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A COMPARISON OF THE CAPITAL COSTS OF LIGHT WATER REACTOR AND LIQUID METAL FAST BREEDER REACTOR POWER PLANTS

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PREPARED FOR THE U. S. ARMS CONTROL AND DISARMAMENT AGENCY

WILLIAM E. MOOZ, SIDNEY SIEGEL

**R-2441-ACDA
FEBRUARY 1979**

Rand
SANTA MONICA, CA. 90406

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PREFACE

The objective of this study, sponsored by the Arms Control and Disarmament Agency (ACDA), was to develop plausible estimates of the relative capital costs of liquid metal fast breeder reactor (LMFBR) and light water reactor (LWR) power plants that might be built early in the next century. Past experience with predictions and actual trends of LWR plant costs indicates that this task is fraught with formidable obstacles.

Almost 60 LWR power plants have been constructed in the United States over the past 20 years. Extensive information is available about these plants and their capital costs. Even with this store of data, however, it is difficult to project capital costs as few as five years into the future. Plants using existing standardized designs for the nuclear steam supply systems and the rest of the plant ("balance of plant") *can* be built for costs that can be confidently estimated, in constant dollars. What is difficult to estimate is the cost of the plants that *will* be built, modified as they may have to be by social and political requirements, with construction schedules set as much by social as by industrial forces.

Projecting nuclear power plant capital costs into the next century thus becomes a subjective process, with wide-ranging results. For the LWR, there is at least the 20-year/60-odd plant data base with which to begin. For the LMFBR, there are no commercial plants in the United States providing a cost history from which cost projections can be made, only the recently completed Fast Test Reactor (FTR) and the still-ongoing design and limited component manufacture of the Clinch River Breeder Reactor (CRBR), plus the results of conceptual design and cost studies.

The present study began with an analysis of cost estimates by three firms experienced in LMFBR design, all participants in the FTR and CRBR projects, and all involved in the design studies of the prototype large breeder reactor (PLBR). With these data, the authors estimated a "current" cost for a mature LMFBR. They then selected two

scenarios for the deployment of nuclear power during the next 40 years. In one, the social and political environment vigorously encourages nuclear power; in the other, nuclear deployment is held to a modest level by continued social and political concerns about current and future perceived hazards. In the latter scenario, the inherent costs of nuclear plants are increased by additional items and procedures for which society is assumed to be willing to allocate its resources.

These scenarios illustrate the major uncertainties. Results are given in the form of sets of capital costs and cost ratios representative of each scenario. Depending on which scenario a user of this study chooses, a plausible LMFBR/LWR cost ratio can be found. The scenarios also help to identify where the real uncertainties lie and to quantify the likely effects of important variables, e.g., construction time. By so doing, estimates by others may be considered in a proper context, and consistencies or contradictions better understood.

The results of this study constitute one input into an overall study designed to estimate the relative costs of generating electricity by LWRs and LMFBRs. Such cost calculations require estimates of fuel cycle costs, operating and maintenance costs, and capacity factors, in addition to capital cost estimates. These estimates, to be provided by other ACDA contractors, will be integrated into a final picture of relative electricity costs by Pan Heuristics, Inc.

Sidney Siegel is a consultant to The Rand Corporation.

SUMMARY

Recent studies by Atomics International, General Electric, and Westinghouse^{*} yielded capital cost estimates for a "fifth of a kind" LMFBR. After adjusting these estimates for plant size and converting them to 1978 dollars, they ranged from \$1043 to \$1495 per kWe, excluding interest during construction (IDC). These cost estimates were compared in this study with a LWR estimated by GE to cost \$900 per kWe, also excluding IDC.

Projecting these costs far into the future entails great uncertainty. An examination of the capital costs of LWRs built in the United States shows that they have increased steadily, in terms of constant dollars, at a rate so great that one could question their competitiveness or economic viability a short time in the future, if the trend were to continue. The data available give no clue as to how or when these cost increases might cease, and without such information, projections of LWR capital costs must rely on assumptions about future conditions that affect these costs. There is no comparable data base for the LMFBR. Instead we have the study estimates from Atomics International, General Electric, and Westinghouse. Projecting these estimates can only be done by examining the LWR experience and postulating how future events might affect costs.

The actual costs of both the LWR and the LMFBR in the early 2000s will depend strongly on the environment for nuclear power at that time. Since we cannot know what that future environment will be like, this study postulated two scenarios that might be representative of two future situations. These scenarios do not represent extremes in points of view; they are simply two different climates affecting nuclear costs. In the first, a vigorous nuclear industry is postulated, numerous LWR plants are being built, and LWR capital costs depart markedly from

^{*} Each of these companies was teamed with an architect engineering firm. Atomics International was paired with Burns and Roe, General Electric with Bechtel, and Westinghouse with Stone and Webster. All references in this report to the companies mean the teams of the companies and the architect engineering firms.

currently observed trends, leveling off at about \$700 per kWe, excluding IDC, and about \$860 per kWe with IDC included. The commercial deployment of LMFBRs begins in 2002, and the number of plants increases in the same fashion as in the early deployment of the LWRs. When the "fifth of kind" LMFBR reaches commercial operation, the LMFBR/LWR cost ratio is about 1.4. Costs decrease thereafter, and eventually become asymptotic at a ratio of about 1.2, assuming equal construction times for both types of plant.

The second scenario postulates a generally unfavorable environment for nuclear power, with continued public opposition and regulatory uncertainties regarding the LMFBR. In this scenario, the nuclear industry is weak, only a few LWRs are being built, and LWR costs are higher than in the first scenario. The LMFBR encounters new safety, safeguards, and political or institutional problems which drive up its costs. The LMFBR/LWR cost ratio is initially about 1.5,* but increases thereafter due to rising LMFBR but relatively stable LWR costs. The ratio eventually reaches 1.75, assuming equal construction times. If the LMFBR construction schedule were 25 percent greater than for an LWR, the cost ratio would be 1.9.

These two scenarios do not necessarily represent upper and lower bounds on future capital costs of these nuclear systems. Technological improvements in LMFBR designs and operating conditions could lower LMFBR per kWe costs below those estimated in the favorable case at some time beyond the horizon of this study. Conversely, unforeseen technical problems and regulatory requirements could result in LMFBR capital costs exceeding those estimated here. The issue of LMFBR costs under these latter circumstances could well be moot, since deployment of the system would be unlikely.

No significant effect on the costs or cost ratio could be associated with a delay, say of 10 years, in the commercial deployment of the LMFBR.

* The initial cost ratio obtained from the raw GE-Bechtel estimates was 1.64.

The principal factors that affect future capital cost ratios between the LMFBR and the LWR are

- o The initial cost ratio that is assumed for the "1977" design plants.
- o Assumptions about changes in scope resulting from the social, political, and regulatory climate.
- o Differential construction times for the two types of plant.

The cost ratios are relatively unaffected by the LMFBR deployment schedule and cost learning effects, differential scaling effects, and the LMFBR introduction date.

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I. INTRODUCTION

The economic benefit of fast breeder reactor power plants, now under development in a number of countries, is a major issue in international and domestic discussions of nuclear power and of nonproliferation policy. The liquid metal fast breeder reactor (LMFBR) is viewed as a possible successor to the current generation of thermal reactors, most of which are light water reactors (LWR). Whether and when fast breeder reactors, the LMFBR in particular, will replace LWRs will depend largely on the costs of generating electricity from each. The objective of this study is to estimate the relative capital costs of LWR and LMFBR power plants at years past the end of the century. These estimates can then be used as inputs for estimating the relative costs of electricity from LWRs and LMFBRs.*

Any capital cost estimate is usually accompanied by uncertainty, whether the subject of the estimate is a house, a ship, a factory, or

* Although the cost of electricity from any nuclear plant is determined primarily by capital costs, it also depends on the capacity factor, the cost of fuel, and other operating expenses. The capacity factor (the amount of electricity that can actually be generated by a plant compared to the theoretical amount) was examined briefly in this study. Both LWR and LMFBR plants are designed according to "good engineering practice," but the designs carry with them no implicit guarantees on capacity factor. For the LWR, capacity factors appear to have varied considerably over time, but have been increasing in recent years. There appear to be differences that can be ascribed to the plant size, and perhaps to such variables as its age, type, and the operating utility. Since the observed differences are not now clearly understood, attempting to ascribe defensible differences between the capacity factors of future LWRs and LMFBRs was not possible without performing research that was beyond the scope of this study. We may speculate that the necessarily automated refueling sequence of the LMFBR, as compared with the more cumbersome head removal and manual refueling methods used in the current LWRs, could in principle give the LMFBR a somewhat greater capacity factor (unless the greater complexity were itself a cause of unreliability). In a similar speculative vein, the existence of additional heat transfer systems in the LMFBR, and their required maintenance, could potentially lower its capacity factor. The available data do not permit us to draw valid conclusions on relative capacity factors.

a power plant. But the normal, or expected, uncertainty that accompanies capital cost estimates is compounded for nuclear power plants. Capital costs of LWR power plants have undergone dramatic increases during their 20-year history. The fact of the increases is unmistakable, but the causes are not completely understood. As a result, we are in a poor position to judge whether the costs will continue to rise as in the past, or even to guess whether the forces behind the historical cost increases will continue to exert pressure. There are substantial uncertainties in projecting future LWR plant costs.

For the liquid metal fast breeder reactor, we are in an even poorer position. No commercial LMFBR power plants have been built in the United States, and the experience of the rest of the world is limited and only available to us in generalities. To compare the costs of LWRs and LMFBRs, the nature of uncertainties in the deployment of LMFBRs must also be addressed.

We begin with an analysis of the capital cost estimates made in three LMFBR design studies carried out recently under Department of Energy/Electric Power Research Institute sponsorship.⁽¹⁻³⁾ The plants studied were all sodium-cooled loop systems, rated near 1000 MWe. The designs were based on current technology, conservatively chosen components (e.g., double-wall steam generator tubes), and conservative operating conditions. The studies included cost estimates, in current dollars, for a "fifth of kind" plant of the same basic design that might be built in later years.

In this report, these estimates are adjusted to a common basis and then are compared with a recent LWR capital cost estimate made by one of the companies that provided an LMFBR estimate. This comparison results in a cost ratio that varies from 1.25 to 1.50, an oftheard expected range. The questions which are then addressed are how these costs might change in the future as a result of cost learning effects, increased scope,^{*} and variations of the date at which the LMFBR is introduced. To address these questions, two scenarios are used that

^{*}Increased scope is often cited as the prime cause of cost increases experienced by LWRs.

bracket a range of possible futures and result in different capital costs and capital cost ratios.

The two scenarios reflect a favorable environment for nuclear power (Scenario A), and an unfavorable environment (Scenario B). The capital cost estimates for the LWR in these scenarios stem in part from the results of a statistical study of past LWR capital costs.⁽⁴⁾

Reference 4 gives a regression equation describing the large LWR capital cost increases in recent years. A scenario might have been adopted that assumed these past increases would continue unabated in the future. Such a scenario was deemed implausible, however, because a linear extrapolation of the past data was judged to be an incorrect projection of the future that would quickly lead to such high costs that the plants would not be economically viable, and would not be built in reality.

Both Scenarios A and B assume a major departure from past trends in LWR capital costs. Scenario A assumes a vigorous nuclear enterprise, with about 400 LWR plants coming into operation between 1990 and 2010. Scenario B assumes a much smaller addition of LWR capacity, about 100 plants in the same period. In Scenario A, LWR plant cost increases end in the near future, around 1980, and decrease thereafter. In Scenario B, LWR costs rise to a higher level and then remain constant beyond about 1990.

For the LMFBR, Scenario A assumes that the regulatory climate and public attitudes toward the system have stabilized during the demonstration plant period preceding commercial plant deployment. Capital costs for the LMFBR are essentially determined by technological characteristics of the system, and decrease modestly as deployment continues after initial introduction in the early 2000s. The LMFBR/LWR cost ratio approaches the asymptote of about 1.2, which is inherently due to technical differences between the two systems. Since both LWR costs and the LMFBR/LWR cost ratio are low in this scenario, it represents a favorable cost picture for the LMFBR.

In Scenario B, it is assumed that the LMFBR encounters an initial period of increasing regulatory requirements and public scrutiny analogous to that which the LWR experienced. The costs of plants beyond

the initial commercial LMFBRs rise until these issues become resolved, then slowly stabilize and turn down. This scenario, then, represents an unfavorable cost picture for the LMFBR, with both high LWR costs and a high LMFBR/LWR ratio.

Neither scenario is necessarily extreme. Technical advances can be conjectured for Scenario A, while unforeseen safety, safeguard, and institutional requirements might arise in Scenario B, to further lower or raise LMFBR capital costs. However, it appears internally contradictory to go much beyond Scenario B, since the likelihood of any LMFBR plants being built if such conditions prevailed appears remote.

The events that affect LMFBR costs are taken as analogies to the events that affected LWR costs. Not explicitly included in either scenario is the effect of any government involvement in LMFBR commercial deployment, which might result in unique internal project forces that could affect cost significantly.

II. CAPITAL COSTS FOR LMFBR POWER PLANTS

A number of capital cost estimates have been made for liquid metal fast breeder reactor plants by companies in the nuclear hardware business. This section discusses estimates provided to Rand by three companies: Atomics International (AI), General Electric (GE), and Westinghouse. As received by Rand, the three estimates were made on differing bases. Plant size was similar but not identical, estimates were made in different year dollars, and some cost categories that should have been identically treated were not. In addition, the three estimates reflected three different plant designs. Although each estimate was made according to Federal Power Commission (FPC)* categories, there is sufficient latitude in the categories that consistent use of them was not assured, despite the fact that each of the estimates was carefully made on a very detailed level. One purpose of this section is to document the steps that were taken to put the estimates on a comparable basis. Comparable basis was defined as:

- o No cost categories are omitted
- o Estimates are based on a "fifth of kind" LMFBR
- o Costs are expressed in 1978 dollars per kWe
- o Interest during construction and other cost categories unrelated to the specific design of the plant are treated similarly.

Once this was done, any remaining differences would be due to differences in design or in estimating techniques.

An independent analysis of the three LMFBR cost estimates was carried out by Southern Science Applications, Inc. (SSAI) of Dunedin, Florida, under a subcontract to Rand. Their task was to identify any omissions or other anomalies in the estimates, and to focus particularly on differences between the LMFBR and a typical LWR. Their study

* Now the Federal Energy Regulatory Commission (FERC).

resulted in another set of adjusted LMFBR costs that will be presented in Sec. III, along with the Rand estimates.

The SSAI report is included as the appendix. It restructured the original estimates to conform with the CONCEPT code of accounts.

ESTIMATES FROM THE REACTOR MANUFACTURERS

The estimates are presented as provided to Rand. All of the data are not given, because sometimes voluminous details were provided to illustrate the care that was exercised in making the estimates. Selected tables reflect the data obtained in the form that they were given to Rand, and those who provided them should recognize them without difficulty.

Atomics International--Burns and Roe

This estimate, shown in Table 1, was made for a 1000 MWe LMFBR and was presented in 1977 dollars.

Table 1

AI ESTIMATE

	<i>Cost, \$ Millions</i>
Nuclear steam supply system (NSSS).....	468
Structures and improvements.....	162.5
Turbine plant equipment.....	94.8
Electric plant equipment.....	75.7
Miscellaneous plant equipment.....	17.1
Main condensor heat rejection system...	15.3
Total direct costs.....	833.4
Indirect.....	150
Total direct and indirect costs.....	983.4

It was noted in this estimate that no provision had been made for land purchase, and that a specific entry for contingencies had not been included. The estimate also did not include interest during construction. Inquiries about these items resulted in AI's assurance that the contingencies expected had been built in to the individual estimates. Thus the \$468 million that was estimated for the nuclear steam supply

system included contingencies to cover uncertainties. Land costs will be added later.

General Electric--Bechtel

The GE estimate initially provided was for a 900 MWe plant and was in 1977 dollars. Interest during construction was included by using 8 percent for 3 1/2 years, which implies a construction time of 7 years, and was calculated as noncompounding interest, i.e., 28 percent of the direct and indirect costs was estimated to be interest. The estimate is shown in Table 2.

Table 2

GE ESTIMATE

	<i>Cost, \$ Millions</i>
NSSS.....	223.2
NSSS engineering.....	54.2
Site improvements and facilities...	9.6
Reactor containment building.....	81.8
Steam generator/Pracs building.....	24.3
Turbine building.....	20.6
Reactor service building.....	13.2
Miscellaneous buildings.....	19.0
Reactor plant equipment.....	86.4
Turbine plant equipment.....	124.1
Electric plant equipment.....	62.9
Miscellaneous plant equipment.....	15.6
Field distributable costs.....	142.6
Engineering and home office.....	115.0
Contingencies.....	161.6
Other costs to owner.....	72.0
Interest during construction ^a	343.3
Grand total.....	1569.4

^aAdjusted from value given for 20th of a kind.

Westinghouse--Stone and Webster

Westinghouse provided an estimate for a 1000 MWe plant in 1978 dollars, which, like the AI estimate and the revised GE estimate, was for

a "fifth of kind" plant. Initially this estimate had no specific contingency costs, and after discussion with Westinghouse it was determined that, like AI, much of the estimated contingency for uncertainty had been included in the individual line items. This had not been done on the balance of plant items, however, and at their suggestion the estimate was modified to include 5 to 10 percent of the balance of plant as a specific contingency. This entry is shown below as though it had been included in the original data.

Interest during construction was estimated at a 9 percent rate, compounded for a period varying from about 4 1/2 to 5 1/2 years to produce the range shown. The estimate appears in Table 3.

Table 3

WESTINGHOUSE ESTIMATE

	<i>Cost, \$ Millions</i>
NSSS.....	475-600
Turbine generator system.....	83-105
Buildings and structures.....	102-164
Electrical plant.....	54
Land and yardwork.....	10
Indirect costs (engineering services, site construction, owner, and other costs).....	120-160
Contingency.....	19- 49
Interest during construction ^a	430-610
<u>Total plant.....</u>	<u>1293-1752</u>

^aUnadjusted for the addition of contingency.

ADJUSTMENTS TO ESTIMATES

Initially it had been hoped that the various estimates could be compared on a disaggregated basis, but it soon became apparent that this would be unwise and produce misleading impressions. The reasons involve the flexibility of the FPC cost format and variations in the way in which each contractor made his estimate. For example, uncertainty is frequently included as a contingency, and is carried in the

estimate as a separate line item. But sometimes it makes more sense to account for this uncertainty at a much more detailed level, and some estimators did that. As a result, costs for any single line item may appear to be widely different from one estimate to another, whereas in reality the differences may only be due to differing definitions and treatment of uncertainty. Consequently, no comparisons should be attempted at a disaggregate level, and no implications should be drawn from the relative cost of any specific line item. For example, if the NSSS cost in one estimate appears as a different fraction of the total costs than in another estimate, no conclusions should be drawn.

Specific adjustments to the estimates were made as follows:

- o Land costs, added to the AI estimate, were equalized among the estimates at \$10 million.
- o Changes were made to the GE estimate so that it represented a "fifth of kind" plant.
- o The GE and AI estimates were adjusted from 1977 dollars to 1/1/78 dollars by the ratio of the Handy-Whitman index values for those two years. This raised the 1977 dollar estimate by 5 percent.*
- o The GE costs were adjusted to costs per kWe by dividing the estimated costs by 0.9. It could be argued that a further adjustment should have been made in this process because the GE design was for a 900 MWe plant compared with 1000 MWe plants designed by AI and Westinghouse. Had GE designed a 1000 MWe plant, there may have been economies of scale that would have reduced the costs per kWe. The subject is not analyzed here. If economies of scale were applicable in this case, unit costs would be reduced about 3 percent.

* This adjustment is from *average* 1977 dollars to 1/1/78 dollars, or about a 6-month change.

- o Interest during construction was removed from both the GE and Westinghouse estimates to put all three estimates of the direct plus indirect costs on a comparable basis. Interest during construction can be added later as required for analysis.

The results of these adjustments are shown in Table 4, together with SSAI's estimates.

Table 4

LMFBR DIRECT PLUS INDIRECT CAPITAL COST ESTIMATES
(Excluding IDC, 1978 dollars per kWe)

Estimator	Rand	SSAI
AI	1043	1105
GE	1495	1326
Westinghouse	863-1142	969-1248

III. ESTIMATES OF LWR COSTS

LWR costs need to be estimated for two purposes. The first is for comparison with the LMFBR cost estimates, so that an initial capital cost ratio can be estimated. For this purpose, the LWR cost must be one that is contemporary with the LMFBR, and specifically for an LWR that begins construction in 1977, which is the design basis for the LMFBR. This was anticipated by GE, who provided an LWR cost estimate that was designed to be used with their LMFBR cost estimate on a comparative basis. A cost ratio could then be derived that would be valid at the time that the fifth LMFBR reached commercial operation. LWR cost estimates were also suggested by AI and Westinghouse, but they were taken from the literature and were judged not to be consistent with their LMFBR estimates. Consequently they were not used in this analysis.

The GE LWR estimate was \$770 million in 1977 dollars for a 900 MWe plant, not including interest during construction. This figure can be adjusted to 1/1/78 dollars per kWe in the same way that the LMFBR costs were, by dividing by 0.9 and multiplying by 1.05, which is the Handy-Whitman construction cost index ratio. The result is \$900 per kWe, not including interest during construction, and this value was intended by GE to be compared with their LMFBR estimate.

The second purpose of estimating LWR costs is to project them, so that LMFBR/LWR cost ratios may be estimated at various dates in the future. For this purpose, we presume that the rapid LWR capital cost increases experienced in the past will be modified in the future, and have based the projected costs on this assumption combined with the statistical findings of Ref. 4. The initial LMFBR/LWR cost ratios are obtained by using the \$900 per kWe LWR estimated by GE, which is consistent with the assumptions made for the LWR projected costs.

We next develop LWR cost estimates based on this general premise, but in two different scenarios. In Scenario A, low LWR costs are realized, and in Scenario B, less optimistic, LWR costs are high. These scenarios will be paired later with similar scenarios for the LMFBR.

LWR DEPLOYMENT SCHEDULES

We begin by using the Department of Energy LWR schedule⁽⁵⁾ reproduced in Table 5. This schedule shows that 194 power plants are expected to be in commercial operation in 1989, and that a total of 216 plants are expected after 1989. Using the 194 power plants in 1989 as a point of departure, we postulate a healthy industry that would be consistent with a low-cost LWR.* Power plants are built at a steady rate, with 400 of them being in commercial operation in 2000. At a nominal size of 1000 MWe, this is equivalent to a generating capacity of 400 GWe in year 2000. The projected rate of construction continues, and about 960 plants are in commercial operation in 2026. For the purpose of estimating capital costs, the exact number of plants projected at periods beyond 2000 is not too important. The main point is that the industry is a healthy one in this scenario, which we designate Scenario A.

For Scenario B, we hypothesize a much lower construction schedule, with capital costs that continue to rise. Again using 194 plants in 1989 as a departure point, we estimate that 250 plants are in commercial operation in 2000.

Both deployment schedules are illustrated in Fig. 1.

LWR CONSTRUCTION TIME[†]

Construction time is important to the LWR analysis for two reasons. The first is that schedules of power plants, such as those listed in Table 5, are usually given in terms of their date of commercial operation. As will become apparent later, this schedule needs to be translated into one that refers to the date on which construction of the plants starts. The construction time is the key to this translation. The second reason construction time is important is that the cost of interest during construction (IDC) is a function of construction time, which must be known.

* And, as we will later see, with the deployment of LMFBRs.

† Construction time is defined as the period from the date the construction permit was issued (CPIS) to the date the operating license was issued (OLIS).

Table 5

NUMBER OF LIGHT WATER REACTORS IN COMMERCIAL OPERATION
VERSUS TIME

Year	MWe Net		No. of Units	
	Annual	Cumulative	Annual	Cumulative
Through 1975		37,341		55
1976	3,749	41,090	4	59
1977	6,381	47,471	7	66
1978	6,034	53,505	7	73
1979	7,711	61,216	7	80
1980	11,417	72,633	11	91
1981	13,418	86,051	12	103
1982	12,704	98,755	12	115
1983	14,062	112,818	13	128
1984	19,260	132,079	18	146
1985	13,732	145,811	12	158
1986	12,684	158,495	11	169
1987	8,953	167,448	8	177
1988	11,363	178,811	10	187
1989	7,878	186,689	7	194
1990 on	17,798	204,487	15	209
Indefinite	7,723	212,210	7	216

SOURCE: Ref. 5.

Reference 4, which specifically addresses construction time, found that for construction permits issued between 1967 and 1972 there was a linear increase in average construction time of about 4.5 months per year, when the effects of other variables were accounted for.* Taken at face value, a projection of construction times using this analysis would imply unreasonable values towards the end of the century. Instead, it is assumed that the observed linear increase will not continue indefinitely, but will bend and cease to increase further at some point. Solving the regression equation[†] developed in the statistical

* Increased construction time is thought to be at least partially due to increased scope, which results from greater regulation to assume safety and environmental protection.

[†] Construction time in months = $4.5 \text{ CPIS} + 0.04 \text{ SIZE} - 8 \text{ LN} - 270$, where CPIS = date construction period issued (1972 = 72); SIZE = plant size, MWe; and LN = natural logarithm of cumulative number of plants built by an architect engineer.

Fig. 1 — Number of LWRs in commercial operation

analysis for construction permits issued in mid-1972, the last point in the regression data base, and setting the other equation variables at reasonable (and fixed) values, yields an estimate of 70 months for the construction of a 1000 MWe plant. We assume that this is the last point on the linear curve, which begins to bend over thereafter.

For Scenario A, we project a fairly rapid bending of the curve, reaching a maximum of about 74 months in 1976 through 1979, and then a gradual diminishing of time thereafter, eventually stabilizing at about 69 months in the early 1990s.

For Scenario B, we project that construction times reach a maximum of 80 months for construction permits issued in 1979, and that this time remains constant thereafter. The regression equation actually shows that there is a reduction in construction time through learning, as more plants are built. But in Scenario B, very few plants are built, which minimizes the learning effect.

Curves for Scenarios A and B are shown in Fig. 2, together with a curve that represents merely a straight linear extrapolation of past trends for comparison.

Fig. 2—Construction time as a function of year of construction permit

CONSTRUCTION START DATES (CPIS)

With the construction time information for both scenarios, the relation of the date of commercial operation to CPIS can be established. CPIS is simply the date of commercial operation minus the construction time and minus an additional six months that represents the period from the completion of construction until the plant reaches commercial operation. The curves expressing the relationship are shown in Fig. 3, again with the regression analysis curve for comparison.

Fig. 3—Date of commercial operation as a function of date of construction permit (see Fig. 2)

TEMPORAL COST CHANGES

Power plant capital costs have increased rapidly in the past, and the statistical results of Ref. 4 indicate that the rate of increase was about \$141 per year for the period CPIS = 1967 to mid-1972, when corrected for the effect of other variables. Again, taken at face value, this projects unlikely costs towards the end of the century.

As with construction time, the assumption is made again that the observed linear increase will taper off. We assume that the cumulative temporal cost increases will be simply in direct proportion to the changes in the construction times shown in Fig. 2. This assumption is plausible, in that it can be argued that a stabilization of the plant scope would result in a stabilization of both plant construction time and plant cost. Using this assumption, the cumulative temporal cost increases beyond 1971 are estimated as though they were proportional to the construction time changes.

The curves shown in Fig. 4 are the results for the two scenarios. The constant of proportionality is the \$141 per year that was obtained in the regression analysis. For example, between 1971 and 1981 the regression analysis shows a schedule increase of 45 months, whereas Scenarios A and B show increases of 8 and 15 months, respectively. Instead of the \$1410 increase during that 10 year period predicted by the linear regression, Scenario A has an increase of $(8/45) \times \$1410 = \250 , and Scenario B has an increase of $(15/45) \times \$1410 = \470 .

For Scenario B, no further construction time or temporal cost increases are projected past CPIS = 1979. Since 1979 is here, the scenario implies that all increases in construction costs that are due, for example, to increased plant scope and regulatory changes are virtually over. This implication may be startling to an industry that has

Fig. 4—Cumulative temporal LWR cost increases

been besieged by temporal cost increases, and it may be even more startling that it is associated with the scenario having the higher costs.

For Scenario A, the implications are even more dramatic. Here we suggest that temporal cost changes peak at CPIS = 1976 to 1979, and then drop, stabilizing at about 1990. This implies that LWR plants that began construction between 1976 and 1979 will experience no further temporal cost increases, and that plants that begin construction subsequent to 1979 will actually experience *diminished* scope and regulation, resulting in *negative* temporal cost changes. We speculate that there now is sufficient experience with LWRs that certain conservative regulations might be relaxed to conform with experience. These relaxations can result in decreases in plant costs, i.e., negative temporal cost changes.

ESTIMATED LWR CAPITAL COSTS

We now have all of the elements required to project capital costs beyond the range of data used in the regression analysis. These elements are the costs resulting from the use of the equation in 1971, the assumed temporal cost changes beyond 1971, and the schedule of plants to be built, which allows the cost learning effect to be taken into account. An assumption needs to be made about the learning effect, which is principally attributed to the architect engineer and not to the industry as a whole. For this study, it has been assumed that one architect engineer builds half of the plants. Therefore the learning effect is estimated by using half of the total number of plants as the equation input. This probably overstates the average learning effect,* but not so as to distort the analysis. The regression equation is

$$\begin{aligned}\text{Capital cost (\$ 1976)} &= 141 \text{ CPIS} - 8885 - 0.2 \text{ SIZE} \\ &+ 92 \text{ TOWER} + 128 \text{ LOCl} - 72 \text{ LN},\end{aligned}$$

* Since the average architect engineer will not have constructed this many plants, this assumption maximizes the learning effect for both LWR scenarios. Similar treatment will be used in the LMFBR scenarios. The result is that the estimates are those of plants that enjoy the maximum benefits of learning.

where CPIS = construction permit issuance date

SIZE = plant size, MWe

TOWER = 1 if there is a cooling tower

LOC1 = 1 if the plant is located in FPC Region I

LN = natural logarithm of N, the cumulative number of plants
built by an architect engineer.

Setting size = 1000 MWe, TOWER and LOC1 at the sample means,^{*}
N = 21, and CPIS = 71, we determine that the estimated capital cost
for a plant on which construction begins in 1971 is \$780 per kWe (\$
1976), or $997 - 72 \text{ LN}$. The costs for plants built subsequent to
CPIS = 71 will be

$$\$997 - 72 \text{ LN} + \text{temporal cost change,}$$

again in 1976 dollars. Using this equation, the convention that half
of the plants built subsequent to 1971 are built by the same architect
engineer, and the temporal cost changes shown in Fig. 4, we solve for
capital costs from CPIS = 1972 onward. These are listed in Table 6
and illustrated in Fig. 5, where they are plotted against CPIS.

Two further steps are required. The capital costs have been esti-
mated in 1976 dollars, since the regression equation was derived in
that form. We first convert the costs so obtained to 1/1/78 dollars
by multiplying the 1976 dollar costs by the ratio of the 1/1/78 Handy-
Whitman power plant construction cost index to the same index for 1976.
This ratio is 1.10. The second step is to translate CPIS to the date
of commercial operation; Fig. 3 is used for this purpose. The results
are listed in Table 7 and illustrated in Fig. 6.

INTEREST DURING CONSTRUCTION (IDC)

The costs estimated above represent total capital costs to a
utility, and thus include interest during construction. To use the
costs estimated in this study in an analysis in which interest costs

^{*}The average values in the data base from which the regression
equation was developed.

Table 6
CAPITAL COSTS BEYOND 1972
(\$ 1976)

Scenario A				Scenario B			
CPIS	N ^a	Cumulative Temporal Costs (Fig. 4)	Cost	CPIS	N ^a	Cumulative Temporal Costs (Fig. 4)	Cost
1972	32	100	850	1972	32	125	870
1973	37	180		1973	37	235	
1974	43	240	970	1974	43	320	1050
1975	49	300		1975	49	380	
1976	56	310	1020	1976	56	420	1130
1977	65	315	1010	1977	65	450	
1978	71	315		1978	71	470	1160
1979	76	310	990	1979	76	480	
1980	80	295	980	1980	80	480	1160
1981	85	275		1981	85	480	
1982	89	255		1982	89	480	
1983	98	240		1983	91	480	
1984	107	225		1984	94	480	
1985	117	215	870	1985	99	480	1150
1986	126	205		1986	102	480	
1987	136	200		1987	104	480	
1988	145	190		1988	107	480	
1989	154	190		1989	109	480	
1990	164	190	820	1990	112	480	1140
1992	182	190		1992	114	480	
1994	201	190		1994	119	480	
1996	220	190		1996	124	480	
1998	238	190		1998	192	480	
2000	257	190	790	2000	134	480	1120
2026	476	190	740	2026	182	480	1100

^aSee text for definition.

are varied parametrically, it is necessary to identify and separate the IDC from the total costs. The fraction of total plant capital costs that is IDC is represented by the expression

$$1 - \frac{1}{1 + (\text{interest rate} \times \text{interest period})} \cdot$$

Fig. 5—Estimated total capital costs (from Table 6)

During the time covered by the regression analysis of LWR power plants, it is understood that the effective interest rate to utilities probably averaged 8 percent and did not vary a great deal.^{*} The interest period has been variously identified as one-third of the total project time[†] or one-half of the construction time, which are about equivalent. For this study, we will use one-half of the construction time. In the discussion above, it was shown that the average construction time lengthened steadily from CPIS = 67 to CPIS = 72, and thus it would be expected that the IDC component would become larger and swell the total costs. The

^{*} Harvey Wycoff, Commonwealth Edison Co., private communication.

[†] Total project time includes the time required to obtain a construction permit, the construction time, and about six months between the end of construction and the time the plant is declared to be in commercial operation.

Table 7

CONVERSION OF COSTS TO 1978 DOLLARS AND CONVERSION OF CPIS
TO YEAR OF COMMERCIAL OPERATION

Scenario A				Scenario B			
Year of Commercial Operation	CPIS (Fig. 3)	Cost, 1976 Dollars (Fig. 5)	Cost, 1978 Dollars	Year of Commercial Operation	CPIS (Fig. 3)	Cost, 1976 Dollars (Fig. 5)	Cost, 1978 Dollars
1979	1973	900	990	1979	1973	940	1030
1980	1974	950	1050	1980	1974	1000	1100
1981	1974	980	1080	1981	1974	1060	1170
1982	1975	1000	1100	1982	1975	1100	1200
1983	1976	1010	1110	1983	1976	1130	1240
1984	1977	1020	1120	1984	1977	1150	1270
1985	1978	1010	1110	1985	1978	1160	1280
1986	1979	990	1090	1986	1979	1160	1280
1987	1980	980	1070	1987	1980	1160	1280
1988	1981	960	1060	1988	1981	1160	1280
1989	1983	930	1020	1989	1982	1160	1280
1990	1984	920	1000	1993	1985	1150	1260
1992	1986	870	960	2000	1993	1130	1240
1998	1992	820	900	2005	1998	1120	1240
2000	1994	820	900	2010	2003	1120	1240
2005	1999	790	860				
2010	2004	790	860				

cost regression reflects this situation implicitly as a part of the temporal cost coefficient. However, since we assume that the effective interest rate during the period covered by the statistical analysis was constant, we can isolate the implicit IDC from the above cost projections by using this constant interest rate and the construction times that have been assumed for the two cost scenarios. The calculations are made in Table 8, and the direct and indirect costs* are plotted in Fig. 7.

* Defined as total costs less IDC.

Fig. 6—LWR capital costs, IDC included

Fig. 7—LWR capital costs, IDC excluded

Table 8

CALCULATION OF IDC AND DIRECT PLUS INDIRECT COSTS

CPIS (Fig. 2)	Construction Time, Months (Fig. 2)	IDC Fraction (Calculated)	Date of Commercial Operation (Fig. 3)	Total Cost (Fig. 6)	IDC (\$ 1978 per kWe)	Direct Plus Indirect Costs (\$ 1978 per kWe)
Scenario A						
1972	68	0.185	1978	930	170	760
1974	72	0.194	1980	1060	210	850
1976	74	0.198	1983	1100	220	880
1978	74	0.198	1985	1100	220	880
1980	74	0.198	1987	1070	210	860
1982	73	0.195	1989	1040	200	840
1984	72	0.194	1991	1000	190	810
1986	71	0.191	1993	960	180	780
1992	70	0.189	1998	900	170	730
1999	69	0.187	2005	860	160	700
2003	69	0.187	2009	860	160	700
Scenario B						
1972	68	0.185	1978	950	180	770
1973	72	0.194	1979.4	1060	210	850
1974	74	0.198	1980.6	1140	230	910
1975	76	0.202	1982	1200	240	960
1976	77.5	0.205	1983	1240	250	990
1977	78.5	0.207	1984	1270	260	1000
1978	79.5	0.209	1985	1280	270	1010
1979	80	0.210	1986	1280	270	1010
1983	80	0.210	1990	1260	260	1000
1992	80	0.210	1999	1240	260	980
1998	80	0.210	2005	1240	260	980
2003	80	0.210	2010	1240	260	980

IV. LMFBR COST SCENARIOS AND COST RATIOS

CURRENT COST RATIO

The 1977 GE cost estimate of an LWR, provided in conjunction with the GE LMFBR design study, was \$900 per kWe, in 1978 dollars. Using the Rand methodology described in the previous sections, the direct plus indirect cost (excluding IDC) for an LWR starting construction in 1977 is \$870 per kWe for Scenario A and \$1000 per kWe for Scenario B; these estimates bracket the independent value of GE.

The costs given above do not include IDC. So long as the construction times for both types of plant are identical, the LMFBR/LWR cost ratio is not affected by the exclusion of IDC, since the same term will appear in numerator and denominator. If the LMFBR takes longer to construct, as some believe, the ratio will increase, depending on the construction time difference and prevailing interest rate.

Assuming equal construction times, the LMFBR costs shown in Table 4, and using the value \$900 per kWe for the LWR, the "1977" LMFBR/LWR cost ratios are as shown in Table 9.

Table 9

LMFBR/LWR COST RATIO IN "1977"

Manufacturer	Rand Estimate	Ratio	SSAI Estimate	Ratio
AI	1043	1.15	1105	1.23
GE	1495	1.61	1326	1.47
Westinghouse	863-1142	1.27	969-1248	1.39

In Table 9 we use the higher Westinghouse figure, since the lower one is implausibly close to, or even lower than, the cost of the LWR being used. Rounding off, it appears that the LMFBR/LWR cost ratio at present lies in the range 1.2 to 1.6, assuming equal construction times. If an LMFBR took 25 percent longer to build, this range would increase by about 5 percent, and would be 1.25 to 1.7. The effects of differing construction times are discussed later in this section.

LMFBR CAPITAL COST SCENARIOS

We will use the estimated capital cost ratios for 1977 from Table 9, the accompanying assumption that the ratio is obtained from the direct and indirect costs alone (IDC is excluded), and the assumption that the same ratio will apply to whatever LWR costs exist at the time the "fifth of kind" LMBR is built. This last assumption is based on the belief that whatever affects LWR costs will affect LMFBR costs as well.

Schedule of Commercial Operation

The earliest date assumed for the LMFBR to enter commercial operation is 2002. The schedule of commercial operation is similar to that for LWR, and is taken from Ref. 5. The schedule appears in Table 10.

LMFBR Scenario A

A basis for examining probable future cost trends for LMFBR power plants is provided by the past and expected future costs of LWRs, as discussed in previous sections.

In the LWR Scenario A, the nuclear enterprise grows vigorously. Nuclear power attains a capacity of 200 GWe in 1990 and it captures a significant percentage of the market for new plants in the ensuing decade, attaining 400 GWe by 2000. Subsequent to 2000, we speculate that the growth rate of total generation declines to perhaps 3 percent per year, but if the nuclear capture rate increases, the total nuclear capacity in 2020 may be expected to reach 900 GWe out of a total of 2900 GWe.

In this projected environment, the reactor manufacturers constitute a vital industry, with several firms competing actively for a substantial market. Many plants--30 to 50--are being built each year and costs have stabilized. Concomitantly, the regulatory climate and public acceptance have become favorable. Basic to this scenario, of course, is a satisfactory resolution of political issues, such as concerns about proliferation, waste management, etc., by institutional and technical advances.

Assuming such a favorable climate for an expanding nuclear enterprise, it is reasonable to expect that an LMFBR demonstration project

Table 10

SCHEDULE OF LMFBRs IN COMMERCIAL
OPERATION

<i>Year</i>	<i>Cumulative Number</i>
2002	1
2003	2
2004	3
2005	4
2006	4
2007	4
2008	4
2009	4
2010	6
2011	8
2012	11
2013	16
2014	22
2015	30
2016	41
2017	50
2018	54

will be initiated in the early 1980s and will be operating around 1990. Alternatively, intergovernment technical exchange agreements and commercial licensing arrangements could provide comparable experience from ongoing foreign LMFBR plant operation and technology development.

A satisfactory technological base for initial commercial LMFBRs will exist, under these premises, by about 1992, after perhaps two years of operation of the prototype large breeder reactor (PLBR) and more than 15 years of experience with similar foreign plants. Provided the capital costs of the LMFBR are acceptable, it is reasonable to believe that LMFBRs will begin to be ordered commercially after 1992, at a gradually increasing pace. Various rates of deployment of commercial breeder plants in the 1990 to 2000 time period can be defended.

One such pattern of growth is simply a repetition of the early history of LWR deployment, in the period 1960 to 1978. There, a sequence of about one order per year for several years was followed by a pause to reexamine earlier decisions, then a fairly rapid surge of

additional orders. If we arbitrarily adopt this growth pattern, even though the logic for it appears unduly pessimistic considering the assumed favorable nuclear power environment, the number of LMFBRs coming into commercial operation subsequent to 2000 is as shown in Table 10 and Fig. 8, along with the number of LWRs assumed earlier.

Fig. 8—Number of nuclear plants in commercial operation

The analysis of LMFBR "fifth of kind" and LWR cost estimates resulted in the cost ratios in Table 9. The ratio experienced with the first few of this family of LMFBRs, whose construction period will probably be longer than that of their LWR contemporaries, will lie toward the top of the range indicated, perhaps 1.6. By the time the fifth plant is built, in this scenario, we believe the ratio will have decreased. The total cost of the LWR, including IDC, has stabilized at about \$860 per kWe; see Fig. 7.

A study of current designs suggests that substantial conservatism and generous contingency allowances have been included for many items,

especially in the NSSS. It seems likely that, as designs are iterated and the basic configuration of the plant is changed from the present loop system to the probably preferable pool configuration, cost savings will accrue. With some degree of cautious optimism, assuming nearly equal construction times and a cost ratio of 1.4, a cost differential of \$340 per kWe appears likely for the "fifth of kind" LMFBR. Unofficial comments on the French experience with Phenix and Super-Phenix support this point of view.

Assuming that three reactor manufacturers are competing for LMFBR sales, with one of them capturing 50 percent of the market, we observe from Fig. 8 that a plant coming on line in 2012 should be "fifth of kind," costing \$1200 per kWe. Thereafter, we should expect some benefits from learning, larger scale multiple manufacture, and possibly stretch capability inherent in the plant design.

The "balance-of-plant" (BOP) does not vary much between the LWR and LMFBR. Since, by 2012, many hundreds of LWRs will have been built, the benefits of learning will be small on the BOP portion, about two-thirds of the LMFBR. Assuming a typical benefit from learning equal to the LWR experience, there would be a saving of 2.7 percent by 2014, 5.4 percent by 2016, and about 8 percent by 2020. These LMFBR costs, declining slightly during the period 2012 to 2020, are shown in Fig. 9, which also repeats the LWR curve of Fig. 6.

These curves suggest that the LMFBR cost will stabilize at a ratio of about 1.2 times LWR cost, but it is unlikely to go below that because of inherent differences, the intermediate heat transfer and the mechanized fuel handling systems being typical examples, between the two systems. Only if major changes from present concepts become acceptable, such as elimination of the intermediate heat transfer system or increasing reactor outlet temperature to a level permitting plant efficiencies of 40 percent or more, could the two system costs approach each other more closely.

It should be observed that the LMFBR cost trends projected here do not at all resemble the experience for the LWRs during the 1960 to 1980 period, when a precipitous rise occurred. The environment for LMFBR deployment we are assuming is favorable. Licensing issues will

Fig. 9 — LMFBF and LWR cost trends for Scenario A, IDC included

have been identified and resolved during the PLBR phase preceding the commercial plants. The licensing delays and "ratcheting" which were experienced during the initial years of LWR deployment will not be repeated for the LMFBF, the regulatory process having become more stable. The plant designs and sizes will remain more standardized than was true for the LWRs, to permit truly multiple manufacture and lower indirect costs.

The cost behavior of this first family of LMFBFs, perhaps the first 50 deployed in a similar temporal pattern, appears unlikely to depend on when the system is actually adopted. If the PLBR and initial commercialization are delayed 10 years, the cost curve of Fig. 9 will simply be shifted to the right by that period. The additional R&D information likely to accrue during the 10 year hiatus does not appear likely to produce significant, or even small, improvements in capital cost. The principal gains from an R&D program would most likely be in fuel cycle costs. The major capital cost benefits arise from operating

experience with prototype and pioneer plants; delays in starting these simply shift the program and the trend of plant costs onward in time.

LMFBR Scenario B

Based on the schedule in Table 10, four LMFBRs reach commercial operation by 2005. We have not specifically examined what their capital costs might be, but it is reasonable to assume that costs were steadily reduced with each succeeding plant, and that the "fifth of kind" plant is the least costly of the first five. We then speculate that in the seven years between 2002 and 2009 serious questions arise regarding safety and security against diversion or sabotage. As a result of these questions and the attempts of regulatory authorities to deal with them, changes are made in the plant design that result in higher capital costs.

The list of changes that could increase capital costs could be sizable. In this scenario, no attempt is made to suggest what items would head the list. Typical items that might be considered are:

Safety items, to prevent loss of coolant and subsequent core melt. A core catcher and additional containment may be necessary.

Security items would include all types of physical security measures that might be taken to prevent sabotage at the plant.

Safeguards are actions that might be taken to deter proliferation; they might include the use of fuels which could require a higher capital cost plant.

Some of these items may be included in the earliest plants, and it should not be implied that plant designers were either unable or unwilling to address them. They are mentioned to illustrate areas of concern that are different from those pertaining to the LWR. Costs may increase because the measures taken may be later judged to be inadequate, or not sufficiently conservative--regardless of how conservative the initial design was thought to be. The cost increases hypothesized

for the high cost scenario result from the continued concern of the regulatory authorities for ever greater assurance against possible malfunctions or accidents, and the engineering changes that ensue.

These concerns begin to take effect after the fifth plant has reached commercial operation. Costs begin to increase because of them, and are hypothesized to increase in a manner analogous to the LWR historical trend and the LWR high cost scenario, except that the rate of temporal cost increase is half that of the LWR. The choice of one-half is based on the assumption that the LMFBR has learned from the LWR experience and has integrated this learning into its design to the maximum extent possible. However, the LMFBR specific items discussed above still increase costs but at half the rate experienced for the LWR. Capital costs rise to the year 2019, at which point the temporal cost increases are just offset by cost learning. Then the cost learning effects take over and costs begin to decrease with increasing deployment of the LMFBR. This is shown in Fig. 10.

Fig. 10 — Capital costs for Scenario B, IDC excluded

From these data, capital cost ratios may be estimated for Scenario B both with and without IDC. From 2009 onward, the LWR direct and indirect costs are virtually constant at \$980 per kWe, and the cost ratio is simply a function of the LMFBR cost estimate. Construction time is a factor in the cost ratios, since if the LMFBR takes longer to build the IDC will be greater because of it. Using the 80 month average construction time for the LWR shown in Fig. 2, multipliers can be developed to adjust the ratio of direct and indirect costs for the effect of construction time differential. Some are shown in Table 11 for a reasonable range. (GE-Bechtel indicated that the construction time ratio might be 1.25.)

Table 11

MULTIPLIERS FOR DIFFERENTIAL CONSTRUCTION TIME

<i>Ratio of LMFBR Construction Time to LWR Construction time</i>	<i>Cost Ratio Multiplier</i>
1.0	1.0
1.1	1.02
1.2	1.04
1.3	1.06

Finally, using the LMFBR costs shown in Fig. 10 and the information in Table 11, we can generate the time-phased cost ratios and total capital costs for various estimated construction times. These appear in Table 12.

This scenario shows that under conditions of equal construction time for both the LWR and LMFBR, the cost ratio will rise from 1.50 to 1.82, and then taper off to about 1.76. Should the LMFBR take longer to construct, as is expected, the ratios will rise.

Direct plus indirect costs of the LMFBR start at \$1460 per kWe in 2009 for the "fifth of kind" plant, then rise due to the imposition of more stringent requirements to a peak of \$1780 per kWe in 2019. They then slowly fall off to \$1720 per kWe in 2028. Interest during construction adds to these costs, bringing the total to \$1850 per kWe in

Table 12

LWR AND LMFBR CAPITAL COSTS AND CAPITAL COST RATIOS FOR SCENARIO B
(in 1978 dollars per kWe)

Year of Commercial Operation	Direct + Indirect Costs		LMFBR/LWR Cost Ratios, for Various Construction Time Ratios, K				LMFBR Costs, ^b Including IDC, for Various LMFBR/LWR Construction Time Ratios, K			
	LMFBR	LMFBR/ LWR ^a	K=1.0	K=1.1	K=1.2	K=1.3	K=1.0	K=1.1	K=1.2	K=1.3
2002										
2003										
2004										
2005										
2006										
2007										
2008										
2009	1460	1.50	1.50	1.53	1.56	1.59	1850	1890	1930	1960
2010	1540	1.58	1.58	1.61	1.64	1.67	1950	1990	2030	2060
2011	1590	1.63	1.63	1.66	1.69	1.73	2010	2050	2090	2140
2012	1620	1.66	1.66	1.69	1.73	1.76	2050	2090	2140	2170
2013	1660	1.70	1.70	1.73	1.77	1.80	2100	2140	2190	2220
2014	1700	1.74	1.74	1.77	1.81	1.84	2150	2190	2240	2270
2015	1720	1.76	1.76	1.80	1.83	1.86	2170	2220	2260	2300
2016	1740	1.78	1.78	1.82	1.85	1.89	2200	2250	2290	2330
2017	1750	1.80	1.80	1.84	1.87	1.91	2220	2270	2310	2360
2018	1780	1.82	1.82	1.86	1.89	1.93	2250	2300	2330	2330
2019	1780	1.82	1.82	1.86	1.89	1.93	2250	2300	2330	2380
2020	1770	1.81	1.81	1.85	1.88	1.92	2240	2290	2320	2370
2021	1750	1.80	1.80	1.84	1.87	1.91	2220	2270	2310	2360
2022	1750	1.80	1.80	1.84	1.87	1.91	2220	2270	2310	2360
2023	1740	1.78	1.78	1.82	1.85	1.89	2200	2250	2290	2330
2024	1740	1.78	1.78	1.82	1.85	1.89	2200	2250	2290	2330
2025	1730	1.77	1.77	1.81	1.84	1.88	2190	2240	2270	2320
2026	1720	1.76	1.76	1.80	1.83	1.86	2170	2220	2260	2300
2027	1720	1.76	1.76	1.80	1.83	1.86	2170	2220	2260	2300
2028	1720	1.76	1.76	1.80	1.83	1.86	2170	2220	2260	2300

^aRatios are obtained by using a cost of \$980 for the LWR. This value is without IDC and is constant for all years.

^bLMFBR costs are equal to an LWR cost of \$1240 (including IDC) times the cost ratios in the columns to the left.

2009, rising to \$2250 in 2018, and trailing off to \$2170 in 2028. If construction time is longer for the LMFBR, these estimates rise.

The increase in direct plus indirect costs in this scenario resulted from more stringent requirements concerning safety and sabotage. The actual amount attributed to these and additional requirements is the difference between the peak cost of \$1780 per kWe and the "fifth of kind" cost of \$1460, or \$320 per kWe. For a 1000 MWe plant, this would represent \$320 million dollars.

V. TIMING OF INTRODUCTION OF LMFBR

The scenarios described in this report are based on the first commercial LMFBR reaching commercial operation in 2002. Other scenarios could address the question of how costs would change if this date were delayed. Capital costs of the LMFBR could change if it were thought that the additional time available could be spent in R&D activities that might lower the cost. They might also change as a result of changes in the costs of the LWR.

The scenarios have already assumed that the LMFBR will take advantage of all available technical knowledge, whether it originates in the LWR, in domestic LMFBR programs, or in foreign LMFBR programs. The state of this knowledge in 2002 will be such that waiting longer before introducing the LMFBR might have only a small effect on its initial capital costs, and probably no effect on its long run costs. LWR capital costs will decrease slightly after 2002 because of cost learning. The reduction is not large in either scenario, and in any event the LMFBR cost ratio will be the same, since this is one of the ground rules that was used. As a result, the cost ratios and the costs themselves would not be substantially different for scenarios in which the LMFBR deployment is delayed.

VI. EFFECT OF VARIATIONS IN ASSUMPTIONS

In this section, we will examine each of the major assumptions, the range over which the values are relevant, and the likely effect on the scenarios.

LMFBR-LWR COST DIFFERENCES

Section II considered the derivation of capital cost ratios that were based on the estimated capital cost differences between the LMFBR and the LWR. These differences, as estimated by SSAI, varied between \$205 per kWe and \$426 per kWe, not including IDC. Rand estimated a wider range, based on slightly different adjustments to the estimates, of \$143 per kWe to \$595 per kWe. Using these latter values would make the capital cost ratios (subject to adjustment for IDC)

$$\frac{143 + 900}{900} \text{ to } \frac{595 + 900}{900}$$

or

$$1.16 \text{ to } 1.66$$

An initial ratio of 1.16 is improbable, and should probably be dismissed. Scenario A implies that the inherent differences between the LMFBR and LWR would be unlikely to result in a cost ratio less than 1.2 without major changes from present concepts. Such changes were not contemplated for the LMFBRs in this study.

If the initial ratio were 1.66 instead of 1.5, the LMFBR costs in Scenario B would rise by about 11 percent, and the cost ratios that were estimated would increase by the difference between 1.66 and 1.5; i.e., by 0.16.

INITIAL CAPITAL COST RATIOS

This subject has been partially covered above. The beginning cost ratios used in the study were 1.20 to 1.60, and were derived without

inclusion of IDC. If IDC were included, these ratios would increase. Assuming that the LMFBR would take 25 percent longer to construct, the beginning ratios would become 1.25 to 1.7. The cost ratios estimated for Scenario A would increase by 0.05 and those for Scenario B by 0.1.

COST LEARNING

The learning effect was maximized uniformly in both scenarios and for the LWR by assuming that the architect engineer employed constructed half of all the plants built. Relaxing this assumption somewhat would raise costs for both scenarios and for both the LMFBR and the LWR. For the LMFBR, learning was applied to only one-third of the plant cost, assuming that the BOP was generally similar enough to that of the LWR that little learning benefit would accrue to that portion of the LMFBR.

COST GROWTH

Assumptions about cost growth due to increased scope are the basis for the cost estimates. For the LWR, cost growth has been projected for both scenarios on bases that seem plausible. However, debate about plausibility may be academic, because the scenarios rely on the premise that the beginning cost ratio holds for whatever LWR costs happen to be at the time the "fifth of kind" LMFBR is deployed. Thus, varying the LWR cost scenarios will have little effect on the *cost ratios*. It would, of course, have a substantial effect on the absolute capital costs.

On the other hand, cost growth for the LMFBR relative to the LWR is the key factor in influencing the cost ratios. Scenario A forecasts no cost growth for the LMFBR, subsequent to the "fifth of kind" plant. Scenario B suggests that the LMFBR costs (excluding IDC) will increase from about \$1460 per kWe to about \$1720 per kWe in 2028, or about 18 percent, due to increased plant scope for reasons of safety, security, and safeguards.

INTEREST DURING CONSTRUCTION (IDC)

If the construction times for an LMFBR and an LWR are equal, the IDC does not enter into the cost ratio calculation. Since the LMFBR

is more complex than the LWR, and since there is more construction work involved, the LMFBR time may exceed the LWR time. Scenario A has assumed that the construction times become equal for plants beyond the "fifth of kind." Any change to this assumption of equal construction time will increase LMFBR costs and increase the cost ratio. If the construction times differ by 25 percent, the cost ratios will increase by about 5 percent at a nominal IDC rate of 8 percent per year. Table 11 for Scenario B shows how the LMFBR costs and cost ratios depend on the ratio of construction times.

COMBINED EFFECTS

Several of the above parameters could assume values that act in the same direction, and since some of the sensitivities are additive and others are multiplicative, general rules for estimating the net effects are not possible. Rather, the guidelines of Sec. VII can be used to estimate the net effects.

VII. A SIMPLIFIED METHOD FOR ESTIMATING COST RATIOS

The two scenarios used in this report may provoke curiosity on the part of a reader who may wish to estimate cost ratios for an alternative scenario. Some simple guidelines will help to make rough estimates.

1. Select a cost for an LWR that reaches commercial operation in 2009.

2. Choose the initial LMFBR/LWR cost ratio. This initial ratio was suggested to be in the range of 1.2 to 1.6 in this study; other studies have suggested ranges of 1.25 to 1.75.

3. Multiply the selected LWR cost by the initial capital cost ratio. This will give the estimated cost of the "fifth of kind" LMFBR.

4. Estimate the degree to which the LMFBR cost trajectory will be similar to that of the LWRs' initial history. In terms of cost increases, use the following guide:

Assumed cost growth beyond "fifth of kind"

50 percent greater than LWR	Add	\$1050 per kWe
25 percent greater than LWR	Add	875 per kWe
The same as LWR	Add	700 per kWe
75 percent as great as LWR	Add	525 per kWe
50 percent as great as LWR	Add	350 per kWe
25 percent as great as LWR	Add	175 per kWe
None	Add	0
25 percent less than none	Subtract	175 per kWe
50 percent less than none	Subtract	350 per kWe
75 percent less than none	Subtract	525 per kWe

5. Add (or subtract) the amount estimated in Step 4 to the LMFBR cost estimated in Step 3. This yields the approximate long run capital cost of the LMFBR, assuming equal LWR and LMFBR construction times.

6. Divide the LMFBR cost obtained in Step 5 by the LWR cost estimated in step one to obtain the LMFBR/LWR capital cost ratio, assuming equal construction time.

7. Select a ratio of LMFBR/LWR construction time, and the appropriate LMFBR capital cost multiplier, from below.

<i>LMFBR/LWR Construction Time</i>	<i>Cost Ratio Multiplier</i>
1.0	1.0
1.1	1.02
1.2	1.04
1.3	1.06

8. Multiply the LMFBR/LWR cost ratio by the multiplier selected in Step 7. This produces the final LMFBR/LWR cost ratio.

The above procedure neglects learning effects, which are not a dominant factor. If they are to be taken into account, assumptions must be made about both the LWR and LMFBR construction schedules and the number to be built by each architect engineer. Capital costs will decrease by about 8 percent for each doubling of the number of plants built by any single architect engineer.

An example of the use of the above estimating method follows:

1. Set LWR cost (in 1978 dollars) in 2009 = \$1000 per kWe.
2. Set initial LMFBR/LWR cost ratio = 1.4.
3. "Fifth of kind" LMFBR cost = $\$1000 \times 1.4 = \1400 per kWe.
4. Set LMFBR cost history equal to "25 percent as great as LWR cost history." (Add \$175 per kWe.)
5. $\$1400 + 175 = \1575 = long run LMFBR cost, at equal construction time with LWR.
6. $\text{LMFBR/LWR cost ratio} = \frac{\$1575}{\$1000} = 1.6.$
7. Set LMFBR/LWR construction time = 1.1. Cost ratio multiplier equals 1.02.
8. $1.6 \times 1.02 = 1.6$ = final cost ratio.

REFERENCES

1. *Liquid Metal Fast Breeder Reactor Conceptual Design*, Atomics International and Burns and Roe, FBR-77-3, May 1977.
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3. *Prototype Large Breeder Reactor, Phase II, Final Report*, Westinghouse Advanced Reactor Division, November 1977.
4. Mooz, W. E., *Cost Analysis of Light Water Reactor Plants*, The Rand Corporation, R-2304-DOE, June 1978.
5. *U.S. Central Station Nuclear Electric Generating Units: Significant Milestones*, U.S. Department of Energy, Division of Nuclear Development, DOE/ET-0030/4(78), 1978.

Appendix

A SUMMARY REVIEW OF LMFBR/LWR CAPITAL COSTS

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I. INTRODUCTION

Plant capital costs are extremely important in the overall assessment and comparison of alternative electric power generating systems. For systems and concepts not yet fully developed, planning for the future requires that capital cost estimates be prepared, evaluated, and reviewed under various sets of ground rules and from different perspectives.

Southern Science Applications, Inc., under contract to The Rand Corporation, has performed a summary review of capital cost estimates for commercial liquid metal fast breeder reactor (LMFBR) plants and has compared these costs to the capital costs for light water reactor (LWR) plants. This work was undertaken in support of a study by The Rand Corporation that covers a hypothesized range of LMFBR/LWR costs.

The Southern Science review of capital cost data supplied to Rand by Atomics International, General Electric, and Westinghouse included evaluations of the overall completeness of the supplied data, estimations of appropriate adjustments to the data, and comparisons of the costs to base LWR costs.

The following section of this report is a summary of the results of the work. Section III provides engineering reviews of the plant designs, presented in a manner that emphasizes the differences in design that affect capital costs. Section IV contains specific reviews of the data supplied by the various vendors, while concluding remarks are given in Section V.

II. SUMMARY

An overall review of specific capital cost estimates for commercial LMFBR plants has been performed. The estimates were made by Atomics International (AI), General Electric (GE) and Westinghouse (W) and supplied to Southern Science by The Rand Corporation. An engineering assessment of the LMFBR plant designs was initially performed that emphasized the differences from LWR plant designs. The LMFBR plants were considered as fifth-of-a-kind designs and compared to a fully developed commercial LWR. The assessment indicated the potential for significant differences in costs compared to LWR costs for the required LMFBR structures and facilities. This difference is expected due to the larger, dual containment and separate steam generator buildings for the LMFBR. Major cost differences are also expected for the reactor plant equipment of the LMFBR compared to the LWR. This is due to a number of items noted in Section III, including the larger reactor vessel, presence of an intermediate loop and associated piping and components, and more complex steam generators for the LMFBR. Some LMFBR balance-of-plant (BOP) structures, systems and components could have costs comparable to an LWR design.

Capital cost estimates associated with the LMFBR designs were reviewed and compared to a base LWR cost. Cost estimates for the AI, GE and W plant designs, direct plus indirect costs only, were \$984.3M, \$1154.1M and \$863M to \$1142M, respectively.* A base cost of \$770** for a 900 Mw(e) LWR (1977) was used. Review of the LMFBR data indicated that major cost elements had been

*The AI estimate is for a 1000 Mw(e) plant in 1977 dollars, the GE estimate is for a 900 Mw(e) plant in 1977 dollars. The range of costs for the W estimate is for a 1000 Mw(e) plant in 1978 dollars. The letter "M" is used to denote millions.

**This is the value estimated by GE. See p. 11.

addressed, although it could be postulated that some items were omitted. There was a lack of evidence that some land, structures, and waste treatment cost elements were covered in the estimates, so independent estimates were made to adjust the cost data. Adjustments of \$22M, \$22M and \$45M to \$58M were made to the AI, GE and W estimates, respectively. These adjustments did not yield a significant change in the basic capital cost data.

Comparing the LMFBR capital costs to the LWR costs corrected to an equal size and time basis yields the following ratios for both the unadjusted and adjusted estimates.

	<u>AI</u>	<u>GE</u>	<u>W</u>
LMFBR/LWR Ratio			
Unadjusted	1.21	1.50	1.01-1.34
Adjusted	1.24	1.53	1.07-1.41

The low range of the W data is judged to be unrealistically low and the remainder of the estimates appear credible considering the differences in the plant designs themselves.

III. ENGINEERING ASSESSMENT OF LMFBR/LWR CAPITAL COST ELEMENTS

An intercomparison of commercial LMFBR and LWR plant designs was performed to identify cost elements that would be expected to yield significant differences in capital costs. To allow this combined technical/economic evaluation, an engineering assessment of the plant designs was performed using the cost account categories of the CONCEPT code.⁽¹⁾ The engineering design information for the AI, GE and W LMFBR plants is based on descriptions developed for the Prototype Large Breeder Reactor (PLBR) project.⁽²⁾ Design information for LWR plants was obtained from typical safety analysis reports.^(3,4) The following paragraphs indicate the capital cost category and the engineering design differences expected to yield different capital costs within that category.

A. Land and Land Rights

No significant differences are foreseen between the LMFBR plant and LWR plant for this category. The exclusion area is expected to be the same for the two plants once the LMFBR reaches commercial status.

B. Structures and Facilities

Differences in plant layout would affect this cost element and several differences in LMFBR and LWR plant layout requirements are noted. The LMFBR designs require larger containments (20 to 50 percent larger diameter) and all incorporate a separate confinement structure. Some of the current generation of BWRs are also being built with a free standing steel containment and a separate confinement structure, but the cost of this is not in the current LWR cost estimates. The LMFBR containment design pressures are 3-10 psig as compared to approximately 15-20 psig for LWR containments.

The LMFBR layouts call for steam generator buildings which are not required for the LWR plants. The PWR steam generators are inside the

containment and the comparable situation is the placement of the intermediate heat exchangers within the LMFBF containments.

The LMFBF plant layouts do not appear to provide for an administrative building, which is typically included in LWR costs.

The LMFBF containment and steam generator buildings will have to provide for sealed and inerted cells for much of the auxiliary equipment and piping runs that carry the sodium coolant. All of these piping galleries and cells will be steel lined to prevent molten sodium interaction with the concrete. These requirements introduce additional complexity into the plant layout for an LMFBF as compared to an LWR.

C. Reactor Plant Equipment

Engineering judgment has been exercised to provide a simple but meaningful intercomparison of the reactor systems. Obviously, almost every component requires different design criteria and materials when comparing an LMFBF to an LWR.

Both concepts have in common a loop-type primary coolant system to remove heat from a core consisting of fuel pins held in fuel subassemblies. The LMFBF has the added equipment cost represented by an intermediate heat transfer loop which requires additional piping, heat exchangers of approximately two-thirds steam generator size, and intermediate pumps equal in size to primary coolant pumps.

The LMFBF is a low pressure system, but the mechanical design criteria are nonetheless challenging because of thermal shock potential due to the high thermal conductivity of the molten sodium. The vessel and primary coolant system must be designed to withstand a high transitory stress caused by rapid sodium vaporization in the core and the intermediate coolant system must be able to withstand a high stress loading from an energetic steam/sodium chemical interaction.

All of the sodium-containing components are constructed entirely of stainless steel in the LMFBR as compared to stainless steel lining in LWR systems.

The LMFBR coolant system is constructed on the guard vessel principle. A rupture any place in the primary system is contained in either the steel guard vessel around the reactor vessel or in guard pipes surrounding the primary cold leg piping. The volume of these guard vessels is limited so that the amount of sodium lost is not sufficient to uncover the core.

The effective core diameter of the LMFBR is approximately twice that of an LWR due to blanket subassemblies and the reflector/shield region. The reactor vessel of an LMFBR has approximately three times the diameter and 30 percent greater height than a PWR reactor vessel. However, the wall thickness of the LMFBR averages three (3) inches compared to eight (8) inches for a PWR. The primary coolant piping is approximately 20 percent greater in diameter than a PWR, but has a smaller wall thickness.

The refueling system for the LMFBR is more complicated than an LWR. This can be appreciated when one realizes that refueling an LWR can be a visual operation (looking down onto the flooded core) as opposed to refueling the LMFBR by remote equipment underneath the reactor vessel head in an opaque coolant. The LMFBR fuel storage facility will also represent a larger investment than the LWR spent fuel pool because of the need for sodium cooling and blanket gas.

The cover gas in the coolant loops will represent an added investment, but this may be roughly matched by the investment in off-gas control required at LWR plants.

Sodium purity monitoring and cleanup systems will be required in the LMFBR, but this investment may be offset by the lack of the chemical and volume control system required for LWRs.

The LMFBRs will require heat tracing on all of the sodium piping and extensive sodium leak detection equipment tied into the plant control system. The cost of these items is partially offset by a reduction in piping restraints required as a result of the absence of blowdown reaction forces on the piping.

The comparison of engineered safeguards systems indicates a diversity of designs for BWR, PWR, and different LMFBR concepts. However, all have to remove approximately the same time-dependent decay heat loading. The LWR systems have diverse coolant injection pumps, residual heat removal heat exchangers, ultimate cooling towers, ultimate heat sinks, and containment cooling systems. The LMFBR concepts employ additional steam generator feed-water backup and independent NaK loops with pumps rejecting heat through air heat exchangers. The LMFBR engineered safeguards systems are not judged to add a significant cost differential.

The steam generators for the LMFBR concepts will have to meet higher design and manufacturing standards in order to preclude a water-to-sodium leak that will result in an energetic chemical reaction. Some of the LMFBR concepts call for duplex tubes and double tube sheets. These stringent requirements will mean additional cost for these LMFBR components.

D. Turbine Plant Equipment

No significant difference is expected in capital cost associated with this category with the exception of the turbine-generator. Cost differentials between the 1800 rpm (saturated) and the 3600 rpm (superheated) systems are controversial. Since one of the LMFBR concepts also specifies a saturated steam cycle, no cost differential is assumed between LWR and LMFBR plants.

E. Electric Plant Equipment

Two of the LMFBR concepts identify three 100-percent-capacity diesel generators and the third concept calls for two 100-percent-capacity diesel generators plus two 100-percent-capacity gas generators. These represent approximately one extra diesel generator in excess of the LWR cost estimates.

IV. CRITIQUE OF LMFBR CAPITAL COST DATA AND COMPARISON TO LWR COSTS

Estimates for commercial LMFBR plant capital costs made by AI, GE and W have been supplied by The Rand Corporation and are summarized in Table I through Table IV. This data was transmitted and identified as three data sets, A, B, and C,⁽⁵⁾ and that convention is also used in this report. Data Set A corresponds to the AI design and Data Set B corresponds to the GE design. The Westinghouse estimate of Data Set C originally contained a range of costs for the various elements and has subsequently been separated into two data sets, C1 and C2, corresponding to the low and high values of the range, respectively.

As utilized in the engineering assessment discussed in Section III, the capital cost accounting structure of the CONCEPT code has been used to facilitate review of the data base. All data sets were converted into this structure. The varying levels of detail, or lack thereof, are more easily accommodated for comparative purposes by this structure. As appropriate, details of the data sets were combined into appropriate subaccounts consistent with the CONCEPT structure and similar accounting guidelines.⁽⁶⁾

Table V presents the four LMFBR capital cost data sets in the CONCEPT account structure. Account numbers and subaccount numbers have been used to identify the various cost elements. Accounts 20, 21, 22, 23, 24 and 25 present the direct costs and accounts 91, 92 and 93 present the indirect costs as obtained from reformatting the data from Tables I-IV. Costs are itemized by subaccounts as detail allowed. For Data Set A, no balance-of-plant detail was available.

The presentation of the LMFBR capital cost data as provided by Table V lends itself to a critique of the cost estimates. One-to-one comparisons appear easy to perform and blanks appear quite obvious. However, a certain amount of caution is warranted. The data sets represent separate designs, or ranges of costs for a given design, so some significant differences are expected. Also, the tabulated data was taken from data sets with varying

levels of detail, with different utilization of contingencies and "other" categories and with slightly different time bases for the costs. For some questions, then, the raw data warrants the benefit of a doubt. The annotations presented on Table V refer to notes or adjustments that attempt to consider these factors.

As an initial assessment, the capital cost data was reviewed for possible omissions. The numerous blanks in several of the accounts suggest several omissions, but further review suggests that actual omissions are likely to yield only small relative cost adjustments. As noted in Table V, certain land costs, structures costs and waste treatment costs and other elements were assumed omitted and appropriate adjustments were made.

Whether a cost element was actually omitted or was covered elsewhere was highly judgmental. For those items that were assumed omitted, independent estimates were made and adjustments indicated in the table. The estimated adjustments (approximate in nature) were based on intercomparison of the LMFBFR data, LWR data ⁽⁷⁾, engineering judgment and significance to the overall plant cost. Considering the magnitude of the final adjustments, the cost associated with any omissions in the basic data is of less consequence than the cost differences that could actually exist due to differences in the LMFBFR designs. The potential value of omissions is also felt to be within the accuracy or contingencies actually present in the estimates themselves.

LMFBFR capital costs presented in Table V are also compared to LWR costs. A reference capital cost for a 900 Mw(e) LWR of 770 million dollars (January 1977) was provided by Rand.⁽⁸⁾ This cost is direct plus indirect only and includes \$95M for NSSS and \$675M for balance-of-plant. Values on comparable power level and time bases as the LMFBFR estimates have been obtained by scaling^(8,9) and given in Table V for a hypothetical cost comparison. Relative cost comparisons between the LMFBFR costs and the LWR data are presented.

Table I LMFBR CAPITAL COST DATA SET A
 Fifth-of-a-Kind 1000 Mw(e) LMFBR Costs
 (\$ Millions, 1977)

<u>NSSS — Major Items</u>		<u>NSSS — Auxiliary Items</u>	
Reactor Vessel	34	Na Piping Preheat and Control	6
Guard Vessel	7	Cover Gas and Pressurizing Systems	8.9
Reactor Internals	30	Cavity Gas Cool Systems	6.7
Deck and Plugs	50	Auxiliary Cooling System	—
Control Rods	5	Coolant Sampling Systems	2.9
Fuel Handling Systems	28	Maintenance Systems	11.6
IHX	34	Na Fire Protection Systems	2.6
Pumps	49	Rad Monitoring Systems	0.6
PHTS, IHTS	19	Fedal	1.6
Decay Heat Removal Systems	12	Flux Monitoring Systems	1.8
Steam Generators	113	Plant Protection System	2.8
Na Auxiliary Systems	9	Plant Control Systems	3.1
Subtotal	390	Console and Data Handling	2.6
		Process I&C	18.7
		Na Inventory	9.0
		Subtotal	78.9
<u>NSSS Summary</u>		<u>Plant Summary</u>	
Major Items	390	Nuclear Steam Supply System	468.9
Auxiliary Items	78.9	Balance-of-Plant	365.4
NSSS Total	468.9	Total Direct	834.3
		Indirect	150
		Total Plant	984.3
		Contingency (included in above)	—
		DATA SET A TOTAL	984.3

Table II LMFBR CAPITAL COST DATA SET B
Fifth-of-a-Kind 900 Mw(e) Net LMFBR Costs
(\$ Millions, 1977)

<u>Nuclear Steam Supply System</u>		
Reactor Equipment	}	175.5
Main Heat Transfer and Transport System		
Safeguards Cooling System		3.3 *
Nuclear Fuel Handling		27.0 *
Other Reactor Plant Equipment		1.8 *
Instrumentation and Control		15.6 (est)
Engineering		54.2
Subtotal		277.4
<u>Balance-of-Plant</u>		
Site Improvements & Facilities		9.6
Reactor Containment Building		81.8
Steam Generator/Pracs Bldg.		24.3
Turbine Building		20.6
Reactor Service Building		13.2
Miscellaneous Buildings		19.0
Reactor Plant Equipment		86.4
Turbine Plant Equipment		124.1
Electric Plant Equipment		62.9
Miscellaneous Plant Equipment		15.6
Field Distributable Costs		142.6
Engineering & Home Office		115.0
Subtotal		715.1
<u>Total Plant</u>		992.5
Contingencies		161.6
DATA SET B TOTAL		1154.1

* Same as 1st and 20th of a kind

** NSSS Equipment Total = 223.2

Table III LMFBF CAPITAL COST DATA SET C1
Fifth-of-a-Kind 1000 Mw(e) LMFBF Costs
(\$ Millions, 1978)

<u>NSSS Components</u>		<u>Balance-of-Plant</u>	
Reactor Vessel	30	<u>Turbine-Generator System</u>	
Reactor Head	20	Turbine-Generator	41
Other Reactor Internals & Enclosure Equipment	75	Feedwater System	8
Primary Pumps	14	Condensing System	6
Primary Pipe, Hangers, Snubbers, Elbows	7	Cooling Tower (wet)	18
Other PHTS Equipment	23	Circulating Water	2
Intermediate Pumps	9	Main Steam Piping and Restraints	6
Intermediate Pipes, Hangers, Snubbers, Elbows	15	Instrumentation and Control	2
Intermediate Heat Exchangers	36		
Other IHTS Equipment	21	Total Turbine-Generator System	83
Steam Generators	48	<u>Buildings and Structures</u>	
Other S/G Equipment	15	Containment	38
Fuel Handling and Storage Equipment	80	Steam Generator	19
NSSS Instrumentation, Control, Monitoring	20	Turbine Generator	33
Auxiliary & Miscellaneous Equipment	62	Auxiliary Buildings	12
NSSS Total	475		
		Total Buildings and Structures	102
		<u>Electrical Plant</u>	
		Switchgear	3
		Station Service	13
		Switchboards	1
		Power and Control Wiring	20
		Structures	16
		Protective Equipment	1
		Total Electrical Plant	54
		Land and Yardwork	10
		Indirect Costs (Engineering Services, Site Construction, Owner, and Other Costs)	120
		Contingency on BOP	19
		BOP Total	388
<u>Plant Summary</u>			
NSSS	475		
BOP	388		
DATA SET C1 TOTAL	863		

Table IV LMFBR CAPITAL COST DATA SET C2
Fifth-of-a-Kind 1000 Mw(e) LMFBR Costs
(\$ Millions, 1978)

<u>NSSS Components</u>	
Reactor Vessel	38
Reactor Head	25
Other Reactor Internals & Enclosure Equipment	90
Primary Pumps	18
Primary Pipe, Hangers, Snubbers, Elbows	9
Other PHTS Equipment	27
Intermediate Pumps	12
Intermediate Pipes, Hangers, Snubbers, Elbows	17
Intermediate Heat Exchangers	42
Other IHTS Equipment	26
Steam Generators	72
Other S/G Equipment	21
Fuel Handling and Storage Equipment	95
NSSS Instrumentation, Control, Monitoring	25
Auxiliary & Miscellaneous Equipment	83
NSSS Total	600

Plant Summary

NSSS	600
BOP	542
DATA SET C2 TOTAL	1142

<u>Balance-of-Plant</u>	
<u>Turbine-Generator System</u>	
Turbine-Generator	47
Feedwater System	10
Condensing System	8
Cooling Tower (wet)	25
Circulating Water	5
Main Steam Piping and Restraints	8
Instrumentation and Control	2
Total Turbine-Generator System	105
<u>Buildings and Structures</u>	
Containment	83
Steam Generator	27
Turbine Generator	40
Auxiliary Buildings	14
Total Building and Structures	164
<u>Electrical Plant</u>	
Switchgear	3
Station Service	13
Switchboards	1
Power and Control Wiring	20
Structures	16
Protective Equipment	1
Total Electrical Plant	54
Land and Yardwork	10
Indirect Costs (Engineering Services, Site Construction, Owner, and Other Costs)	160
Contingency on BOP	49
BOP Total	542

Table V LMFBR CAPITAL COST EVALUATION BY CONCEPT COST ANALYSIS ACCOUNT STRUCTURE

ACCOUNT NUMBER	ACCOUNT TITLE	Date Set:	Cost, Millions \$			
			1977 A	1977 B	1978 C1	1978 C2
20	LAND AND LAND RIGHTS	a		- b	10	10
21	STRUCTURES & FACILITIES					
211	Site Improvements & Facilities	c		9.6	d	d
212	Reactor Building ^e			106.1	57	110
213	Turbine Building			20.6	33	40
214	Intake & Discharge Struc. ^f			-	-	-
215	Reactor Auxiliaries Bldg.			13.2	12	14
216	Radioactive Waste Bldg. ^g			-	-	-
217	Fuel Storage Bldg.			- h	- i	- i
218	Other			19.0	- j	- j
		c		168.5	102	164
22	REACTOR PLANT EQUIPMENT					
221	Reactor Equipment		126	175.5 ^k	125	153
222	Main Heat Transfer and Transport Systems		223.9		188	244
223	Safeguards Cooling Systems		12	3.3 ^l	- m	- m
224	Radioactive Waste Treatment ⁿ and Disposal		-	-	-	-
225	Nuclear Fuel Handling & Storage Systems		28	27.0	80	95
226	Other Reactor Plant Equip.		47.8	88.2	62	83
227	Instrumentation & Control		31.2	15.6	20	25
			468.9	309.6	475	600
23	TURBINE PLANT EQUIPMENT					
231	Turbine-Generators				41	47
232	Heat Removal Systems				20	30
233	Condensing Systems				6	8
234	Feed Heating System				8	10
235	Other Turbine Plant Equip.				6	8
236	Instrumentation & Control				2	2
		c		124.1	83	105

Table V LMFBR CAPITAL COST EVALUATION BY CONCEPT COST ANALYSIS ACCOUNT STRUCTURE
(continued)

ACCOUNT NUMBER	ACCOUNT TITLE	Date Set:	Cost, Millions \$			
			1977 A	1977 B	1978 C1	1978 C2
24	ELECTRIC PLANT EQUIPMENT					
241	Switchgear				3	3
242	Station Service Equip.				13	13
243	Switchboards				1	1
244	Protective Equipment				1	1
245	Electrical Structures & Wiring Containers				16	16
246	Power and Control Wiring				20	20
			<u>c</u>	<u>62.9</u>	<u>54</u>	<u>54</u>
25	MISCELLANEOUS PLANT EQUIP		c	15.6	- ^o	- ^o
91	CONSTRUCTION FACILITIES, EQUIPMENT, AND SERVICES	150	p	142.6	120 p	160 p
92	ENGINEERING & CONSTRUCTION MANAGEMENT SERVICES		p	169.2	p	p
93	OTHER COSTS		p	- ^g	p	p
	Data Set A BOP		365.4			
	CONTINGENCIES		r	161.6	19 ^s	49 ^s
	LMFBR UNADJUSTED TOTAL		<u>984.3</u>	<u>1154.1</u>	<u>863</u>	<u>1142</u>
	NET ADJUSTMENT		<u>22</u>	<u>22</u>	<u>45</u>	<u>58</u>
	LMFBR ADJUSTED TOTAL		1006.3	1176.1	908	1200
	LWR COMPARABLE COST ^t		811	770	852	852
	LMFBR/LWR RATIO					
	UNADJUSTED		1.21	1.50	1.01	1.34
	ADJUSTED		1.24	1.53	1.07	1.41
	LMFBR-LWR DIFFERENTIAL, Millions \$					
	UNADJUSTED		173.3	384.1	11	290
	ADJUSTED		195.3	406.1	56	348

Table V LMFBR CAPITAL COST EVALUATION BY CONCEPT COST ANALYSIS ACCOUNT STRUCTURE
(continued)

Notes and Adjustments:

- a. Possibly included in Data Set A BOP cost, but an additional \$10M adjustment assumed.
- b. Apparently omitted, an additional \$10M assumed.
- c. Accounts 21, 23, 24 and 25 assumed completely covered by Data Set A BOP cost.
- d. Not specifically noted elsewhere and assumed omitted; an adjustment ranging from \$8M to \$10M is assumed for Data Set C.
- e. Steam generator building(s) included here.
- f. This subaccount not considered strictly applicable for use of cooling towers, costs associated with this item are assumed to be covered by subaccounts 218 or 232.
- g. Function covered in reactor auxiliary building, cost assumed covered in subaccount 215.
- h. Function covered in reactor and auxiliary building.
- i. A separate fuel handling building is assumed present, an adjustment of \$4M to \$6M is assumed for Data Set C.
- j. Separate diesel-generator and control buildings are assumed present, an adjustment of \$8M to \$10M is assumed for Data Set C.
- k. Total for subaccounts 221 and 222, some costs may also be covered in subaccount 226.
- l. Additional costs are expected associated with this category, but are considered to be covered by subaccount 226.
- m. Although not specifically noted to be included elsewhere, costs for this subaccount are assumed to be covered by subaccount 226.
- n. This category is not specifically noted to be included elsewhere and even though subaccount 226 is considered possibly sufficient to cover appropriate costs, an adjustment appears appropriate. Adjustments of \$12M, \$12M, \$12M, and \$15M are assumed for Data Sets A,B, C1 and C2, respectively.
- o. Specific costs for this category are not noted to be covered elsewhere, although this is quite likely. However, an adjustment of about 1.5% of the unadjusted total is assumed to be appropriate. This yields adjustments of \$13M for C1 and \$17M for C2.

Table V LMFBR CAPITAL COST EVALUATION BY CONCEPT COST ANALYSIS ACCOUNT STRUCTURE
(continued)

- p. The total costs for accounts 91, 92 and 93 are assumed to be included within the value indicated for account 91.
- q. Considering the magnitude of other noted indirect costs, this subaccount is assumed to be covered.
- r. Contingencies have been assumed to be included in basic estimates.
- s. BOP contingency only, other has been assumed to be included in basic estimates.
- t. Based on \$770/kw (1/77) direct plus indirect costs for a 900 MW(e) net LWR plant; Cost multiplier for scaling to 1978\$ is assumed to be 1.05; scaling for capacity is assumed to be by $(P_1/P_2)^{0.5}$.

V. CONCLUDING REMARKS

Based on the review of the LMFBF capital cost estimates presented in the preceding pages, we conclude that all items with major cost impact have been included. Although some specific elements that provide important plant functions may have been omitted, the significance of the items to the total LMFBF capital cost appears small. Consequently, comparison to LWR capital costs would be expected to be reasonable.

Review of the comparative data shows that the LMFBF costs would appear to range from costs comparable to the LWR to costs about 50 percent higher. However, LMFBF capital costs comparable to LWR costs do not appear realistic based on the engineering assessment of Section III. Examination of Data Set C1 shows that the closeness of the LMFBF estimate to the LWR value is due to a low balance-of-plant cost. The BOP costs for the LMFBF could possibly be comparable to BOP costs in the LWR, but significantly higher NSSS costs are expected for the LMFBF: consequently, total cost would not be expected to be comparable. It was noted that Data Set C1 gave the low values of a range and is, indeed, considered to be low. The remaining data sets appear to be reasonably credible and consistent with the design differences. The high indirect costs of Data Set B are worthy of note, and are perhaps the most realistic values given for a fifth-of-a-kind LMFBF.

Capital cost estimates have previously been made for commercial power plants at various stages of development, and studies^(7,9,10) of LWR costs have shown significant variations — not all of which have been fully explained. The LMFBF estimates discussed here are considered to be no more or no less sound than other estimates made at comparable stages of development. Though the LWR is considered commercially developed, there remains enough variation in its costs to add yet another element of uncertainty to relative-cost evaluations of the LMFBF.

REFERENCES TO APPENDIX

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3. Reference Safety Analysis Report, RESAR-414, Westinghouse Nuclear Energy Systems, NRC Docket No. 50-572, December 30, 1976 and subsequent amendments.
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