is broken into two parts; the first part compares results obtained for nuclear industrial complexes, while the second part discusses results for various nuclear agro-industrial complexes. Some of the major objectives are:

1. to study the scaling effect of the nuclear heat source on capital costs,
2. to compare reactor technologies,
3. to determine the effect of varying product mix,
4. to assess the economic benefits or penalties associated with construction outside the United States,
5. to indicate the sensitivity of the economic analysis to changes in capital costs and product prices,
6. to show the economic effect of substituting a one-reactor station for a multiple-reactor station.

Two price levels were assumed for industrial products from non-U.S. complexes; these were called "domestic" and "world market" prices. The former represent prices paid in a developing country, whereas the latter were assumed to be the same as United States prices. This same plan was followed for the agricultural products, with the domestic prices consisting of the price paid to farmers in exporting nations plus transportation and handling costs for shipping about 7500 miles. The latter costs amount approximately to an additional 30% above the exporting farmer's price. Industrial product prices are given in Table 5.9, and agricultural product prices are listed in Table 6.7.

7.4.1 Nuclear Industrial Complexes

Comparison of Reactor Technologies and United States vs Foreign Construction. – A summary of individual plant investments, raw material inputs, product outputs, and electric power requirements is shown in Table 7.1 for a nominal 2000 Mw(electrical) industrial complex producing ammonia;

elemental phosphorus; aluminum sheet, plate, and wire; and caustic-chlorine. For a more complete listing of raw material costs and product prices, refer to Table 5.9. Note that the listed power requirements are for each process alone. When complexed, some reduction in power usage is possible because of integration. For example, by-product hydrogen from brine electrolysis is combined with hydrogen from water electrolysis, and thus capital investment and power usage for ammonia production are reduced somewhat. From a 1000-ton/day chlorine plant, hydrogen equivalent

Table 7.1. Data Summary for a 2000 Mw(Electrical) Industrial Complex (Product Mix I)

A. Facilities

Facility	Size (tons)		Electric Power		Capital Investment (millions of dollars)	
	Per Day	Per Year	Kilowatt-Hours per Ton	Megawatts	U.S.	Foreign
Product						
Ammonia	3000	1,040,250	8300	1037	62.5	69.1
Elemental phosphorus	1120	380,184	12,300	574	56.6	62.3
Aluminum[a]	514	187,610	14,400	308	301.3	323.3
Chlorine	1000	346,750	3,200	133	18.5	20.7
Caustic	1130	391,828	100	4[b]	c	6.2
Off-sites					24.8	27.6
				Total	463.7	509.3

B. Major Raw Materials

Raw material	Requirement (tons/year)	Cost (dollars/ton)	
		U.S.	Foreign
	$\times 10^6$		
Phosphate rock	3.3	9.60	19.00
Coke	0.5	17.00	17.00
Silica gravel	1.0	1.00	1.00
Bauxite	0.8	8.00	5.50
Salt	1.3[d]	3.00	3.00

C. Employment

	U.S. Installation	Foreign Installation
Total employees	2900	8800

[a] Facilities include alumina refining plant, aluminum smelting, and fabrication plant.

[b] Power required for caustic concentrator only.

[c] Caustic is currently in oversupply in the United States; therefore this product is given no value, and facilities for its production are not included, in United States complexes.

[d] In the absence of caustic concentration; if concentrator is present, salt requirements are halved.

to 143 tons of ammonia per day is produced as a by-product.

An economic analysis of the complex is summarized in Table 7.2 for three different reactor technologies, and a United States location is compared with a foreign location. Note that the tabulated data are independent of the cost of money until, near the bottom of the table, the economic appraisal is listed. Since the magnitude of the interest charges during construction depends on the annual cost of money to be determined, the listed capital expenditures do not include interest charges during construction.

Interest during construction is given in footnote *b* in the table for the LWR cases computed by the method discussed in Appendix 3A. The annual net benefits listed represent the uniform annual difference between income and all expenses – both operating and charges against investment. The net annual benefits are thus the "profits" before taxes, insurance, and selling expenses. The annual expenses attributed to investment depend on the cost of money (interest rate), from which the interest charges during construction and the annual cost of investment recovery or replacement are calculated. The annual cost of recovery of investment is calculated using the sinking fund concept, corrected for salvage value. Because replacements to infinity are included in the analysis, the calculated annual net benefits continue indefinitely.

Although the fast breeder reactor is estimated to require a considerable increase in capital expenditure over the light-water reactor ($68 million in Table 7.2), the additional return seems to be well worth the expense. The incremental return on this additional capital is about 20% at a cost of money equal to 10%/year [(24.0 – 10.1)/(880.4 – 812.0)].

The chief advantage of the thermal breeder reactor over the fast breeder is the decrease in capital expenditures, mainly because of the reduction in fuel inventory with continuous reprocessing of the molten salt containing the fuel. Calculated annual net benefits for the two advanced breeder reactors are very nearly the same; however, the estimated overall capital costs are reduced by about $90 million in the case of the thermal breeder reactor. Note also that the value of bred fuel is much higher for the fast breeder because of its higher breeding ratio.

The comparison of a complex located in the United States with one located in a non-United States country indicates a considerable advantage for the latter if the products are intended for domestic markets. Although capital expenditure is about 15% higher (including interest during construction) for the non-United States complex, the internal rates of return and net annual benefits are much more attractive. This is due to higher sales value (Table 5.9) of products intended for the domestic market of a developing nation. However, if the products are intended for export trade, they must meet world prices in order to compete for markets, and in this situation the internal rates of return drop to about 70% of those for United States complexes.

For those areas where the products are intended for internal consumption, additional benefits would be gained because of reductions in foreign exchange requirements, which are usually critical in developing countries. However, these additional benefits were not assigned a monetary value for economic evaluations in this report.

Effect of Eliminating Production of Aluminum. – Because of the highly capital-intensive nature of the aluminum industry, as shown in Table 7.1, a complex without this product was considered. Table 7.3 lists capital investments, products, and raw materials for such a complex. The production of elemental phosphorus and chlorine-caustic was increased to maintain about the same total usage of electric power, and thus the same reactors were used for this complex as were used for the complex with aluminum (Table 7.2). The economic summary for this complex is shown in Table 7.4. Note the stabilizing effect of the increased capital investment for complexes including aluminum when the world export price level is applied to product sale. For domestic prices the internal rates of return are about the same with and without aluminum; however, for product sale at world market price levels, the decreases in the internal rates of return were about 15 to 20% less for the more capital-intensive complexes (see Tables 7.2 and 7.4). The LWR-powered complex without aluminum probably could not compete on the world market, since its internal rate of return of 4.5% is less than the cost of money in most cases. However, to realize the apparent economic returns noted for domestic sales, it would be necessary to determine that

Table 7.2. Economic Analysis of a 2000 Mw(Electrical) Nuclear Industrial Complex Comparing Reactor Technologies and United States vs Foreign Construction

See Table 7.1 for product mix

Industrial power,[a] Mw	2044	2044	2044	2048	2048	2048
Grid power, Mw	56	56	56	52	52	52
Total electric power, Mw	2100	2100	2100	2100	2100	2100
Station size, Mw(thermal)	6800	6100	4900	6800	6100	4900
Number of reactors	2	2	4	2	2	4
Technology	LWR-NT	FBR	TBR	LWR-NT	FBR	TBR
Cost basis	U.S.	U.S.	U.S.	Foreign	Foreign	Foreign
Investment, millions of dollars						
Nuclear island	106.5	156.0	124.2	119.3	174.7	139.1
Fuel processing plant			9.8			11.0
Turbine-generator—condenser island	120.2	90.9	88.9	134.6	101.8	99.6
Industrial complex	463.7	463.7	463.7	509.3	509.3	509.3
Harbor	23.9	23.9	23.9	23.9	23.9	23.9
Grid tie facilities	3.7	3.7	3.7	3.7	3.7	3.7
Fuel inventory	42.9	97.4	37.7	42.9	97.4	37.7
Working capital	51.1	44.8	43.7	56.6	50.2	49.2
Total[b]	812.0	880.4	795.6	890.3	961.0	873.5
Annual operating costs, millions of dollars						
Nuclear island	2.3	1.6	1.7	2.3	1.6	1.7
Fuel cycle	23.3	5.1	2.2	23.3	5.1	2.2
Turbine-generator island	0.8	0.7	0.7	0.8	0.7	0.7
Industrial complex	125.9	125.9	125.9	142.2	142.2	142.2
Total	152.3	133.3	130.5	169.2	150.2	144.6
Value of products (income), millions of dollars per year						
Credit for fissile material	4.1	8.2	1.4	4.1	8.2	1.4
Electricity to grid	1.5[c]	0.8[d]	0.8[d]	1.4[c]	0.8[d]	0.8[d]
Industrial products	257.5	257.5	257.5	342.2	342.2	342.2
Total	263.1	266.5	259.7	347.7	351.2	344.4
Economic appraisal						
Annual net benefits,[e] millions of dollars per year						
$i = 2.5\%$	63.7	81.9	82.6	126.6	145.8	145.7
$i = 5\%$	47.2	64.0	66.5	107.0	124.8	126.4
$i = 10\%$	10.2	24.0	30.2	63.9	78.5	84.2
$i = 20\%$	−81.7	−75.4	−59.9	−50.3	−44.1	−28.1
Internal rate of return, %						
Domestic market prices	11.4	12.9	14.1	16.1	16.8	18.0
World market prices				7.7	9.4	10.2

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[a] Foreign industrial power is slightly higher due to addition of caustic concentrator.

[b] Without interest during construction; for example, for a time value of money equal to 10%, one must add about $62 million and $110 million, respectively, to the total United States and foreign investments shown for LWR-NT.

[c] Valued at 3.4 mills/kwhr.

[d] Valued at 2.0 mills/kwhr.

[e] Benefits are after allowance for interest during construction and assume domestic market price levels for products.

an adequate market existed for this large product volume. Market surveys and analyses for specific areas are required before a realistic picture of the economic benefits of any particular product mix can be obtained.

Effect of Number of Reactors per Station. – The economic effect of the number of reactors per station was examined for a 1050 Mw(electrical) nuclear industrial complex using a fast breeder reactor. The industrial output was 50% of that shown for the complex listed in Table 7.1. The capital investment in the nuclear power station was reduced by 18% for the one-reactor station, while the annual operating costs were reduced by $0.6 million. These factors resulted in an increase in the internal rate of return from 8.9% for the two-reactor station to 9.6% for the one-reactor station, both on a United States basis. It was concluded

Table 7.3. Summary of Data for 2000 Mw(Electrical) Complex Without Aluminum (Product Mix VI)

A. Facilities

Facility	Size		Electric Power		Capital Investment (millions of dollars)	
	Tons/Day	Tons/Year	Kilowatt-Hours per Ton	Megawatts	U.S.	Foreign
Product						
Ammonia	3080	1,067,990	8300	1065	61.9	68.4
Elemental phosphorus	1500	509,175	12,300	769	73.6	81.0
Chlorine	2000	693,500	3200	266	32.9	36.8
Caustic	2260	783,655	100	9[a]	*b*	10.6
Off-sites					18.2	20.2
				Total	186.6	217.0

B. Major Raw Materials

Raw material	Requirement (tons/year)	Cost (dollars/ton)	
		U.S.	Foreign
	$\times 10^6$		
Phosphate rock	4.4	9.60	19.00
Coke	0.7	17.00	17.00
Silica gravel	1.3	1.00	1.00
Salt	2.6[c]	3.00	3.00

C. Employment

	U.S. Installation	Foreign Installation
Total employees	630	1900

[a] Power required for caustic concentrator only.

[b] Caustic is currently in oversupply in the United States; therefore this product is given no value, and facilities for its production are not included, in United States complexes.

[c] In the absence of caustic concentration; if concentrator is present, salt requirements are halved.

Table 7.4. Economic Analysis of a 2000 Mw(Electrical) Nuclear Industrial Complex Comparing Reactor Technologies and United States vs Foreign Construction for Industry Without Aluminum

See Table 7.3 for product mix

Industrial power,[a] Mw	2017	2017	2017	2026	2026	2026
Grid power, Mw	83	83	83	74	74	74
Total electric power, Mw	2100	2100	2100	2100	2100	2100
Station size, Mw (thermal)	6800	6100	4900	6800	6100	4900
Number of reactors	2	2	4	2	2	4
Technology	LWR-NT	FBR	TBR	LWR-NT	FBR	TBR
Cost basis	U.S.	U.S.	U.S.	Foreign	Foreign	Foreign
Investment, millions of dollars						
Nuclear island	106.5	156.0	124.2	119.3	174.7	139.1
Fuel processing plant			9.8			11.0
Turbine-generator—condenser island	120.2	90.9	88.9	134.6	101.8	99.6
Industrial complex	186.6	186.6	186.6	217.0	217.0	217.0
Harbor	23.9	23.9	23.9	23.9	23.9	23.9
Grid-tie facilities	4.6	4.6	4.6	4.6	4.6	4.6
Fuel inventory	42.9	97.4	37.7	42.9	97.4	37.7
Working capital	35.8	29.5	28.8	50.0	43.7	43.0
Total[b]	520.5	588.9	504.4	592.3	663.1	575.9
Annual operating costs, millions of dollars						
Nuclear island	2.3	1.6	1.7	2.3	1.6	1.7
Fuel cycle	23.3	5.1	2.2	23.3	5.1	2.2
Turbine generator island	0.8	0.7	0.7	0.8	0.7	0.7
Industrial complex	83.3	83.3	83.3	122.6	122.6	122.6
Total	109.7	90.7	87.9	149.0	130.0	127.2
Value of products (income), millions of dollars per year						
Credit for fissile material	4.1	8.2	1.4	4.1	8.2	1.4
Electricity to grid	2.2[c]	1.3[d]	1.3[d]	2.0[c]	1.2[d]	1.2[d]
Industrial products	183.3	183.3	183.3	263.5	263.5	263.5
Total	189.6	192.8	186.0	269.6	272.9	269.1
Economic appraisal						
Annual net benefits,[e] millions of dollars per year						
$i = 2.5\%$	52.0	71.1	70.8	88.6	107.7	110.5
$i = 5\%$	41.2	58.8	60.3	75.6	93.2	97.9
$i = 10\%$	16.7	31.3	36.6	45.8	60.2	68.8
$i = 20\%$	−45.6	−38.5	−24.0	−33.5	−27.3	−8.5
Internal rate of return, %						
Domestic market prices	13.1	14.9	16.5	16.3	17.3	19.1
World market prices				4.3	7.1	8.0

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[a] Foreign industrial power is slightly higher due to addition of caustic concentrator.

[b] Without interest during construction; for example, for a time value of money equal to 10%, one must add about $47 million and $79 million, respectively, to the total United States and foreign investment shown for LWR-NT.

[c] Valued at 3.4 mills/kwhr.

[d] Valued at 2.0 mills/kwhr.

[e] Benefits are after allowance for interest during construction and assume domestic market price levels for products.

that this small gain in profitability would probably not be worth the loss in reliability if dependence on a single reactor was required.

Effect of Size on Complex Economics. – The beneficial effect of increased size on the unit cost of nuclear power plants is well known and has been thoroughly discussed in various references.[2] Scaling factors for industrial plant investments as a function of capacity usually favor building plants as large as possible. However, for near-term applications of the concept of combined nuclear industrial complexes, market, transportation, and financing considerations suggested the advisability of investigating the economics of complexes consuming less than 2000 Mw(electrical). The output listed in Table 7.1 for the 2000-Mw complex including an aluminum industry was scaled down to 25 and 50% to provide the nucleus of a 500 and a 1000 Mw(electrical) complex respectively. A summary of the economics for a 500-, 1000-, and 2000-Mw complex, United States and foreign, is shown in Table 7.5.

To provide for increased reliability, all complexes discussed previously have utilized a two-reactor station. However, for the 500 Mw(electrical) reactor, only a single reactor was assumed since accurate cost data for smaller reactors were not available. To provide the reliability needed for the aluminum industry (discussed in Chap. 5), a grid-tie facility capable of providing 80% of the power needed for aluminum was included for the single-reactor 500 Mw(electrical) station.

The net annual benefits for the United States 500-Mw complex as shown in Table 7.5 appear unfavorable, with an internal rate of return of only 4.5%, although it should be recognized that a relatively large fraction of the power (50%) is used to make ammonia, a relatively unprofitable product. A complex having about the same power usage but only manufacturing elemental phosphorus and fabricated aluminum sheet, plate, and wire had an internal rate of return of 8.7% for United States and 13.1% for non-United States locations selling to domestic markets. This indicates that proper choice of the product mix, based on the availability of cheap raw materials, might even permit economic operation of complexes as small as 500 Mw(electrical) in the United States.

The return listed for the medium-sized 1000 Mw(electrical) United States complex in Table 7.5 is not very attractive either; however, if money were available at low interest rates, this complex might be considered. Specific applications might result in considerable reduction in operating costs for the industry. For example, location in Florida, near the source of phosphate rock, would reduce the annual cost of this raw material by $6.8 million. This reduction in operating cost would increase the predicted internal rate of return to about 8.5%.

Florida, being a source for phosphate rock and near bauxite, which is located in Surinam and Jamaica, would be well suited for an industry manufacturing elemental phosphorus and aluminum. Formulation of this complex with the production of 1150 tons of elemental phosphorus per day and 685 tons of aluminum ingot per day demonstrated that smaller complexes are economically feasible when they are tailored to take advantage of cheap raw materials. Using a two-reactor station (LWR) with a power output of 1050 Mw, the internal rate of return for this complex was estimated to be 18.7%. Again, however, to ensure that this large production rate does not flood the market and force prices down to uneconomic levels, a thorough market survey would obviously be required.

The problems involved in marketing products cannot be overemphasized, as evidenced by the large overcapacity in the fertilizer industry of the United States today. This is primarily the result of insufficient attention to marketing problems and too much dependence on an export market which did not materialize because of critical shortages of foreign exchange.[3]

The economic advantage of producing products for domestic markets in developing nations as compared with producing for export to the world market is apparent in Table 7.5. The internal rates of return for the former are quite attractive; even the 500-Mw complex has a reasonable return of almost 10%. However, large capital investments and the assumption of imported phosphate rock result in unattractive internal rates of return for complexes exporting their products to the world market. In general, favorable location with respect to raw materials or markets may permit

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[2] H. A. Sindt, I. Spiewak, and T. D. Anderson, *Chem. Eng. Progr.* **63**, 41 (1967).

[3] "All That Fertilizer and No Place to Grow," *Fortune*, June 1, 1968, p. 91.

Table 7.5. Effect of Size on the Economic Benefits of a Nuclear-Powered Industrial Complex

25, 50, and 100% of Product Outputs Shown in Table 7.1

Industrial power,[a] Mw	516	1022	2044	517	1024	2048
Grid power, Mw	9	28	56	8	26	52
Total electric power, Mw	525	1050	2100	525	1050	2100
Station size, Mw(thermal)	1700	3400	6800	1700	3400	6800
Number of Reactors	1	2	2	1	2	2
Technology	LWR-NT	LWR-NT	LWR-NT	LWR-NT	LWR-NT	LWR-NT
Cost basis	U.S.	U.S.	U.S.	Foreign	Foreign	Foreign
Investment, millions of dollars						
Nuclear island	37.5	69.7	106.5	42.0	78.1	119.3
Turbine-generator–condenser island	34.9	66.5	120.2	39.1	74.5	134.6
Industrial complex	161.0	271.1	463.7	176.8	297.5	509.3
Harbor		21.0	23.9	18.0	21.0	23.9
Grid-tie facilities	4.2	2.8	3.7	4.2	2.8	3.7
Fuel inventory	12.0	22.8	42.9	12.0	22.8	42.9
Working capital	15.3	28.2	51.1	16.1	30.2	56.6
Total[b]	264.9	482.1	812.0	308.2	526.9	890.3
Annual operating costs, millions of dollars						
Nuclear island	1.1	1.8	2.3	1.1	1.8	2.3
Fuel cycle	6.6	12.4	23.3	6.6	12.4	23.3
Turbine generator island	0.4	0.6	0.8	0.4	0.6	0.8
Industrial complex	37.5	69.1	125.9	39.9	75.3	142.2
Total	45.6	83.9	152.3	48.0	90.1	169.2
Value of products (income), millions of dollars per year						
Credit for fissile material	1.0	2.1	4.1	1.0	2.1	4.1
Electricity to grid[c]	0.2	0.8	1.5	0.2	0.7	1.4
Industrial products	64.4	128.8	257.5	85.5	171.1	342.2
Total	65.6	131.7	263.1	86.7	173.9	347.7
Economic appraisal						
Annual net benefits,[d] millions of dollars per year						
$i = 2.5\%$	4.4	19.9	63.7	20.5	52.7	126.6
$i = 5\%$	–1.0	10.2	47.2	13.7	41.2	107.0
$i = 10\%$	–13.0	–12.2	10.2	–1.2	15.6	63.9
$i = 20\%$	–42.7	–66.8	–81.7	–40.6	–52.3	–50.3
Internal rate of return, %						
Domestic market prices	4.5	7.4	11.4	9.7	12.7	16.1
World market prices				2.4	5.3	7.7

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[a] Foreign industrial power is slightly higher due to addition of caustic concentrator.

[b] Without interest during construction; for example, for a time value of money equal to 10%, one must add about $10, $37, and $62 million, respectively, for United States complexes and $38, $65, and $110 million, respectively, for foreign complexes.

[c] Valued at 3.4 mills/kwhr.

[d] Benefits are after allowance for interest during construction and assume domestic market price levels for products.

the assumption of competitive world market prices for a complex, as shown by the mix tailored for Florida.

All internal rates of return as calculated are for the entire complex, including the nuclear power plant. This is in contrast to present-day economic practice, where power plants and chemical plants assume somewhat different rates of return. However, under these conditions the power plant is usually operated as a public utility, whereas in the context of this report it would not be.

Summarized as a series of bar graphs in Fig. 7.1 are the data of Table 7.5. Some data from Table 7.4 are superimposed to show the effect of deleting the capital-intensive aluminum plant. [Had this comparison been made using a recent fabricated aluminium f.o.b. price of $800/ton (40¢/lb) instead of $650/ton, the differences shown would disappear.] Other effects shown in the graph are one vs two reactors and the Florida complex producing only elemental phosphorus and aluminum. Note that the economic gains (relative to the capital investments) to be made by shifting from light-water to breeder reactors are greater for United States complexes than for foreign complexes. This is because the 23% increase in capital investment (including interest during construction) required for a fast breeder reactor is more costly at the higher rates of return achieved by foreign complexes.

Table 7.6 summarizes the economic data on the nuclear industrial complex cases evaluated. Note that deletion of ammonia increases profit (compare complexes 4 and 2). This is because the manufacturing cost of power from a light-water reactor at an internal rate of return of 7.4% is about 3 mills/kwhr (see Fig. 4.4). At that price of power and assuming a cost of money the same as the internal rate of return, the manufacturing cost of ammonia is about $37.00/ton. This is about $7.00/ton higher than the assumed selling price of $30.00/ton (see Table 5.9) under United States conditions.

Comparison of complexes 1 and 5 suggests that even small 500-Mw complexes can be economically competitive in the United States under certain conditions. Location near a site of cheap raw materials would enhance the profits of complex 5 considerably. The cost of transportation of raw materials and/or products may completely change the economics of a complex and is a very important factor to consider in a specific site survey, as discussed in Chap. 8.

The rates of return shown for foreign complexes producing for a domestic market are satisfactory even for complexes as small as 500 Mw. In addition, the listed internal rates of return do not reflect the total benefits to a developing nation's economy. The replacement of products purchased with foreign exchange by indigenous products

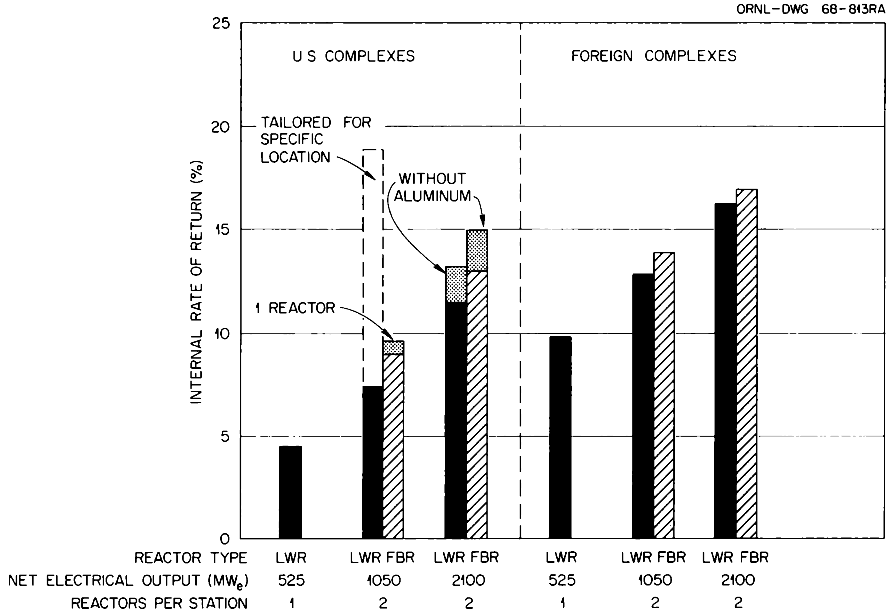

Fig. 7.1. Effect of Size and Reactor Technology on the Internal Rate of Return of Nuclear Industrial Complexes.

Table 7.6. Summary of Nuclear Industrial Complexes

Product mix	I	II	III	IV	V	VI
Production (tons/day)						
NH_3	3000					3080
P_4	1120	1120	1150	1180	1280	1500
Al	514	514	685	685	342	
Cl_2	1000	1000			1000	2000
Caustic	1130	1130			1130	2260
Electric power consumption, Mw	2048	1050	1038	1050	1021	2026

				United States				Foreign				
Complex No.	Product Mix[a]	Industrial Plant Power (Mw)	Technology	Capital Investment (dollars)	Annual Operating Costs (dollars)	Annual Product Values (dollars)	Internal Rate of Return, %	Capital Investment (dollars)	Annual Operating Costs (dollars)	Annual Product Value[b] (dollars)	Internal Rate of Return, %	
											Domestic Prices	Export Prices
				× 10^6	× 10^6	× 10^6		× 10^6	× 10^6	× 10^6		
1	I	512	LWR	265	46	66	4.5	308	48	87	9.7	2.4
2	I	1024	LWR	482	84	132	7.4	527	90	174	12.7	5.3
3	I	2048	LWR	812	152	263	11.4	890	169	348	16.1	7.7
4	II	1050	LWR	628	137	229	12.1	693	154	298	16.6	7.8
5	III	519	LWR	392	82	127	8.7	440	87	160	13.1	5.9
6	III	1038	LWR	699	149	254	12.7	755	164	320	16.6	8.9
7[c]	IV	1050	LWR	508	106	219	18.7					
8	V	1021	LWR	555	125	201	11.4	612	150	264	15.1	5.5
9	VI	2026	LWR	521	110	189	13.1	592	149	270	16.3	4.5
10	VI	2026	FBR	589	91	193	14.9	663	130	273	17.3	7.1
11	VI	2026	TBR	504	88	186	16.5	576	127	269	19.1	8.0
12	I	1024	FBR	513	73	132	9.2	581	79	174	13.6	6.5
13	I	2048	FBR	880	133	267	12.9	961	150	351	16.8	9.4
14	I	2048	TBR	796	131	260	14.1	874	145	344	18.0	10.2

[a] Product output scaled to power rate.

[b] Based on domestic or import price levels; product value using export prices is lower by a factor of 1.3.

[c] Florida location near phosphate rock deposits; aluminum made into ingot only.

renders monetary benefits to their economy over and above those listed in this report. These additional benefits might be sufficient to make a marginally attractive enterprise very attractive to a developing nation.

In general, when the products of non-United States complexes are sold at world market prices, their returns are much less attractive (see Table 7.6). This is because the products are being sold at essentially United States prices but with increased capital and raw material costs assumed because of their location. Favorable location with respect to raw materials or a specific market would improve these returns.

7.4.2 Nuclear Agro-Industrial Complexes

This section discusses the assembly and economic analysis of a nuclear agro-industrial complex. All the factors discussed in previous sections of the report are brought together as a unit, and the practicability of the idea is examined. Since the United States has abundant food production capabilities and does not have an extensive coastal desert area, the merit of nuclear agro-industrial complexes is examined only for foreign locations. The critical need of many developing countries for large increases in food production is quite evident and is adequately discussed elsewhere.[4]

Comparison of Reactor and Evaporator Technologies. – The effect of advances in reactor and evaporator technology was studied for a nuclear agro-industrial complex consisting of an industry with the product mix and output listed in Table 7.3 and a farm producing the high profit crop mix (Table 6.15) summarized in Table 6.18.

With operation of the turbines under optimum conditions, namely, in the back-pressure region, the power requirement of the coupled industry dictates the amount of water to be produced by the evaporator plant for a given evaporator performance ratio [see Appendix 7A, Eqs. (14) and (15)]. For light-water reactor cases (Table 7.7) a total of 2715 Mw of electricity is required for the industrial plants, grid, evaporator pumping, and irrigation system. Based on this power requirement the output of the evaporator is 1250 Mgd for an evaporator performance ratio of 12 lb of water per 1000 Btu. The size of the farm was based on the utilization of 1220 Mgd, with 30 Mgd to supply town and industrial needs. The costs, income, and acreages listed in Table 6.18 for the high-profit farm were scaled linearly by the factor 1.22 (1220 Mgd/1000 Mgd).

The pertinent economic data are summarized in Table 7.7 for two light-water reactors, one coupled to a MSF evaporator and one to a VTE. Also listed in the table is a fast breeder reactor coupled to a VTE. Thus conclusions can be drawn comparing the relative effects of (1) changing evaporator technology, (2) changing reactor technology, and (3) simultaneously changing evaporator and reactor technologies. To eliminate the large excess block of power available for the FBR-VTE combination, a case is also shown when about 25% of the prime steam is bypassed directly to the evaporator through a pressure-reducing valve. The economic penalty incurred in doing this is not noticeable in the internal rate of return; however, the annual net benefits are reduced by about $10 million at a 10% cost of money.

Note that a significant decrease in electric power usage results when changing evaporator technology from MSF to VTE. This is due to the large decrease in seawater pumping power for the latter. The large increase in grid sales shown for the LWR-VTE combination is a direct result of this decrease in power for water production. The additional grid sales shown for the FBR-VTE combination are due to the difference in turbine cycle efficiencies between LWR and FBR reactors (see Appendix 7A, Table 7A.1) and the fact that the water requirement is set according to the conditions of the lower efficiency. If the electrical generation had been kept the same as for the LWR cases, the amount of water produced would have been reduced to 954 Mgd.

The capital investment of the industry is somewhat higher than listed in Table 7.4 because of the hydrogen requirements for seawater treatment with hydrochloric acid. The use of a portion of the hydrogen output of the chlorine plant to produce hydrochloric acid requires an increase in the capital investment for the electrolytic hydrogen plant. This also increases the electrical power requirement of the industries by 44 Mw.

The fast breeder reactor has a distinct economic advantage over the light-water reactor even though

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[4] U.S. President's Science Advisory Committee, *The World Food Problem*, vol. I, 1967.

Table 7.7. Effect of Reactor and Evaporator Technologies on the Economic Benefits of a Nuclear Agro-Industrial Complex

Type of evaporator	MSF	VTE	VTE	VTE (Bypass)[a]
Industrial power,[b] Mw	2070	2070	2070	2070
Power for water, Mw	620	367	367	367
Grid power, Mw	25	278	1165	25
Total electric power, Mw	2715	2715	3602	2462
Desalted water, Mgd	1250	1250	1250	1250
Station size, Mw(thermal)	13,651	13,755	14,662	13,425
Farm size,[c] acres	390,224	390,224	390,224	390,224
Number of reactors	2	2	2	2
Technology	LWR-NT	LWR-NT	FBR	FBR
Cost basis	Foreign	Foreign	Foreign	Foreign
Investment, millions of dollars				
Nuclear island	195.0	195.0	297.9	283.0
Turbine generator island	149.5	149.5	146.8	104.9
Evaporator plant	497.3	350.6	350.6	350.6
Seawater treatment plant[d]	0.3	0.3	0.3	0.3
Industrial complex	219.0	219.0	219.0	219.0
Farm	373.7	373.7	373.7	373.7
Harbor	40.3	40.3	40.3	40.3
Town	19.2	19.2	19.2	19.2
Grid-tie facility	2.7	7.7	14.3	2.7
Fuel inventory	87.1	87.1	234.6	215.2
Working capital	83.0	83.3	71.2	70.9
Total[e]	1653.1	1511.1	1753.6	1665.5
Annual operating costs, millions of dollars				
Nuclear island	2.9	2.9	2.5	2.4
Fuel cycle	46.8	46.8	12.2	11.2
Turbine generator island	0.9	0.9	0.8	0.7
Evaporator plant	6.5	5.6	5.6	5.6
Industrial complex	122.7	122.7	122.7	122.7
Farm	70.0	70.0	70.0	70.0
Total	249.8	248.9	213.8	212.6
Value of products (income), millions of dollars per year				
Credit for fissile material	8.2	8.2	19.9	18.2
Electricity to grid	0.7[f]	7.4[f]	18.4[f]	0.4[g]
Industrial products	257.5	257.5	257.5	257.5
Farm products	237.1	237.1	237.1	237.1
Total	503.5	510.2	532.9	513.2
Economic appraisal				
Annual net benefits,[h] millions of dollars per year				
$i = 2.5\%$	171.2	183.1	233.4	220.0
$i = 5\%$	131.6	147.4	195.5	180.0
$i = 10\%$	44.4	72.3	109.5	99.0
$i = 20\%$	−178.1	−122.9	−108.3	−107.6
Internal rate of return at domestic market prices, %	12.9	14.5	15.3	15.3

[a] VTE (bypass) indicates evaporator operated with about 25% bypass of prime steam to reduce electric power output; all other cases are operated in back-pressure region.

[b] See Table 7.3 for product output of industrial complex.

[c] See Table 6.17 for base case used in costing the farm.

[d] Hydrochloric acid treatment.

[e] Excluding interest during construction; charges at 10% cost of money would add $187, $164, $185, and $173 million respectively.

[f] Valued at 3.4 mills/kwhr.

[g] Valued at 2.0 mills/kwhr.

[h] Benefits are after allowance for interest during construction and assume domestic market price levels for products.

the overall capital investment for the former is increased by about 16% (including interest during construction). For a 10% cost of money, the economic appraisal listed in Table 7.7 indicates that the net annual profit advantage (after paying interest charges on all money, putting aside enough money to replace the complex at the end of its lifetime, and paying all operating costs) for the fast breeder is $37 million per year with an estimated additional investment of $264 million including interest during construction (IDC).

Incrementally, it is apparent that advanced evaporator technology is somewhat more important to the economic viability of nuclear agro-industrial complexes in foreign locations than the incorporation of fast breeder reactor technology. Table 7.7

Table 7.8. Effect of Size of Nuclear Agro-Industrial Complex on Economic Benefits Using MSF Evaporators

Industrial power,[a] Mw	528	1046	2092
Power for water, Mw	154	311	632
Grid power, Mw	6	15	25
Total electric power, Mw	688	1370	2749
Desalted water, Mgd	320	625	1280
Station size, Mw(thermal)	3525	6911	14,096
Farm size,[b] acres	99,157	195,115	399,825
Number of reactors	2	2	2
Technology	LWR-NT	LWR-NT	LWR-NT
Cost basis	Foreign	Foreign	Foreign
Investment, millions of dollars			
Nuclear reactor island	80.5	120.0	196.9
Turbine generator island	50.0	80.4	152.5
Evaporator plant	137.8	255.4	508.0
Seawater treatment plant[c]	0.1	0.2	0.3
Industrial complex	177.3	298.5	511.3
Farm	94.9	186.7	382.5
Harbor	20.0	28.3	40.3
Town	10.1	18.0	31.8
Grid-tie facility	1.5	2.0	2.7
Fuel inventory	23.6	43.8	89.3
Working capital	24.5	46.2	89.4
Total[d]	620.3	1079.5	2005.0
Annual operating costs, millions of dollars			
Nuclear island	1.8	2.3	2.9
Fuel cycle	12.9	23.7	48.3
Turbine generator island	0.6	0.7	0.9
Evaporator plant	2.1	3.6	6.3
Industrial complex	39.9	75.3	142.2
Farm	17.8	35.0	71.7
Total	75.1	140.6	272.3
Value of products (income), millions of dollars per year			
Credit for fissile material	2.1	4.2	8.5
Electricity to grid[e]	0.2	0.4	0.7
Industrial products	84.0	168.1	336.0
Farm products	60.2	118.6	243.0
Total	146.5	291.3	588.2

Table 7.8 (continued)

Economic appraisal			
Annual net benefits,[f] millions of dollars per year			
$i = 2.5\%$	38.1	92.5	211.4
$i = 5\%$	25.0	69.9	167.0
$i = 10\%$	–5.0	17.3	70.1
$i = 20\%$	–83.5	–119.1	180.9
Internal rate of return at domestic market prices, %	9.3	11.5	13.2

[a] See Table 7.1 for product output of base industrial complex.

[b] See Table 6.18 for base case used in costing the farm.

[c] Hydrochloric acid treatment.

[d] Excluding interest during construction; charges at 10% cost of money would add $70, $118, and $210 million respectively.

[e] Valued at 3.4 mills/kwhr.

[f] Benefits are after allowance for interest during construction.

indicates that the effect of changing only the evaporator technology from MSF to VTE, while holding reactor technology constant (LWR), results in a $28 million increase in profit, with a concurrent reduction of $165 million (10%) in capital investment (including IDC). However, achieving the technological advance from near term (LWR-MSF) to far term (FBR-VTE) results in an impressive 56% return on the additional capital (including IDC) at a 10% cost of money.

Effect of Size of Nuclear Agro-Industrial Complex. – The effect of size of the nuclear agro-industrial complex was examined in Table 7.8 by adding an evaporator and a farm to the nominal 500, 1000, and 2000 Mw(electrical) nuclear industrial complexes listed in Table 7.5. Minor differences in industrial capital investment and power requirements are again caused by decreases in the hydrogen available as a by-product from the chlorine plant.

The farm is based upon the use of 310, 610, and 1250 Mgd, respectively, with the remainder of the water allocated to town and industrial use. Linear scaling was applied to the basic farm case, shown in Table 6.18, to obtain the capital investments, operating costs, and product sales shown in Table 7.8.

The effect of size on net annual benefits is very similar to that shown for the nuclear industrial complexes shown in Table 7.5, although the dependence of net annual benefits on the cost of money is much greater. This is due to the approximate doubling of the capital investment in the case of nuclear agro-industrial complexes. The internal rate of return increases about 2 percentage points for each step in reactor size (500 and 1000 Mw steps).

Incremental Rate of Return of the Farm. – The internal rate of return was computed for the incremental addition of a farm and its ancillary equipment to the nuclear industrial complexes shown in Tables 7.4 and 7.5. The economic analyses procedures as outlined in Chap. 3 and Appendix 3A were applied to the differences in capital costs, operating costs, and annual sales to arrive at an internal rate of return for the farm increment. For each case examined, the grid power for the nuclear agro-industrial complex was equal to that of the corresponding nuclear industrial complex.

Incremental rates of return were determined for three of the farms shown in Table 7.7 to determine the effect of reactor and evaporator technology on farm economics. For the LWR-MSF case the incremental internal rate of return was 10.6%, as compared with 12.9% for the entire complex. By utilizing advanced evaporator technology in the form of a vertical-tube evaporator (LWR-VTE), the incremental return for the farm increased to 13.7%, compared with 14.5% for the entire nuclear agro-industrial complex.

Finally, for the most advanced technology represented by the FBR-VTE case, the incremental return on the farm was estimated at 15.0%, as compared with 15.3% for the entire complex. These data again emphasize that the achievement of advanced evaporator technology (VTE) is incrementally more important to improving farm economics than the achievement of advanced reactor technology.

Incremental returns were computed for the farm as a function of size by comparing the data of Tables 7.5 and 7.8. These data are based on near-term technology, namely, light-water reactors and MSF evaporators. The three energy centers, nominal 500, 1000, and 2000 net Mw, produce water at the rate of 320, 625, and 1280 Mgd respectively. The data are summarized in Table 7.9. Note that the incremental rate of return for the farm remains relatively constant regardless of size. This is due to the relatively small scaling benefits available for MSF evaporators and the fact that the farm is scaled linearly according to water plant size.

The internal rates of return for industry alone and for the farm and industry together, and the incremental return for the farm alone suggest that large farming operations utilizing advanced farming methods can produce returns which compare favorably with those of industry. The farm does depress the internal rate of return more as its size increases, but this is because the scaling of industry is logarithmic whereas that of the farm is linear.

Another important factor which must be considered as somewhat detrimental to industry is the problem of marketing products. The larger industrial complexes appear quite attractive, but the problems of selling their large outputs would depend to a large extent on market considerations and the presence of an adequate economy able to pay for the products. In certain developing countries the latter may turn out to be an insurmountable obstacle. Moreover, people must eat, and thus an adequate market for food usually can be assumed to exist in a developing nation, although food prices are important. Other nonmonetary benefits, when evaluated, may lend additional support to the idea. One such benefit might be that present nonproductive coastal desert land could be brought under cultivation to provide additional food in underdeveloped nations. Another benefit, more diffuse and difficult to evaluate, might be the example provided to the nation's small farmers by a concentrated farming industry utilizing advanced agricultural practices. This example might be expected to influence the small farmers' methods of cultivating and in this way tremendously increasing the nation's food production. Again, however, these results are highly speculative and not subject to an economic appraisal.

Single-Purpose vs Dual-Purpose Nuclear-Powered Complexes. – Analogous to industry-only complexes, it seemed informative to evaluate a farm-only case. Since reactors producing low-temperature steam for seawater distillation are in only early stages of study,[5,6] it was necessary to use the high-temperature steam produced by light-water and fast breeder reactors by first passing it through a pressure-reducing valve and thence into the evaporator. This is inefficient utilization of the avail-

Table 7.9. Summary of Internal Rates of Return as a Function of Farm Size Based on Sales to a Domestic Market and Using Near-Term Technology (LWR-MSF)

Industrial product mix listed in Table 7.5; farms described in Table 7.8; product sales at domestic price levels

Industry Size [Mw(electrical)]	Water Plant Size (Mgd)	Internal Rate of Return, %		
		Farm and Industry	Farm Incremental	Industry Alone
528	320	9.3	8.9	9.7
1046	625	11.5	10.3	12.7
2092	1280	13.2	10.7	16.1

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[5] R. P. Hammond *et al.*, *High Gain Breeders for Desalting or Power Using Unclad Metal Fuels*, ORNL-4202 (to be published).

[6] T. D. Anderson *et al.*, "A Metallic Uranium Fueled PWR for Single Purpose Desalting," *ANS/CNA Trans.* 11(1), 355; presented at 1968 Meeting, Toronto, Canada, June 1968.

able energy; however, it does offer the opportunity of evaluating a farm-only case. For these cases it was decided to set the output of the water plant at 1000 Mgd, and thus, to obtain data for comparable dual-purpose plants, the industry size was scaled down to 1585 Mw of electricity, with the products and their production listed in footnote *a* of Table 7.10.

The economic advantage of dual-purpose over single-purpose nuclear power stations is readily seen in Table 7.10. The incremental returns on the farm for the dual-purpose plants are about 44% higher than the returns listed for the farms of the single-purpose plants.

The grid power shown for the dual-purpose FBR plant, about 1000 Mw (electrical), is rather high but is necessary in order to produce 1000 Mgd of desalted water while operating in the back-pressure region. However, this grid power can be eliminated by decreasing the thermal power of the station by about 9% and making the same amount of water by bypassing 25% of the prime steam directly to the evaporator. In this case the internal rate of return is about the same, 16.4%, as shown in Table 7.10. However, if electricity is priced at 3.4 mills/kwhr instead of 2 mills/kwhr, a slight disadvantage would be noted for the bypass case. A price of 3.4 mills/kwhr would be required to pay all costs for a FBR at a cost of money of 16.4% (see FBR base case, 0.90 load factor, Fig. 4.4). This serves to illustrate that partial bypass of prime steam may be permitted without imposing significant economic penalties on the overall complex.

Effect of Price Level and Product Processing. – The most important single item in determining the relative merit of the various complexes discussed in this report is the price level assumed for raw materials and for the sale of products. The prices of raw materials listed in Table 5.9 are intended to represent these materials at the complex site after being shipped in from various distances. Assumption of a complex site at a source of raw material would improve the economic picture. The product prices listed in Tables 5.9 and 6.7 are intended to represent two levels, domestic market prices and world market prices. The former prices listed for non-United States locations are intended to represent their indigenous value to the country as a replacement of a foreign expenditure for the same product (no shadow rate of exchange).

Assuming that all the products of the two dual-purpose complexes of Table 7.10 were sold at world prices resulted in reductions of about 40% in their internal rates of return. This suggests that these complexes would have difficulty competing on the world market unless a favorable raw material source existed within the country.

It should be recognized that additional processing steps for some of the products might make the economic returns more promising. For example, conversion of all the ammonia production listed in Table 7.10 into ammonium nitrate and urea for the dual-purpose LWR case resulted in an internal rate of return of 16.1%, an improvement of 1.5 percentage points. Similarly, the addition of food processing for the farm products should improve the economics of the farm; however, intensive study of this possible source of additional income was beyond the scope of the study.

Summary. – The results obtained for nuclear agro-industrial complexes are summarized in Table 7.11. It should be recognized that alternative methods of feeding people and producing power and water exist; however, their serious consideration as alternatives should be dependent upon achieving a similar level of economic benefaction. Evaluation of alternatives to the nuclear agro-industrial concept was beyond the scope of the present report.

Another area which requires more study involves the choice of a range of internal rates of return which would represent an attractive investment. The range would be dependent on the alternatives available for a particular area and would require a market survey to determine the types and amounts of products which could be absorbed within the area.

To summarize the economic studies on nuclear agro-industrial projects, one must conclude that on a strictly monetary basis they are not quite as attractive as nuclear-industrial complexes, especially with near-term evaporator technology. However, it should be stated that small changes in the basic water-yield relationships (Table 6.3), crop prices (Table 6.7), irrigation requirements (Table 6.1), more high-value crops, or the addition of some food processing facilities could significantly change the economic comparison. It must also be recognized that most of the conditions attained in the analysis reported here would result in a cost for water in excess of 10¢/1000 gal (see Fig. 4.11). This has been generally accepted as about the limit that one could pay for irrigation water under usual conditions. Nevertheless, it should be noted that at a water production rate of 1000 Mgd and at a cost of money of 10%, the cost of water is about 24¢ and

Table 7.10. Comparison of Water-Only Production with Power and Water Production Using Light-Water and Fast Breeder Reactors

Type of complex	Single purpose	Dual purpose	Single purpose	Dual purpose
Industrial power,[a] Mw	0	1585	0	1585
Power for water, Mw	497	497	294	294
Grid power, Mw	20	25	20	987
Total electric power, Mw	517	2108	314	2866
Desalted water, Mgd	1000	1000	1000	1000
Station size, Mw(thermal)	9031	11,108	8819	11,923
Farm size, acres	320,000	320,000	320,000	320,000
Number of reactors	2	2	2	2
Technology	LWR-MSF	LWR-MSF	FBR-VTE	FBR-VTE
Cost basis	Foreign	Foreign	Foreign	Foreign
Investment, millions of dollars				
Nuclear island	144.1	166.5	217.3	260.8
Turbine generator island	39.2	120.0	20.0	118.1
Evaporator	403.2	403.2	278.9	278.9
Seawater treatment plant	0[b]	0.3[c]	0[b]	0.3[c]
Industrial complex	0	570.3	0	570.3
Farm	306.0	306.0	306.0	306.0
Harbor	30.0	35.0	30.0	35.0
Town	13.5	32.0	13.5	32.0
Grid-tie facility	2.5	2.7	2.5	13.1
Fuel inventory	57.2	70.4	141.1	190.8
Working capital	36.2	78.7	27.6	71.0
Total	1031.9	1785.1	1036.9	1876.3
Annual operating costs, millions of dollars				
Nuclear island	2.5	2.7	2.0	2.3
Fuel cycle	31.0	38.1	6.6	9.9
Turbine generator island	0.5	0.8	0.4	0.8
Evaporator	12.5[b]	5.5	11.7[b]	4.6
Industrial complex	0	133.0	0	133.0
Farm	62.0[d]	56.0[e]	62.0[d]	56.0[e]
Total	108.5	236.1	82.7	206.6
Value of products (income), millions of dollars per year				
Credit for fissile material	5.5	6.7	10.8	16.2
Electricity to grid	0.5	0.6	0.5	15.2
Industrial products	0	347.1	0	347.1
Farm products	194.4	194.4	194.4	194.4
Total	200.4	548.8	205.7	572.9
Internal rate of return, %				
Domestic sales prices	7.4	14.6	10.1	16.4
World market prices		8.2		10.4
Farm, incremental, domestic prices		10.6		14.5

[a] Industrial production (tons/day): ammonia, 1740; phosphorus, 765; aluminum, 685; chlorine, 1500; caustic soda, 1695.

[b] Assumes purchase of sulfuric acid from an on-site plant at $22.50/ton ($60.00/ton sulfur).

[c] Hydrochloric acid scale preventive treatment.

[d] Fertilizer purchased.

[e] No fertilizer costs; sales are reduced by amount of fertilizer needed.

Table 7.11. Summary of Nuclear Agro-Industrial Complexes for Non-United States Locations

Complex No.	Product Mix[a]	Industry Size [Mw(electrical)]	Water Plant Size (Mgd)	Technology	Capital Investment (dollars)	Annual Operating Costs (dollars)	Annual Product Sales (dollars)	Internal Rate of Return, %			
								Farm and Industry	Farm Incremental	Farm Alone	Industry Alone
					$\times 10^6$	$\times 10^6$	$\times 10^6$				
15	VI	2070	1250	LWR-MSF	1653	250	504	12.9	10.6		16.3
16	VI	2070	1250	LWR-VTE	1511	249	510	14.5	13.7		16.3
17	VI	2070	1250	FBR-VTE[b]	1754	214	533	15.3	15.0		17.3
18	I	523	320	LWR-MSF	620	75	146	9.3	8.9		9.7
19	I	1046	640	LWR-MSF	1080	141	291	11.5	10.3		12.7
20	I	2092	1280	LWR-MSF	2005	272	588	13.2	10.7		16.1
21	Water only[c]	0	1000	LWR-MSF	1029	109	200			7.4	
22	Water only[c]	0	1000	FBR-VTE	1035	83	205			10.1	
23	VII	1585	1000	LWR-MSF	1781	236	548	14.6	10.6		
24	VII	1585	1000	LWR-MSF	1781	236	422[d]	8.2[d]			
25	VIII	1585	1000	LWR-MSF	1947	255	609	16.1			
26	VII	1585	1000	FBR-VTE	1876[b]	207	573	16.4	14.5		
27	VII	1585	1000	FBR-VTE	1876[b]	207	445[d]	10.4[d]			
28	VII	1585	1000	FBR-VTE	1790[e]	205	556	16.4			

[a] Industrial product mixes I and VI same as in Table 7.6; farm products as in high-value pattern and scaled to water rate. Product mixes VII and VIII are (tons/day):

VII		VIII	
NH_3	1740	Urea	1450
P_4	765	NH_4NO_3	1860
Al	685	P_4	765
Cl_2	1500	Al	685
Caustic	1695	Cl_2	1500
		Caustic	1695

[b] Excess electricity (~1000 Mw) sold to utility grid.

[c] No industry — 85% steam bypass to evaporator plant.

[d] At export or world market price levels; all other values are at the import or domestic market price levels.

[e] No electricity sales to grid — 25% steam bypass.

17¢/1000 gal from LWR-MSF and FBR-VTE combinations respectively (see Fig. 4.11). The results of this study appear to indicate that intensive farming of basic staple crops with water at these costs is possible and, in fact, may be profitable for developing countries.

7.5 Typical Layout of Complex

Figure 7.2 is a plot plan of the industrial portion of a typical nuclear agro-industrial complex as shown in the Frontispiece and is presented here to provide more detailed information than is given in the artist's drawing and the accompanying explanation. As indicated previously, it includes two 1200 Mw(electrical) nuclear reactors, a 2000-Mgd seawater treatment facility, a 1000-Mgd seawater evaporator plant, three turbine stations, and industrial plants to produce 3000 tons of ammonia per day from electrolytic hydrogen (1035 Mw), 1500 tons/day of elemental phosphorus (750 Mw), 685 tons/day of fabricated aluminum sheet and bar from bauxite (410 Mw), and 2000 tons/day of chlorine and 2200 tons/day of caustic by brine electrolysis (175 Mw). The detailed list at the top of the drawing provides the legend for the facility numbers on the plot plan.

The overall land requirements are about 2 sq miles: about 1 mile from the shore to the railroad marshaling yard and 2 miles from the alumina refining plant to the far edge of the phosphorus plant. It is believed that this amount of land will permit an uncrowded arrangement of the facilities that are shown and will also leave room enough for the addition of several other facilities (particularly for the production of fertilizers such as urea, ammonium nitrate, diammonium phosphate, and nitric phosphate), and possibly a few small plants for the production of several other products such as insecticides, refractory-grade alumina, and bromine from seawater. Larger additions, such as an iron and steel plant, an arc process acetylene plant, and plants to reclaim potassium sulfate or chloride, gypsum, and anhydrous magnesium chloride from seawater, including also the production of magnesium from the magnesium chloride and of sulfuric acid and portland cement from the gypsum, would require additional land. Therefore, a well-planned agro-industrial complex should include at least a 1-mile-wide buffer zone between its initial industrial installations and the adjacent food factory or town. The largest possible industrial land requirement should be that associated with a solar salt works. For example, about 40 sq miles (25,000 acres) would be required to recover 1,000,000 tons of salt a year. This may be a good investment, however, since salt is a commodity in great demand, and use of a seawater evaporator effluent will cut down the land requirement by 40 to 70%, depending on the evaporator concentration ratio.

One of the problems which will need solving for such a complex is the disposal of waste products. For example, about 6 acres/year are required for red mud disposal (Fig. 7.2, item 56) from the alumina refining plant and 60 acres/year for the phosphorus plant slag (83). Air and water pollution could also be problems, and careful design and the expenditure of extra funds to minimize these problems before they arise may be warranted.

Another problem which will bear much consideration is materials movement, since over 10,000,000 tons of raw materials and products must be moved into and out of the complex each year. Since an agro-industrial complex must be on a seacoast because of the seawater evaporator, a natural or artificial harbor would permit the receipt of raw materials and shipment of products by lower-cost ocean freight. Nearby inland raw materials and markets must be served by trucks or by railroad and perhaps pipeline; however, the quantities involved almost eliminate trucks. Material handling at the docks and within the complex would be done as much as possible by conveyors. All three means of material transport are shown in Fig. 7.2.

A common services area is shown between the evaporators (3) and the seawater treatment thickeners (10). These facilities would include such services as overall administrative quarters for the complex; fire, health, security, and safety facilities; general shops and warehouses; and research and development facilities.

Finally, the seawater preevaporation treatment system shown is one based exclusively on the use of caustic (except for a small amount of hydrochloric acid for final pH adjustment of the treated seawater). Use of equimolar amounts of caustic and hydrochloric acid, the minimum cost system, would reduce the number of seawater treatment thickeners (10) from 6 to 3. This system would require 355 tons of chlorine and 400 tons of caustic per day, leaving 1645 tons of chlorine and 1855 tons of caustic per day for sale. Going to all HCl treatment would eliminate all the thickeners shown.

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LIST OF FACILITIES

1. NUCLEAR REACTORS
2. TURBINE ROOMS
3. EVAPORATORS
4. SEAWATER INTAKES
5. RAW SEAWATER CANAL
6. TREATED SEAWATER CANAL
7. EVAPORATOR EFFLUENT CANAL
8. CANAL TO SALT WORKS
9. SEAWATER DISCHARGE
10. SEAWATER TREATMENT THICKENERS
11. $CaCO_3$ FILTERS
12. $CaCO_3$ DRIERS
13. $CaCO_3$ CALCINERS
14. BURNT LIME STORAGE
22. FRESH WATER CONDUIT TO FARM
23. BRINE ELECTROLYSIS CELLS
24. HYDROGEN CLEANUP
25. Cl_2 PURIFICATION
26. Cl_2 STORAGE
27. HCl SYNTHESIS
28. HCl STORAGE
29. CAUSTIC PURIFICATION & CONCENTRATION
30. 50% CAUSTIC STORAGE
31. CELL LIQUOR STORAGE
32. RAW BRINE STORAGE
33. BRINE PURIFICATION
34. BRINE FILTRATION
35. PURIFIED BRINE STORAGE
36. CAUSTIC-CHLORINE ADMINISTRATION BLDG.
37. CAUSTIC-CHLORINE WAREHOUSE AREA
38. CAUSTIC-CHLORINE SHOP AREA
39. BAUXITE RECEIPT & STORAGE
40. BAUXITE CRUSHING
41. CRUSHED BAUXITE STORAGE
42. BAUXITE CAUSTIC SLURRY MIXERS
43. ALUMINA DIGESTORS
44. FLASHERS & HEAT EXCHANGERS
45. ALUMINA PRECIPITATORS
46. ALUMINA THICKENERS
47. ALUMINA FILTERS
48. ALUMINA CALCINERS
49. ALUMINA STORAGE
50. LIME STORAGE AND CALCINER
51. RED MUD THICKENERS & WASHERS
52. RED MUD FILTERS
53. CAUSTIC STORAGE
54. CAUSTIC RECYCLE EVAPORATOR
55. ALUMINA REFINERY SHOPS & OFFICES
56. RED MUD DISCARD AREA
57. ALUMINUM SMELTING CELLS
58. CRYOLITE MAKEUP SUPPLIES
59. FLUORINE CLEANUP
60. ANODE RAW MATERIAL
61. ANODE MANUFACTURE
62. ANODE BAKING
63. ANODE RODDING
64. ALUMINUM INGOT CASTING
65. ALUMINUM SHEET & BAR FABRICATION
66. ALUMINUM PLANT SHOPS AND OFFICES
67. ELECTROLYTIC HYDROGEN GENERATION
68. AIR LIQUEFACTION & FRACTIONATION PLANT
69. AMMONIA SYNTHESIS PLANT
70. AMMONIA STORAGE AREA
71. PHOSPHATE ROCK RECEIPT & STORAGE
72. PHOSPHATE MATRIX RECEIPT & STORAGE
73. COKE RECEIPT & STORAGE
74. NODULIZING KILNS
75. NODULE STORAGE
76. COKE DRYING, CRUSHING & SCREENING
77. PHOSPHORUS ELECTRIC FURNACES
78. FERROPHOSPHORUS REMOVAL SYSTEM
79. FURNACE SLAG PITS
80. ELEMENTAL PHOSPHORUS STORAGE
81. PHOSPHORUS WATER CLEANUP SYSTEM
82. PHOSPHORUS WATER SETTLING POND
83. SLAG DISPOSAL AREA
84. FUTURE AREA FOR H_3PO_4 & DAP PLANTS
85. FUTURE AREA FOR NITRIC PHOSPHATE PLANT
86. FUTURE AREA FOR HNO_3, NH_4NO_3 & UREA PLANTS
87. PIER FOR PHOSPHATE ROCK, MATRIX & COKE RECEIPT AND SALT, PHOSPHORUS, SLAG AND FeP AND CaO EXPORT
88. PIER FOR Cl_2, NaOH, HCl AND NH_3 EXPORT
89. PIER FOR BAUXITE RECEIPT AND Al_2O_3 AND Al EXPORT
90. PIERS FOR AGRICULTURAL PRODUCT EXPORT
91. AGRICULTURAL PRODUCT WAREHOUSES
92. RAILROAD MARSHALLING YARDS
93. COMPLEX ADMINISTRATIVE OFFICE
94. COMPLEX CAFETERIA
95. COMPLEX FIRE STATION
96. COMPLEX DISPENSARY & FIRST AID
97. COMPLEX SECURITY OFFICE
98. COMPLEX AUTOMOTIVE SHOP
99. COMPLEX WAREHOUSES & SHOPS
100. COMPLEX LABORATORY
101. ELECTRICAL SUBSTATIONS
102. COOLING WATER TOWERS
103. SEWAGE TREATMENT PLANT
104. PRODUCT WATER SURGE BASIN
105. PRODUCT WATER PUMP HOUSE
106. PROTECTIVE BREAKWATER
107. FUEL OIL AND GASOLINE STORAGE
108. FUEL OIL AND GASOLINE TANKER MOORING

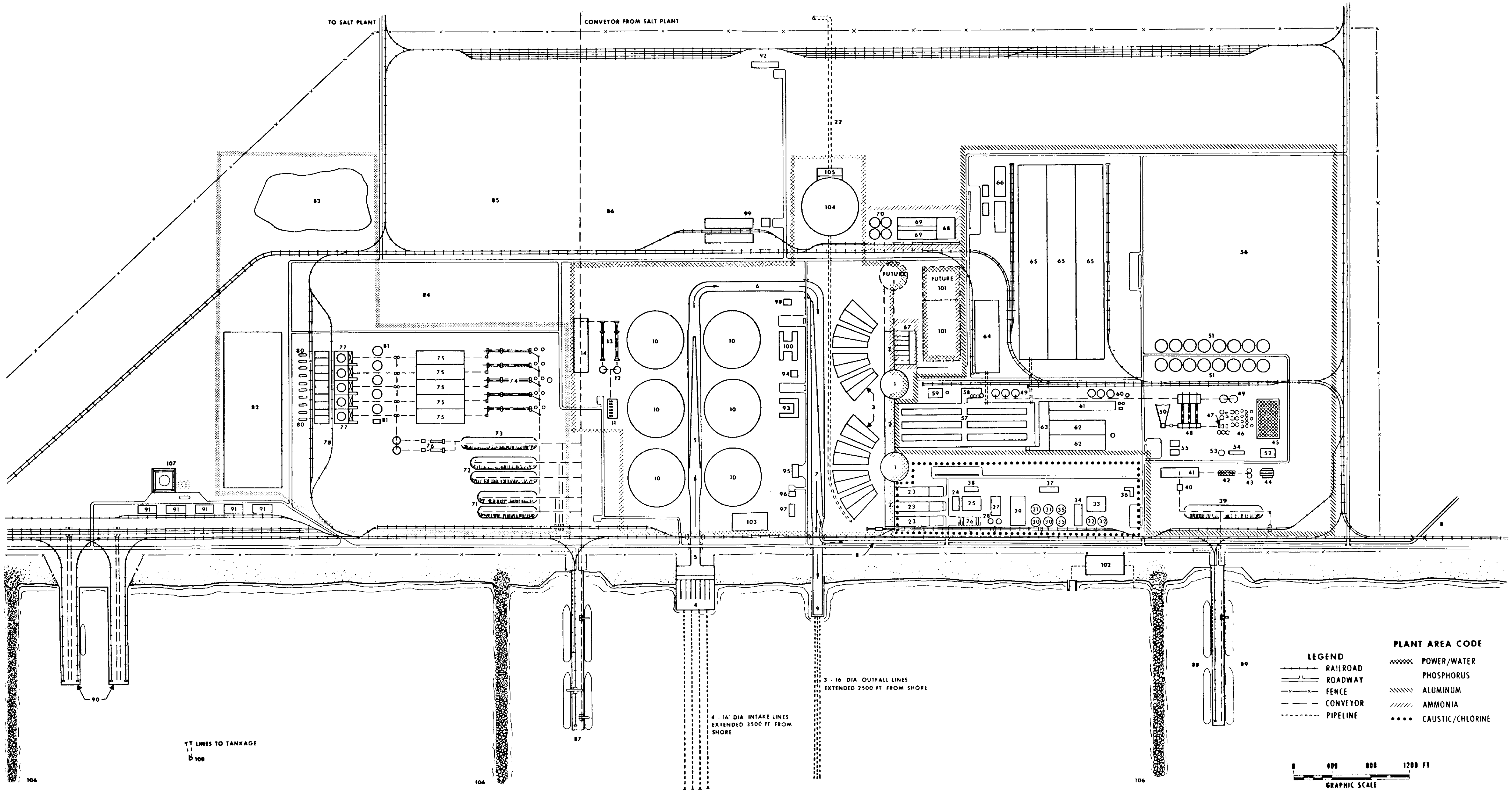

Fig. 7.2. Typical Layout of Agro-Industrial Complex.

8. LOCATION, ACCOMMODATION, AND IMPLEMENTATION OF COMPLEXES

A meaningful evaluation of an agricultural-industrial (AI) complex requires an analysis of the concept in relation to real world conditions. Ideally this would involve detailed surveys of a large number of specific potential sites, but this was considered to be beyond the scope of this study project, since it required much more detailed information than was available. Consequently, the intent has been to select several general areas (locales) which appear to be suitable and to provide a preliminary discussion and evaluation of each. In this way, ranges for input design variables can be established which reflect real world conditions and give some answers to the following questions:

1. Are there areas in the world that satisfy the premises underlying the agro-industrial complex concept?
2. Are such areas unique, or is there a broad applicability for the concept throughout the world?
3. What impact would such a complex have on a number of specific locales?

8.1 General Considerations in Locale Selection

The major motivating advantage behind the agro-industrial or industrial-only complex is the ability to provide low-cost energy in an area, almost without regard to the native resources in the area. Thus the impact of low-cost energy generated from nuclear power is greatest in those areas where conventional or potential energy costs for conventional power by hydro or fossil fuel sources are relatively high.

In the selection of suitable locations, the primary consideration is whether significant on-site agriculture is to be carried on, or if the complex will center on industrial processes only. If significant on-site agriculture is to be conducted at the complex, the land area requirements and the agricultural requirements are the dominant parameters and almost exclusively determine the selection of suitable locales. This is because the constraints imposed by the agricultural considerations are much more restrictive in evaluating the suitability of complex locations than are those concerned primarily with the industrial processes.

Selecting land for potential agricultural development encompasses social, political, economic, and physical factors. In this phase of the study we are concerned primarily with the physical factors. In principle, farm development cost and income are related to physical land factors under given land management practices.

The suitability of land for the proposed agricultural operation will depend on the cost of reclamation and preparation; acceptable levels of cost will be influenced by crop yields and values as well as water requirement. Consequently, in evaluating desert land for agriculture, physical factors were considered in the light of development costs.

The initial criteria for screening potential agricultural areas for further investigation included consideration of:

1. proximity to and elevation above the ocean (the desalting plant requires a large source of saline water; therefore, areas in or near the oceans were selected);
2. climatic conditions favorable for the production of two or more crops per year (this limited potential locales to those between 35° north and 35° south latitudes);
3. use of land not now under active intensive cultivation (this limited consideration to desert and semidesert areas receiving less than 15 in. annual rainfall);
4. suitability of soil and topography for agricultural purposes;
5. land area required [this was established on the basis of the amount of water to be produced by the desalting plant; for a plant producing 1,000,000,000 (10^9) gal of distilled water per day, the average land required is approximately 275,000 acres, or 425 sq miles, assuming that each acre grows two crops per year and each crop requires 2 ft of water].

In addition, several factors of importance to both an agro-industrial and an industrial-only complex were considered:

1. the availability of a source of cooling water for the reactor system and the industrial processes,
2. the desirability of fresh water production for local industrial or municipal needs,
3. the presence of raw materials which are important to energy-intensive proposed processes and

to competitive processes (raw materials such as methane as a source of hydrogen for ammonia production to compete with the proposed process of obtaining hydrogen from the electrolysis of water, and sulfur for sulfuric acid used in the wet acid production of phosphate fertilizers as a competitor to phosphorus produced via the electric furnace method).

Finally, the general problems associated with any large industrial complex were reviewed. These include consideration of the transport facilities, particularly available harbor facilities or the potential for port development and the available rail facilities. The type and proximity of local markets for the products of the complex are of importance as well as the availability of a power grid into which surplus power might be marketed and from which emergency power might be withdrawn. A discussion of the social, political, and cultural factors is also included in this chapter.

From these considerations, five areas in the world were selected (Fig. 8.1) as being typical arid coastal regions. These are the west coast of Australia near Carnarvon, the Kutch Peninsula of India, the Magdalena Plain of Baja California, in Mexico, the Sechura Desert of the northwest Peruvian lowland, and the Sinai-Negev Desert (of the Middle East) along the southeastern Mediterranean coast. These five areas do not exhaust the potentially suitable areas in the world,[1] but they do appear to exhibit certain characteristics which are common to most coastal deserts; however, each locale has characteristics unique to its own setting. Various characteristics significant in locale selection are discussed below, and each of the five selected locales is evaluated on the basis of those characteristics.

8.2 Characteristics Significant in Locale Selection

8.2.1 Climate

In selecting areas for potential application of the agro-industrial complex, many factors had to be considered. The physical factors discussed in this section are limited to those which are especially significant to relatively undeveloped coastal deserts.

Differences in temperature not only influence the choice of crop to be grown, but also the time of planting of the crop for each locale. Wheat, for example, is sensitive to high temperature and humidity; sowing of wheat would therefore be timed so that it will reach maturity before too high temperatures are reached. For some crops, night temperatures are important. For instance, tomatoes do not set their fruit with night temperatures above 72°F or below 50°F; hence the specific temperature requirements of various crops (thermoperiodism) must be considered in selecting sites and crops.

The selection of crops and varieties will also depend on day length; this climatic factor depends on latitude. For example, soybean is generally a short-day plant, but various varieties of this crop differ widely in response to relative length of day and night (photoperiodism) between emergence to flowering and from postflowering to maturity.

Although natural precipitation is limited in the selected locales, its distribution will have a strong influence on irrigation schedules and water usage. Other climatic factors which influence plant growth and crop production include wind, light intensity and quality, relative humidity, and fog.[2] All these climatic factors, with their interrelationships and influences, require investigation prior to the implementation of an agro-industrial complex. Thus an experimental research farm or test station should be established at an early stage to develop the best farming system for desert irrigated agriculture for each locale.

8.2.2 Soils

The dry or very dry and irregular climate of arid zones produces soils which are commonly shallow in depth, have soluble salts in the profile, are low in organic matter and rich in primary minerals, and have poorly defined structures. These characteristics differ depending on age, parent material, topography, vegetation, and climate. The origin of the parent material is of particular significance to the locales for our study because these soils are derived from materials which have been transported to the area from elsewhere. The materials of the deserts of India, Mexico, and Peru, for example, were transported from higher elevations by rivers

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[1] P. Meigs, "Geography of Coastal Deserts," Series No. 23 in *Arid Zone Research*, UNESCO, 1966.

[2] C. P. Wilsie, *Crop Adaptation and Distribution*, W. H. Freeman and Co., San Francisco, Calif., 1962.

Location chart

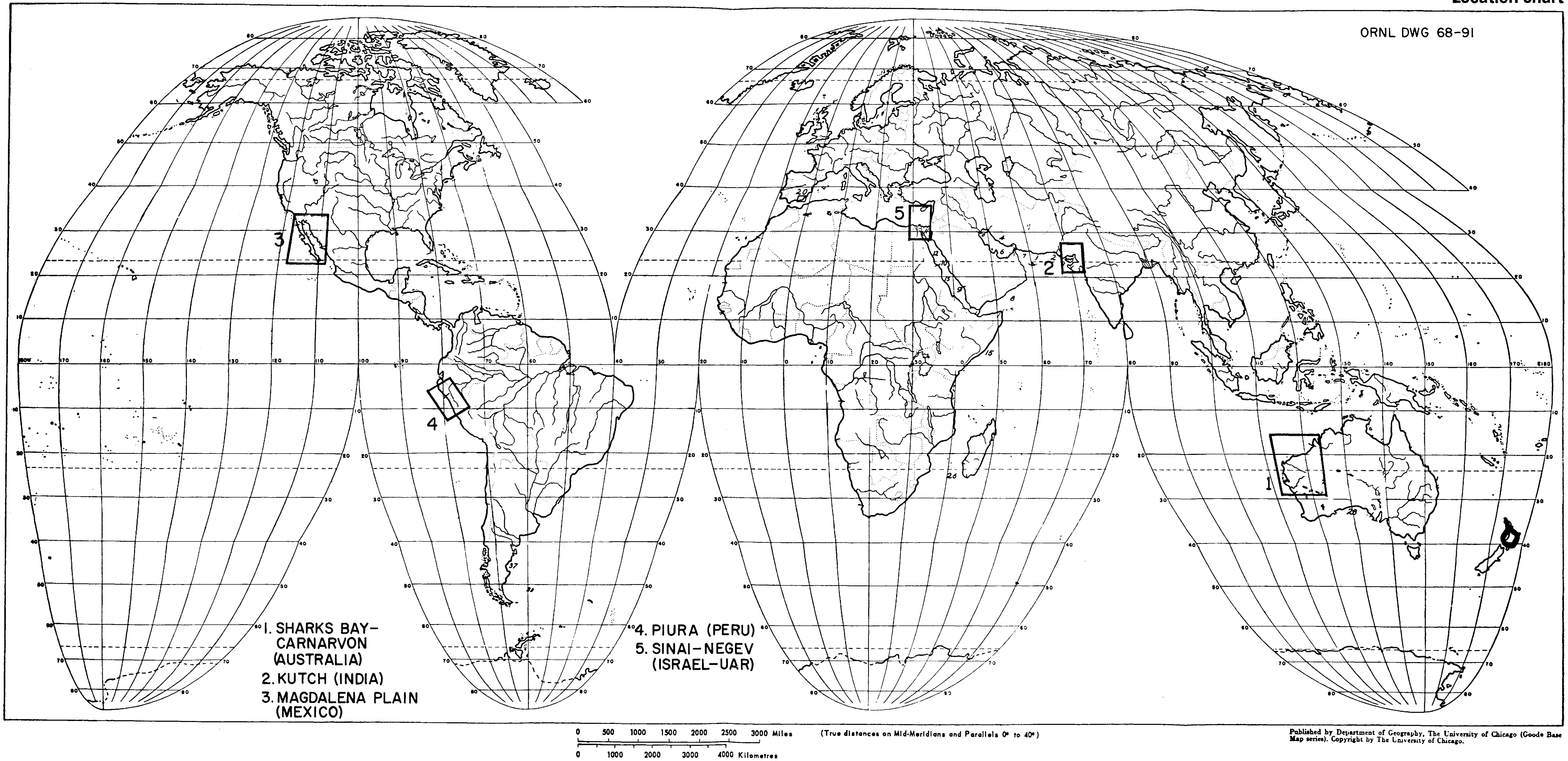

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Fig. 8.1. World Location of Five Areas Selected for Study.

and streams and deposited in areas subsequently raised above the ocean level. In the Sinai-Negev Desert, most of the soils are derived from deposits of material carried by wind, while in Australia the soils appear to have been transported from higher elevations and subjected to weathering under a more humid condition than that now prevailing. Thus, in the selected areas, soils normally have deeper unconsolidated materials than their desert counterparts formed on crystalline rocks.

The soils frequently found in the locales situated in desert and subhumid regions include red deserts, sierozems, reddish browns, arid red earths, dunes, solonchaks, and solonetzes.[3] The red desert and sierozem soils are generally formed under 4 to 10 in. annual rainfall; the low rainfall results in minimal profile development. The reddish-brown soils are found in areas of higher and irregularly distributed rainfall (10 to 15 in./year) and are usually of heavier (clayey) texture. Lime, if present, is usually leached from the surface and accumulates at about 15 to 30 in. below the surface, and gypsum and soluble salts accumulate at depths greater than 30 in. Arid red earth is unique to Australia and represents a soil which has once undergone development under more humid conditions than now existing. Arid red earths are acid in reaction, in contrast to neutral to alkaline reactions of the other soils. Dunes are an accumulation of sands blown to an area by wind. Solonchaks are saline soils where the soluble salt content in a saturated paste is sufficient to give conductivity readings above 4 millimhos/cm at 25°C. Solonetz soils have a low soluble salt content, but the adsorbed cations on the clays contain over 15% sodium. The latter condition causes dispersion of the clays; the soils have low permeability and are difficult to manage. Solonchak and solonetz soils require reclamation before optimum yields can be expected.[4]

Most crops are adversely affected by the presence of excess soluble salts.[2] Soils containing these salts, mostly sodium chloride, must be reclaimed by leaching prior to being placed in production. At such a site, water at, for example, $33.00 per acre-ft (10¢/1000 gal) is the most expensive item in reclamation by leaching; hence economics will determine whether land reclamation is feasible. Also, analysis is required for such toxic elements as boron, lithium, and selenium, though limited data from the locales suggest that these ions will not pose problems in the selected areas.

The prediction of drainage requirements is crucial in selecting land for irrigation. Major costs are incurred when subsurface drainage is required.[5] Costs of drainage systems vary with spacing, depth of placement, size of pipes, and type of drainage. For example, with a system having 200-ft spacing with 4-in. drain tile 4 ft deep, the cost is about $100.00 per acre. For all locales, sufficient information for preliminary estimates of drainage requirements is lacking.

With the advance already made in the agricultural sciences and technologies, these edaphic (soils) factors should not be strong deterrents in developing a region. Soils today have a lesser role in determining productivity than previously, and the level of technology of a society may decide the suitability of a soil more than its native characteristics.

8.2.3 Topography

The major topographic features which determine suitability of land for irrigation are slope, relief, and elevation. In delineating land for potential sites, soils on level, gently undulating, or undulating landscape (classes A and B)[6] were given priority. These landscapes generally have low soil erosion, and they permit the use of all types of ordinary agricultural machinery without difficulty. Soils of all selected locales had slopes generally less than 5%, thus meeting this requirement.

In general, soils associated with excessive relief are lithosolic (rocky) and are too shallow for crops to provide optimum yields. These areas were avoided in estimating land area availability. The elevation of irrigable land will affect the cost of delivered water. The operating cost for pumping using power at 5 mills/kwhr and a 65% pump efficiency

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[3] G. Aubert, "Arid Zone Soils," pp. 115–37 in *The Problems of the Arid Zones*, Series No. 18, UNESCO, 1966.

[4] L. A. Richards, ed., "Diagnosis and Improvement of Saline and Alkaline Soils," *Agricultural Handbook No. 60*, USDA, Washington, D.C., 1954.

[5] J. T. Maletic and T. B. Hutchings, "Selection and Classification of Irrigable Land," pp. 125–73 in *Irrigation of Agricultural Land*, No. 11 in Agronomy Series, American Society of Agronomy, 1967.

[6] *Soil Survey Manual*, Agricultural Research Administration, U.S. Department of Agriculture, Handbook 18, 1951.

factor was estimated to be 0.23¢/1000 gal per 100 ft of lift. The locale of highest elevation was 600 ft in Peru. However, it is believed that with better definition of land areas now in productive use, land at the lower elevations could be utilized in Peru.

8.2.4 Water Resources

Only limited information on the groundwater resources of coastal deserts was available for this study. It appears that in most cases where water is available, irrigation agriculture is already practiced; however, the poor quality or the limited quantity of water has restricted development. These sites may not only benefit from additional water but may prove even more valuable as potential sites because of the possibility of subsurface storage of water during periods of reduced demand.

8.2.5 Mineral Resources

The processes selected for the industrial aspects of a complex are primarily those which are energy intensive. Of these processes, two which are dependent on mineral deposits and appear to be most promising are aluminum production from bauxite and elemental phosphorus from rock phosphate. Other processes discussed in Chap. 5 of this report but of lesser importance to the complex and in locale selection are the production of ammonia, iron, salt, and caustic-chlorine. A survey of the resources within the country of those locales selected for the agro-industrial complex was made to locate indigenous raw materials for the complex and, particularly, sources of bauxite and phosphate rock. Included in the resources survey were oil, natural gas, coal, and iron. Coal, oil, and gas affect the cost of competitive energy and the price of hydrogen. The information obtained represents that which was readily available and is not the result of an exhaustive literature survey of the entire resources of a nation. The quality of the raw material and the mining costs were in general not available for this study, and such information would be required for a detailed evaluation of a particular locale. It is desirable that the raw materials required for the major processes proposed for the complex be readily available, and of course the processes in turn would be influenced by the available raw materials. The production of 250,000 tons of aluminum per year requires about 1,000,000 tons of bauxite annually. Similarly, production of phosphorus in the quantities suggested in Chap. 5 will require 5,000,000 to 6,000,000 tons of phosphate rock, coke, and other materials annually. The quantities of other resources required were significantly less than for aluminum and phosphorus and did not have a strong influence on locale selection. The availability of sulfur within a country also influenced the economics of the electric furnace production of phosphorus (see Chap. 5).

8.2.6 Transport Facilities

The complex using 2500 Mw of electricity will require between 10×10^6 and 15×10^6 tons of material to be shipped in and out of the facility each year. If on-site agriculture is part of the complex, an additional several million tons of agricultural product must be shipped out of the complex. Table 8.1 lists a typical set of products and raw materials for an agro-industrial complex. These quantities of material will require that extensive facilities for transport handling be available. Products and raw materials procured from inland points must be transported by rail or by barge to the complex. It is expected that the greater part of the tonnage, however, will enter and leave the complex via the harbor.

Harbors. – The cost of providing a harbor facility capable of handling approximately 15×10^6 tons/year (10% of the tonnage handled by the Port of New York) has been estimated at approximately $35 to $50 million (subject to wide variations depending on local conditions).[7] For remote complex locations the harbor and port facilities must be constructed essentially from scratch. If nearby port facilities are available which can be enlarged to meet the requirements, this would probably be advantageous. The port facility should be at the complex to eliminate the cost of transshipment of material between port and complex.

Whether the requirement for good natural harbor facilities can be satisfied for an agro-industrial complex is uncertain, since the agricultural parameters largely control the complex location. The presence of a protected natural deepwater harbor would materially reduce dredging and breakwater

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[7] Ralph M. Parsons Company, *Rationale for Complex Support Cost Estimate*, ORNL-AISP-1-167 (1967).

costs. Provisions for anchorage of ships would have to be made.

The increasing trend to the larger cargo carriers and tankers should be accommodated in the harbor and port facilities. Ship turnaround time in the harbor must be minimized and anchor facilities provided for periods when berths are not available. Table 8.2 itemizes the major harbor and port facility components and cost estimates for a harbor facility capable of handling the tonnages and materials listed in Table 8.1.

Table 8.1. Products and Raw Materials for an Agro-Industrial Complex

A. Industrial Products

Product	Maximum Production Rate (tons/day)	Raw Materials	Quantity (tons/day)
Ammonia	3000		
Phosphorus	1500	Coke	2,000
		Phosphate rock	13,000
		Silica rock	3,800
Aluminum	700	Bauxite	2,750
		Petroleum coke and pitch	350
Chlorine	2000	Salt	7,500
Caustic	2250		
Salt	2700		

B. Farm Products

High-profit system (Chap. 6)

Product	Maximum Production Rate (tons/year)
Wheat	770×10^3
Potatoes	1435×10^3
Tomatoes	300×10^3
Cotton	91×10^3[a]
Oranges	220×10^3
Beans	285×10^3

[a] Including cottonseed.

Table 8.2. Cost Estimates for Harbor and Port Facility

Component	Cost
Phosphorus plant dock	$ 5,000,000
General industrial dock	3,500,000
Aluminum plant dock	3,000,000
Farm and community docks	10,000,000
Dredging (if harbor shallow)	6,000,000
Breakwater (if harbor unprotected)	12,000,000
Tanker moorings	100,000
Port facility boats	1,800,000
Bauxite unloader facilities	1,000,000
Phosphate rock unloading facilities	3,500,000
Ammonia loading line	250,000
Phosphorus loading	400,000
Chlorine loading	80,000
Salt handling facilities	2,000,000

The estimates included in Table 8.2 are only of a preliminary nature. Comprehensive estimates are obviously strongly dependent on the harbor potential of the locale. Newer techniques for providing harbor protection involving wave dampers may also be feasible.

Railroads. – Standard or broad-gage railroads connecting the complex with the nearest railhead and with the rail network of the country may have to be provided. In the event that the complex location is many hundreds of miles from any rail network, the cost of such lines may be prohibitive, and connecting rail lines would probably not be constructed. Construction costs for rail beds vary greatly with terrain,[8] but a value of $200,000 per mile including necessary trestles, etc.,[8] has been used for estimating purposes.

If indigenous raw materials are to be considered for use in the complex, then these often must be transported by rail. If the complex is remotely located and this is the major reason for requiring rail construction, then the capital costs of such construction should be included in the total cost of

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[8] Personal communications, Office of Chief of Engineering, Southern Railway, Atlanta, Ga.

the project. In the case of a captive rail line between the complex and a source for raw material, the capital cost for the rail rolling stock may also be charged to the complex. These amortized capital charges must ultimately be reflected in the manufacturing costs for the products using the facilities.

In the case of complexes located in areas well served by rail, these costs are not present. It should be recognized that in many developing countries, rail car carrying capacities are much below those in the United States; therefore some accommodation must be made for this. It is assumed that the trend toward the broad-gage railroads will continue and that car carrying capacities equivalent to those in the United States today (currently of the order of 100 tons) will be feasible in the locales considered.

Power Grids. – In its simplest form the energy center complex could produce only the raw materials of energy and water. These commodities could then be transported to areas of need and then used at those points. This would require the construction of power lines and pipelines and the transmission of the commodities. The techniques for such transport are well defined, and the costs are well understood. The transmission costs would tend to negate the advantages of low-cost energy and water gained by scale and location. To circumvent this problem the concept proposed in this report envisions not only the generation of power and water in areas where little or none presently exists but the construction of the facilities for consuming the power and water directly at the complex site. The products from the industry and the farm which are established have to be transmitted to their point of use – their market area. The problem becomes one of transmitting industrial and agricultural products instead of water and electricity.

It should be recognized, however, that if the complex is relatively close to an existing power network, a grid tieline would be of mutual benefit in providing startup and emergency power to the complex or in transmitting low-cost power from the complex to the existing grid.

8.2.7 Markets

The selection of arid coastal regions of relatively low population density as suitable locales for the agro-industrial complex generally limits the market potential directly around the complex because there are usually limited industrial, commercial, and agricultural activities other than those associated with the complex. This means that the vast majority of agricultural and industrial products must be transported significant distances to the market areas. The location and size of the markets and the cost of transport determine to a large degree the marketability of the various products. Thus the potential market area for a locale is of fundamental importance to the evaluation of a locale. No attempt was made in this study to perform a market analysis for each of the locales considered, but an examination of some of the important factors which would influence the market is relevant.

The cost of transporting commodities is a complex function of distance, transport medium, type of commodity, competitive position of the transport medium, and legislative effects on transport costs. In general, however, for the transport of bulk commodities (ores, grains, and coal) in the United States the costs indicated in Table 8.3 convey the range of transport costs one might encounter.

The cost of shipping products such as liquid ammonia or phosphorus in rail tank cars may be as high as 3 to 4¢/ton-mile. An indication of the effect of transport costs on the cost per ton of product as a function of the distance transported is shown in Fig. 8.2. The figure permits a determination of the added cost attributable to product transport. Products having higher transport costs and those having a relatively low dollar value per unit weight are particularly sensitive to the transport cost. In attempting to assess the advantages of the complex over the smaller individual plants which may be located nearer the market areas, a number of factors must be considered:

1. line haul transport costs for the product to the market area;

Table 8.3. Transport Costs

Transport Medium	Cost Range (¢/ton-mile)
Oceangoing ship	0.15–0.25
Barge	0.4–0.6
Train	0.8–1.25
Truck	6.5

2. capital costs for the installation of transport facilities, including handling facilities for marketing the product in the area;
3. costs associated with the storage of the product in the market area prior to final distribution.

The final product cost in the market area is a function of the costs resulting from the above considerations, and this in turn determines the area within which the product may be competitive with alternate plant locations. A breakdown of the costs according to the above categories can then be approximately expressed in terms of transport costs per ton-mile. A comparison of the advantages of lower production costs in a large complex as compared with a number of small plants dispersed with respect to markets is shown in Fig. 8.3. Also shown in the figure is the added product cost per ton as a function of transport cost in mills per ton-mile. The transport cost range for ammonia is also indicated. Plotted as horizontal dashed lines are cost differentials between ammonia production for a 3000-ton/day plant at the complex operating with 2-mill power and a 600-ton/day plant operating with 2-mill and also with 3-mill power. This figure then indicates that the market radius within which ammonia produced at a complex could be competitive with that produced with electrolytic hydrogen in a smaller plant is limited to about 200 miles for rail shipments. If the electric power cost is 3 mills/kwhr for the smaller plant, then the market radius is 600 to 700 miles. However, as shown in Chap. 5 of this report, at power costs above 3 mills the production of hydrogen by electrolysis does not appear competitive with other methods, and the comparison would have to include hydrogen from other sources. The figures do indicate how the economic limits for satisfying internal markets within a country from large coastal complexes may be determined. The significantly lower transport costs via ocean tankers or barge carriers offer opportunities for shipments from the complex to market areas near other harbor installations.

Figure 8.4 is a geometric representation of typical considerations which must be made in a market analysis. The rectangle represents a country, and point C represents the complex location, so that market areas might be represented by the lettered zones as shown on the figure. The radius for economic shipment of products is a function of distance, type of transport, and a capital cost allocation factor which includes costs attributable to capital transport facility expenditures and storage and handling costs at market locations. The market radius at the complex C and at other consumption and distribution centers *a*, *b*, *d*, and *e* may be different for each product. The potential world market will of course be dependent on the f.o.b. product price at the complex.

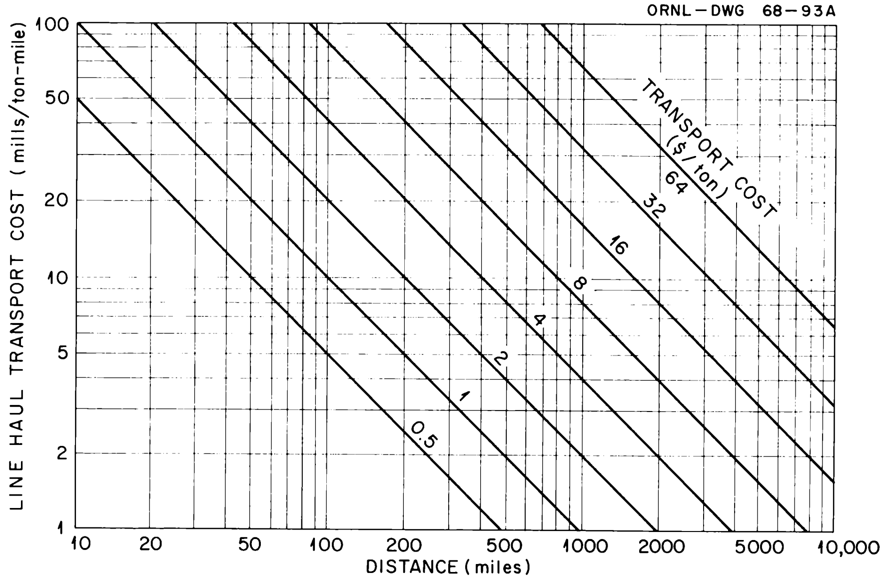

Fig. 8.2. Transport Cost as a Function of Line Haul Cost and Shipping Distance.

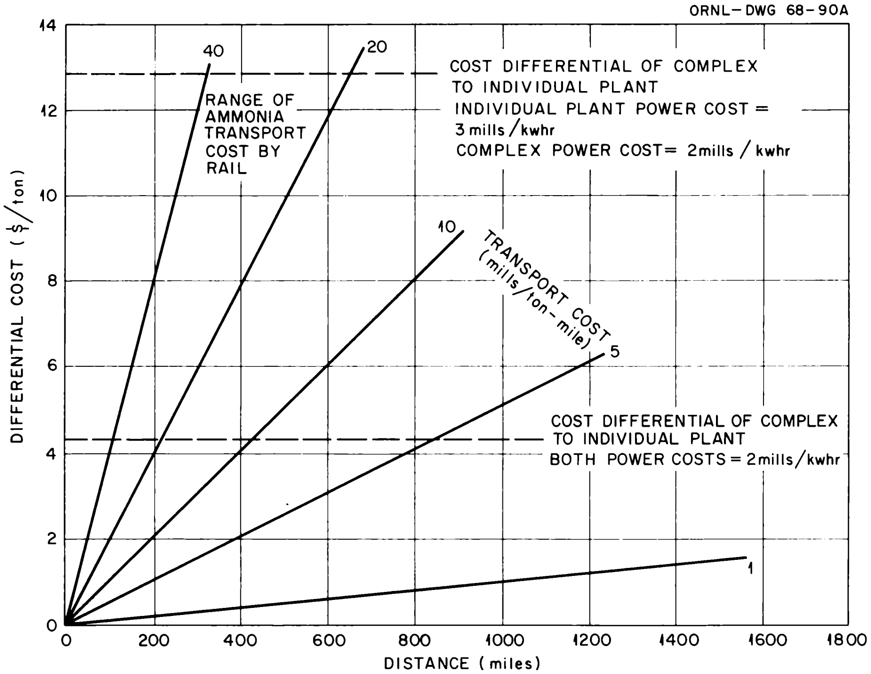

Fig. 8.3. Economically Feasible Distance of Transport of Ammonia as a Function of Production Cost Differential Based on a 600-ton/day Ammonia Plant at the Market and a 3000-ton/day Plant at a Complex. Dotted lines indicate differential costs at 2 and 3 mills/kwhr power costs.

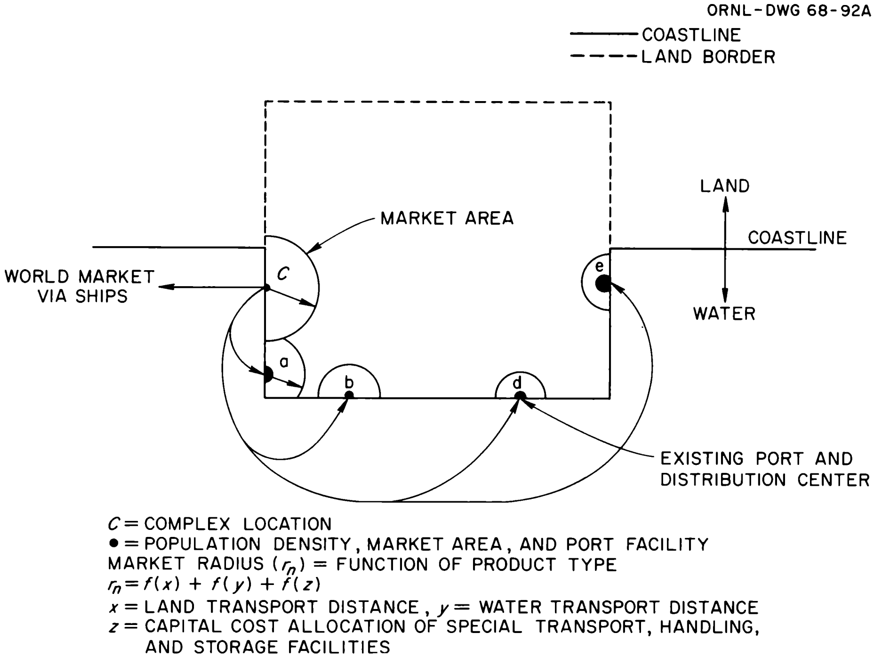

Fig. 8.4. Considerations Required in Market Analysis. See text for explanation.

The effects of transport costs on marketability depend to a large extent on product value per unit weight. For aluminum, for example, with a product value of approximately $500.00 per ton, transport costs of $10.00 or $20.00 per ton may not be excessive, but similar charges for bulk material such as solid fertilizers or other low-value material could not be tolerated. Thus, in general, markets for the higher-cost products are less affected by transport considerations.

In order to reduce transport and storage costs, it is desirable in general to reduce the product form to the most concentrated product value. Thus it is more economical to ship phosphorus in the elemental form than as a phosphate fertilizer. Similarly, for agricultural products, processing of foods to a form having a higher dollar value per unit weight would be desirable. For example, citrus and tomato products would probably be processed at the complex to less-perishable and higher-valued products before shipment to markets.

8.3 Characteristics of Selected Agro-Industrial Locales

The locations of the five areas selected for evaluation are shown in Fig. 8.1. All the locales satisfied the initial criteria established for potential development of on-site agriculture. Time limitations prevented investigation of more locales; and, even for the selected locales, paucity of data for some factors left much to be desired. Each locale must be investigated in much greater detail before final decisions can be made regarding the potential for actual development; nevertheless, the considerations given here will aid in defining those areas which require better definition and characterization.

Table 8.4 summarizes the characteristics significant in agriculture for the five locales considered. In ORNL-4293 (to be published) the characteristics of each locale are described in greater detail. In addition to the five agro-industrial locales, additional areas potentially suitable for industrial-only complexes are also included. The following paragraphs mainly describe the contrasting features of the locales which thereby illustrate the different conditions existing in different areas of the world.

Of the five locales, the Sinai-Negev area is subject to occasional frost conditions during the winter months. The Mexican locales may also suffer occasional frost conditions, though the information is scant for this region. The remaining locales enjoy frost-free growing conditions throughout the year. India is marked by the distinct annual monsoon season, which contributes significant rainfall. Over 90% of the annual rainfall of 13.9 in. falls during the months of June through September. In the Mexican locales, hurricanes of one-per-year frequency are experienced, generally in September. In contrast to the summer monsoon rain of India, the predominant rainfall in the Sinai-Negev region and in Western Australia is during the winter months. In regions where intense rainfall periods exist, careful planning of cropping cycles is required to minimize crop and soil losses.

Shifting sand dunes occur in all locales. In the Peruvian and Mexican locales, areas of solonchaks have been mapped. In India the reddish-brown soils are associated with regur soils, and this association implies compact subsurface conditions in the reddish-brown soils. The presence of all these soils and soil conditions suggests the need for more detailed soil information, with close attention to land reclamation needs. In addition, information on subsurface geologic conditions is scant for all locales, and if water storage is contemplated in underground formations, much more information will be required.

The locales are not rich in mineral resources. In the Peruvian locale, phosphate ore is being developed. In the Sinai-Negev locale, the nearest phosphate ore is 100 miles away. In India, bauxite is available in the Kutch Peninsula, but little information on quality of the deposits was available. Transport facilities must be developed at all of the locales to accommodate the import of raw materials and export of goods. None of the locales has existing facilities capable of handling the anticipated loads from the complexes.

8.4 Characteristics of Selected Industrial Locales

If industrial-only complexes are to be considered, there are many areas in the world where favorable conditions exist for their location. A number of potentially suitable areas are listed in ORNL-4293, special consideration being given to sites in the general area of the agro-industrial locales. In addition, information on Florida and Moroccan locales is given. In general, the agro-industrial locales

Table 8.4. Characteristics of On-Site Agriculture Locales

Locale	Soil Group	Elevation (ft)	Surface Configuration	Average Annual Rainfall (in.)	Mean Annual Temperature (°F)		Population Density (persons/sq mile)
					Maximum	Minimum	
Australia (Sharks Bay—Carnarvon)	Arid red earths	<500	Flat to rolling plains with scattered hills; numerous clay pans and salt pans	8.6	80.0	62.0	0.06
India (Kutch)	Reddish brown, regurs, solonchak, solonetz	0–300	Flat to gently rolling plains; slopes commonly less than 10%	13.9	84.0	73.0	25–99
Mexico (Magdalena Plain)	Red desert, dunes, solonchak	<300	Flat to gently rolling plains; slopes less than 5% but up to 10%	4.8	81.0	66.0	3.4
Peru (Piura Department)	Red desert, solonchak, dunes	0–600	Predominantly flat to gently rolling plains with numerous sand dunes and scattered salt flats; slopes largely less than 10%	3.1	89.0	65.4	50–65
Israel-U.A.R. (Sinai-Negev)	Reddish brown, sierozems, dunes	0–350	Flat to gently rolling plains; slopes less than 5%	3.8	77.0	57.0	

are in remote areas with limited transport facilities or markets. They were located primarily for suitable potential irrigation agriculture. They are often neither particularly close to major power networks nor to mineral resources. Because the land area requirements for the industrial-only complex are minor relative to the agro-industrial complex, the former can be located nearer large population centers without evicting large numbers of people.

In both agro-industrial and industrial-only complexes, detailed examination of all the influential factors was not carried out. Obviously, further studies must be made to permit better evaluation of locales. It should be emphasized that in contrast to the production of industrial products, the production of food crops has not progressed to a degree sufficient to assure success when the raw materials (seeds, etc.) from one locale are processed (grown) in another. Therefore, even if sufficient land area is available, climatic conditions appear favorable, and the technology has been developed for successful agriculture, large-scale investment in the utilization of these locales should await more specific information and experimentally proven yields of crop varieties for each location. Since agricultural research has been chiefly oriented to the more temperate regions, it is highly desirable and strongly recommended that research on the utilization of hot arid zones for agriculture be implemented in the immediate future.

8.5 Implementation

The implementation of a large agro-industrial project was not specifically studied, although it was recognized that the technical and economic feasibility will depend to a large extent on overcoming a number of problems associated with the actual building and operating of such a complex. A number of the potential problem areas that may exist in some developing countries have been identified with a view that these could be further explored as required in any future study of a particular site.

Although much outside assistance in various forms will be needed in order to get the complex constructed and operating satisfactorily in the beginning, it should be understood that a transfer to local operation and control must be made as soon as feasible. By incorporating this concept in the earliest stages of planning so that it is clear from the beginning to everyone concerned, the project will have greater acceptance and support by the many people whose lives can be improved by it.

A further general aspect of implementation that demands prior study is the effect of such a large and drastic change of land use. Existing life on the region, both animal and vegetable, will obviously be disturbed; there may also be minor but still significant effects on the climate of the region.

The attitude of countries neighboring the host country will be of considerable importance. If they are willing to cooperate, both they and the project could benefit. Although the complex would be located in one country, it is within reason that it could be undertaken by a group of countries who are already working together in a regional common market or some form of economic cooperation. The power, fertilizer, and electrochemicals produced by an agro-industrial complex could overcome a number of national shortages in less-developed countries.

If undertaken in a fashion that is economical, this massive effort will produce quantities of products, both food and otherwise, so sizable they will affect world markets. Thus, either directly or indirectly, all nations engaged in international trade will be affected. The distribution of the new production must be carefully planned so as to minimize possible undesirable effects of an enlarged capacity to produce standard commodities.

8.5.1 Internal Management

The sociopolitical situation in the host country will undoubtedly have a significant influence on the long-range success of the complex. It is important that the continuity of the management be assured even though changes in government may occur. At the same time a capacity for innovation and change is essential. A well-established system of laws, courts, and taxation will be critical for the operation of the complex. Other concerns would normally be attracted to the locale of the complex or would set up installations elsewhere dependent upon it. They, as well as the management of the complex, need guarantees of consistent legal procedures and regulations.

In a smaller, developing country the agro-industrial complex could also generate inflationary or deflationary pressures, depending upon the stage of the project. Thus the planning and adjustment must be carried on in several ministries of the government simultaneously. It cannot be left solely in the hands of a special authority or agency.

8.5.2 Finance, Ownership, and Control

Over the next decade or two, no host country could undertake the project as a government monopoly and achieve the benefits claimed. Too much of the vital technology is possessed by scientifically sophisticated international firms. The government might be involved in establishing much of the infrastructure required for the successful operation of the complex, but the management of the complex itself should be at least semiautonomous, so as to be able to negotiate with a multiplicity of interests. The complex itself should be operated as an economic unit that is self-supporting and will reproduce its capital. Any of a number of formulas for mixed consortiums (similar to COMSAT in the United States) might fit the needs. The formula would undoubtedly depend greatly upon location.

8.5.3 Training and Education

It seems clear that the complex will have to undertake a considerable program of training and education for a long period of time in order to ensure an adequate number of qualified personnel for its various jobs. Accompanying such an emphasis upon training and education will probably be a relatively high turnover rate of labor if the experience in other countries is a guide. This high rate of turnover is simply another cost of doing business and must be regarded as one of the contributions to economic development.

The following training and education will probably be required: (1) a program for training operators, technicians, and supervisory personnel for the advanced processes and for specific pieces of equipment; (2) a program for the training of mechanics and others in manual skills for use throughout the complex; and (3) a program of background education to be added to both the primary and secondary curricula for young people. Since much of the prerequisite education probably exists in the host country at the present time, it will only need to be expanded or further developed in order to satisfy increased requirements.

The higher education that exists in the locale at the time the complex is undertaken should be utilized and may have to be extended. A cooperative education program such that students spend some time in the classroom and some time working in the complex on a cooperative educational basis would probably be useful. Much thought and planning must be given to the development of the workers, especially for the food factory. The development must include not only technical competence but motivation. While the former development can be reasonably defined and implemented, the latter development will require careful consideration of the people's customs, mores, habits, and attitudes. If the land is unused and unoccupied at the time when the food factory is installed, the problems associated with land reform programs of many countries may be minimized; these considerations obviously require the close cooperation of the host country.

8.5.4 Community Facilities

At least one town will have to be created for the agro-industrial complex and possibly a number of smaller ones. Much thought and planning must be devoted to these towns and provisions made for the usual facilities such as water, sewer, power, roads, streets, police, recreation, worship, firefighting, waste collection and disposal, hospitals, and school systems. Although not all of these may be needed during the early stages of the community development, planning must provide for them at a later stage. In addition, guest houses and tourist facilities will be needed; however, these might be contracted out to private investors. City planning should allow for both expansion of the city itself and expansion in the direction of additional industry and business that will be attracted to the area.

Health and disease control must be established from the beginning, and proper habits of sanitation should be developed among the citizens. Our knowledge of cities and their problems should make it possible to establish new communities near the complex which will be able to avoid some of the problems presently being faced by the older cities of the world.

8.5.5 Startup

There is a tendency to speak of the agro-industrial complex in its final state. More realistically, however, attention should be devoted to the problems of construction and startup. Obviously, three to five years will be necessary to construct the core of facilities envisioned for the complex and to reclaim the necessary land. Much of the industrial production plant would be started up after the reactor was brought into operation. A two-reactor station would allow one reactor to be installed first to provide energy for the early installations, with the other reactor installed later as the other industrial installations were completed. The entire installation process would appear to be ideal for using critical path scheduling techniques. This method of scheduling has been used on construction projects, and its use in this case should extend to the matter of training and development of people to operate the complex.

From an overall startup point of view, it seems that an equal effort will have to be directed simultaneously along three lines:

1. The physical phase of actual construction of buildings, reclamation of land, and preparation for the food factory would have to be pushed as rapidly as possible, making use of both local contractors and overseas contractors as necessary.
2. The human phase of working with those people and organizations available in the host country would determine the rate at which construction, startup, and operation of these installations would progress. Such people and organizations may not have the experience, training, and background that would be ideally desired for such work, but compromises must be made during the early stages in order to get under way.
3. The groundwork phase entails the development of institutions which will generally support the agro-industrial complex as well as the community and country at large in the years to come. This will include institutions for basic education and training as well as business and community organization.

9. CONCLUSIONS AND RECOMMENDATIONS

This study has indicated that low-cost energy anticipated from nuclear power reactors may have a significant impact on industrial and agricultural development both in the United States and throughout the world. While there is currently some local overcapacity for the production of some basic products, the long-term worldwide needs for both industrial and agricultural products are great and will require tremendous quantities of energy to fulfill. One small example would be in providing adequate nitrogen fertilizer only for the Upper Gangetic Plain of India. This would require about 6×10^6 tons of naphtha per year or about 9000 Mw of electrical generating capacity.

The concept of a nuclear-powered agro-industrial complex as discussed in this study appears capable of opening up new avenues for economic growth, particularly in areas with attractive mineral deposits but devoid of energy and sources of fresh water.

In many parts of the world such a complex entails a large step change in industrial and agricultural production and would represent sizable economic advantages over the alternative of adding small production increments in widely scattered sections of a country.

The results of the study also indicate that the relatively large investments initially required are regenerated in a reasonable time period and could significantly reduce foreign exchange requirements in the long run. Additional benefits which would be available are in providing technical training and employment opportunities, which are needed in many developing countries.

Specific conclusions drawn from this study project, together with recommendations for future work, are summarized below according to the major sections of the report.

9.1 Economic Ground Rules

The ground rules adopted for the economic analyses in this study were based on a generalized approach and would need substantial revision before application to a specific site for investment-type decisions. The main changes would center on the inclusion of such locale-sensitive parameters as the current money rates available, taxes, special site costs, and marketing expenses. A more complete benefit analysis should be made, including the effects on the overall economy and considering labor availability and foreign exchange requirements. Thus detailed market analyses, including transportation and pricing considerations, would certainly be required. Specific studies for a particular site should also include comprehensive comparisons with alternative schemes for achieving the same total product output or set of benefits.

9.2 Rationale for Power and Water Costs

While no new or unique conclusions were derived from this portion of the work, it may be of interest to list some of the important results to reinforce previous work in this area.

1. Cost of money is a major factor in determining the cost of power and desalted water from a nuclear plant. Since these costs in turn control, to a large measure, the economic attractiveness of the complexes considered in this study, it is recommended that exploratory work be started to determine possible means and costs of financing such a project.
2. Achieving the predicted gains from the advanced technologies of breeder reactors and vertical-tube evaporators would result in appreciable decreases in the costs of power and water. To ensure this happening within the time period envisaged, the research and development programs now in progress should be reviewed and, if necessary, their support increased. These should include development of dual-purpose plants as well as water-only and power-only plants.
3. The possible contribution to industrial growth and the production of food which appears possible from agro-industrial complexes underlines the need for early construction of prototype desalting plants of a size sufficient to confirm designs and cost estimates.
4. Any future study of a specific application of a nuclear complex should include considerations of nuclear safety and other siting considerations.

9.3 Industrial Processes

Cost information for the production of a large number of basic chemicals and metals was accumulated and computerized in a "building block" form. This information consists primarily of the direct capital cost (as a function of plant size) and operating and maintenance labor and material requirements, including raw materials and utilities. The computer program allows variations in the basic input costs, including the cost of money, and outputs the total investment and the unit product manufacturing costs. The products considered are primarily those utilizing relatively large quantities of electricity in their production and include hydrogen (via water electrolysis and used mainly in ammonia synthesis), phosphorus (via electric furnace), chlorine and caustic, and aluminum. Data on the manufacture of secondary products, such as ammonium nitrate and urea, were also compiled; however, in the final analysis most of the proposed complexes manufactured only the basic products.

A computer program of this type proved quite valuable in evaluating industrial processes and in performing industrial complex studies under a wide range of conditions and led to a number of conclusions and recommendations for additional work:

1. For the use of near-term light-water reactors at outputs of 1000 Mw(electrical) or more, which produce power for 2.5 to 3.5 mills/kwhr, all major processes studied are economically competitive except possibly electrolytic hydrogen for ammonia synthesis. This process should, however, find economic near-term applications in some specialized situations and more generalized uses in the far term with the advent of advanced-design electrolysis cells and breeder reactors. The near-term uses would be where off-peak or incremental power is available at attractive rates and load factors, in remote areas which are far from fossil fuel sources, and where there is a nearby demand for the high-purity oxygen which is made as a by-product. The electrolytic process is adaptable to production changes by wide variation in the cell current density and is therefore well suited for use as a utility load-leveling device. Because of the importance of ammonia as a fertilizer, it is recommended that development programs to utilize recent fuel-cell technology for the production of electrolytic hydrogen together with improved methods of generating and regulating direct-current electricity be implemented and studies be undertaken to determine how the by-product oxygen can best be utilized. Use in iron and steel manufacture and sewage treatment are obvious possibilities.

2. Lower-cost power will hasten the adoption of energy-intensive alternative processes, such as electrolytic hydrogen for ammonia and possibly for iron ore reduction, acetylene synthesis via the arc process, and electric furnace phosphorus production, over non-energy-intensive competitive processes now in general use. Those with higher break-even power costs (phosphorus) can be expected to be adopted earlier than those with lower break-even power costs (ammonia). In most cases the competing process requires a critical raw material (e.g., fossil fuel for hydrogen production or sulfur for phosphate fertilizers) which is not readily available in many parts of the world, thus providing additional impetus for the application of electricity-intensive processes.

3. The industrial processes given primary consideration were those requiring relatively large quantities of electrical energy. Future work should also investigate processes requiring large amounts of process heat or steam; examples might be the manufacture of pulp and paper, cement manufacture, and coal gasification. Most of these applications require higher-temperature heat than is available from the current designs of LWR's but may be available in the far term from some versions of advanced reactor systems.

4. Preliminary studies on alternative methods of producing iron and steel were sufficiently encouraging to warrant further study by organizations knowledgeable in the detailed technology of this industry. Steel is a basic material in the development of any nation and, wherever iron ore is present, should be exploited using the most inexpensive means available. For smaller developing countries the blast furnace route is probably too expensive, and alternatives must be carefully selected and used.

5. Production of secondary products such as urea and nitric phosphate from the products made by highly energy-intensive processes can be even more profitable than production of the primary products alone, provided transportation costs are not excessive, and their inclusion should be considered in more detailed studies for a specific area. Also other uses of the basic products should be included, such as ammonia in plastics manufacture and as a specialized fuel, and other uses for hydrogen or perhaps sodium, which could be made by fused-salt electrolysis.

6. Production of many basic products using highly energy-intensive processes in general appears to cost less (including shipping costs) at a large industrial complex than in a number of similar plants of smaller capacity (where total capac-

ity is the same as the complex) located close to the consumer.

7. Although the estimated cost of building and operating an industrial complex producing basic chemicals is higher under non-United States conditions, the profitability is greater if the products are produced for domestic markets of the country. While this appears to be generally true, a complex designed specifically to exploit a "special situation," such as the Florida phosphate case considered in this study, underscores one of the particular advantages which the ubiquitousness of nuclear power offers to areas possessing deposits of minerals which can be processed by energy-intensive methods.

8. For industrial complexes which produce distilled water by seawater evaporation, the concentrated brine effluent from the evaporator is a valuable source of salt, potassium fertilizer, gypsum, anhydrous magnesium chloride, magnesium, bromine, caustic-chlorine (by brine electrolysis), and, indirectly, sulfuric acid and portland cement. The use of concentrated brine in a solar salt works results in a 40 to 70% reduction in the land required for the evaporation ponds as compared with the direct use of seawater. Processing of bitterns from the solar salt works can be done by solar evaporation; however, using exhaust steam at this stage may be cheaper, and this should be evaluated further. Processing of bitterns leads to two highly energy-intensive processes (ideal for a nuclear industrial complex): electrolytic smelting of anhydrous magnesium chloride to magnesium and chlorine, and brine electrolysis to produce caustic and chlorine. At the present time the world markets for solar salt, magnesium, and chlorine are increasing rapidly.

9. An adjunct to the above is the use of internally produced caustic and hydrochloric acid for pretreatment of raw seawater. This method was shown to be generally cheaper than treatment by the conventional sulfuric acid method. In addition, the former permits evaporator operation at higher temperatures, permits reclamation of large quantities of calcium carbonate or carbon dioxide[1] for urea synthesis or other uses, and permits wide adjustment of the quantities of excess caustic and chlorine to meet changing market requirements for these two products.

10. Variations in the product mix, number of products produced, size of an industrial complex, and location (United States vs foreign) were evaluated in relation to the profitability as constrained by the general ground rules of this study. In this portion of the study, power was assumed to be purchased at a fixed rate, which was varied to determine its effect on the total manufacturing costs. Cost of money was also varied parametrically. Detailed conclusions from this study were:

a) As expected, when the production of the least profitable product, electrolytic-based ammonia, was reduced, profitability of the complex increased.

b) Profitability under the foreign conditions for sale of products to domestic markets was greater than under United States conditions.

c) Manufacture of secondary fertilizer products increased profitability.

d) Increases in the plant size for most of the processes considered significantly increased profitability.

Other more detailed conclusions are not cited here because of the great sensitivity of the results to the price assumptions, which may not apply in some specific locales. This would suggest that careful market analyses be made in future studies prior to this type of evaluation for specific sites.

11. With the basic products considered, only a few cases of beneficial by-product uses within a complex were discovered. Hydrogen, normally a by-product from caustic-chlorine production, was used in the ammonia synthesis, thus reducing the investment in hydrogen production for this process. Production of seawater pretreatment chemicals in some cases was considered as a by-product; for example, chlorine was assumed to have no value in a foreign complex and as hydrochloric acid was used for seawater treatment. By-product carbon dioxide from seawater treatment or from the aluminum or phosphorus processes was used in the production of urea. Whenever nitric acid was produced in a complex, the nitrogen by-product from the air-ammonia reaction was used in the ammonia synthesis step, thus eliminating the need for an air liquefaction plant.

Other by-product use possibilities which were recognized but not applied were:

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[1] Sulfuric acid also permits recovery of carbon dioxide but not calcium carbonate.

a) Carbon monoxide from the phosphorus furnace could be a source of hydrogen (via the shift reaction) for use in ammonia synthesis. It could also be used in some iron manufacturing processes and perhaps in cement manufacture.

b) If phosphoric acid is produced by the steam-phosphorus reaction, hydrogen is formed as a by-product and could be used to supplement electrolytic hydrogen.

c) By-product oxygen from the water electrolysis process would have many applications in the iron-steel and nonferrous industries. It has many uses in the chemicals industry, for example, the manufacture of ammonia from coal, methanol, titanium dioxide, and ethylene oxide. There are also potential uses to assist in pollution control of stack gases and in sewage treatment.

d) Heavy water could be considered a by-product of the electrolysis process, with obvious uses in some types of nuclear reactors.

e) By-product ferrophosphorus and slag from the phosphorus furnace process have some uses in special steel production and road construction respectively.

f) A large number of products can be made from the bitterns available from salt manufacture via solar evaporation of seawater or evaporator effluent. Some of these are potassium chloride (or sulfate), magnesium chloride, bromine, and gypsum. The latter substance can in turn be used for sulfuric acid and cement production.

g) Calcium carbonate precipitated in the seawater caustic pretreatment process is a source of carbon dioxide and lime.

h) Sodium metal could be made using the fused-salt process. Sodium has a number of metallurgical and chemical uses and may develop as a commercial electrical conductor.

Future studies should attempt to evaluate the effects of including by-product credits and to discover new possible interactions between processes.

9.4 Agriculture

The results of this study indicate that a highly productive and profitable agriculture can be developed in several areas of the world which are now unproductive coastal deserts. This agriculture could be based on the supply of desalted water from a nuclear-powered plant; no serious technical disadvantages could be found in the use of such a water supply.

This conclusion is based on a generalized study of five coastal desert locales and the following specific assumptions:

1. Desalted water would be available at a projected cost ranging from 10¢ to 30¢ per 1000 gal ($33.00 to $99.00 per acre-foot) and could be delivered to a farm using an 80% efficient sprinkler irrigation system.
2. The crop water requirements adopted were based on climatologically estimated values for one of the locales at which experimental data on water requirements and yields were also available.
3. The yield levels adopted were based on estimates by crop specialists and are generally representative of those now being obtained by the best of today's commercial producers in comparable irrigation districts.

The assumed prices for the agricultural products in general reflect world export market levels during recent years. For some comparisons a second level, 30% above world export market prices, was adopted to represent the situation in many developing countries where food is imported or where national policy results in higher prices. Present-day United States costs were taken for farm equipment and irrigation systems with the addition of an overseas cost factor.

Ten crops were included in three alternative agricultural systems. One such system, containing wheat and dry beans as staple food crops as well as limited acreages of high-value crops such as potatoes, cotton, citrus, and tomatoes, was estimated to develop an internal rate of return of 13% at world export market price levels and 25% at domestic market prices, with water costing 10¢ per 1000 gal in both cases. If the water cost is 20¢ per 1000 gal, these returns would decrease to 1 and 16% respectively. The remaining crops (soybeans, safflower, peanuts, and sorghum) were found to be less profitable at the assumed yields and prices. This particular farming system, utilizing a plant output of 1,000,000,000 gal of water per day, was estimated to be theoretically capable of supplying the calorie and protein[2] requirements of 5.2 million people.

An alternative farming system, designed to maximize calorie production, could feed an estimated 6.2 million persons with an internal rate of return of 11%, assuming sales at domestic prices and using a water cost of 20¢ per 1000 gal.

The results of the analyses showed that interest rates and costs of land development as well as the levels of crop water requirements, yields, and prices were all critical items in determining the profitability of the various farming systems examined. The shortage of reliable data on just these critical points was very apparent in this study, even for the few areas of the world where advanced systems of irrigated desert agriculture are in existence. Also of great importance were the acreage allotments to high-value crops, which were generally restricted to a small fraction of the total to comply with a generalized marketing situation. Moreover, these same critical factors may be expected to vary significantly at the different locales that may be considered (see Appendix 6A).

Any detailed study of the agricultural possibilities of a particular locale should consider additional specific crops as well as secondary forms of agricultural production, such as livestock and aquaculture, which could utilize the by-products from the crops. Another possible by-product use which could be important in some regions would be the manufacture of pulp and paper from straw or other by-product cellulose materials. Also, food processing and packaging as well as existing market requirements and their development potential should be studied. An admittedly oversimplified human diet requirement was used in this study, with no provisions to supply the proper spectrum of proteins, minerals, and vitamins. Along with the production of animal protein, these requirements should be better defined. It would also be of interest to assess the long-term potential of meeting part of the protein requirements with synthetic amino acid manufacture.

An especially important variable which must be determined is the hydrology of the underlying area of any specific site. Water storage may be a potentially difficult problem that would be expensive to solve for a desalting plant producing a constant water output for a farm whose water requirements vary seasonally depending on climatic conditions and cropping patterns.

Alternative cropping patterns should be drawn up in the light of the special characteristics and requirements of each specific locale. For example, these might well include cropping systems substituting labor for high capital investment.

A pilot farm should be established at a very early stage in the implementation program. It is needed to provide accurate local data on crop water requirements, yields, and crop rotations as well as invaluable experience in land development, cropping, and management techniques. At the same time there appears to be a great and immediate need for the development of basic crop information under a variety of climatic conditions such as could be provided by a large controlled environment chamber. It is recommended that further study be made of such a device to establish its cost and potential benefits.

Other problems associated with implementation of this concept at a particular site which would require intensive study include

1. detailed soil analyses and an associated optimized farm and irrigation system layout;
2. crop sequencing on a limited time basis, including the logistics of handling the harvested crops and planting the next crop;
3. labor and management requirements, including peak harvesting labor needs, and problems of land ownership;
4. the possible requirement for other plant nutrients, including the trace elements.

This concept of irrigated desert agriculture opens up new priorities for agricultural research, stressing the need for crop varieties and production techniques which combine high yield potential, short cropping season, and low water requirements, particularly in the tropical or subtropical coastal desert regions of the world.

9.5 Economic Analyses of Nuclear Industrial and Nuclear Agro-Industrial Complexes

The following general conclusions are suggested by the various economic comparisons described in Chap. 7. These comparisons included the effects of level of technology, size of installation, product

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[2] Adequate in quantity but not in quality; achieving the recommended protein spectrum would require supplemental animal or synthetic protein.

mix, price level, and location (United States or foreign) on the internal rate of return (IRR) for the complex. Also, the penalty imposed by the use of two reactors per station instead of one was evaluated. It is important to recognize that the examples selected in this portion of the study were intended to be illustrative of *general* locations and are highly restrained by the products selected and the associated price structure for raw materials and products (see Table 5.9).

1. The size of a complex is an important variable; for example, using a light-water reactor power source and producing ammonia, phosphorus, aluminum, and caustic, the IRR at a United States location increased from 4.5% for a 500 Mw(electrical) industrial complex to 11.4% for 2000 Mw. The corresponding values for a foreign complex were 9.7 and 16.1% with domestic price levels and 2.4 and 7.7% with export prices. Where substantial advantages in raw material prices exist, that is, near a source of raw material such as a Florida phosphate rock mine, and when the production of ammonia, the least profitable of the basic products considered, is omitted, the IRR increased from 7.5% to nearly 19% for a 1000 Mw(electrical) complex with near-term reactor technology. These results emphasize the importance in future studies of "tailoring" the industrial products to the raw materials available at any given locale and in selecting realistic price levels for the products. This would in turn require the development of detailed data on resources and market conditions for a given site.

2. Other examples of complexes in which ammonia manufacture was omitted showed that the IRR could be increased by about 60% from a value of 7.4% to 11.5–12.5% for a 1000 Mw(electrical) LWR United States case. The IRR for the corresponding foreign case increased by 26% (from 12.7 to about 16%) using the domestic price level. However, an example which illustrated the effect of incrementally adding a large ammonia plant to a 1000 Mw(electrical) complex, thus giving a 2000 Mw(electrical) complex, showed that the IRR was decreased by only 3%.

3. A change in reactor technology from the light-water type to a fast breeder increased the IRR by about one to two points. A further increase of about one point occurred when the thermal breeder reactor was used.

4. The economic results indicate that the penalty incurred in using a two-reactor power station instead of a single reactor is minor. Improved reliability achieved by the former should outweigh the small extra costs.

5. The advantages of a large central nuclear power station distributing power to various industrial areas should be evaluated relative to many small power plants located near the point of use.

6. For nuclear agro-industrial complexes located in developing nations, the development of improved evaporator technology, leading to lower capital costs and reduced seawater pumping requirements, is very important to the economic viability of the agricultural portion of the complex. The effect of improved reactor technology is important also, but it is not as important to agriculture as advanced evaporators. Utilizing advanced reactor and evaporator technology (ABR-VTE) yielded overall returns of 15 to 16% and an incremental return for the farm only slightly less than the overall farm-industry return.

7. The relatively large amount of electricity produced from a dual-purpose reactor plant (particularly ABR's) operating at the back-pressure point presents a significant "disposal" problem in many parts of the world. Development work on high water-to-power ratio and water-only plants should proceed in order to provide more flexibility in the design of plants under various conditions. To illustrate the potential gains available from a plant of improved design, a value of 7.4% IRR was computed for a farm based on a water-only plant (LWR-MSF) using an admittedly inefficient concept of prime steam bypass. In this case, 85% of the prime steam was bypassed around the back-pressure turbine directly to the seawater evaporator plant. This may be compared with the incremental return attributed to the farm of 10.6% computed for the same size farm in an industry-farm complex using a dual-purpose plant.

8. Increasing the size of a nuclear agro-industrial complex improves the rate of return for the complex as well as for the farm increment; for example; with LWR-MSF technology the IRR increased from 9.3 to 13.2% in going from a 500/320 [Mw(electrical) industry/Mgd farm] size to a 2000/1280 [Mw(electrical)/Mgd]. The incremental return due to the farm increased from 8.9 to 10.7%. Since one of the assumptions used was linear size scaling for the farm costs, additional work should be done on the capital and operating costs of farms as a function of size, particularly in the range of 75,000 to 400,000 acres.

9. The sensitivity analyses indicated that the incremental rate of return was much less affected by the capital cost of the complex than by the product price assumptions. Thus an increase of between 20 and 40% in the capital cost of any single component of the complex (reactor, evaporator, industrial complex, or farm) only resulted in a one percentage point decrease in the internal rate of return, whereas a decrease of only 6 to 11% in the annual sales income caused the same one-point decrease.

9.6 Locale Studies

The study on locale selection, accommodation, and implementation was necessarily of a preliminary nature. Nevertheless, as a result of the work carried out, a number of conclusions and recommendations can be enumerated.

1. A number of areas in the world, presently neither agriculturally nor industrially fruitful, can be made productive through the implementation of the agro-industrial concept.
2. It appears that some of these areas can be made agriculturally productive on a year-round basis provided the crop variety selected and its management are tailored carefully to the local climate.
3. Agricultural requirements impose significant limitations on the number of locations which can be considered for an agro-industrial complex. Many locales suitable for the agro-industrial complex would not be selected for an industrial complex and vice versa.
4. In the context of this study with its nuclear viewpoint, the locales suitable for an industrial complex would not have extensive fossil fuel or hydro energy sources, but they would take advantage of other natural resources and industrial markets. The basic ideas, however, for industrial and agro-industrial complexes would apply for locales having cheap and abundant fossil fuel, provided due consideration is given to the type of industrial processes used. The number of potential locales open to an industrial complex appears to be much greater than for an agro-industrial complex.
5. Additional information on the agricultural parameters, such as soils, topography, climate, crop water requirements, and water storage possibilities, as well as labor quality and availability, are required before a satisfactory final evaluation of an individual locale can be carried out.
6. The problems of markets and transport of agricultural products suggest much more detailed consideration of on-site food handling and processing.
7. The special study of markets, resources, and transport media, as well as the potential benefits derived, should be more *regionally* oriented, as opposed to the individual nation concept adopted for this study, to adequately reflect the influence of areas adjacent to the locales.
8. Additional consideration of the utilization and contribution of marine resources to the operation of an agro-industrial complex may yield extra benefits.
9. Much creative thinking is needed concerning the social, political, cultural, and financial problems of implementation for each locale and the ultimate effects on the host country.

Appendix 1A

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Indian Aluminum Company	
Indian Embassy	N. R. Verma
Indian Oil Company	
Ingersoll-Rand Company	J. M. Suttle
Instituto Nacional de Promocion Industrial	Juan Bazo
International Bank for Reconstruction and Development	
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Appendix 3A

ECONOMIC ANALYSIS BASED ON THE INTERNAL RATE OF RETURN

This appendix presents an iterative mathematical procedure for computing the internal rate of return together with a solved example. Also included is a procedure for calculating factors for interest during construction at different costs of money based on a symmetrical distribution of payments. The construction periods, service lives, and salvage values assumed for the components of nuclear-powered complexes are listed for United States and non-United States locations.

3A.1 Internal Rate of Return

The internal rate of return may be considered to be the interest rate at which a project will break even in the sense that the income from the investment equals all costs including return (at that interest rate) on investment. The use of the internal rate of return has the advantage of allowing an initial step to be made in the evaluation of a proposal without requiring an assumption as to the present or future value of money. In comparing alternative proposals, however, the most economically attractive one can be selected only when (1) the internal rate of return is calculated for the difference in their cash flows and (2) this result is compared with the cost of money, that is, with the minimum acceptable rate of return. In the design of a proposal, portions are added or dropped off, and an internal rate of return is calculated for each increment. The size of the proposed investment is expanded or contracted until the marginal rate of return just equals that interest rate judged to be the expected cost of money. This optimization technique may be considered simply as a process for maximizing the discounted net benefits.

Calculation of the internal rate of return requires several arithmetical steps. The method presented here is sufficient for investments which yield more or less uniform annual income and operating expenses. The method and numerical data are readily applied to the end objective of calculating and maximizing the overall discounted return once the time value of money is agreed upon.

3A.2 Mathematical Formulation

If an investment of amount P results in an annual return W, the rate of return is defined as

$$r = \frac{W}{P} . \tag{1}$$

Thus, if a \$100.00 investment yields \$6.00 a year forever, the rate of return is 0.06 or 6%.

If instead of a single investment and a constant stream of annual returns there is instead a nonuniform series, a rate of return can still be defined. In doing this it is not necessary to identify which expenditures will be called investments and which will be called current expenditures, but it is only necessary to indicate the time period (year) in which each expenditure and each income transaction is expected to occur. The comparison of the general formulation with Eq. (1) can be illustrated as follows. First, Eq. (1) is rearranged:

$$0 = -P + \frac{W}{r} . \tag{2}$$

Then the last term is expanded as an infinite series, and the term $-P$ is divided by $(1 + r)^0 = 1$. The result is

$$0 = -\frac{P}{(1 + r)^0} + \frac{W}{1 + r} + \frac{W}{(1 + r)^2} + \frac{W}{(1 + r)^3} + \dots . \tag{3}$$

The infinite series which was used in the expansion is:

$$\frac{1}{r} = \frac{1}{1 + r} + \frac{1}{(1 + r)^2} + \frac{1}{(1 + r)^3} + \dots .$$

To demonstrate this, let $x = 1/(1 + r)$ and note that $1/(1 - x) = 1 + x + x^2 + \dots$. Then

$$\frac{1}{r} = \frac{x}{1 - x}$$

$$= x\,(1 + x + x^2 + \dots)$$

$$= x + x^2 + x^3 + \dots \; .$$

Equation (3) may be compared with a more general formulation:

$$0 = R_0 + \frac{R_1}{1 + r} + \frac{R_2}{(1 + r)^2} + \frac{R_3}{(1 + r)^3} + \dots \; , \qquad (4)$$

which may be compared with Eq. (3) if R_0 were equal to $-P$ and the other R's set equal to W. A still more general formulation results if each term of Eq. (4) is multiplied by $(1 + r)^m$, where m is a positive integer. This gives

$$0 = R_0(1 + r)^m + R_1(1 + r)^{m-1} + R_2(1 + r)^{m-2} + \dots \; .$$

If a change of variables is introduced to match the subscripts to the superscripts,

$$0 = S_m\,(1 + r)^m + S_{m-1}(1 + r)^{m-1} + \dots + S_0(1 + r)^0 + \frac{S_1}{1 + r} + \frac{S_2}{(1 + r)^2} + \dots \; , \qquad (5)$$

where $S_m = R_0$, $S_{m-1} = R_1$, ... $S_0 = R_m$, $S_1 = R_{m+1}$ ... , etc.

Each term on the right-hand side can be interpreted as the net returns for a particular year reduced to their present worth in year zero at an interest rate equal to r. (Note that in the formula, the interest rate is expressed as a decimal, such as 0.06, whereas in charts and in the text, it is usually shown as a percentile.) The internal rate of return is found as the solution of Eq. (5) in terms of the annual net returns S. The equation may have more than one root, and some of the roots may be negative. The purpose, however, of calculating r is to compare a proposal with other opportunities to invest money for which there is a positive rate of return. Although for some proposed projects the rate of return may be negative, a proposal will be considered "feasible" only if r is positive. Furthermore, investigation of this equation for the S_t (net returns in year t) encountered in this study indicated that there is a single positive root, which removes possibility of ambiguity.

3A.3 Interest During Construction

The augmentation of the initial terms by powers of $1 + r$ can be interpreted or labeled as "interest during construction." In the economic appraisal of proposals, the concept of a construction period is arbitrary and not necessary at all. All net receipts can be discounted to the initial year of construction of the project, to the initial year in which income is received, or to any other year. This changes the value of m in Eq. (5), but in the solution of Eq. (5), it does not change the value of r.

As with all income and expense transactions in this study, it is assumed that payments during the construction period occur at the end of each year. Thus, if the construction period is one year, it is assumed that the investment is all paid at the end of the year. Since this is also the date to which all transactions are referred, the one-year construction period results in no calculated interest charges during construction. If the construction period lasts several years, we assume that the payments will concentrate in the center of the period with a symmetrical distribution of payments, as shown in Table 3A.1.

With the foregoing schedule of construction payments, a factor for including interest charges during construction is readily calculated. For example, if $i = 10\%$ and the construction period is five years, this factor is

$$f = 0.07\,(1.1)^4 + 0.22\,(1.1)^3 + 0.42\,(1.1)^2 + 0.22\,(1.1)^1 + 0.07\,(1.1)^0$$

$$= 1.2150\;.$$

The initial investment (excluding interest during construction) multiplied by f gives the present worth of the investment (i.e., including interest during construction). The datum point for the present worth is the date of initial operation of the complex.

In Table 3A.2 the factor *f* is given for four interest rates from 2.5 to 20% and for construction periods ranging from one to six years.

3A.4 Delayed Returns

In some agricultural activities, such as citrus culture, a stream of expenses can precede the flow of income by a period of years. Citrus trees require five or more years before they bear fruit. The discounting procedure suggested by Eq. (4) handles this situation, as the returns S_t may differ from one year to the next.

The time required for the trees to mature is analogous to the construction period for an industrial project; however, income flow from other crops and from the factories may start at an earlier date. In this case, *W* can be broken into two streams, *U* and *V*, with *U* commencing *s* years earlier than *V*. Then,

$$W = U + \frac{V}{(1 + r)^s} .$$

Table 3A.1. Assumed Schedule of Construction Payments

Payments at end of each year as a percent of total

	Payment for Construction Period of –					
	1 Year	2 Years	3 Years	4 Years	5 Years	6 Years
Construction period						
1st year	100	50	18	10	7	5
2d year		50	64	40	22	13
3d year			18	40	42	32
4th year				10	22	32
5th year					7	13
6th year						5
Years subject to interest charges						
5th year						5
4th year					7	13
3d year				10	22	32
2d year			18	40	42	32
1st year		50	64	40	22	13
0 year	100	50	18	10	7	5

Table 3A.2. Factor *f* for Interest Charges During Construction

Cost of Money, *i* (%)	*f* for Construction Period of –					
	1 Year	2 Years	3 Years	4 Years	5 Years	6 Years
2.5	1	1.0125	1.0251	1.0379	1.0509	1.0641
5	1	1.025	1.0505	1.0768	1.1038	1.1316
10	1	1.050	1.1018	1.1571	1.2150	1.2770
20	1	1.100	1.2071	1.3288	1.4644	1.6139

In the example of citrus trees, the expected life of the trees is quite long (in the order of 50 years), and the present worth of replacement costs is negligible.

3A.5 Mathematical Solution

Under certain conditions, the solution of the general equation for internal rate of return, Eq. (5), can be reduced to

$$r = \frac{W}{P'}, \tag{6}$$

where P' is a function of r and where, as contrasted to Eq. (1), P' is not the investment but rather the present worth of the investment stream required to establish and maintain the net income W each year. This augmented investment P' includes interest during construction and the present worth of replacements to infinity calculated at an interest rate equal to r (rather than at the time value of money i).

$$P' = Pf(r + qe)/r \, , \tag{7}$$

where

P = initial investment,

f = factor for inclusion of interest during construction (see Table 3A.2),

q = factor to account for the net salvage value of an investment and for reductions due to technology in the cost of replacements (ratio of end-of-life replacement cost to initial investment),

$e = \dfrac{r}{(1 + r)^n - 1}$, the sinking fund deposit factor, where n is the project life in years.

For convenience, we define the product $f(r + qe)$ which appears in Eq. (7) as

$$\ell \equiv f(r + qe) \, , \tag{8}$$

so that

$$P' = P\ell/r \tag{9}$$

and

$$P\ell = W \, . \tag{10}$$

The quantity ℓ is a function of r; it can be evaluated at any interest rate r. If it is evaluated for an interest rate equal to the time value of money, then it takes on a special meaning, and Eq. (10) no longer holds. Instead,

$$B = W - P\ell \, , \tag{11}$$

where B equals the excess of W over $P\ell$. The quantity B is referred to as "venture profit." It is the equivalent of all transactions (including investment) levelized to a uniform annual amount using a time value of money equal to i. Since this is a uniform annual series, extended indefinitely, B/i is the present worth of the net benefits, which is a quantity upon which comparison of projects can be made.

One procedure for solving for the internal rate of return is in terms of its original definition (the interest rate at which the project breaks even so that income equals all costs, including return on investment). In other words, r is the interest rate for which $B = 0$ in Eq. (11) [the equation then reduces to Eq. (10)]. The numerical or graphical procedure would be to evaluate B for various interest rates and solve by trial and error for the interest rate which reduces B to zero.

A more direct approach in the iterative procedure is:

1. For a trial interest rate r_0, calculate $\mathcal{L}_0$.
2. Solve for a new approximation:

$$r_1 = Wr_0/P\mathcal{L}_0$$

or more generally

$$r_{n+1} = Wr_n/P\mathcal{L}_n \ . \tag{12}$$

The iterative procedure converges rapidly. One iteration is usually sufficient.

For a set of problems involving the same $\mathcal{L}$ function but different values of W and P, it is convenient to prepare and use a graph of $\mathcal{L}$ vs i, as shown in Fig. 3A.1.

3A.6 Multiple Investments

A complex may represent the combined investment in power plant, factories, harbor, etc., each with its own construction interval, service life, and end-of-life replacement cost. In this situation the product $P\mathcal{L}$ in Eqs. (10) to (12) is replaced by

$$\sum_i P_i \mathcal{L}_i \ ;$$

that is, for each component of the complex, its initial investment is multiplied by its $\mathcal{L}$ function. The sum of these products is then the uniform annual amount equivalent to the entire investment stream. The parameters defining the various $\mathcal{L}$ functions used in our analysis of agro-industrial complexes are listed in Table 3A.3.

3A.7 Illustrative Example

An example of a nonuniform series of annual income and expenditure is given in Table 3A.4. The series consists of annual income of 25 and expenditure of 5 each year, starting with the third year, plus expenditure of 50 in the first two years and expenditure of 40 in the first two years of each succeeding decade. The items in the table refer to activities that take place during each year but for which the monetary transaction occurs at the end of the year.

The general equation for the internal rate of return r is

$$0 = \frac{-50}{(1+r)^0} + \frac{-50}{1+r} + \frac{20}{(1+r)^2} + \frac{20}{(1+r)^3} + \ldots + \frac{-20}{(1+r)^{10}} + \ldots \ ,$$

where each term is interpreted as a net receipt for a given year converted to its "present worth" for the year 1970.

When multiplied by $(1 + r)$, the result is

$$0 = -50(1+r) - 50 + \frac{20}{1+r} + \frac{20}{(1+r)^2} + \ldots + \frac{-20}{(1+r)^9} + \ldots \ .$$

The interpretation is now that each term is a net receipt converted to its present worth as of December 31, 1971. The term that equals $50 + 50r$ may be considered as a principal of 50 and interest of $50r$. The first two terms can be characterized as an initial investment of 100 spread over a construction period of two years but excluding interest during construction.

3A.8 Solution of the Equation

First, expenditures are rearranged as shown in Table 3A.5. This groups together terms which are identified as the initial investment and the replacement investment. The income and annual expenditure columns can be consolidated into a net amount of 20 per year. The present worth in 1971 of this series can be summed to a single term:

$$\frac{20}{1+r} + \frac{20}{(1+r)^2} + \frac{20}{(1+r)^3} + \ldots = \frac{20}{r} \ .$$

The two initial investment terms can be consolidated:

$$-50(1+r) - 50 = -100\left(1 + \frac{r}{2}\right) \ .$$

Table 3A.3. Factors for Conversion of Various Types of Investments to a Uniform Annual Equivalent Cost, Including Replacement and Interest During Construction

	Construction Period (years)	Service Life (years)	Replacement Cost (fraction of initial cost)	Annual Equivalent Cost as a Fraction of Initial Investment: $\mathcal{L}$ Function, Eq. (10)			
				$i = 0\%$	$i = 5\%$	$i = 10\%$	$i = 20\%$
United States Cost Basis							
Reactor and turbine generator							
95% of initial investment	4	30	0.90	0.032	0.070	0.122	0.264
Remaining 5% (interim replacements)	1	15	1.00				
Initial fuel cycle costs	1	30	0.35	0.012	0.056	0.102	0.200
Evaporator tubes and sheets							
Copper-nickel (for MSF)	3	30	0.90	0.030	0.067	0.116	0.242
OLIN alloy (for VTE)	3	15	0.90	0.060	0.096	0.141	0.256
Evaporator less tubes and sheets							
93% of initial investment	3	30	0.90	0.033	0.069	0.117	0.240
Remaining 7% (interim replacement)	1	15	1.00				
Industrial plants	2	15	0.75	0.050	0.087	0.130	0.232
Harbor	3	30	0.60	0.020	0.062	0.114	0.242
Electrical grid interconnection	1	30	0.90	0.030	0.064	0.106	0.201
Working capital	1	Infinite	0.00	0.000	0.050	0.100	0.200
Foreign Cost Basis							
Reactor and turbine generator							
95% of initial investment	5	30	0.90	0.032	0.071	0.128	0.290
Remaining 5% (interim replacements)	1	15	1.00				
Initial fuel cycle costs	1	30	0.35	0.012	0.056	0.102	0.200
Evaporator tubes and sheets							
Copper-nickel (for MSF)	4	30	0.90	0.030	0.068	0.122	0.267
OLIN alloy (for VTE)	4	15	0.90	0.060	0.099	0.149	0.282
Evaporator less tubes and sheets							
93% of initial investment	4	30	0.90	0.033	0.070	0.123	0.263
Remaining 7% (interim replacement)	1	15	1.00				
Industrial plants	3	15	0.75	0.050	0.089	0.136	0.254
Harbor	3	30	0.60	0.020	0.062	0.114	0.242
Electrical grid interconnection	1	30	0.90	0.030	0.064	0.106	0.201
Farm							
Structures, including roads and pipelines	2	40	0.90	0.022	0.059	0.107	0.220
Equipment	1	15	0.90	0.060	0.092	0.128	0.213
Working capital	1	Infinite	0.00	0.000	0.050	0.100	0.200

Similarly, each pair of replacement expenditures can be reduced to a single term:

$$-\frac{40}{(1+r)^9} - \frac{40}{(1+r)^{10}} = -80\left(1+\frac{r}{2}\right)\frac{1}{(1+r)^{10}}\ .$$

The stream of replacement expenditures can be consolidated:

$$-80\left(1+\frac{r}{2}\right)\frac{1}{(1+r)^{10}} - 80\left(1+\frac{r}{2}\right)\frac{1}{(1+r)^{20}} - \ldots$$

$$= -80\left(1+\frac{r}{2}\right)\left[\frac{1}{(1+r)^{10}} + \frac{1}{(1+r)^{20}} + \ldots\right]$$

$$= -80\left(1+\frac{r}{2}\right)\frac{1}{(1+r)^{10}-1}\ .$$

This algebraic manipulation can be seen by letting $x = 1/(1+r)^{10}$ and noting again that

$$x + x^2 + x^3 + \ldots = \frac{x}{1-x}\ .$$

Table 3A.4. Income, Expenditure, and Net Receipts for a Hypothetical Proposal

Year	Income	Expenditure	Net Receipts
1970	0	50	–50
1971	0	50	–50
1972	25	5	20
1973	25	5	20
1974	25	5	20
1975	25	5	20
1976	25	5	20
1977	25	5	20
1978	25	5	20
1979	25	5	20
1980	25	45	–20
1981	25	45	–20
1982	25	5	20
.	.	.	.
.	.	.	.
.	.	.	.

Table 3A.5. Separation of Expenditures in the Hypothetical Proposal

Year	Income	Expenditure	Investment	
1970	0	0	50	initial
1971	0	0	50	
1972	25	5	0	
1973	25	5	0	
1974	25	5	0	
1975	25	5	0	
1976	25	5	0	
1977	25	5	0	
1978	25	5	0	
1979	25	5	0	
1980	25	5	40	replacement
1981	25	5	40	
1982	25	5	0	
1983	25	5	0	
.	.	.	.	
.	.	.	.	
.	.	.	.	

All the items in Table 3A.5 may now be gathered together, and the equation for r becomes:

$$0 = -100\left(1+\frac{r}{2}\right) - 80\left(1+\frac{r}{2}\right)\frac{1}{(1+r)^{10}-1} + \frac{20}{r},$$

or

$$r = 20\left\{100\left(1+\frac{r}{2}\right)\left[1+\frac{0.8}{(1+r)^{10}-1}\right]\right\}^{-1}$$

$$= \frac{W}{P'},$$

where

$$P' = 100\left(1+\frac{r}{2}\right)\left[r+\frac{0.8r}{(1+r)^{10}-1}\right]r^{-1}$$

$$= Pf(r+qe)/r\ . \tag{7}$$

In this example

$P = 100$, the initial investment ,

$f = 1 + \frac{r}{2}$, interest during construction — two-year period,

$q = 0.8$, ratio of end-of-life replacement cost to initial investment,

$e = \frac{r}{(1 + r)^{10} - 1}$, sinking fund deposit factor for a ten-year project life.

To solve for the internal rate of return in the example, let $r_0 = 10\%$; then from Fig. 3A.1, $\ell_0 = 0.158$, and as shown previously, $W = 20$; therefore, using Eq. (12):

Iteration 1:

$$r_1 = \frac{20 \times 0.10}{100 \times 0.158}$$

$$= 0.127\ .$$

From Fig. 3A.1, for $r_1 = 12.7\%$,

$$\ell_1 = 0.181\ .$$

Iteration 2:

$$r_2 = \frac{20 \times 0.127}{100 \times 0.181}$$

$$= 0.140\ .$$

From Fig. 3A.1, for $r_2 = 14\%$,

$$\ell_2 = 0.194\ .$$

Iteration 3:

$$r_3 = \frac{20 \times 0.14}{100 \times 0.194}$$

$$= 0.144\ .$$

From Fig. 3A.1, for $r_3 = 14.4\%$,

$$\ell_3 = 0.198\ .$$

Iteration 4:

$$r_4 = \frac{20 \times 0.144}{100 \times 0.198}$$

$$= 0.145\ .$$

Thus the internal rate of return for this example is 14.5%. Four iterations were required because the initial guess of 10% was off by 45%. A better approximation of r_0 would reduce the number of iterations.

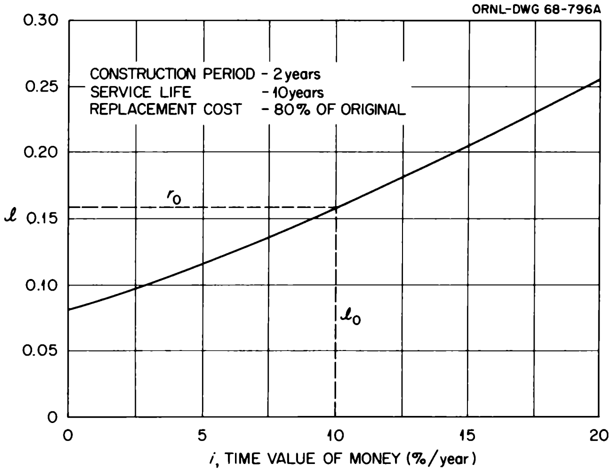

Fig. 3A.1. Ratio of Equivalent Annual Cost to Investment.

Appendix 4A

RATIONALE FOR POWER AND WATER COSTS

This appendix provides detailed information on the costs of nuclear power stations and on seawater evaporator plants as well as some discussion of the technologies used in this study. The discussion of power costs for light-water reactors (LWR) includes the following:

1. capital costs for major components,
2. multiple-unit stations,
3. thermal efficiency,
4. plant load factor,
5. operating, maintenance, and insurance costs,
6. annual fixed charges against investment,
7. nuclear fuel cycle costs,
8. example calculation of electricity costs.

The discussions on power costs from advanced breeder reactors are divided into three main topics: capital investment, operation and maintenance, and fuel cycle.

The section of the appendix which discusses the assumptions relating to seawater evaporator technology and costs includes the following topics:

1. performance ratio,
2. maximum brine temperature and chemical pretreatment of seawater,
3. concentration ratio,
4. seawater temperature,
5. train size,
6. major cost factors.

4A.1 Cost of Power from Light-Water Reactor Power Stations

To facilitate estimating the capital and operating costs of power reactors which can supply steam at maximum temperature, extraction steam at lower temperatures for desalting and/or process use, and/or electricity, the nuclear power plants were considered to consist of three interrelated parts, the nuclear island (N.I.), the turbogenerator island (T.I.), and the condenser island (C.I.). The nuclear island includes all facilities required to produce the prime steam and thus includes the reactor and its auxiliaries, the primary cooling system, and heat exchanger boilers. The turbogenerator island includes the facilities required to produce electricity and extraction steam from prime steam. The condenser island includes the facilities required to condense any steam emerging from the turbogenerator island which is not sent to process or desalting use.

Much of the capital cost information available concerning nuclear power stations pertains to single-purpose electricity-generating stations and hence relates to stations combining nuclear island, condensing turbogenerator island, and condenser island costs. A number of the available cost breakdowns for such nuclear electricity-generating stations (see refs. 2, 3, 9, 10, 11, 12 in Chap. 4) were examined, and, using engineering judgment, the costs of the individual components of the stations were assigned to the headings of nuclear island, turbogenerator island, and condenser island. There was good agreement in the relative distribution of the costs from different sources, and the following relationships were developed:

$$\%\ \text{N.I.} = 50\left(\frac{P_t}{3000}\right)^{-0.1},$$

$$\%\ \text{T.I.} = 0.88(100 - \%\ \text{N.I.}),$$

$$\%\ \text{C.I.} = 0.12(100 - \%\ \text{N.I.}),$$

where P_t is thermal power rating of the reactor, Mw, and % N.I., T.I., C.I. are fractions (as percent) of the total capital cost of a single-purpose power station due to the reactor island, turbogenerator island, and condenser island respectively.

When the pertinent data from the above references for the capital cost for LWR's were brought together, the correlations presented in Figs. 4A.1 and 4A.2 were obtained. These figures provide the basis for estimating the capital costs for LWR's used in this study.

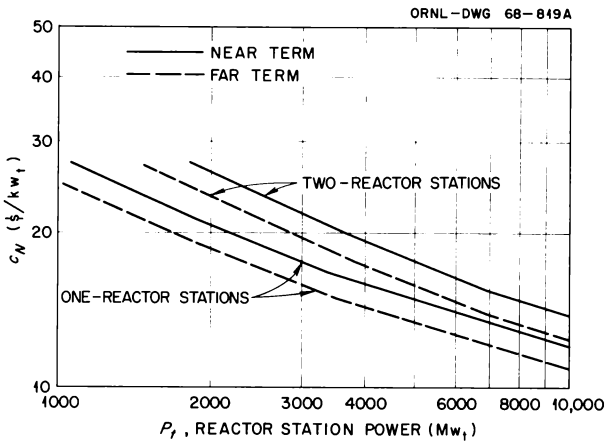

Fig. 4A.1. Nuclear Island Installed Costs – LWR (Excluding Interest During Construction).

These correlations of estimated capital costs show three distinct ranges of costs in which the "scaling laws" vary in magnitude. The ranges are approximately 1200 to 1860 Mw(thermal) [(400 to 600 Mw(electrical)], 1860 to 3400 Mw (thermal) [(600 to 1000 Mw(electrical)], and above 3400 Mw(thermal) [(1100 Mw(electrical)].

Capital costs for fully constructed (less interest during construction and land cost) LWR's were calculated for the nuclear island and the turbogenerator-condenser island as a function of time period and size using Eqs. (1) and (2) and the parameters listed in Table 4A.1 (see Figs. 4A.1 and 4A.2 for capital costs):

$$c_N = c_{NR}\left(\frac{P_t}{PR_t}\right)^{-n} , \qquad (1)$$

$$c_{TC} = c_{TCR}\left(\frac{P_e}{PR_e}\right)^{-m} , \qquad (2)$$

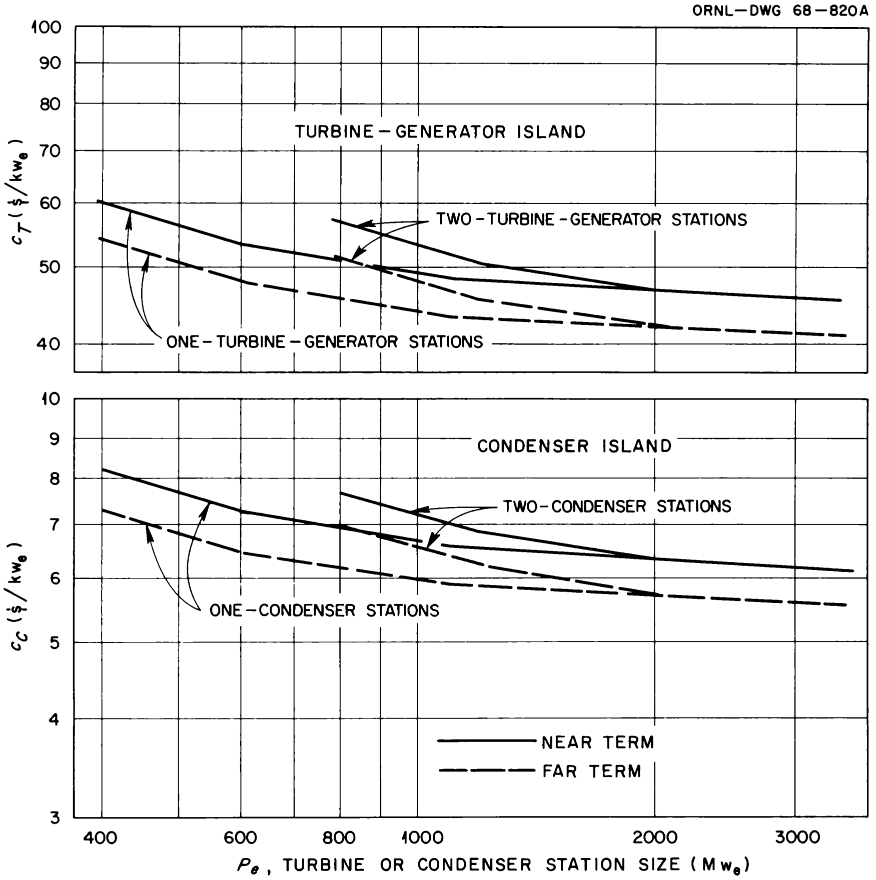

Fig. 4A.2. Turbine and Condenser Island Costs – LWR (Excluding Interest During Construction).

Table 4A.1. Parameters for Estimating Installed Capital Costs for LWR's (Excluding Interest During Construction)

One-Unit Systems

Power range of application			
P_t, Mw	<1860	1860–3400	3400–10,000
P_e, Mw	<600	600–1100	1100–3230
Scaling factors			
n	0.44	0.40	0.30
m	0.29	0.15	0.05
Near-term ("1977") LWR systems			
PR_t, Mw	1860	3400	3400
c_{NR}, \$/kwt	21.4	16.7	16.7
PR_e, Mw	600	1100	1100
c_{TCR}, \$/kwe	60	55	55
c_{TR}, \$/kwe	53	48	48
c_{CR}, \$/kwe	7.3	6.6	6.6
Far-term ("1987") LWR systems			
PR_t, Mw	1860	3400	3400
c_{NR}, \$/kwt	19.2	15.1	15.1
PR_e, Mw	600	1100	1100
c_{TCR}, \$/kwe	54	49	49
c_{TR}, \$/kwe	48	43	43
c_{CR}, \$/kwe	6.5	5.9	5.9

Two-Unit Systems

Power range of application			
P_t, Mw	<3720	3720–6800	>6800
P_e, Mw	<1200	1200–2000	>2000
Scaling factors			
n	0.44	0.40	0.30
m	0.29	0.15	0.05
Near-term ("1977") LWR systems			
PR_t, Mw	3720	6800	6800
c_{NR}, \$/kwt	19.8	15.5	15.5
PR_e, Mw	1200	1200	1100
c_{TCR}, \$/kwe	58	58	55
c_{TR}, \$/kwe	51	51	48
c_{CR}, \$/kwe	6.9	6.9	6.6
Far-term ("1987") LWR systems			
PR_t, Mw	3720	6800	6800
c_{NR}, \$/kwt	17.8	14.0	14.0
PR_e, Mw	1200	1200	1100
c_{TCR}, \$/kwe	52	52	49
c_{TR}, \$/kwe	46	46	43
c_{CR}, \$/kwe	6.3	6.3	5.9

$$c_T = c_{TR}\left(\frac{P_e}{PR_e}\right)^{-m}, \qquad (3)$$

$$c_C = c_{CR}\left(\frac{P_{ce}}{PR_e}\right)^{-m}, \qquad (4)$$

where:

c_N = dollars/kw(thermal) for nuclear island at desired thermal power level, P_t, in megawatts,

c_{TC} = dollars/kw(electrical) for complete turbogenerator-condenser island for a condensing turbine system of electrical power level P_e in megawatts,

c_T = dollars/kw(electrical) for turbogenerator island at desired electric power level, P_e, in megawatts,

c_C = dollars/kw(electrical) for condenser island for the electric power level for condensing turbine portion of a dual-purpose plant, where P_{ce} is the electric power generated by the condensing turbine in megawatts,

P = desired power level, Mw(thermal or electrical),

R = reference (base cost or power level),

n = scaling factor for N.I.,

m = scaling factor for T.I. and C.I.,

t = thermal,

e = electric.

In estimating the cost of dual-purpose (electricity and water) plants, the costs of the turbogenerator island and the condenser island must be estimated separately using Eqs. (3) and (4) and the appropriate parameters listed in Table 4A.1 (see Fig. 4A.2). The unit cost of the turbogenerator stations, c_T, is obtained by entering Eq. (3) or Fig. 4A.2 with P_e equal to the total electric generator capacity. The unit cost of the condenser, c_C, is obtained by entering Eq. (4) or Fig. 4A.2 with the gross electrical power produced by a condensing turbogenerator fed by prime steam.

4A.1.1 Multiple-Unit Stations

Capital costs of two-unit nuclear islands (two reactors) and turbogenerator-condenser islands (two turbogenerators) have been estimated for "near-term" plants (see Figs. 4A.1 and 4A.2). Assuming that the ratios of costs between two- and one-unit stations remain the same, similar costs for two-unit stations have been estimated for "far-term" plants (see Figs. 4A.1 and 4A.2).

Unit capital costs are seen to decrease more rapidly with increasing plant capacity in the case of the smaller power stations than in the case of large power stations. The largest individual reactors ordered to date have been of about 3300 Mw(thermal) capacity, and the largest turbines have been of about 1100 Mw(electrical) capacity. Studies have been made of a design for reactors of up to 10,000 Mw (thermal) (refs. 12 and 18, Chap. 4). Results of cost estimates based on these designs are included in Figs. 4A.1 and 4A.2. Extrapolations of the turbogenerator size-cost relationships indicated little additional benefit of increasing turbine size indefinitely. Above about 1500 Mw (electrical) total station capacity, all turbine-generator stations are assumed to contain at least two turbine generators.

4A.1.2 Thermal Efficiency

For use in calculating the conversion of thermal energy into electric energy in the turbine generator of LWR systems, prime steam conditions of 965 psia and 540°F and an exhaust temperature of 92°F for condensing turbines were used. This resulted in a gross turbine cycle efficiency of 34.2% and a net power plant efficiency of 32.6%, both for condensing turbine systems. Efficiencies for back-pressure (turbine) operation, which is frequently utilized in dual-purpose electricity-desalting stations, are lower, decreasing as the exhaust temperature increases.

4A.1.3 Plant Load Factor

The concept of energy centers supplying continuously operating industrial and water-producing complexes implies a high load factor. Since nuclear stations are designed for high availability, a plant load (or use) factor of 90% (i.e., 7900 hr/year) was used in estimating costs.

4A.1.4 Operation, Maintenance, and Insurance Costs

Several estimates of the cost of operating, maintaining, and insuring nuclear power stations were reviewed (refs. 4, 9, and 13, Chap. 4). These sources were in good agreement, and the resulting averaged estimated costs for operation and maintenance for the nuclear island of LWR's are presented in Fig. 4A.3. Similar estimates of the annual operation and maintenance costs for the turbine-generator plants are presented in Fig. 4A.4. The information shown in these figures was used to estimate the operation and maintenance cost in the near term. Considering the infant state of the industry at this time, it was assumed that the operation and maintenance cost for far-term applications would be 85% of the values shown in these two figures.

It was assumed that each near-term nuclear station would incur costs for nuclear liability and indemnity insurance equal to that now experienced in the United States. Since present insurance rate contracts have a provision for reduced rates after a period of good experience, the estimated cost for nuclear insurance was assumed to be lower in the far term than in the near term. Estimated costs for nuclear insurance (on the nuclear island) used in this study were therefore obtained from the following relationships:

near term:

$$\text{insurance (dollars/year)} = 30P_t + 260{,}000U ,$$

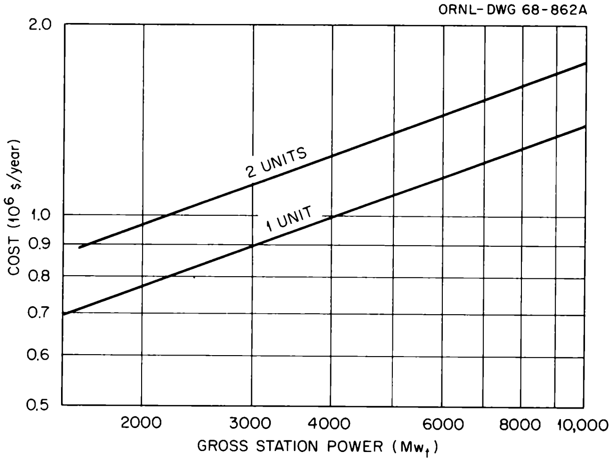

Fig. 4A.3. Annual Operating and Maintenance Costs for Nuclear Island of LWR.

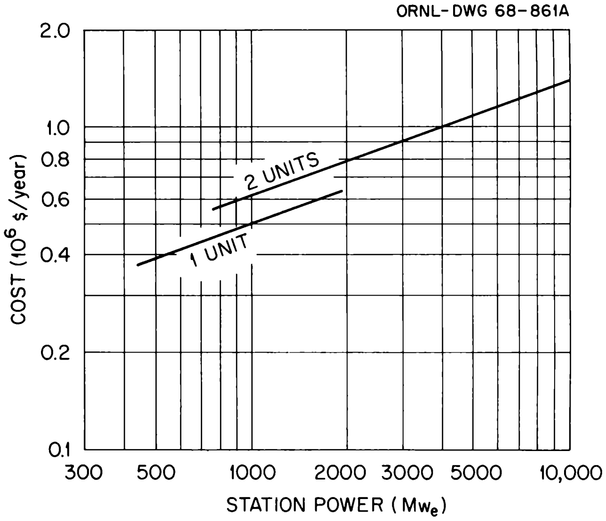

Fig. 4A.4. Annual Operating and Maintenance Cost for Turbine Generator Plant.

far term:

$$\text{insurance (dollars/year)} = 24P_t + 210{,}000U ,$$

where P_t is thermal power of the nuclear station, Mw, and U is number of units (reactors) in the station.

In reporting the costs of nuclear power, all-risk property damage insurance is included together with nuclear liability insurance (see example in Sect. 4A.1.7, No. 5). This is to place the computed power costs on the same basis as literature data.

4A.1.5 Annual Fixed Charges Against Investment

The production of electricity and water from nuclear energy are capital-intensive processes, and consequently the total costs of production are sensitive to the method used to convert investment into annual charges. In this study the total depreciating investment in power stations was considered to consist of the erected cost of the power plant equipment and facilities (not including the nuclear fuel, which is carried as a separate item) plus interest charges during construction (see Appendix 3A for discussion). Nondepreciating investment comprised the cost of nuclear fuel and operating working capital.

The customary present practice among power-producing utility organizations in the United States is to employ an annual fixed charge rate on total investment which includes allowances for (1) return on investment, or cost of borrowed money, (2) amortization or recovery of investment over the life of the plant, (3) taxes on net income, (4) local property taxes, (5) other taxes, (6) insurance, and (7) interim replacements. Specific practice varies, and differences exist, especially between taxpaying (private) utilities and those which are not subject to full taxation (public). Discussions with representatives of both types of utilities revealed that there was general agreement on average values for annual fixed charges. In the present and near term, average annual fixed charge rates of 12% for private and 8% for public power producers were suggested; for the far term, values of 11 and 7%, respectively, were suggested to reflect possible reductions in interest rates. The interest rate included in these fixed charge rates was stated to be $5\frac{1}{2}$% in the present and near term and $4\frac{1}{2}$%/year in the far term for both types of utilities.

These annual fixed charge rates are used in estimating the cost of steam and electricity from nuclear power stations under conditions now prevalent in the United States. However, since the cost of money, level and type of taxes, and attitudes toward insurance vary widely around the world, the rationalization of power and water costs used in this study took a more generalized approach to fixed charge rates. As explained in Sect. 3.1 of Chap. 3, the term "fixed charge rate" as used in this study includes allowance for the cost of money (return on investment) and for amortization using a sinking fund method of calculation. The cost of money, i, was varied parametrically at values of 2.5, 5, 10, and 20%.

In the calculation of interest charges during construction and amortization of nuclear power stations, the time of construction and startup was assumed to be 4 years in the United States and 5 years in developing countries; a service life of 30 years was assumed for both cases.

4A.1.6 Nuclear Fuel Cycle Costs

Fuel cycle costs depend upon a number of physics and engineering design factors. Since this study was not concerned with any one particular reactor design, size, or specific method of fuel management, a generalized approach to the estimation of fuel cycle costs was employed. In common with other comparative studies (refs. 5, 9, and 17, Chap. 4), fuel cycle costs are based on operating conditions in the reactor system after steady state is achieved (this is sometimes referred to as the equilibrium fuel cycle). Thus, fuel exposure, enrichments, inventories, and throughput rates are all based on a single set of conditions. The bases employed in this study for estimating fuel cycle costs for light-water reactors were consistent with those of the previously referenced studies, and the method generally utilizes the ground rules which have been employed in evaluating desalination reactor systems (ref. 18, Chap. 4); the bases used are given in Table 4A.2. Fuel inventories were based on the uranium and plutonium contained in the reactor system (in core and out of core) at steady state. Other initial or inventory costs are provided for by an allowance for working capital. The investments in uranium, plutonium, and working capital are treated as nondepreciating items. Costs of fuel preparation, fabrication, burnup reprocessing, and processing losses are treated as annual operating costs.

A breakdown of fuel cycle costs based on the information in Table 4A.2 is given in Table 4A.3 for light-water reactors of 1550, 3100, and 10,000 Mw(thermal) capacities for near-term (late 1970's) conditions and for an LWR of 10,000 Mw under far-term (late 1980's) conditions. For the example values presented here, a cost of money equal to 10%/year was used in calculating interest charges on fuel inventory and working capital. Nuclear fuel costs are seen to decrease with increasing reactor size as a result of decreased neutron leakage and hence better neutron economy in the reactor core. The general relationships used to compute the direct fuel cycle costs as a function of reactor size, excluding plutonium credit, are summarized below:

Near Term	
Up to 2500 Mw(thermal)	0.493 mills/kwhr(thermal)
From 2500 to 4600 Mw(thermal)	0.464 mills/kwhr(thermal)
Above 4600 Mw(thermal)	0.435 mills/kwhr(thermal)
Far Term	
Above 3300 Mw(thermal)	0.389 mills/kwhr(thermal)

Table 4A.2. Fuel Cycle Costs – Light-Water Reactor

	Near Term			Far Term, 10,000 Mw (Thermal)
	1550 Mw (Thermal)	3100 Mw (Thermal)	10,000 Mw (Thermal)	
Uranium				
Natural uranium, dollars per pound of U_3O_8	8.00	8.00	8.00	8.00
Separative work, dollars/kg (use AEC price list for enriched UF_6; includes $U_3O_8 \rightarrow UF_6$)	30.00	30.00	30.00	30.00
Fuel exposure,[a] *E*, Mwd/metric ton	33,000	33,000	33,000	33,000
Uranium burnup,[b] wt %	3.7	3.7	3.7	3.7
Feed enrichment, % ^{235}U	3.95[c]	3.30[d]	3.09[c]	3.09[c]
Spent fuel[a]				
Percent ^{235}U	0.89[c]	0.89[d]	0.89[c]	0.89[c]
Grams of Pu fissile per kilogram	6.15[c]	6.15[d]	6.15[c]	6.15[c]
^{236}U penalty	0	0	0	0
Feed fuel value, dollars per kilogram of U	308.42	287.50	264.79	264.79
Spent fuel value, dollars per kilogram of U	38.06	38.06	38.06	38.06
Fuel preparation and fabrication				
Plant throughput,[e] metric tons/day	←	1	→	3
Losses,[e] %		0.2		0.2
Days/year[f,g]		260		260
Plant investment,[f,g] millions of dollars		27.7		61.0
Operating costs,[f,g] millions of dollars per year		7.4		13.6
Hardware,[f,g] millions of dollars per year		7.0		18.0
Dollars per kilogram of U[(h)] at 22% per year		80		58
Reprocessing				
Plant throughput, metric tons/day	←	2[e]	→	5[i]
Losses,[e] %		1		1
Days/year[g]		260		260
Capital cost,[g] millions of dollars		37		50
Operating cost,[g] millions of dollars per year		3.7		5.0
Waste disposal,[g] millions of dollars per year		3.0		3.0
Dollars per kilogram of U[(h)] at 22% per year		28.60		14.60
Conversion to UF_6,[j] dollars per kilogram of U		3.00		2.25
Shipping costs[a,e,k]				
Feed fuel, dollars per kilogram of U	←	1.49	→	1.49
Spent fuel, dollars per kilogram of U		3.39		3.39
Total, dollars per kilogram of U		4.88		4.88

Table 4A.2. Fuel Cycle Costs – Light-Water Reactor (Cont.)

	Near Term			Far Term,
	1550 Mw (Thermal)	3100 Mw (Thermal)	10,000 Mw (Thermal)	10,000 Mw (Thermal)
Pu credit as nitrate				
5/6 value of 90% ^{235}U	←	10.00	→	10.00
Inventory times				
Pre exposure, total, days	←	113	→	113
Pre exposure, at reactor, days		60		60
Post exposure, days		220		220
Specific power,[j] S.P., kw/kg		37		46
Fuel exposure, Mwd/metric ton		33,000		33,000
Reactor load factor, L.F.		0.9		0.9
Reactor inventory time, days[l]		990		796
Thermal efficiency, %	←	32.3	→	32.3

[a] Reference 17, chap. 4.

[b] Calculated at 9000 Mwd/metric ton = 1% burnup to fission products.

[c] Estimated from ORNL-3686 with Systems Analysis values as starting point; enrichment and plutonium content numbers used only in estimating inventory charges.

[d] R. Salmon, personal communication, AEC Systems Analysis Evaluation, for 1000-Mw(electrical) PWR.

[e] 1975 and 1985 ground rules, ref. 18, chap. 4.

[f] ORNL-CF-64-8-51 (fabrication).

[g] ORNL-3921 (preparation and processing).

[h] Assumes fabrication, preparation and reprocessing are conducted off site; fixed charge rate of 22% used to yield the "price" (see *a* and *g*).

[i] 1985 generating capacity is assumed to be 200,000 Mw(electrical);

$$\frac{200{,}000\ \text{Mw(electrical)}}{(0.323)\ (4\ \text{plants})\ (33{,}000\ \text{Mwd/metric ton})} = 4.7\ \text{tons/day} = 5\ \text{tons/day}.$$

[j] PWR reactor conditions from ref. 9, chap. 4.

[k] 1000 miles round trip by rail – see footnotes *a* and *e*.

[l] Reactor inventory time $= \dfrac{\text{Mwd/metric ton}}{(\text{kw/kg})\ (\text{load factor})}$.

The general relationships used to compute the value in dollars of the fuel inventory are as follows:

Near Term

Up to 2500 Mw(thermal)	$7057P_t$
From 2500 to 4600 Mw(thermal)	$6710P_t$
Above 4600 Mw(thermal)	$6333P_t$

Far Term

Above 3300 Mw(thermal)	$5368P_t$

Here P_t is the reactor thermal power level in megawatts.

4A.1.7 Example Calculation of Electricity Cost for an LWR

The cost of electricity for a nuclear reactor is made up of three items: (1) charges associated with the capital investment (including interest during construction), (2) fuel cycle costs (including nondepreciating capital charges on fuel in-

Table 4A.3. Estimated Fuel Cycle Costs for Light-Water Reactors

	Near Term			Far Term, 10,000 Mw (Thermal)
	1550 Mw (Thermal)	3100 Mw (Thermal)	10,000 Mw (Thermal)	
	Mills per Kilowatt-hour (electrical)			
Uranium burnup and losses	1.07	0.98	0.89	0.89
Plutonium credit[a]	−0.24	−0.24	−0.24	−0.24
Net burnup cost	0.83	0.74	0.65	0.65
Fabrication	0.31	0.31	0.31	0.23
Shipping	0.02	0.02	0.02	0.02
Reprocessing and conversion to UF_6	0.12	0.12	0.12	0.07
Direct costs	1.28	1.19	1.10	0.97
Inventory and working capital charges at 10%/year	0.30	0.29	0.27	0.20[b]
	1.58[c]	1.48[d]	1.37[e]	1.17[f]

[a] Based on 0.0769 mill/kwhr(thermal) ($10.00 per gram of Pu).

[b] At 9%/year.

[c] To 800 Mw(electrical) [2500 Mw(thermal)] = 1.29 + 2.98i mills/kwhr(electrical).

[d] 800 to 1500 Mw(electrical) [2500 to 4600 Mw(thermal)] = 1.20 + 2.86i mills/kwhr(electrical).

[e] 1500 to 3660 Mw(electrical) [4600 to 10,000 Mw(thermal)] = 1.11 + 2.70i mills/kwhr(electrical).

[f] >1500 Mw(electrical) [3300 to 10,000 Mw(thermal)] = 0.97 + 2.28i mills/kwhr(electrical).

ventory), and (3) operation, maintenance, and insurance (nuclear liability and property damage insurance) costs.

Example. – Assumptions: (1) 9000 Mw(thermal) reactor station, (2) light-water reactor, near-term technology, (3) two reactors, (4) 5% cost of money, (5) 0.80 load factor (7000 hr/year), (6) 4-year construction period, 30-year plant life.

1. Calculate nuclear island capital cost from Fig. 4A.1; for 9000 Mw(thermal), two reactors, capital cost equals $14.25/kw(thermal); therefore

$$\text{N.I.} = 9 \times 10^6 \text{ kw(thermal)} \times \$14.25/\text{kw(thermal)} = \$128.2 \times 10^6 \ .$$

2. Calculate turbogenerator-condenser island capital cost from Fig. 4A.2. Gross output of electricity is calculated using Eq. (13) and Table 7A.1 of Appendix 7A:

$$\begin{aligned} P_c &= \eta_c Q_c \\ &= 0.3425 \text{ Mw(electrical)/Mw(thermal)} \times 9000 \text{ Mw(thermal)} \\ &= 3082 \text{ Mw(electrical)}. \end{aligned}$$

From Fig. 4A.2, capital cost of turbogenerator-condenser island; for 3082 Mw(electrical) (gross), cost is $45.75 + $6.20 = $51.95/kw(electrical); therefore

$$\text{TCI} = 3.082 \times 10^6 \text{ kw(electrical)} \times \$51.95/\text{kw(electrical)} = \$160.1 \times 10^6 \ .$$

3. Calculate total installed cost of nuclear power plant. Interest during construction factor for four-year construction period and 5% cost of money is 1.0768 (Table 3A.2, Appendix 3A). From steps 1 and 2,

$$\text{total cost} = 1.0768(\$128.2 \times 10^6 + \$160.1 \times 10^6) = \$310.4 \times 10^6 \ .$$

The unit cost in dollars per kilowatt (electrical) is based on the net electrical output of the station after auxiliary power required to run the turbine and reactor are deducted; from Table 7A.1, Appendix 7A,

$$\begin{aligned} \text{net efficiency} &= 0.3425 \text{ Mw(electrical)/Mw(thermal)} \\ &\quad - 0.00864 \text{ Mw(electrical)/Mw(thermal)} \\ &\quad \underline{- 0.0078 \text{ Mw(electrical)/Mw(thermal)},} \\ \text{net power} &= 0.326 \text{ Mw(electrical)/Mw(thermal)} \\ &\qquad \times 9000 \text{ Mw(thermal)} \\ &= 2934 \text{ Mw(electrical)} ; \end{aligned}$$

therefore

$$\begin{aligned} \text{unit cost} &= \$310.4 \times 10^6/2934 \times 10^3 \text{ kw(electrical)} \\ &= \$106/\text{kw(electrical)} . \end{aligned}$$

The capital charge rate for a cost of money of 5% is 6.5%,[1] including the sinking fund deposit factor of 1.5%.[2] Thus the unit electricity cost due to capital investment is

$$\begin{aligned} C_I &= \$310.4 \times 10^6 \times 0.065/(2934 \times 10^3 \text{ kw(electrical)} \\ &\qquad \times 7000 \text{ hr/year}) \\ &= 0.98 \text{ mill/kwhr(electrical)} . \end{aligned}$$

4. Fuel cycle costs from Table 4A.3, footnote *b*, at 5% cost of money:

$$\begin{aligned} \text{F.C.} &= 1.11 + 2.70 \times 0.05 \\ &= 1.25 \text{ mills/kwhr(electrical)} . \end{aligned}$$

5. Operation, maintenance, and insurance costs:

Operation and maintenance for nuclear island from Fig. 4A.3	$\$1.7 \times 10^6$
Operation and maintenance for TGC island from Fig. 4A.4	$\$0.92 \times 10^6$
Liability insurance from Sect. 4A.1.4	$\$0.79 \times 10^6$
Property damage insurance	
0.25% of depreciating capital investment	$\$0.78 \times 10^6$
0.4% of nondepreciating investment (fuel inventory)[3]	$\$0.23 \times 10^6$
Total	$\$4.4 \times 10^6$

Unit cost = $\$4.4 \times 10^6/(2934 \times 10^3$ kw(electrical) × 7000 hr/year) = 0.22 mill/kwhr(electrical).

6. The total unit cost of electricity from this 9000 Mw(thermal) two-LWR station under the given assumptions is the sum of the unit costs in items 3, 4, and 5:

Capital charges	0.98
Fuel cycle	1.25
Operation, maintenance, and insurance	0.22
Total	2.45 mills/kwhr(electrical)

4A.2 Estimated Cost of Power from Fast Breeder Reactors (FBR)

Capital cost data, shown in Table 4A.4, for the 10,000 Mw(thermal) FBR are from ORNL's evaluation (ref. 5, Chap. 4) of a conceptual design (ref. 19, Chap. 4) prepared by the Argonne National Laboratory. The reactor produces prime steam at 2400 psia and 900°F with live steam reheat to 660°F. Pertinent characteristics of this reactor are shown in Table 4A.5. It should be noted that the ANL design is not considered a "first generation" fast breeder; it is probably representative of advanced, fully developed fast reactors which could be available for construction in the 1980–85 period.

4A.2.1 Capital Costs

All other capital cost data were obtained by extrapolating the individual cost accounts for the 10,000 Mw(thermal) reactor to lower power ratings. These extrapolations were made by using extrapolation data on other reactor concepts (BWR, HTGR, and HWOCR) as guides, but it was necessary to make intuitive judgments on the degree of applicability of the data from other concepts. In short, the cost trend with size given in Fig. 4A.5 is speculative. These costs include indirect construction cost factors (24 to 28% of direct plant cost) and allow for general and administrative, miscellaneous construction, architect-engineer fees, nuclear engineer fees, startup, and contingency. They do not include escalation and interest during construction. The breakdown of capital cost into three equipment groups (nuclear island, turbine plant, and condenser package) is somewhat arbitrary because there are no clear-cut interfaces

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[1] Generally, the capital charge rate also includes allowances for taxes and interim replacements; however, these are excluded in this example.

[2] Chapter 3, Sect. 3.3, Eq. (1).

[3] Fuel inventory = 6333 × 9000 = $\$57 \times 10^6$ (from Sect. 4A.1.6).

Table 4A.4. Capital Cost Summary for 10,000 Mw(Thermal) [3880 Mw(Electrical)] LMFBR

Cost Account	Cost (millions of dollars) Nuclear Island	Turbine-Generator Plant Without Condenser	Condenser Package	Power Plant
Direct Cost				
Structures	20.80	5.50	1.60	27.90
Reactor	112.85	16.35		129.20
Turbine generator		84.25	14.40	98.65
Accessory electric	6.00	5.40	0.20	11.60
Miscellaneous power plant equipment	1.00	1.00		2.00
Total direct cost	140.65	112.50	16.20	269.35
Indirect cost excluding interest during construction	34.06	27.25	3.92	65.23
Total construction cost excluding interest during construction and land	174.71	139.75	20.12	334.58

among these groups. Nevertheless, there is no way to avoid this arbitrariness in the "building block" approach to evaluating a desalting complex.

4A.2.2 Operation and Maintenance

It will be several years before operation and maintenance costs are known for large light-water reactors. Estimates of operation and maintenance costs for large fast breeder reactors are estimated to be 85% of operation and maintenance estimates for light-water reactors and are little more than guesses. It is not essential, however, that the operation and maintenance cost be known precisely, since this component is not usually a major contributor to the total cost of energy from large reactors.

4A.2.3 Fuel Cycle

Fuel cycle costs are based on the equilibrium fuel cycle described in ref. 19, Chap. 4, and the cost data developed at ORNL and summarized in Table 4A.6. The main assumptions required to compute the fuel cycle costs are:

Total annual quantity of U + Pu required	93.2 metric tons
Annual quantity of U + Pu required for core and axial blanket	42.6 metric tons
Annual quantity of U required for radial blanket	50.6 metric tons
Reactor loading of Pu_f	10.5 metric tons
Value of Pu	\$10.00 per gram
Cost of U_3O_8	\$8.00 per pound
Pu credit	0.172 mill/kwhr (thermal)
Fraction of fuel inventory not in core (based on a fuel hold-up period of 182.5 days)	0.45

4A.3 Estimated Power Cost from Molten-Salt Breeder Reactors (MSBR)

4A.3.1 Capital Costs

The capital cost estimates, given in Table 4A.7, for a 1000 Mw(electrical) MSBR are based on the current ORNL reference design for a fully de-

Table 4A.5. Characteristics of 10,000 Mw(Thermal) LMFBR

Coolant	Sodium
Core geometry	Annular
Fuel material	
Core and axial blanket	(U + Pu)C
Radial blanket	U–10 wt % Zr
Cladding material	304 SS
Core dimensions	
Active height, ft	3.6
Inside diameter, ft	20
Outside diameter, ft	25
Core volume, ft^3	600
Core inlet pressure, psia	120
Core inlet temperature, °F	720
Core outlet temperature, °F	1050
Fissile loading, metric tons	10.5
Fertile loading, metric tons	246
Breeding ratio	1.4
Doubling time, years	7
Average core burnup, Mwd/Metric ton	110,000
Life of fuel in core, years	2
Refuelings per year	2
Reactor vessel	
Material	304 SS
Inside diameter, ft	40
Inside height, ft	64
Cooling system	
Number of loops	6
Steam pressure, psia	2400
Steam temperature, °F	900

veloped reactor. This design is the same in concept, but not in detail, as the reference plant presented in ref. 21, Chap. 4. One of the more significant changes is the present four-module arrangement as opposed to the previous single-module plant. This change was based on reliability considerations. Pertinent design characteristics are summarized in Table 4A.8.

The reference design, designated MSBR (Pa), is a two-region, two-fluid system with fuel salt separated from the blanket salt by graphite tubes. The fuel salt consists of uranium fluoride dissolved in a carrier salt of lithium and beryllium fluorides, and the blanket salt contains thorium fluoride dissolved in a similar carrier salt. The energy generated in the reactor fluid is transferred to a secondary coolant-salt circuit, which couples the reactor to a supercritical steam cycle.

Reactor capital cost data for the 4500 Mw(electrical) unit also shown in Table 4A.7 were obtained by extrapolating the individual cost accounts of the reference design. The rationale for this is based on the observation that each module in the present reference design is one-fourth the size of the module in the earlier design; thus a comparison of the costs gives an indication of the cost-scaling characteristics of the cost accounts for structures and reactor. In the present study, a four-module arrangement was assumed for all reactor ratings. Although the cost estimates for very large MSBR's are speculative, they are the best that can be obtained without a design. Capital costs, based on the data in Table 4A.7 and including indirect costs as used for the FBR case above, are shown as a function of station size in Fig. 4A.5.

4A.3.2 Operation and Maintenance

Operation and maintenance costs were taken the same as for the FBR case.

If the MSBR development and demonstration program progresses as planned, construction could be started on a commercial 1000 Mw(electrical) MSBR in the period 1975 to 1980. Construction on a larger version could begin in the period 1980 to 1985.

4A.3.3 Fuel Cycle Costs

The fuel cycle cost variation with reactor rating is directly related to the decrease in unit capital and operating costs as the on-site fuel-recycle processing plant becomes larger. In fuel processing, fluoride-volatility and vacuum-distillation operations are used for the fuel fluid, and direct-protactinium-removal processing is applied to the blanket stream. Detailed information on processing is given in ref. 21, Chap. 4, and in ref. 4. The fuel cycle cost is made up of the following five components:

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[4] W. L. Carter and M. E. Whatley, *Fuel and Blanket Processing Development for Molten Salt Breeder Reactors*, ORNL-TM-1852 (June 1967).

1. processing plant fixed cost,
2. processing plant operating cost,
3. material inventory cost,
4. material replacement cost,
5. fissile production credit.

The basic data required to calculate each of the above components are shown in Table 4A.9 for two reactor ratings. Based on these data, Fig. 4A.6 was prepared to show the effect of interest rate and reactor size on the fuel cycle cost.

4A.4 Evaporator Technology and Capital Costs

This section of the appendix contains a brief discussion of the evaporator technologies and the major cost factors used in this study.

4A.4.1 Performance Ratio

The performance ratio (PR) is defined as the number of pounds of desalted water produced per 1000 Btu of input heat. The PR may be increased

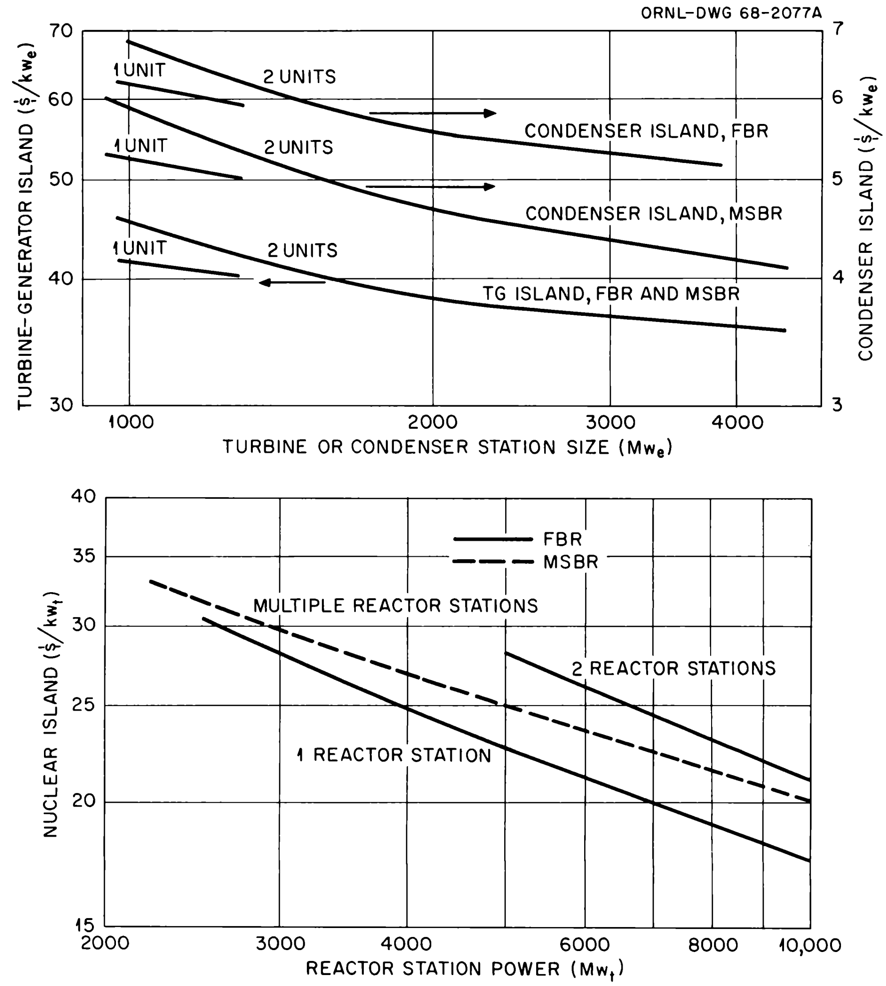

Fig. 4A.5. Installed Costs of Nuclear, Turbine-Generator, and Condenser Islands for Advanced Breeder Reactor Power Stations.

Table 4A.6. Estimated Fuel Cycle Costs for 10,000 Mw(Thermal) FBR[a]

Fuel Preparation. Core, Axial Blanket, and Radial Blanket

Plant throughput, metric tons/day	2.70
Losses, %	0.2
Operating days per year	260
Plant investment, millions of dollars	14.8
Operating cost, millions of dollars per year	3.1
Dollars per kilogram of U + Pu at fixed charge rate = 22%/year	9.0

Fuel Fabrication. Plant Size for 50,000 Mw(Thermal)

	Core plus Axial Blanket	Radial Blanket
Plant throughput, metric tons/day	0.82	0.96
Operating days per year	260	260
Plant investment, millions of dollars	22.9	10.1
Operating costs, millions of dollars per year	5.1	3.2
Hardware, millions of dollars per year	8.5	3.4
Dollars per kilogram of U + Pu at fixed charge rate = 22%/year	88	35

Reprocessing. Dual-Purpose Plant[b]

Plant design capacity, metric tons/day	10[c]
Losses, %	1
Operating days per year	260
Plant investment, millions of dollars	70.4
Operating cost, millions of dollars per year	7.0
Waste disposal, millions of dollars per year	6.5
Daily processing charge, dollars per day	112,000
Throughput on LMFBR fuel, metric ton/day	6
Days per year on LMFBR fuel	116
Total annual cost for LMFBR fuel, millions of dollars	13.0
Dollars per kilogram of U + Pu for LMFBR fuel[d]	18.6

Shipping Costs

	Core plus Axial Blanket	Radial Blanket
Feed fuel, dollars per kilogram of U + Pu	2.0	0.60
Spent fuel, dollars per kilogram of U + Pu[e]	16.0	2.40
Total, dollars per kilogram of U + Pu	18.0	3.00

[a] Fuel cycle costs are based on the 1985 desalination ground rules, ref. 18, chap. 4.

[b] Plant processing both LWR and FBR Fuel.

[c] On light-water reactor fuel.

[d] For core, axial blanket, and radial blanket processed together.

[e] Fuel assemblies shipped in fully assembled condition.

Table 4A.7. Capital Cost Summary for 2225 Mw(Thermal) [1000 Mw(Electrical)] and 10,000 Mw(Thermal) [4500 Mw(Electrical)] MSBR

Cost Account	Cost (millions of dollars) for 1000 Mw(Electrical) Plant				Cost (millions of dollars) for 4500 Mw(Electrical) Plant			
	Nuclear Island	Turbine-Generator Plant Without Condenser	Condenser Package	Power Plant	Nuclear Island	Turbine-Generator Plant Without Condenser	Condenser Package	Power Plant
Direct costs								
Structures	7.20	2.80	0.80	10.80	14.10	6.70	1.90	22.70
Reactor	47.10	6.80	0	53.90	141.10	24.0	0	165.10
Turbine generator	0	20.00	3.20	23.20	0	90.00	12.70	102.70
Accessory electric	2.20	2.20	0.10	4.50	6.00	5.40	0.20	11.60
Miscellaneous power plant equipment	0.50	0.50	0	1.00	1.00	1.00	0	2.00
Total direct cost	57.00	32.30	4.10	93.40	162.20	127.10	14.80	304.10
Indirect costs, excluding interest during construction	16.36	9.27	1.18	26.81	38.93	30.50	3.55	72.98
Total construction cost excluding interest during construction and land	73.36	41.57	5.28	120.21	201.13	157.60	18.35	377.08

by adding more heat transfer surface in either the MSF or VTE concept. The installed capital cost of the evaporator increases with an increase in PR, as shown in Fig. 4A.7, where the costs are given for both evaporator types and for several plant sizes. Over the current range of interest, it has been shown that the optimum PR is relatively insensitive to variations in the design parameters considered for this application, and, as is indicated in Sect. 4.5 of Chap. 4, a PR value of 12 was used as the reference value.

4A.4.2 Maximum Brine Temperature and Chemical Pretreatment of Seawater

If untreated seawater is heated to a temperature above about 170°F, some of the salts will precipitate and form a scale on the heat transfer surface and thereby reduce the heat transfer effectiveness. The conventional treatment method of sulfuric acid addition and deaeration (removal of CO_2) allows this temperature to be increased to 250 or 260°F. This treatment has been adopted for the reference design, but an alternative method using caustic and/or hydrochloric acid (from electrolysis of brine), as discussed in Appendix 5A, is considered in some of the complexes. The main advantages of this method are the elimination of a dependence on sulfur ($\sim 10^5$ tons/year for a 1000-Mgd evaporator plant) and an economic attractiveness of integration in the industrial complex.

The incoming seawater is also treated for algae control by chlorine addition, and a defoaming agent is also added. Costs associated with these processes are included in the overall costs for the plant.

Allowances have also been made for product water treatment to reduce subsequent system cor-

Table 4A.8. Characteristics of a 1000 Mw(Electrical) [2225 Mw(Thermal)] MSBR

Plant arrangement	Four modules
Reactor vessel (one of four)	
Outside diameter, ft	~11
Overall height, ft	~12
Material	Hastelloy N
Core (one of four)	
Active height, ft	8.0
Diameter, ft	6.3
Volume, ft^3	253
Average power density, kw/liter	80
Fuel salt	
Nominal composition, mole %	
LiF	63.6
BeF_2	36.2
UF_4 (fissile)	0.22
Inlet temperature, °F	1000
Outlet temperature, °F	1300
Blanket salt	
Composition, mole %	
LiF	71.0
BeF_2	2.0
ThF_4	27.0
Inlet temperature, °F	1150
Outlet temperature, °F	1250
System inventory, kg	
Fissile	712.0
Fertile	126,000
Net breeding ratio	1.062
Doubling time for system of reactors, years	10.2
Steam temperature, °F	1000
Steam pressure, psia	3600
Net electrical efficiency, %	45.0

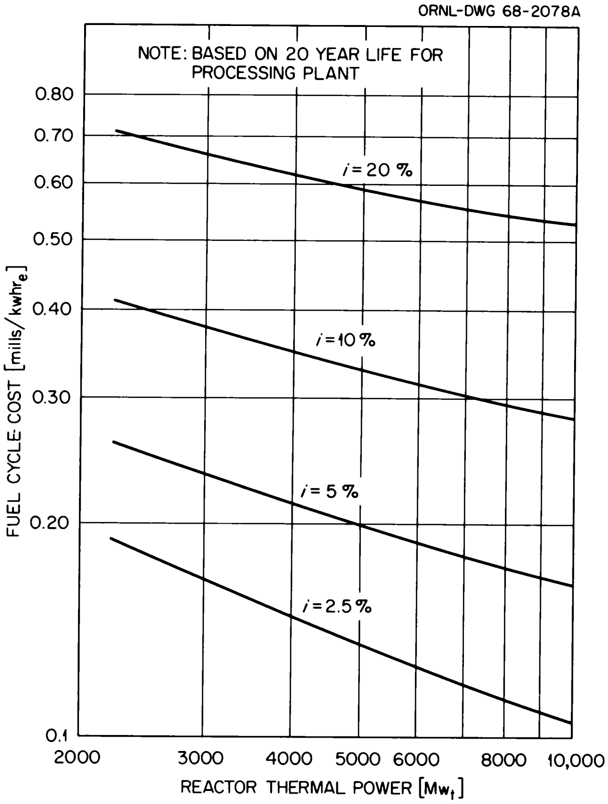

Fig. 4A.6. Fuel Cycle Costs for Molten-Salt Breeder Reactors with Associated Fuel Processing Plants.

rosion; however, this is an area for further study and ultimately may not be required for the water used in agriculture.

4A.4.3 Concentration Ratio

The evaporator concentration ratio (CR) is defined as the ratio of the solids concentration in the brine blowdown to that in the incoming seawater. From past studies the optimum value of CR was shown to be between 2 and 3. The values adopted in this study were 2.0 for the MSF design and 2.5 for the VTE.

If a solar salt farm is included as part of the complex, there is some advantage in using a higher concentration ratio, since this decreases the land area requirements of the salt works.

4A.4.4 Seawater Temperature

The seawater temperature influences to a small degree the cost and/or the output of an evaporator. Since this temperature will vary seasonally over the period of a year, the output of a given evaporator will change. A temperature rise from 60°F to 80°F would cause less than a 3% decrease in the

Table 4A.9. Summary of Fuel Cycle Data for an MSBR

	1000 Mw(Electrical) [2225 Mw(Thermal)]	4000 Mw(Electrical) [8900 Mw(Thermal)]
Plant factor	0.9	0.9
Material inventory, kg		
Fissile		
^{233}U	712.0	2848.0
^{235}U	68.4	273.6
^{233}Pa	100.4	401.6
Fertile: ^{232}Th	126,000	504,000
Carrier: Li-Be-F	123,600	494,400
Material inventory values, millions of dollars		
Fissile		
^{233}U[a]	9.968	39.872
^{235}U	0.834	3.335
^{233}Pa	1.406	5.622
Fertile: ^{232}Th	1.559	6.234
Carrier: Li-Be-F	3.210	12.840
Total material value	16.98	67.94
Fissile production rate, kg/year		
^{233}U	41.128	164.510
^{235}U	3.968	15.872
Credit for fissile production, millions of dollars per year		
^{233}U	0.5683	2.2730
^{235}U	0.0478	0.1912
Total credit	0.6161	2.4642
Material replacement rates, kg/year		
Fertile	3258.7	13034.8
Carrier	20892.6	83570.4
Material replacement costs, millions of dollars per year		
Fertile	0.0403	0.1612
Carrier	0.5426	2.1704
Total replacement costs	0.5829	2.3316
Annual operating cost for processing plant, millions of dollars per year	0.6113	1.187
Capital cost of processing plant, millions of dollars	7.960	11.390

[a] ^{233}U valued at $14.00 per gram, including a penalty for ^{236}U. This is consistent with the desalting ground rules, which specify a value of $17.59 per gram for pure ^{233}U.

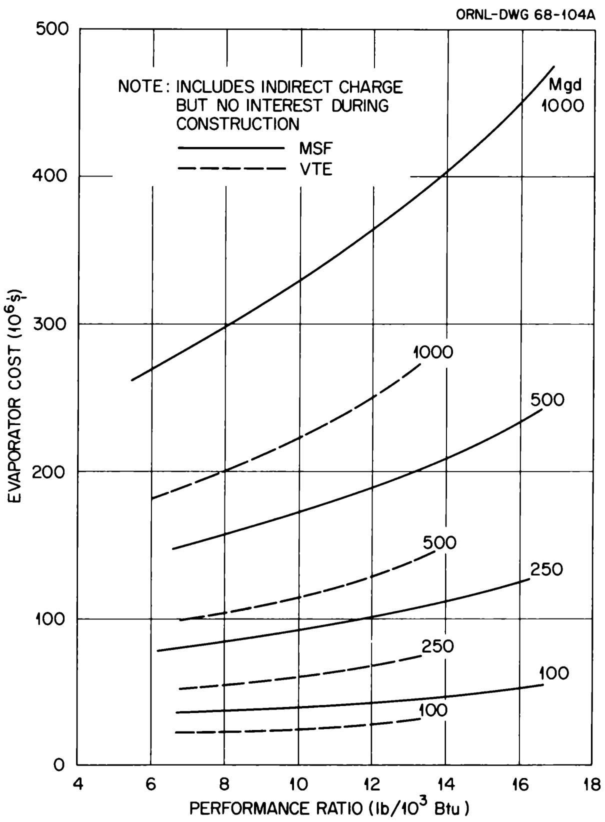

Fig. 4A.7. Capital Costs for Evaporator.

plant output.[5] This change of 20°F due to seasonal temperature variations would be typical of the plant locations considered in this study and would mean that the evaporator capability would be somewhat less in summer than in winter.

The reference design value for the mean seawater temperature was taken as 65°F, and the brine blowdown was 92°F. Increasing the mean seawater temperature by 10°F would increase the investment cost by about 7%. Since data on the mean seawater temperatures were not obtained for the applications considered in this study, the effect of this parameter on evaporator cost was not included.

4A.4.5 Train Size

It is desirable to divide large evaporators into parallel operating evaporator units, or trains, so that portions of the plant can be shut down for maintenance or emergency repairs without completely stopping water production. In the absence of a detailed analysis, it was decided to assume train sizes of 50 to 250 Mgd and two to five trains per plant, depending on plant size.

4A.4.6 Major Cost Factors

The evaporator designs and costs were based primarily on the ORNL design and the associated optimization computer code (ref. 27, Chap. 4). The cost of the heat exchange tubing is the major single cost item of an evaporator plant, comprising 45% of the MSF cost and about 40% for the VTE. The evaporator shell is the next largest contributor to the total cost, being about 18%. Auxiliary facilities, including seawater intake, chemical treatment, and deaerator, would account for approximately 15% of the direct costs of the entire evaporator plant. Pumps, piping, and valves also nominally make up about 15% of the evaporator capital cost in both designs. The total cost for a given size plant, however, is significantly less for the VTE design.

The installed tubing cost using 90/10 (Cu/Ni) alloy was taken as $2.60 per square foot for the MSF plant and for the MSF preheater in the vertical-tube plant. The tubing (doubly fluted) cost for the VTE using Olin 194 alloy (91.3% Cu, 8.0% Fe, 0.8% P) was taken as $3.00 per square foot (10 ft long). The 90/10 tubes were assumed to have a 30-year lifetime, whereas the Olin 194 tubes were assumed to require replacement after 15 years of service.

Operation and maintenance costs include labor for the normal operation of the plant plus labor for both routine and emergency maintenance and repair. Maintenance materials are also part of this cost. The maintenance costs in a dual-purpose plant (power/water) as considered in this study are less than for separate power and water plants since personnel, both laborers and supervisors, can be shared. The increment in operation and maintenance costs for inclusion of an evaporator in a dual-purpose plant was assumed to vary (to the 0.7 power) with the cost of the evaporator. The annual operation and maintenance cost (excluding chemical treatment costs) for a $250 million evaporator was taken as $2.7 million. This method was chosen in order to be consistent with the

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[5] H. R. Payne, R. A. Ebel, and R. B. Winsbro, *An Investigation of Dual-Purpose Power and Water Plants for Israel*, ORNL-CF-68-1-19 (Jan. 19, 1968).

Office of Saline Water and ORNL recommendations.

The indirect charge factor of 1.124 used in this study is made up of the following factors: 1.01 for temporary structures, 1.03 for design and supervision, and 1.08 for contingencies. The indirect charge factor is applied to the total direct construction cost. Interest during construction was computed separately as a function of the cost of money and assumes a three-year construction period in the United States and four years overseas. The factors used to allow for interest during construction are discussed in Chap. 3, Sect. 3.4. Also included in Chap. 3 is a discussion of how other charges against capital, such as sinking fund and return on investment, are included.

The capital costs (direct plus indirect costs) for both MSF and VT evaporators based on the above-discussed design and cost assumptions are summarized in Fig. 4A.8 as the cost per gallon per day vs capacity in millions of gallons per day for several performance ratios. It should be emphasized that these data do not include interest during construction, since allowance for this is made later (see Chap. 7).

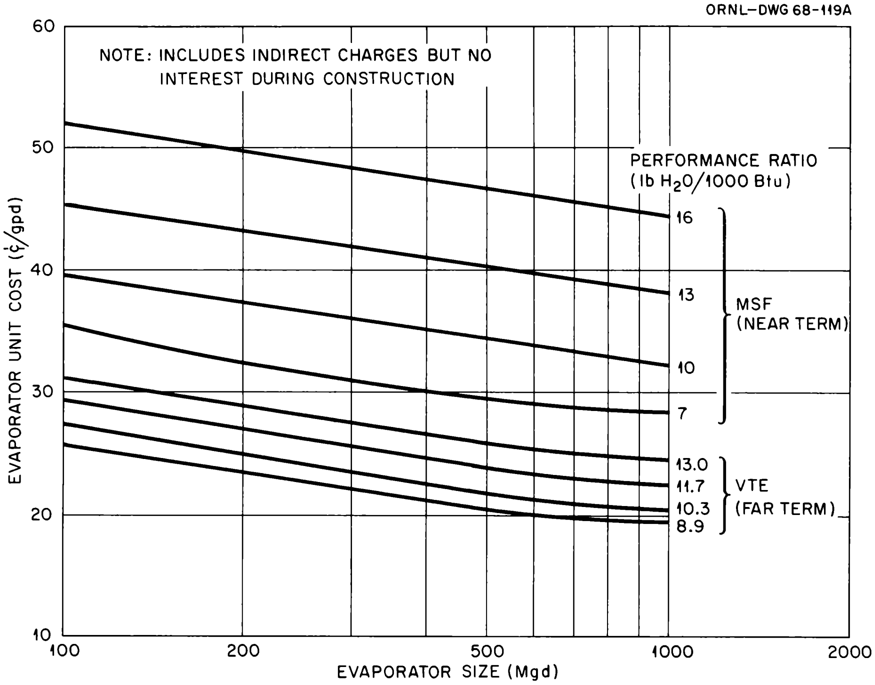


Fig. 4A.8. Unit Costs for Evaporator.

Appendix 5A

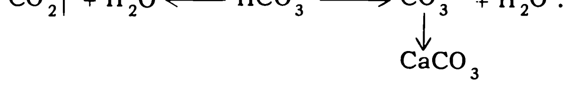
PREEVAPORATION SEAWATER TREATMENT AND PRODUCTION OF CHEMICALS FROM SOLAR SALT BITTERNS

This appendix provides additional data on (1) seawater pretreatment methods designed to prevent scaling of the heat transfer surfaces in the seawater evaporator, (2) the recovery of chemicals from solar salt bitterns, and (3) the electrolytic reduction of anhydrous magnesium chloride to magnesium metal. The first part of the appendix provides further technical background on the information presented in Sect. 5.3.3; the latter part of the appendix gives additional details of the cost analyses and comparisons presented in Sect. 5.5.1.

5A.1 Process Descriptions

Seawater Treatment. – Caustic-chlorine production offers the possibility of using a closed-cycle seawater treatment scheme which employs caustic soda, hydrochloric acid, or any combination thereof. For acid treatment of seawater, the hydrochloric acid is formed by the recombination and aqueous dissolution of the chlorine and hydrogen produced in brine electrolysis. With caustic soda treatment, the spent brine electrolysis cell liquor, containing equimolar amounts of caustic soda and unelectrolyzed salt, is added directly to the seawater.

Seawater treatment prior to freshwater production by evaporation includes (1) the removal of bicarbonate from the seawater to prevent the formation of alkaline scale [$CaCO_3$, $Mg(OH)_2$] at evaporator temperatures of 170 to 180°F and (2) partial to complete removal of calcium to prevent the precipitation of calcium sulfate as anhydrite ($CaSO_4$) at 260°F and above. Acid treatment converts bicarbonate to carbon dioxide gas, whereas caustic treatment yields carbonate ion, which combines with the calcium ion present in seawater to precipitate calcium carbonate. The mechanisms of these reactions are:



$$CO_2\uparrow + H_2O \xleftarrow{H^+} HCO_3^- \xrightarrow{OH^-} \underset{\substack{\downarrow\\ CaCO_3}}{\overset{\substack{Ca^{2+}\\ +}}{CO_3^{2-}}} + H_2O\ .$$

In either case, only one mole-equivalent of reagent is required to convert one equivalent of bicarbonate to either CO_2 or $CaCO_3$. Thus the caustic-chlorine plant size when applied to seawater treatment alone, including sale of by-products, is fixed by the volume of seawater to be treated.

In a nuclear desalination plant that produces 1000 Mgd of fresh water with a brine concentration factor of 2, a caustic-chlorine plant that produces a minimum of 710 tons of Cl_2 per day would be required to treat 2000 Mgd of seawater in cases where either NaOH or HCl, alone, is used for seawater treatment. For the equimolar treatment case, in which one half of the seawater is treated with HCl and the remainder with NaOH, the minimum-size plant would be reduced to 355 tons of Cl_2 per day; in this case all the caustic and chlorine (as HCl) produced would be consumed in seawater treatment.

Bicarbonate removal with hydrochloric acid alone should allow a maximum brine temperature of 272°F. Caustic soda treatment should allow a maximum temperature of 294°F, since 23% of the calcium is removed in addition to all of the bicarbonate. Treatment of one half of the seawater with HCl and the remainder with NaOH (12% calcium removal) should allow a maximum brine temperature of 283°F. These are all projected temperatures based on the equilibrium data of Marshall and Slusher[1] and on the actual brine temperature of 260°F attained in practice after sulfuric acid treatment.[2] Either sulfuric acid or nitric acid could be used as alternatives for acid treatment; HNO_3, like HCl, should allow temperatures as high as 272°F vs 260°F for sulfuric acid.

If an evaporator temperature of over 294°F is desired in order to raise the ratio of water to power produced or to achieve a more economical process

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[1] W. L. Marshall and R. Slusher, "Aqueous Systems at High Temperature. Solubility of Calcium Sulfate and Its Hydrates in Seawater and Saline Water Concentrates and Temperature Concentration Limits," *J. Chem. Eng. Data* 13, 83 (January 1968).

[2] *Saline Water Conversion Report for 1965*, p. 218, U.S. Dept. of Interior, Office of Saline Water, Washington, D.C.

in a dual-purpose plant operating at the back-pressure point and assuming that evaporator materials and high-pressure design problems can be solved, then additional calcium removal is necessary. This can be accomplished by the addition of soda ash (Na_2CO_3) along with caustic soda to precipitate calcium in excess of that equivalent to the HCO_3^- present. The soda ash can be produced by several methods, including (1) treatment of caustic with carbon dioxide obtained, for example, from calcination of $CaCO_3$ previously precipitated by seawater treatment, or (2) the Solvay process, which produces soda ash and ammonium chloride from salt, ammonia, and recycled carbon dioxide. The ammonia can also be totally recycled if the ammonium chloride product is converted to calcium chloride ($CaCl_2$) by reaction with calcium hydroxide. As will be shown later, use of $CaCl_2$ to produce sulfate-free bitterns greatly increases KCl and $MgCl_2$ yields and provides the possibility of producing sulfuric acid and portland cement from the solar salt bitterns.

Caustic-chlorine production in conjunction with seawater treatment can also be adapted to the demand in a particular locale for each product. Seawater treatment with NaOH alone and sale of all the chlorine should be most advantageous in an industrialized nation; the reverse approach would be best in a developing country. Actually, any ratio of Cl_2/NaOH can be produced for sale by appropriate ratioing of the NaOH/Cl_2 to be used for seawater treatment. As noted previously, excess hydrogen from brine electrolysis can be used either for additional ammonia production or the reduction of iron ore.

The seawater treatment system will include, first, a rough screening system to remove seawater life, sand, shells, coral, driftwood, and other debris. When only acid treatment is used, treatment can be achieved in a series of large, open acid-seawater mixers. If CO_2 recovery is desired for urea synthesis or for other uses, closed mixers and CO_2 collection, compression, and storage equipment will be required. With caustic treatment all the treated seawater must go through thickeners to concentrate the $CaCO_3$ precipitate. The treated seawater overflows the thickener and continues on to the evaporator after the addition of small amounts of chlorine and foam inhibitors; the thickened $CaCO_3$ underflow is pumped to a filter where excess seawater is removed and residual seawater washed out with fresh water to avoid corrosion in subsequent equipment. The $CaCO_3$ could then be dried at 150°C to remove the remaining water and finally calcined in a closed calciner at 1000°C to produce burnt lime (CaO) and CO_2, which may be collected, compressed, and stored for possible use in urea synthesis.

Recovery of Chemicals from Solar Salt Bitterns. – The bitterns from the solar salt works can be processed by any one of several schemes to recover Br_2, $CaSO_4$, KCl, K_2SO_4, and $MgCl_2$. Only the two more generally used systems will be discussed here. In either case the recovery of bromine may be done first with the addition of chlorine and steam. Chlorination of the bitterns at 32° Bé oxidizes the bromide ion to free bromine gas, which can then be recovered by steam displacement. About 0.61 ton of chlorine is required per ton of bromine recovered. In the first scheme, bromine recovery is followed by production of sulfate-free bitterns by precipitation of $CaSO_4$ with $CaCl_2$. The $CaSO_4$ can then be used in the production of cement and sulfuric acid. The sulfate-free bitterns are then concentrated further to recover KCl by the precipitation of carnallite ($KCl\cdot MgCl_2\cdot 6H_2O$) at 33 to 36° Bé, by amine flotation to separate the carnallite from the coprecipitated halite (NaCl), and by leaching the carnallite with salt bitterns recycle liquor, which dissolves $MgCl_2$ and leaves KCl as solid crystals. In the second scheme, kainite ($KCl\cdot MgSO_4\cdot 3H_2O$) is precipitated at 33 to 36° Bé from sulfate-containing bitterns, is changed into schoenite ($K_2SO_4\cdot MgSO_4\cdot 6H_2O$) by a solid-state transformation, and is processed by amine flotation and water leaching. The mother liquor in both cases is primarily $MgCl_2$, containing some sulfate in the second case. The $MgCl_2$ liquor from either scheme is then concentrated by additional solar (or possibly steam) evaporation to 40° Bé and then spray dried at 1200 to 1650°F to produce $MgCl_2\cdot H_2O$, which is dehydrated in an electric fusion furnace at 1550 to 1750°F to produce anhydrous $MgCl_2\cdot xMgO$. This compound is then chlorinated to provide anhydrous $MgCl_2$ for use in magnesium metal production, as already explained in Sect. 5.3.2.

If gypsum recovery is desired, scheme 1 is employed. An excess of calcium chloride is added to precipitate all the remaining sulfate from the Br_2-free bitterns as gypsum ($CaSO_4\cdot 2H_2O$). The filtered and dried gypsum can then be reacted with sand, clay, and coke at 2300°F in a kiln or a fluidized bed to produce cement clinker; the sulfur dioxide off-gas can then be converted to concentrated (96%) sulfuric acid by the contact process.

Regarding recoveries of potassium and magnesium, the first scheme, using sulfate-free bitterns, appears to provide greater yields than when sulfate-bearing bitterns are employed. With the first scheme, 83% of the potassium and 47% of the magnesium are recovered; in the alternative scheme, only 62% of the potassium and only 23% of the magnesium are recovered. On the other hand, agriculturalists generally prefer the sulfate form of potassium and will pay a premium for it.

5A.2 Seawater Treatment Cost Analysis

Cost of Seawater Treatment with HCl and NaOH. – Three methods of seawater treatment with HCl and/or NaOH were considered: (1) NaOH treatment of one half of the seawater and the balance with HCl, (2) HCl treatment of all the seawater[3] with a credit for the co-produced NaOH, and (3) NaOH treatment of all the seawater with a credit for the chlorine co-produced. All ratios of HCl/NaOH from zero to infinity are feasible, the optimum ratio being determined by the cost of seawater treatment and by the market demand for caustic and chlorine in a given locale. Cost estimates of these methods were compared with the conventional method of sulfuric acid addition and with alternative methods also in the development stage: namely, CO_2-suppression[4] and the lime–magnesium carbonate (LMC) process.[5]

For this report, one specific case was studied: the treatment of 2000 Mgd of seawater for use in a nuclear desalination plant that produces 1000 Mgd of fresh water at a brine concentration factor of 2. The cost of salt for caustic-chlorine production was assumed to be $2/ton, which includes some allowance for shipping charges. However, when a nuclear desalination plant is located in an arid coastal desert region, salt could be recovered from brine evaporator effluent by solar evaporation; its cost of recovery is about $1/ton (see Sect. 5.5.1, subsection entitled "Solar Salt Manufacturing Costs") when the plant capacity is 6000 tons/day (2 million tons/year) of NaCl.

The results of this study are shown in Figs. 5A.1 to 5A.3. Figures 5A.1*a*–*d* are comparisons of the seawater treatment costs, in cents per thousand gallons of softened seawater, for 2.5, 5, 10, and 20% cost of money, respectively, and for power costs in the range of 1 to 8 mills/kwhr; no by-product credits are assumed in this set of figures, and costs are under United States conditions unless otherwise noted. Until recently, sulfuric acid treatment was most economic, but the steady rise in the price of sulfur has led to the consideration of alternative methods of treating seawater. Taking Fig. 5A.1c (10% cost of money) as an example, it is apparent that the sulfuric acid method was cheapest when sulfur prices were below $30/ton. Now with the world price of sulfur at about $50/ton (prices as high as $63/ton have been quoted), the break-even power cost for equimolar NaOH and HCl treatment of seawater is 5.1 mills/kwhr. Break-even costs for the methods that use HCl, NaOH, or CO_2 suppression are at sulfur costs higher than $50/ton. The LMC method is not competitive with the conventional method of sulfuric acid addition.

Figures 5A.2*a* and 5A.2*b* compare sulfuric acid treatment with the methods that use HCl alone or NaOH alone and show the reduction in the cost of treating seawater by taking caustic credits for the HCl process and chlorine credit for the NaOH process. In a developing country, caustic is the commodity in greater demand; there, seawater treatment with HCl would be the more likely choice. In an industrial nation, chlorine is the more marketable item, and for this situation seawater treatment with caustic would be preferred. For these conditions a caustic value in a developing country was taken as $80/ton and a chlorine value in the United States at $50/ton. For the opposite conditions, world dump prices for caustic and chlorine were employed. Caustic credits in the range of $11 and $40/ton were used. Since the current "dump" price for caustic on the world market is $20 to $25/ton, at one-half of the dump price, $11 per ton of NaOH, the break-even power cost for HCl treatment (Fig. 5A.2*a*) is 3.9 mills/kwhr when sulfur is $50/ton; at a credit of $20 per ton of NaOH, 6.7 mills/kwhr. Break-even power costs for NaOH treatment (Fig. 5A.2*b*) are 2.1 and 4.3 mills/kwhr at credits of

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[3] Presently being used in a desalination plant in Kuwait; use of caustic for seawater treatment requires development.

[4] E. A. Cadwallader, "Carbon Dioxide – The Key to Economical Desalination," *Ind. Eng. Chem.* **59**(10) (October 1967).

[5] LMC Process, *Development of Precipitation Processes for Removal of Scale Formers from Sea Water*, U.S. Department of the Interior, OSW, Research and Development Progress Report 192.

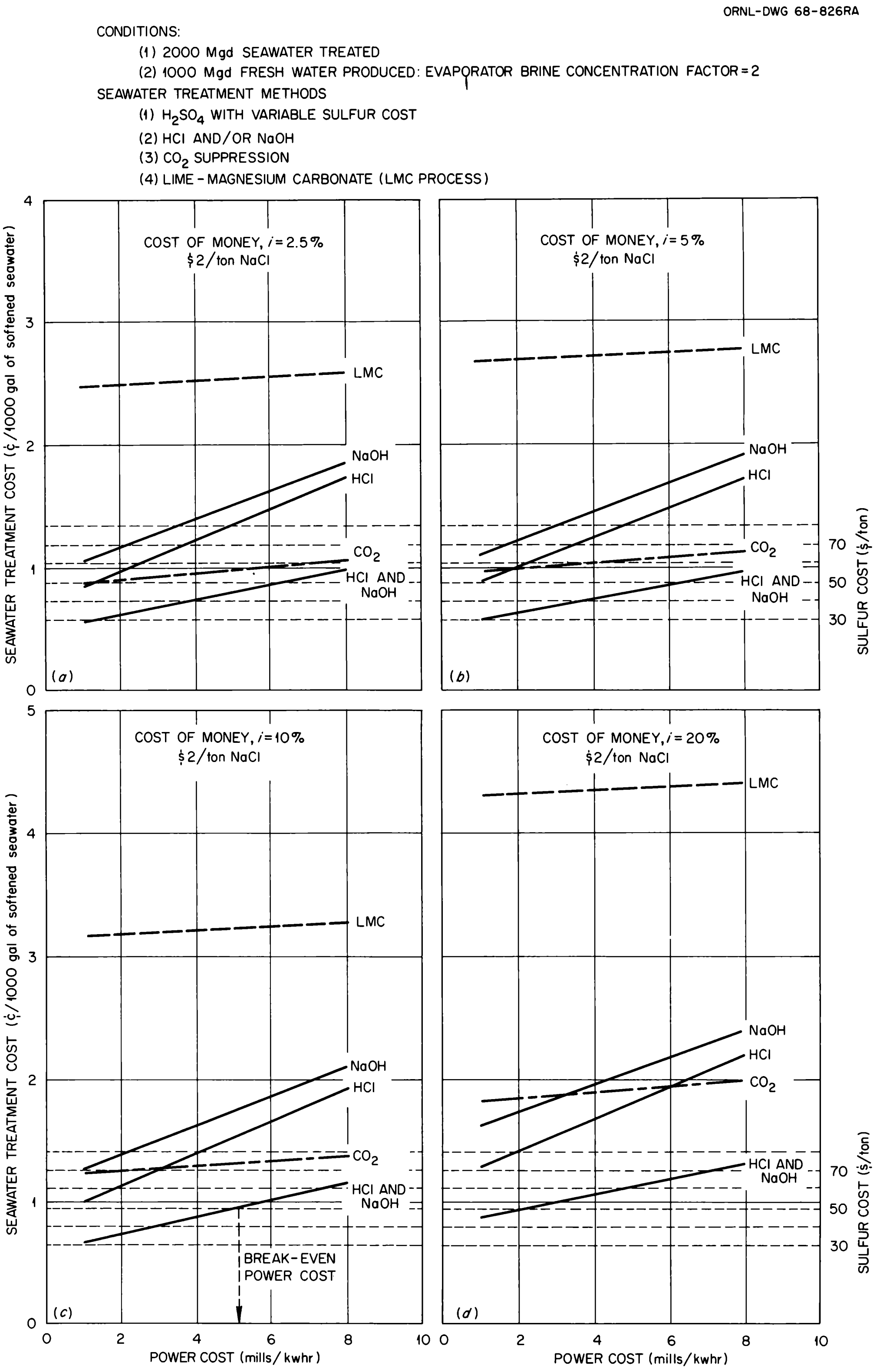

Fig. 5A.1. Cost Comparison of Seawater Treatment Methods as a Function of Power Cost and Cost of Money.

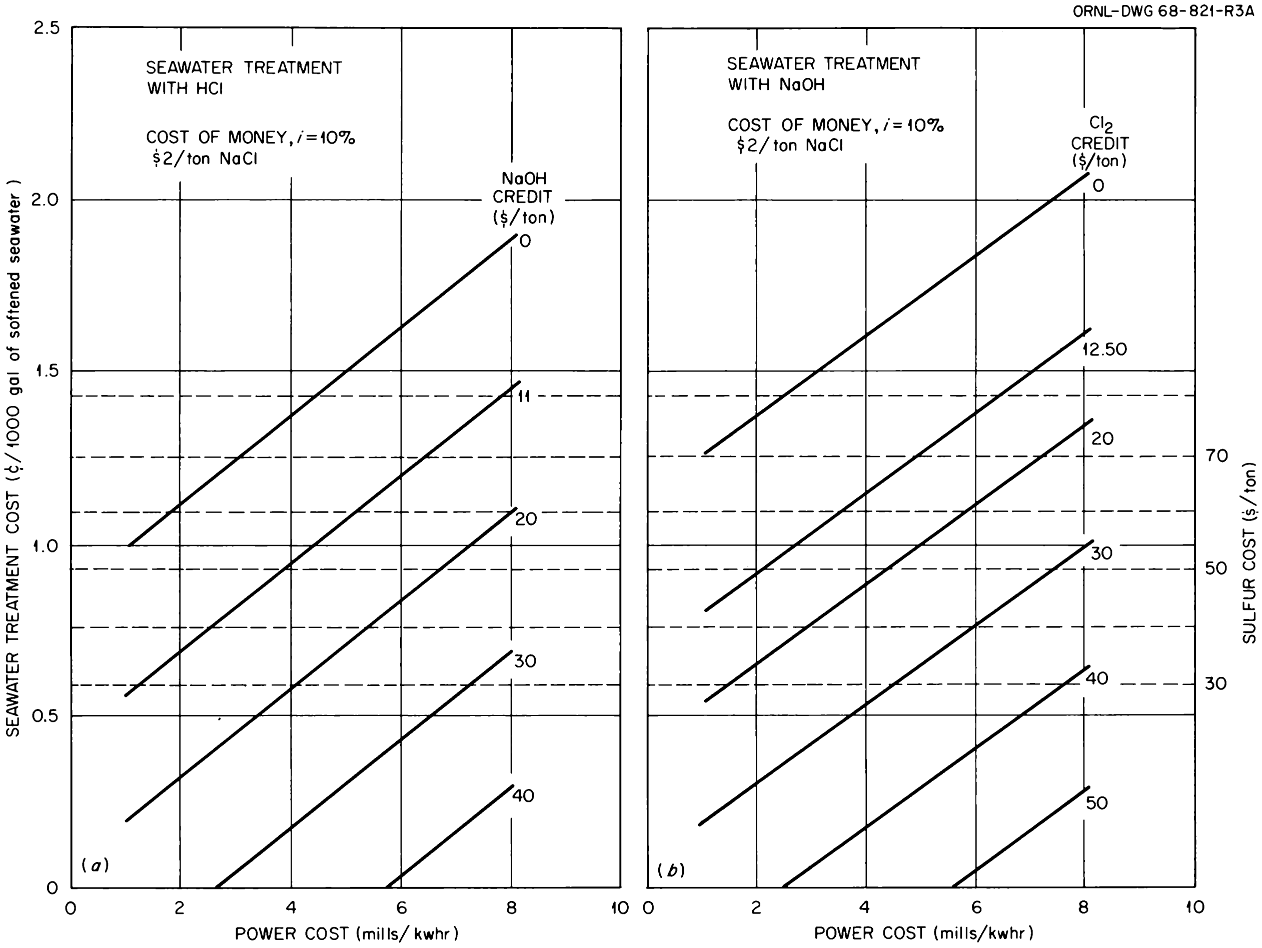

Fig. 5A.2. Effect of By-Product Credits on the Cost of Seawater Treatment by the HCl or NaOH Process Compared with the Sulfuric Acid Process.

$12.50 and $20 per ton of Cl_2 respectively. The estimated dump price for chlorine may be $40/ton[6] within a developing nation like India, where chlorine supply is likely to be in excess of chlorine demand. In an industrialized nation like the United States, chlorine is a valuable basic chemical and sells for $50/ton or more.

The HCl and NaOH processes are compared with sulfuric acid treatment in Figs. 5A.3*a* and 5A.3*b* at 10% cost of money as a function of the cost of sulfur and several values of by-product credit. The equimolar HCl-NaOH process is included for comparison. Figure 5A.3*a* shows that, with sulfur at $50/ton, the break-even power cost for HCl treatment is 3.9 mills/kwhr when caustic is sold for $11/ton; for equimolar treatment, 5.3 mills/kwhr. In Fig. 5A.3*b*, the break-even power cost for the NaOH process is 2 mills/kwhr when chlorine is $12.50/ton; for equimolar treatment, 5.9 mills/kwhr.

Seawater treatment systems using caustic-chlorine are capital cost and power cost intensive, while those using sulfuric acid are raw material cost intensive. In addition to the electrolytic cell, auxiliary equipment requirements for equimolar HCl-NaOH treatment include a recombiner to make HCl from Cl_2 and H_2 and a clarifier system to separate and recover the calcium carbonate precipitated from the caustic-treated seawater. Treatment with HCl alone requires a recombiner and a caustic concentrator to produce 50% NaOH if the caustic is marketed. Treatment with NaOH alone requires a clarification system which is twice as large as the one needed for equimolar HCl-NaOH treatment. The cost of sulfuric acid treatment is highly dependent on the cost of sulfur. The example given in Table 5A.1 shows that the

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[6] A. D. Little, Inc., private communication.

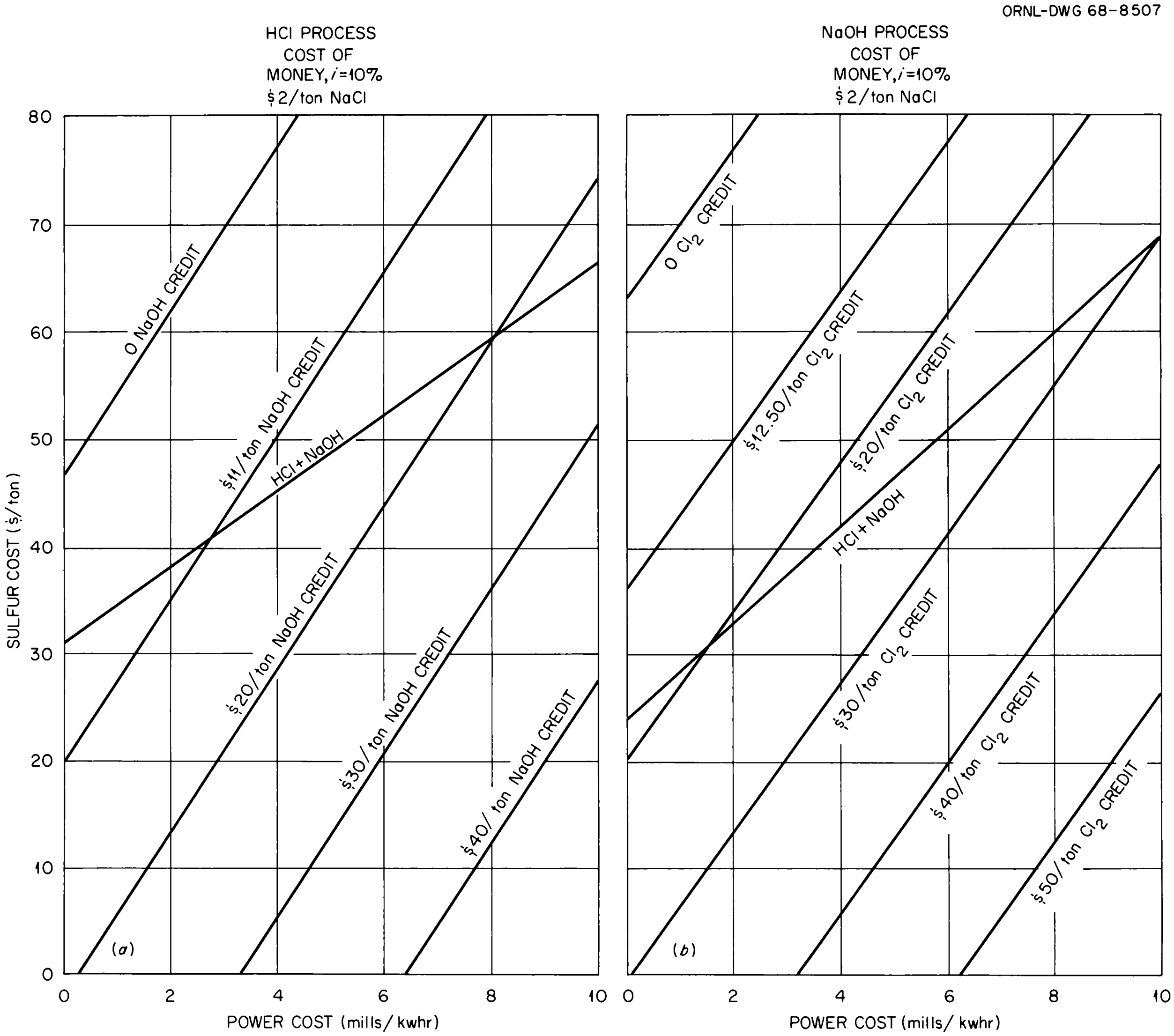

Fig. 5A.3. Break-Even Power Cost for the Treatment of Seawater by the HCl or NaOH Processes as Compared with the Sulfuric Acid Process.

plant investment in a caustic-chlorine system is 6 to 14 times higher than in the sulfuric acid system. Direct operating costs, however, for equimolar HCl-NaOH treatment are 50 to 65% (2 and 4 mills/kwhr respectively) lower than those for H_2SO_4 treatment when sulfur is $50/ton. When HCl alone is used, the direct cost is 85 to 112% of the H_2SO_4 process; NaOH alone, 97 to 124%. On an overall cost basis, the graphs and the table show that when even small by-product credits are allowed, the HCl and NaOH processes are competitive with the equimolar HCl-NaOH process and that all three are cheaper than the conventional sulfuric acid process. When no by-product credits are allowed, the equimolar process is the cheapest.

If there is a need for both caustic and chlorine within the complex or its surroundings, and if an additional amount of capacity is needed to satisfy the seawater treatment demand, then the added incremental capacity will result in lower costs of seawater treatment because the scaling factor for the caustic-chlorine plant is less than unity.

If evaporator temperatures higher than 295°F are desired, which is unlikely in the near future, caustic treatment must be supplemented with soda ash treatment to precipitate additional calcium.

Table 5A.1. Cost Summary for Treatment of 2000 Mgd[a] Seawater. Sulfuric Acid and Caustic-Chlorine Plants

	Sulfuric Acid Plant	Caustic-Chlorine Plants		
Seawater treatment method	H_2SO_4	NaOH + HCl	HCl	NaOH
Marketable product			NaOH	Cl_2
Plant capacity, tons/day				
H_2SO_4	980			
Cl_2		355	710	710
NaOH		401	802	802
Overall costs, millions of dollars				
Plant investment	2.28	14.12	18.66	25.41
Operating cost[b]	5.65	3.62	6.55	7.02
Total annual cost[c]	6.06	5.60	9.13	10.55
Credit for marketing by-product, $50/ton Cl_2; $44.25/ton NaOH			11.66	11.66
Net annual credit for by-products[d]			(2.53)	(0.11)

[a] Desalination plant produces 1000 Mgd of fresh water with a brine concentration factor of 2.0.

[b] Sulfur at $50/ton, salt at $2/ton, power at 4 mills/kwhr.

[c] Including an annual cost of plant investment. For this table, an interest charge (time value of money) of 10% was used.

[d] Credit for by-product exceeds total annual cost.

The cost of this combined treatment is not available at this time.

Nitric acid has also been proposed as a substitute for sulfuric acid treatment, since a large plant might be in operation at the complex to produce ammonium nitrate or nitric phosphate. A 1259-ton/day HNO_3 plant would be needed to treat 2000 Mgd of seawater. Costwise, it would be more expensive than equimolar treatment with caustic and hydrochloric acid, which is the most economical method utilizing caustic and/or chlorine when no by-product credits are taken. The *direct* operating cost using HNO_3 would be 0.62¢/1000 gal of softened seawater produced, as compared with 0.44¢/1000 gal using NaOH and HCl.

5A.3 Seawater Chemicals Cost Analyses

Manufacturing costs for recovery of potassium salts and the manufacture of sulfuric acid and cement from precipitated calcium sulfate will be discussed first, followed by a summary of production costs for anhydrous magnesium chloride and its reduction to magnesium metal. All costs are for United States conditions except as noted.

Potassium Fertilizer Manufacturing Cost. – Potassium salts can be crystallized by solar evaporation of the salt bitterns just before recovering magnesium chloride.[7] As indicated above, when no attempt is made to remove sulfate from the bitterns, potassium sulfate (the form preferred by farmers) will be the normal fertilizer product; with sulfate-free bitterns, potassium chloride is the product. In both cases, only the additional expense of separating and purifying the potassium fertilizer is accounted for in our cost analysis; all other costs are assigned to magnesium chloride recovery, as discussed below. Production costs are given in Fig. 5A.4 for potassium sulfate production using electric power costs in the range of 1 to 8 mills/kwhr and interest rates of 2.5, 5, 10, and 20%. In a 100,000-ton/year K_2SO_4 plant,

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[7] Other methods such as recovery by extraction from seawater with dipicrylamine were not studied, since they are believed to be more expensive.

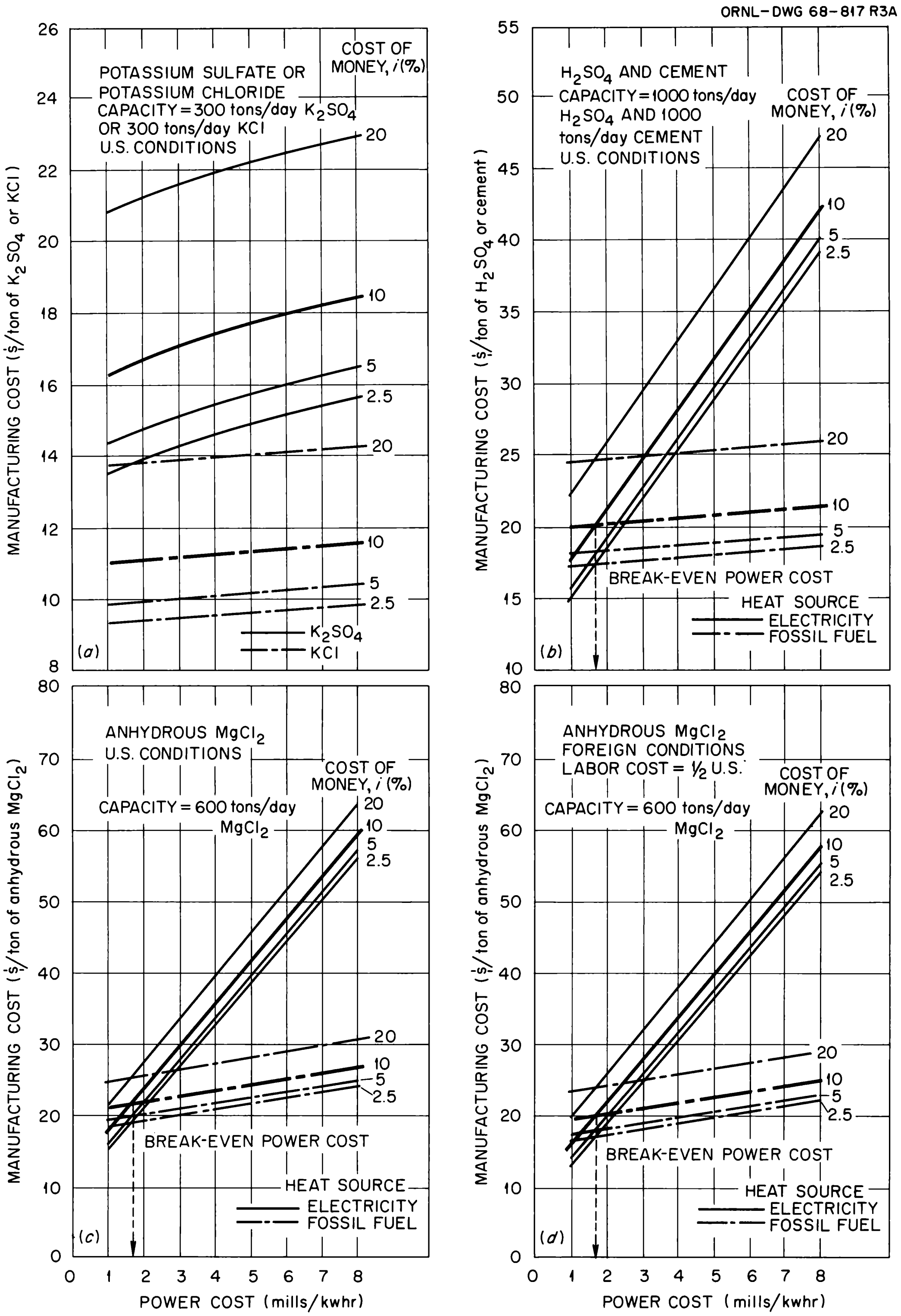

Fig. 5A.4. Manufacturing Costs for the Production of Potassium Fertilizer, Sulfuric Acid, Cement, and Anhydrous Magnesium Chloride from Solar Salt Bitterns.

electric power requirements are small (about 110 kwhr/ton), but there is a need for 6 MMBtu/ton of exhaust steam in the recrystallation portion of the process. At an interest charge of 10%, the cost ranges from \$16.20 to \$18.40 per ton of K_2SO_4 (\$32 to \$37 per ton of K_2O) as the power cost is increased from 1 to 8 mills/kwhr. The market price of K_2SO_4 in bulk is currently depressed at about \$25/ton f.o.b. plant.

Production of potassium chloride from sulfate-free bitterns is cheaper. The cost of power has little effect on the manufacturing cost, because the requirements for both power and steam are small. For a 100,000-ton/year KCl plant, the cost ranges from \$11 to \$12 per ton of KCl (\$18 to \$19 per ton of K_2O) at an interest charge of 10%. This compares favorably with the current depressed market price of \$23/ton f.o.b. port. The price includes \$14/ton f.o.b. plant, and a charge of \$9/ton[8] for shipment from inland locations, where the current large sources of supply are located, to a coastal shipping point. Logistics then tend to favor the production of potassium fertilizer in an arid coastal desert region. Potassium recovery from salt bitterns would provide an internal source of supply for developing nations like India which currently have to import all their potash needs.

In a solar salt operation, salt, potash, and other chemical yields can be expected to increase with time because of an increase in imperviousness of the salt works and bitterns pond bottoms, thereby reducing leakage. Table 5A.2 illustrates this, based on the expectation of the Baja California solar salt operation.[9] If, for example, salt and potash were recovered from seawater evaporator effluent that was twice the concentration of raw seawater, the potash yield might triple in ten years, from 0.52 to 1.7 tons of K_2O per acre-year of salt works. As a result, the farm (grain) acre-

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[8] *Chem. Week* 102(15), 47 (Apr. 13, 1968).

[9] Private communication, National Bulk Carriers Corporation, New York.

Table 5A.2. Farm Utilization of Potash Yields from Seawater Concentrates. Potential Improvements by Reduction of Pond Leakage Rate[a]

Seawater Concentration Factor[b]	Operation Time (years)	Land Required for Solar Salt Works (acres per 10^6 tons/year of NaCl)	Annual Potash Yield[c] per Acre (tons/year)	Acres of Farmland Served per Acre of Salt Works[d] $\left(\frac{K_2O\ \text{req'd/acre}_{\text{grain}}}{K_2O\ \text{yield/acre}_{\text{salt}}}\right)$
1	Initial	40,000	0.31	4.1
	3	24,000	0.52	6.9
	10	12,000	1.04	14
2	Initial	24,000	0.52	6.9
	3	14,400	0.87	12
	10	7,200	1.74	23
2.5	Initial	20,000	0.63	8.4
	3	12,000	1.04	14
	10	6,000	2.09	28
3	Initial	16,000	0.78	10
	3	9,600	1.30	17
	10	4,800	2.60	35

[a] Based on data supplied by National Bulk Carriers Corporation, New York, for their Baja California solar salt operation. They expect that the soils of their salt farm operation will become increasingly impervious with operating time, and salt and potash yields should increase proportionally.

[b] Raw seawater = 1.

[c] Assuming 100,000 tons/year K_2O per 8 million tons/year NaCl.

[d] Assume 75 lb K_2O applied per 150 lb N_2 per crop. If 37.5 lb K_2O per 150 lb N_2, grain farmland treatable would double.

age which can be treated (two crops per year at 75 lb of K_2O per acre-crop) from the yield of 1 acre of salt works would increase from 7 acres to 23 acres. In ten years, then, the amount of farmland which could be fertilized from a 100,000-acre salt works would increase from 700,000 acres to 2,300,000 acres. Thus in the same period the amount of K_2O in excess of that required for a 300,000-acre food factory would increase from 133% to 667%. This increasing excess could be used elsewhere in the country and/or could be exported to improve the nation's balance-of-payment situation. That part exported would most likely be exported directly as KCl or K_2SO_4 to minimize shipping charges. The part used indigenously could be shipped to off-site mixing plants or mixed locally at the complex. If the complex also produces 2500 tons of nitrogen per day as usable nitrogenous fertilizers, 1500 tons of P_2O_5 per day as usable phosphatic fertilizers, and all of the excess K_2O is used in producing mixed fertilizers, a fertilizer ratio of 6.4 : 3.2 : 1 could be obtained after the salt works has run for ten years (Table 5A.3). If the evaporator effluent was three times raw seawater concentration, a 4 : 2 : 1 mixed fertilizer could be made. Because of the long time required to reduce solar salt works leakage and to achieve increased seawater chemical yields, a solar salt works, if included in a complex, should be one of the first facilities to be installed.

The capital cost of a 100,000-ton/year potassium sulfate plant is $5 million or less, while that for potassium chloride is about $3 million. A scaling factor of 0.6 should hold for plant sizes up to about 500,000 tons/year of either type of potassium fertilizer.

Sulfuric Acid and Cement Manufacturing Cost. – Cement and sulfuric acid are commodities which are basic, especially in a developing nation. Sulfuric acid prices have increased considerably in the past two years because worldwide demand for sulfur has exceeded the supply of Frasch-type elemental sulfur, traditionally the cheapest source available. The sulfur price now exceeds $35/ton,

Table 5A.3. Potash Production for Farm Use and for Export

Basis: 100,000-acre solar salt works

Seawater Concentration Factor	Plant Operation Time (years)	Annual Potash (K_2O) Yield[a] (tons per year per 10^5 acres)	Potash (K_2O) Applied on Farm[b] (tons per year per 3×10^5 acres)	Potash (K_2O) Available for Export (tons/year)	Potash (K_2O) Available for Export (tons/day)	N_2/K_2O Ratio of Potash Exportable as Balanced Fertilizer[c]
1	Initial	31,000	45,000			
	3	52,000	45,000	7,000	21	
	10	104,000	45,000	59,000	180	120
2	Initial	52,000	45,000	7,000	21	120
	3	87,000	45,000	42,000	125	20
	10	174,000	45,000	129,000	390	6.4
2.5	Initial	63,000	45,000	18,000	55	45
	3	104,000	45,000	59,000	180	14
	10	209,000	45,000	164,000	495	5.0
3	Initial	78,000	45,000	33,000	100	25
	3	130,000	45,000	85,000	260	10
	10	260,000	45,000	215,000	650	3.8

[a] Assuming 100,000 tons/year K_2O per 8 million tons/year NaCl.

[b] Assume two crops per year on 300,000-acre farm and, on each acre, 150 lb N_2 and 75 lb K_2O applied per crop.

[c] N_2/K_2O ratio in relation to a complex that produces 2500 tons/day N_2 (3000 tons/day NH_3) and 1500 tons/day P_2O_5. Ultimate potash yields (~10 years operation) from 3x concentrated seawater could be sufficient to supply the farm potash demand and to produce a balanced fertilizer with a N-P-K ratio of 4 : 2 : 1.

the price at which experts consider high-price sources of sulfur (gypsum, pyrites, and sour gas) to be competitive with cheap Frasch process sulfur.[10] Gypsum recovery from evaporator concentrates by solar evaporation provides a potentially attractive indirect source of sulfur (as sulfuric acid), especially when the co-produced cement is also in demand.

Figure 5A.4*b* shows the manufacturing costs for a plant that produces 1000 tons/day of each product, assuming 2 tons of gypsum are required to produce 1 ton each of sulfuric acid and cement clinker. A comparison is made between a plant that uses fossil fuel as a heat source (11 MMBtu/ton) and one that uses electric heating (3400 kwhr/ton). Costs are presented in terms of one product or the other, but in the discussion below the costs are considered to be evenly split between the sulfuric acid and the cement. At an interest charge of 10%, the manufacturing cost for the process that employs fossil fuel (at 50¢/MMBtu) ranges from \$20.00 to \$21.50 per ton of H_2SO_4 or cement when the power cost ranges from 1 to 8 mills/kwhr; this is about \$10.00 to \$10.75 per ton of co-product. The break-even power cost of the power-intensive process is 1.75 mills/kwhr if fossil fuel costs \$0.50/MMBtu. The raw material, gypsum, is assumed to have a cost of zero for these calculations.

The break-even power cost for the gypsum process that uses fossil fuel is greater than 8 mills/kwhr, relative to the current market price of the two products. Sulfuric acid is about \$35/ton and cement is about \$15/ton. The sum, \$50 per ton of co-product, then, means that even in the power-intensive plant, the break-even power cost is beyond 8 mills/kwhr at an interest charge of 20%. Thus, the process is worth considering in any complex that has a seawater evaporator and a solar ponding operation and in any locale where there is a demand for both products.

The capital cost of a 1000-ton/day sulfuric acid–cement plant is about \$17 million. The exponential scaling factor is 0.63 for plant capacities from 300 to 1000 tons/day. For larger capacities, two separate plants would probably be advisable.

Production Cost of Anhydrous $MgCl_2$. – Anhydrous magnesium chloride, recovered from either sulfate-free or sulfate-containing bitterns, is a commodity which, we believe, will have a rapidly expanding market over the next ten years as worldwide requirements for magnesium metal and chlorine grow. A developing nation may initially wish to export this material to an industrialized country for reduction to metal, but as its own requirements for the metal and chlorine increase, reduction will later be done in the producer nation. In this regard the pattern will be much the same as the one now fairly widespread for alumina and aluminum. At present, exportation of $MgCl_2$ to the United States is expensive because tariff barriers are so high that it pays to recover $MgCl_2$ from Great Salt Lake brines, even though royalties are paid on the mineral rights on the land required for solar ponding and on the magnesium recovered.

The manufacturing costs of anhydrous $MgCl_2$ from solar salt bitterns under both United States and overseas conditions are given in Figs. 5A.3*c* and 5A.3*d*. Comparisons are made between the plant that uses fossil fuel as a heat source (17 MMBtu/ton) and one that is power intensive (5800 kwhr/ton), and they show the costs for a 198,000-ton/year plant for power costs of 1 to 8 mills/kwhr and for interest charges of 2.5, 5, 10, and 20%. At an interest charge of 10% and a power cost of 4 mills/kwhr, the non-U.S. production cost at a plant that uses fossil fuel (at 50¢/MMBtu) is \$21.50 per ton of $MgCl_2$. At Great Salt Lake the estimated cost of $MgCl_2$, including royalty charges, is \$35/ton. Thus the break-even power cost at an interest charge of 10% is greater than 8 mills/kwhr for a plant that recovers $MgCl_2$ from solar salt bitterns using fossil fuel and that is located on a tropical or semitropical arid coast. A power-intensive plant could be considered as a substitute for one that uses fossil fuel when the cost of power is 1.75 mills/kwhr and the cost of fuel is 50¢/MMBtu.

The capital cost of a 198,000-ton/year anhydrous $MgCl_2$ plant is estimated to be about \$8 million. The exponential scaling factor is about 0.6 for plant capacities for up to about 500,000 tons/year.

Magnesium Metal Manufacturing Costs. – The production of magnesium metal from $MgCl_2$ obtained from brine concentrate instead of from $Mg(OH)_2$ obtained from seawater, which is traditional, promises to lower manufacturing costs because chlorine is produced instead of being consumed. Chlorine is a valuable by-product that is in great demand in industrialized nations, especially when hard-to-sell

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[10] *Chem. Week*, p. 72 (Feb. 12, 1966).

caustic soda is not co-produced, as is the case with brine electrolysis. National Lead Company[11] has recently announced that it will build a large magnesium plant at Great Salt Lake which uses the local brine concentrate as the raw material for magnesium manufacture. When completed, about 1970, it will be the first new magnesium plant to be built in the United States since World War II and will represent a magnesium capacity which is over 50% of the present United States capacity. With the assurance that there will be two large suppliers of lower-cost magnesium, Dow Chemical Company and National Lead Company, it is predicted that the automotive industry will use magnesium metal for many of its die-cast parts, and, as a result, there will probably be a several-fold increase in magnesium demand during the 1970's in the United States alone.

Magnesium manufacturing costs are given in Fig. 5A.5*a–d* for metal production from concentrated brine evaporator effluent, which is assumed to have zero cost. Only one plant capacity, 45,000 tons/year (about 130 tons/day), is discussed for several situations under United States conditions; the effect of capacity on costs will be presented in a later report, since complete data were not obtained in time to present a thorough analysis here. The cost of production is based on the use of 4.4 tons of anhydrous $MgCl_2$ per ton of metal produced and is shown as a function of the power cost and the cost of money. The net cost is also shown after a credit is taken for the co-produced chlorine, assuming a yield of 2.2 out of a theoretical 2.9 tons of Cl_2 per ton of magnesium metal and $50/ton chlorine. Figure 5A.5*a* gives the cost of the metal reduction alone. Figure 5A.5*b* gives the cost for a combined $MgCl_2$ recovery and metal reduction operation and includes a comparison of the use of fossil fuel (at 50¢/MMBtu) for heat to dehydrate $MgCl_2$ and electric power for the same purpose; at a cost of money of 10%, the break-even cost of the power-intensive plant is 1.75 mills/kwhr. Figures 5A.5*c* and 5A.5*d* show, at an interest charge of 10% only, the effect of imported $MgCl_2$ on the production costs of a metal-reduction plant at a distance of about 6000 miles from the nuclear-industrial complex; Fig. 5A.5*c* shows power costs as the main variable, and Fig. 5A.5*d* shows the costs of imported anhydrous $MgCl_2$ (including shipping but not tariff).

These graphs can be used to compare the cost of producing the metal under two sets of United States conditions and in an integrated $MgCl_2$–Mg metal operation at a nuclear-industrial complex. The first set of United States conditions involves the recovery of $MgCl_2$ from Great Salt Lake brine for $35/ton, including royalties, and its reduction to magnesium metal on-site at a power cost of 4 mills/kwhr. The second set involves the importation of anhydrous $MgCl_2$ from the Persian Gulf to a fictitious plant in the United States northwest for an estimated $25/ton delivered, but not including tariff charges, and its reduction at a power cost of 2 mills/kwhr. Without a credit for chlorine, the costs of metal production at a cost of money of 10% are $450 and $375/ton respectively (current magnesium metal selling price, $720/ton); with chlorine credits, $343 and $265/ton. At an integrated operation in a nuclear complex, the cost without a credit for chlorine would be $375/ton (4 mills/kwhr) and $330/ton (2 mills/kwhr); with chlorine credits, $265 and $222/ton. These comparisons show that the integrated operation at the complex would be indeed competitive with the two stated United States cases.

The final comparison is between the old and new technology. The *direct* operating cost for producing magnesium metal by the traditional seawater–$Mg(OH)_2$ process, which consumes chlorine, is estimated to be about $350/ton when the power cost is 4 mills/kwhr. On the other hand, the corresponding cost for the brine concentrate–$MgCl_2$ process is $270/ton; with a credit for the co-producing chlorine, $160/ton or about 55% of the *direct* operating costs of the traditional process. If the cost of money was 10%, it would add $100 (per ton of magnesium metal) to the *direct* costs of each process when the cost of power is 4 mills/kwhr. This assumes that the capital investments in both processes are the same. Indications are, however, that a new seawater–$Mg(OH)_2$ plant built today would cost much more than those built during World War II. This implies that the total manufacturing cost of the traditional process would be much higher and, therefore, uneconomic when compared with the brine concentrate–$MgCl_2$ process.

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[11] *Chem. Eng. News* **46**(18), 11 (Apr. 22, 1968).

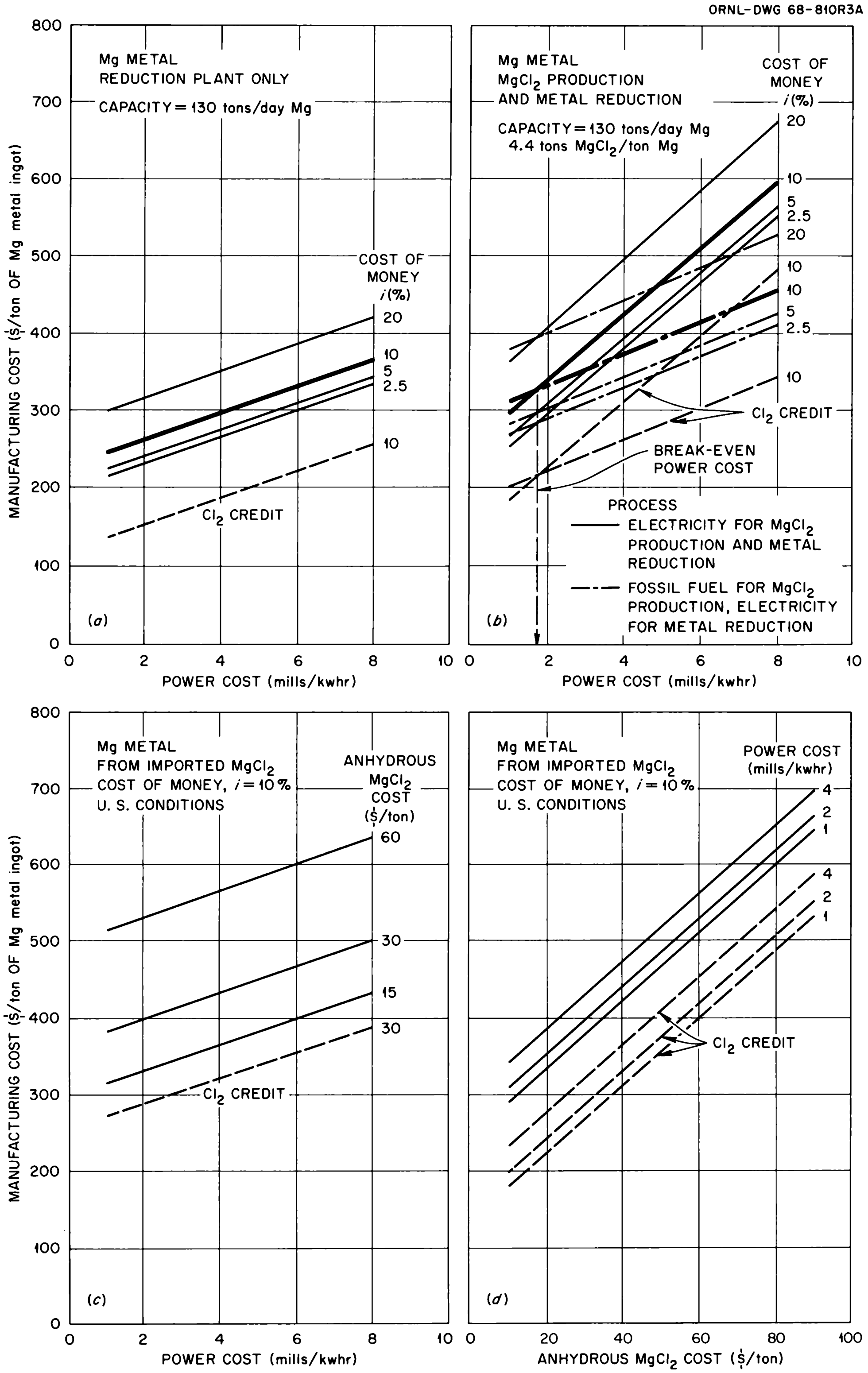

Fig. 5A.5. Manufacturing Costs for the Production of Magnesium Metal.

The capital cost of an integrated 45,000-ton/year magnesium plant is estimated to be $34 million. This includes $8 million for a 198,000-ton/year anhydrous $MgCl_2$ plant and $26 million for the reduction plant. The scaling factor is about 0.6 for plants up to 45,000 tons/year, 0.7 between 45,000 and 75,000 tons/year, and 0.8 above a capacity of 75,000 tons/year. All operating costs, except labor, will scale linearly. The exponential scaling factor for labor should be about 0.75 for plant sizes up to 100,000 tons/year of magnesium metal.

Appendix 6A

POTENTIAL WATER REQUIREMENT AND PRODUCTIVITY OF THE VARIOUS AGRICULTURAL LOCALES

The quantity of irrigation water needed to produce each unit of crop yield – the water use efficiency ratio – is a key parameter in determining the economic feasibility of the agricultural complex.

In this appendix the potential water use efficiency as well as the absolute values of potential water requirement and dry matter production of the various locales investigated have been compared and contrasted.

It should be emphasized that the estimates refer to a hypothetical, short crop which completely covers the ground and whose growth and water loss is unlimited by soil water content or physiological factors. In actual farming practice the crops selected and their rotation, spacing, and irrigation treatment would substantially modify these figures.

For example, in the Southeastern Mediterranean locale, the weighted mean annual water requirements per acre for the three different cropping systems considered in Chap. 6 were calculated to be 88, 74, and 63% of the estimated potential irrigation water requirement.

It should also be recognized that the figures presented for each locale are mean values based on two stations on the periphery of each site. The within-site differences in annual water requirements were 15% for the Western Australian locale, 8% for the Peruvian locale, 5% for the Indian locale, and 3% for the Southeastern Mediterranean locale.

It is of course true that the actual crop water requirements and, to an even greater extent, the crop yields may well differ markedly from the potential amounts. At present, however, potential rates are the only practical basis for comparison, in that reliable data on actual rates require a long, difficult, and expensive field research program at each site which cannot as yet be replaced by centralized controlled-environment research or by theoretical calculations.

Two physical methods of calculation based on climatological data were used to compute the potential rates used for the comparisons. Potential water requirements were based on open water surface evaporation values computed by the combined energy balance and aerodynamic method of Penman (1956), while potential photosynthesis was calculated by de Wit's method (1965). Details of the climatological data used are given in Table 6A.1, and the results of the calculations are presented on an annual basis in Table 6A.2 and on a monthly basis in Table 6A.3.

The potential irrigation water requirements were calculated assuming an irrigation application efficiency of 0.80 and a similar size crop factor relating potential evapotranspiration to open water surface evaporation. Since, on a monthly basis, the water requirement exceeded rainfall at all locales, there was no drainage complication.

It can be seen from Table 6A.2 that there was a considerable difference (25%) in the annual water requirement of the locale with the greatest annual water demand (the Indian site) and that having the least (the S.E. Mediterranean).

The peak water demand at the various locales is an important factor in determining the size and cost of the irrigation system. The locale differences in peak water demand found were greater than for the annual water requirements. The greatest peak demand (at the Australian locale) was 60% more than that at the lowest (the Peruvian) locale.

Even greater site differences were found in the potential water storage requirements. These values were calculated on the basis of an even year-round rate of water production without any allowance for shutdown time or water storage losses. The greatest water storage requirement was at the W. Australian locale and was five times that of the Peruvian locale, which had the lowest storage need.

The differences between the potential photosynthesis at the different locales were much less than the potential water requirements, although larger differences in seasonal production were found (Table 6A.2). This seasonal variation is of some significance where an even year-round rate of crop production is desirable for crop processing, for livestock feeding, or for reducing the need for crop-storage facilities.

The potential water use efficiency at the different locales varied in a similar way to their water requirements. When efficiency of annual

Table 6A.1. Sources of Climatological Data Used

Number of years data averaged is given in parentheses

Locale	S. E. Mediterranean, Sinai-Negev	Indian, Kutch Peninsula	Peruvian, Piura Department	W. Australian, Sharks Bay
Climatological stations	Gilat, 31° 20' N, 34° 40' E 450' m.s.l.	*a*) Bhuj, *b*) Dwarka *a*) 23° 15' N, 69° 48' E, 343' m.s.l. *b*) 22° 22' N, 69° 00' E, 37' m.s.l.	*a*) Piura, *b*) Lambayeque *a*) 15° 12' S, 80° 37' W, 159' m.s.l. *b*) 06° 42' S, 79° 54' W, 84' m.s.l.	*a*) Carnarvon, *b*) Geraldton *a*) 24° 54' S, 113° 39' E, 15' m.s.l. *b*) 28° 45' S, 114° 36' E, 13' m.s.l.
Sources of data	Volcani Institute of Agricultural Research, Rehovot, Israel	"Climatological tables." Observatories in India. Meteorological Department, Bombay, 1953.	"Boletin de estadistica Meteorologica e hydrologica," 1962, No. 4 & No. 6, Lima.	Bureau of Meteorology, Canberra and "Climatic Averages," Australia Bureau of Meteorology, 1956.
Potential Evapotranspiration				
Energy term				
Incident short wave	Measured (6)	Interpolated from national maps	Calculated from measured hours of bright sunshine (19)	Interpolated from national maps
Reflected short wave	From tables for open water according to month and latitude (Budyko, 1958)			
Net long wave	Calculated from measurements of air temperature, vapor pressure, and cloud cover (Penman, 1948)			
	(6) (6) (6)	(50) (50)	(19) (19) (19)	(42) (30) (12)
Aerodynamic term				
Saturation vapor pressure deficit	Measured as daily mean (6)	Measured twice daily (50)		Measured once daily (36)
Wind run	Measured daily totals at 6' (6)	Corrected from measured daily totals at 30' (*a*) and 20' (*b*) (50)	Calculated from Piche evaporimeter measurements (17) (Stanhill, 1962)	Corrected from mean of seven daily measurements at 20' (*a*) and 33' (*b*) (4)
Potential Photosynthesis				
Incident shortwave radiation	Measured (6)	Interpolated from national maps	Calculated from measured hours of bright sunshine (19)	Interpolated from national maps

Table 6A.2. Mean Annual Values of Potential Water Demand and Productivity

	S. E. Mediterranean	Indian	Peruvian	W. Australian
	Water Demand (in./year)			
Potential evapotranspiration	55.0	71.2	53.4	65.5
Rainfall	9.0	13.8	1.9	13.8
Potential irrigation water requirement	57.5	71.8	64.4	64.7
As ratio	1.00	1.25	1.12	1.13
	Maximum Irrigation Demand (in./month)			
Maximum monthly water requirement	9.10	9.5	6.3	10.2
As ratio	1.00	1.04	0.69	1.12
	Maximum Water Storage Demand (in.)			
Maximum water storage requirement	18.5	9.4	3.0	18.6
As ratio	1.00	0.51	0.16	1.01
	Productivity (tonnes per acre per year)			
Potential photosynthesis	51.2	52.7	48.4	50.1
	Water-Use Efficiency			
Potential evapotranspiration per unit potential photosynthesis	109	137	112	133
As ratio	1.00	1.25	1.03	1.22
Potential irrigation water requirement per unit potential photosynthesis	114	138	135	131
As ratio	1.00	1.21	1.18	1.15
	Crop Storage Demand			
Ratio of maximum to minimum monthly	1.83	1.36	1.26	1.86
Potential photosynthesis, As ratio	1.00	0.74	0.69	1.02

Table 6A.3. Mean Monthly Values of Potential Water Requirement and Photosynthesis

	Locale[a]	Jan.		Feb.		Mar.		Apr.		May		June		July		Aug.		Sept.		Oct.		Nov.		Dec.	
		E	*A*	*E*	*A*	*E*	*A*	*E*	*A*	*E*	*A*	*E*	*A*	*E*	*A*	*E*	*A*	*E*	*A*	*E*	*A*	*E*	*A*	*E*	*A*
Open water surface evaporation; energy (*E*) and aerodynamic term (*A*); mm/day, weighted values	1	1.4	0.8	1.9	0.8	3.0	1.0	4.3	1.2	5.2	1.4	6.0	1.5	6.3	1.2	5.9	1.0	4.7	1.0	3.3	0.9	1.6	1.2	1.2	0.9
	2	2.3	1.7	3.4	1.6	5.0	1.9	6.0	2.1	5.8	2.1	5.1	2.1	4.8	1.6	5.6	1.4	5.6	1.3	4.5	1.6	3.3	1.7	2.3	1.5
	3	4.5	0.8	4.6	0.9	4.6	0.8	4.2	0.9	3.4	0.9	3.0	0.7	2.9	0.6	3.4	0.6	3.8	0.6	4.1	0.7	4.1	0.8	4.1	0.8
	4	6.1	2.7	5.7	2.4	4.2	2.4	3.1	2.0	1.9	1.5	1.2	1.4	1.3	1.2	2.1	1.3	2.6	2.3	4.3	2.1	5.7	2.3	6.2	2.2
		N	*I*	*N*	*I*	*N*	*I*	*N*	*I*	*N*	*I*	*N*	*I*	*N*	*I*	*N*	*I*	*N*	*I*	*N*	*I*	*N*	*I*	*N*	*I*
Rainfall (*N*) and irrigation water requirements (*I*); in./month	1	2.09	0.57	1.61	0.76	1.28	3.28	0.29	6.06	0.12	7.88	0	8.86	0	9.10	0	8.42	0	6.69	0.22	4.84	1.34	1.27	2.02	0.03
	2	0.09	4.69	0.20	5.18	0.11	8.29	0.05	9.39	0.14	9.48	1.70	6.34	6.64	0	2.75	5.10	1.64	6.18	0.29	7.16	0.08	5.81	0.08	4.63
	3	0.24	6.16	0.47	5.48	0.49	5.96	0.35	5.59	0.04	5.20	0.02	4.35	0	4.27	0.02	4.85	0.02	5.18	0.04	5.81	0.04	5.74	0.16	5.78
	4	0.40	10.24	0.60	8.18	0.81	7.05	0.78	4.96	2.10	1.56	3.39	0	2.55	0	1.65	2.03	0.70	5.18	0.48	7.16	0.15	9.25	0.19	10.31
		P	*P/I*	*P*	*P/I*	*P*	*P/I*	*P*	*P/I*	*P*	*P/I*	*P*	*P/I*	*P*	*P/I*	*P*	*P/I*	*P*	*P/I*	*P*	*P/I*	*P*	*P/I*	*P*	*P/I*
Potential photosynthesis, tons per acre per month, and irrigation efficiency (= *P/I* in consistent units)	1	3.20	1.6	3.27	2.4	4.18	8.0	4.64	1.33	5.25	1.52	5.34	1.66	5.45	1.70	5.10	1.68	4.47	1.52	4.02	1.19	3.25	4.0	3.01	1.0
	2	3.86	1.23	3.89	1.35	4.84	1.74	4.97	1.92	5.20	1.85	5.26	1.22	4.44		4.14	1.25	4.21	1.49	3.98	1.83	4.05	1.45	3.86	1.22
	3	4.30	1.46	3.87	1.44	4.30	1.41	4.07	1.40	3.92	1.35	3.57	1.24	3.81	1.14	3.95	1.25	4.05	1.30	4.35	1.36	4.18	1.40	4.30	1.37
	4	5.31	1.96	4.51	1.84	4.41	1.62	3.71	1.35	3.26	4.9	2.87		3.04		3.61	5.7	4.08	1.29	4.74	1.53	5.10	1.84	5.44	1.92

[a] Locale 1 = S. E. Mediterranean, 2 = Indian, 3 = Peruvian, and 4 = Australia.

water use was compared on the basis of irrigation water requirements, then the difference between the most efficient locale (S.E. Mediterranean) and the least efficient (Indian) was just over 20%.

The theoretical water use efficiency, expressed as grams of irrigation water application per gram potential photosynthesis, was 84 at the most efficient locale during the wheat growing season. Approximately one-third of the photosynthesis might be harvested as grain, altering the efficiency ratio to 252. This value can be compared with 750, the ratio derived for the wheat yield and water requirements assumed for this same locale in the agricultural complex. Early field studies of the water use efficiency of grain produced by irrigated wheat crops and arid zones (Shantz and Piemeisal, 1927) showed ratios twice as large.

These large contrasts underline the great progress in water use efficiency that has been made in irrigated agriculture and the potential for further progress that remains.

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Appendix 7A

SIZING OF NUCLEAR REACTOR

Presented in this appendix are equations for the calculation of thermal heat load for single- or dual-purpose nuclear reactors and electrical power output from the turbogenerator island. A tabular listing of the thermal efficiencies for LW, LMFB, and MSB reactors and their auxiliary power requirements is included. Pumping power requirements for MSF and VT evaporators are also listed.

Glossary of Terms

L = electrical load, peak, Mw
LF = load factor
E = annual energy load, Mwhr/year
Q = thermal load, peak, Mw
W = desalted water output, peak, Mgd
R = evaporator performance ratio, lb per 1000 Btu $\equiv 1/S$
η = thermal efficiency, Mw(electrical)/Mw(thermal) (Table 7A.1)
b = auxiliary power loads, reactor and turbine, Mw(electrical)/Mw(thermal) (Table 7A.1)
d = auxiliary power load, evaporator, Mw(electrical)/Mgd (Table 7A.1)
P = electrical generating capacity, peak, Mw

Subscripts:

0 = total
I = industrial complex
G = grid (includes town load)
P = water conveyance and sprinkling
H = peak process steam load, Mw(thermal) (excluding evaporator)
A = back-pressure turbine
C = condensing turbine
B = bypass steam (reactor prime steam directly to evaporator)
X = unit conversion
R = nuclear island
T = turbogenerator-condenser island
E = evaporator
L = peak low-pressure process steam load, Mw(thermal)

Equations for Sizing of Reactor

1.0 Electricity load of evaporator, L_E, Mw:

$$L_E = d_E W \tag{1}$$

Table 7A.1. Thermal Efficiency and Reactor, Turbine, and Evaporator Auxiliary Power for Several Types of Reactors and Evaporators

	Reactor Type		
	LWR	LMFBR	MSBR
Thermal efficiency, Mw(electrical)/Mw(thermal)			
Back-pressure turbine, η_A	0.2137	0.2683	0.374
Condensing turbine, η_C	0.3425	0.412	0.475
Auxiliary power, Mw(electrical)/Mw(thermal)			
Back-pressure turbine, b_A	0.00549	0.01290	0.01595
Condensing turbine, b_C	0.00864	0.01584	0.01875
Reactor, b_R	0.00780	0.00793	0.00542
Auxiliary power, evaporator, d_E, Mw(electrical)/Mgd			
Multistage flash	0.345	0.345	0.345
Vertical-tube effect	0.142	0.142	0.142

1.1 Total electrical load of reactor, L_0, Mw:

$$L_0 = L_I + L_G + L_E + L_P \tag{2}$$

1.2 Average load factor, $(\mathrm{LF})_{\mathrm{av}}$:

$$(\mathrm{LF})_{\mathrm{av}} = \frac{\sum_i E_i/8760 + \sum_j L_j(\mathrm{LF})_j}{L_0} \tag{3}$$

where i refers to loads where E_i is given and j refers to loads where L_j and $(\mathrm{LF})_j$ are given.

1.3 Peak electric power, P_0, from turbogenerator island less auxiliary power for nuclear island and turbogenerator-condenser island:

$$P_0 = L_0\,(\mathrm{LF})_{\mathrm{av}}/(\mathrm{LF})_R \text{ for } (\mathrm{LF})_{\mathrm{av}} \geqq (\mathrm{LF})_R \tag{4}$$

$$P_0 = L_0 \text{ for } (\mathrm{LF})_{\mathrm{av}} < (\mathrm{LF})_R \tag{5}$$

$$P_0 = P_A + P_C - P_R - P_T \tag{6}$$

1.4 Conversion of W and R into mass units:

$$S_X = \frac{1}{R_X} = \frac{1}{3.413 \times 10^{-3} R}, \quad \text{Mwhr(thermal)}/10^6 \text{ lb} \tag{7}$$

$$W_X = 0.3474W,\ 10^6 \text{ lb/hr} \tag{8}$$

$$W_X = R_X[(1 - \eta_A)Q_A + Q_B - Q_L] \tag{9}$$

1.5 Heat flow to, and power from, back-pressure turbine:

$$Q_A = \frac{Q_L}{1 - \eta_A} + \frac{S_X W_X}{1 - \eta_A}, \text{ Mw(thermal)} \tag{10}$$

$$P_A = \eta_A Q_A, \text{ Mw(electrical)} \tag{11}$$

1.6 Heat flow to, and power from, condensing turbine:

$$Q_C = \frac{P_0 + b_R Q_H}{\eta_C - b_C - b_R} - \frac{\eta_A - b_A - b_R}{\eta_C - b_C - b_R} Q_A \tag{12}$$

$$P_C = \eta_C Q_C \tag{13}$$

1.7 Maximum water production without bypassing steam (full back-pressure operation):

$$Q_B = Q_C = 0$$

$$W_X = \frac{(P_0 + b_R Q_H)(1 - \eta_A) - Q_L(\eta_A - b_A - b_R)}{S_X(\eta_A - b_A - b_R)} \tag{14}$$

If $Q_L = Q_H = 0$:

$$W_X = \frac{P_0(1 - \eta_A)}{S_X(\eta_A - b_A - b_R)} = \frac{P_0 R_X(1 - \eta_A)}{\eta_A - b_A - b_R} \tag{15}$$

1.8 Total reactor thermal load, Q_0:

$$Q_0 = Q_A + Q_C + Q_H + Q_B \tag{16}$$

where

$$Q_B = S_X W_X + Q_L - (1 - \eta_A)Q_A \tag{17}$$

Note: In most of the cases discussed in Chap. 7, bypass prime steam is not utilized for water production; and thus maximum W_X is calculated for $Q_B = 0$ for any Q_A.

Appendix 7B

PROCEDURE FOR ASSEMBLING AND ANALYZING THE ECONOMICS OF NUCLEAR-POWERED INDUSTRIAL OR AGRO-INDUSTRIAL COMPLEXES

The following represents a step-by-step procedure for the formulation and economic analysis of nuclear-industrial or nuclear agro-industrial complexes.

1. Select industries, and determine peak power and steam requirements using Table 6 of ORNL-4296.
2. If a farm is desired, select water production rate (Mgd) and determine the power requirements of the evaporator[1] and the irrigation pumping power.[2]
3. Select amount of grid power sales, and compute peak total electrical load on reactor, Eqs. (2) through (6), Appendix 7A.
4. If an evaporator is included and operation under full back-pressure conditions is desired, use Eqs. (14)[3] or (15) and (8) and the desired reactor technology (LWR, FBR, or MSBR, Table 7A.1) to determine if the electric power desired is sufficient to obtain the required water output. If power requirements are too low, the direct use of prime steam may be warranted, and in this case Eq. (17) is used to determine the increase in reactor thermal power needed. If power requirements are greater than needed to provided the necessary water output using back-pressure steam turbines, condensing turbines can be provided to make more efficient use of all or part of the steam. Heat flow to back-pressure turbines is calculated using Eqs. (10) and (11); here the brine heater of the evaporator serves as the condenser. In the absence of a desalting evaporator, heat flow to a condensing turbine is computed using Eqs. (12) and (13).
5. Compute capital investments for the nuclear reactor and the turbine generator or the turbine generator and condenser according to the type of reactor desired (LWR, FBR, or MSBR), the number of reactors per station, United States or non-United States construction, and the total heat load (Mw). Table 4A.1 and Figs. 4A.1 and 4A.2 contain data for light-water reactors, turbine generators, and condensers; Fig. 4A.5 contains cost data for fast breeder and molten-salt breeder reactors. Nuclear power station capital costs for United States locations, from Chap. 4 and Appendix 4A, are increased by 12% for non-United States construction, as discussed in Sect. 3.5 of Chap. 3.
6. Fuel inventory capital, a nondepreciating item, is computed for the three different types of reactors according to the following relationships:

LWR	2500 Mw(thermal)	\$7057/Mw(thermal)
	2500 to 4600 Mw(thermal)	\$6710/Mw(thermal)
	4600 Mw(thermal)	\$6333/Mw(thermal)
FBR	All	\$16,000/Mw(thermal)
MSBR	All	\$7634/Mw(thermal)

7. Operating costs of the reactor and the turbine generator are determined by reference to Figs. 4A.3 and 4A.4 for LWR's. Operating costs for fast breeder and molten-salt breeder power stations are computed as 85% of the operating costs shown for a light-water reactor of the same thermal power.
8. Capital investments for multistage flash and vertical-tube evaporators are shown in Figs. 4A.7 and 4A.8. The performance ratio assumed in this report is 12 lb of H_2O per 1000 Btu. Operation and maintenance costs for an evaporator, in dollars per year, are calculated using the equation

$$C_{EOM} = 4350 \times \left(\frac{C_E}{101}\right)^{0.7} \times 365 \times \mathrm{LF}_e, \qquad (1)$$

where C_E is capital cost of evaporator, millions of dollars, and LF_e is the load factor of the evaporator. Additional costs are incurred by the evaporator plant for chlorination of intake water to prevent algae growth and for the addition of antifoam materials and calcium to the product water to prevent corrosion. The amount of chlorine needed, in tons per year, is

$$T_c = 5W_pR_cH_c \frac{(365 \times \mathrm{LF}_e)}{48{,}000}, \qquad (2)$$

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[1] Evaporator power depends upon type of evaporator selected, VTE or MSF. Auxiliary power requirements for each are listed in Table 7A.1, Appendix 7A.

[2] Power for irrigation pumping is proportioned to the required water production rate in Mgd based on the requirement of 204,000 hp for a 1000-Mgd irrigation system (system 2, Table 6.13).

[3] All equation numbers refer to Appendix 7A.

where W_p = fresh water output, Mgd,

R_c = 5 ppm, rate of Cl_2 addition,

H_c = 2 hr/day treatment time.

The cost of calcium and antifoam chemicals, in dollars per year, is

$$C_M = 1720W_p . \tag{3}$$

The cost of scale prevention on heat transfer surfaces in the evaporator is dependent on the method used. This report assumes the use of caustic and/or chlorine because they are products of the complex. In the case of a non-United States location for a nuclear agro-industrial complex, the logical treatment choice would be hydrochloric acid, since chlorine is assumed to have no value (see Table 5.9). The annual chlorine requirement is

$$T_A = \frac{(W_B + W_p) \times 710}{2000} (365 \times \mathrm{LF}_e) , \tag{4}$$

where T_A is annual chlorine requirement, tons/year, and $W_B + W_p$ is volume of brine blowdown plus fresh water product, Mgd. If a sufficiently large brine electrolysis plant is part of the industrial complex, the only additional capital cost is the cost of the recombiner,

$$C_A = 0.096[0.00332(W_B + W_p)]^{0.60} , \tag{5}$$

where C_A is capital cost of recombiner for hydrochloric acid treatment of seawater, millions of dollars. For a country which has excess caustic soda capacity, scale preventive treatment might be accomplished by partial precipitation of calcium with caustic. The annual requirement of caustic, in tons per year, for seawater treatment is

$$T_B = 1.13T_A , \tag{6}$$

with T_A from Eq. (4). This is sufficient caustic soda to precipitate 23% of the calcium present in 2000 Mgd of seawater. The additional capital cost (above that of the caustic-chlorine plant) is the cost of clarification equipment,

$$C_B = 0.00577(W_B + W_p) , \tag{7}$$

where C_B is the capital investment in millions of dollars. Another variation which might be used is the equimolar treatment, where one-half of the incoming seawater is treated using chlorine as hydrochloric acid and the remainder is treated using caustic soda to precipitate calcium. The annual consumption of chlorine is

$$T'_A = \frac{(W_B + W_p) \times 355}{2000} (365 \times \mathrm{LF}_e) . \tag{8}$$

The annual caustic requirement is

$$T'_B = 1.13T'_A . \tag{9}$$

The capital investment is the combined cost of a recombiner and the clarification equipment,

$$C_{EM} = 0.00289(W_B + W_p) + 0.096[0.00166(W_B + W_p)]^{0.60} , \tag{10}$$

where C_{EM} is capital investment, millions of dollars. If the chlorine output is insufficient or absent completely, other methods might be chosen, such as sulfuric acid treatment or CO_2 suppression.[4] The amount of sulfuric acid required to treat the incoming seawater to an evaporator plant, in tons per year, is

$$T_{AC} = 8.34(W_B + W_p) \times \mathrm{ppm}_{AC} \frac{365 \times \mathrm{LF}_e}{2000}, \tag{11}$$

where ppm_{AC} = 114 to 119, rate of addition of H_2SO_4, ppm. A good approximation to the manufacturing cost of H_2SO_4 is given by using the equation

$$C_{AC} = 0.333P_s + 2.50 \pm 0.75 \tag{12}$$

over the range 250 to 1000 tons/day of H_2SO_4,[5] where C_{AC} = dollars per ton of 100% H_2SO_4 and where P_s = price of sulfur, dollars/short ton. To summarize, the total operation and maintenance costs of the evaporator are computed as the sum of Eqs. (1) and (3) plus the cost of scale prevention, which depends upon the method used. Caustic and chlorine used in the complex are deducted from the annual sales of the complex, or, if sulfuric

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[4] U.S.-Mexico Study (to be published). See also Appendix 5A.

[5] Phosphatic Fertilizers, Technical Bulletin No. 8, The Sulfur Institute, Washington, D. C. (1966).

acid is used, the costs as computed by Eqs. (11) and (12) are added to operation and maintenance costs.

9\. For the sale of power to a grid or for a grid-tie interconnection to provide reliability when only one reactor is assumed, it is necessary to add the capital investments needed for this facility. The capital investment, in millions of dollars, is given by

$$C_G = 7.3\left(\frac{L_G}{250}\right)^{0.43}, \tag{13}$$

where L_G is grid power, Mw. This investment is based on power transmission over a 100-mile distance and includes a switchyard incorporating stepup transformers and their associated high-voltage breaker, high-voltage transmission breaker, transmission lines, and receiving-end switchyard incorporating only breakers. It is based on data presented in a report entitled *Cost Study of Product Water Conveyance and Electric Power Transmission for Large Nuclear Dual-Purpose Plants.*[6]

10\. The costs of harbor facilities include harbor improvements and administration facilities. In general, improvements include two- and four-position docks, 100 ft wide by 1000 to 1500 ft long. Dredging is included, assuming a bottom consisting of half sand and half rock and costs of \$6.00 per cubic yard. Breakwaters to shield the docks and tanker mooring and submarine fuel lines are included. Harbor administration consists of an administration building, harbor fire station, and miscellaneous vessels. For complexes manufacturing ammonia, elemental phosphorus, aluminum, and caustic-chlorine, the capital investment for a harbor may be approximated using the relationship

$$C_H = 18\left(\frac{\mathrm{Mw_e}}{500}\right)^{0.21} \tag{14}$$

where C_H is capital cost, millions of dollars, and $\mathrm{Mw_e}$ = power plant net electrical output in megawatts after deduction of grid power. For nuclear agro-industrial complexes also producing food, the cost of harbor facilities may be approximated using

$$C_H = 18\left(\frac{\mathrm{Mw_e}}{700}\right)^{0.6}, \tag{15}$$

where $\mathrm{Mw_e}$ is power plant net output in megawatts after deduction of grid power but including power for water. These relationships are valid over the power range of 500 to 2700 Mw. Equation (15) is only valid for operation of turbines in the back-pressure region without bypass.

11\. A town was provided only for foreign locations of nuclear agro-industrial complexes. To size the town the following assumptions were made:

1. For each agricultural and for each industrial worker one additional service worker is required.
2. On the average there would be five people per household and five workers for each three households.

In other words, there will be two nonworkers for each worker. Thus, as an example, assume 3000 industrial workers and 5500 agricultural workers at a complex. The town would contain 8500 service workers in addition to the above industrial and agricultural workers, and the total population would be 51,000. The capital investment needed to provide facilities for the workers and their families was calculated based on an allowance of \$300.00 per person. This money is not intended to furnish all the facilities needed for the town, but it is sufficient to provide initial housing for the workers and their families, sanitary and water facilities, and streets.

12\. Capital and operating costs for United States industrial complexes are computed by reference to ORNL-4296; capital costs of the various industries may be found in Table 1 or 2. The direct and indirect costs are obtained by use of the approximate tables which are indexed in this report. However, the cost of utilities must not be included when determining the economic balance sheet for a nuclear-powered complex. For non-United States conditions, indirect costs for individual processes must be increased in proportion to the increase in capital costs for overseas construction, while labor costs must be halved.

13\. Capital investment for the farm is linearly scaled according to its water requirements, using as base cases the farms for a 1000-Mgd evaporator listed in Table 6.17. Gross receipts from this table are scaled similarly. Direct operating costs and overhead for the three farm systems without costs of power, water, and fertilizer, in millions of dollars

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[6] Subcontract 2893, Job No. 4087-1, 31 August 1967; prepared for the Oak Ridge National Laboratory by Ralph M. Parsons Company.

per year, are as follows: system 1, 75.7; system 2, 63; and system 3, 56.1. Fertilizer application rates for each of the crops are listed in Table 6.5. Total fertilizer application may be calculated using this table and the crop acreages listed in Table 6.13. Total sales of the complex are reduced by an amount necessary to provide sufficient fertilizer for the farm needs, remembering that ammonia contains only 82% nitrogen.

14. Working capital for complexes is computed as one-third of the annual direct operating costs of the complex.

15. Off-site facilities for complexes are based upon the total capital investment in battery limits plant facilities and are calculated using Eq. (1) or (2) of Sect. 5.6.1.

16. The value of products or gross sales of the complex are computed by using production rate, operating days per year, and the appropriate product sales price f.o.b. factory as listed in Tables 5.9 for industry and 6.7 for the farm. Note that two product price levels, domestic and world export, are assumed for industrial and agricultural products from non-United States complexes. The world export price level for industrial products is assumed to be the same as the United States price level, while for agricultural products this level is assumed to be those prices which are paid to farmers in exporting countries. The domestic price level is, in general, about 30% higher than world export prices and is assumed to represent prices paid by nations which must import these products.

Credit for fissile material produced by the nuclear power source is calculated using the gross thermal power of the reactor, operating hours per year, and reactor technology. Credits for fissile material for the respective technologies are:

LWR	0.0769 mills/kwhr (thermal)
FBR	0.172 mills/kwhr (thermal)
MSBR	0.0351 mills/kwhr (thermal)

Credit for grid power is computed based on output in kilowatts electric, operating hours per year, and the price of power:

LWR	3.4 mills/kwhr (electrical)
FBR and MSBR	2.0 mills/kwhr (electrical)

17. Internal rates of return for the complexes are calculated as described in Chap. 3 and Appendix 3A. Net annual benefits are obtained by deducting all expenses, including the present worth of all investment charges (including interest during construction), computed at the various costs of money (2.5, 5, 10, 20%), from the gross sales of the complex.

NOTE ADDED IN PROOF

In the course of the on-going program on Nuclear Energy Centers, new data have been developed and the old further refined. It is the purpose of this note to call attention to the most significant of these changes and to give an indication of their overall effect.

1) **Aluminum**: The capital cost of a plant producing fabricated aluminum was found to be too high by about 20%. Also, the United States price used for fabricated aluminum of 32$\frac{1}{2}$¢/lb should be increased to at least 37¢/lb. The effect of including these corrections would be to increase the internal rate of return of the complexes producing aluminum by about 1 point. Furthermore, there would be little difference in rate of return between complexes with and without fabricated aluminum production (Fig. 7.1, p. 139).
2) **Electrolytic Ammonia**: The indirect cost factor for the water-electrolysis plant should be increased, causing an increase in the overall plant investment of about 9%. This change would cause a decrease in the internal rate of return of less than 0.1 point.

The above changes do not affect the overall conclusions of the report. A detailed discussion of the recommended changes will be included in ORNL-4296, *Tables for Computing Manufacturing Costs of Industrial Products in an Agro-Industrial Complex,* by H. E. Goeller (to be published).