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EFFECT OF MAXIMUM BRINE TEMPERATURE ON THE OUTPUT OF LARGE NUCLEAR STATIONS FOR PRODUCTION OF WATER AND ELECTRICITY

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ABSTRACT

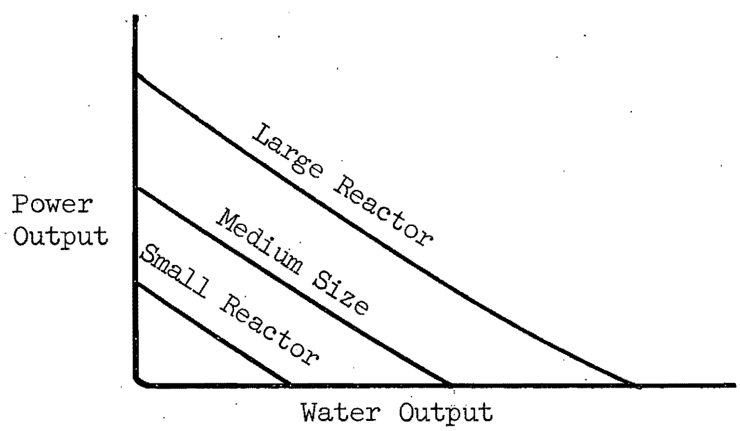
The effect of brine temperature on the cost of water from large municipally-owned D_2O reactor stations was investigated. It was found that water costs from 25,000 Mwt stations varied between 11.7¢ and 12.6¢/1000 gal in the range of maximum brine temperature of 160°F to 350°F. By-product electric power was sold at 1.49 mills/kwhr.

The optimum size of reactors for producing combinations of 1 to 3 billion gpd and 1000 to 5000 Mwe was determined. From these optima, incremental costs of producing power and water were computed.

Introduction

Assuming a particular nuclear steam generator, the amount of electricity which can be generated is related directly to the turbine discharge temperature. The amount of water produced is related both to the temperature difference between the turbine discharge and the heat sink, and to the temperature driving forces used in the distillation plant for regeneration of heat. This memo attempts to indicate the effect of maximum brine temperature (assumed 20°F below turbine discharge temperature) on the water output and cost from the 25,000 Mwt reference ORNL reactor station.

If a grid is made of water output vs. electric output, one can plot curves of optimum reactor thermal output for given power-water splits, as follows:



If this type of plot were fully available, the equipment supplier could rapidly provide each customer with the optimum plant for his needs.

25,000 Mw Results

As the turbine discharge temperature is increased from 92°F (normal temperature in single-purpose plant, corresponding to 1.5 in. Hg absolute) toward the inlet temperature of 486°F (600 psia saturated steam), the amount of electricity which can be extracted is approximately proportional to the ΔT, if a regenerative feed-water heating cycle is used. The standard cycle starting with 600 psia saturated steam gives

31.0% gross thermal efficiency.

The amount of heat rejected to the water plant is equal to the reactor power minus the electrical gross output.

Table I summarizes the basic capital cost estimates for various portions of a 25,000 Mwt D_2O reactor station, based on ORNL and UCNC design studies.

Table I

Capital Costs of D_2O Nuclear Water-Electric Plant

Item	Unit Cost, 25,000 Mw Plant	Assumed Variation of Unit Cost with Small Changes in Plant Size
Reactor Plant	\$13/kwth	- 0.2 power
Heavy Water	\$ 4/kwth	none
Electric Plant	\$50/kwe gross	none
Condenser (if used)	\$15/kwe gross	none
Distillation Plant	$(12 + \frac{25}{R} + \frac{2.5R}{D}) \frac{¢}{\text{daily gal}}$	none

Where R is performance ratio of water plant, in lb product/1000 Btu input, and D is $\frac{\text{maximum brine temperature—sea-water temperature.}}{115^{\circ}\text{F reference}}$

Selecting a given turbine discharge temperature the electric plant output can be calculated, the costs of operating the reactor and electric plant estimated, and the power sale credited if a price is established. Based on the ORNL ground rules for municipal ownership (see Appendix), a power price of 1.49 mills/kwhre is derived for a single-purpose 25,000 Mwt D_2O electric generating station. Crediting the reactor-electric portion of the plant with power revenue, a heat cost is obtained by difference which is charged to the water plant.

Knowing the cost of heat and its quantity and the maximum brine temperature (assumed 20°F below turbine discharge temperature), the water plant R can be optimized by trial-and-error to give the lowest water cost. Table II summarizes such a process for maximum brine temperatures of 350°F, 300°F, 250°F, 200°F and 160°F, respectively.

Table II

Summary of Water Production Costs in 25,000 Mwt Nuclear Stations at Varying Maximum Brine Temperatures (Electricity = 1.49 mills/kwhr)

Max. Brine Temp. °F	Net Electric Output Mw	Performance Ratio, R lb prod. per 1000 Btu	Water Production billions of gpd	Capital Cost of Plant* $ billions	Water Price ¢/1000 gal
350	1600	10	2.25	1.013	12.42
		13	2.92	1.262	12.02
		15	3.37	1.452	12.05
		20	4.49	2.014	12.57
		25	5.61	2.69	13.5
300	2580	10	2.17	1.089	12.14
		11	2.385	1.170	12.03
		12	2.605	1.269	12.10
		15	3.25	1.579	12.40
		20	4.34	2.22	13.45
250	3570	7	1.436	0.941	12.65
		9	1.843	1.104	12.42
		10	2.05	1.197	12.46
		12	2.46	1.404	12.78
		15	3.07	1.765	13.55
200	4550	5	0.978	0.880	12.82
		6	1.173	0.958	12.60
		7	1.369	0.995	12.62
		8	1.564	1.091	12.80
		10	1.955	1.364	13.47
160	5340	3	0.563	0.810	12.14
		4	0.750	0.883	11.67
		5	0.938	0.970	11.8
		6	1.125	1.071	12.23

*Does not include fuel and D_2O, another $150 million.

The cost of water from 160° brine is slightly less than the others because chemical treatment is assumed unnecessary at the low temperatures.

Figure 1 shows the same information graphically.

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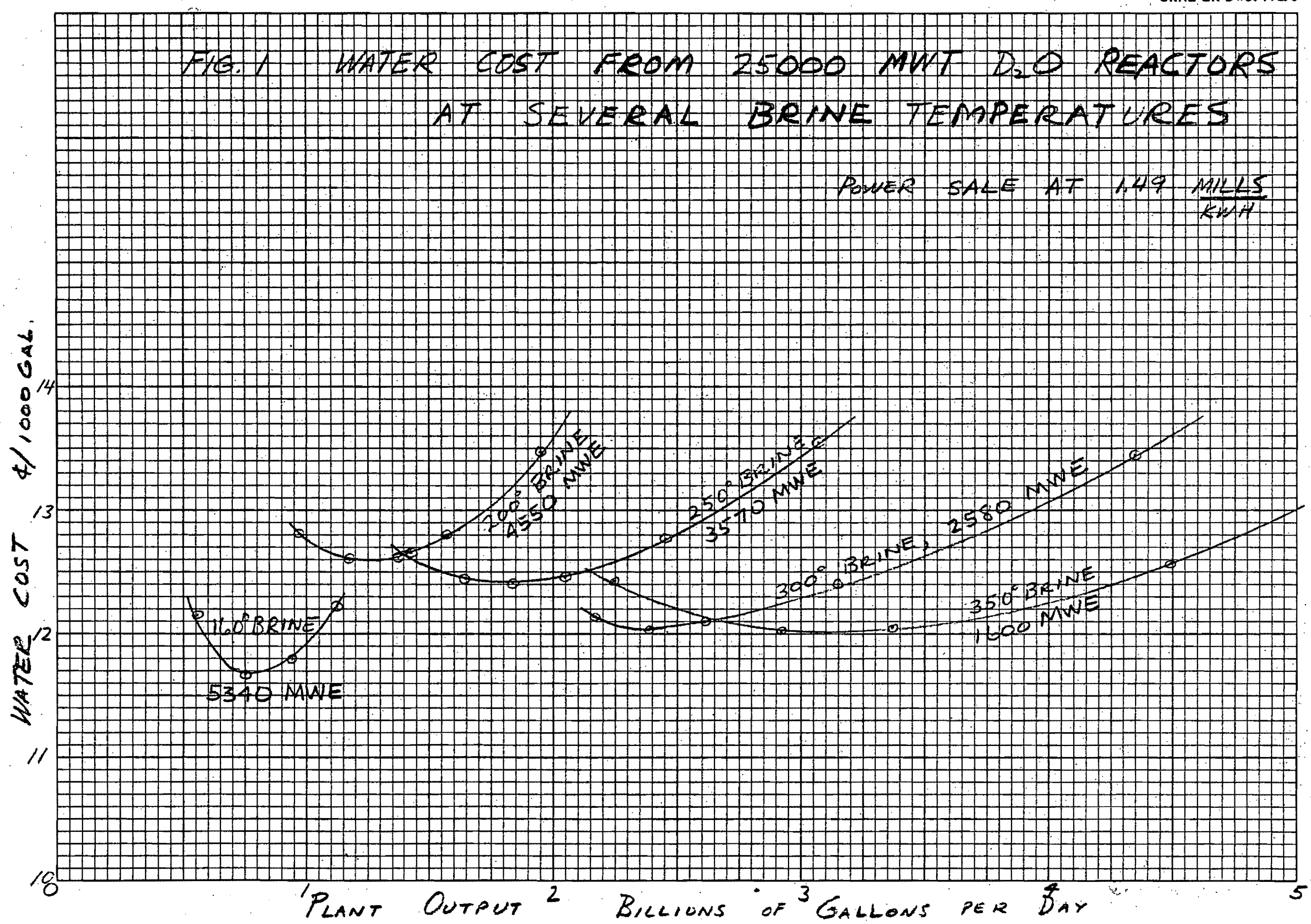

FIG. 1 WATER COST FROM 25000 MWT D_2O REACTORS AT SEVERAL BRINE TEMPERATURES

To determine how sensitive the cost of water is to proper selection of reactor thermal output, water costs were estimated in 23,000 Mw, 25,000 Mw, 27,000 Mw and 29,000 Mw reactor stations with common outputs of water and power. This information is summarized in Table III and Figure 2.

Table III

Water Costs from Stations of 23,000 to 29,000 Mwt Power, with Fixed Water-Electric Outputs

Fixed Water Output bgd	Fixed Electric Output Mw	23,000 Mw Reactor Brine* Temp.	23,000 Mw Reactor Water* Cost	25,000 Mw Reactor Brine Temp.	25,000 Mw Reactor Water Cost	27,000 Mw Reactor Brine Temp.	27,000 Mw Reactor Water Cost	29,000 Mw Reactor Brine Temp.	29,000 Mw Reactor Water Cost
2.92	1600	341	12.18	350	12.02	359	11.95		
1.843	3570	233	12.87	250	12.42	267	12.26	284	12.25
1.173	4550	179	12.93	200	12.60	221	12.55	237	12.86

*in °F and ¢/1000 gal, respectively.

Discussion and Conclusions, 25,000 Mw Stations

The most striking result from the above analysis is that the water cost is about 12.5¢/1000 gal over an extremely wide range of water-power split, maximum brine temperature and performance ratio, R. The analysis assumes that there is no equipment cost penalty or operating cost penalty as a result of high pressure (temperature) operation of flash evaporator plants — in other words, that high temperature heat exchange surface, shells and piping cost the same per unit of heat transferred as standard equipment, and that the chemical and maintenance costs per unit of product are comparable. To the extent that this assumption is true, the analysis is valid.

Development by OSW of high temperature distillation would give potential plant customers the maximum flexibility in power-water split. The converse of the above conclusion is that the cost of water from lower-temperature evaporators is about the same as from high temperature evaporators if there is a market for the power by-product.

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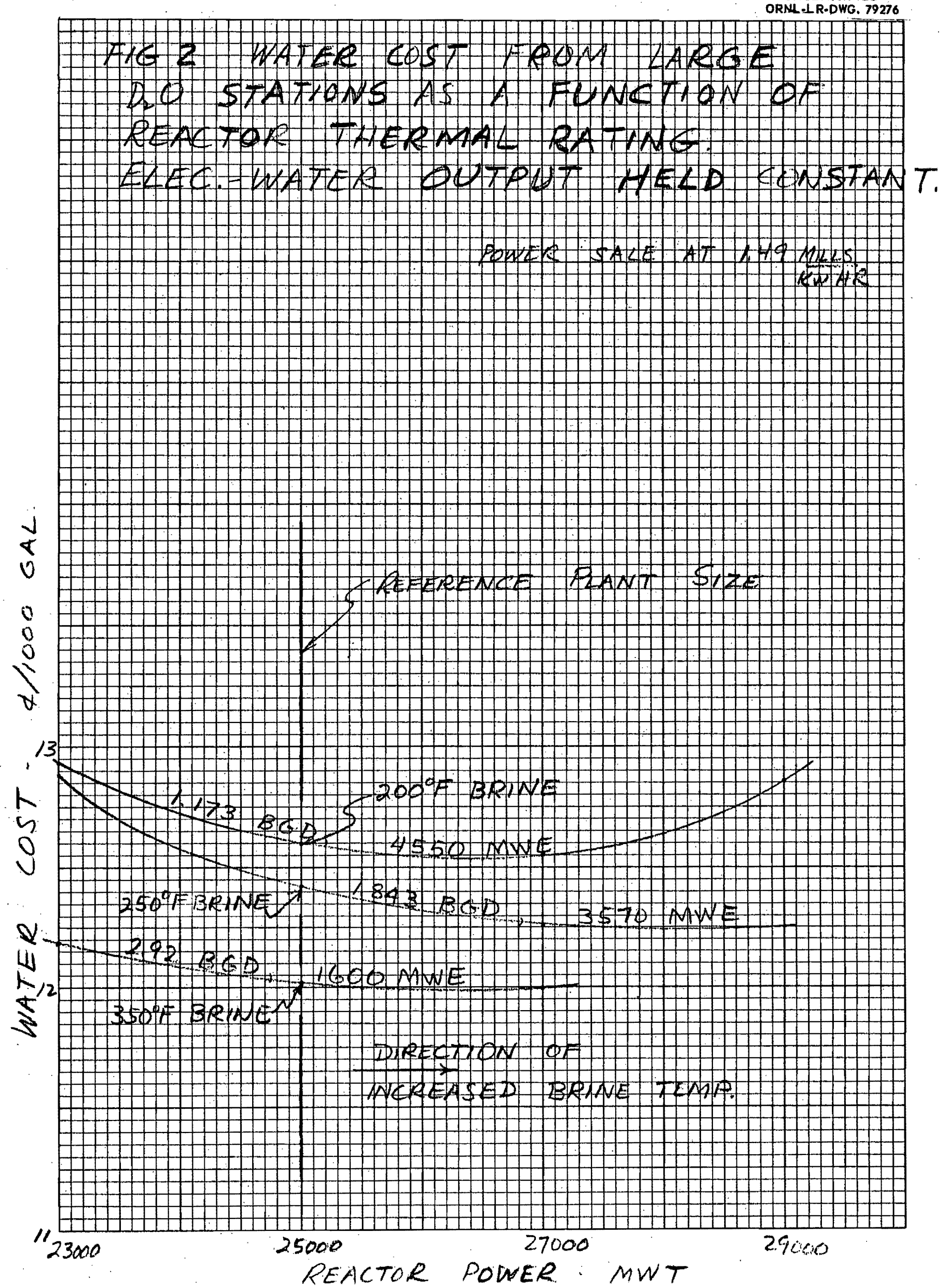

Therefore, it would seem prudent to evaluate evaporator plants at the highest brine temperature which can be handled in an engineering sense without cost penalty (expensive materials or chemicals). Evaluating evaporator plants in a region in which there is little engineering information would be likely to lead to high water costs because the design engineer is likely to be overconservative.

Regarding the current study of nuclear water conversion, Bechtel is probably in the best position to select an appropriate maximum engineering temperature. OSW should be encouraged to extend the range of engineering information to higher temperatures.

Brief Study of 8333 Mwt Plant

The above type of study was repeated for 8333 Mwt plants at maximum brine temperatures of 200°F and 250°F. In this case power was credited at 1.65 mills/kwhre, its cost from a single-purpose 8333 Mw reactor of the same type. Results are shown in Figure 3 and Table IV. Large fuel cycle facilities (10 ton/day) were assumed.

Table IV

Water Cost from 8333 Mwt D_2O Reactors

Max. Brine Temp. °F	Net Electric Output Mw	R lb prod. per 1000 Btu	Water Production mgd	Capital Cost of Plant* $ million	Water Price ¢/1000 gal
200°F	1513	5	326	318	13.6
		6	391	344	13.28
		8	521	405	13.33
		10	652	479	13.86
250°F	1190	7	479	339	13.37
		9	614	393	12.97
		12	820	493	13.2
		15	1023	613	13.92

*Does not include $50 million of D_2O and fuel.

The analysis shows that billion gpd plants can be built this size with only moderate increase in water cost, assuming that a large fueling industry was established.

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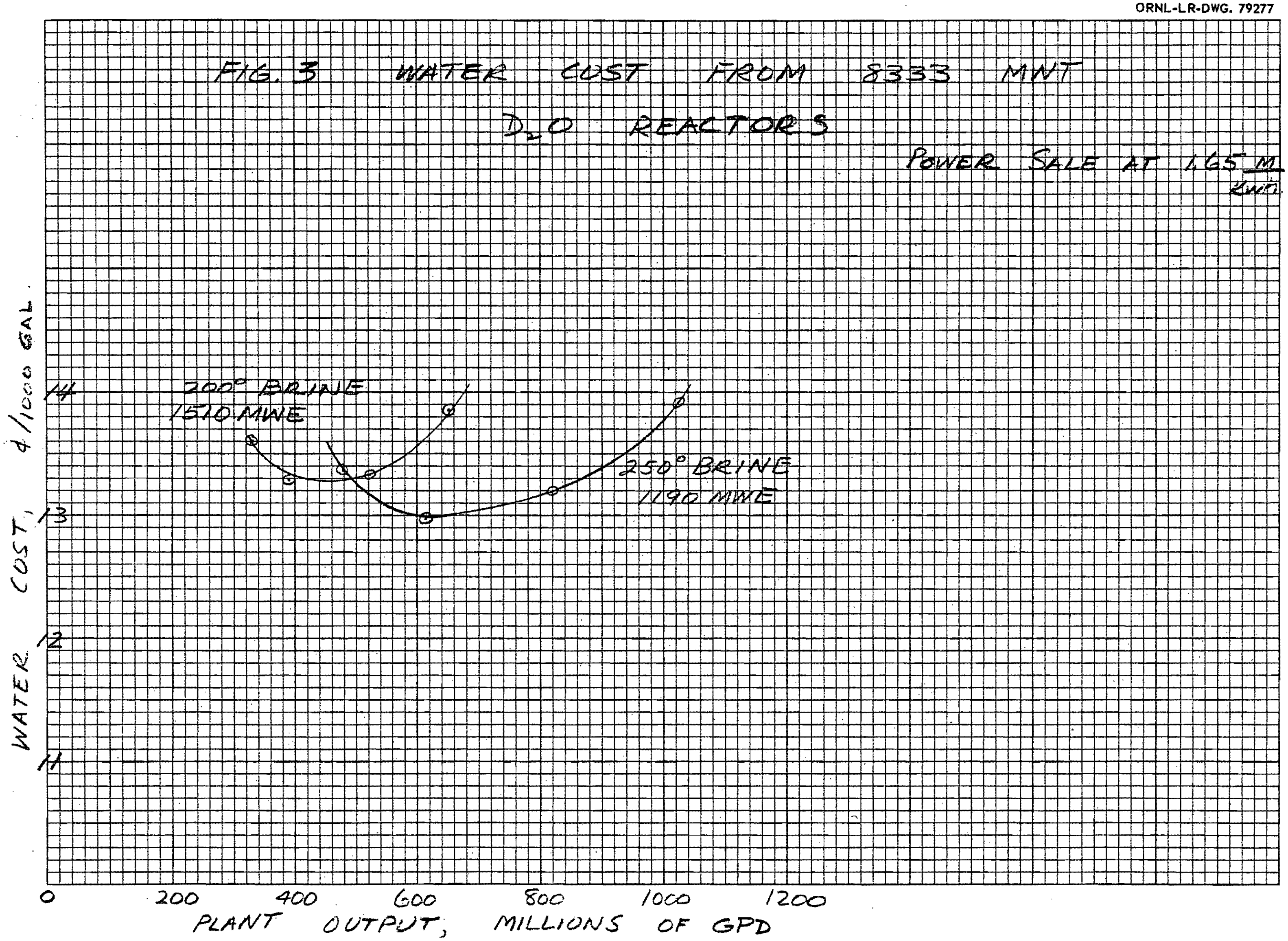

Optimum Water-Power Split and Incremental Cost of Electricity and Water

The 25,000 Mwt reactor stations giving minimum water costs (Fig. 1) are not truly optimum plants (Fig. 2) since the same outputs can be obtained cheaper from slightly different reactors. The reason they are not optimum is analogous to the classical economic example where a merchant does not sell goods at the maximum price but at the price at which he will make the most profit. Some ideal power price exists where the plant would be optimized at the minimum water price but that ideal price is unknown.

The optimum sized reactor can be determined by trial and error for a given amount of water and electric products. This was done for all combinations of electricity = 0, 1000 Mw, 3000 Mw, 5000 Mw and water = 0, 1 bgd, 2 bgd, 3 bgd.

Results are tabulated in Table V. The total annual costs in optimum plants can be used to calculate incremental costs of increasing water-production holding electricity-production fixed, and the incremental costs of electricity holding water production fixed. Figure 4 shows such incremental costs of electricity and water for every optimum plant, in addition to each annual operating cost.

The incremental cost of water production is everywhere between 10 to 14¢/1000 gal. The incremental cost of power production is quite low from the water-only plants, but generally is close to 1.4 mills/kwhr in dual-purpose or electricity-only plants. The costs get lower as the station increases in size.

Plotted also in Figure 4 are the optimum water-electric splits in 25,000 Mwt stations, obtained by interpolation between the grid points.

Conclusions

The optimum plants produce water at about the same costs as do the 25,000 Mwt plants. For the type of financing and industry assumed in this study, agricultural water prices are approached either a) in plants producing substantial quantities of electricity and heating brine to 250°F or below, or b) in plants producing little or no electricity but heating brine to 350°F.

Table V

Optimum Stations for Specified Water-Electric Production

(90% Load Factor)

Specified Electricity 1000 Mwe	Specified Water bgd	Reactor Power Mwt	Max. Brine Temp. °F	R lb per 1000 Btu	Station Capital Cost* $ million	Station Annual Cost $ million
0	1	7,000	350	14.14	406	45.6
0	2	13,000	350	15.2	798	88.0
0	3	19,580	350	15.5	1225	130.0
0	3.83	25,000	350	15.5	1554	163.5
1	0	3,400	---	----	147	15.4
1	1	12,000	307	9.63	527	56.7
1	2	18,370	350	12.13	886	94.8
1	3	24,000	350	13.62	1262	133.9
3	0	10,180	---	----	363	38.2
3	1	20,000	232	6.2	741	79.9
3	2	27,000	293	8.68	1072	115.9
3	3	33,000	324	10.38	1403	151.2
5	0	16,960	---	----	579	60.8
5	1	27,000	198.5	4.75	928	98.0
5	2	34,000	254	7.16	1259	135.9
7.37	0	25,000	---	----	833	86.2

*Exclusive of fuel and D_2O, another $6/kwt.

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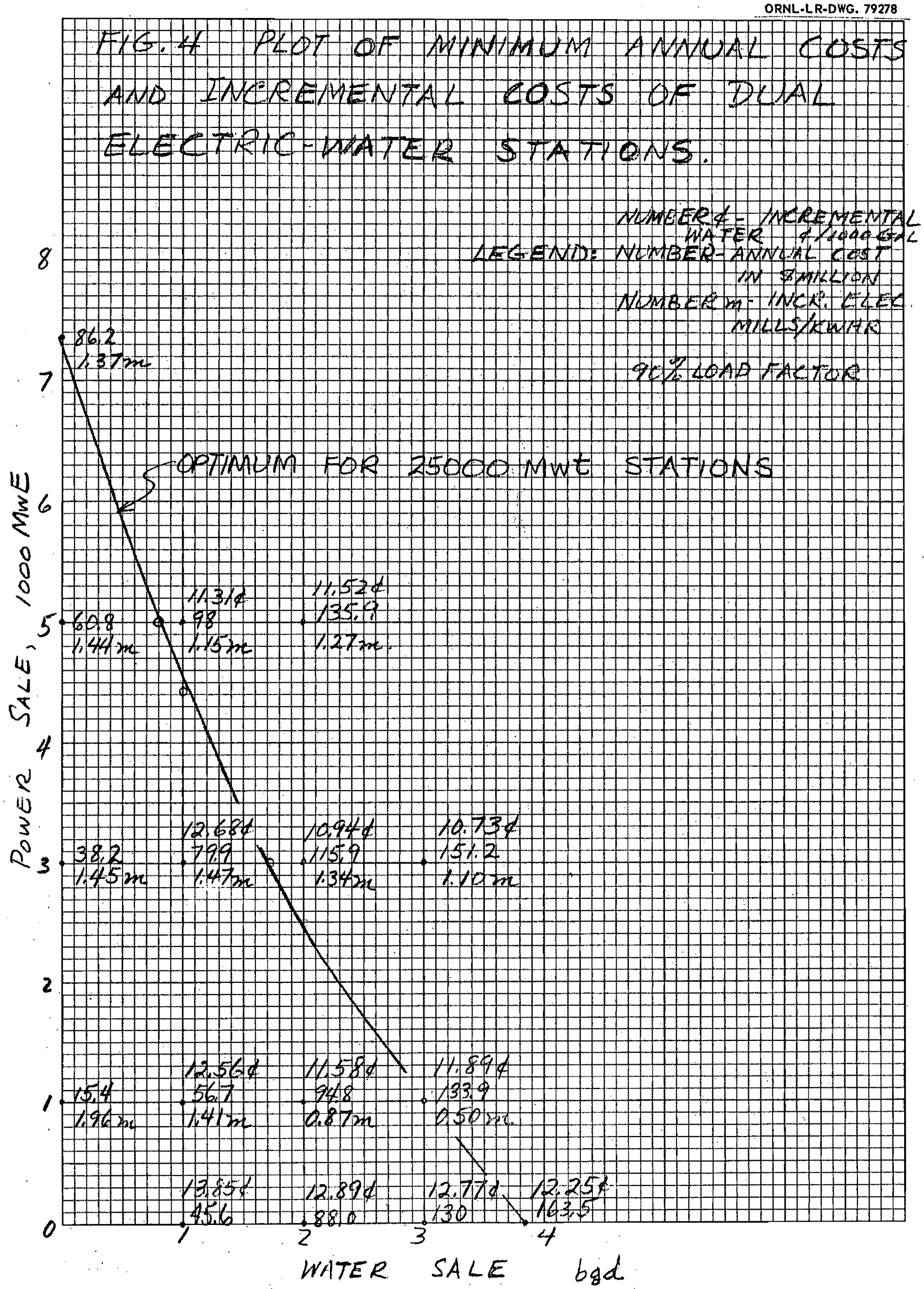

Development of the technology of using high temperature brine would greatly increase the flexibility of water-electricity split, but would not appreciably reduce the water cost as long as the power can be marketed.

Appendix

Ground Rules and Assumptions

Fuel cycle cost is based on U_3O_8 purchase at \$5/lb, Pu salt at \$6.70/g, and fabrication and processing in a 10 ton/day municipally-owned plant.

Charge on Capital: 7.7%/yr depreciating assets
5.5%/yr nondepreciating assets

Operating and Maintenance Costs per Year:
Reactor + Electric Plant - 0.0393 (Capital Cost in $\$10^6)^{0.814}$
Water Plant - 1% of Capital Cost

Chemicals Used in Flash Evaporator:
1.0¢/1000 gal based on H_2SO_4 produced in on-site large plant

Nuclear Insurance: Annual cost assumed 40× the total station power in Mwt.

D_2O Loss: Assumed 1% per year

D_2O Inventory: \$4/kwt

Additional data are given in Table I.

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