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

ORNL - TM - 432

COPY NO. - 21

DATE - November 1, 1962

PRELIMINARY BACKGROUND STUDIES OF THE PROSPECTS FOR ECONOMICAL DESALINATION OF SEA WATER USING NUCLEAR ENERGY

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SUMMARY

1. Very large reactors supplying heat to evaporators seem likely to be capable of producing fresh water from the sea which is cheaper than can be anticipated from any other presently proposed method, and possibly cheap enough for irrigation. This likelihood is especially strong if production of electric power is combined with production of water.

2. The low cost could be achieved, however, only if quantities of water are produced which are much larger than have heretofore been considered in the saline water program. The cost of such a project and the amounts of water and power concerned tend to approach the scale of large river development projects.

3. It is probably economically practical for municipalities to construct dual-purpose plants for production of power and city water using current technology. These moderate-sized plants could be either nuclear or fossil-fueled.

4. Intermediate size nuclear water plants might be useful as an instrument of foreign aid. Once constructed, such plants would be cheap to operate, especially if existing U. S. reactor fueling facilities were utilized. The small plants would serve as pilot plants for developing larger stations.

INTRODUCTION

The group of summary reports presented here is part of a continuing study of nuclear-powered sea-water-distilling plants at the Oak Ridge National Laboratory. The evaluation is far from complete and the work given here is highly preliminary, but it is offered to give a view of the general trend of results at as early a date as possible.

The somewhat surprising results obtained here do not stem from a major change in technology. Instead, they are a direct consequence of three things: (1) choosing reactors which burn cheap fuels, (2) reducing unit capital cost by scaling to large size, and (3) using low municipal or federal interest rates.

The dual-purpose plants utilize a well-known principle of conserving the latent heat available in a power turbine exhaust to obtain electric power and process steam more efficiently than either could be produced alone.

The reactors discussed represent three different stages of development: (1) a reactor which could be undertaken at once, (2) an improved large reactor of the same type, and (3) an advanced breeder reactor many years off. The evaporators with which they are coupled all represent the current state of the art. Evaporator technology is not expected to remain dormant, but the probable degree of improvement is difficult to assess.

Many of the individual studies have been done in more detail than is reported here, particularly the studies of fueling costs and of the siting and hazards problem. The cost estimating rules of the AEC guide have been followed generally in the economic analysis.

Section 1

DUAL-PURPOSE POWER AND WATER PLANTS FOR MUNICIPAL SUPPLY USING CURRENT TECHNOLOGY

1.1 Du Pont Heavy-Water Natural-Uranium Reactor[1,2]

The information below is presented through the courtesy of the Du Pont Company, Wilmington, Delaware, who have been engaged in developing heavy-water-moderated reactor designs under contract with the AEC, as part of the latter's ten-year program for attaining economic power reactors. It is our understanding that the design work was undertaken within the framework of current technology, and that such a reactor could be considered suitable for construction in the near future.

The reactor consists of a cylindrical calandria tank 18.5 ft in diameter by 17 ft high containing cold D_2O moderator, with 244 vertical pressure tubes containing 41.7 tonnes of natural uranium fuel. The reactor was designed to deliver 302 Mwe net at a thermal rating of 1260 Mw. The fuel elements are cooled by circulating pressurized heavy water entering at 223°C and leaving at 280°C. Steam is generated in U-tube stainless steel heat exchangers at 287 psig.

The steam is admitted to a turbogenerator which may be either non-condensing or partial extraction. Low pressure exhaust or extracted steam at about 10 psig passes into a brine heater. The heated brine is pumped into a flash evaporator, based on current technology, where fresh water is prepared.

The reactor's reference fuel elements, concentric UO_2 tubes clad in Zircaloy-2, are being actively developed as part of the Savannah River Laboratory's experimental program. Alternate Zircaloy-clad uranium metal fuel elements are being developed both at Savannah River and at Hanford (NPR), while Canadian 19-rod cluster elements are other feasible alternates.

Some important additional design parameters are as follows:

1.	Pressure tube, ID, OD	3.896, 4.189 in.
2.	Lattice pitch	11 in.

3.	No. of concentric UO_2 tubes in element	3
4.	Wt. of fuel	25 lb/ft
5.	Fuel cladding thickness	0.020 in.
6.	Fuel length in channel	15 ft
7.	Maximum fuel temperature	2000°C
8.	Maximum surface temperature	294°C
9.	Maximum heat flux	687,000 Btu/hr-ft^2
10.	Maximum, average specific power	54, 30 Mw/tonne
11.	Average pile exposure	7090 Mwd/tonne
12.	Throughput of uranium	51.9 tonne/yr
13.	Maximum coolant velocity	34 ft/sec
14.	System pressure	958 psia
15.	Average moderator temperature	80°C
16.	% of reactor power in moderator	7.2%
17.	Axial and radial D_2O reflector thickness	1 ft
18.	D_2O inventory	625,000 lb
19.	Containment vessel height, diameter	190, 120 ft
20.	Containment vessel design pressure	22.4 psig

Table 1 presents station costs on two bases: one which produces water and only enough steam power to run the plant services, and another using the same reactor in which part of the thermal output is developed for sale of electricity. The costs given are based upon municipal-type financing for a 30-year self-liquidating project; i.e., the burden upon equipment capital is taken as 7.7% per year, with 5.5% upon nondepreciating inventory.

The direct cost of the reactor plant, and reactor auxiliaries and structures is estimated by Du Pont to be $20,405,000.[2] Indirects recommended by the AEC increase this by 68% to a total of $34,200,000. This corresponds to $27.1 per installed thermal kilowatt.

The D_2O inventory, at the currently forecast price of $20/lb, is worth $12,500,000 or $9.9 per installed thermal kilowatt.

Table 1

Cost Estimates for 1260 Thermal Mw Water Conversion Reactor Plant, With and Without Electric Power Sales

		Water Only	Water and Power
1.	Reactor heat output (Mw)	1260	1260
2.	Electric output (net Mw)	0	214
3.	Heat output to water plant (net Mw)	1150	530
4.	Evaporator performance ratio	11.7	7.7
5.	Water output (gal/day)	132 million	40 million
6.	Construction costs ($ million)		
	Reactor	$ 34.2	$ 34.2
	Evaporator plant	68.0	14.5
	Turbogenerator and electric	----	21.5
	Heavy water	12.5	12.5
		$ 114.7	$ 82.7
7.	Annual operating charges ($ thousands)		
	Reactor capital	$ 2630	$2630
	D_2O inventory	688	688
	Net fuel cycle	762	762
	Reactor operating	1725	1725
	Electric plant capital		1657
	Electric plant operating		200
	Evaporator plant capital	5240	1116
	Evaporator plant operating	2230	553
	Total annual cost = revenue	$13,275	$9331
8.	Annual revenue from power (5 mills, 80% LF)		$7,550,000
9.	Annual revenue from water (90% LF)	$13,275,000	$1,781,000
10.	Water price (¢/1000 gal)	30.5 ¢	13.5 ¢

ORNL has revised the Du Pont fuel costs on the following bases: natural uranium purchase at \$5/lb U_3O_8, Du Pont fuel fabrication (\$33.5/kg U) and shipping costs, a revised fuel inventory charge at 5.5%, chemical processing for \$3.70/kg U and Pu sale at \$6.70/g nitrate. As discussed in Section 3, the assumed processing cost is based on existing technology when applied at a large central facility serving such reactors. The materials costs are consistent with current AEC projections for the coming decade. This yields a fuel cost of 0.078 mills/kw-hr-t.

1.2 Coal-Fired Station

A modern coal-fired power station was also considered as a heat source for saline water conversion. Operating as a single-purpose plant for producing electricity, the station is assumed to achieve a heat rate of 8500 Btu/net kw-hr. Under these conditions, 42% of the heat is converted to power (40% net), 12% goes up the stack, and 46% goes into the condenser.

When operated as a dual-purpose plant, the evaporator is substituted for part of the low-pressure stage of the turbine and the condenser. The electrical efficiency drops to 26-34% net; up to 60% of the heat goes to the evaporator.

No consideration was given to a fossil-fuel-fired single-purpose saline water converter because the cost of fuel alone would be 20¢/million Btu or more, compared to 18.4¢/million Btu for steam delivered to the evaporator from the single-purpose Du Pont reactor.

1.3 Discussion of the Economics of Coal and Nuclear-Powered Plants for Municipal Power and Water Supply

Table 2 illustrates power and water costs from the Du Pont natural-uranium reactor and the coal-fired plant cited earlier, each operated at 1260 Mwt. Coal is assumed available at 30¢/10^6 Btu, a relatively low price. Power is sold at 5.0 mills, which is below the price attained with private financing in a coal-fired plant using 30¢ coal.

The table indicates that water can be produced at 13 to 15¢/1000 gal in these plants. The coal-fired plant produces a higher ratio of power

Table 2

Comparison of Reactor and Coal-Fired Plants

1. Capital Cost as Plants for Power Only, $/kwe

	Du Pont Reactor	Coal-Fired Plant
Reactor, boiler	$ 113	$ 55
Turbogenerator and electric	87	70
Condenser system	19	10
Heavy water	41	
Capital cost	$ 260	$ 135

2. Power Cost (mills/kw-hr) With Various Financing

	Du Pont		Coal-Fired	
	Private	Municipal	Private	Municipal
Fixed charges	4.94	2.72	2.69	1.48
Fuel cost (coal at 30¢/10^6 Btu)	0.35	0.31	2.55	2.55
Operation and maintenance	0.71	0.71	0.2	0.2
	6.00	3.74	5.44	4.23

Dual-Purpose Plants, 1260 Mwt	Du Pont	Coal-Fired
3. Electric Output (net Mw)	214	431
4. Heat Output to Water Plant (net Mw)	530	314
5. Evaporator Performance Ratio	7.7	13
6. Water Output (million gal/day)	40	40
7. Capital Cost ($ million)		
Reactor, boiler	$ 34.2	$ 27.7
Turbogenerator and electric	21.5	33.1
Heavy water	12.5	
Evaporator plant	14.5	22.6
Total plant	$ 82.7	$ 83.4
8. Annual Operating Charges ($ million)		
Capital	6.09	6.42
Fuel	0.76	9.03
Operating and maintenance	2.48	1.39
Total annual cost = revenue	$ 9.33	$ 16.84
9. Annual Receipts ($ million)		
Power sale (5.0 mills, 80% LF)	$ 7.55	$ 15.14
Water sale (90, 80% LF)	1.78	1.70
10. Water Price (¢/1000 gallons)	13.5	14.5

to water than does the lower-temperature nuclear plant. The economic choice between a fossil plant and a reactor would vary depending on local conditions as would the distribution of capacity between water and power. If power had to be sold at 4 mills, the nuclear plant water cost would rise to 23.5¢; the coal-fired-plant water price would be about 35¢/1000 gal.

The allocation of the reactor energy between water and power capacity will vary widely with locality. Considerable flexibility in these parameters is available in the dual-purpose plants.

References

1. J. W. Wade, A Computer Program for Economic Studies of Heavy Water Power Reactors, DP-707 (May 1962), E. I. du Pont de Nemours and Co.

2. Heavy Water Moderated Power Reactors Progress Report - March 1962, DP-275 (Issue Date: April 1962), E. I. du Pont de Nemours and Co.

Section 2

ADVANCED POWER AND WATER PLANTS FOR REGIONAL DEVELOPMENT

Present-day power plants, both nuclear and conventional, appear to have promise for saline water conversion for municipal and industrial use, as outlined in Section 1. Costs must approximately be halved, however, to achieve heat costs consistent with supply of large quantities of agricultural water.

A cost reduction of this magnitude appears to be feasible in very large reactor stations with inexpensive fuel cycles. Of reactor types considered close to current technology, the most promising for low costs appears to be the natural-uranium-fueled, D_2O-moderated and boiling-H_2O-cooled reactor described below. Even more promising potentially are large breeder reactors, also described.

2.1 Advanced Natural-Uranium Reactor

The following information must be regarded as highly preliminary.

ORNL is evaluating the use of boiling light-water-cooled, heavy-water-moderated reactors for production of water and power. These reactors are similar to the 1260-Mw reactor described in Section 1, except that ordinary water is boiled inside the reactor core pressure tubes, and the reactors are much larger.

The reference station contains installed capacity of 25,000 thermal megawatts arranged in three separate reactors. Although the three reactors share a common containment building and operating crew, they are operated independently and any one reactor can be repaired while the other two are operating. The containment building is a Quonset hut 170 ft high and 940 ft long with two perpendicular turbine wings containing four 190 ft long turbine-generators with a combined gross output of 4230 Mw. Net plant output is 3545 Mw since the water plant is a substantial power load.

The reactor vessels and primary circulating systems are composed of 1389-Mwt modules, each containing 220 pressure tubes. There are 6 modules per reactor; the reactor itself is rectangular in shape.

Every effort is being made in preliminary reactor evaluations to make use of mass-produced components to cut costs.

The reactors are refueled while in operation, similarly to the manner in which Canadian heavy water reactors are fueled. The on-stream refueling permits one to operate with very little reactivity associated with control rods or poisons. Numerous small control elements are used to control so-called xenon instabilities, which are characteristic of large reactors. A soluble poison is added to the heavy-water moderator to aid in reactor startup, but the poison is removed in an ion exchange system for continuous operation. The heavy water is drained from the calandria tank to scram the reactor. The general control philosophy is very similar to that used in CANDU, the Canadian 200-Mwe project.

A preliminary investigation of siting problems for a 25,000-Mwt station was made. Assuming that a prototype reactor had operated to demonstrate safety of the particular reactor type, it is our impression that such a station could be sited with an exclusion area radius of 0.8 miles, a low-population zone of 12 miles radius and a population center distance of 16 miles. The containment design could be extremely conservative: a double shell with evacuation and iodine trapping of the space between shells.

Some important station parameters are as follows:

Gross thermal output	26,200 Mw
Net thermal output to H_2O coolant	25,000 Mw
Net heat supplied to water plant	20,800 Mw
Number of reactors	3
Core height, width, length per reactor	30 ft x 25 ft x 30 ft
Pressure tube, ID, OD	4.614, 4.864 in.
Lattice pitch	9-in. square
Number of concentric UO_2 tubes in element	2
Length of each fuel element	6 ft
Weight of fuel	41.6 lb U/ft
Fuel cladding thickness	0.020 in.
Fuel length in channel	30 ft
Maximum fuel temperature	2000°C

Maximum heat flux	303,000 Btu/hr ft^2
Maximum, average specific power	15.4, 11.7 kw/kg U
Average pile exposure	7000 Mwd/tonne U
Throughput at 90% thermal load factor	3.14 tonnes/day
System pressure	600 psia
Average moderator temperature	70°C
% of reactor power in moderator	4.5%
Axial and radial graphite reflector thickness	2 ft
D_2O inventory in 25,000-Mw station	1626 tonnes
U inventory in 25,000-Mw station	2230 tonnes
Containment vessel design pressure	8 psig

In addition to evaluating the 25,000-Mw station, ORNL is also considering a 3500-Mw "pilot plant." If there were a substantial industry of reactors of this type based on standardized construction and central reprocessing, reactors of the 3500-Mw-thermal-output-size range should have very attractive costs.

The use of light water boiling coolant introduces reactor physics problems requiring a substantial research and development program to define the optimum design parameters. There are uncertainties in lattice physics requiring critical experiments, and in reactor control requiring "Borax"-type experiments.

The Du Pont program for developing Zircaloy-clad UO_2-tube fuel elements for D_2O reactors is quite germane to the development of fuel elements for the H_2O-cooled reactor. Additional development and testing would be required, however. The chances of developing an appropriate fuel appears to be good, but success is by no means assured. Additional development of refueling machines is required.

Assuming successful research and development, a very preliminary cost estimate for a 25,000-Mwt station is given in Table 3.

It would be appropriate to comment on the prices assigned to power (2.5 mills/kw-hr) and to water (9.8¢/1000 gal) in the table. The power sale essentially pays for the investment in both reactor and turbogenerator plant, while the water sale pays for the evaporator plant investment.

Table 3

Costs of 25,000-Mw Natural Uranium Reactor for Regional Development

	Water Only	Water and Power
1. Electric output (net Mw)	--	3545
2. Heat output to water plant (net Mw)	25,000	20,800
3. Evaporator performance ratio	6.6	4.9
4. Water output (gal/day)	1.64 billion	1 billion
5. Construction costs ($ million)		
Reactor plant	$ 375	$ 375
Turbogenerator plant		275
Heavy water	72	72
Evaporator plant	526	257
	$ 973	$ 979
6. Annual operating charges ($ million) Reactor plus electric plant		
Capital charges	$ 28.9	$ 50
D_2O inventory charge	3.96	3.96
Fuel cycle gross	37.1	37.1
Plutonium sale (at $6.7/g)	(32.9)	(32.9)
D_2O losses	0.72	0.72
Operating and maintenance	3.0	3.45
Nuclear liability insurance	1.0	1.0
Power sale at 2.5 mills/kw-hr, 80% LF		(62.5)
	$ 41.8	$ 0.83
7. Annual charges, evaporator plant ($ million)		
Cost of heat	$ 41.8	$ 0.83
Capital charges on evaporator	40.5	19.8
Operating costs	21.3	11.72
Total water cost = water sale	$ 103.6	$ 32.35
8. Price of water (¢/1000 gal)(90% LF)	19.2	9.8

This pattern seems to have evolved in large hydro-development projects because the industrial power users can readily afford the cheap electricity, subsidizing to a certain extent the agricultural water users. As in any dual purpose system, the allocation of costs is arbitrary.

2.2 A Large Breeder Plant and Cost Estimate

The following information must be regarded as highly preliminary.

The lowest thermal energy cost which can now be foreseen is that from breeder reactors, especially those of the mobile fuel type. Figure 1 gives the results of a preliminary study of potential heat costs for advanced fast plutonium breeders as a function of their size. As the figure shows, heat costs under 3¢ per million Btu may eventually be obtained. The study was based on solid-fuel fast breeders of the type proposed by General Electric APED[1] and did not assume any value for plutonium produced nor for by-product power. The nuclear stability problems of the reactor were assumed solved, but no materials performances were assumed that have not already been demonstrated.[2,3]

The capital cost of large breeder reactors was estimated by starting with a detailed design study which existed for a 1000-Mw size, and redesigning and cost estimating each component or sub-system separately at tenfold and hundredfold larger sizes. The three points for each component were then plotted and a power law approximation derived for each set. The sum of the power laws for all the components gave the cost law for the whole reactor. This is given in Fig. 2. The method has been fully described in other reports.[4,5] The principal factors that lead to such low estimated heat costs for large fast breeders are the high power density, inexpensive materials used, the high fuel burnup attainable (100,000 Mw days per ton), and especially the lack of a burnup cost. As discussed in Section 4, graphic extrapolation of existing reactor costs leads to considerably higher cost estimates than does Fig. 2. Until detailed cost projections can be made, the higher numbers must be used.

Thorium breeders have the potentiality of achieving very low heat costs. Unfortunately there is not at present a suitable design and cost study of this type reactor which could be used as a basis for scaling to large size.

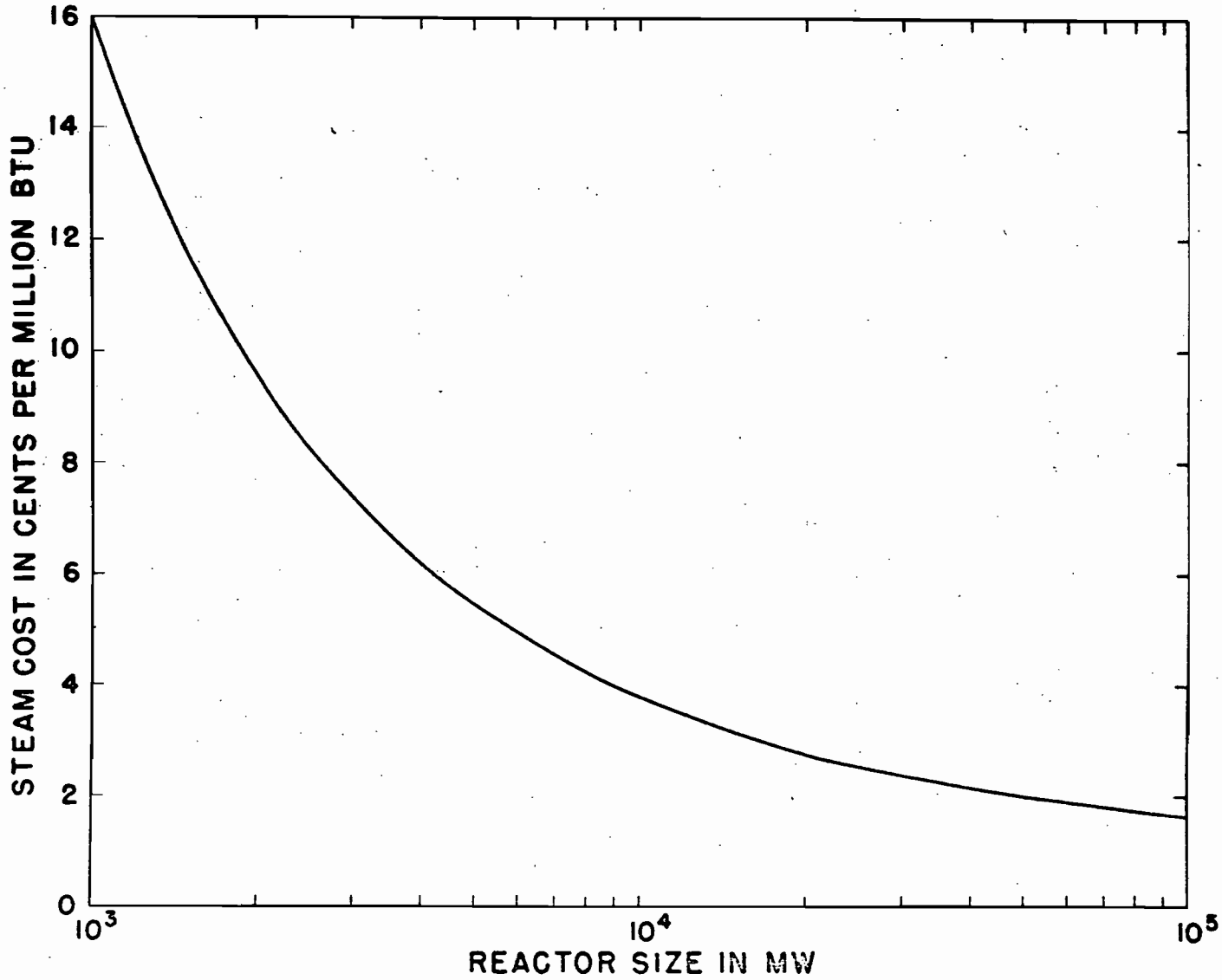
STEAM COST IN CENTS PER MILLION BTU
16
14
12
10
8
6
4
2
0
10^3
10^4
10^5
REACTOR SIZE IN MW

Fig. 1

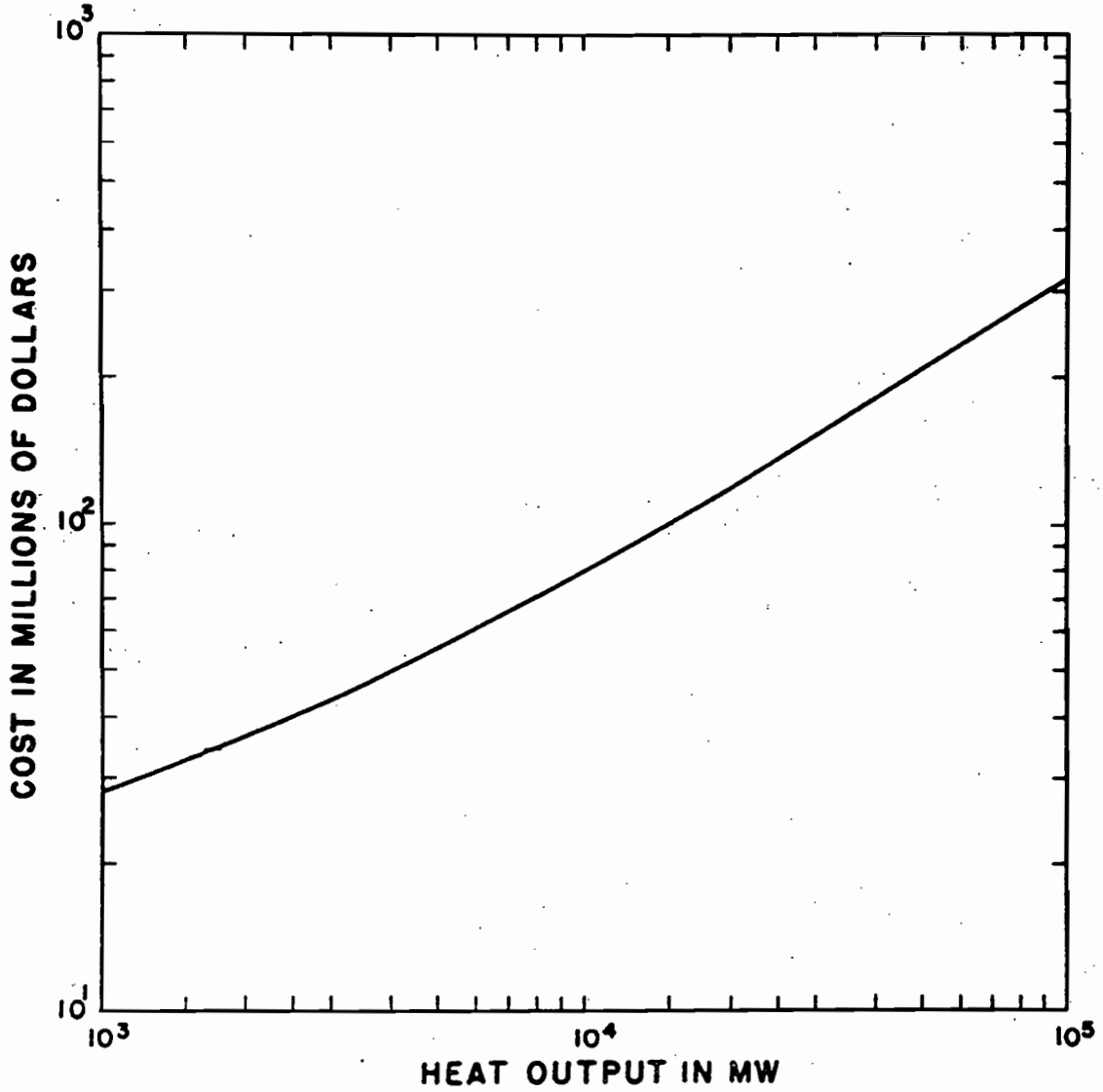
COST IN MILLIONS OF DOLLARS
10^3
10^2
10^1
10^3
10^4
10^5
HEAT OUTPUT IN MW

Fig. 2

Both plutonium and thorium breeders can benefit from development of mobile-fuel reactors, and promising approaches to such fuels exist for each type. It is too early to assess these possibilities, but they would tend to reduce heat costs still further, or to permit low cost to be reached at a smaller size.

A 25,000-Mw station was chosen for a conservative estimate of a breeder which might be developed within 20 years, for comparison with other large energy sources. The construction cost from Fig. 2 was $135 million; this was arbitrarily increased to $250 million, which, at $10/kw, falls in the range of 8 to $16 predicted in Section 4. The thermal performance and specific power of the reactor were decreased relative to the General Electric design, and the operating temperature was reduced. The core is annular in shape.

The same type of fuel preparation, fabrication, and other steps discussed in Section 3 for the natural-uranium system would apply to the fast reactor as well, except that depleted uranium oxide is used and plutonium oxide is admixed. The chemical steps are also the same, except that better criticality control must be exercised in the dissolver. The cost recommendations of Section 3 were increased to adequately cover the use of plutonium. The reactor costs are summarized in Table 4, and parameters of interest are given in Table 5. The cost of heat is estimated to be 5.2¢ per million Btu at the reactor discharge. In the next section this station is compared with others.

It is of interest to note that the low specific power assumed has made the plutonium inventory charge just equal to the plutonium credit. This particular reactor, therefore, is independent in its costs of any assumption as to the price of plutonium. The value assigned to electric power in this example is lower than before—2 mills/kw-hr. Even at this low figure the water receives a subsidy. Although the reactor is an advanced type, no improvement has been assumed in the evaporator art.

Table 4

Costs of 25,000-Mw Fast Oxide Breeder for Regional Development

		Water Only	Water and Power
1.	Electric output (net Mw)		5000
2.	Heat output to water plant (net Mw)	25,000	19,500
3.	Evaporator performance ratio	6.25	5.25
4.	Water output (gal/day)	1.53 billion	1 billion
5.	Construction cost ($ million)		
	Reactor plant	$250	$250
	Turbogenerator plant		300
	Evaporator plant	470	270
		$720	$820
6.	Annual operating charges ($ million) Reactor and electric plant		
	Capital charges	$ 19.25	$ 42.3
	Fuel cycle cost	12.0	12.0
	Plutonium inventory charge	15.8	15.8
	Plutonium sale (at $6.7/g)	(15.8)	(15.8)
	Operating and maintenance	3.0	3.6
	Nuclear liability insurance	1.0	1.0
	Power sale at 2 mills/kw-hr, 80% LF		(70.5)
		$ 35.25	($11.6)
7.	Annual charges, evaporator plant ($ million)		
	Cost of heat	$ 35.25	($11.6)
	Capital charges on evaporator	36.2	20.8
	Operating costs	19.5	12.0
	Total water cost = water sale	$ 90.95	$ 21.2
8.	Price of water (¢/1000 gal) (90% LF)	18.1 ¢	6.1 ¢

Table 5

Parameters of 25,000-Mw Breeder Reactor

Core diameter, ft (ID, OD)	11, 33
Core height, ft	4
Blanket thickness, ft	3
Core power density, Mw per liter	0.3
Core heat flux, average, Btu/hr ft^2	500,000
Specific power, Mw/kg Pu	.76
Inventory ratio, total system/reactor	1.5
Mean fission energy, kev	300
Core composition, vol %	
Fuel	30
Sodium	60
Steel	10
Coolant temperature rise, °C	150
Total coolant flow, gpm x 10^6	2.5

2.3 Comparison of Natural-Uranium Reactor, Breeder Reactor, and Coal-Fired Plant With Large River Projects

Table 6 shows a comparison of the large reactor projects with fossil-fueled and hydro-development projects. They are compared on the basis of a "merit" index which is essentially the percentage of annual economic worth relative to the initial investment. Since the true value of water and power varies from region to region, and with time, the merit index can be regarded as only very approximate.

The comparison shows something we already suspect—that rain water, if available, is usually cheaper than water produced in nuclear reactors. The Aswan Dam's water benefits alone rapidly pay off the initial investment if the water is used effectively. The large reactors' power and water benefits are 8 to 11% of the initial price. The California Water Plan, on the other hand, on the average gives less benefit than the postulated reactors. If one examines the California Water Plan

Table 6

Comparison of Large Projects

		Aswan Dam	Breeder Reactor	Natural U Reactor	Cal. Water Plan	25,000 Mw Coal Plant
1.	Capital cost ($ million)	1200	824	996	11,838	1420
2.	Annual operating cost ($ million)	low	35	22	moderate	212
3.	Net electric output (Mw)	2400	5000	3545	negative	8180
4.	Water output (billions of gpd)	16	1	1	21	1
5.	Water price (¢/1000 gal)	low	6.4¢	9.8¢	5-20¢	20¢
6.	Power price	?	2.0	2.5	----	4.5
7.	Merit index*	51	11	8	6	0-

*Defined as $100 \frac{(P + W - C)}{I}$, where P is annual power benefit if power is worth 2.5 mills/kw-hr, W is annual water benefit if water is worth 10¢ per 1000 gal, C is annual direct operating expense, and I is initial investment. The merit index shows how rapidly the initial investment benefits the economy.

in greater detail, the hydro and irrigation projects in central California are comparable to Aswan in benefits. The Plan in southern California, which really needs the water, does not appear competitive with nuclear-powered desalination. At such large sizes, the coal-fired station is completely out of the running because of its high annual costs (mainly 30¢/10^6 Btu coal).

The postulated reactors can supply water for either a 5-million urban population or food for 2 million persons. The power is sufficient for 4 million. These figures are based on current U.S. standards.

To summarize, regions which have large undeveloped rivers should develop them if they need power and water. Coastal regions which do not have large rivers can be developed with nuclear energy.

References

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Section 3

THE EFFECT OF INDUSTRY SIZE ON NATURAL-URANIUM REACTOR FUEL COSTS

Discussions were held with leading U.S. authorities in fuel element fabrication and chemical processing, and with zirconium fabricators. On the basis of these discussions and from unclassified reports, costs were derived by ORNL for fabricating and processing the reference fuel elements for the H_2O-cooled natural-uranium reactor as a function of plant capacity. A primary reference on fuel element fabrication costs is DP-570.[1] The cost of Zircaloy tubing components was based primarily on recent information from the Harvey Aluminum Company, suppliers of Zircaloy tubing for Hanford's NPR.[2] Chemical processing plant costs were based on a Du Pont study,[3] modified slightly for siting at a regional development site.[4]

The fuel element, 6 ft long, contains two concentric rings of vibratory-compacted UO_2 clad in 0.020 in. Zircaloy. The outer diameters of the two UO_2 rings are 4.326 in. and 2.718 in., respectively; the inner diameters are 3.152 and 1.424 in. The UO_2 density is 9.81 g/cc, 90% of theoretical.

Costs of various steps in the fuel fabrication process are summarized in Table 7, and the total cost is plotted as a function of capacity in Fig. 3. The costs are based on AEC projections of 1970 natural uranium and plutonium prices, \$5/lb U_3O_8 and \$6.7/g Pu respectively. Since natural uranium and plutonium prices are closely related, the natural uranium net fuel cycle costs are nearly independent of natural-uranium price in the range 5 to \$8 per pound of U_3O_8.

The table illustrates a spectacular improvement in fuel cycle costs as mass production methods are applied to fuel fabricating and processing. The natural-uranium reactors in this report have been postulated to be served by a central plant of 10 tons U/day capacity. The postulated 10-ton-per-day rate requires an industry of 75,000 Mw thermal—sufficient to supply about 1/15 of the present U.S. power needs and 3 billion gallons per day of water. The plutonium output would be about 15,000 kg/yr, or sufficient to start up a 25,000 Mw fast breeder every 3 years.

Table 7

Fuel Fabrication Costs, $/kg U

Step	Capacity 1 tonne U/day	Capacity 10 tonnes 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	Based on 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, 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, tonnes/day	1	1	10
Processing capacity, tonnes/day	1	10	10
Fuel element fabrication	$ 30.56	$ 30.56	$ 22.04
Shipping fuel	1.42	1.42	1.40
Chemical processing	25.25	3.70	3.70
Fuel inventory cost*	3.82	3.82	3.09
Plutonium credit**	(26.80)	(26.80)	(26.80)
Total	$ 34.25	$ 12.70	$ 3.43
Mills/kw-hr-t	0.214	0.079	0.0213

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

**At $6.70/g projected by AEC for 1970.

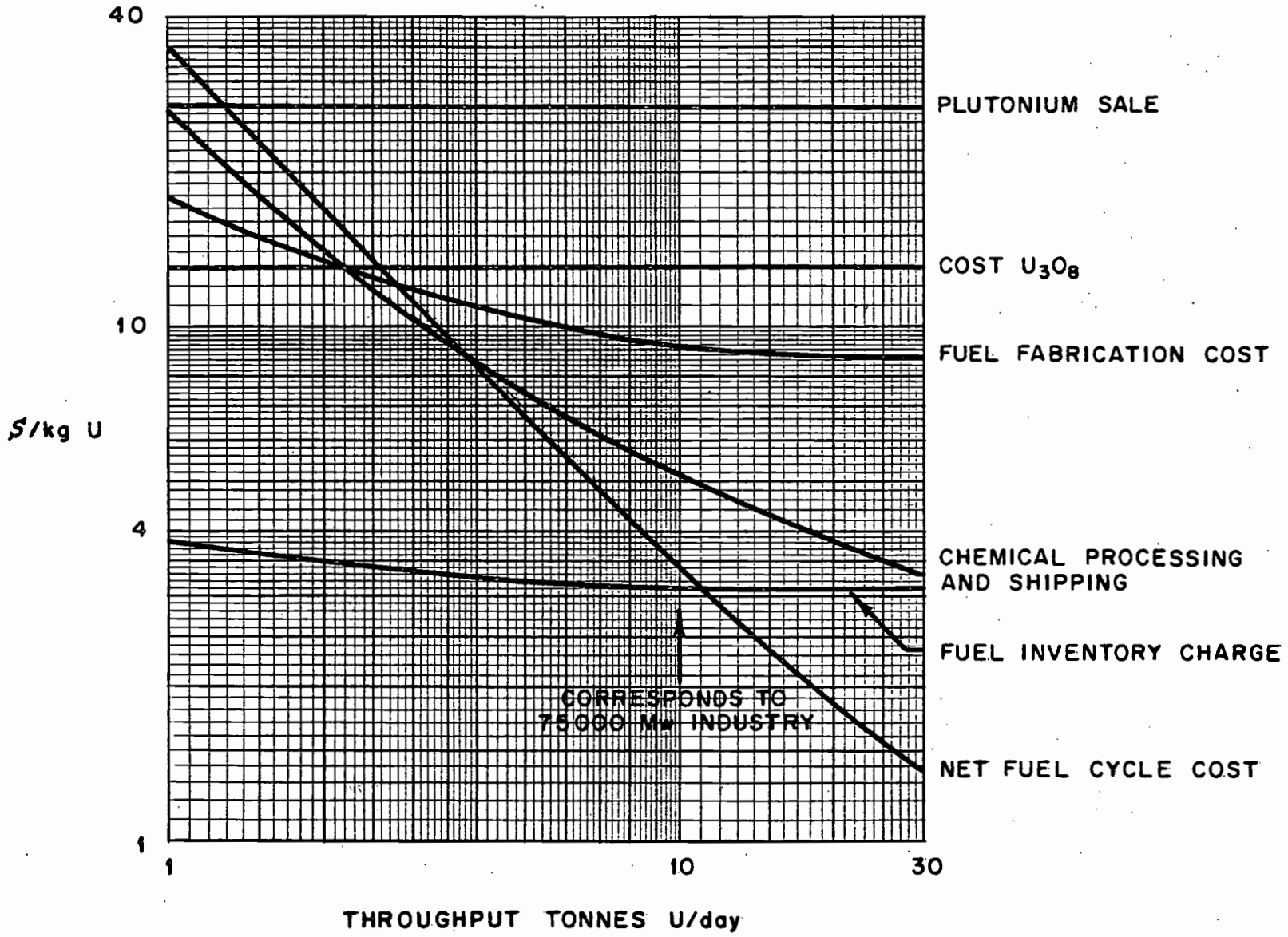
40
10
4
1
$/kg U
1
10
30
THROUGHPUT TONNES U/day
PLUTONIUM SALE
COST U_3O_8
FUEL FABRICATION COST
CHEMICAL PROCESSING AND SHIPPING
FUEL INVENTORY CHARGE
NET FUEL CYCLE COST
CORRESPONDS TO 75000 MW INDUSTRY

Fig. 3

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Section 4

SCALING LAWS FOR ESTIMATING COSTS OF LARGE NUCLEAR STEAM-GENERATING PLANTS

Experience in the chemical and process industries indicates that the comparative cost of individual components will vary as the 0.6 power of size or capacity. This same general rule has been applied to estimates of the influence of plant size on the costs of nuclear plants, in which case costs per unit of capacity would vary as $1/P^{0.4}$; however, data in the literature are inadequate to establish the validity of such a relationship or the value of the exponent for specific types of plants. This approach, therefore, cannot be used with any degree of reliability; nevertheless, it does provide a rough indication of the possible trend in costs of very large plants.

Data on the costs of nuclear electric plants built in the United States[1] for power demonstration purposes in the size range of 50 to 1000 Mw thermal indicate that costs per kilowatt are roughly proportional to $1/P^{0.33}$. The distribution of costs between the nuclear steam-generation portion of the plant and the turbine-generator and accessory electrical components appears to be independent of plant capacity; therefore, one can conclude that nuclear steam plants should also scale as $1/P^{0.33}$. A study by NDA[2] of sodium-cooled D_2O-moderated reactors ranging in size from 40 Mwe to 500 Mwe verified this relationship for reactor plant unit costs excluding those for the sodium heat removal system. AEC-sponsored cost studies of other reactor types in the size range of 300 to 1000 Mwe are now under way to provide a better indication of nuclear plant size-cost relationships; however, these results will not be available until 1963.

Preliminary studies of the costs of plants in the size range of 1000 to 100,000 Mw thermal have been carried out by R. P. Hammond[3,4] and I. Spiewak and R. H. Chapman.[5] These indicate values of the exponents of 0.5 and 0.4, respectively.

Published costs of 1000-Mw thermal nuclear plants indicate that unit costs for the steam-generation portion only fall in the range of 30 to $40/kwt. On this basis, and assuming that unit costs scale inversely proportional to $P^{0.40}$ and $P^{0.33}$ respectively, costs for a 10,000-Mw thermal plant would amount to from 12 to $18/kwt. Costs for a 25,000-Mw thermal nuclear plant would drop to from 8 to $16/kwt.

The construction cost assumed for the large natural uranium reactor discussed in this report was obtained from a preliminary design, plant layout, and cost analysis. Since a much more thorough effort of this type would be necessary to produce a really authoritative estimate, the considerations of scaling given in this section may perhaps be used to provide an independent perspective. The method of scaling individual systems and components mentioned in Section 2 has not been verified sufficiently to become a recognized procedure. The cost of the fast breeder station for this report was therefore increased arbitrarily to nearly double the projected value. The resulting unit cost of $10/kwt lies within the range of 8 to $16 projected in this section.

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Section 5

CURRENT EVAPORATOR TECHNOLOGY AND POSSIBLE IMPROVEMENTS

This section summarizes the present technology for sea water evaporators, develops a formula for cost estimation, and lists the prospects and direction of future development. Although evaporators themselves are as old as civilization, the present state of the art of sea water conversion cannot be described as sophisticated. One of the most promising types of equipment has been developed only in the recent past, and the barest glance at current methods reveals striking possibilities for improvement.

Presently operating plants range from very small shipboard units up to permanent installations at Kuwait, Aruba, Guernsey, etc., and the demonstration plants of the Office of Saline Water at Point Loma and Freeport. The largest single unit now operating is rated at about 1.2 million gallons per day (mgpd) and two 1.7-mgpd units are under construction in England for installation in Curacao. These units cost about 75¢ to $1 per daily gallon to construct and produce water costing about $1 per thousand gallons using fossil fuels.

Under the impetus of the Office of Saline Water, studies have been made of larger plants. Companies concerned in this field are W. L. Badger Associates, Inc., Westinghouse, Cleaver-Brooks, Griscom-Russell, Fluor Corporation, and Bechtel Corporation in the U. S., and Weir and Westgarth in England. These studies have shown that substantial reductions in unit cost are obtained at larger sizes in the range of 15 to 40 mgpd. The 15- to 40-mgpd-size range is presently considered to be the largest which can be shop constructed and transported. Larger units would require field fabrication, which would tend to increase some of the costs. Very large units, of the scale needed for the big reactors considered here, would have to be field fabricated, but this would permit the maximum freedom in plant layout and component selection. With a very large installation it becomes economic to construct on-site shops.

In comparing the results of various studies, it is convenient to resolve the cost of the evaporator plant into two categories—those which vary with the amount of heat transfer surface per unit of capacity, and those which vary only with the product capacity. The first group contains primarily the evaporator heat transfer surface, which increases not only with plant capacity but with the performance ratio, R. (R is a measure of the heat economy of the apparatus, being equal to the number of pounds of water produced per pound of heating steam consumed.) The second group contains the land, sea water intakes, filters, pumps, and piping external to the evaporator itself. It is of course true that some of the components do not belong exactly in either category.

The available literature has been used to deduce suitable parameters of the above type, as has also been done by Silver.[1] For the equation $C = y + zR$, C is the installed plant cost (not including the heat source), in cents per daily gallon of capacity, and y and z are taken as constants. For a small unit of 0.5 mgpd of the type now operating, Silver estimates $y = 56$ and $z = 5.36$. He states that these coefficients would be smaller for a larger unit. Brice and Townsend[2,3] have reported on a flash evaporator plant of 50 mgpd studied by Fluor. Their cost can be represented approximately by $y = 9$ and $z = 3.9$. Another type of evaporator, the multiple-effect long-tube type, was studied at 17.3 mgpd capacity and reported by Standiford and Bjork.[4] Their estimates, omitting the vapor compressor which they used, have been resolved by Hammond[5] into $y = 4.7$ and $z = 3.3$. A review of both of these efforts and independent quotations of some of the components gives sufficient verification for considering these last two sets as bracketing the current state of evaporator technology. The resulting average equation is

$$C = 7 + 3.8\,R \qquad (1)$$

which is used to estimate water plant costs in this report.

It is useful to convert this expression to one which gives the cost of water produced as a function of the cost of heat. The performance ratio, R, is increased at the expense of additional heat transfer surface for a given capacity, but with a saving in heat required for the same

capacity. The heat required is inversely proportional to R, but the equipment cost increases approximately linearly with R, as shown in (1). It is apparent that there is an optimum value of R giving minimum water cost.

If capital charges on the evaporator are 7.7%, plant operating factor is 90%, operation and maintenance are 2% of construction, and the cost of chemicals to prevent scale is 2¢ per thousand gallons, equation (1) can be transformed into

$$W = 4 + 1.09\,R + \frac{8.3\,H}{R} \qquad (2)$$

wherein W is water cost in cents per thousand gallons and H is heat cost in cents per million Btu (MBU). The optimum R is obtained by differentiating equation (2), giving

$$R_{opt} = 2.7\sqrt{H} \qquad (3)$$

Substitution of R_{opt} for R in equation (2) gives

$$W = 4 + 6\sqrt{H} \qquad (4)$$

which is the minimum cost of water from a given heat cost. (The heat cost must include the net operating and capital charges on the heat source.) Equation (4) gives a water cost of about 40 cents per thousand gallons for heat costing 35¢ per MBU (fuel 30¢), which is approximately correct for the Fluor and Badger studies. In view of the assumptions involved, these equations should not be expected to apply for values of R less than about 3, nor for plants smaller than 50 mgpd. Figure 4 gives a plot of equations (3) and (4). These do not apply to a dual-purpose plant until the energy allocation and cost distribution have been fixed. The dual-purpose examples cited are therefore arbitrary and not optimized.

In contemplating plant installations of the size required for large reactor heat sources, the present technology of construction can only be considered a point of departure. The use of prestressed concrete vessel shells, mammoth pumps, and evaporators designed for field construction shops should result in some significant cost reductions. To evaluate these possibilities will be an important part of any proposal to apply reactors to large-scale sea water distillation.

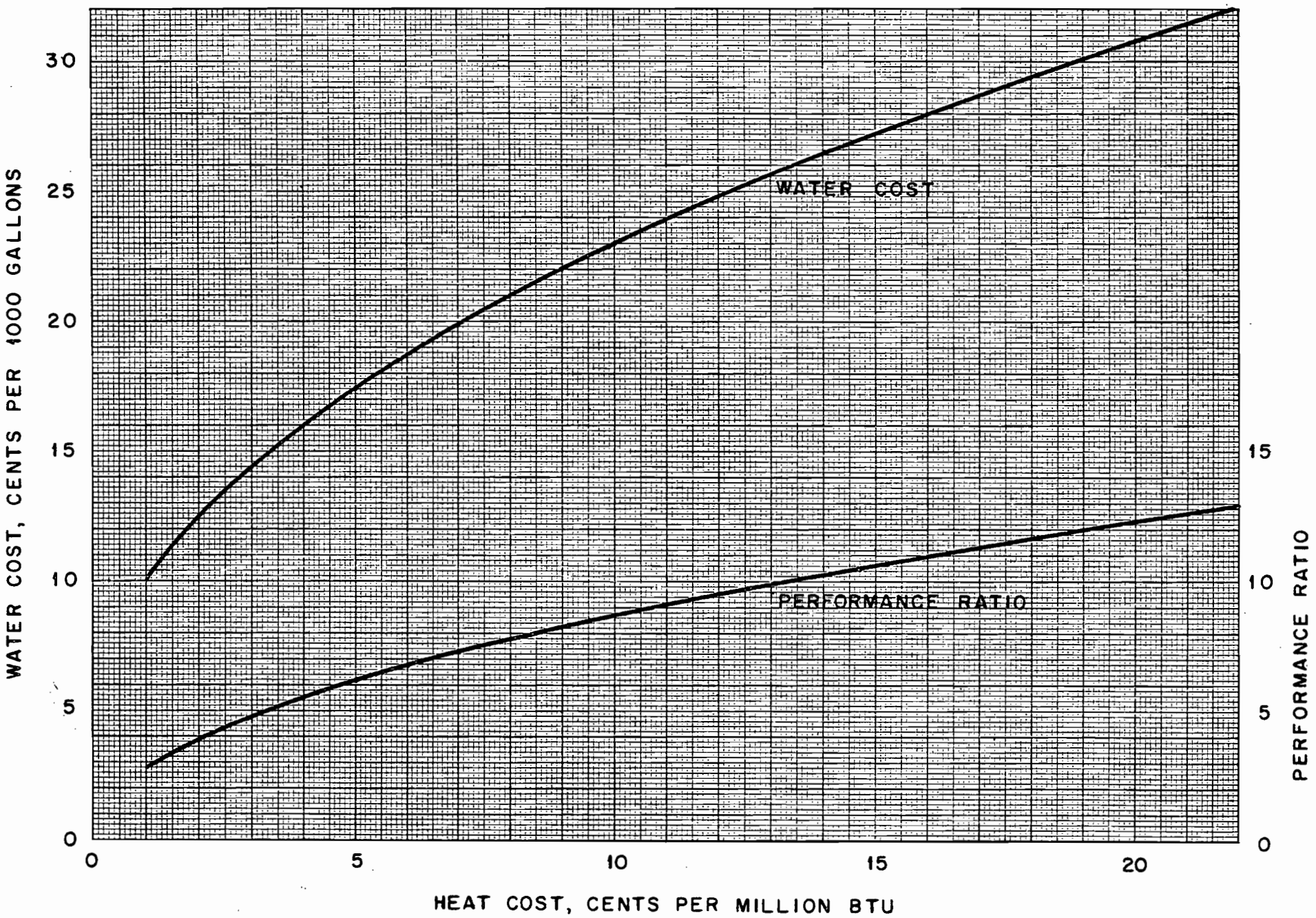
WATER COST, CENTS PER 1000 GALLONS
30
25
20
15
10
5
0
WATER COST
PERFORMANCE RATIO
15
10
5
0
PERFORMANCE RATIO
0
5
10
15
20
HEAT COST, CENTS PER MILLION BTU

Fig. 4

Even more important possibilities for cost reduction lie in the use of higher brine temperatures, higher brine velocities, use of steel instead of bronze tubing, and in eliminating the use of scale-control chemicals. It is hardly to be expected that development work will permit progress in all of these areas simultaneously, but it is not at all unlikely, in view of present laboratory tests, that water costs may be decreased to half those estimated by equation (4).

An additional area which offers promise for investigation is concerned with a different type of evaporator—the vapor-compression type. The very low-cost energy available from a large reactor would remove the big penalty for purchased power which has afflicted this type. A somewhat different version, using steam jet thermocompressors, may be even more suitable to the nuclear plant, since the equipment costs are very low and the reactor produces a supply of steam of the appropriate quality. The combination of steam-jet vapor compressors and flash evaporators is being studied as still another promising scheme.

The present study, let us repeat, is based on present-day technology and does not take credit for probable improvements in the evaporator plant.

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