Public Issues of Nuclear Power
"The Breeder Reactor"

by

Thomas B. Cochran

11 November 1974

Introductory Remarks by Herbert S. Isbin

I believe that it is fair to say that our speaker, Dr. Thomas Cochran, has emerged as one of the nation's foremost critics of the liquid metal fast breeder reactor. His recent book on this subject presents an important environmental and economic critique. Dr. Cochran's approach has not been one of just rhetoric. On the contrary, he has tried to base his arguments on substantial technical grounds. Our speaker obtained his undergraduate degree in electrical engineering, his masters degree in physics and his doctorate degree in physics (in 1967) from Vanderbilt University, and did post-graduate doctorate work at the University of Colorado. Although his specialty was in high energy physics, he has since become involved in monitoring the civilian nuclear power industry. He spent two years teaching at the U. S. Naval Postgraduate School in Monterey, California. After two years with the Litton Industry, he was associated with Resources for the Future, Inc., in Washington, D. C., and it was there that he wrote his book, The Liquid Metal Fast Breeder Reactor: An Environmental and Economic Critique, published in 1974. Currently, Dr. Cochran is a staff scientist at Natural Resources Defense Council. This group has interacted with the AEC in many of the draft environmental impact statements, and NRDC's critiques are among the most detailed, critical, constructive and provocative that the AEC has received. Dr. Cochran has participated also in several national groups such as the National Academy of Sciences' Panel on Nuclear Merchant Ships and a task force at the Federal Power Commission's National Power Survey examining energy conversion research. He remains a consultant to the Resources for the Future, and is a consultant to the West Michigan Environmental Action Council.

Our speaker opposes the breeder reactor on the grounds that the breeder does not at this time provide any justifiable economic incentives, nor provide suitable environmental incentives. Dr. Cochran is very much concerned with the safeguards issues. Further, he believes that our nation's priorities on energy research have been misplaced. Although he is not an advocate for a moratorium on nuclear power, he does believe that an orderly fazing out would be the proper approach. He favors replacing nuclear power by viable alternatives.

Tom, our class in the public issues of nuclear power is generally acquainted with these issues, and what we would like to learn from you is your position on nuclear power, and the technical bases for your judgments.

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Remarks of Thomas B. Cochran

Thank you very much for the kind introduction. Let me start by saying a few words about Natural Resources Defense Council (NRDC), for those who are not familiar with it. NRDC is a non-profit public interest law firm with 16 lawyers and four scientists, located in three offices; Washington, D. C., New York, and Palo Alto. Its budget is roughly 1.3 million dollars a year, a third from the Ford Foundation, twenty percent from 10 dollar memberships (if you would like to join) and the remainder from small grants and large contributors. I will leave with Dr. Isbin a copy of a booklet that summarizes some of NRDC's past litigation. NRDC has been active in areas related to the Clean Air Act of 1970, the Federal Water Pollution Control Act of 1972 (including the Toxic Substances Act), and has been involved in resource management and conservation issues such as timber cutting, stream channelization, protection of wilderness areas and strip mining. In the energy area, NRDC's involvement includes, among others, the Alaska Pipeline controversy, off shore oil and gas leasing policy, and several nuclear issues. I have been associated with three of the nuclear issues; namely, the monitoring of the AEC's liquid metal fast breeder (LMFBR) program, the plutonium recycle issue (i.e., the use of plutonium in light water reactors), and the radiation protection standards for plutonium (i.e., the so-called hot particle issue). NRDC's Palo Alto office is monitoring the AEC's radioactive waste management program. In the limited time available, I will concentrate on the AEC's LMFBR program, although hopefully, I will have time to say a few words on some of these other issues.

For those unfamiliar with the LMFBR, it's a nuclear reactor which generates electrical energy in a manner similar to the commercial nuclear reactors that are currently being operated. The term "liquid metal" refers to the use of liquid sodium as a coolant, as opposed to water in the conventional reactors. It is called a "fast breeder": "fast" because the neutrons in the reactor core are not slowed down before they are reabsorbed in the fission chain reaction process. The neutrons in effect remain fast. In the conventional light water reactor the water serves as the moderator, slowing down the neutrons. In the LMFBR, the liquid sodium does not serve the same purpose.

The LMFBR is called a "breeder," because it breeds more fuel than it burns. On the average there are roughly 2.9 neutrons produced per fission and at least one of these is necessary to produce another fission, otherwise you would not have a chain reaction. Of the remaining 1.9 or so neutrons, some are lost from the system. Others are absorbed in uranium-238, which is mixed with plutonium-239. The plutonium-239 is the fissionable material which serves as the breeder reactor's primary fuel. When neutrons are absorbed in uranium-238, this material is converted to plutonium-239. In the breeder reactor you create more plutonium-239 than you burn. By "burn" we simply mean fission atoms in the reactor. Hence, we speak of "breeding" and "burning" fuel. In a conventional reactor, less neutrons are absorbed by the uranium-238 which is mixed with uranium-235, the primary fuel of this reactor. Hence, plutonium-239 is not produced as fast as the uranium-235 (and plutonium-239) are fissioned in the fission process. Thus, while these reactors are not "breeders," they convert substantial amounts of uranium-238 to plutonium-239, and thus are called "convertor" reactors.

The principal advantages of a breeder reactor, over the conventional "convertor" reactor, is that the uranium-238 is used more efficiently. Natural uranium is composed of about 99.3% uranium-238. Only 0.7% of it is uranium-235, the fissionable material in natural uranium. The current reactors are only capable of using about one percent of the total uranium (U-235 plus U-238) in the fission process. In effect, they're using about half the uranium-235 and a small amount of plutonium that has been produced by conversion from uranium-238. On the other hand, by breeding more plutonium than is burned and recycling this fuel, breeders can ultimately utilize about 50% to 60% of the total natural uranium. In effect, the breeder enables us to stretch our uranium resource providing what is often termed "an inexhaustible supply" of uranium. While not truely inexhaustible, it will last at least several hundred years. Furthermore, because the breeder reactor uses the uranium-238 so efficiently, much less mining of natural uranium is required and also, the price of the nuclear fuel in the breeder reactor is much less sensitive to the price of the uranium ore because so little uranium ore is required. In summary, the breeder offers the combination of being able to provide an essentially inexhaustible supply of nuclear fuel at a cost that is very insensitive to the price of uranium.

Given the fact that the fuel cycle of the breeder reactor is insensitive to the price of uranium, does this mean that the electricity is cheaper from a breeder reactor than from a conventional reactor? The answer is "not necessarily," because the electricity from a nuclear reactor depends on more than just the uranium costs -- more, in fact, than just the fuel cycle costs. It depends primarily on the cost of building the reactor, plus the additional operating and maintenance costs and finally, the fuel cycle costs of which the fuel (uranium) costs are only a part (see Figure 1).

Today, the light water reactor costs are such that about 75% of the cost of power produced (at the bus bar) by this reactor actually

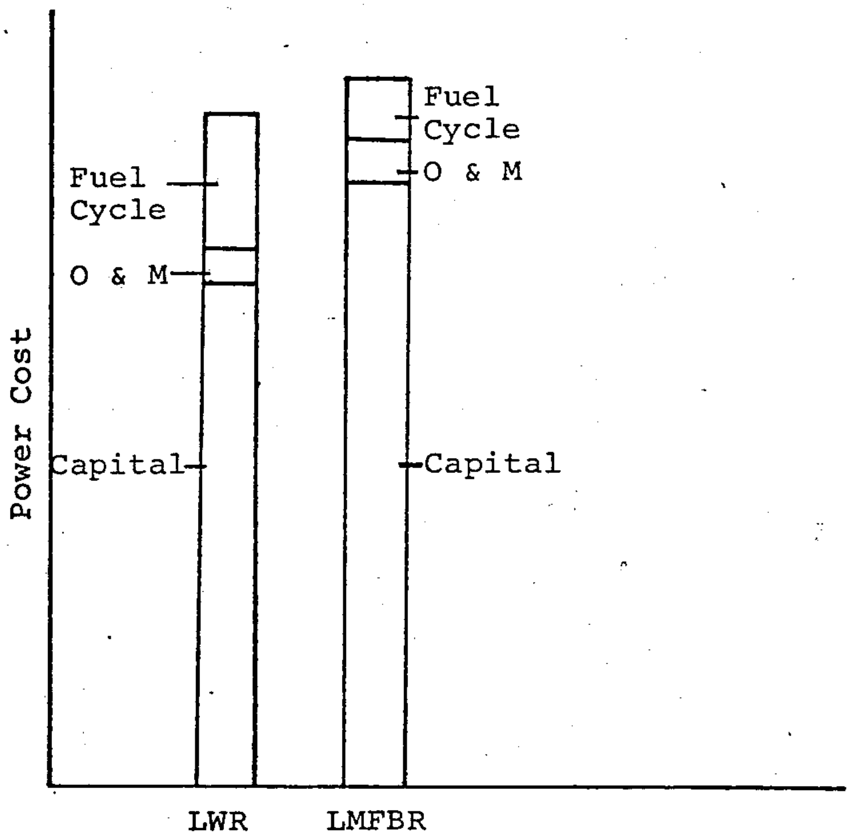


Figure 1: Relative cost of power generated by LWR's and LMFBR's.

represents capital costs, that is, the investment required to build the plant itself. The bus bar cost of electricity from reactors that are going on line today, or in the next few years, is somewhere on the order of 10 mills/kwh. About 7 1/2 mills is the capital costs, and 0.5 mills/kwh is the operating and maintenance cost. The fuel cycle costs represent about 2 mills/kwh. In an attempt to determine whether the LMFBR is competitive with the light water reactor one must examine the sum of all these costs for each reactor and project these costs out into the future. In Figure 1, I have depicted the LMFBR as costing a little more to build than a LWR; assumed the two have the same operating and maintenance cost (the LMFBR is probably a few percent more); and assumed the LMFBR fuel cycle costs are less because it doesn't use as much uranium and doesn't have the enrichment requirement. Now the question arises, of these two alternative energy supplies, which one has the cheaper overall cost of energy? This is the principal issue I want to discuss this afternoon.

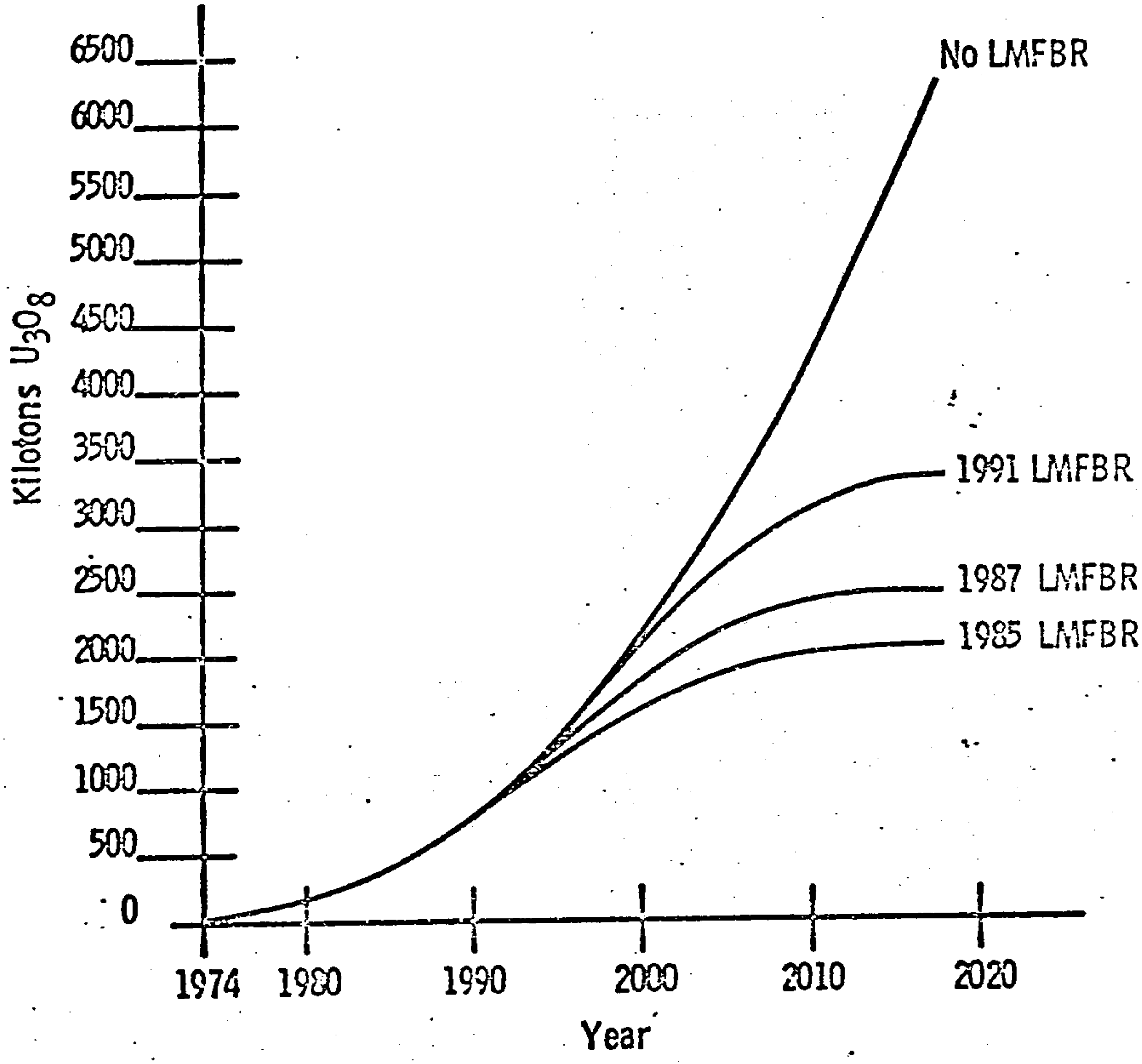
The key, as you see from Figure 1, is the difference in the capital costs of the two reactors compared to the difference in the fuel cycle costs. In reality, uranium prices are going to go up in the future increasing the LWR fuel costs, and capital costs are going to change in the future, and so forth. Therefore, in order to perform this analysis more rigorously, one must do this analysis as a function of time. The AEC has built an elaborate cost-benefit computer model to do just this, examining the cost trends over a fifty year period, e.g., between now and the year 2020. The AEC has used this model to perform three cost-benefit anlayses, the latest one appearing in the DRAFT LMFBR Environmental Impact Statement. This draft statement was released last March and subsequently the cost-benefit anlaysis has been revised for the FINAL statement. However, this latest version has not yet been released.

The results of these LMFBR cost-benefit studies turn out to be very sensitive to the assumptions you make about some of the key variables. In the limited time we have available, I will not attempt to convince you that my assumptions about the key variables are the correct assumptions and that the AEC's assumptions are for the most part incorrect. Instead, I will try simply to review a few of these variables to give you a feeling for the sensitivity of the results of the AEC's cost-benefit analyses to some of the more important assumptions, and the extent of the uncertainties in these same assumptions. In other words, my purpose is simply to give you a feel for the shaky foundation on which the economic justification of this technology is based.

In my view, the AEC for promotional reasons has selected very favorable assumptions of key variables simply to generate large benefits on paper for this program. The AEC studies are classical examples of the way cost-benefit studies are used to justify uneconomical programs. You'll have to accept this as my bias coming into this discussion. I won't try to convince you that this view is justified. I understand Merrill Whitman from the AEC is scheduled for a later session. He will discuss this issue at length. Perhaps he will be able to present the AEC's side with respect to some of these variables.

As we go through some of these key assumptions and key variables, don't get bogged down in the details and the numbers. I will be presenting considerable data in rapid fashion. I simply want you to notice the trends, and not the details. Some of the data are taken directly from the AEC's analysis and I don't believe many of them myself. Unfortunately, we don't have time to discuss these in any detail. Before reviewing the key assumptions, it may be useful to examine a couple of results, beginning with Figure 2. This is from the AEC's latest cost-benefit analysis, from the DRAFT LMFBR Environmental Impact Statement. It shows cumulative uranium (in the form of uranium U_3O_8) usage as a function of time. You see, for example, according to the AEC if the breeder is introduced in 1985, because it uses very much less natural uranium, the uranium demand is turned over by about 2010 so that only about 2 million tons of uranium are ultimately required. If you delay the introduction of the breeder the cumulative total demand goes up and up. In the limiting case where the breeder is not introduced at all, the cumulative demand rises by the year 2020 to something like 6 1/2 million tons. This is an AEC estimate. My estimate is a much lower number. By turning the demand over less uranium is required and its price will not rise as high as it would otherwise. We see from Figure 3, according to the AEC, in 1985 the price of uranium will remain below about $20/lb. However, if the breeder is never introduced, by the year 2020 it will go up to on the order of $100/lb, according to the AEC. This, as seen from Figure 4, can be translated into an increase in the bus bar cost of power from light water reactors on the order of 5 mills/kwh. Figure 4 shows the sensitivity of the price of electricity to changes in the generating cost for several reactor types. Here it is seen that even if the cost of uranium goes up to about $50/lb, this has little effect on the cost of electricity, using the breeder. Doubling the price from about $8 - $16/lb will increase the price of electricity using LWR

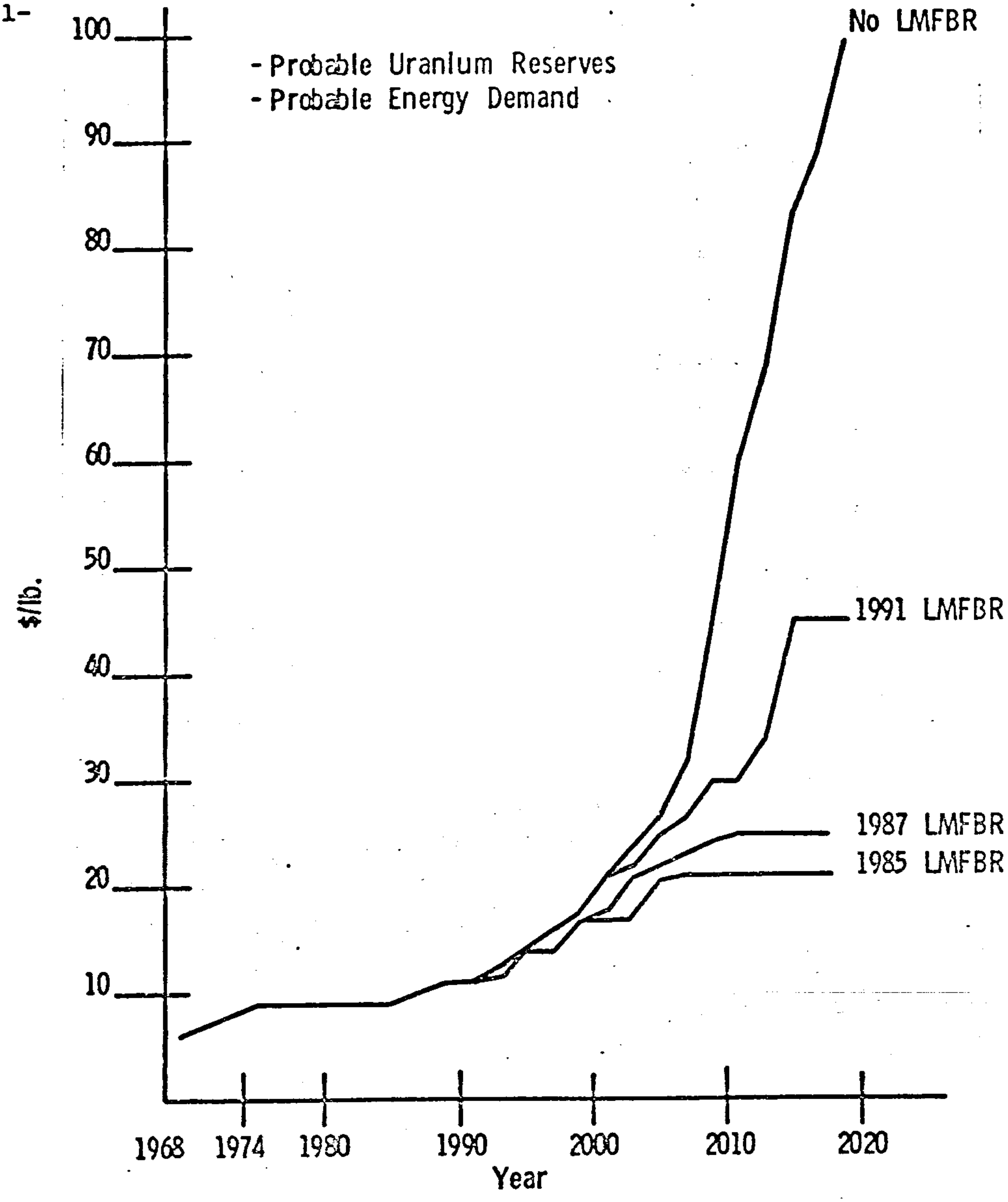
- Probable Energy Demand
- Probable Uranium Reserves



CUMULATIVE U_3O_8 USAGE

Figure 2

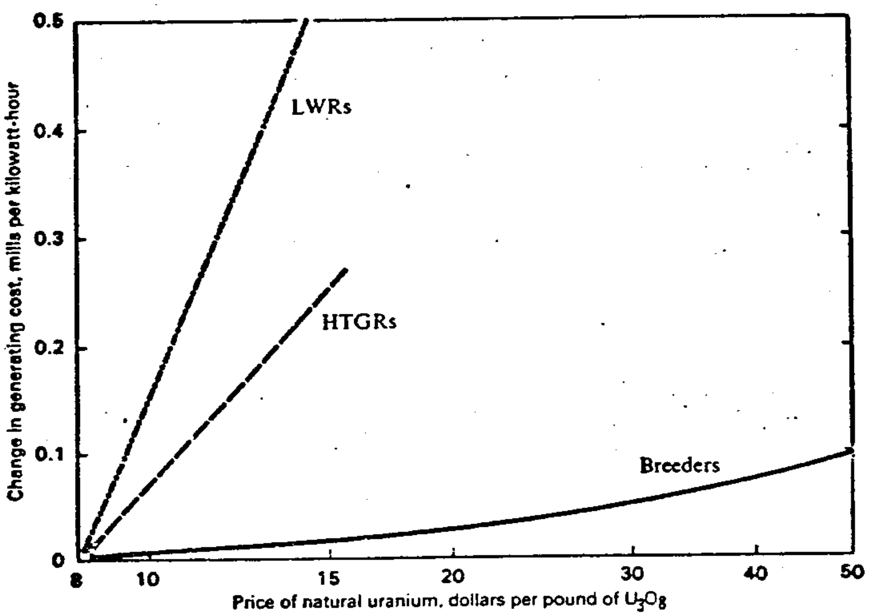
Source: DRAFT LMFBR EIS [Draft Environmental Statement Liquid Metal Fast Breeder Reactor Program, U. S. Atomic Energy Commission, (March 1974)], Volume III, p. 3-24.



U_3O_8 PRICE

Figure 3

Source: DRAFT LMFBR EIS, op. cit., Volume III, p. 3-25.



SOURCE: Robert D. Nininger, "Nuclear Resources," paper presented at Energy Resources Conference, College of Engineering, University of Kentucky (Lexington, May 11, 1971).

NOTE: The HTGR curve (linear slope = $0.035\ \frac{\text{mills/Kwh}}{\$/\text{lb}}$) was recalcu-

Figure 4: Sensitivity of Nuclear Energy Generating Cost to Price of Natural Uranium

Source: Cochran, Thomas B., The Liquid Metal Fast Breeder Reactor: An Environmental and Economic Critique, Resources for the Future, Washington, D. C. (1974), p. 77.

by about 0.5 mill/kwh, which is really only about 5% of the total bus bar cost of electricity. The point here is that doubling the price of uranium ore does not result in a terribly significant effect on the price of electricity even in the light water reactor.

I want to turn now to the cost-benefit model of the AEC and review briefly how it works. It is a linear programming computer model which optimizes, actually minimizes, the total cost of electricity from a mix of technological options over a specified period of time. As seen from Table 1, one makes input aasumptions about the electricity demand, uranium price, construction costs of various reactors, etc., and when these various nuclear reactors (and fossil fuel plants) are commercially available. The computer then selects the appropriate mix of these technologies to minimize the total cost of electricity over the entire period of the analysis, usually fifty years. One, of course, can run as many cases as one wants. As seen from Table 2, the AEC's latest analysis consists of thirty cases where the introduction date of the LMFBR, and assumptions regarding the uranium supply and energy demand, were varied. The labels "probably," "optimistic," etc., under "uranium resource availability" and "energy demand" represent AEC opinions. These assumptions are sources of considerable debate. For each case, the cost-benefit model calculates the total energy cost, that is, the sum of the total energy cost of all the reactors built over the fifty year period. This is done for the cases with and without the LMFBR (see Cases 1 and 3). The difference between the energy costs without and with the LMFBR, all other assumptions remaining the same, gives the benefits (positive or negative) of introducing the breeder in that given year. As seen

Cases Considered for 1973 Cost-Benefit Analysis

Group No.	Case No.	LMFBR Introduction Date	Uranium Resource Availability	Energy Demand Projection	Assumed Conditions
1	1		Probable	Probable	Base Set
	2	1985	Probable	Probable	Base Set
	3	1987	Probable	Probable	Base Set
	4	1991	Probable	Probable	Base Set
2	5		Optimistic	Probable	
	6	1985	Optimistic	Probable	
	7	1987	Optimistic	Probable	
	8	1991	Optimistic	Probable	
3	9		Low	Probable	
	10	1985	Low	Probable	
	11	1987	Low	Probable	
	12	1991	Low	Probable	
4	13		Probable	Low	
	14	1985	Probable	Low	
	15	1987	Probable	Low	
	16	1991	Probable	Low	
5	17		Probable	High	
	18	1985	Probable	High	
	19	1987	Probable	High	
	30	1991	Probable	High	
6	21	1987	Probable	Probable	Note (a)
7	22		Probable	Probable	Note (b)
	23	1985	Probable	Probable	
	24	1987	Probable	Probable	
	25	1991	Probable	Probable	
8	26	1987	Probable	Probable	Note (c)
	27	1987	Probable	Probable	Note (c,d)
	28	1987	Probable	High	Note (c)
9	29	1985	Probable	Probable	Note (d)
	30	1987	Probable	Probable	Note (d)
	31	1991	Probable	Probable	Note (d)
	32	1987	Probable	High	Note (d)
10	33		Probable	Probable	Note (e)
	34		Probable	Probable	Note (e,f)
	35	1987	Probable	Probable	Note (e)
11	36		Probable	Probable	Note (g)
	37	1987	Probable	Probable	Note (g)
12	38		Probable	Probable	Note (h)
	39		Probable	Probable	Note (g,h)
	40	1987	Probable	Probable	Note (h)

NOTES:

(a)	LMFBR capital costs remain $50/KW higher than LWR after 2000.
(b)	Includes 5% escalation; optimized at 10% discount.
(c)	365-day post-irradiation cooling for LMFBR fuel.
(d)	Carbide-fueled breeder assumed not to be available.
(e)	No constraints on HTGR construction beyond 2000.
(f)	No semi-annual refueling.
(g)	No HTGR's introduced beyond 1982.
(h)	Fossil fuel plants included.

Table 1

Source: DRAFT LMFBR EIS, <u>op. cit.</u>, Volume III, p. 3-2.

SUMMARY OF COST-BENEFIT STUDY RESULTS (10% Discount)

Case	Uranium Resources Availability	Energy Demand	LMFBR Intro Date	Billions of Dollars Discounted at 10% to mid-1974 Energy Cost (1)	Gross Benefit (2)	R&D Cost (3)	Net Benefit (2)-(3)	Benefit/ Cost Ratio (2) ÷ (3)
1	Probable	Probable	--	271.3	--			
2	"	"	1985	247.8	23.5	3.9	19.6	6.0
3	"	"	1987	249.1	22.2	4.0	18.2	5.6
4	"	"	1991	250.2	21.1	4.5	16.6	4.7
5	Optimistic	Probable	--	258.4	--			
6	"	"	1985	246.6	11.9	3.9	8.0	3.1
7	"	"	1987	247.3	11.2	4.0	7.2	2.8
8	"	"	1991	249.0	9.4	4.5	4.9	2.1
9	Low	Probable	--	272.7	--			
10	"	"	1985	250.6	22.1	3.9	18.2	5.7
11	"	"	1987	253.3	19.4	4.0	15.4	4.9
12	"	"	1991	260.4	12.3	4.5	7.8	2.7
13	Probable	Low	--	242.6	--			
14	"	"	1985	226.1	16.5	3.9	12.6	4.2
15	"	"	1987	227.0	15.5	4.0	11.5	3.9
16	"	"	1991	229.1	13.4	4.5	8.9	3.0
17	Probable	High	--	301.2	--			
18	"	"	1985	270.8	30.4	3.9	26.5	7.8
19	"	"	1987	272.0	29.3	4.0	25.3	7.3
20	"	"	1991	276.0	25.2	4.5	20.7	5.6
21	Probable	Probable	1987(a)	256.5	14.8	4.0	10.8	3.7
22	Probable	Probable	--	956.4	--			
23	"	"	1985(b)	804.6	191.8	5.0	186.8	38.4
24	"	"	1987(b)	809.3	187.1	5.1	182.0	36.7
25	"	"	1991(b)	817.7	178.7	6.1	172.6	29.3
26	Probable	Probable	1987(c)	249.3	22.0	4.0	18.0	5.5
27	"	"	1987(c,d)	252.1	19.2	4.0	15.2	4.8
28	"	High	1987(c)	272.5	28.7	4.0	24.7	7.2
29	Probable	Probable	1985(d)	250.3	21.0	3.9	17.1	5.4
30	"	"	1987(d)	250.9	20.4	4.0	16.4	5.1
31	"	"	1991(d)	254.7	16.6	4.5	12.1	3.7
32	"	High	1987(d)	273.8	27.4	4.0	23.4	6.9
33	Probable	Probable	--- (e)	265.4	--			
34	"	"	--- (e,f)	269.6	--			
35	"	"	1987(e)	247.9	17.5* 21.7**	4.0 4.0	13.5 17.7	4.4 5.4
36	Probable	Probable	--- (g)	276.2	--			
37	"	"	1987(g)	249.7	26.5	4.0	22.5	6.6
38	Probable	Probable	--- (h)	489.3	--			
39	"	"	---(g,h)	493.9				
40	"	"	1987(h)	461.8	27.5† 32.1††	4.0 4.0	23.5 28.1	6.9 8.0

Notes:
(a) LMFBR capital costs remain $50/kw higher than LWR after 2000.
(b) Includes 5% escalation; optimized at 10% discount.
(c) 365-day post-irradiation cooling for LMFBR fuel.

(d) Carbide-fueled breeder assumed not to be available.
(e) No constraints on HTGR construction beyond 2000.
(f) No semi-annual refueling.
(g) No HTGR's introduced beyond 1982.
(h) Fossil Fuel plants included.
* Benefits compared with Case 33.
** Benefits compared with Case 34.
† Results compared with Case 38.
†† Results compared with Case 39.

Table 2

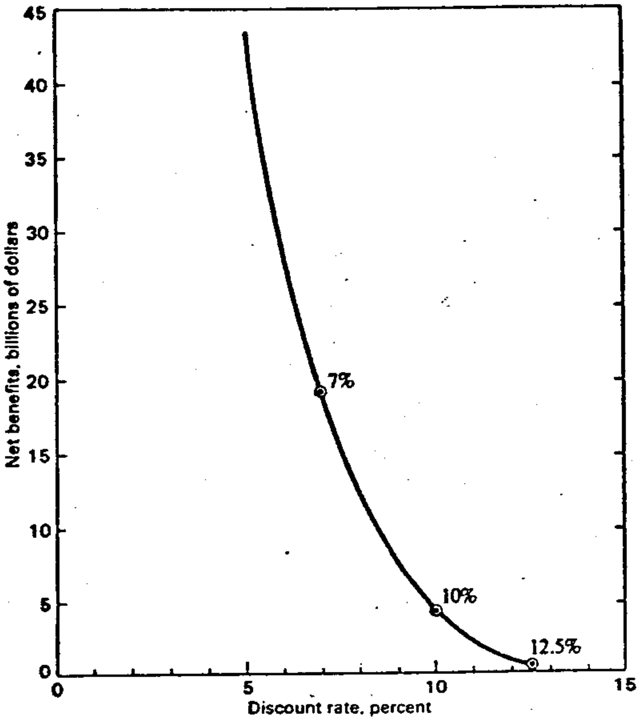
Source: DRAFT LMFBR EIS, <u>op. cit.</u>, Volume III, p. 3-11.

from Table 2, Case 3, according to the AEC, for a 1987 LMFBR introduction, the gross benefits would be $22.2 billion. Subtracting the R&D costs of the breeder program leaves a net benefit of $18.2 billion.

These calculations have been done at a 10% discount rate. The AEC prefers a 7.5% discount rate which results in $55.5 billion net benefits. Anytime you perform an economic analysis of this type you've got to take into account the fact that money has different values at different times. For example, if I asked you whether you would rather have one dollar today or two dollars next year, you would probably say two dollars next year. However, if the choice is one dollar today or $1.10 next year you would have to think a bit to decide how much a dollar today would be worth next year. In econometric models the difference in the worth of the money over time is taken into account by the choice of the discount rate. The discount rate generally does not include inflation. In the AEC model the effect of inflation is already subtracted out.

Now let's look at the sensitivity of the results of the cost-benefit analysis such as the AEC's best estimate that $55.5 billion worth of benefits if the LMFBR is introduced as scheduled in 1987. Keep in mind, this is an AEC estimate that if you introduce the LMFBR in 1987 it would save us, in today's dollars, $55.5 billion over the next fifty years. That appears to be a worthwhile undertaking, or is it? Let's first look at the sensitivity of this result to the discount rate assumption. Figure 5 is from a previous AEC analysis, but the results haven't changed qualitatively. In this analysis the AEC suggested that a 7% discount rate was the appropriate choice. As

Sensitivity of Present Value (Mid-1971) Net Benefits of the LMFBR Program to Discount Rate, AEC Case 3



SOURCE: AEC, Division of Reactor Development and Technology, *Updated (1970) Cost-Benefit Analysis of the U.S. Breeder Reactor Program,* WASH 1184 (Jan. 1972), pp. 28-31.

*The circles represent case 3 of the 1970 Analysis (see Table 6). Case 3 reflects the AEC's judgment of the most likely values of the other parameters varied in the analysis.

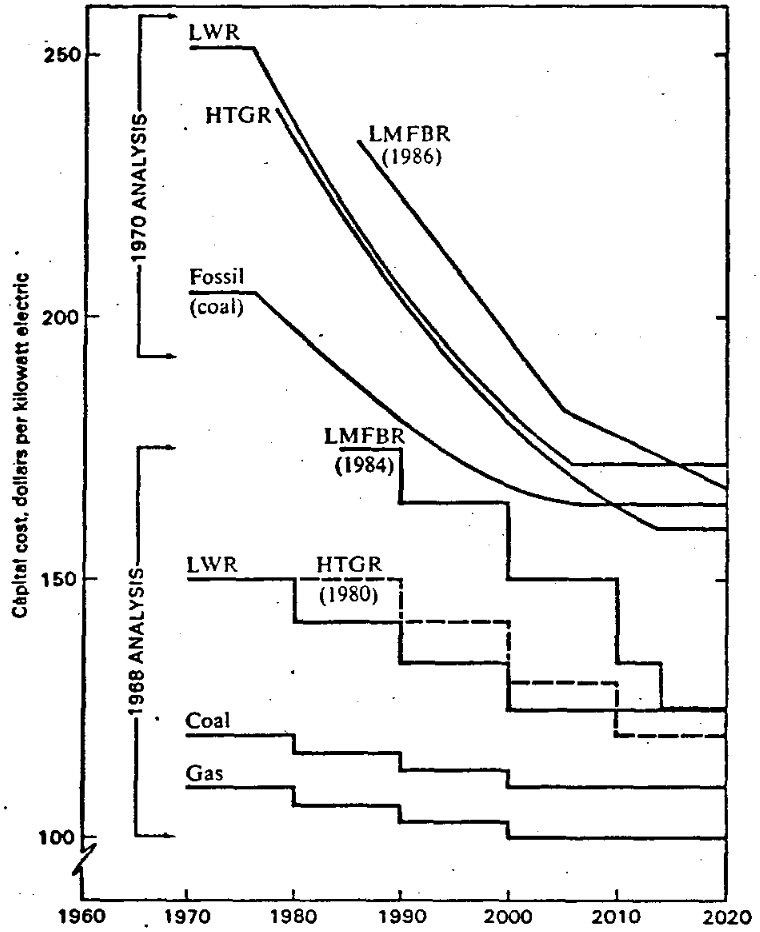
Figure 5

Source: Cochran, Thomas B., op. cit., p. 25.

can be seen from the figure, had they chosen a 10% rate about three-fourths of the computed benefits would be lost. In disagreement with the AEC, the Office of Management and Budget believes 10 percent is the appropriate discount rate and in fact there is an OMB Circular requiring federal agencies to use the 10% discount rate when evaluating projects such as the LMFBR program. There is considerable economic literature on this subject that suggests that the appropriate rate should be 10 percent or even higher. The AEC feels that 7% or 7.5% is the more appropriate rate for evaluating the LMFBR. I don't want to argue about the choice of the rate. I simply wish to demonstrate that if you shift to what other people feel is a more appropriate discount rate you reduce the AEC's best estimate of the LMFBR benefits considerably, down to $18.2 billion as seen from Case 3 in Table 2.

I pointed out earlier that one of the most sensitive cost-benefit assumptions is with respect to the capital costs of the reactors. Recall the issue is whether the savings in the fuel cost of the breeder over that of the LWR offset any increase in the breeder's capital cost over that of the LWR. Hence, the important parameter is the difference in capital costs of these two reactors -- what I call the capital cost differential. In Figure 6 are presented capital cost assumptions in the two previous AEC cost-benefit analyses (1968 and 1970). The difference between the LMFBR and the light water reactor curves is (in each analysis) the capital cost difference as a function of time. This is the important parameter for our discussion here. The costs are in constant dollars which means cost increases due to inflation have been subtracted out. These costs are assumed to vary over time. It is seen that the costs decrease with time.

Projected Power Plant Capital Costs Used in AEC's Cost-Benefit Analysis



SOURCE: AEC. *Updated (1970) Analysis,* WASH 1184, p. 37.

Figure 6

Source: Cochran, Thomas B., op. cit., p. 32.

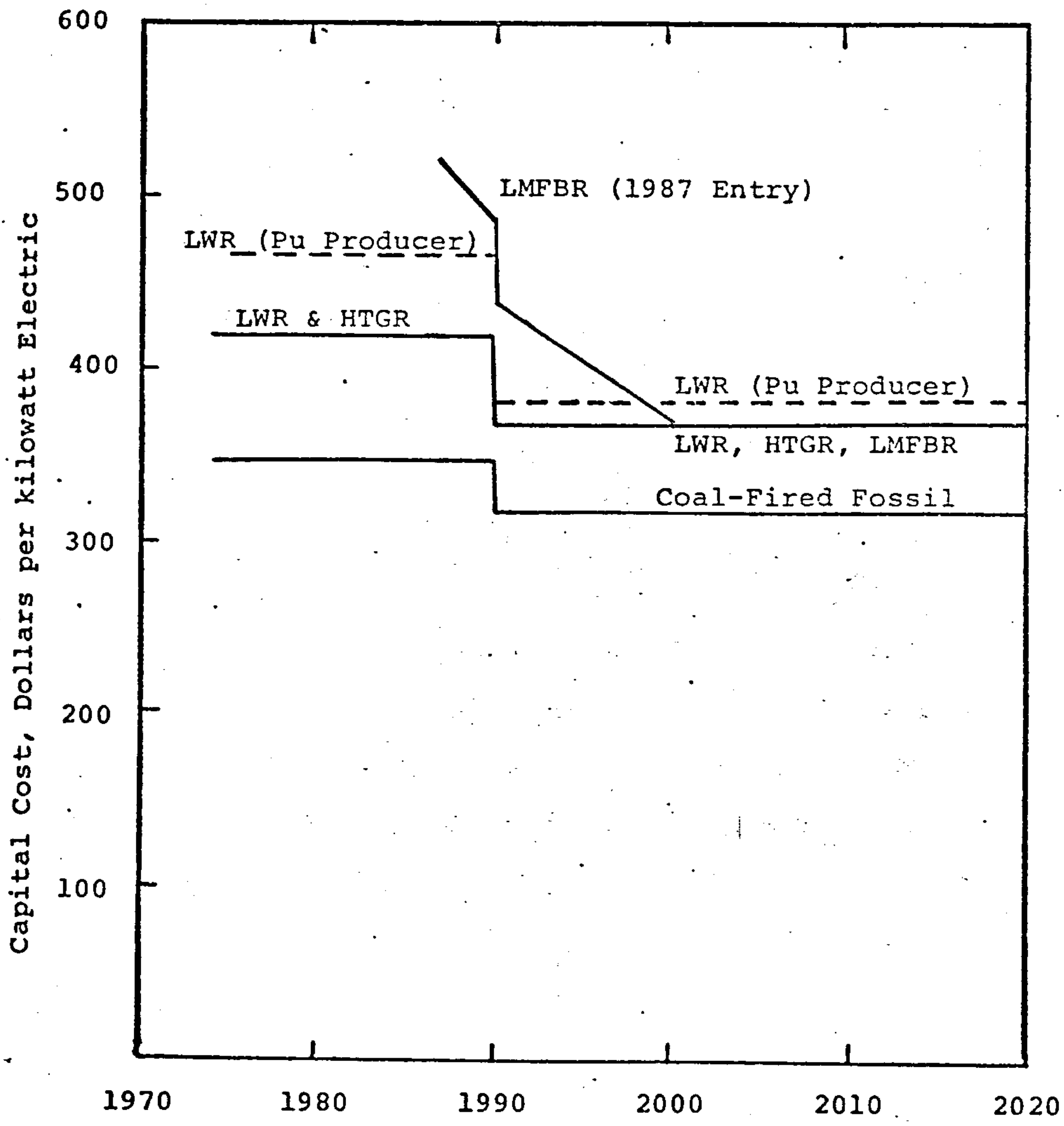
The AEC has assumed that over time the more reactors that are built, the more the industry learns in process, and the cheaper they become. The AEC has also assumed that as the plants become bigger the cost per kilowatt of energy produced becomes less. The first is a learning effect, the second is called a cost reduction through economies of scale.

Learning curves are clearly seen in trends in transistor costs and airplane assembly line production costs. The more units you produce the cheaper the cost per unit. Let's examine whether this assumption applies to reactors.

Notice from Figure 6 that in the 1968 analysis the AEC assumed that light water reactors would cost $150/kilowatt, and the price would go down over the years between 1970 and the year 2020. In fact, between 1968 and the next analysis, conducted in 1970, the price of light water reactors didn't go down. It went up to $250/kilowatt as seen from Figure 6. The capital cost of light water reactors assumed in the latest AEC analysis could not be plotted in Figure 6. It is off the page. As seen in Figure 7, the LWR capital cost (in constant dollars) is now around $400/kilowatt. We see that while the AEC assumed the cost of power plants would go down, in fact they've risen astronomically.

The absolute numbers are not so important. The cost differential is. It is seen from Figure 7 that the AEC assumed in the latest cost-benefit analysis that the LMFBR would cost $100/kw more than a LWR in 1987. One hundred dollars/kw translates into about 2 mills/kwh. With this capital cost difference the LMFBR clearly cannot compete economically with the light water reactor, because the LMFBR would have to save that 2 mills/kwh in the fuel cycle costs. But the fuel

Figure 7: Projected Plant Capital Costs Used In AEC's 1973 Cost-Benefit Analysis of the U. S. Breeder Program.

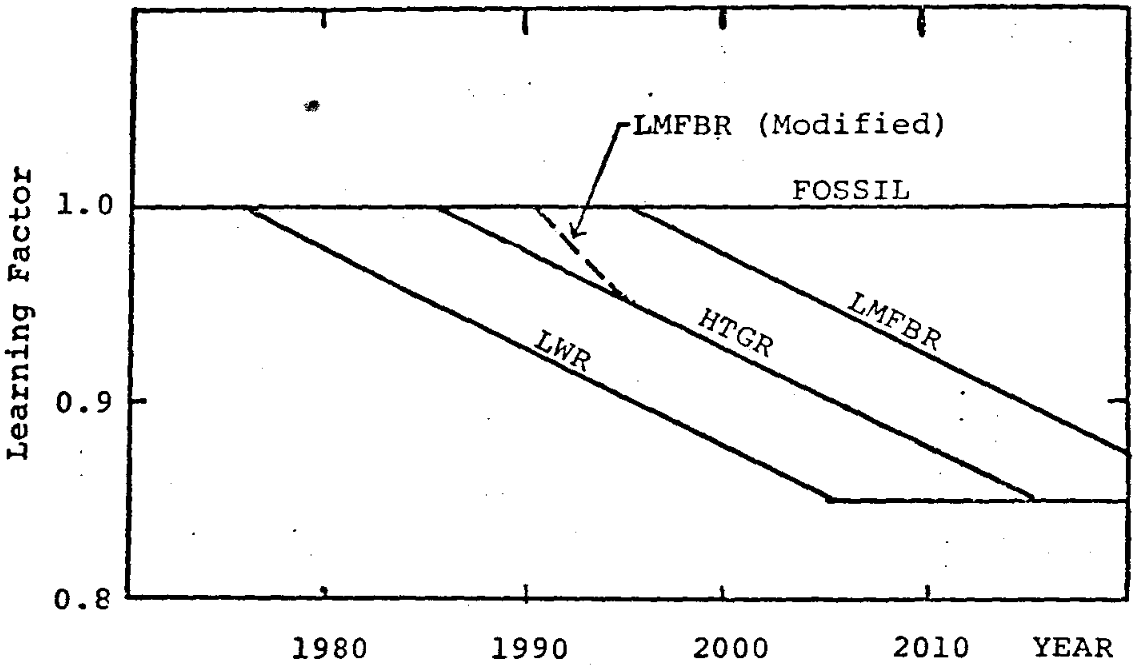


Note: The discontinuities in the curves in 1990 are due to the assumption that plant unit sizes will increase from 1300-Mw to 2000-Mw which in turn will effect a cost savings on a per kilowatt basis.

cycle costs in a light water reactor today are about 2 mills/kwh, and we know the LMFBR is not going to have a zero fuel cycle cost. If you were promoting the LMFBR program and wanted to generate benefits, to justify the program economically, you might be tempted to reduce the cost differential on paper at least. One, for example, could project a higher rate of learning for the breeder than the LWR thereby reducing the capital cost differential. Let us examine what the AEC has done.

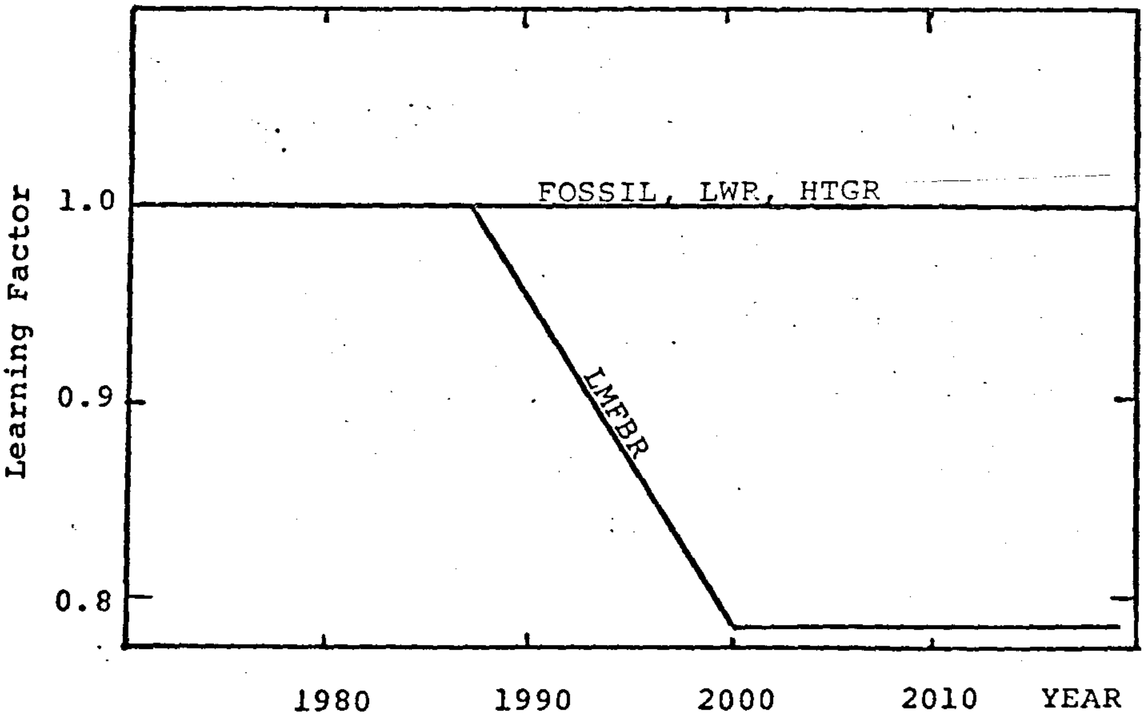
As seen from Figure 7, between about 1988 and the year 2000 the capital cost difference between the LMFBR and the LWR has been reduced to zero. The computer would then see the total costs of the LMFBR as cheaper and project that no more LWRs would be built. Furthermore, these cheaper reactors would equate to cumulative energy cost savings which are enormous. But the only reason you get those large savings is because they have arbitrarily assumed that the cost differential goes back to zero. So the learning curve is a key assumption. If you took the learning off of the LMFBR you would in effect lose most of the calculated benefits and the computer program would say LMFBRs would not be economical until sometime into the next century. In sum, the AEC couldn't justify the LMFBR program. In the previous (1970) cost-benefit analysis, the AEC applied the learning factors in Figure 8a to project the cost trends of the various reactor types. The best in a given year is found by multiplying a base cost by the learning factor for that year. The AEC assumed that in the year 1975 light water reactors would start learning and costs would go down about 5% per decade. About 10 years after the high temperature gas reactor (HTGR) is introduced, its costs go down about

Figure 8: Learning Curves Assumed in AEC Cost-Benefit Analyses



(a) 1970 Analysis

Source: Howard I. Bowers and M.L. Myers, "Estimated Capital Costs of Nuclear and Fossil Power Plants," Oak Ridge National Laboratory, ORNL-TM-3243 (March 5, 1971), p. 20.



(b) 1973 Analysis

5% per decade until they are reduced to about 85% of their initial cost. Ten years after the proposed LMFBR commercial introduction date, the LMFBR followed the same learning curve. The latest cost-benefit analysis of the AEC assumed the learning factors in Figure 8b. Had they used the learning curves for the 1970 analysis, very few if any benefits would have been generated. The AEC removed the learning curves off of all the reactors except the LMFBR. The LMFBR is now the only reactor whose costs are reduced over time. This is what drives that cost differential back to zero. This is an example of the sort of the hanky-panky that goes on in the cost-benefit analyses to generate on paper program benefits.

Let's look at one more variable -- electrical energy demand. Because the data are convenient I will use results from the AEC's 1970 cost-benefit analysis. In Figure 9 are plotted as a function of year the historical electric energy demand or consumption in the United States, from about 1945 to 1970. The middle of the solid curves labeled "probable" is the AEC's best estimate of the demand through 2020. It is based on a 1970 Federal Power Commission projection out to 1990. The dotted curves represent another forecast based on a historical trend in electric energy generation versus GNP growth rate. As seen in Figure 10, there is a remarkable correlation between electrical energy demand and GNP between about 1947 and the present. By fitting a straight line to these data and then making an assumption about the GNP growth rate, Searl has projected energy demand functions represented by the dotted lines in Figure 9. Notice in the year 2000 the AEC projected an annual U. S. electrical energy demand of about 10 trillion kwh. Assuming a 3 1/2% GNP

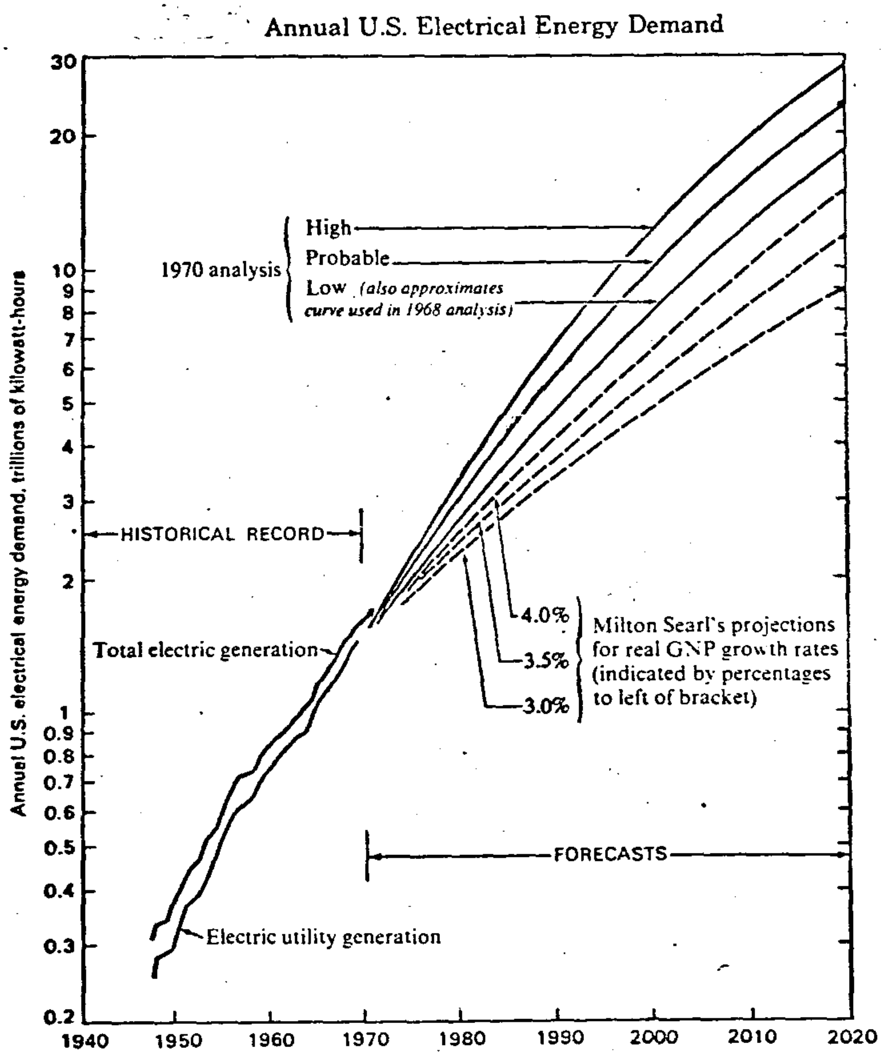
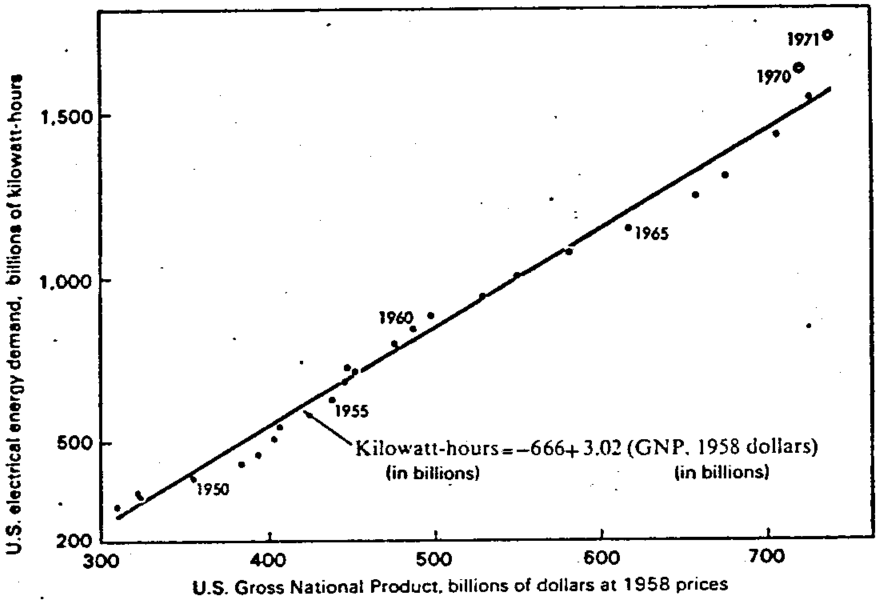


Figure 9

Source: Cochran, Thomas B., <u>op. cit.</u>, p. 111.

Correlation Between U.S. Electrical Energy Demand and Gross National Product, in Constant Dollars



SOURCE: Milton Searl, private communication.

Figure 10

Source: Cochran, Thomas B., <u>op. cit.</u>, p. 113.

growth rate and Searl's correlation, one projects between 5 and 6 trillion kwh. Because Figure 9 is a simi-log plot, it doesn't look like it, but you get almost half the energy demand in the year 2000.

New, let's look at the sensitivity of the AEC's cost-benefit results to the electrical energy demand assumption. Qualitatively, if electrical energy demand is reduced, fewer nuclear plants are built, and any projected benefits of the breeder would be less. Furthermore, less uranium would be required by the LWRs so the price of uranium would not go up so fast resulting in a lower LWR fuel cycle cost. The AEC performed a sensitivity analysis to see how the net benefits change with changes in energy demand. Figure 11 is from the latest cost-benefit analysis. Here the AEC's most probable energy demand number was estimated to be about 10.6 trillion kwh in the year 2000. If Searl's projection turns out to be correct -- recent events certainly point in that direction -- then the net benefits of the breeder are essentially zero. In other words, if the energy demand in the year 2000 turns out to be closer to between 5 and 6 trillion kwh, than 10 trillion kwh, then without changing any other assumptions (e.g., capital costs), all the so-called benefits of the LMFBR program are lost.

Where does this leave us? The controversy with respect to LMFBR economics which we have only touched on briefly, is a controversy about the selection of these key input assumptions, and whether in fact there are any net benefits to the LMFBR program. In my view, as I stated earlier, if you select reasonable assumptions today, you calculate that the breeder simply will not be competitive with the existing light water reactors. Of course, the AEC takes the opposite view.

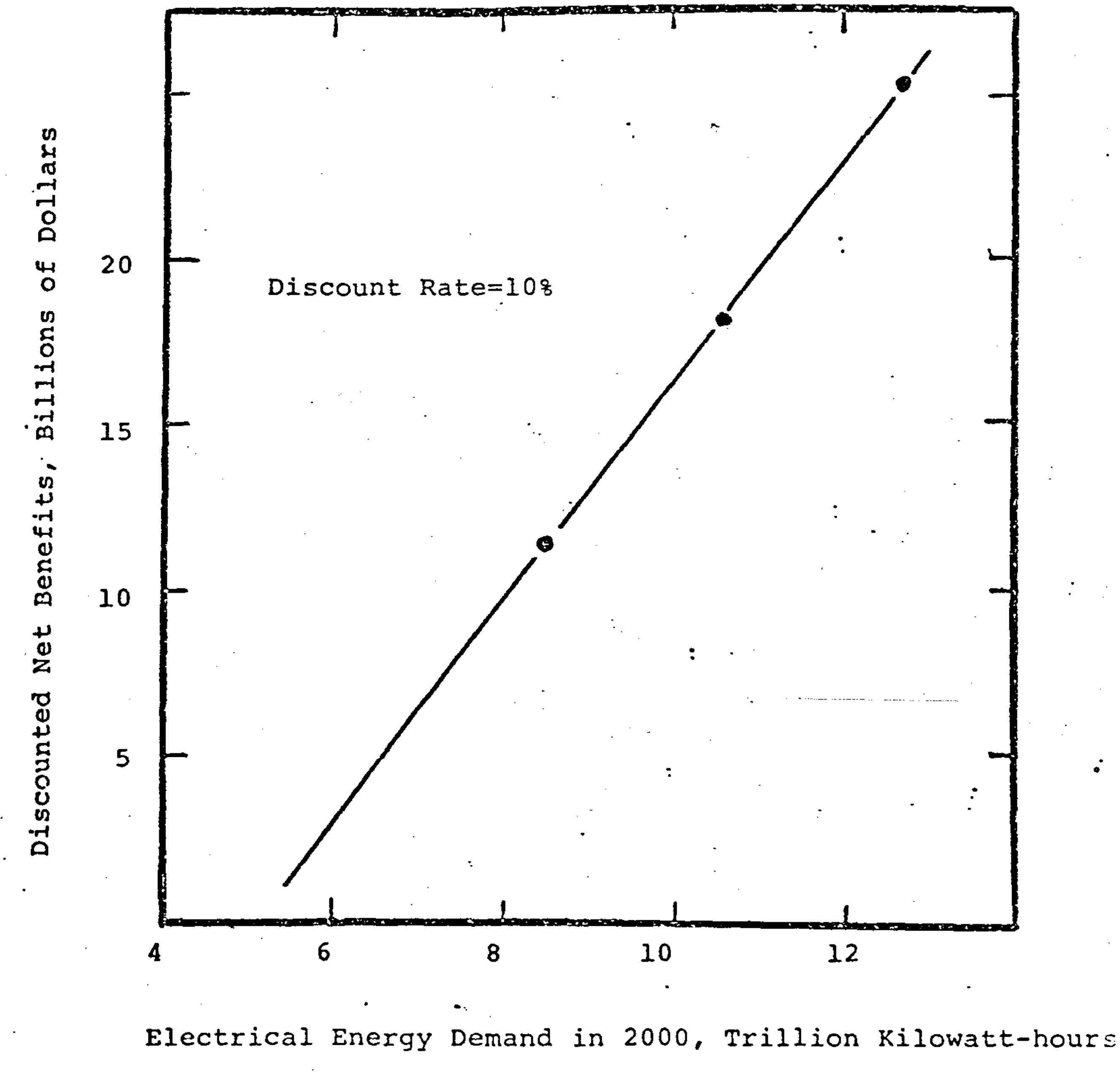


Figure 11. Sensitivity of 1973 Analysis Results to Changes in Electrical Energy Demand

Assuming I'm correct, does our federal energy R&D budget make sense? Historically we've spent far more money developing the breeder reactor than any other energy technology, with the exception of the light water reactor. The LMFBR became the priority energy program in the federal budget in about 1967. The LMFBR budget as a fraction of the total energy R&D budget grew between 1967 and 1973 to about 43 percent. The 1975 budget was put together at the height of the oil embargo and when the prevailing view was that we could not spend enough on energy. The total energy R&D budget jumped from about $1 billion to $1.8 billion. While the LMFBR budget increased by about $100 million to $500 million, the fraction of the total went down to about 28 percent. This is still a substantial fraction of the total energy R&D budget when you consider that all the other energy options, nuclear and non-nuclear, must be funded out of the same budget. In my view, given the present lack of economic justification for the breeder, we shouldn't be spending this much money on this single program to the expense of other promising alternatives. Other alternatives, for example, solar energy and geothermal are receiving comparatively little funding. The current geothermal funding level is $45 million, and $60 million for solar energy.

Two federally sponsored solar energy panels, the NSAS/NSF Panel and the AEC's Panel IX, have concluded that solar energy should be funded at a higher level. The AEC's Panel IX, reporting to Dixy Lee Ray as part of her $10 billion energy study for President Nixon, stated that an orderly accelerated solar energy program could absorb something like $100 million in FY 1975, whereas solar energy was only allotted $60 million in that year. This, I believe, is an example of an under funded technology. Geothermal fits in the same category.

There are some disturbing features about the proposed LMFBR program budget. As seen from Table 3, in 1968 the LMFBR was estimated to cost about $2 billion. Actually, most of the "Support Technology" budget listed in this table is LMFBR money, so "Total Breeders" is more representative of the LMFBR budget. The estimated cost-to-completion of the LMFBR has grown over the years and in 1973 the cost-to-completion was estimated at $6.8 billion. The unofficial number is now between $8 and $10 billion. The federal government has already spent about $1.6 billion to $2 billion on the LMFBR program, most of this between 1967 and 1974. It is clear that the more we spend on the program, the greater the estimate of the cost-to-completion of the program, even in constant dollars. This is somewhat disturbing because it says the more you spend the more you learn it's going to cost to finish the project. While not really fair, an extrapolation of this trend would suggest the total costs of the project would be infinite. Figure 12 is a curve of the estimated cost of the Clinch River Breeder Reactor, the LMFBR demonstration plant. This is a major component of the LMFBR program. In 1971, it was estimated to cost about $400 million, in late 1972 roughly $700 million and now it's up to $1.7 billion. In other words, the cost estimates in the last year or so have been increasing so fast that they have been doubling on an annual basis. Clearly when you examine the LMFBR budget and the cost of some of the key items in this program, they are increasing at an alarming rate that cannot be attributed to inflation. This is not unlike the overruns that have occured in programs like the SST and the G-5A.

In the remaining few minutes I want to say a few words about some of the environmental problems of the LMFBR. The disadvantages

Estimates of the Undiscounted Breeder Program Expenditures from AEC Cost-Benefit Analyses.

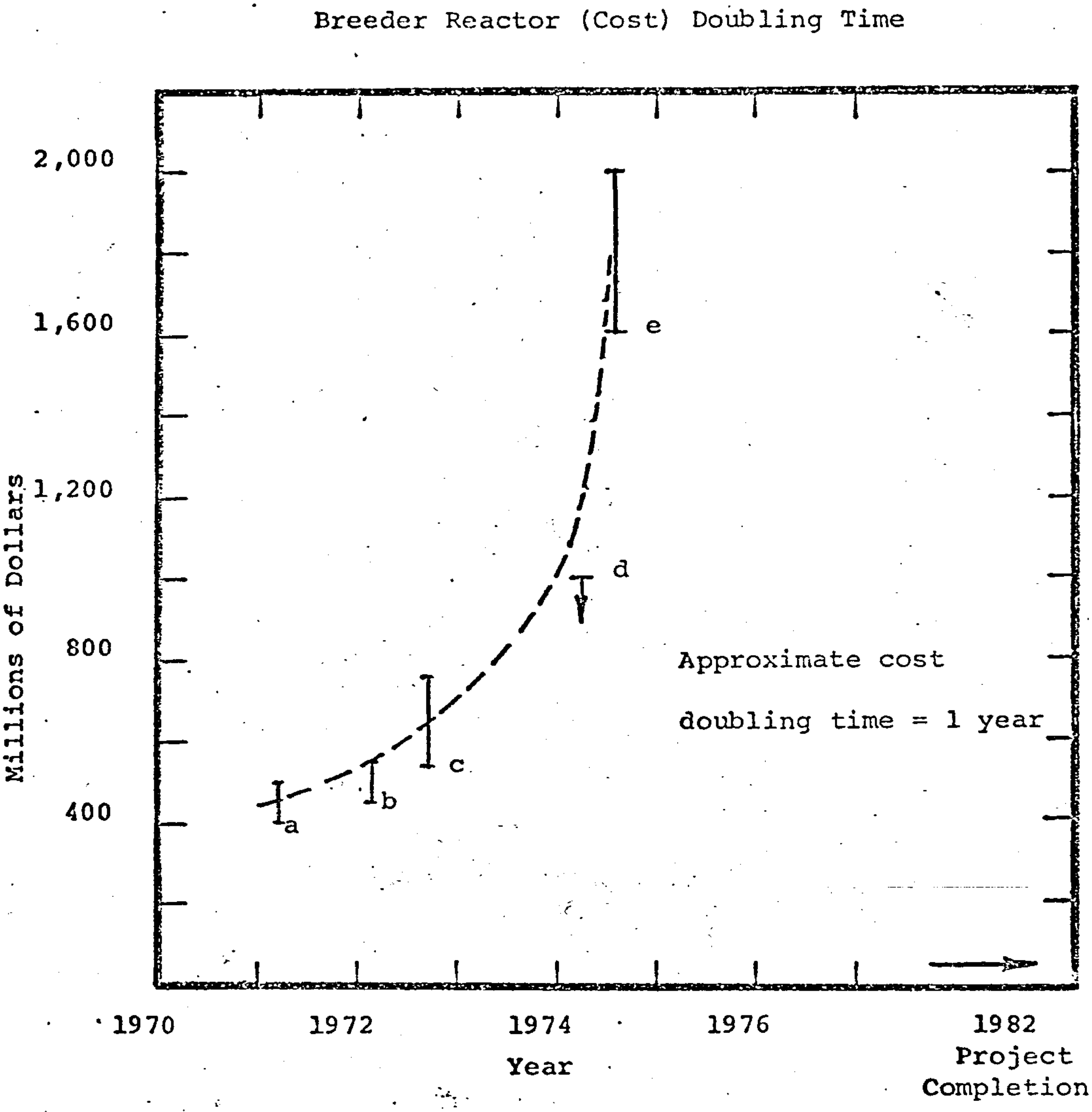
	1968[21] Estimate	1970[22] Estimate	late-1973[23] Estimate
Breeders			
LMFBR	2.2	2.5	4.0
Other Breeders	0.8	0.1	0.2
Support Technology	1.4	1.2	2.6
Total Breeders	4.4	3.8	6.8
Non-Breeders	0.7	0.5	0.5
General Support	2.6	2.5	(not given)

21/ U.S. Atomic Energy Commission, WASH-1126, Op. cit. 1986 LMFBR Introduction.

22/ U.S. Atomic Energy Commission, WASH-1184, Op. cit. 1986 LMFBR Introduction.

23/ Draft EIS, Vol. III, Appendix III-B, p. 3-6. 1987 LMFBR Introduction.

Table 3



AEC Estimates of the Range in the Cost of the Clinch River Breeder Reactor.

Sources:
- (a) JCAE Hearings, AEC Authorizing Legislation - FY 1972, p. 702.
- b) JCAE Hearings, AEC Authorizing Legislation - FY 1973, pp. 1156-1159.
- c) JCAE Hearings, LMFBR Demonstration Plant, Hearings, p. 44.
- d) Nucleonics Week, 15, March 21, 1974, p.1.
- e) Weekly Energy Report, 30, July 29, 1974, p.1.

Figure 12

of the breeder reactor are that for the most part it exacerbates many of the disadvantages common to all sources of nuclear fission energy -- for instance, the safeguards problem as it relates to diversion of plutonium. With a breeder economy you would have a plutonium throughput in the fuel cycle roughly three times what you would have operating with light water reactors recycling plutonium.

The reactor safety issue is somewhat complicated in the LMFBR case. It would take more time than I have to develop it here. As most, if not all of you are aware, the LWR safety debate is principally with respect to whether one of these reactors will lose its coolant as a result of a pipe break and the emergency core cooling system subsequently fail to operate. It is generally assumed that the core would melt and then there is further debate as to the quantities of the gaseous and volatile fission products that would be released. A substantial fraction of these released from the containment could kill large numbers of people and contaminate large areas of the country. The LMFBR safety issue, rather than being related to meltdown of the core and subsequent release of the fission products, centers around whether the LMFBR can undergo a nuclear explosion. Such an explosion, while very mild compared to a bomb, possibly could be sufficient to breach the containment. One can postulate a condition where a fraction of the core material would be vaporized; something between a few kilograms and a maximum of about two tons of the plutonium in the core. If the explosion were sufficient to breach the containment -- here I'm talking in terms of an explosion on the order of 1,000 pounds of TNT -- then there's the possibility that a substantial fraction of vaporized material would be released from the reactor vessel and ultimately to the environment as it leaks from the second containment. And if the explosion is, as some people believe, very small, on the order of a few tens of pounds of TNT, then the explosion would be easily contained be the strength of the reactor vessel. Other people believe you can not rule out the possibility that the explosion could be much larger, on the order of several hundred pounds of TNT equivalent, or even on the order of 1,000 pounds of TNT (a few people will not rule out numbers an order of magnitude larger). Above several hundred pounds of TNT equivalent and you're talking about the possibility of releasing substantial quantities of the plutonium inventory. Plutonium is one of the most toxic of the radioactive materials in the reactor. It is possible that such an explosion could have much more severe consequences than the LWR meltdown accident. This concerns many people today.

Whether an LMFBR is safer or less safe than an LWR is strongly dependent on assumptions about whether you can shut the reactor down reliably with the control systems. If you assume that the controls systems are sufficiently reliable then the LMFBR is probably safer (from the large reactor accident) than the light water reactor. After you shut an LMFBR down, the liquid sodium serves as very good heat transfer fluid and you're probably less likely to have a meltdown of the core. The LMFBR is a low pressure system so one doesn't have the same worry about pipe breaks that one has with respect to light water reactors operating with high pressure steam. In the light water reactor following a large pipe break, even if you shut down you can still get a core meltdown if the emergency cooling system doesn't operate. In the LMFBR you have to assume that the shut down systems fail in order to produce substantial core melting. If you assume that the two shut down systems fail to operate concurrently with, say, a failure of power to the sodium pumps, then you can postulate accident sequences that can get you into real trouble, and you can postulate very large energy releases. So the debate here is whether the sequences of events you have postulated are credible.

In analyzing the LMFBR accident scenarios one runs into problems immediately when trying to model postulated sequences of events in the accident scenario using computer codes. After the fuel starts melting you want to throw up your hands. It's virtually impossible to model physically what's happening once the fuel rods begin to melt and the core geometry begins to change substantially. The tendency, once this happens, is to jump from that point in the analysis to a later point where some very arbitrary assumptions are made regarding how this fuel might recompact itself leading to one of these explosions, or how the fuel might be swept out of the reactor core region shutting the nuclear reaction off. There's a tremendous gap in our knowledge, making it very difficult to predict the intervening sequence of events. This in turn leads to the debate over the intensity of the postulated explosion.

We are out of time. Perhaps we can open it up for questions.

Q: On one of the charts [Figure 4] you showed you had sensitivity of electrical costs to fuel costs, and you had a plot of the curve for light water reactors, a plot for breeder reactors, and a plot for high temperature gas reactors. The question is why there is a fairly sharp distinction between the costs of the light water reactor and the high temperature gas reactor. On the ordinate you had costs of electricity in mills/kwh and on the abcissa I think you had costs of the fuel.

A: All of these reactors convert some of the non-fissile material such as U-238, to fissile material. The HTGR converts thorium to U-233. Although it's not efficient enough to breed more fissile fuel than it burns, the HTGR does this conversion more efficiently than the light water reactor. It has a conversion rate that's higher. Therefore, the HTGR over its lifetime requires less makeup fuel, and therefore is less sensitive to price.

Q: In your report, "Radiation Standards for Hot Particles," you point out that you believe that the AEC radiation protection standards limiting the amount of exposure to plutonium to the public are roughly 100,000 times too lax -- would you tell us what the reasons are for that conclusion?

A: The plutonium in the nuclear fuel cycle is generally in the form of plutonium dioxide, PuO_2. This material is released routinely, and can be released accidently as small aerosol size particles. When inhaled, some fraction of these particles are trapped in the deep respiratory tissue. Since PuO_2 is insoluble in human tissue these particles remain there for long periods of time. If PuO_2 were soluble, they would move more rapidly to other organs such as the bone, liver and lymph nodes.

Present radiation standards are based on the assumption that it is appropriate to calculate the average dose or dose rate to the entire organ at risk. An occupational worker is allowed to receive 15 rem/year to the lung. The dose in rems can be thought of as proportional to the energy deposited per gram of tissue.

A single particle of PuO_2 does not irradiate the entire lung. The alpha radiation from Pu-239, for example, only travels a few tens of microns in tissue, and a particle of $^{239}PuO_2$ one micron in diameter only irradiates 65×10^{-6} grams of lung tissue compared to the 1000 gram mass of the lung. This single particle irradiates the local tissue immediately surrounding the particles (the 65×10^{-6} grams) at a dose rate of 4000 rem/year. However, when averaging the energy deposited over the entire lung including tissue that is not irradiated, the dose rate from the same particle is only 0.0003 rem/year.

In our view, based on the limited relevant biological data, the probability of getting cancer from a single particle lodged in the lung such as the one just described may be on the order of one in 2000. Under the present radiation standards one could have between 50,000 and 60,000 such particles in the lung. If the risk per particle is 1/2000, you can appreciate the need to lower the standard.

There are major uncertainties in the values we have selected for the risk per particle and the minimum activity of an alpha particle earning this risk. The factor of 100,000 falls out from our choice of these values which again are based on limited biological data.