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SUBJECT: Radiochemical Reprocessing Costs in an Expanding Nuclear Economy

TO: F. L. Culler, Jr.

FROM: C. E. Guthrie

Abstract

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RADIOCHEMICAL REPROCESSING COSTS IN AN EXPANDING NUCLEAR ECONOMY

By

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U. S. Atomic Energy Commission

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INTRODUCTION

The fuel cycle 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 or production of UO_2 must be included as fuel costs. These costs will decrease as the nuclear economy grows, but they will probably never be negligible.

One of the questions facing industry today is: When can private industry enter the radiochemical reprocessing business with reprocessing costs that the reactor operator can afford to pay? The economic analyses presented were made in an attempt to answer this question.

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.[7] 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 1.5% enriched uranium irradiated to 8000 Mwd/ton, the nuclear fuel costs are:

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*The reactor was assumed to be a pressurized water reactor with a 0.75 conversion ratio, 78 Kw/kg specific power, 25% thermal efficiency and 80% load factor.

Inventory (2 cores at 4%)[8]	0.14 mills/kwh
Burnup, including Pu credit[8,12] ($12/gm Pu value assumed)	0.73
Overall recycle loss (2%)	0.06
Conversion of UF_6 to UO_2[13] ($4.50/kg UO_2 assumed)	0.18
Conversion of $UO_2(NO_3)_2$ to UF_6[14] ($5.60/kg U assumed)	0.11
Shipping ($10/kg U assumed)	0.21
Fabrication and radiochemical reprocessing (by difference)	1.17
TOTAL	2.60 mills/kwh

Fabrication and radiochemical reprocessing would, therefore, cost about 1.17 mills/kwh for nuclear power plants to be competitive with conventional plants at the same investment. It is probable that nuclear plants will require at least a 10% larger investment than a conventional plant, therefore, refabrication and reprocessing costs of ~0.8 mill/kwh would have to be realized at 8000 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 a large extent on the design, tolerances, testing, and batch size for the specific reactor. If it is assumed that fabrication can eventually be reduced to $10/lb of uranium (~0.45 mills/kwh), fuel-recovery costs must be around 0.35 mill/kwh in order to achieve competitive nuclear power in the U.S. In the economic analyses that follow, 0.35 mill/kwh is assumed to be a reasonable radiochemical reprocessing cost for competitive nuclear power.

REPROCESSING COSTS

Several studies[1-6] 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 and are currently under development. 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 slightly enriched uranium, assuming that natural and slightly enriched uranium could be processed at the same rate and using the equivalent of 44 kg highly enriched capacity equal to 1 ton/day of slightly enriched capacity.

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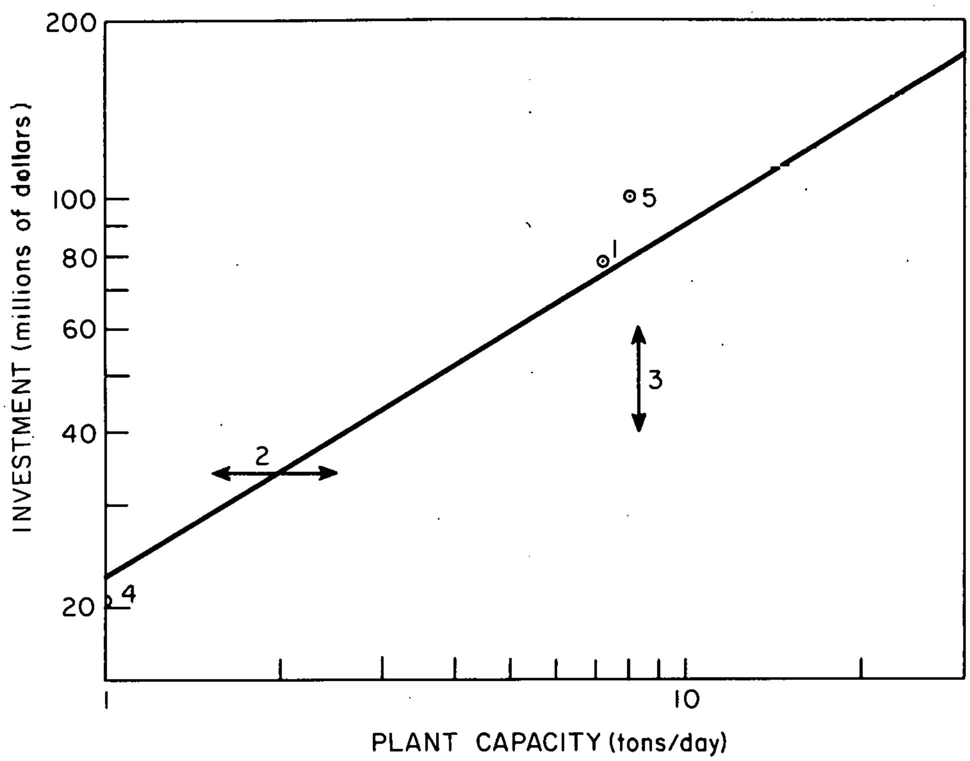

1. 6 tons/day Natural U Plus 50 kg/day U^{235} (no volatility plant).
2. 25 kg/day U^{235} Plus 1-2 tons/day Natural U.
3. 8.3 tons/day Natural U.
4. 1 ton/day Natural U.
5. 8 tons/day Natural U.

Fig. 1. Reprocessing Plant Investment vs Plant Capacity. Basis: 44 kg capacity for highly enriched assumed equivalent to 1 ton/day of slightly enriched or natural uranium. References on page 18.

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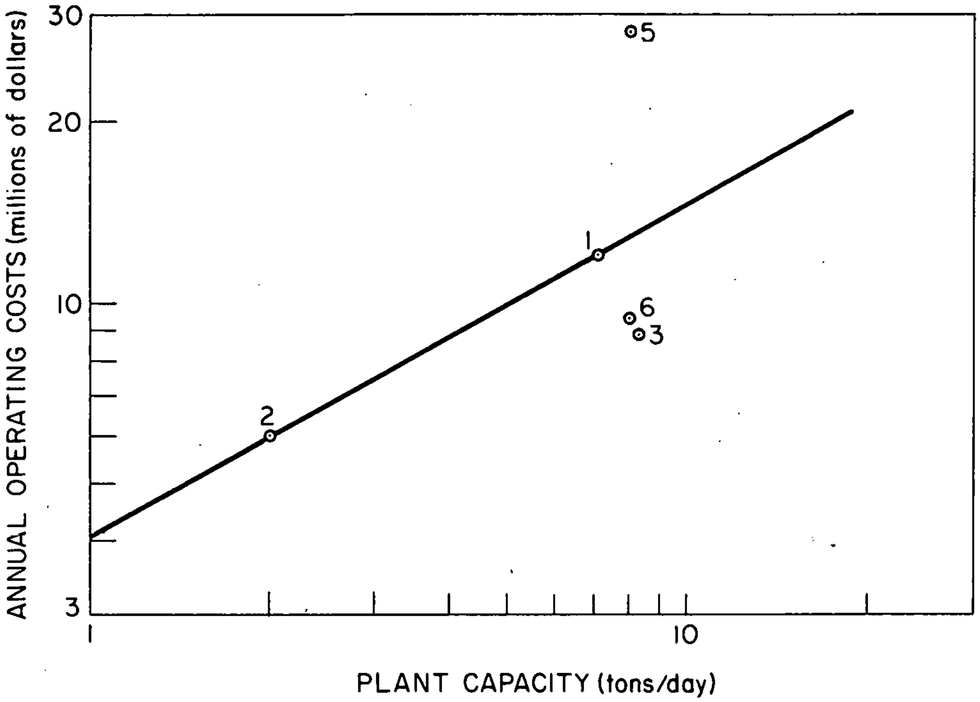

1. 6 tons/day Natural U Plus 50 kg/day U^{235} (no volatility plant)
2. 25 kg/day U^{235} Plus 1-2 tons/day Natural U.
5 & 6. 8 tons/day Natural U.

Fig. 2. Direct Operating Costs vs Plant Capacity. Basis: 44 kg capacity for highly enriched assumed equivalent to 1 ton/day of slightly enriched or natural uranium. References on page 18.

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The effect of plant size and loading on the radiochemical reprocessing cost ($/kg) is shown in Fig. 3. This is based on the investment and operating costs shown in Figs. 1 and 2 and the following factors: (a) 6-2/3 year amortization, (b) 15% return on investment for profit, taxes and insurance, and (c) 300 day/year chemical plant operation. In addition Fig. 3 shows reprocessing cost in mills/kwh assuming slightly enriched fuel, irradiated to 8000 Mwd/ton and 80% power load factor. The mills/kwh are inversely proportional to Mwd/ton for a given plant size and loading.

It may be concluded from Fig. 3 that in order to reprocess spent fuels for 0.35 mill/kwh (at 8000 Mwd/ton burnup) a 6 ton/day plant operating at capacity would be required. This would require an installed nuclear capacity of 48,000 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 0.35 mill/kwh a 10 ton/day capacity plant must process in excess of 8 tons/day. This would require an installed nuclear capacity of 64,000 Mw(heat).

NUCLEAR POWER BUILDUP

Several predictions have been made of the buildup of nuclear power in the U.S. The predictions of Lane[9], Davis[10], and the average of the predictions in the McKinney[11] report are shown in

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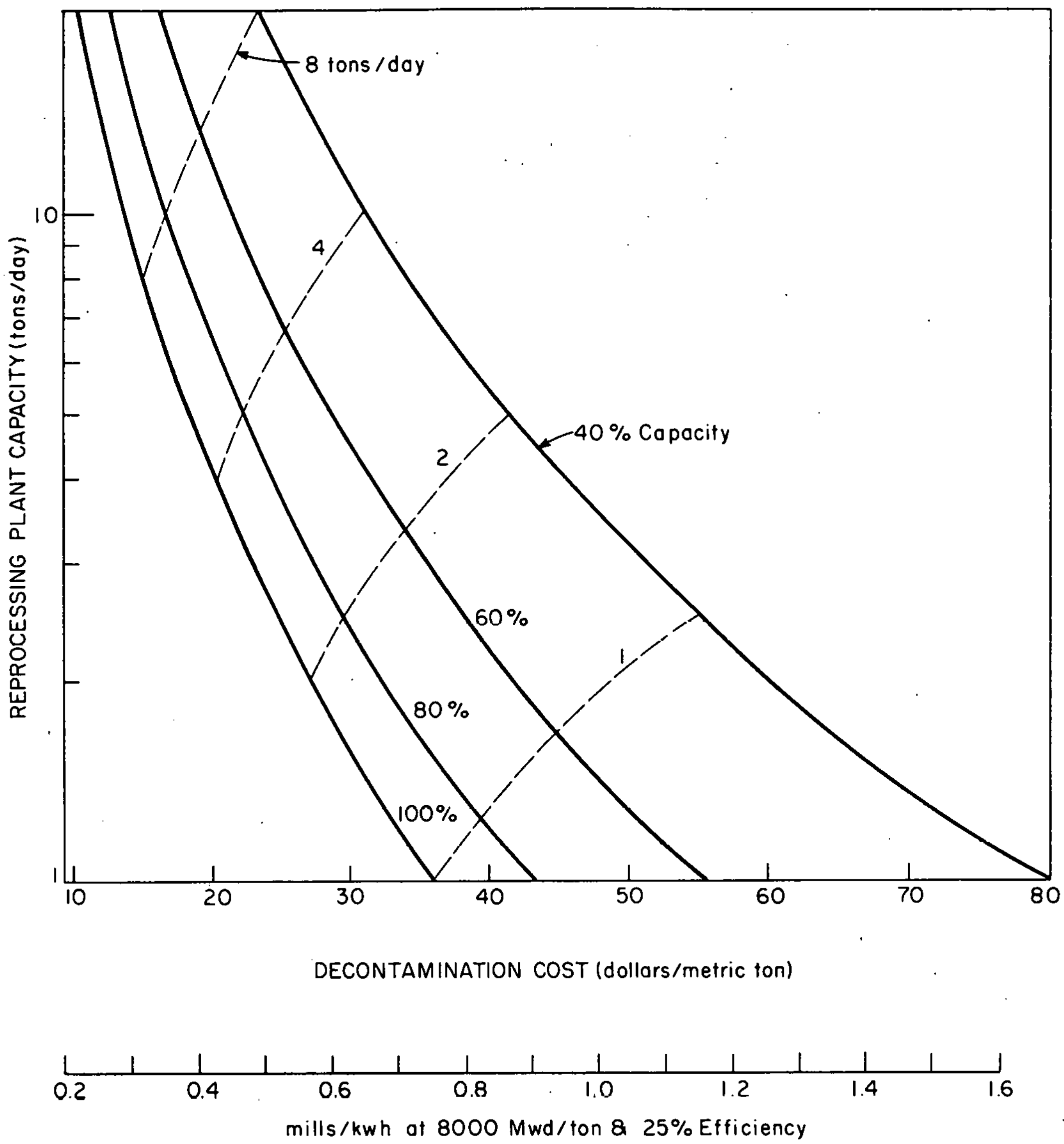

Fig. 3. Reprocessing Cost vs Capacity and Loading. Basis: Chemical plant with 300 days/year operation, $6\frac{2}{3}$ years amortization, and 15 % return on investment for profit, taxes and insurance.

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Fig. 4 (they have been adjusted to agree with reactors proposed in 1962). Shown also is the reprocessing plant load assuming 8000 Mwd/ton and 25% thermal efficiency. 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.

EFFECT OF GROWTH AND STOCKPILING ON REPROCESSING COSTS

The power buildup curves (Fig. 4) indicate that the 48,000 Mw (heat) minimum nuclear capacity required to achieve 0.35 mill/kwh radiochemical reprocessing costs from a single reprocessing plant would be available between 1968-1973, or in 1970 if one assumes the McKinney averages correct. 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 1970 there were three 2-ton/day plants instead of a single 6-ton/day plant, the reprocessing cost would be 0.56 instead of 0.35 mill/kwh.

There are several ways in which the reprocessing industry could grow in the early years of nuclear power. Two of the more probable are: (1) Reprocessing plant capacity growth to match the rate of fuel discharged from reactors, and (2) Spent fuel stockpile until there is enough fuel to support an economic size reprocessing plant (~6 tons/day capacity).

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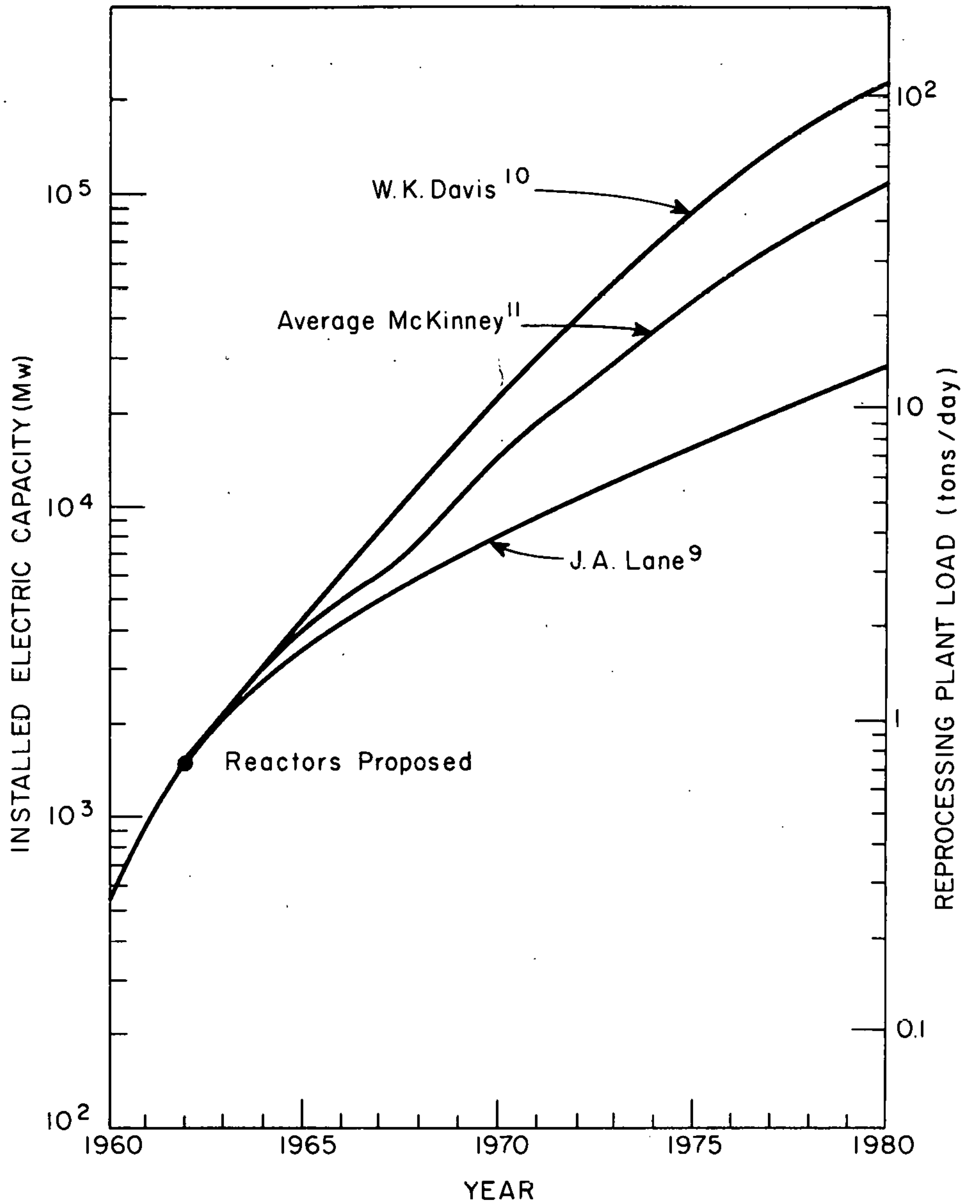

Fig. 4. Estimated Stationary Nuclear Power and Reprocessing Load Growth. Basis: 8000 Mwd/ton, 25 % thermal efficiency, 80 % load factor, and 300 day/yr reprocessing plant operation.

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The radiochemical reprocessing plant installation and the reprocessing charges* that can be envisioned if private reprocessing plants are built starting in 1962 to match the power reactor fuel load are shown in Fig. 5. The upper curve shows the plant capacity (tons/day) while the lower curve shows the reprocessing charges (mills/kwh). Because of the samll size of the reprocessing load, small plants and therefore relative high reprocessing costs result during the early years. 0.35 mill/kwh reprocessing costs would not be realized until 1972.

0.35 mill/kwh reprocessing cost could be realized sooner (in 1967) if spent fuel from the whole industry were stockpiled in the early years. By this means a backlog of fuel would be accumulated so that an economical plant might be built at an earlier date. Figure 6 shows the reprocessing and use cost on stockpiled material as mills/kwh and the reprocessing plant capacity. In this case the early reprocessing costs are much higher than the previous case because of use charge on stockpiled material, however, the later costs are lower because large plants are built at an earlier date.

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*The assumptions used in the following analyses are: average McKinney nuclear growth curve, reprocessing plant investment shown from Fig. 1 and operating costs from Fig. 2. 8000 Mwd/ton irradiation 25% thermal efficiency, 80% load factor, 300 day/year chemical plant operation, and processing plant load lags 1 year behind power growth curve.

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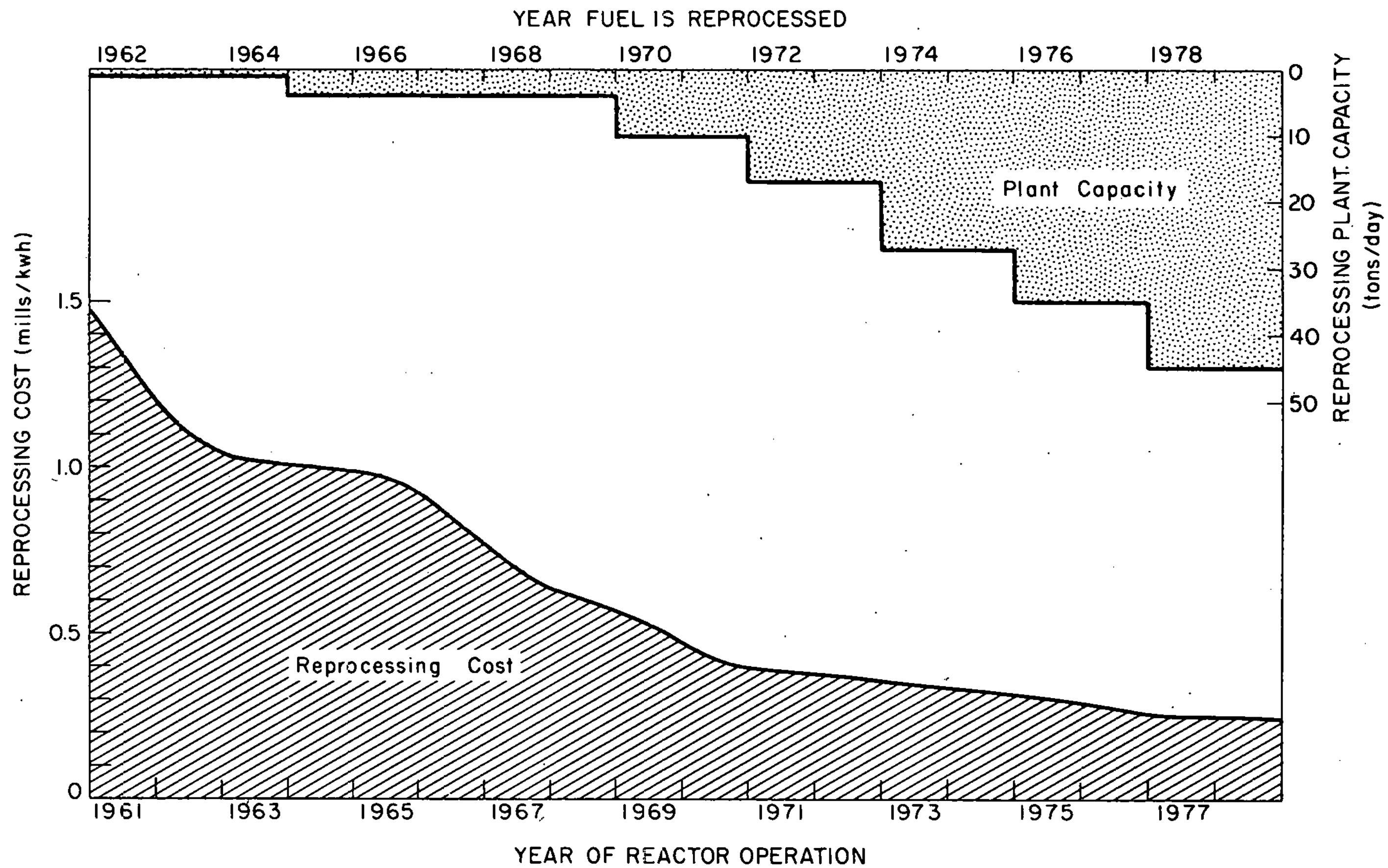

Fig. 5. Power Reactor Fuel Reprocessing Costs and Plant Capacity - No Stockpiling.

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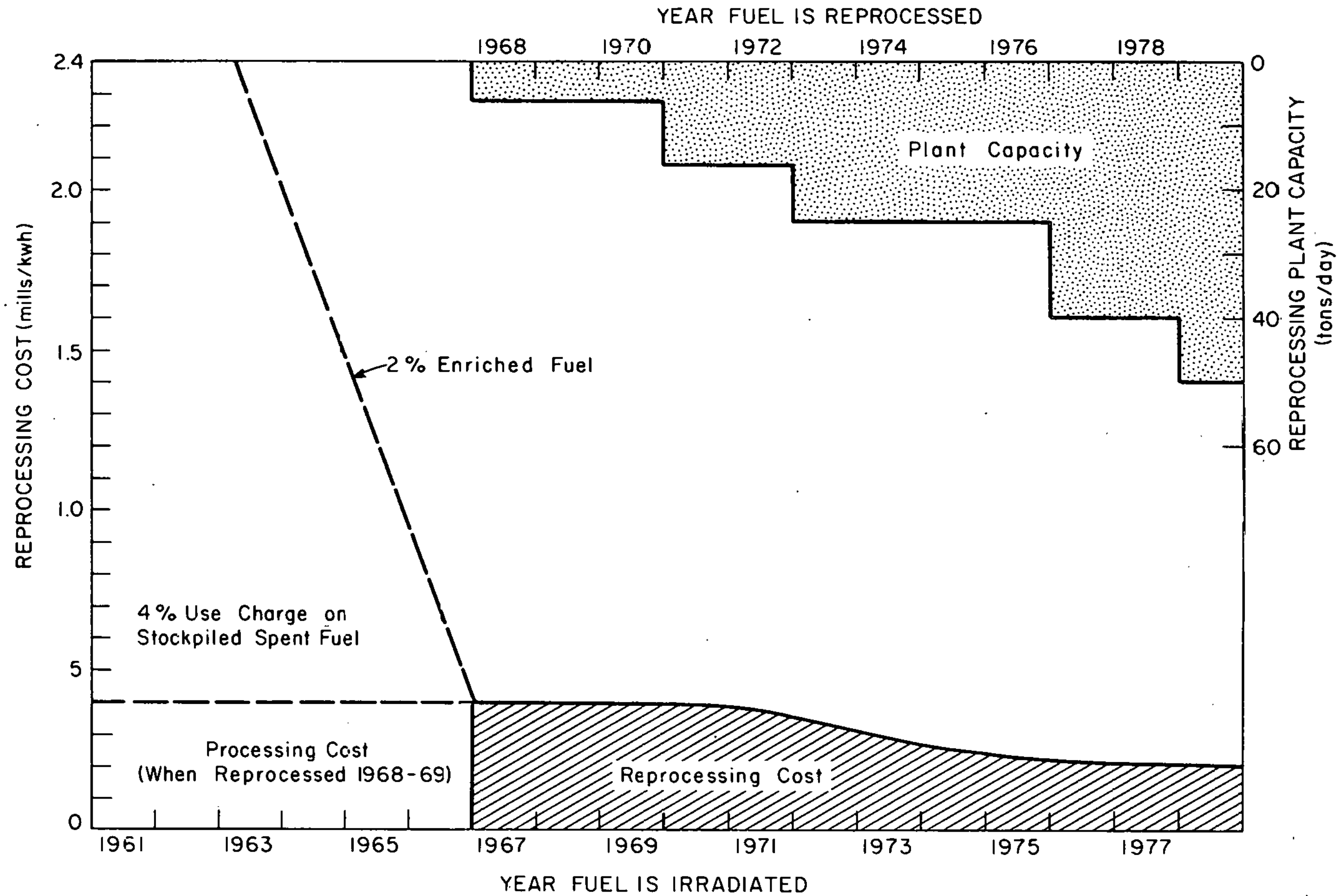

Fig. 6. Power Reactor Fuel Reprocessing Costs and Plant Capacity - Stockpile of Spent Fuel.

If instead of mills/kwh reprocessing charges one looks at the total outlay required for reprocessing and spent fuel stockpiling (Fig. 7) one can see that there may be an advantage (even when assuming 2% instead of 1-1/2% enrichment) to the industry as a whole to stockpile fuel in the early years. This is a result of lower unit costs being attained in the later years when there is a larger economy. With the exception of the pilot plants necessary for development work, it probably would be advantageous for the nuclear industry to stockpile fuel until there is enough nuclear generating capacity to support a larger more economic plant. It is obvious that the individual reactor operator could not afford to stockpile fuel because use charges would be excessive. To be successful this would have to be an industry wide or government sponsored program.

The government's interim processing program guarantees reprocessing costs through FY-1967. Stockpiling from 1967 instead of 1962 would delay the date at which a plant could be built by approximately one year (the amount of fuel discharged in the early years is small). The interim processing program thus reduces the cost of reprocessing without appreciably delaying the date at which private enterprise can enter the business with reasonable costs.

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 processed per unit of electricity. The reprocessing costs are not cut in half, however, since with less fuel reprocessed the unit cost is higher. The following table illustrates the effect of

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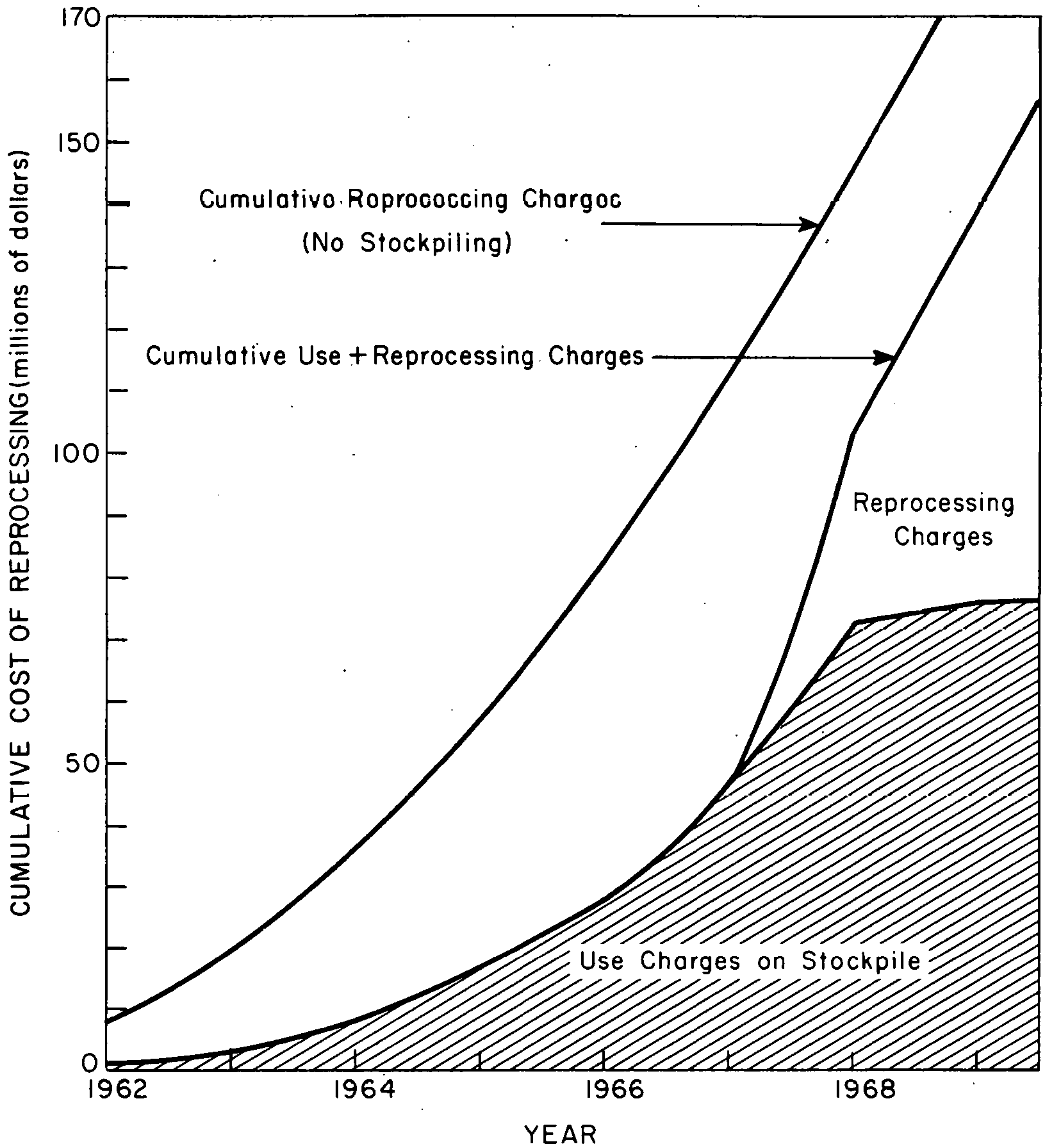

Fig. 7. Effect of Stockpiling on Cumulative Cost of Reprocessing Fuel. Basis: 2% Enriched fuel burned to 8000 Mwd/ton, average McKinney buildup curve, 25% thermal efficiency.

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increasing the burnup from 8,000 to 12,000 Mwd/ton:

Fuel Burnup, Mwd/ton	8,000	12,000	12,000
Heat Generation Rate, Mw	48,000	48,000	30,000
Fuel Processed, tons/day	6	3	2.5
Unit Cost, $/kg U	17	20	25.5
Mills/kwh	0.35	0.29	0.35
Year Expected	1970	1970	1968

It can be seen that by increasing from 8,000 to 12,000 Mwd/ton burnup the expected fuel costs in 1970 would be decreased from 0.35 to 0.29 mill/kwh and 0.35 mill/kwh fuel costs would be obtained in 1968 instead of 1970.

Increasing the burnup (or thermal efficiency) should not change the general conclusions reached in this study. Economic reprocessing will, however, be realized at an earlier date.

The above analyses do not take into account the money required for the process development, the economics possible in expanding an existing plant rather than building a new one, fuel storage costs or the effect of the Government reprocessing or stockpiling spent fuels. These are additional factors which will have to be investigated by private industry before entering the fuel reprocessing business.

SUMMARY

Reprocessing costs in the order of 0.35 mill/kwh are required for nuclear power to be competitive in the United States at 8000 Mwd/ton fuel burnup. Based on solvent extraction technology existing or under development it is estimated that these cost could be attained by private industry in a radiochemical plant having a 6 ton/day capacity. The date at which such a plant could be built would depend on the nuclear power buildup. Buildup predictions put it somewhere between 1968 and 1973. It would probably be advantageous to the industry as a whole to stockpile spent fuel during the early years, until a single large scale reprocessing plant can be built, rather than build small plants (except for the necessary pilot plants for development work) to reprocess spent fuel immediately.

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