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CHEMICAL TECHNOLOGY DIVISION

THE EFFECT OF THE RADIOCHEMICAL REPROCESSING INDUSTRY'S GROWTH ON SPENT REPROCESSING COSTS

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1.0 ABSTRACT

An economic study of radiochemical reprocessing has been made to determine the means by which reasonable reprocessing costs (less than 0.75 mill/kwh) can be attained at the earliest possible date. It is assumed that the fuel is 2% enriched uranium irradiated to 4000 Mwd/ton. In a free economy, in which plants must be built to reprocess the fuel with minimum delay, reasonable reprocessing costs will not be attained until the nuclear power capacity reaches 80,000 Mw (heat), which is expected in about 1971. Reasonable reprocessing costs can be attained in a single plant from a nuclear capacity of 28,000 Mw (heat), which may be available around 1967, if the reactor operator does not have to pay use charges on the spent fuel. Several support programs by which the government could maintain reasonable radiochemical reprocessing costs in the projected economy prior to 1971 have been investigated. The government could support fuel recovery costs with the least expense by supplying the process development, and repurchasing and stockpiling spent reactor fuels until a single economical reprocessing plant can be built by private industry.

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2.0 INTRODUCTION

The fuel cost is not negligible in a nuclear power reactor as many people assumed a few years ago. In fact, on some of the demonstration reactors being built, the fuel element fabrication cost alone is more than the fuel cost in a coal-fired power plant. Moreover, in addition to fabrication, the costs of decay inventory charges, spent fuel shipping, radiochemical reprocessing, re-enrichment, and reduction to metal must be included as fuel costs. These costs will decrease as the nuclear economy grows, but they will probably never be negligible.

Some of the questions facing industry and the government today are: (1) Can nuclear power compete with conventional power generation in the U. S. while there is still an abundant supply of fossil fuel? (2) Where can research and development be most advantageously used to reduce nuclear power costs? (3) Can private industry enter the radiochemical reprocessing business in the next few years with reprocessing costs that the reactor operator can afford to pay? (4) If reprocessing must be subsidized in order to expedite the growth of nuclear power, how should it be done? The economic analyses included in this report were made in an attempt to answer these questions.

3.0 ALLOWABLE FUEL CYCLE COSTS

It is informative to look at some of the more predictable nuclear power costs to see what we can afford to pay for the ones that we cannot predict. The average cost for electricity from heat in the U. S. is 6.8 mills/kwh.[1] Of this 2.6 mills/kwh is fuel, 3.7 mills/kwh is fixed costs, and 0.5 mill/kwh is operation and maintenance costs. Nuclear plants will certainly be more expensive to build and maintain than conventional plants, and the fuel cost for a nuclear reactor, therefore, must be less than 2.6 mills/kwh to compete, on the average, in the U. S. By subtracting the fuel cycle costs that can be predicted with fair accuracy, we can determine what remains for the cost of fuel element fabrication and spent fuel recovery. For reactors costing the same as the average conventional plant, and assuming that the fuel is 2%

enriched uranium irradiated to 4000 Mwd/ton, the nuclear fuel costs are:

Inventory (1.25 cores at 4%)[14]	0.50 mills/kwh
Burnup, including Pu credit[14]	0.15
Overall recycle loss (2%)	0.18
Conversion of UF_6 to metal	0.10
Conversion of $UO_2(NO_3)_2$ to	0.15
Fabrication and radiochemical reprocessing by difference	1.52
Total	2.6 mills/kwh

Fabrication and radiochemical reprocessing would, therefore, cost about 1.5 mills/kwh for nuclear power plants to be competitive with conventional plants at the same investment. If the nuclear plant required a 12% larger investment than a conventional plant, however, refabrication and reprocessing costs of ~ 1.0 mill/kwh would have to be realized at 4000 Mwd/ton before nuclear power could be competitive. These costs are much less than can be currently achieved.

It is not known at present what relative contributions fabrication and radiochemical reprocessing will make to fuel cycle costs. There is some basis for radiochemical reprocessing costs but fabrication costs are still highly unpredictable since they depend to such a large extent on the design, tolerances, testing, and batch size for the specific reactor. If, for simplification, the two costs are assumed to be equal, fabrication and spent-fuel-recovery costs must be less than 0.75 mill/kwh, and probably around 0.5 mill/kwh each in order to achieve competitive nuclear power in the U. S. In the economic analyses that follow, 0.75 mill/kwh is assumed to be a reasonable cost for radiochemical reprocessing during the early years of nuclear power.

4.0 REPROCESSING COSTS

Several studies[3-8] have been made on the cost and operating expenses of large-scale radiochemical reprocessing plants to handle a wide variety of fuel elements. These studies are based on extrapolations of present dissolution and solvent-extraction procedures that have shown reasonable promise in laboratory-scale tests. The more recent estimates show remarkable consistency considering that they were made independently for different processes. This is due primarily to the fact that the actual processing equipment represents a relatively minor portion of the investment in a radiochemical processing plant. It should be noted that these estimates are based on plants that carry the product only as far as decontaminated nitrate.

The investment and operating costs are shown as a function of plant size in Figs. 1 and 2, respectively. The size has been normalized to tons per day of 2% enriched uranium, assuming that natural and 2% enriched uranium could be processed at the same rate and using the equivalent of 10 kg fully enriched capacity equal to 1 ton/day of 2% enriched capacity.

The effect of plant size and loading on the radiochemical reprocessing cost is shown in Fig. 3. This is based on the investment and operating costs shown in Fig. 1 and 2 and the following factors: (a) decay and shipping at 0.29 mill/kwh, (b) 6-2/3 year amortization, (c) 15% return on investment, (d) 90% power load factor, (e) 330 day/year chemical plant operation, and (f) 2% enriched uranium fuel irradiated to 4000 Mwd/ton. The reprocessing costs shown are inversely proportional to the burnup so that for 8000 Mwd/ton irradiation the reprocessing cost would be half the value shown at the same reprocessing plant throughput (twice the installed power).

It may be concluded from Fig. 3 that in order to reprocess spent fuels for less than 0.75 mill/kwh (at 4000 Mwd/ton burnup) a plant larger than 7 tons/day operating at capacity will be required. This would require an installed nuclear capacity in excess of 28,000 Mw (heat). It is also important to note the effect of plant loading. If a plant is to operate at less than capacity, which is quite likely during the first few years of operation, a larger fuel loading is required to achieve reasonable costs. For example, in order to achieve costs of less than 0.75 mill/kwh (4000 Mwd/ton) at 80% plant load factor, a plant larger than 10 tons/day capacity, processing in excess of 8 tons/day of spent fuel, is needed. This would require an installed nuclear capacity in excess of 32,000 Mw (heat).

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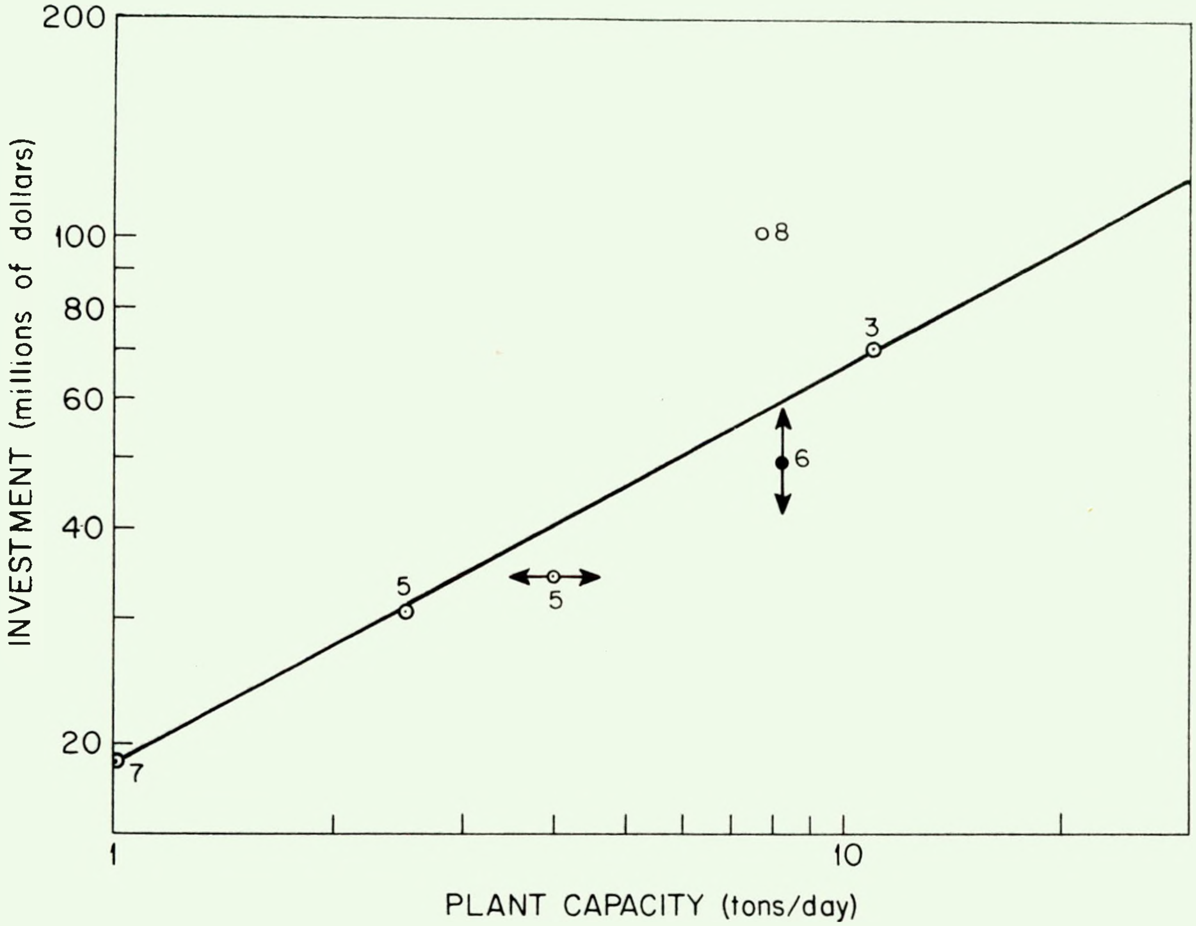
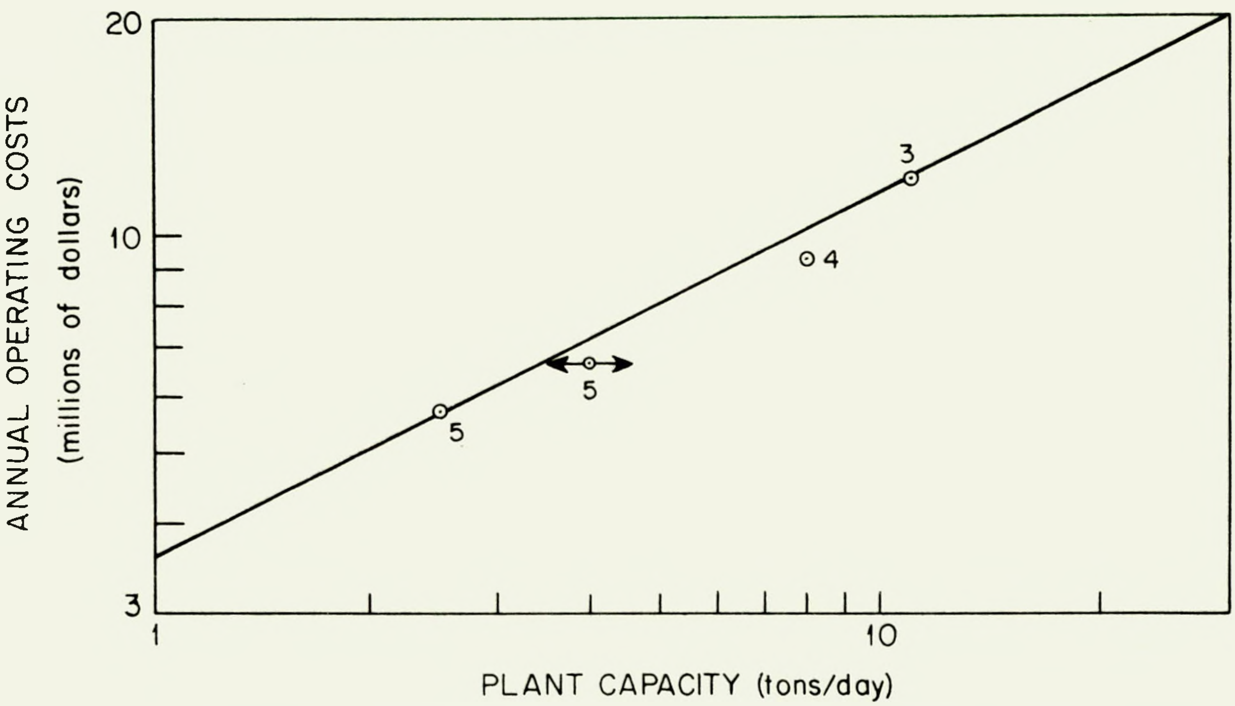


3. 6 tons/day Natural U Plus 50 kg/day U^{235} (no volatility plant)
5. 25 kg/day U^{235} and 25 kg/day U^{235} Plus 1-2 tons/day Natural U
6. 8.3 tons/day Natural U
7. 1 ton/day Natural U
8. 8 tons/day Natural U

Fig. 1. Reprocessing Plant Investment vs Plant Capacity. Basis: 2% enriched uranium; 10 kg capacity for enriched assumed equivalent to 1 ton/day of 2% enriched. References on page 20.



3. 6 tons/day Natural U Plus 50 kg/day U^{235} (no volatility plant)
4. 8 tons/day Natural U
5. 25 kg/day U^{235} and 25 kg/day U^{235} Plus 1-2 tons/day Natural U

Fig. 2. Direct Operating Costs vs Plant Capacity. Basis: 2% enriched uranium; 10 kg capacity for enriched assumed equivalent to 1 ton/day of 2% enriched. References on page 20.

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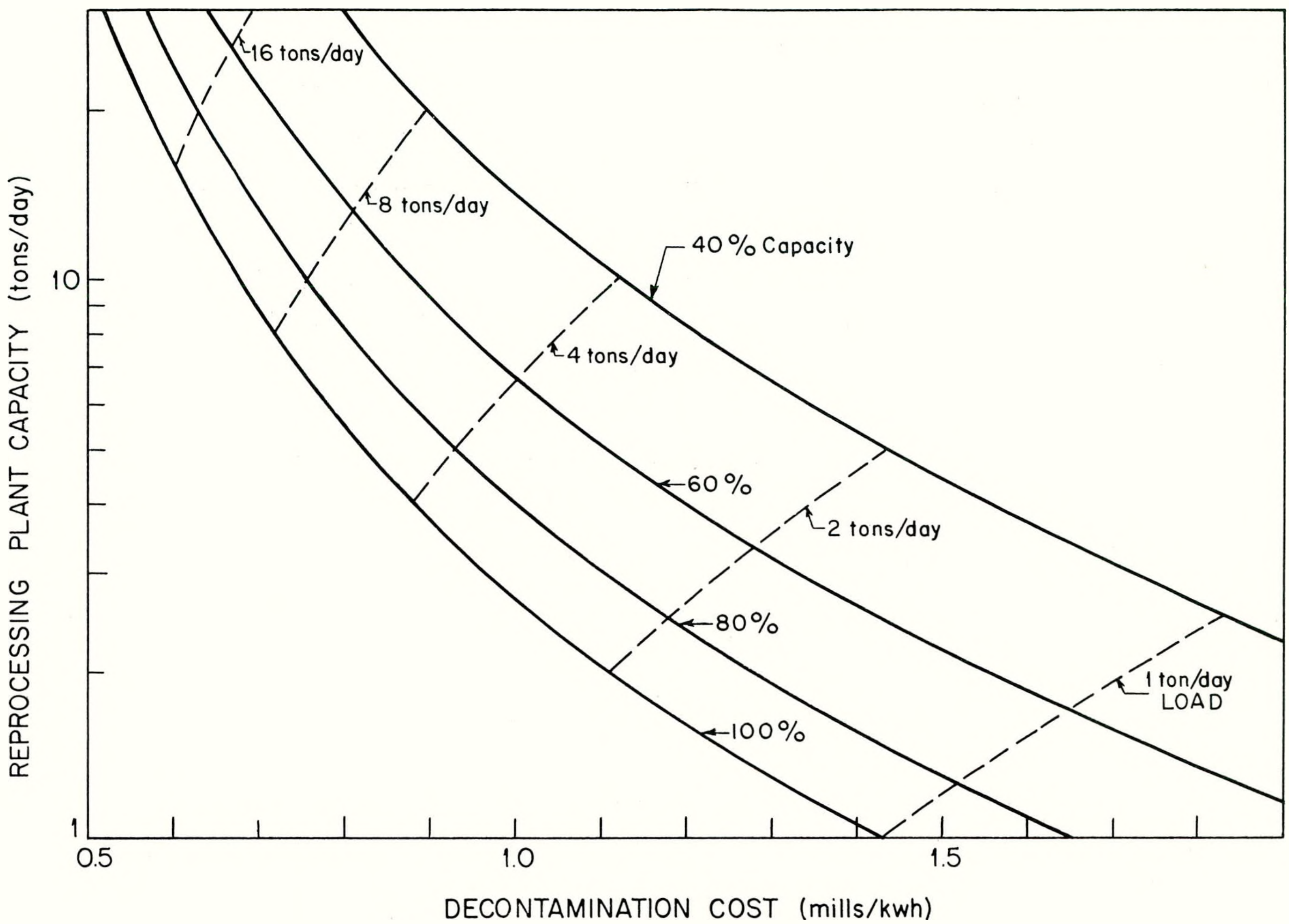

Fig. 3. Reprocessing Cost vs Plant Capacity and Loading. Basis: Reactors with 25% thermal efficiency, 2 % enriched uranium fuel, and 4000 Mwd/ton burnup; chemical plant with 330 days/year operation, $6\frac{2}{3}$ years amortization, and 15% return on investment; 0.29 mill / kwh for fuel decay and shipping.

5.0 NUCLEAR POWER BUILDUP

Several predictions[9-13] have been made of the buildup of nuclear power in the United States. It is impossible to say, of course, which is most likely to be right. The McKinney Report, the most recent, has both an optimistic and a conservative prediction on nuclear power growth. If the average of these values is assumed correct (except for the early years, where it falls below the reactors announced and under construction for 1962), the power growth will be as shown in Fig. 4. The fuel to be processed from power reactors then would be as shown in Fig. 5, assuming that the fuel from all reactors is 2% enriched uranium and is irradiated to 4000 Mwd/ton. Although research and propulsion reactor fuels will be the first available for reprocessing, they will probably not add a significant amount of fuel to the reprocessing plant load after 1962 and, therefore, have not been included in the estimates.

6.0 EFFECT OF GROWTH AND GOVERNMENT SUPPORT ON REPROCESSING COSTS

The power buildup curve (Fig. 4) indicates that the 28,000 Mw (heat) minimum nuclear capacity required to achieve 0.75 mill/kwh radiochemical reprocessing costs from a single reprocessing plant would not be available until 1967. This is not the complete story, however, since the way in which the reprocessing industry grows will have an effect on the reprocessing costs. For example, if in 1967 there are five 2-ton/day plants instead of a single 10-ton/day plant, the reprocessing cost would be ~ 1.3 instead of 0.75 mill/kwh.

There are many ways in which the reprocessing industry could grow. The most probable are:

1. A completely free reprocessing economy with no government support or process development.

2. Government process development plus government spent-fuel repurchasing and stockpiling until an economically sized private radiochemical reprocessing plant could be built to reprocess fuels at 0.75 mill/kwh. During the repurchase period the government would credit the reactor operator for the value (as nitrates) of the uranium and plutonium contained in the

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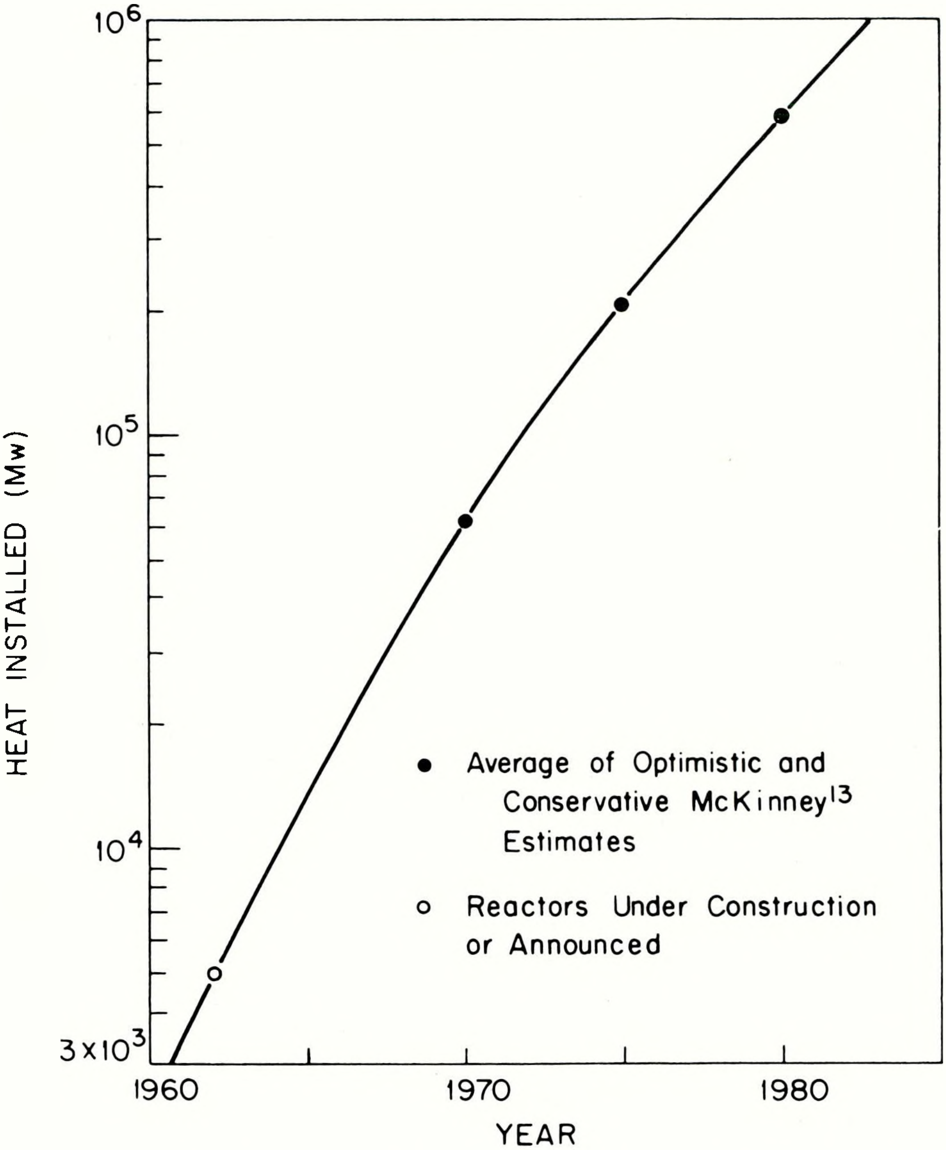

Fig. 4. Estimated Stationary Nuclear Power Growth.

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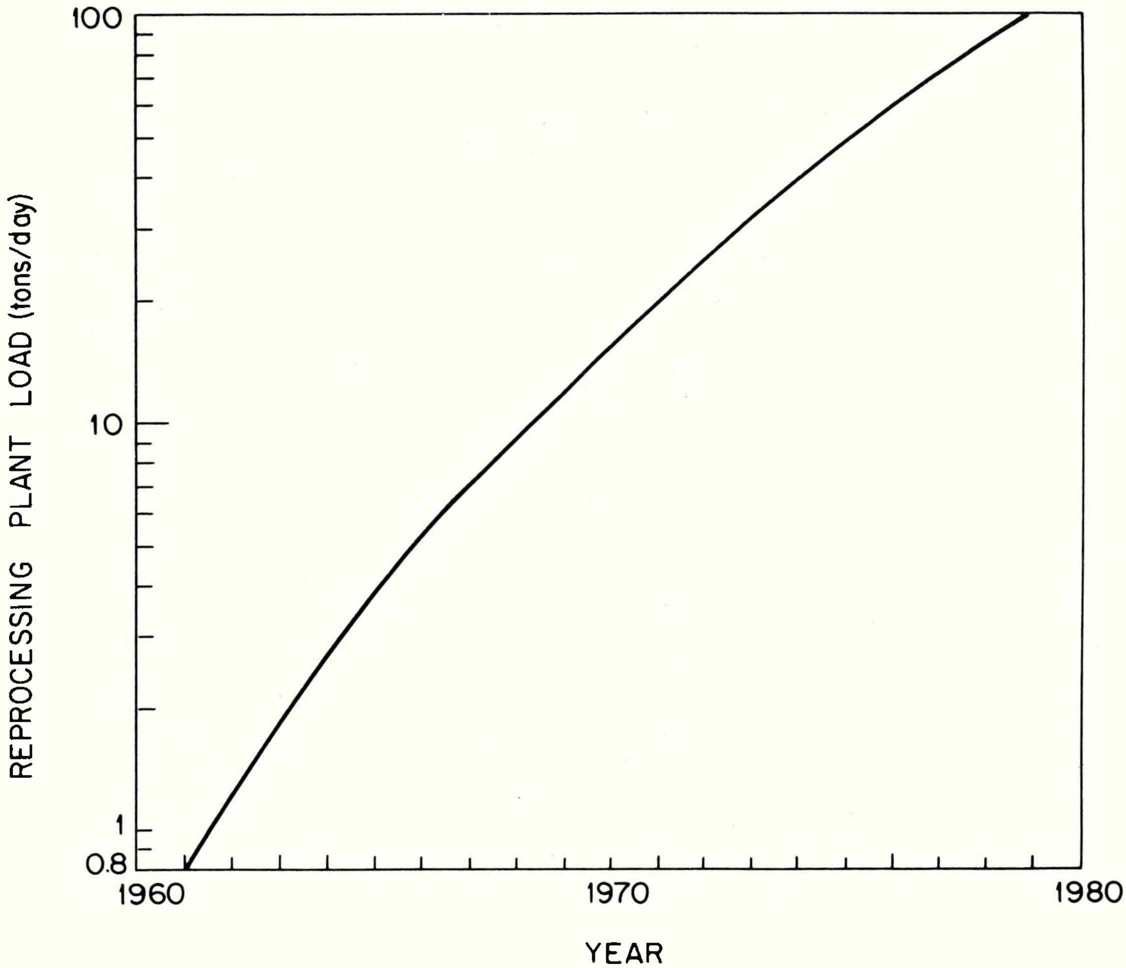

Fig. 5. Estimated Reprocessing Plant Load. Basis: Power growth from Fig. 1, 2% enriched fuel burned to 4000 Mwd/ton, 90% power load factor, 330 day/year reprocessing plant operation.

spent fuel minus a 0.75 mill/kwh decontamination charge.

3. Government process development plus a base load of non-power-reactor fuels supplied by the government to support an economically sized private radiochemical reprocessing plant.

The radiochemical reprocessing plant buildup and reprocessing costs have been calculated* for each of these cases.

6.1 Case 1 (Free Economy)

In a free economy the reactor operator cannot afford to store spent fuel and wait for a larger scale plant to decrease reprocessing costs because use charges on the fuel would more than offset any saving in reprocessing. (For each year he retains the fuel he must pay 0.4 mill/kwh additional in use charges.) For example, it would be more economical for a reactor operator to pay 2.0 mills/kwh in 1963 for fuel reprocessing than to wait until 1967 to have the fuel reprocessed at 0.75 mill/kwh and pay 1.6 mills/kwh for use charge (a total of 2.35 mills/kwh). In a free economy, therefore, reprocessing plants would be built at an early date despite the high unit costs of the small plants.

The radiochemical reprocessing plant installations and the reprocessing charges that can be envisioned in a completely free economy are shown in Fig. 6. In this case a pilot plant would be built around 1960 and expanded to a 2-ton/day plant in 1963. A second plant of 4 tons/day capacity would be installed in 1966 and a 12-ton/day plant would replace the original 2-ton/day plant (which would no longer be competitive) in 1969. Let us see, for example, what costs will be involved when the fuel from reactors in operation (48,000 Mw heat) in 1969 is discharged and radiochemically reprocessed in 1970. The spent-fuel available will be 12 tons/day and there will be 16 tons/day of reprocessing plant capacity (a 4 ton/day and a 12 ton/day plant). Fuel decay and shipping charges will be 0.29 mill/kwh, reprocessing costs including profit will be 0.53 mill/kwh and interest on development investment will be

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*The following basis has been used for these calculations: (1) Power buildup shown in Fig. 4; (2) all reactors fueled with 2% enriched uranium burned to 4000 Mwd/ton and having a 90% load factor; (3) $50 $\bar{M}$ process development required; (4) reprocessing plant investments and operating costs as shown in Figs. 1 and 2; (5) 6-2/3 years' amortization; (6) 15% return on investment; (7) 330-day/year reprocessing plant operation; (8) fuel shipping and decay costs at 0.29 mill/kwh; and (9) 4% inventory charge.

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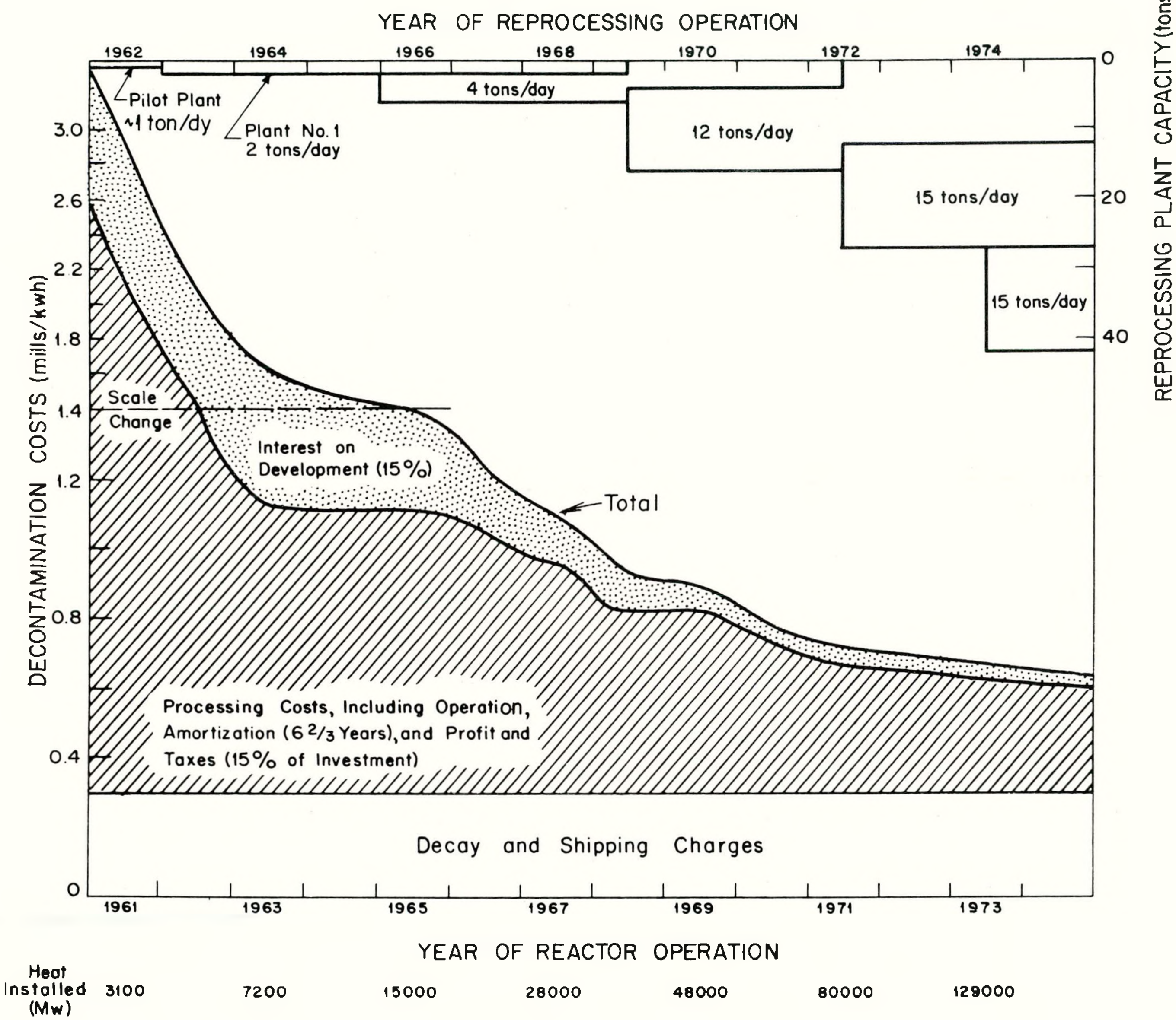

Fig. 6. Power Reactor Fuel Reprocessing Plant Capacity and Costs with no Government Support. Basis: 90% load factor, 2% enriched uranium fuel, 4000 Mwd/ton burnup, development investment required \$50 $\overline{M}$.

0.08 mill/kwh for a total of 0.9 mill/kwh that the reactor operator must pay to have his fuel decontaminated. Reprocessing costs of 0.75 mill/kwh would not be realized until late in 1970 (fuel processed in 1971). Even if the government supported the development cost, 0.75 mill/kwh processing costs would be realized only about six months sooner.

6.2 Case 2 (Government Spent-Fuel Repurchase and Stockpile)

Plant capacities and radiochemical reprocessing costs that can be prophesided if the government supports the process development and repurchases and stockpiles the spent power reactor fuels until an economical radiochemical processing plant can be built are shown in Fig. 7. In this case the first plant would be built in 1967 and would have 10 tons/day capacity. During the first two or three years there would be sufficient excess capacity to reprocess the stockpiled fuel. Thus a 0.75-mill/kwh processing cost would be realized in a free economy in 1966 (fuel processed in 1967).

During the period 1960-1966 a pilot plant would be operated to develop and demonstrate the processes for the larger plant. There may be an advantage to the government to have such a plant act as an interim processing plant during the later stages of process development. For example, it is evident from Fig. 8 that, if the pilot plant processed fuel at a rate of 1 ton/day from 1962 through 1966, the saving in the 4% use charge would amount to \$38 $\bar{M}$ (\$72 $\bar{M}$ - \$34 $\bar{M}$). This is more than enough to offset the ~ \$12 $\bar{M}$ additional operating costs required for interim processing in the existing pilot plant. The total stockpiling program costs with interim processing would be \$96 $\bar{M}$ (\$34 $\bar{M}$ for use charge, \$50 $\bar{M}$ for development, and \$12 $\bar{M}$ for interim processing operation).

It is obvious that these figures are valid only if the government levies use charges on material contained in spent-fuel elements in its own stockpiles. If use charges are not levied on this fuel the cost to the government would be only the \$50 $\bar{M}$ required for process development. In this latter case the justification for interim processing would be to return the fuel to use at an earlier date.

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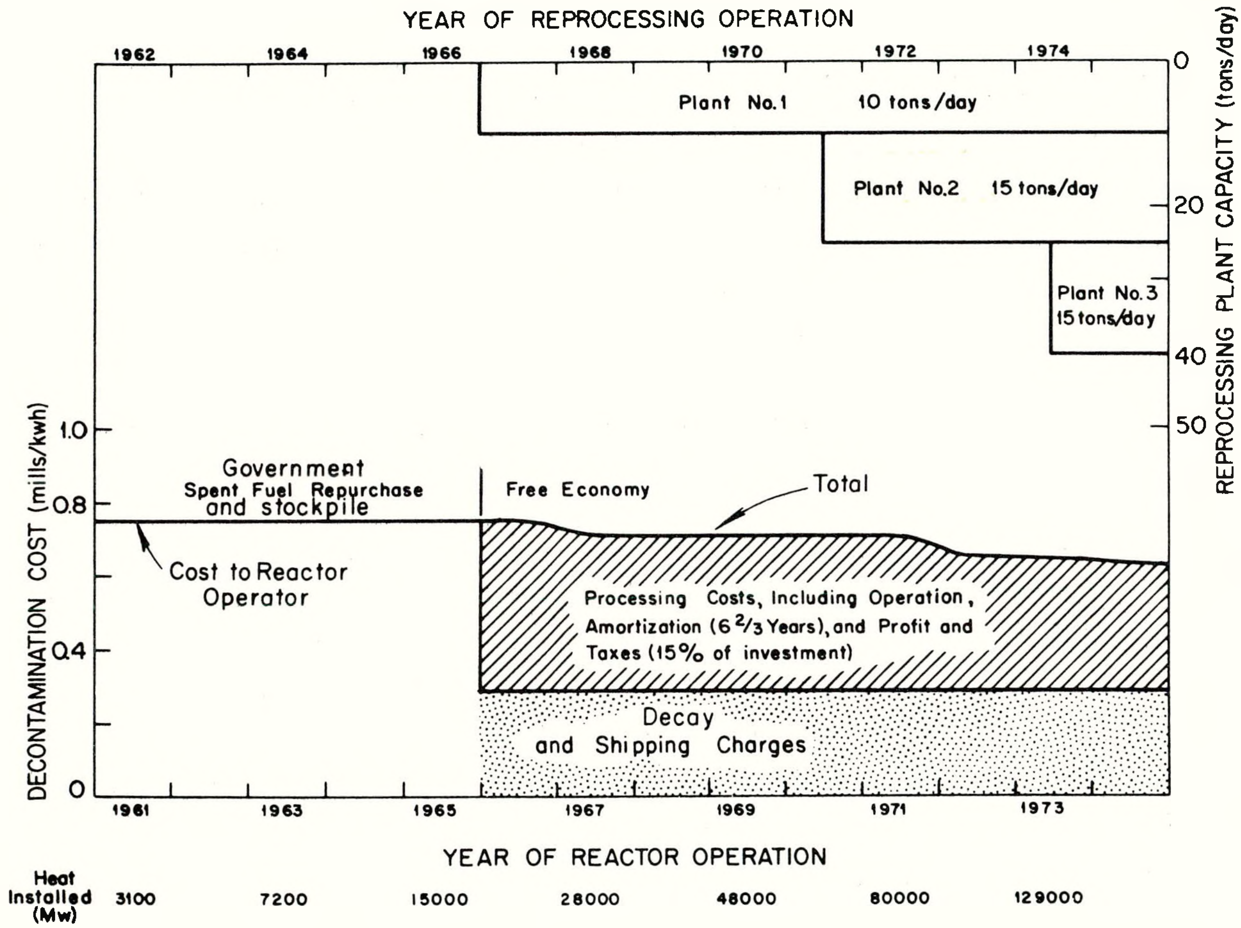

Fig. 7. Power Reactor Fuel Reprocessing Plant Capacity and Cost with Government Spent Fuel Repurchase Through 1966. Basis: 90% load factor, 2% enriched uranium fuel, 4000 Mwd/ton burnup, process development by government.

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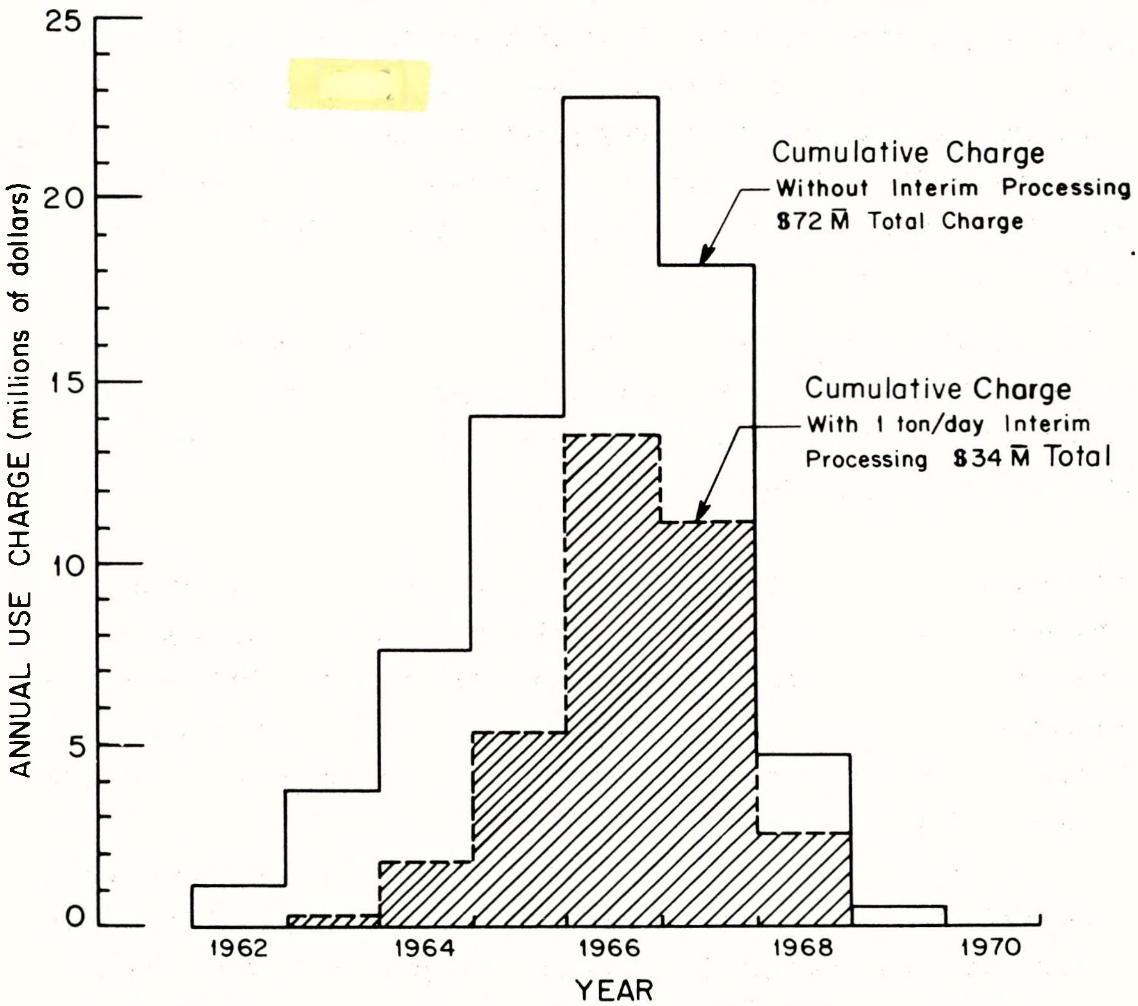

Fig. 8. Use Charges on Stockpiled Spent Fuel. Basis: 2% enriched uranium burned to 4000 Mwd/ton stockpiled through 1966, private processing plant start-up in 1967.

6.3 Case 3 (Government Fuel Base Load)

It has been suggested that a guaranteed base load of government fuel might allow private industry to build an economical plant during the early years when there is not enough power reactor fuel to support such a plant. The base load required to achieve a cost of 0.75 mill/kwh, the processing plant buildup, and the processing costs are shown in Fig. 9. For example, in 1964 when radiochemically reprocessing the fuel from the 7200 Mw (heat) operating in 1963, a government base load of 6 tons/day of natural uranium* (or 4 tons/day of natural uranium plus 20 kg/day of enriched fuel) would be required to load the 10 ton/day plant to the point where 0.75 mill/kwh reprocessing costs would be possible. The government base fuel load would gradually decrease from the 7 tons/day required in 1963 until it is no longer required after 1968.

This base load is too large to be practical. It is extremely unlikely that there would be this much surplus fuel to reprocess from the government's production operations and it would not make economic sense to remove fuel from existing processing plants.

7.0 CONCLUSIONS

Spent fuel recovery costs well in excess of 1 mill/kwh during the early years of nuclear power in a free economy (Fig. 6) could greatly depress nuclear power buildup. Government support of fuel element fabrication and spent fuel recovery, similar to the present support of reactor development, will probably be required if nuclear power is to become competitive at the earliest possible date.

The cost to the government of such a support program would depend on the way it is carried out. If private industry builds small reprocessing plants in order to minimize use charges (case 1) and the government supports the reprocessing cost at 0.75 mill/kwh, the total cost to the government would be \$165 $\bar{M}$.** This could be decreased to \$125 $\bar{M}$ (\$75 $\bar{M}$** support and \$50 $\bar{M}$ development) if the government did the development. Such support would no longer be required after 1970.

If, on the other hand, the government repurchased the spent fuel (or

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*The reprocessing cost (excluding shipping) for the government fuel would be \$11,000/ton.

**These figures result from integrating the costs above 0.75 mill/kwh in Fig. 6.

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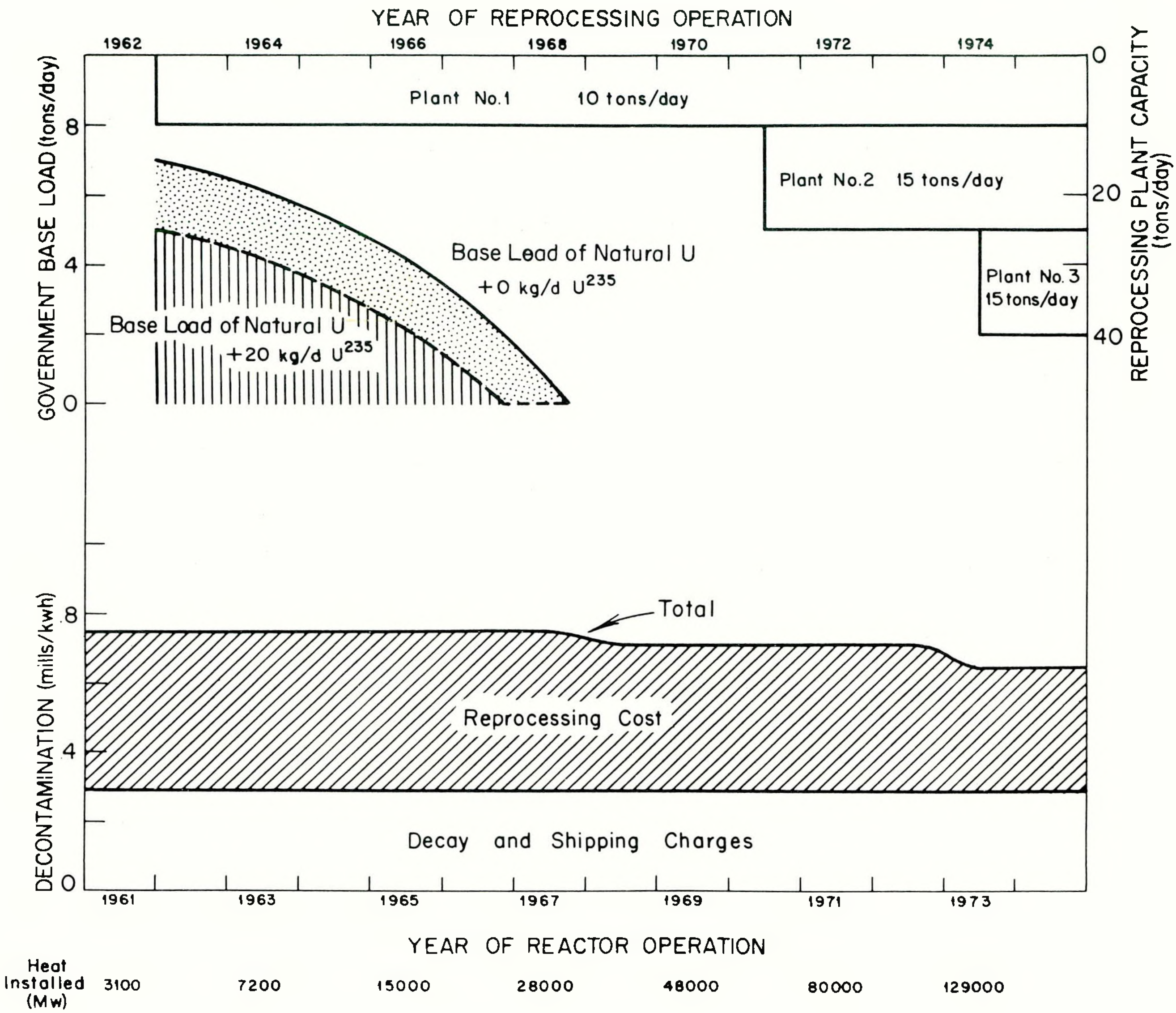

Fig. 9. Power Reactor Fuel Reprocessing Plant Capacity and Cost with Government Base Load. Basis: 90% load factor, 2% enriched uranium fuel, 4000 Mwd/ton burnup, process development by government.

waived the use charges on spent fuel), invested \$50 M̄ on process development, and used the development facility for interim processing at a rate of 1 ton/day, a total expenditure of \$96 M̄ would be necessary. (Since \$34 M̄ of this is use charge the actual cost may amount to only \$62 M̄.) A free economy would be obtained in 1966 when a single large-scale private processing facility could be built.

It is not possible to calculate how much it would cost to supply a government base load to a processing plant since this would depend on the amount of surplus fuel from production operations and the demand for plutonium. This means of support would be economically attractive only if there was a large demand for plutonium during the period 1963-1968.

It is evident that, unless there is a large surplus of production fuel to supply a base load, spent fuel repurchase and stockpiling by the government coupled with process development and a pilot plant that may operate at 1 ton/day would allow a free reprocessing economy at the earliest date with the least cost to the government. It should be borne in mind that the above discussion involves only the radiochemical reprocessing cost. Fuel element fabrication will require equal or greater development and support.

8.0 EFFECT OF BURNUP

The burnup attained in the reactors will, of course, affect the economics. At twice the burnup only half as much fuel has to be reprocessed per unit of electricity. The reprocessing costs are not cut in half, however, since with less fuel reprocessed the unit cost per ton of fuel is higher. For a hypothetical power economy of 8000 Mw (heat), the effect of burnup on costs is:

Burnup, Mwd/ton	4000	8000
Fuel processed, tons/day	2	1
Processing cost, mills/kwh (from Fig. 3)	1.1	0.71

In this case doubling the burnup decreases the processing cost by only 35% instead of the 50% that might be expected at first.

The reprocessing plant installations and the reprocessing charges that can be envisioned in a completely free economy with 8000 Mwd/ton burnup are shown in Fig. 10. A comparison with Fig. 6, which was based on 4000 Mwd/ton burnup, shows that 0.75 mill/kwh processing costs would be realized approximately 3.5 years sooner (mid-1966 instead of 1970) and that the ultimate reprocessing costs would be about 0.4 instead of 0.65 mill/kwh. The justification for government support of reprocessing during the first few years of nuclear power is not changed since very high reprocessing costs would be necessary in a free economy in either case. The main effect of increased burnup would be to shorten the period during which government support would be necessary.

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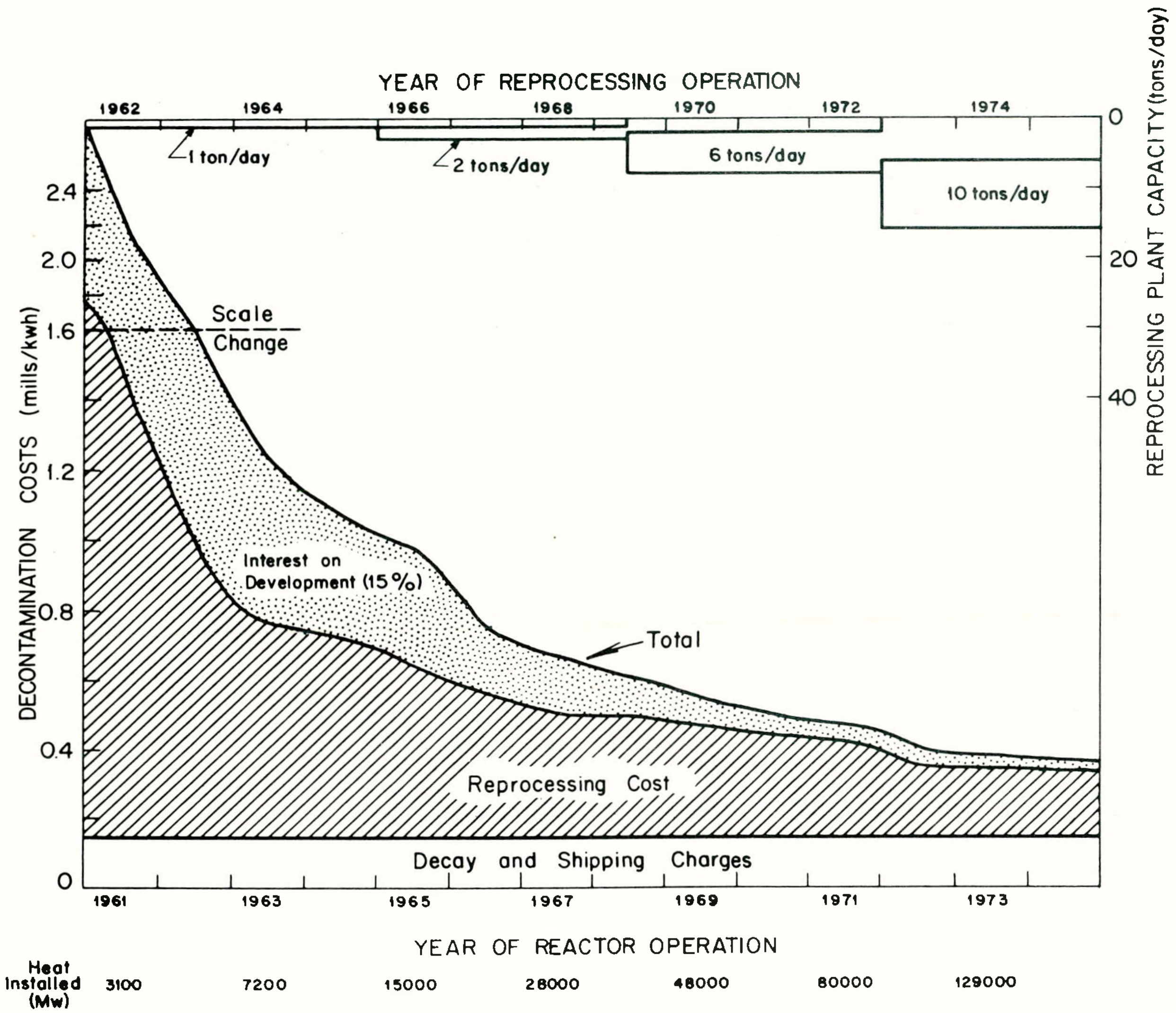

Fig. 10. Power Reactor Fuel Reprocessing Plant Capacity and Cost with no Government Support. Basis: 90% load factor, 2% enriched uranium fuel, 8000 Mwd/ton burnup, development investment total required \$50 $\overline{M}$.

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