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PROSPECTS FOR SEA-WATER DESALINATION WITH NUCLEAR ENERGY

AN EVALUATION PROGRAM

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PROSPECTS FOR SEA-WATER DESALINATION WITH NUCLEAR ENERGY

AN EVALUATION PROGRAM

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ABSTRACT

An evaluation and preliminary design program is proposed for the application of large nuclear reactors to the distillation of sea water. The applicable technology of evaporation processes and low-fuel-cost reactors is surveyed and applied to the projection of the cost of producing fresh water in large plants.

1. SUMMARY

Shortages of fresh water are increasingly apparent at a number of places in the United States and in other parts of the world. As demand increases and water tables and other local supplies are exhausted, each new water-diversion project becomes more costly. Many of the areas affected are near the sea, so that any possibilities of an economical supply from this unlimited source are of immediate interest. For many potentially productive regions of the world the sea is the only feasible new water source.

Recent preliminary studies indicate that large nuclear reactors may provide a way to produce fresh water for such areas at costs acceptable for municipal and industrial use, and possibly for crop irrigation as well. At the same time, sufficient electric power could be generated to supply the needs for regional growth. Natural-uranium-fueled reactors, which are currently feasible to construct in the size range of 1000 to 3000 Mwt, appear to offer attractive water costs under the conditions of municipal ownership. When producing byproduct power, such stations are estimated to attain water costs of about 15¢ per thousand gallons under current price conditions. There is an existing market for such water in several areas.

The present and potential demand for water in many cases is large enough to consume blocks of energy for desalination which are considerably larger than have been contemplated for nuclear electric stations. Although additional study is needed, there is evidence that nuclear energy in such blocks may be cheaper to construct and cheaper to fuel than in smaller units. Studies made independently by Oak Ridge National Laboratory, Sargent & Lundy, and Los Alamos Scientific Laboratory indicate that the steam-raising portion of a nuclear plant, which now costs \$25 to \$35 per

thermal kilowatt at 1000-Mw capacity, might be reduced to $15 per kilowatt and below in sizes above 10,000 Mw. Combined with power generation and large-scale fueling economies, such a reactor, if attainable, would offer water costs in the range below 10¢ per thousand gallons.

Such estimates are naturally dependent on the assumed marketing conditions. For the large reactors, it was assumed that power produced would be worth 2.5 mills/kwhr, and that plutonium could be sold at $6.70 per gram. Although major savings from improvement and scaleup of evaporator units were not assumed, a brief study at Oak Ridge National Laboratory and consultation with experts in the field indicate cost savings in this area are possible. The range of uncertainty in water cost estimates is large at present, but acceptable costs cover an even wider range in some water-shortage areas of the U. S. and abroad.

The work to date has shown that the subject of nuclear-powered sea-water-conversion plants is a complex one in which both reactor and evaporator equipment must be studied in an economic environment different from their customary applications and must satisfy new types of technical, siting, and marketing conditions. The preliminary indications must be verified and extended, and the technical basis obtained for planning a sound program of orderly development as indicated by the information produced. The Oak Ridge National Laboratory proposes a thorough evaluation program to fulfill these objectives and to form the basis of a continuing program if justified by the results. Most of the effort at first would be employed in the evaluation of sea-water plants using reactor types representing existing technology. A smaller effort would be devoted to selection of advanced technical concepts which can potentially offer lower water costs.

Table 1.1 summarizes the range of water costs which may be obtainable by the application of nuclear energy to the water supply problem.

Table 1.1. Projected Cost of Water From Nuclear-Powered Water-Distillation Plants

Type of Reactor	Cost of Water (¢/1000 gal)		Assumed Value of Power (mills/kwhr)
	Water Only	Water + Power	
Short-range converter	31	14	5
Improved converter	19	10	2.5
Advanced breeder	18	6	2

2. PURPOSE, FEASIBILITY, AND OUTLINE OF CONCEPT

2.1 Purpose

The program of investigation proposed in this report is aimed at a possible new area for the utilization of nuclear energy, the large-scale desalination of sea water. Over the past few months the Oak Ridge National Laboratory has made a preliminary survey of nuclear sea-water plants and of the status of the associated technology. The results of the survey are believed to be sufficiently promising to warrant the proposed further work.

This report presents in Sec. 3 a brief summary of some of the reactor and water-conversion technology which is applicable to sea-water desalination, and illustrates with a few examples the nature and possible performance of plants which are believed feasible in the near future as well as those expected with some advance in technology.

Although the indicated water costs are substantially lower than are those expected from any other route to water desalting, there is at present no program for development of very large reactors or large-scale evaporator plants which would lead to the type of unit needed. Therefore, it is essential that a thorough evaluation be made of the prospects for economical nuclear water plants and of their utility in relieving water shortages in the United States and abroad. The needed study would include an investigation of alternative technical routes and development of recommendations for the appropriate development of this new resource. The proposal does not include construction of a sea-water plant at this time, although this would be technically feasible. A period of rapid technical advance is anticipated in the early stages of the investigation, and any recommendation for construction of a pilot or developmental plant would be made later when appropriate. It is expected that such construction, when warranted, would be undertaken through the normal industrial channels.

An important part of the problem of developing the large plants would be gaining the capability of constructing equipment of great capacity. One purpose of a developmental plant would thus be the testing of components. The program in its entirety will require the cooperation of many laboratories, contractors, and agencies of the Government, to add their special abilities to the effort proposed herein.

2.2 Technical and Economic Feasibility

The technical feasibility of the proposed application is assured, since it is clearly possible to construct a reactor which generates steam and to couple this with turbines and sea-water evaporators. The technical aspects that must be considered are those concerned with cost, and these must be related to the nature of the market served. Oak Ridge National Laboratory has studied the available information as to the current and projected needs for water supply in certain water-shortage areas, in order to get some idea of the price at which desalinated water would become attractive and in what quantity.

Although there are projected needs for extremely large quantities of water in the future, both for city water and for crop irrigation, it was surprising to find that there are large present-day critical needs which can support high water costs. Quantities of 200 million to 2 billion gallons per day could be marketed in several areas at municipal water prices of 20 to 30¢ per thousand gallons. Some examples of these water supply situations are summarized in Appendix I.

2.3 Status of Non-Nuclear Water Costs

The technology of conventional saline water conversion is characterized by attempts to reach an acceptable compromise between energy conservation, equipment cost, and operating cost. The proven process that is currently least expensive when applied to sea water is regenerative evaporation using steam heat from a fossil-fuel boiler. Two small demonstration plants of this type are in operation under the program of the Office of Saline Water, U. S. Department of the Interior, and a third is under construction. Each uses a different type of regenerative evaporator equipment. Projected water costs from large plants using this process are in the range of 35 to 60¢ per thousand gallons for single-purpose plants and can be reduced by using exhaust steam from a power plant. There are other potentially attractive water-conversion processes, but none are as well developed as the evaporation process and they have not so far been evaluated for the application of nuclear energy. A symposium published by the American Chemical Society summarizes the recent work in the field.[1]

2.4 Comparison of Fossil-Fueled and Nuclear Plants and Significant Cost Areas

For the evaporation process, the substitution of a nuclear reactor for the boiler is worthwhile only if it can produce cheaper heat. It is of interest to compare the nuclear and fossil heat sources with respect to the components of heat cost. Table 2.1 gives an approximate breakdown of the steam costs from the two 1100-Mw heat sources studied later in this report.

It is readily apparent that the net fuel cost of 2.5¢ per million Btu for the natural uranium reactor is of major significance compared to the cost of fossil fuels. The value of fuel cost in the table is based on a

Table 2.1. Comparison of Steam Cost Components, 1100-Mw Plants

	Coal-Fired	Natural Uranium
Capital cost, ¢/10^6 Btu	8.0	8.5
Operation and maintenance (includes D_2O charges)	2.0	7.8
Fuel	34.1	7.5
Plutonium credit	——	(5.0)
Total	44.1	18.8

municipally financed large-scale fuel plant, and the plutonium credit is based on fuel value in enriched reactors or fast breeders. There are other reactor fuels which are potentially attractive, and costs of these are also subject to various influences and assumptions. The effect of various assumptions on the cost of water and the basis of the fuel costs chosen for this report are discussed in Secs. 3.2 and 3.4.

Under the municipal ownership assumptions used in Table 2.1, the cost of coal predominates in the one case, and the capital and operating charges are most important in the other. Building of larger-capacity units may be expected to lead to improvement in both capital cost and operating cost. Such improvement, if attainable, can be seen from the table to offer much more significant gains in the case of the reactor than for the boiler. The effect of scaling reactors to large sizes, discussed in Sec. 3.1, is thus an important aspect of the study of nuclear water-conversion plants.

The third technical area which merits attention is the evaporator portion of the plant. There is no basic difference in the equipment whether operated on steam from a reactor or a boiler. However, the large unit sizes in which reactors must be constructed to obtain low cost give impetus to consideration of larger evaporator units and more compact plant arrangement than has been customary. The lower cost of heat from reactors, if attained, will make possible evaporators requiring fewer stages of regeneration, thereby leading to lower construction cost. New materials and techniques of construction, some developed in the reactor industry, may find application in the large-capacity plants needed for major water supplies. A survey of the status of this technology is presented in Sec. 3.3.

3. TECHNICAL STATUS

This section briefly outlines the preliminary studies and current status of technical problems in the application of large reactors to water desalination. From the available information, projections are made of expected water costs, both for short-range and long-range prospects. From this background, the need and character of proposed further work can be assessed.

3.1 Reactor Capital Costs

Experience with construction cost of reactors so far shows a pronounced trend toward lower unit cost as the size increases. Unfortunately, the larger reactors are also the most recently built, in many cases, so that the possibility of technical improvements and removal of unnecessary safety factors tends to prevent any clearcut conclusion as to the effect of scaling to larger size. Other industries, however, notably the chemical and electric power industries, observe construction cost economies occurring at larger size, for reasons which are probably equally valid in the case of reactors. The very large units which are justified by water plant needs could take advantage of such a trend, and pronounced reduction in the cost of water could result.

Short of actually constructing a large and a small plant at the same time, the most reliable source of evidence on the effect of size is a plant design, layout, and complete cost estimate. There are presently available four studies of large reactors of the natural-uranium-fueled heavy-water-moderated type of interest for sea-water-conversion plants.[2,3] Three of these studies used the plant layout method of cost estimation. Table 3.1

lists the results of these estimates, and the exponential ratio exhibited. In each case only the steam-generating portion of the plant is included, and appropriate indirect construction costs are added. The cost of D_2O inventory is not included, being treated as an operating charge. All the plants are referred to the same small Du Pont reactor to obtain a scaling law. The last column of the table gives cost per thermal kilowatt. The 25,000-Mw Oak Ridge design is actually three 8300-Mw reactors in interconnected separate enclosures. The ORNL and Sargent & Lundy estimates of this design used separate layouts, but some of the sources of information from vendors were the same.

Table 3.1. Construction Cost Projections for Large Reactors

	Estimator	Reactor Designer	Thermal Output (Mw)	Cost ($\$x10^6$)	Scaling Law ($C \sim P^x$)	Cost/kwt ($)
A.	Natural Uranium, D_2O Moderated Reactors*					
1.	Du Pont	Du Pont	1,260	34.2	--	27
2.	Du Pont	Du Pont	3,700	73	0.7	20
3.	Sargent & Lundy	ORNL	3,500	72	0.7	21
4.	ORNL	ORNL	25,000	375	0.8	15
5.	Sargent & Lundy	ORNL	25,000	325	0.75	13
B.	Pressurized Water Reactors (Low-Temperature Process Heat)					
6.	ORNL	ORNL	1,000	18.9	--	19
7.	ORNL	ORNL	10,000	62.4	0.5	6
C.	Fast Breeder Reactors					
8.	LASL	APDA	1,000	28	--	28
9.	LASL	LASL	10,000	80	0.5	8
10.	ORNL	LASL	25,000	144	0.5	6

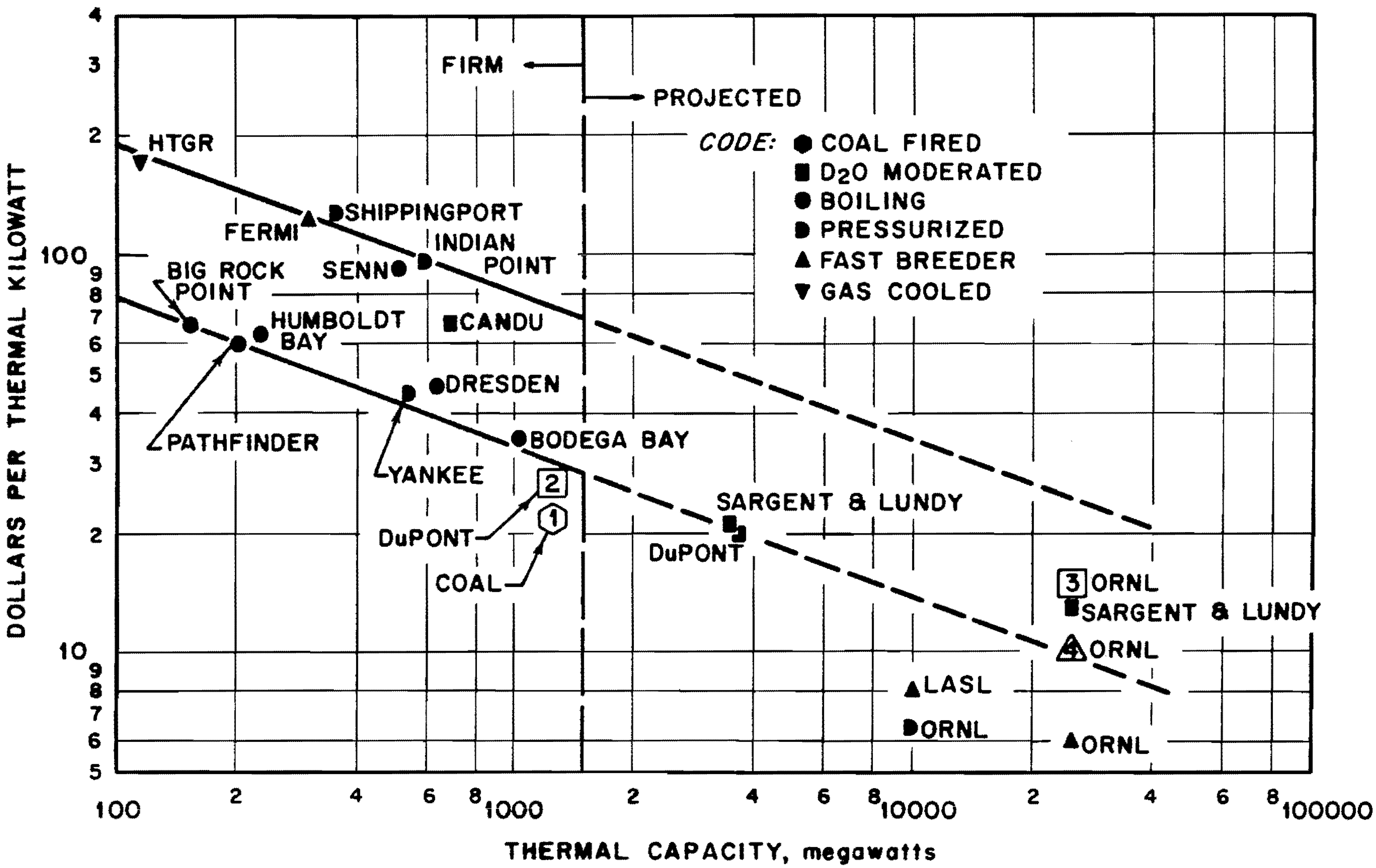
*D_2O inventory cost is treated as an operating expense and is not included in construction cost.

Items 6-7 and 8-9-10 in Table 3.1 represent another method of estimating the effect of scaleup. In this method, each of the major components or subsystems of the plant is roughly designed, its size and weight estimated, and cost assigned to the large-scale item on a comparative basis with the known cost or estimate for the small item. The sum of the small items equals the total cost of the small plant, and the sum of the large items is taken as the cost of the large plant. The type of plant layout needed for this method is less detailed than for the previous method, and the results are necessarily less reliable.

Comparison of the indicated scaling laws for the three types of reactors gives some ground for suspecting that different types of reactors may scale somewhat differently, and that this difference may be related to the compactness of the core.

A third method of estimating scaling effects consists of plotting the known costs of as many reactors as possible as a function of capacity and observing the envelope of the points. This method can be made more useful by plotting families of reactors of the same type, and excluding extremely small or first-generation reactors and experiments. Figure 3.1 gives some selected sets of this type. In each case, the electrical portions of the plant have been excluded. The estimates given in Table 3.1 are also shown. All values plotted represent cost per thermal kilowatt including the appropriate portion of indirect costs. The numbered points represent the four steam sources (No. 1 is coal-fired) used to estimate water costs in this report.

The work to date on the subject of cost scaling is preliminary and incomplete. There is nevertheless some basis for expecting an appreciable



Costs of Nuclear Steam Generating Facilities.

FIG. 3.1

cost benefit to be available for sea-water-conversion reactors from their utility in large sizes. It is clear that further work is needed to assess this benefit in more quantitative terms, using reactor designs which are optimized for their task and plant layouts which are carefully matched to the needs of safety requirements, evaporator arrangement, etc. It would be highly desirable to have available the cost of a given type of desalination reactor as a well-defined function of its capacity. This would permit the rapid optimization of plant design to suit the needs of any given water supply problem.

3.2 Fuel Cycle Costs

3.2.1 The Effect of Industry Size on Natural Uranium Fuel Cost.

The study of this topic was based on current technology and existing operating experience. The fabricating costs for vibration-compacted UO_2 were based on current work in this field by Du Pont at Savannah River and by General Electric at Hanford. As shown in Table 3.2 and the accompanying graph, Fig. 3.2, fabricating cost is halved by a tenfold increase in plant throughput. Chemical processing cost is derived from plants designed by Du Pont[4] for 1- and 10-ton-per-day throughput using well-developed Purex processing. The sevenfold variation in cost with one decade of capacity range is a reflection of the fact that a large processing plant is still relatively small as chemical plants go, and the costs are therefore quite scale sensitive. Shipping costs used are based on actual experience in fuel shipments between Chalk River and Savannah River. The plutonium credit of \$6.70 per gram as nitrate is consistent with AEC projections[5] based on U_3O_8 at \$5.00 per pound. The effect of changes in the plutonium price is discussed later.

Table 3.2. Fuel Cost of Natural Uranium Reactors Under Municipal Ownership

Fuel Fabrication Costs ($/kg U)

Step	Capacity (1 ton U/day)	Capacity (10 tons U/day)	Remarks
Purchase U_3O_8	$ 13.00	$ 13.00	Based on AEC prediction of $5/lb U_3O_8 in 1970.
Conversion $U_3O_8 \rightarrow UO_3$	3.00	0.68	Harrington and Ruehle's *Uranium Production Technology*.
Zircaloy components	7.41	6.12	Quotation from Harvey Aluminum Co.
Plant capital cost* for conversion $UO_3 \rightarrow UO_2$, "Dynapak" treatment of UO_2, final assembly and inspection	1.79	0.70	Costs based on DP-570,[6] discussions with Du Pont and General Electric personnel.
Plant operating costs	5.36	1.54	
Cost of complete element ($/kg U)	$ 30.56	$ 22.04	

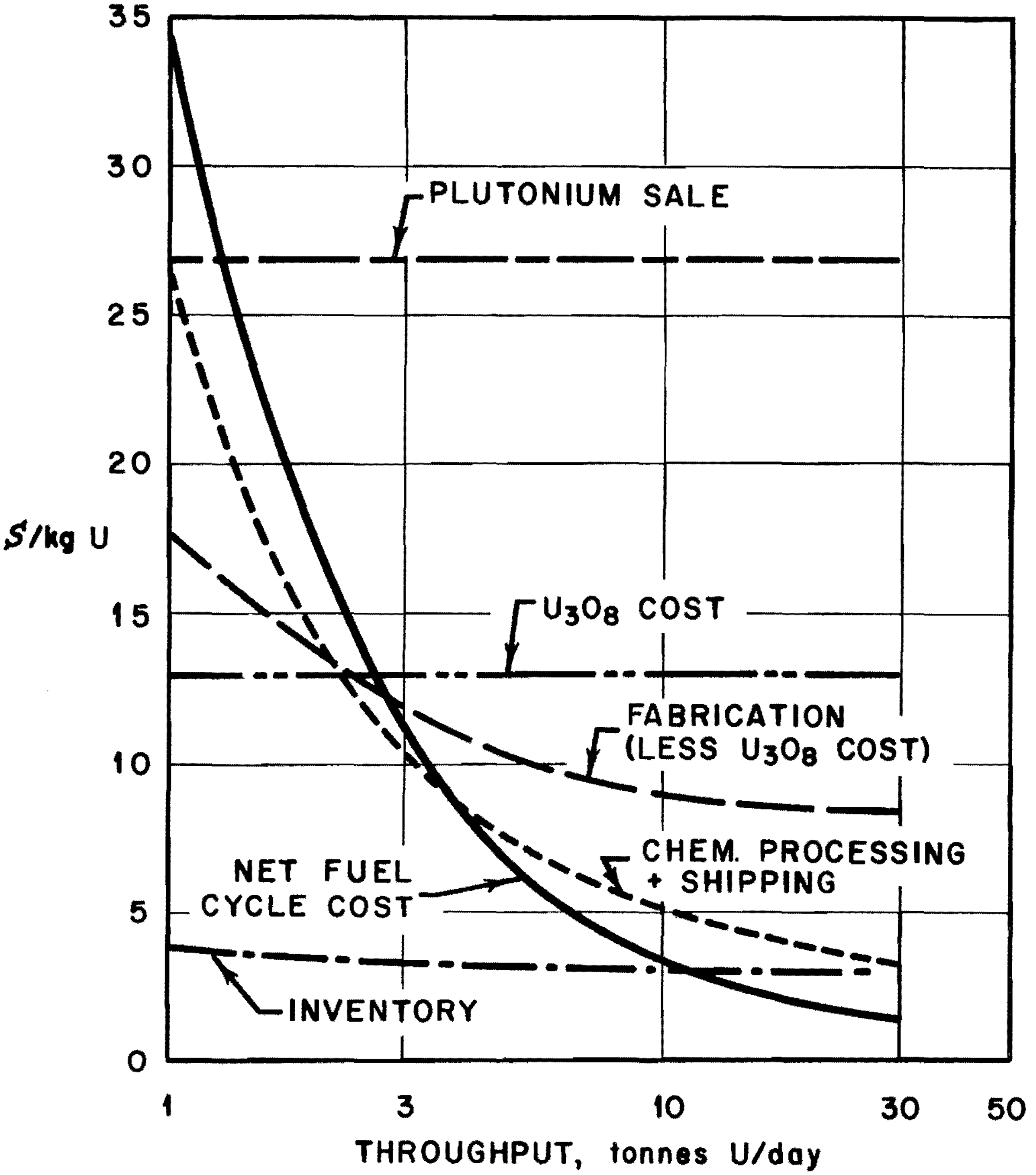
Complete Fuel Cycle Costs ($/kg U)

Step	Fabrication Capacity (tons/day) / Processing Capacity (tons/day)	1 / 1	1 / 10	10 / 10
Fuel element fabrication, including U_3O_8		$30.56	$30.56	$22.04
Shipping fuel		1.42	1.42	1.40
Chemical processing		25.25	3.70	3.70
Fuel inventory costs**		3.82	3.82	3.09
Plutonium credit***		(26.80)	(26.80)	(26.80)
	Total	$34.25	$12.70	$ 3.43
	Mills/kwhr(t)	0.214	0.079	0.0213

*Based on municipal financing charges.

**Based on 5.5% annual charge on complete fuel element inventory, 2.1-yr fuel cycle.

***At $6.70 per gram projected by AEC for 1970.



Fuel Costs in Natural Uranium Reactors as a Function of the Size of the Industry.

FIG. 3.2

As the plant capacity changes from 1 to 10 tons per day, the gross fuel cost changes from $61 to $30, but the net fuel cost changes tenfold—from $34.25 to $3.43. A 10-ton-per-day plant corresponds to 75,000-Mw thermal output. The Commission's existing plants give assurance that operations in this general-capacity range are feasible.

For estimating water costs, the middle column of Table 3.2 was used for the Du Pont reactor, representing a series of 1-ton-per-day fabricating plants and a single 10-ton-per-day processing plant for a total industry of 75,000-Mw thermal output. The resulting fuel cycle cost is 0.079 mill/kwhr(t). Column 3 was used for the 25,000-Mw station, representing a unified 10-ton fabricating and processing plant. The study also showed continued lowering of fuel cost up to plants of 30-ton-per-day throughput.

For the fast breeder reactor, the same fueling estimates were used with appropriate adjustments to reflect the much higher costs at certain steps due to the presence of plutonium, higher enrichment level, and higher burnup and power density.

3.2.2 <u>Significance of Study</u>. This study indicates the possibility of obtaining very low fuel costs with a present-day reactor type by merely building enough of them to sustain a large central plant. The same general principles would apply to fuels for reactors other than the natural uranium type, but those having a high burnup charge and lower byproduct production would experience a much less significant total effect from scaleup. If desired, existing unused capacity in the Commission's fabricating and processing plants at Hanford and Savannah River could be used to fuel water stations until a large plant could be sustained by the water industry alone.

A specific fuel element design optimized for a saline-water-conversion reactor does not now exist. The preliminary efforts in this direction should be extended to include lattice and thermal optimization, measurement of void coefficient, and in-pile performance testing. The possibilities of plutonium recycle and use of thorium as a fertile material should be investigated. Fast breeder and thermal breeder fuel cycles should be analyzed under the conditions imposed upon water-desalting reactors, and conclusions obtained as to their cost potential and technical utility for such application. The important possibility of obtaining reduced cost and improved safety through the use of mobile fuels should be investigated.

3.3 The Cost of Evaporators

The cost studies reported here are restricted to regenerative evaporators of the multi-stage flash type and of the multi-effect vertical type. These types are in successful operation in several locations throughout the world in small units having a maximum capacity of about 1 million gallons per day (gpd). This size plant has approximately the same condensate output and heat transfer surface as the condenser(s) for a 200-Mwe steam turbine. Considerably larger units are used in the chemical industry for concentrating liquids other than sea water, but none approach the capacity needed for a nuclear sea-water station using an economic size of reactor.

Under the auspices of the Office of Saline Water, larger sea-water plants extending up to 50 million gpd have been studied by W. L. Badger Associates, Inc., by the Fluor Corporation, and by Bechtel Corporation. At the request of ORNL, estimates for larger installations, including, in one case, single units of 100 million gpd, have been prepared by W. L. Badger Associates, and by engineers of Union Carbide Nuclear Corporation.

There is considerable variation in the plant costs predicted. The variations are caused by different site conditions, different sea water and steam supply temperatures, the use of different types of evaporators, and by the provision of different degrees of heat regeneration. Heat regeneration is expressed by the performance ratio, R, defined as the pounds of water distilled per 1000 Btu of heat input.

The evaluation of evaporator plant costs is facilitated by breaking the total into two categories: 1) the cost of heat transfer equipment, which is approximately proportional to R, and 2) the cost of sea water supply, pumps, site preparation, etc., which are relatively independent of R. The cost of the heat source is not included, it being considered a part of the cost of heat.

Table 3.3 summarizes the available studies of large evaporator plants, and lists total plant costs in terms of capital investment per daily gallon of distillate capacity. The table includes a breakdown into the cost of non-heat exchanger portion and of the heat exchanger portion per unit R.

As commonly operated, multi-stage flash evaporators are limited by solids deposition to about 50°F lower brine temperatures than are the vertical type. In the last column of the table, the heat exchange costs of these evaporators have been corrected in order to show all types relative to the same temperature differences.

It can be seen from the table that the cost per daily gallon of evaporator equipment itself can be rather reliably ascertained, while the cost of sea water supply and other auxiliary installations is less certain. It would be expected that the size of the installation would have a strong influence on this latter term and that, as in irrigation canals and pumping

Table 3.3. Projected Costs of Sea-Water Evaporator Stations (Less Heat Source)

Estimate By	Evap. Unit Size (gpd x 10^6)	Type	Performance Ratio, R	Total Cost (¢/dg)	Non-Heat-Ex. Portion (¢/dg)	Heat Ex. Portion Per Unit R (¢/dg)	Corrected to Equal Steam Temp. (¢/dg)
Bechtel	8	LTV*	10.7	109	34	6.9	6.9
Bechtel	14	MF**	13.65	77.2	28	3.6	2.5
Badger	15	LTV	9.5	38.0	4.7	3.5	3.4
UCN	18.5	MF	5	37.4	9.3	5.6	3.8
Fluor	25	MF	13.65	63.7	12.3	3.8	2.6
Badger	100	LTV	3.3	17.3	5.7	3.3	3.3
ORNL	Large				7.0		3.8

*Long-tube vertical type.

**Multi-stage flash type.

plants generally, the cost of a unit of capacity is less for a large project than a small one.

The last row in Table 3.3 lists the values chosen for estimating the cost of water plants used as examples in this report: 3.8 x R for the evaporators, and 7.0 for the rest of the water plant. Thus, a 1-billion-gpd plant would cost $260 million if R = 5, and $450 million if R = 10.

The appropriate value of R is chosen to give the minimum cost of water and depends primarily on the cost of heat. For the cost formula chosen, the optimum performance ratio is given by $R = 2.7\sqrt{H}$, where H is the cost of heat in ¢/million Btu. The low heat costs offered by large reactors thus favor low performance ratios and hence a relatively small evaporator investment per unit of capacity. If heat were somehow provided free, there would be no incentive to conserve it, and a simple still would be used instead of a regenerative type. Assuming the same costs for chemical treatment, maintenance, and operation as for the other evaporators, the water produced with free heat would cost about 6¢ per thousand gallons.

The development of evaporators suitable for large-scale nuclear water plants calls for a scaleup in capacity of 100-fold or more over existing plants. It is to be expected that new concepts of evaporator design, plant layout, and technique of construction will be found best suited to this new size category. Oak Ridge National Laboratory has found that the following possibilities already show sufficient promise to warrant further study: 1) prestressed concrete shells, 2) use of very long tubes fabricated on-site, 3) use of titanium tubes, 4) multi-level flash evaporators. Other areas which should be probed are corrosion control, alternative materials for tube sheets and baffles, use of vapor compression stills, and freezing processes. The possibility that lower cost can be obtained from such investigations is strong, since large evaporator plants have received so little attention so far.

3.4 Examples of Sea-Water-Conversion Plants and Water Costs

Utilizing the information presented above, estimates have been developed for eight plants, using four heat sources: 1) a modern coal-fired boiler, 2) a converter reactor which could be undertaken at once, 3) an improved large reactor of the same type, and 4) an advanced breeder reactor. Each heat source is studied both as a plant producing water only, and as a dual-purpose plant in which some of the energy in the steam is converted to electric power before entering the evaporator. Since the supply of water is traditionally a function of governmental agencies, the plants studied were all assumed to be 30-yr self-liquidating projects under municipal ownership. The procedures of the AEC Cost Evaluation Guide[7] were followed, using the fixed charge rates given therein for a municipal owner: 7.7% on plant equipment and 5.5% on working capital and non-depreciating inventories.

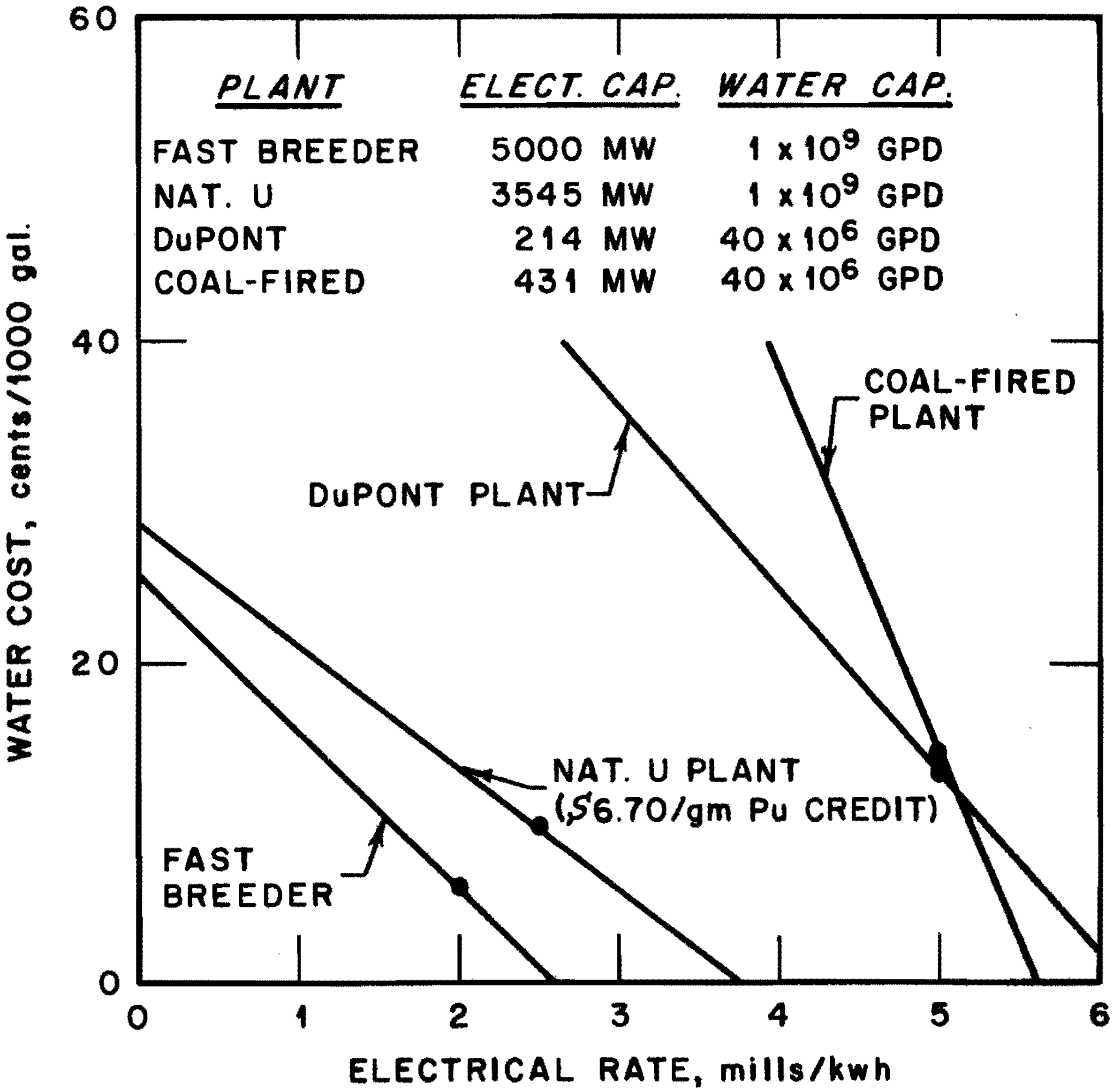
The eight plants are compared in summary form in Table 3.4. The operating costs shown include capital charges, inventory charges, fuel cycle costs, losses, operating and maintenance expenses, and cost of nuclear liability insurance. A description of the reactors and a breakdown of operating costs are given in ORNL-TM-432.[8] For the plants producing water only, the optimum performance ratio is used in the evaporator. For those producing water and power, an arbitrary split of energy between water and power output is made, and the evaporator performance ratio is arbitrary.

The market value assigned to power produced is, of course, an arbitrary one, as the total operating costs could be allocated between the two products in various ways. In Fig. 3.3 the four dual-purpose plants may be compared for the effect on water cost of choosing other values for byproduct power.

For the natural uranium reactors the value of byproduct plutonium is an important element in operating cost. The price of $6.70 per gram assumed is based on AEC projections of value as a fuel material in enriched reactors. If it were assumed that enriched or fast breeder reactors did not eventually provide a market for plutonium, the fuel cost and the cost of water would be higher than shown in the examples. It would be necessary then to consider recycle in D_2O reactors. The alternatives are: 1) a throwaway cycle, 2) Pu recycle in natural uranium, 3) Pu recycle in depleted uranium, 4) Pu recycle in thorium. The physics of these

Table 3.4. Summary of Cost Estimates for Nuclear Water Plants

Plant Type	Coal-Fired	Natural U, D_2O (Du Pont)	Natural U, D_2O (ORNL)	Fast Breeder (APDA Type)
Thermal output (Mw net)	1110	1150	25,000	25,000
Water output, single-purpose (10^6 gpd)	130	132	1640	1530
Evaporator performance ratio	13	11.7	6.6	6.3
Construction cost ($\$10^6$)				
Steam source	27.7	34.2	375	250
Evaporator plant	74.7	68.0	526	470
Total (less D_2O)	102.4	102.2	901	720
D_2O inventory ($\$10^6$)		12.5	72	
Annual cost ($\$10^6$)				
Capital	7.9	7.9	69.4	55.4
Inventory, fuel, and operating expenses (coal, 30¢/10^6 Btu)	13.0	5.4	34.2	35.5
Total	20.9	13.3	103.6	90.9
Cost of steam only (¢/10^6 Btu)	44	18.8	6.2	5.2
Cost of water (¢/1000 gal)	49	30.5	19.2	18.1
Water output, dual-purpose (10^6 gpd)	40	40	1000	1000
Electric output (Mw)	431	214	3545	5000
Evaporator performance ratio	13	7.7	4.9	5.3
Construction cost ($\$10^6$)				
Steam source	27.7	34.2	375	250
Turbo-electric plant	33.1	21.5	275	300
Evaporator plant	22.6	14.5	257	270
Total (less D_2O)	83.4	70.2	907	820
D_2O inventory ($\$10^6$)		12.5	72	
Power price assumed (mills/kwhr)	5.0	5.0	2.5	2.0
Total annual charges and expense ($\$10^6$)	16.8	9.3	94.8	91.7
Power revenue (80% LF)	15.1	7.5	62.4	70.5
Water revenue (90% LF), (*80% LF)	1.7*	1.8	32.4	21.2
Cost of water (¢/1000 gal)	14.5	13.5	9.8	6.1



Effect of Electrical Rate on Water Production Costs.

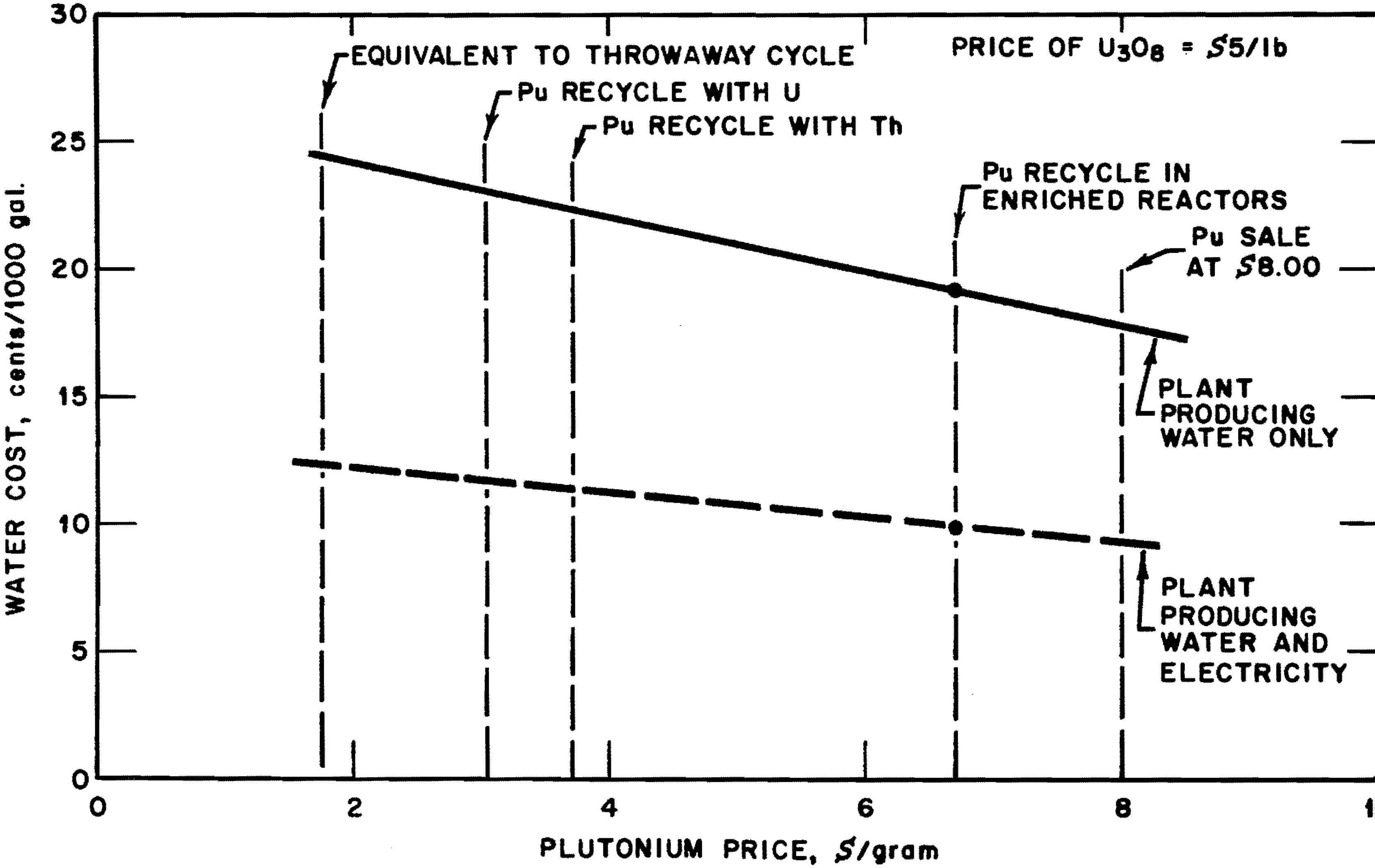
FIG. 3.3

alternatives has been briefly examined, and it appears that a partial or complete reloading of the same reactor with any of the recycle fuels would be successful. A more thorough study of this possibility is embodied in the proposal, particularly emphasizing the most favorable case of recycle in thorium. Figure 3.4 shows the effect of the market value of plutonium on the cost of water from the large natural uranium reactor. The vertical bars represent the value corresponding to each of the various marketing or recycle assumptions.

3.5 Conclusions and Indications for Further Work

The application of nuclear energy to large-scale distillation of sea water is technically feasible at the present time. The usefulness of such plants would depend upon their ability to meet economic conditions affecting the supply of water. Preliminary indications have been found that these requirements can be met with existing technology in limited cases of municipal water supply in extreme shortage areas. Larger supplies for regional development of arid land will require advances in technology to obtain lower cost heat and to acquire the capability of constructing and safely operating the large-unit plants required.

At least one technical route to the objective seems to be open, and it is proposed that others be sought as well. This route emphasizes the use of reactors having a high neutron economy to achieve a low burnup cost in the fuel used. There is strong indication that other fuel costs can be reduced by operating large-scale fuel plants, which are compatible with the projected needs for water. Reactor capital costs also are likely to be reduced, though less rapidly than fuel costs, by scaleup to large-size units. A quantitative study of this effect and of the concurrent problems



Effect of Plutonium Price on Water Cost-25000 MwT Natural Uranium Reactor.

FIG. 3.4

of developing large-scale plant components is essential in any further program. In very large reactors using on-stream refueling, boiling light-water cooling is believed practical, permitting the heavy-water investment to be reduced to about $3 per thermal kilowatt. A survey of evaporator technology indicates that existing processes are adequate for the objective and that the scaleup of existing construction techniques, while requiring a major effort, is feasible.

An important aspect of any program for following up the preliminary indications would be the tailoring of the technical plant parameters to a specific need or "customer". Study of water-shortage areas, market conditions, site selection, hazards and waste disposal analysis must be undertaken, and the results will exert major influences on the optimization of the reactor and water plant. Thus it is essential that an integrated approach to the water supply task be adopted, since the feasibility of each proposed plant must be judged independently.

For the longer range aspect, it is believed that advanced converter and breeder reactors will ultimately provide heat more economically than the best current types. Advancement in water-conversion processes and technology is to be expected also. Together, the potential advancements may result in greatly lowered water costs. Some of these benefits may be obtainable in a relatively short time. For these reasons, a continued probing and evaluation of advanced plants is a necessary part of any investigation of the prospects for nuclear-powered desalination of sea water.

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Appendix I

EXAMPLES OF SHORT-RANGE MARKET FOR MUNICIPAL WATER WHICH COULD BE SUPPLIED USING CURRENT TECHNOLOGY

The future needs for new water supply have been well documented. Perhaps less well known is the fact that there are currently existing requirements for municipal water in the quantities discussed in this report. The Oak Ridge National Laboratory has been advised of the following specific needs.

1. The city of Phoenix, Arizona, and the surrounding Maricopa County, currently have a water deficit of 2 billion gallons a day. This is currently being met by pumping their water table down at the disastrous rate of 20 ft a year. If litigation currently before the Supreme Court is decided in favor of Arizona, about half of this deficit will be met by further diversion from the Colorado River, at the expense of California's allotment. Alternate sources of uncommitted water are almost prohibitively expensive. Some preliminary planning has been done for bringing water over 800 miles from the Klamath River, near the California-Oregon border, to Phoenix. Oak Ridge National Laboratory has given some study to the possibility of relieving this situation by siting a nuclear desalination plant on the Gulf of California near Yuma, Arizona, feeding fresh water to California irrigation projects and to Los Angeles through existing canals. An equivalent amount of Colorado River water could thereupon be released to Arizona further upstream for diversion to Phoenix. This water, though used partly for irrigation, could command a price of 25¢ per thousand gallons, if necessary, in view of the lack of cheaper alternatives.

2. In a 1944 treaty the Mexican Government was guaranteed an average of 1.5 billion gallons per day of Colorado River water at the border near Yuma. They are receiving this amount, but during periods of heavy irrigation, their portion is nearly all return flow from American irrigation projects and is too salty for use. (Salt content is stated to reach 2500 ppm.) Since the Mexicans have developed expensive irrigation projects based on this water, a troublesome international controversy has developed. There is strong reason to believe that this situation could be relieved by providing a small continuous supply of distilled water, with storage, which could be released to dilute the river water at the periods when it is otherwise unusable. The quantity required might be as little as 250 million gallons a day, and since it serves to reclaim about sixfold its volume of other water, it could command a price several times that of irrigation water.

3. A part of the California Water Plan known as the Feather River Project will bring water from northern California into the Los Angeles-San Diego area and points enroute. The portion of this project which crosses the Tehachapi Mountains into the Los Angeles plain is calculated by the proponents of the plan to furnish water at about 18¢ per thousand gallons when very low capital charges are used. The quantity available will reach 2 billion gallons a day by 1998. The power deficit of this portion of the project is about 100 Mw.

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The above information has been obtained from the literature and by informal consultation with various authorities. The Oak Ridge National Laboratory believes that this important subject should receive a much more thorough study and documentation as part of any continuing study.

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