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THE FAST BREEDER REACTOR DECISION: AN ANALYSIS OF LIMITS AND THE LIMITS OF ANALYSIS

A STUDY

PREPARED FOR THE USE OF THE

JOINT ECONOMIC COMMITTEE
CONGRESS OF THE UNITED STATES

APRIL 19, 1976

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LETTERS OF TRANSMITTAL

APRIL 16, 1976.

To the Members of the Joint Economic Committee:

Transmitted herewith for the use of the Members of the Joint Economic Committee and other Members of Congress is a study entitled "The Fast Breeder Reactor Decision: An Analysis of Limits and the Limits of Analysis," prepared for the Joint Economic Committee. The study evaluates the major cost-benefit analyses, which review the benefits of developing and introducing commercially the Liquid Metal Fast Breeder Reactor.

HUBERT H. HUMPHREY,
Chairman, Joint Economic Committee.

APRIL 15, 1976.

Hon. HUBERT H. HUMPHREY,
Chairman, Joint Economic Committee,
U.S. Congress, Washington, D.C.

DEAR MR. CHAIRMAN: Transmitted herewith is a study entitled "The Fast Breeder Reactor Decision: An Analysis of Limits and the Limits of Analysis," prepared by Mark Sharefkin of Resources for the Future, Inc., for the use of the Joint Economic Committee. This study provides a timely analysis of this nation's largest energy research and development project.

Mr. Sharefkin examines the basic premises underlying the major cost-benefit analyses of the Fast Breeder Reactor. The paper raises questions about the cost-benefit analyses' assumptions concerning electricity demand, uranium supply, nuclear reactor capital cost differentials, and discount rates. It also suggests specific ways that conventional cost-benefit analysis fails to shed light on the crucial breeder timing issue.

The views expressed in this study, of course, are those of its author and not necessarily those of the committee, any of its individual members, or the Joint Economic Committee staff.

William Cox and Larry Yuspeh of the Joint Economic Committee staff managed and edited this study.

JOHN R. STARK,
Executive Director, Joint Economic Committee.

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POINT-BY-POINT SUMMARY

1. All of the major cost-benefit studies of the liquid metal fast breeder reactor (LMFBR) are incomplete, because they ignore the possibility that substantial costs in the form of long-lived radioactive wastes and their consequences will be transferred to future generations. The nuclear waste question pushes cost-benefit analysis beyond its capacity. A new analytical method may be required.
2. It may be very misleading to jump to conclusions of impending uranium shortages on the basis that uranium's reserve-production ratio is declining. In 1938, oil's reserve-production ratio was about 12. It would have been a serious error, however, to argue that the United States would run out of oil in 12 years unless something drastic was done. Although oil production has increased at 7.5 percent per year, oil's 1974 reserve-production ratio was 18. To argue similarly about uranium in 1976 probably is just as wrong.
3. Major increases in uranium reserve estimates over the past few years emphasize the uncertainties surrounding this resource base.
4. Because uranium reserves are expensive to prove and because uranium inventories are expensive to obtain and hold, proven reserves and inventories will tend to be low relative to other materials.
5. Uranium reserves also are low, because, until recently, uranium prices were declining. Incentives for exploration and development, therefore, have been weak.
6. The uranium resource analyses exclude consideration of major determinants of future uranium resources. They are structured in such a way as to impart a pessimistic bias to uranium supply projections.
7. Projected growth rates of electricity demand are a key to the decision on when to proceed with the breeder program. It appears that electricity growth rates beyond 1980 may be closer to 2 percent per year than to the historical growth rate of 7 percent. With a 2 percent growth rate, electricity consumption will be only 3.3 trillion kilowatt-hours in the year 2000, compared to projections of as high as 6.1 trillion in the major breeder cost-benefit studies. Thus the breeder could be delayed.
8. The major reason for slower projected power demand growth in the future is that the era of declining electricity prices seems to be over. The reasons for the end of declining electricity prices include (1) the end of scale economies for power generation, (2) the intensity of environmental concern and the internalization of some of the external costs of power production, and (3) the recent rapid increases in fossil fuel costs and in the capital costs of light-water reactor plants.
9. The capital cost differential between light-water and breeder reactors is a key to the breeder decision. Everyone agrees that the breeder's capital cost will be much higher than that of light-water reactors, but no one is sure how much higher it will be. If the differential is greater than $125 per kilowatt, the LMFBR's electricity will cost more than light-water reactor electricity.

10. Many analyses assume that LMFBR capital costs will decline with experience (i.e., "learning"). There is not much reason to believe there will be any decline, however. Light-water reactor construction on the contrary has experienced persistently increasing cost and has not displayed a learning-curve pattern. There is not much reason to believe that the breeder will fare better in this regard.

11. Most economists agree that intertemporal efficiency comparisons require the discounting of future costs and benefits, but they do not agree on what the particular value of the discount rate should be. Because the study by Stauffer et al. uses a discount rate for the breeder's benefits substantially less than the 10-percent rate used in the other studies, it finds that the benefits of breeder development are quite high.

12. A problem with all of the breeder cost-benefit studies except that by Manne involves their specification of the future alternatives. The Manne study reviews two scenarios of the future—one with a certain date for breeder commercialization and one with various possible commercialization dates with probabilities attached. The other studies analyze only one future that assumes *certain* breeder commercialization as of a certain date. If breeder commercialization has benefits, all of the studies that analyze one future with certain breeder commercialization will find that the earliest breeder commercialization date will yield the greatest benefits. Because of this characteristic, these studies shed no light on the crucial issue of the timing of the breeder's development.

13. If cost-benefit analysis is to be applied effectively to the breeder development decision, alternative program timing strategies must be analyzed. Indeed, it can be argued that an assessment of such broadly defined alternative program strategies is the most important role for cost-benefit analysis to serve.

THE FAST BREEDER REACTOR DECISION: AN ANALYSIS OF LIMITS AND THE LIMITS OF ANALYSIS[1]

By Mark Sharefkin[2]

INTRODUCTION

The liquid metal fast breeder reactor (LMFBR) program has been the centerpiece of our long-term energy supply strategy for more than a decade. During that period the widening and deepening of information on this technology has prompted changes in LMFBR program focus, strategy, and organization, but the underlying rationale for the program has not changed. Program advocates have argued that without the breeder, uranium scarcity will drive the real costs of producing electricity higher over the next half century. They argue that with the breeder, we can significantly expand the effective uranium resource base and thus postpone for several centuries uranium-related electricity cost increases.

COST-BENEFIT ANALYSIS OF RESOURCE LIMITS UNDER UNCERTAINTY

The main vehicle for formalizing and quantifying this argument has been cost-benefit analysis. The cost-benefit analyst identifies the uncertainties affecting evaluation of the LMFBR program and then specifies a consistent framework for LMFBR program evaluation. Given any set of assumptions about those uncertain elements, a cost-benefit analysis gives a dollar figure—the discounted present value of the net benefits to the Nation from successful development of a commercial LMFBR.

The methodology of cost-benefit analysis grew up in the evaluation of government water resource projects. Critics argue that, even in water project evaluation, it is as much a framework for political compromise as an objective analytical method,[3] but it seems clear cost-benefit methods have at least allowed spectacularly inefficient projects to be identified and, on occasion, blocked.

Are the extensions of cost-benefit analysis required for the analysis of the LMFBR program appropriate and convincing; and are the analyses themselves likely to be as persuasive? A balanced answer to the first of these questions requires a hard look at the way in which LMFBR cost-benefit analyses model uncertainty. For, unlike the water resource problems where the technologies—of dams and of hydroelectric generation—have been either stable or changing fairly pre-

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[1] My RFF colleagues Joy Dunkerley and Clifford Russell generously read, and improved, a draft of this paper; I lay claim to whatever faults remain.

[2] Research associate, Resources for the Future, Inc. The views expressed here are those of the author, and do not necessarily reflect the views of the trustees or staff of RFF.

[3] See J. Ferejohn, "The Half Empty Pork Barrel" (Palo Alto: Stanford University Press, 1975).

dictably, nuclear technology in general, and LMFBR technology in particular is extremely dynamic. And a careful answer to the second of these questions requires a close look at the correspondence between the issues that are resolvable by cost-benefit analysis and the issues central to the nuclear controversy.

Uncertainty, Heroic Assumptions and Analysis

What are the uncertain elements which must be accommodated in an analysis of the LMFBR program? Since the prospect of future uranium price increases is basic to the argument, we must make explicit assumptions about the extent of the uranium resource base and the way in which that resource base will change over time as uranium prices change. Since the rate of depletion of the uranium resource base depends upon the behavior over time of the demand for electricity from which the demand for uranium is derived, we must also have explicit assumptions about the behavior of electricity demand over time. Since the computation of a time stream of LMFBR program net benefits requires that we know how electricity is being generated over that time period, we must effectively forecast technological change in electric power generation over it.

In sum, the list of required assumptions is long and heroic. Given any such set of assumptions, we can compute a corresponding net benefit figure; and given any set of subjective probabilities of LMFBR commercialization dates, etc., we can compute an expected net benefit figure; but this is not the only way, and perhaps not the most informative way, of looking at the LMFBR problem as a decision problem under uncertainty. Because of the very long time period involved, the absolute net benefit figures are so sensitive to the chosen value of the social discount rate that an all-or-nothing LMFBR program decision based upon a net benefit estimate seems almost reckless.

But there is another way to use cost-benefit analysis in guiding LMFBR decisions. Instead of casting the LMFBR problem as one of "to have or not to have an LMFBR," net benefit estimates can be used to evaluate alternative LMFBR development strategies, with the overall social evaluation of the program left to other, broader devices, including legislative decision. We believe that the character of the uncertainties listed above—and discussed below in the section, "Uncertainty: Source and Implications"—suggests such an approach. Further, posing the LMFBR question this way brings to the fore the issue of the timing of LMFBR commercialization.

The Limits of Analysis

LMFBR program analyses have been built upon the analysis of uranium resource limits. Cost-benefit analysis has its limits as well. These are limits on the kinds of questions it can answer and the kinds of questions it must neglect and leave to other decision mechanisms and procedures. First among these is the question of the distribution of costs and benefits. In principle the distribution of costs and benefits, both interpersonally and intertemporally, can be computed, but good cost-benefit analysis makes no pretense to competence in choosing among alternative distributions of costs and benefits.

Among the most serious problems of nuclear power is the possibility that substantial costs, in the form of long-lived radioactive wastes, wil be transferred inequitably and incompensably onto future generations. None of the major LMFBR program studies examined below, in the section entitled "Cost Benefit Analysis of the LMFBR Program," attempts to quantify these costs. Had they been quantified, many people still would balk at discounting them back to present values. The procedure seems unfair, and that impression can be given a rigorous formulation. Though we will not explore the question, the point is clear: "We have reached the limits of analysis, or at least of this kind of analysis, and a different sort of analysis is required for thinking about these problems.

This second level of analysis is explored in a concluding section, "The Limits of Analysis." Short of analysis at this second level, we believe that LMFBR program analyses are likely to remain unpersuasive.

UNCERTAINTY: SOURCES AND IMPLICATIONS

We have identified the sources of uncertainty in the economic analysis of any technology, such as the LMFBR, intended as an offset to cost increases for exhaustible resources. But identifying uncertainties is only a first step toward properly accommodating them in an economic analysis, for there are various kinds of uncertainty requiring distinct modeling approaches. Our purpose here is a clear understanding of the character of the major uncertainties in LMFBR program analysis, so that later we can see how well these distinctions are captured in the LMFBR program studies and how sensitive the conclusions of the studies may be to the choice of modeling approach.

The Uranium Resource Base

The fact of resource exhaustibility seems self-evident. Since the earth is finite, resources such as uranium and coal are obviously finite. It is tempting and customary to identify that unknown, ultimately finite stock of resources using the many presently available measures of the size of exhaustible resources, but this temptation should be resisted. Proven reserves—particularly of minerals like uranium which are expensive to prove—are those amounts that enterprises have found it profitable and prudent to "prove," and are more analogous to a firm's inventory of some raw material input than to the finite stock of nonrenewable supplies which textbook economics forces shipwrecked sailors to allocate over time. Because inventories are costly to obtain and hold, no firm will hold an unlimited inventory of any input. The amount actually held will be determined by balancing off the benefits, such as assurance of supply and continuity of the production process; and the balancing of costs, such as the interest or carrying charges on the investment represented by the inventory and the costs of storage of that inventory. Similarly, no firm will hold infinite reserves of the exhaustible resource input. Reserves that are actually proven through exploration and to some extent developed to the point of relatively ready access will be determined by their value to the industry in reduced uncertainty and supply continuity, weighed against the costs of exploration and development required to prove reserves.

Thus it may be seriously misleading to jump from declines in the reserve-production ratio to conclusions about impending shortage. The notion that the resource may "run out" in a number of years approximately equal to the reserve-production ratio is almost certainly misleading. In 1938, the reserve-production ratio for oil was roughly 12. In 1974, though production increased at roughly 7.5 percent per annum in the interim, that ratio had increased to roughly 118. One would have been entirely mistaken to conclude, in 1938, that the world would be out of oil in 12 years unless "something were done." One would be equally mistaken to argue similarly at any other time. In general, where a resource is expensive to locate and develop, as in the case of oil, we expect the optimal reserves held by the industry to be lower than in the case of an industry, such as coal, whose reserves are relatively inexpensive to locate and develop.

Turning to the case of uranium, it is vital to note the newness of uranium as an economic resource and the dominant position of the Government on the demand side of the market for most of that short history. Relative to the enormous sums expended in the search for exhaustible resources, such as oil, which have been of major importance in the domestic economy for over 50 years, uranium exploration and development is in its infancy. The present 18-month-old program to obtain a more definitive assessment of our uranium reserves, the Preliminary National Uranium Resource Evaluation Program (PNURE), is budgeted for millions of dollars over its 5-year life. The way in which reserve estimates have shifted in the recent past and the dramatic way in which they have shifted in the first 18 months of the PNURE program are indicators of the uncertainties surrounding the assessment of this resource base.

Table 1 below appears in the AEC's "Proposed Final Environmental Statement for the LMFBR Program"[1] (hereafter this document is referred to as AEC (1974)) and represents the AEC's best estimates as of January 1974, though they are based upon earlier data and analyses. Table 2 below appears in ERDA's first published document, "Report of the Liquid Metal Fast Breeder Reactor Program Review Group,"[2] and represents best estimates as of September 1974. Obviously table 2 is more extensively differentiated and more informative than table 1, but the two are essentially comparable.

Above we have spoken of reserves as an inventory, but the analogy with an inventory of goods on the shelf is overly simplistic and inadequate for real reserve classification. Since exhaustible resource reserves are costly to "prove," i.e., to establish with reasonable certainty, mining firms generally will hold a "portfolio" of reserves proven in varying degrees of certainty. In recognition of this important distinction, AEC data differentiates[3] "reserves" (referred to as "identified" in table 2) from "potential reserves." Reserves include only uranium in known deposits, for which the quantity, grade and physical characteristics have been established with reasonable certainty by detailed sampling, and which these tests indicate can be recovered at costs less than or equal to an assumed price level. The AEC "reserve" figure is therefore what elsewhere is called a *proven* reserve figure. The AEC reserve estimates in this category are relatively uncontroversial, and one writer on uranium resource problems suggests that the AEC reserve category be understood as "reasonably assured resources."[4] Note that the reserve estimates of tables 1 and 2 are identical. Cumulative reserves below $30 per short ton "forward costs" are, in both cases, 700,000 short tons.[5]

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[1] U.S. Atomic Energy Commission, "Proposed Final Environmental Statement, Liquid Metal Fast Breeder Reactor Program," WASH–1535, December 1974.

[2] Energy Research and Development Administration, "Report of the Liquid Metal Fast Breeder Reactor Program Review Group," January 1975.

[3] For definitions of the AEC categories see AEC, "Statistical Data of the Uranium Mining Industry" (Grand Junction, Colo.: Grant Junction Office), June 12, 1974, p. 13.

[4] Electric Power Research Institute, "Uranium Resources To Meet Long Term Uranium Requirements" (Palo Alto; Calif.: Electric Power Research Institute, November 1974), p. 44.

[5] See p. 7 for discussion of the concept of "forward cost."

The AEC's potential reserve (or potential resource) category includes by definition only "conventional" uranium deposits and uranium surmised to occur in (1) unexplored extensions of known deposits, (2) postulated deposits within known uranium areas, or (3) postulated deposits in other areas known to be geologically favorable for uranium. In sum, these potential reserves (see tables 1 and 2) are resources whose existence is inferred from existing information and experience, but not yet confirmed by direct sampling.

The significant comparison between tables 1 and 2 is between the sum of reserves plus potential reserves at $30 per pound forward cost in table 1—2,400,000 short tons of U_3O_8—and the corresponding total of 3,450,000 short tons in table 2. As the footnote on the new total indicates, the increase of 1,150,000 short tons is entirely due to the results of the first 18 months work of the PNURE program.

TABLE 1.—AEC ESTIMATES OF U.S. URANIUM RESOURCES

	Cumulative thousands of short tons of U_3O_8		
	Reserves	Potential	Total
U_3O_8 cost up to (per pound):			
$8	280	450	730
$10	340	700	1,040
$15	520	1,000	1,520
$30	700	1,700	2,400

Source: U.S. AEC, proposed final environmental statement, liquid metal fast breeder program (December 1974), p. 11.2-67.

TABLE 2.—*ERDA estimates of U.S. uranium resources*

[Thousands of Short Tons U_3O_8(1) as of September 1974]

INDEX COSTS \$/lb. U_3O_8(4)		IDENTIFIED(2,6)			POTENTIAL (UNDISCOVERED)(3)			
		DEMONSTRATED		INFERRED	PROBABLE	POSSIBLE	SPECULATIVE	TOTALS
		MEASURED	INDICATED		KNOWN DISTRICTS PRODUCTIVE FORMATIONS	PRODUCTIVE PROVINCES PRODUCTIVE FORMATIONS	NEW PROVINCES NEW FORMATIONS	BY INDEX COST, IDENTIFIED & POTENTIAL
\$8	ECONOMIC (1974)		Reserves 280		300	210	30	820
\$8-10	NOT YET ECONOMIC		60		160	190	80	490
\$10-15			Reasonably 180		230	250	100	760
\$15-30			Assured 180		280	710	210	1380
		TOTALS	700		970	1360	420	3450(5)

DECREASING DEGREE OF ASSURANCE →

\$30 to \$100	UNKNOWN	HOST FORMATIONS, OTHER THAN SANDSTONE (SEE TABLE 4), 100-500 ppm U_3O_8	??
\$100+	UNLIKELY	CHATTANOOGA SHALES, 60-80 PPM U_3O_8 Approx.	5000
\$150+		CHATTANOOGA SHALE, 25-60 PPM U_3O_8 Approx.	8000

(1) 1.3 Short Tons U_3O_8=1.18 Metric Tonnes U_3O_8=1000 kilograms uranium.

(2) Ores to grades down to approximately 0.12% U_3O_8: approximately 95% from sandstone host rocks.

(3) Ores to grades down to approximately 0.10% U_3O_8, primarily from sandstone host, but including small contributions from other host formations such as veins, conglomerates and tuffaceous material at grades down to approximately 0.025% U_3O_8, where there are sufficient data to judge the possible quantity of uranium.

(4) The index cost is not the average cost of production. And more importantly, *it is not the price* at which uranium will be sold. See text for a discussion of index costs, projected actual costs and prices.

(5) This is a new total, approximately 1,200,000 short tons U_3O_8 higher than 1-1-74 estimates, a result of the Preliminary National Uranium Resource Evaluation Program (PNURE), started approximately 18 mos. ago.

(6) There are other small domestic sources of uranium:

200,000 metric tonnes of *depleted* uranium tails, available to stock LMFBRs (sufficient for at least 2000—1000 Mwe LMFBRs).

20,000 short tons of U_3O_8 recoverable from copper ore leach solutions between now and year 2000.

70,000 short tons of U_3O_8 recoverable from phosphoric acid made from Florida phosphate rock between now and year 2000.

2,000-3,000 short tons U_3O_8 per year by year 2000 from lignite gasification assuming 75% recovery of U_3O_8 and 20% of natural gas demand supplied from lignite. (No production now planned.)

Source: ERDA, Report of the Liquid Metal Fast Breeder Reactor Group (January 1975), p. 16.

There are other circumstances which reinforce what seem to be the optimistic implications of this recent substantial upward revision of potential uranium reserve estimates. The behavior over time of uranium reserves, production and prices seems, in a very rough way, to be similar to the pattern typical of other mineral resources, with similar implications about fears of exhaustion and of impending rapid price increases.[6] The definition of potential reserves is itself fairly conservative, with estimates of higher cost reserves and potential reserves not encompassing *all* such resources but only those in *presently known* producing areas and in areas geologically similar to presently known

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[6] The AEC source cited in footnote 2 above has time series on reserves, production, and prices.

producing areas.[7] Until very recently, uranium markets have been soft, with declining prices, so that incentives for exploration and development have been weak.

Finally, the uranium resource data base, excellent when compared to what faces the analyst of other mineral resources, is structured and reported in a way that may impart a pessimistic bias to the uranium resource picture. Thus the AEC's tabulation of reserves and of potential reserves by cost levels indicates the amounts of each of these categories presumed to be available at less than certain levels of so-called "forward cost," which is the cost of future extraction. This extraction cost concept, which excludes past or "sunk" cost, is the economically relevant cost concept. But since *maximum* forward cost figures are used to demarcate the reserve tabulation, the actual cost of extraction for much of the reserve under each cost ceiling is well below the maximum forward cost figure. And since the forward cost intervals are stated in current dollars, inflation erodes the better grade resources in the lower cost intervals in such a way that changes over time in the resource distribution among cost intervals are not good indicators of changes in the physical resource stock.

Thus there are several ways in which the uranium reserve estimates may be biased downward. Moreover, the analyses that have been done do not get full mileage out of the present data base. They are structured in a way which may impart a further pessimistic bias to uranium supply projection and which certainly excludes consideration of major determinants of future uranium resources. There are ways to bring some of the economic incentives that bear on resource exploration and discovery into an economic model for forecasting future reserves, but I am not aware of any published modeling effort of this kind for the American uranium resource base. Such modeling is a difficult task. Poor models can and have produced silly results. But present reasoning from "models" which in effect neglect the economic determinants of the extractive resource base is almost certainly worse. Thus, an OECD model of the uranium resource exploration and development process[8] reportedly projects uranium resources larger by a factor of 15 than present estimates.

The OECD results suggest that partial models of the future uranium resource base may understate that base by a very large amount. Moreover those partial models allow only the crudest exploration of the sensitivity of LMFBR cost-benefit results to resource base assumptions. Below we will comment on the sensitivity problem, and in our overview of LMFBR cost-benefit analyses we will set out some criteria for the modeling of the uranium resource sector in analyses of the LMFBR program.

FUTURE ELECTRICITY DEMAND

The demand for uranium and plutonium for fueling light water reactors (LWR's) and LMFBR's alike is of course derived from the

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[7] The traditional AEC "potential" resources category is restricted to "conventional" uranium deposits—deposits in sandstone or veins, much like present reserve-category deposits. See the discussion in Electric Power Research Institute, op. cit., pp. 46–47.

[8] Here I am reporting the very brief description of results obtained with this model given in I. C. Bupp and J. Derian, "The Breeder Reactor in the U.S.: A New Economic Analysis," *Technology Review* (July–August, 1974). Reporting the results of a model of this kind at second hand is always tricky. Time did not permit me to obtain a first-hand description of this model.

demand for electricity produced by those reactors, and any projection of uranium "requirements" depends upon an electricity demand forecast.

Demand forecasting builds upon economic models and economic data and is relatively free of the serious uncertainties about the natural world that plague resource reserve estimates. But demand forecasts have their own particular uncertainties and instabilities, and these can be as serious for LMFBR program analysis as the uncertainties in uranium resource estimates.

Although there is a range of demand forecasting methods, that range is illuminated by contrasting two approaches. The first amounts to simple extrapolation of past consumption trends; we will call the second econometric demand analysis. Though different in concept, they can give similar results if past trends in economic growth and electricity rates are expected to continue. In other cases the results of the two kinds of analyses can be wildly divergent. Econometric demand analysis yields forecasts based on the separate influences of various determinants of demand and therefore is more useful in a period during which those determinants are changing at rates markedly different from the past.

The method of extrapolating past growth means just that. Trends in electricity consumption over some past period are summarized in a single number—a growth rate; then ignorance of future conditions is recognized by adopting a span of growth rates around this historical average. Because the growth rate of electricity demand over the 25 postwar years, 1945–70, was exceptionally high—roughly 7 percent in the 1960's and much higher than that of the economy as a whole—the band of growth rates of electricity consumption frequently used for projections covers a range around 5 percent or 6 percent.

There are numerous variations on this method. In one, the growth of GNP is forecast, and the ratio of electricity consumption to GNP is assumed constant, thereby providing a forecast of the growth rate of electricity demand. The kinds of electricity consumption estimates produced by this extrapolation method are illustrated by table 3, taken from a uranium resource study which extrapolates electricity consumption based upon "an excellent correlation between real gross national product and total electricity generation." For comparison with the results of forecasts based on econometric demand analysis, the reader should focus on the column headed "Reference based upon GNP," in particular the forecasts of 2.9 trillion kWh consumption in 1980 and 6.1 trillion kWh consumption in 2000.

TABLE 3.—ELECTRICITY CONSUMPTION FORECASTS BASED UPON EXTRAPOLATIONS OF HISTORICAL CONSUMPTION

	Total (trillion kilowatt hours)		
Year	Assumed low[1]	Reference based on GNP	Assumed high[1]
1980	2.9	2.9	2.9
2000	4.5	6.1	9.2
2020	6.7	10.6	18.9
2040	10.0	15.9	38.8

[1] These figures lie far outside 3 standard deviations from the reference case.

Source: Electric Power Research Institute, "Uranium Resources To Meet Long Term Uranium Requirements" (November 1974) p. 12.

In econometric demand and supply analysis, there is an effort to identify the causal factors involved in shifts over time in the demand for electricity and in shifts over time of the costs of supplying electricity. On the demand side, electricity prices and the incomes of consumers are typically important variables, and, on the supply side, technological change and changes in environmental standards and the costs associated with those standards are likely to be significant. In a recent report prepared for the Federal Power Commission,[9] such an analysis gives an estimate of 2.2 trillion kWh for 1980 electricity generation, to be compared with the estimate shown in table 3 of 2.9 trillion kWh for 1980, based on a GNP-related extrapolation. Utility industry estimates of 1980 generation have been as high as 3.2 trillion kWh.

The FPC study makes no estimates beyond 1980, but the growth rates implicit in its estimates for 1980—closer to 2 percent per annum than to the historical 7-percent rate—will obviously give consumption figures for the years 1980–2000 much lower than estimates based on extrapolation of history, such as those of table 3, since small changes in compound growth rates result in successively larger divergences in the estimate over time. With a 2-percent annual growth in electricity consumption, for example, a 1980 consumption estimate of 2.2 trillion kWh grows to roughly 3.3 trillion kWh by the year 2000. To gage the difference between the results of this method and those of historical extrapolation, compare the "reference" forecast in table 3 of 6.1 trillion kWh for the year 2000 and the "low" estimate of 4.5 trillion kWh for that year with this 3.3 trillion kWh figure.

None of this should be surprising to anyone familiar with the mechanics of compound growth. The vast range of demand forecasts which reasonable demand estimation methods can give is clear. The problem for an assessment of the LMFBR is to choose between the assumptions which underlie the extrapolation and the demand analysis methods and to judge which more appropriately describes the economic environment for the future. The two forecasting methods need not give dissimilar results. When relative production costs and prices are changing as in the past, and when the economy is expanding more or less proportionately across sectors, the two methods should give results in close agreement. That they do not concur implies that some of these conditions do not hold and is indicative of the superiority, for present purposes, of econometric demand analysis.

The 1960's pattern of rapid expansion in electricity consumption—expansion at rates higher than the real growth of GNP—follows a pattern observed in several other industries during that period, such as data processing, long-distance communications and commercial air transportation.[10] All of these industries grew much more rapidly than the rest of the economy in the 1960's, and all were the locus of rapid technological change during that decade—change which significantly lowered the costs of producing and delivering existing services and which introduced a wide range of substantially new services. With the apparent exhaustion of that burst of technological change, the related declines in cost and the supernormal industry growth rates also slowed.

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[9] Duane Chapman et al., "Power Generation: Conservation, Health, and Fuel Supply," draft report to the Task Force on Conservation and Fuel Supply, Technical Advisory Committee on Conservation of Energy, 1973, National Power Survey, U.S. Federal Power Commission.

[10] I am indebted to Lawrence Moss for this analogy.

Similarly, electric power costs and prices declined both relatively and absolutely during the 1960's, as successively larger generating units exploited the substantial economies of scale then remaining in generation. For a variety of reasons the era of declining electricity prices seems to be over. These include (1) the apparent end of scale economies of generation, (2) the period of intense environmental concern and the internationalization of some of the external costs of power production, and (3) the recent rapid increases in fossil fuel costs and in the capital costs of thermal and nuclear LWR plants. Extrapolation forecasts of power consumption which abstract from these recent changes in the price trends are incomplete and subject to the same kinds of errors as the extrapolation forecasts of commercial aid travel with which the airlines planned their way into the 1970's, only to be left with substantial excess capacity.

In sum, the extrapolation of past electricity demand growth at a fixed growth rate is an inferior method of projecting future electricity consumption. It probably leads to an upward bias in future consumption estimates for the next quarter century, and in the estimates of net benefits from the LMFBR program. Electricity demand projections rooted in a more complete demand analysis not only tend to yield scenarios with lower consumption growth rates but, if properly structured, also allow additional flexibility and realism in LMFBR cost-benefit analyses. We return to these problems in our survey of the existing LMFBR studies, and there we will draw some guidelines for an adequate projection of electricity demand.

THE LWR–LMFBR CAPITAL COST DIFFERENTIAL

The rational for the LMFBR program, as noted above, rests on the exhaustibility of uranium and other fossil fuels and upon the rising market prices that uranium depletion will impose over time. Presumably the utilities will begin buying LMFBR's when their electricity is economically competitive with LWR electricity, i.e., when uranium prices have risen enough to offset the expected higher capital costs of the LMFBR.

Cost analysts are in general agreement that LMFBR installations will be more costly than LWR's. For any time path of future nuclear fuel prices there is obviously some LMFBR capital cost disadvantage at which cost-minimizing utilities will balk at purchasing LMFBR's. And the commercial future of the LMFBR therefore rides on the size that LMFBR–LWR capital cost differential. Hence, the capital cost differential assumption is a key determinant of the results obtained by any LMFBR program cost-benefit analysis.

Unfortunately there is no consensus about the probable size of that differential. And the uncertainties surrounding this number are harder to strip away than the uncertainties surrounding many other economic variables, largely because a major source of uncertainty about nuclear capital costs is the lack of consensus on the social acceptability of nuclear power of any kind, and the reflection of that lack of consensus in the regulations on the expansion of nuclear power.

Our experience with LWR capital cost forecasting is directly relevant and instructive here. The rapid and unanticipated increases in the capital costs of LWR plants over the past decade are familiar to all energy analysts. While in 1965 estimates of $130 per kW were typical for large LWR's, capital costs for the 1,000 MWE plants now on order and expected to be on line in the early 1980's are being estimated at $700 per kW. Some plants scheduled to be on line in the mid and later 1980's are already being estimated at $900 per kW. The reasons for these cost increases are not at all clear, and there is substantial disagreement implicit in the explanations offered by the principal concerned parties.

Some contributing factors are not in dispute. The kind of LWR built has changed over time in step with technological improvements and with changes in licensing and other procedural requirements, so that later and earlier installations are of different kinds, and their capital costs not directly comparable. But most other elements of the LWR capital cost picture are shrouded in controversy.

A recent analysis of LWR cost trends [11] has skillfully summarized the depth and breadth of that controversy by highlighting the extent to which the AEC and the utilities have developed distinctive and opposing views of the capital cost problem. The utility view emphasizes changes which have been imposed upon the industry principally in response to environmental and safety concerns—the burden of preparing environmental impact statements and answering AEC information requests, the provision of additional radiation shielding to meet "as low as practicable" radiation release standards, and of safety equipment required by the AEC's upward revision of safety standards. The AEC's view has, on the other hand, emphasized production-related difficulties—declining construction labor productivity, late delivery of major equipment, and legal challenges to plant siting and to regulatory practice, the latter often requiring changes in regulatory procedure.

The authors of this analysis, basing their conclusions on an unpublished analysis of LWR cost data, offer their own interpretation of LWR cost increases. First, the source of the problem can be somewhat more precisely located. The constant-dollar costs of the nuclear steam supply system itself—the "heart" of a nuclear power plant, built by one of the major reactor vendors—have *not* been increasing; they have, if anything, been decreasing. The component of the nuclear power plant cost under the control of the architect engineer, who oversees the design and construction of power plants built around the vendor-supplied nuclear steam system, is almost entirely responsible for the big LWR capital cost increases. Those cost increases are, in turn, attributable primarily to plant changes and delays arising from the licensing procedure.

But it is crucial to recognize that the common interpretation of those delays as either the unfortunate result of willful obstructionism or the fortunate result of dragon-slaying are misdirected. What really matters is that we have no broad consensus on the social costs and benefits of nuclear power. Nor have we any decisive consensus on the procedures appropriate to establishing those social costs and benefits: For weighting claims of distributional burdens imposed upon some by nuclear power, for arriving at some overall policy on fission power, or, for that matter, on the many smaller decisions which have arisen and will arise along the way.

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[11] I. C. Bupp and J. Derian, "The Economics of Nuclear Power," *Technology Review* (February 1975).

In this no-consensus situation the evaluation of the social costs and benefits of nuclear power is being carried out, de facto, in a variety of forums—regulatory, judicial, and administrative—and under a variety of arrangements not always suitable for this purpose. But these are the only forums and arrangements we have. If one believes that it is improbable that a clearer and more definitive consensus on fission power will emerge, then there is little reason to believe that LWR costs are about to fall, and much reason to fear that present LWR cost trends may persist.

It is against this background that projections of capital costs differentials between LWR's and LMFBR's should be interpreted. The LMFBR's economic competitiveness with the LWR is based upon its lower fuel costs, and those fuel costs must be sufficiently lower to offset what almost all analysts believe will be the higher capital cost of LMFBR's. It is estimated that, if the LMFBR–LWR capital cost differential is more than $125 per kW, LMFBR electricity will be more expensive than LWR power over the entire "reasonable" range of future nuclear fuel prices. It follows that if the uncertainties in the estimates of the LMFBR–LWR capital cost differential are larger than $125 per kW, the future competitiveness of the LMFBR is uncertain, and so are both the magnitude and the sign of the benefit-cost difference imputed to the LMFBR.

Our experience with commercial LWR's is still very narrow and we are still unsure of their ultimate capital costs. But it can easily be appreciated that the situation is far worse for the LMFBR's, where we have no commercial experience to draw upon. The Clinch River Breeder Reactor, the first in a proposed series of demonstration plants intended to bring the LMFBR to full commercial status, now bears a capital cost estimate of $3,000 per kW. Clinch River is a one of a kind plant and emphatically not a commercial design, so this figure must be somewhat discounted, but it is not reassuring.

So much for the magnitude, character, and importance of the uncertainties surrounding the LMFBR–LWR capital cost differential. How well or badly are these uncertainties mirrored in analyses of the LMFBR program? Cost-benefit analyses typically assume that a high initial LMFBR–LWR capital cost differential is gradually reduced by learning: That is, that experience with the technology lowers its costs so that ultimate LMFBR–LWR capital cost differential falls into a range—usually $100 per kW or less—in which the LMFBR is economically competitive with the LWR. There is no question that something like this does happen in some industries and for some production processes. In a classic example, the cost of assembling a standardized airframe was found to decrease with the number of airframes produced, the explanation presumably being the accumulation of experience by the assembly crews. Unfortunately, the history of LWR costs raises serious doubts about the relevance of this kind of learning effect to the LMFBR problem. Ten years after completion of the first nonturnkey reactors, we have not yet gotten this technology on a classical learning curve. The LWR case, in fact, has been a social learning process. Over time we have tried to evaluate the social costs and benefits of the most important new technology of the postwar period. I find little reason to believe that the way for the LMFBR has been cleared by this experience, and much reason to believe that this newer kind of learning effect, not the "airframe effect," will dominate the LMFBR commercialization process. I do not believe that present LMFBR program analyses capture this feature of the problem; below I argue that a program analysis can be structured to reflect some of these crucial difficulties.

COST-BENEFIT ANALYSIS OF THE LMFBR PROGRAM

Our purpose in this section is an overview and assessment of the major cost-benefit analyses of the LMFBR program and, in particular, an understanding of how well or poorly they come to terms with the problem of uncertainty. Beginning with a few comments on the general problems of cost-benefit analysis, we then turn to a detailed comparative evaluation of the major program studies, and finally to ways in which the program analyses can be broadened and improved.

LIMITS OF COST-BENEFIT ANALYSIS

The principle underlying cost-benefit analysis is simple and unexceptional. One should not undertake a project unless the aggregate benefits flowing from the project can be expected to exceed project costs. Where the budget of the decisionmaker is constrained, so that not all beneficial projects can be undertaken, the bundle of projects yielding the highest aggregate net benefit within the budget constraint should be chosen.

This principle is relatively easy to apply when the set of alternatives open is small and relatively well defined, where there is little ambiguity and uncertainty on the demand side, and where technology is relatively stable. And the cost-benefit analyst's decision rule—proceed with the project if aggregate net benefits are positive—is likely to be acceptable when the distribution of benefits and costs is relatively equitable.

How many of these preconditions for the accuracy and acceptability of cost-benefit analysis are present in the LMFBR case? We shall argue below that the answer is almost none. The range of energy policy alternatives faced by the Government is very broad, and arbitrary constraints of the range of alternatives considered can bias the conclusions of a cost-benefit analysis. "Cost" cannot be correctly measured without reference to the correct range of alternatives. Nuclear power technology is still developing rapidly and, as we have argued above, the cost of that technology is still very much the subject of regulatory determination. Central to the arguments against fission power of any kind is the fear of an inequitable and noncompensable transfer of costs onto future generations. Still, as we shall see below, most of the major LMFBR cost-benefit studies are quite conventionally conceived.

THE MAJOR LMFBR STUDIES

Cost-benefit analysis of the LMFBR program has become a small industry in the past few years, but many of the published analyses are updates or revisions, so that it is sufficient to consider five major recent analyses. Only the latest of the three AEC analyses published during the 5-year period, 1969–74, need be considered here, since the three differ mainly through updating to incorporate revised and improved information on costs and technology and in efforts to be responsive to critics of the earlier versions,[1] but not in method or policy conclusions. Prominent among the critics of the AEC analysis has been Thomas Cochran of the Natural Resources Defense Council, whose book on the LMFBR program[2] is a lengthy critique of the AEC's 1972 update of the 1970 cost-benefit analysis. Professor Alan Manne, now at Harvard University, has published several cost-benefit analyses of the LMFBR, some of them in collaboration with other authors.[3] And Professor Thomas Stauffer of Harvard, H. L. Wycoff of Commonwealth Edison Co., and R. S. Palmer of the General Electric Co. have published still another.[4]

All of these studies are cast within the usual cost-benefit framework. Nevertheless they generate widely divergent "base case" net benefit figures for the LMFBR. In gaging the relevance of these conclusions for policy, it is important to understand the sources of this divergence. First, all of the studies acknowledge the existence of uncertainties in uranium availability, electricity demand growth and future LMFBR–LWR capital cost differentials, but they differ on the likely range of these uncertainties, and on the likelihood of the individual values within each range. Each calculation puts forward a "base case"—or most probable case—for these uncertain conditions, and the different studies put forward different "base cases."

But even if the authors of all of these studies were in agreement on a single base case, their net benefit results would differ for several reasons. First, in order to compute a net benefit figure for the LMFBR program, each study constructs a model of the electric utility industry, tracing the expansion of generating capacity to meet base case electricity demand over some planning horizon. (Only one of the studies, Manne (1973), considers scenarios in which demand is price dependent; in all the others, the effects of price changes on consumption are subsumed into the growth rate of consumption chosen. Though there are difficulties of interpretation involved in direct comparisons of the Manne (1973) study with the others, the study results are sufficiently important in their implications, for overall energy policy and for the interpretation of the other studies, to warrant inclusion here.) There is no unique way to model utility behavior, and in choosing among alternative models there is a tradeoff between fidelity to detail and simplicity affording a clearer understanding of the workings of the model. The divergence between net benefit results arising from dif-

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[1] These successive AEC studies are as follows: AEC "Liquid Metal Fast Breeder Reactor Program Plan," vols. 1–10, WASH 1101–1110 (1968); AEC, updated (1970) "Cost-Benefit Analysis of the U.S. Breeder Reactor Program," WASH 1184 (January 1972); and "AEC, Proposed Final Environmental Statement, Liquid Metal Fast Breeder Reactor Program," WASH 1535 (December 1974).

[2] Thomas B. Cochran, "The Liquid Metal Fast Breeder Reactor: An Environmental and Economic Critique" (Baltimore: The Johns Hopkins University Press for Resources for the Future, Inc., 1974).

[3] A. Manne and O. Yu, "Breeder Benefits and Uranium Ore Availability," preliminary draft (Oct. 1, 1974); and A. Manne, "Waiting for the Breeder," in M. Macrakis (ed.) *Energy* (Cambridge, Mass.: MIT Press, 1973).

[4] The results of this study are summarized in T. Stauffer, H. L. Wycoff, and R. S. Palmer, "The Liquid Metal Fast Breeder Reactor: Assessment of Economic Incentives," preliminary (1975). The model of the electric utility sector employed in calculating these results is described in general terms in this reference, but a detailed description of this model is not yet available, and time did not permit me to discuss details of the model with the authors. The theoretical justification for the relatively low-base-case discount rate employed in this paper, 6 percent, is the subject of another paper, presently in circulation only in preliminary draft form: T. Stauffer, "A Generalized Cost-Benefit Calculus for Selecting Alternate Energy Technologies," preliminary (Mar. 2, 1975).

ferences among studies in the modeling of the electric utility sector is relatively minor, I believe, and the direction of that minor difference—the sign of the differential net benefits obtained—is predictable and consistent with the results of the different studies.[5]

Second, though most economists agree that intertemporal efficiency comparisons require the discounting of future costs and benefits, there is very little agreement on a particular numerical value for the discount rate. One of the studies, Stauffer et al. (1974), argues for a discount rate substantially smaller than the rates in the other studies and lower than the OMB-recommended[6] uniform rate of discount of 10 percent. The argument for that lower rate, an argument circulated in a preliminary report by Stauffer,[7] is discussed below.

Third, the various studies are based upon very different assumptions about the way in which the R. & D. costs of the LMFBR program will be incurred over time. For most of the studies, and some of the cases in all of the studies, the net benefit figure is sensitive to this assumption. The structure of the individual studies therefore restricts, and is intended to restrict, both the range of LMFBR program strategy options and the broader range of energy policy options which can be compared. In particular, a major LMFBR program issue, the "timing" of LMFBR commercialization, cannot be considered at all in most of these models, and in the discussion below we will see why.

Fourth, because of the way in which electricity consumption growth is specified, many of the models cannot provide a measure of the relative value of supply-oriented energy programs, such as the LMFBR program, versus demand-oriented strategies, such as the peakload pricing of electricity. One of the models compared here, Manne (1973), is very different in emphasis from the others and has been included here because it can do this, or at least points the way to the comparative evaluation of supply-side and demand-side strategies within a consistent framework.

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[5] All of the cost-benefit studies surveyed here, except for Stauffer et al. (1974), are based upon once-and-for-all optimization of electric generating capacity expansion over some time horizon extending into the next century. Since Stauffer et al. allow utilities to reformulate their plans—as they in fact can and do—during this period, it is conceivable that these additional degrees of freedom contribute to a higher net benefit estimate. But Stauffer et al. iterate until plans are always consistent with realized time paths, and therefore these degrees of freedom may not exist. It is difficult to say without detailed descriptions of the model. In any event, it seems reasonably certain that the major factor in the large net benefit figure obtained by Stauffer et al. is the low-base-case discount rate these authors argue for, and use.

[6] Office of Management and Budget, Circular No. A–94 (revised), Mar. 27, 1972, a memorandum on "Discount rates to be used in evaluating time-distributed costs and benefits," suggests that a rate of 10 percent be used, except that, "where relevant, any other rate prescribed by or pursuant to law, Executive Order, or other relevant circulars" be employed The caveat is very likely intended in deference to legally mandated discount rates for the evaluation of water resource projects.

[7] T. Stauffer, op. cit., in footnote 4 above.

THE RANGE AND INTERPRETATION OF NET BENEFIT ESTIMATES

Table 4 compares the five major cost-benefit analyses of the LMFBR program. Column (6) of that table shows the net benefits in the "base case"—the case rated most probable by the authors—for four of the five studies. Those results range from a high figure of $79 billion 1974 dollars, the base-case net benefit figure computed by Stauffer et al. (1974), to a low figure of $16 billion, the base-case result obtained on a comparable basis by the most recent (1975) version of the AEC LMFBR program analysis. The figure entered in the corresponding column for the Manne (1973) study is not strictly comparable to these figures, as noted in footnote h to the table, but is recorded there for reasons to be explained shortly.

With the exception of Manne (1973), all of these studies pose the LMFBR decision problem in the same way. They identify the same range of alternatives, and they implicitly suggest that choice among those alternatives be guided by aggregate net project benefits. And, further, they are similar in that the calculation of costs and benefits is based upon internal costs and benefits only. Though AEC (1974) goes to considerable length to enumerate the environmental impacts of fission power with and without the LMFBR, these impacts are never reduced to dollar terms, and they do not enter into the cost-benefit calculations.

To be more precise about the similarity in specification, the cost-benefit calculations of AEC (1974), Manne and Yu (1974), and Stauffer et al. (1975) are a comparison of two future worlds. In the first, the range of technologies available for generating electricity includes several present technologies but not the LMFBR; in the second, an LMFBR R. & D. program adds the LMFBR to this mix of technological alternatives at some future date. Assuming that electric utilities choose new generating plants by minimizing cost, LMFBR's will be purchased when they become commercially competitive, and the costs of generating electricity to serve any specified future consumption pattern will be lower in every year following the commercial introduction of the LMFBR than they would have been without the LMFBR. Of course each comparison of these two worlds requires a specific set of assumptions regarding the four major uncertainties discussed above, but the essential comparison in the three LMFBR cost-benefit analyses is between these two alternative futures. Although it is not clear that this is done consistently in all these studies,[1] it is the clear intent of all of them.

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[1] For example, the AEC cost-benefit analysis appears, for the cases in which HTGR capacity is constrained, to calculate net benefits by comparing two cases. In one there is an LMFBR and the HTGR is constrained up to the year 2000, while in the other there is no LMFBR and the HTGR is constrained up to the year 2000. The correct comparison is, of course, one between two worlds differing only in that in one there is an LMFBR and in the other there is no LMFBR. This possible inconsistency was noted by EPA in their comments in the AEC Preliminary Final Environmental Statement.

TABLE 4.—COMPARISON OF MAJOR-COST BENEFIT ANALYSES OF THE LMFBR PROGRAM

Study	Base case assumptions: Uranium resources (millions of short tons of U_3O_8) (1)	Base case assumptions: Electricity demand growth rate (2)	Base case assumptions: LMFBR-LWR capital cost differential (dollars per kWe) (3)	Base case assumptions: Discount rate (percent) (4)	LMFBR-R. & D. program cost assumptions (5)	LMFBR program net benefits (billion 1975$) (6)	Optimum LMFBR commercialization date (7)	Modeling of electric power industry (8)	(Explicit or implicit) Criterion for decision under uncertainty (9)
AEC (1974)	Price (1974$lb) — Cumulative supply 8 — 0 13 — 1 21 — 2 30 — 3 60 — 4 60 — 4 80 — 5	5.2 percent [a]	100 when LMFBR first available; decreases linearly to 0 in year 2000.	10	Assumed to increase if commercialization delayed; for specific program costs see table 5.	15.8 [b]	1985—Earlier LMFBR commercialization always implies higher net benefits.	Industry-wide linear programing model, minimizing discounted present value of cost of meeting demand; plus "introduction constraints" on LMFBR capacity expansion.	No explicit criterion; see discussion in text of this paper.
Manne (1973)	Unlimited uranium resources available at a constant cost equivalent mills/kWH (for LWR's) and 1 mill/kWh (for LMFBR's).	6.6 percent, 1981–90; 5.3 percent, 1991–2000; 3 percent thereafter.	≤50 [d]; otherwise LMFBR's not competitive in this model.	10	No discussion of R. & D. costs.	4.8 [e]	No optimum LMF/BR commercialization date in this model; competetiveness date a random variable.	Industrty-wide sequential linear programing model, minimizing discounted present value of cost of meeting demand.	Minimize discounted present value of expected cost of meeting demand, with expected values based upon (subjective) probability estimates of year of LMFBR commercial activity.

Manne and Yu (1974).	2 base case assumptions: pessimistic case (assumption 1).[f] Price (1974$ lb) — Cumulative supply 15 — 1.7 30 — 2.3	5 percent	50	10 [g]	do	25 in pessimistic case; 2 in optimistic case.	Availability and commercialization date identical under cost assumptions of this model.	Industry-wide linear programing; discounted present value of cost of meeting demand; plus "introduction constraints" on rate of change in generation mode mix.	Minimize discounted present value of expected costs of meeting demand with expected values based upon (subjective) probabilities of various states of the world.
Stauffer et al. (1975).	Economic cost [h] — Cumulative supply $10-$15 — 0.75 $15-$65 — 2.43	6 percent	97 based upon assumed LWR capital costs of $385/kW, and an assumed LMFBR capital cost differential of 25 percent.	6	Assumed in the 5 to 10 billion 1975 dollar range.	76	Earlier LMFBR introduction always implies higher net benefits.	Sequential instantaneous cost-minimizing capacity decisions by individual utilities; iterated to assure consistency (at all times) of capacity decisions and prices.	Argues that the maximum loss from the LMFBR program (essentially the program cost) much less than the (social) cost of bearing the risk of future uranium scarcity.

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[a] Imputed from the exponential curve drawn for base case electricity demand growth on p. 11.2–107 of AEC (1974). Though no compound growth rate is stated—electricity demand assumptions are given in terms of the 2020 demand of 27.6×10^{12} kWh—the base case demand seems to be a compound growth curve drawn through the 1975 and 2020 demand points.

[b] This is the case on p. IV-D-1 of AEC (1974) in which the HTGR is constrained until 1998.

[c] "Introduction constraints" mean that the rate of change of generation mode mix is effectively constrained, though the constraint may not be stated in terms of the rate of change variable. Both AEC (1974) and Manne and Yu (1974) use such constraints.

[d] This is a somewhat ad hoc assumption, apparently required by the mechanics of the model—since for higher LMFBR-LWR capital cost differentials this model never "builds" any LMFBR's—and not indicative of any guess of the author's as to the probable actual value of the capital cost differential.

[e] In this model "availability" and "commercial competitiveness" dates are definitionally identical; the distinction between the two, which can be made operational but is not in any of the models under discussion, is considered below. The $4,800,000,000 figure represents cost savings from certain 1990 availability as opposed to uncertain availability, and is therefore not strictly comparable with the other net benefit estimates in this column.

[f] In actual calculations, Manne and Yu (1974) use step-function approximation of a quadratic fitted to these 2 points.

[g] Manne and Yu (1974) actually do calculations over a range of discount rates, and do not favor any one rate as more reasonable than any other; the 10 percent case has been chosen here for comparability with 2 other studies that use this rate.

[h] Stauffer et al. argue that a reasonable approximation to economic cost is obtained by doubling the AEC's forward cost estimates for uranium supplies. They report this doubled estimate as "economic cost," rather than as price, presumably because user cost will push price above economic cost.

Manne (1973) poses the question quite differently, and provides some perspective on the definition of this LMFBR/non-LMFBR dichotomy and on cost-benefit calculations based upon this dichotomy as guides to LMFBR program policy. Below we will see that this seemingly innocent change in formulating the question leads to answers differing considerably in their policy implications from the more conventional analyses. Before turning to this broader LMFBR analysis, we conclude our overview of the more conventional analyses by examining the major source of the discrepancies in the net benefit estimates reported by the three studies: The different discount rates employed.

THE DISCOUNT RATE AND THE RANGE OF NET BENEFIT ESTIMATES

The extreme estimate is the very high base-case net benefit figure obtained by Stauffer et al. This high estimate is almost entirely a consequence of the choice of a relatively low, 6-percent discount rate in this model. It can be seen from column (6) of table 4 that all the other studies choose a 10-percent discount rate and obtain net base-case benefits of the order of $10 billion. Below we shall see that a decision to proceed with the project based on benefits of this size easily could be reversed by plausible changes in LMFBR program cost assumptions.

The argument for a 6-percent rate of discount has not been circulated in final form by Stauffer. Pending the circulation of a revision of a preliminary verson of their paper[2] judgment on these results must be suspended.

TOWARD A BROADER PERSPECTIVE ON THE LMFBR DECISION

Rather than comparing futures with and without the LMFBR, Manne compares two kinds of futures, both with LMFBR's. In one, the date at which the LMFBR becomes available and commercially competitive is certain and is set in 1990. (The availability and commercial competitiveness are identical in Mannes' analysis, though they need not be in general and, as we shall see, the difference can matter.) In the second scenario, the introduction date for the LMFBR is uncertain, and Manne takes for illustrative purposes probabilities of 0.2, 0.4, and 0.4 for LMFBR introduction in the periods 1988–92, 1993–97, and 1998–2002, respectively. He then calculates the discounted present value of meeting electricity consumption in these two futures.

In the case with introduction certain in 1990, the calculation is similar to that in the three other studies, while the calculation in the uncertain case is done by finding the pattern of generating capacity expansion that minimizes the discounted present value of the expected costs of meeting consumption requirements. Naturally, it is more costly to meet demand in an uncertain future. The $4.8 billion entry for the Manne study in column (7) of table 4 is the measure of the costs this uncertainty will impose upon the economy. Put another way, according to the Manne (1973) calculation, the Nation should be willing to pay up to $4.8 billion now for certain "delivery" of the LMFBR technology in 1990, given the other assumptions of the study.

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[2] T. Stauffer, op. cit.

THE LMFBR TIMING ISSUE

It may be instructive to compare this $4.8 billion figure with the LMFBR program cost estimates. Tables 5 and 6 below, identical in format but differing in contents, are from two recent government documents. Table 5 is from AEC (1974), the Proposed Final Environmental Statement, and table 6 is from a recent General Accounting Office report[3] to the Congress on the LMFBR program. The two estimates of total undiscounted program costs for the period 1975–2000 differ by roughly $700 million. (By the year 2000 the LMFBR program is assumed completed with no public money going to LMFBR development.) Since table 5 is in fiscal year 1975 dollars and table 6 in fiscal year 1976 dollars, one might assume that this difference is almost entirely due to inflation, but inspection of the differences in individual entries makes it clear that inflation cannot be the source of all the differences.

Let us suppose, based on these studies, however, that future undiscounted program costs are roughly $8 billion. How should these program costs be deducted from the reduction in discounted costs of meeting electricity requirements to arrive at a net benefit figure? Unfortunately the answer depends upon the time pattern in which R. & D. costs are incurred, and there is no agreement upon the time patterns of R. & D. costs likely to be associated with alternative LMFBR program strategies. All of the cost-benefit analyses listed in table 4 make assumptions about the time pattern of LMFBR R. & D. expenditures which favor the LMFBR net benefit figure, and in most cases the result of the net benefit calculation is sensitive to this assumption.

Column (6) of table 4 summarizes the LMFBR program cost assumptions, and it is important to realize that one important range of possibilities is excluded from all of them. Scanning column (6), one sees that AEC (1974) assumes that the undiscounted LMFBR program costs are as shown in table 5. These costs are thus discounted to 1975 at the same rate of discount applied to LMFBR program benefits, and the difference between the two discounted figures is the net LMFBR program benefit. Possibly superior R. & D. timing strategies are not considered here. Implicity, the assumption is that we either incur the time pattern of program costs illustrated in table 6 or we do not get an LMFBR.

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[3] General Accounting Office, "The Liquid Metal Fast Breeder Reactor: Program, Past, Present and Future" (Apr. 28, 1975).

TABLE 5.—DETAIL OF LMFBR PROGRAM COST PROJECTIONS (1975 THROUGH 2020) BASED UPON 1987 LMFBR INTRODUCTION

[Millions of fiscal year 1975 dollars]

	1975	1976	3 mo transition	1977	1978	1979	Subtotal, 1975–79	Subtotal, 1980–2020	Total 1975–2020
Liquid metal fast breeder—reactor:									
Research and Development:									
R.& D.	65	46	12	46	37	37	243	526	769
CRBR	44	44	12	64	50	33	247	67	314
Support facilities	43	47	13	60	63	63	289	613	902
Engineering and technology:									
Technology	52	53	15	57	60	63	299	588	887
Engineering	49	53	15	69	94	123	403	759	1, 162
Cooperative projects:									
CRBR	21	73	5	155	160	140	554	200	754
NCBR				5	18	64	87	189	276
Capital equipment	19	17	5	23	24	26	114	201	315
Construction projects:									
FFTF	132	74					206		706
Plant component test facility		5		9	41	110	165	203	368
Rad and repair eng. facility				9	18	14	41	5	46
Advanced fuel laboratory				9	18		27		27
Fuels and materials exam facility				23			23		23
Hot reprocessing pilot plant				2	7	28	37	239	276
Miscellaneous projects	15	18	3	20	28	17	101	91	192
Total, LMFBR	440	430	80	551	618	718	2, 836	3, 681	6, 517
Supporting technology:									
Safety:									
Research and development	37	40	12	46	52	58	245	646	891
Equipment	4	4	2	4	3	4	21	49	70
Construction:									
Safety test facility		3		9	18	46	76	108	184
Transient reactor safety test facility				11	9	7	27		27
Advanced fuel technology	12	15	5	18	23	28	101	352	453
Total, supporting technology	53	62	19	88	105	143	470	1, 155	1, 625
Total, LMFBR and support	493	492	99	639	723	861	3, 306	4, 836	8, 142

Source: U.S. AEC, proposed final environmental statement, liquid metal fast breeder program (December 1974), p. 11.2–34.

TABLE 6,—DETAIL OF LMFBR PROGRAM COST PROJECTIONS (1975 THROUGH 2020) BASED UPON 1987 LMFBR INTRODUCTION

[In millions of fiscal year 1976 dollars]

	Fiscal year—			Fiscal year—			Total			
	1975	1976	3-mo transition	1977	1978	1979	1975–79	1975–87	1987–2020	1975–2020
LMFBR:										
R.& D.:										
FFTF	65	50	13	50	40	40	258	565	265	830
CRBR	42	50	13	58	46	44	253	351		351
Support facilities	43	51	14	65	68	69	310	776	101	977
Technology	52	56	16	62	65	60	319	838	121	959
Engineering	49	55	15	75	103	134	439	1, 170	84	1, 254
Cooperative projects:										
CRBR	14	35	20	169	178	177	593	838		838
NCDR				5	20	70	95	300		100
Capital equipment	19	18	5	25	26	28	121	291	53	344
Construction projects:										
FFTF	132	80		100			312	312		312
Plant component test facility				13	53	65	131	200		200
Radiation and repair engineering facility					4	11	17	36		36
High performance fuel laboratory				9	18	18	45	54		54
LMFBR fuels and materials examination facility					5	18	23	50		50
LMFBR fuels reprocessing hot pilot plant					9	37	46	300		300
Sodium pump test facility					9	18	37	40		40
Miscellaneous projects	15	23	9	19	11	19	99	202		202
Total LMFBR	430	417	98	650	665	818	3, 078	6, 323	724	7, 047
Support technology (LMFBR):										
Safety:										
R. & D	36	41	11	63	69	77	297	778	245	1, 023
Equipment	4	3	1	5	6	6	25	62	18	80
Construction:										
Safety research experiment facility				13	29	61	101	230		230
Sodium loop safety facility upgrade					4	3	7	7		7
Advanced fuel technology	11	13	1	20	25	30	101	378	108	486
Total support technology (LMFBR)	51	57	16	101	333	177	535	1, 453	371	1, 876
Total LMFBR and support technology	481	474	114	751	798	995	3, 613	7, 773	3, 065	8, 873

Source: U.S. GAO, "The Liquid Metal Fast Breeder Reactor Program—Past, Present and Future" (Apr. 28, 1975).

Manne (1973), as we have explained above, does not compute a net benefit figure in the same sense that the other studies do but rather estimates the penalty the Nation will pay if, rather than assuring LMFBR introduction in 1990, it allows the introduction date to remain subject to the probabilistic uncertainties he assumes for illustrative purposes. Were all observers in agreement on the probability assumptions which give the $4.8 billion penalty figure in Manne's example, one could compare that $4.8 billion figure with the additional costs required to bring the LMFBR program to certain fruition in 1990. But without an estimate of what those added costs might be, this comparison—the relevant comparison for comparing alternative LMFBR program strategies given a commitment to some LMFBR program—cannot be made directly. Since this is not Manne's purpose he does not make this kind of comparison; below we shall consider what such a comparison might indicate.

In Manne and Yu (1974) there is no explicit treatment of LMFBR program costs and consequently no explicit treatment of corresponding alternative LMFBR timing strategies leading to commercially competitive reactors in different years at different costs. But this range of alternatives can, in principle, be compared within the framework of this model. The assumption on capital cost differentials of Manne and Yu (1974) defines the date at which the LMFBR becomes commercially competitive and therefore defines an optimal introduction date for any given LMFBR program cost assumption. Introduction of the breeder at any later date imposes a power cost penalty which, when weighed against the development cost reductions associated with stretched-out LMFBR development strategies, defines an optimal or least-cost LMFBR program strategy.

Finally, Stauffer et al. define net benefits gross of R. & D. costs; since their results for net benefits thus defined are so much larger than their estimates of future LMFBR R. & D. costs—they cite $5–$10 billion in costs but specify no time pattern—the question of LMFBR development timing cannot be raised in their framework.

In summary, none of the LMFBR cost-benefit studies which compare a world without an LMFBR to one with an LMFBR is structured so as to answer questions about the best timing strategy an LMFBR program might pursue. Consequently, they give the same answer to the question of the optimal timing the LMFBR's commercialization: as shown in column (9) of table 4. Earlier introduction dates always give higher net benefit figures, and the optimum commercialization date is the earliest feasible date.

It is relatively easy to see that this result is a consequence of the assumption that the time pattern of LMFBR program costs is not a "decision variable," i.e., that there are no alternative LMFBR program strategies with different time patterns of R. & D. costs, or that LMFBR program costs are necessarily higher the longer the introduction is delayed. It is easy to demonstrate that, once the distinction is drawn between "availability date" (the date at which some LMFBR technology is "on the shelf") and "commercialization date," (the date at which the LMFBR generates electricity more cheaply than alternative technologies), and once there is a range of R. & D. strategies with different associated time patterns of cost, it is no longer true that an earlier LMFBR introduction date always increases net benefits. To the contrary, there will be an *optimum* introduction date, and what has been called an "LMFBR timing" issue arises.[4]

The LMFBR program as presently constituted is an enormous and complex undertaking—indeed some observers believe that it is organizationally too complex to operate effectively.[5] One should not underestimate the difficulty of guiding the strategy of such an enterprise using cost-benefit criteria. But if cost-benefit calculations are to be applied to the program as a whole, then it seems reasonable to ask that some alternative program timing strategies be analyzed, and none of the major studies do this. It might even be argued that such an assessment of broadly defined alternative program strategies, rather than provision of a single number or set of numbers as an evaluation of the program, is the role for which cost-benefit analysis is best suited.

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[4] See appendix to this study.

[5] See the remarks on LMFBR program structure and program performance in General Accounting Office, op. cit.

CONCLUSION: THE PURPOSES AND LIMITS OF ANALYSIS

The energy R. & D. budget is limited, and energy R. & D. programs are among our major instruments for broadening our energy supply options and thus for widening the range of futures we will have to choose among and live within. But framing that allocation problem in ways that are useful as guides to energy R. & D. policy is exceptionally difficult. A correct understanding of the range of alternative futures is required, and that understanding turns on identification of variables determining those futures which are either under control or can reasonably be brought under control. That choice of variables limits the range of strategies among which we can choose and influences ranking of those strategies. Finally, we need criteria in order to choose among alternative futures; criteria applicable when we are certain that particular strategies will lead to particular futures, and criteria for proceeding when uncertainty obscures the linkage between present strategies and alternative futures.

In order to slice into this circle of circumstance and choice, it is necessary to limit the full range of possibilities to a smaller range and then to introduce simple criteria for choice among these plausible futures. All of the cost-benefit studies of the LMFBR we have surveyed do this, and all do it in ways that are very similar. There can be no quarrel with the necessity of this reduction. But the particular range chosen and the particular criteria chosen for the guidance of choices among those alternatives, if overly narrow and/or excluding some major alternatives, can seriously constrict our view of the options open to us and of the strategies available to us for broadening those options.

THE RANGE OF ALTERNATIVES

Here an illustrative example may be useful in sharpening the moral of the LMFBR timing issue story. A slight change in the range of alternatives considered can lead to a significant change in program evaluation. All the major LMFBR cost-benefit analyses we have surveyed, except for Manne (1973), compare LMFBR and non-LMFBR futures and therefore focus entirely upon energy supply-side alternatives. Only Manne (1973) attempts a comparative evaluation of the payoff to one major demand-side energy measure, the peakload pricing of electricity, and the numerical results are strikingly larger than the computed payoffs to LMFBR development.

Manne computes many cases, but one can be taken as illustrative. Under the assumptions summarized in table 4 the cost savings from certain 1990 availability of the LMFBR are roughly $4.8 billion, while the generating capacity cost savings from improved pricing of peak-demand period electricity—a halfway version of peakload pricing—are roughly $38 billion. There is some danger of misinterpretation in citing these two figures for comparison but not, I think, as much danger as there is in leaving out this kind of comparison. The point is that the economic benefits from removing one of the major distortions in energy pricing are significantly larger than the economic costs we may incur by delaying the introduction of the LMFBR.

There is overwhelming evidence suggesting that we have, in the past, and especially in the recent past, systematically underestimated the difficulties in supply-side energy strategies, whether these be solutions involving previously unexploited exhaustible resources or the introduction of new energy technologies. The expansion of LWR capacity has been significantly slower than was foreseen 5, 10, and 20 years ago. In the light of this history the projected LMFBR program schedule seems optimistic. There are numerous technical deadlines to be met, the number of demonstration plants that will be required before full commercialization remains uncertain, and there is little that can be said with assurance about the licensability of the ultimate commercial LMFBR. Given the technological and institutional constraints and uncertainties surrounding supply-side solutions, it seems imperative that supply-side solutions be explored and evaluated in a framework allowing consistent comparison with demand-side energy strategies.

THE LIMITS OF ANALYSIS

Finally, many of the opponents of nuclear power—in their arguments against a commitment to an expansion of nuclear power, both LWR's and LMFBR's, stress the problem of intertemporal equity, especially the unresolved problems of disposing of long-lived actinide. Because plutonium and the other actinides have half-lives ranging into the hundreds of thousands of years, the possibility of an enormous transfer of environmental costs onto future generations cannot be entirely ruled out short of a resolution of the waste disposal problem. In this case, the earlier generations benefiting from fission clearly cannot compensate later, unluckier generations, and the cost-benefit criterion loses both its regorous basis and its aura of fairness. This is a dilemma that cannot be resolved by cost-benefit analysts. Decisions that may involve significant nontransferable gains for some and major noncompensable losses for others are decisions that should be made in the final analysis by legislatures and courts, arenas in which potential losers can get a hearing. While the future cannot represent itself, we can and do on occasion arrange for decision rules and processes that make the time perspective of the decision either shorter or longer. The definition of appropriate institutions and procedures for nuclear decisionmaking requires more serious and precise thought.

I do not believe that this dimension of the problem has received due consideration in our public deliberations, most of which have been concerned with particular aspects of the nuclear fuel cycle. Short of tackling these broader aspects of the problem, the stalemate over nuclear power is unlikely to be broken.

APPENDIX

Here is a simple example: There are two technologies (1, 2) for meeting some constant demand over some finite time horizon T. Technology 2, the "LFMBR," is initially expensive than technology 1, the "LWR." But with learning—assumed proportional to operating time—technology 2 becomes cheaper. To "buy into" technology 2 there must be a one-time payment, *P*, of R. & D. funds. That payment and the switchover to technology 2 define *a*, the "availability" date. The commercialization date, *c*, is the date at which technology 2 expenses have been "learned down" so that technology 2 is competitive with technology 1. Summarizing and setting out the model:

$C_1(d)$=total cost of meeting demand *d* with technology 1

$C_2(d, t-a)$=total cost of meeting demand *d*, with technology 2, at $(t-a)$ after the availability date *a*

T=time horizon of problem

P=one-time R. & D. payment at *a* for "availability" of technology 2

r=social rate of discount

Then the problem of meeting demand *d* at minimum present value of cost is:

$$\min_a Z$$

where

$$Z=\int_0^a e^{-rt}C_1(d(t))dt+Pe^{-ra}+\int_a^T e^{-rt}C_2(d(t),\ t-a)dt \tag{1}$$

The corresponding first-order condition $\frac{\partial Z}{\partial a}=0$ implies

$$C_1(d(a))-rP-C_2(d(a),\ 0)+e^{ra}\int_a^T dte^{-rt}\ \frac{\partial C_2(d(t),\ t-r)}{\partial a}=0 \tag{2}$$

If we take a simple explicit form for the time dependence of C—one consistent with the assumption that technology 2 costs are reduced over time due to learning to a level below technology 1 costs, such as

$$C_2(d(t),\ t-a)=(C_2(d(t))(1+ge^{-h(t-a)})) \tag{3}$$

where $g>0$, $h>0$ are constants parameterizing the effect, then the integral in (2) can be explicitly evaluated, and an analytical solution can be obtained for the optimum availability time a^*:

$$a^*=T+\frac{1}{r+h}\ln\left(1+\left(\frac{r+h}{gh}\right)\left(\frac{C_1-C_2-rp}{C_2}\right)\right) \tag{4}$$

From this model one can see how changes in capital cost differentials (C_1-C_2), learning rate assumptions $(g,\ h)$, R. & D. costs (P), and the discount rate (r) affect optimal timing. The important point for our purposes is that there is a timing issue, and that there will be one in any model that specifies the range of alternative program strategies somewhat more broadly than most of the studies surveyed here.

O