FUSION-FISSION ENERGY SYSTEMS
SOME UTILITY PERSPECTIVES

by

Raymond A. Huse
Manager - Research and Development
Public Service Electric and Gas Company
Newark, New Jersey

James M. Burger
Associate Research Physicist
Public Service Electric and Gas Company
Newark, New Jersey

Michael Lotker
Associate Scientist
Advanced Energy Conversion Research
Northeast Utilities
Hartford, Connecticut

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I  INTRODUCTION

While fusion researchers point to a commercialization date by the year 2000 for thermonuclear reactors, the subsequent introduction of these devices on utility systems will be governed by incentives of reliability, economy, safety, and environmental compatibility demonstrated in earlier research phases. First generation fusion reactors, subject to all the uncertainties of any new energy conversion technology along with the extraordinary challenges of the D-T fuel cycle, exotic structural material requirements, superconducting magnet and/or laser technology, may well be less attractive than fission or coal fired generation options in this time frame.

The principal attraction of fusion-fission energy systems lies in the potential for relaxing some of the engineering requirements of pure fusion systems. Although they may advance the date of commercial demonstration experiments by only some five to ten years, the more limited extension of state-of-the-art required and the enhanced reliance on proven technology may accelerate the utilization of the hybrids by utilities. Furthermore, these systems offer the utilities an interim alternative which should smooth the transition from fission to fusion dominated generation of electricity with a minimum of risk. During this
interim period, which may be as long as 50-100 years or more, fusion-fission hybrids can effectively contribute to the solution of the pressing fuel availability and waste disposal problems of the fission economy. If studies currently underway and shortly to begin support the technical and economic promise of these systems' enhanced relevance to our energy future, an increased priority for fusion research should result.

Below we discuss some of the issues that will be important in assessing fusion-fission energy systems from a utility perspective. We begin by making a number of qualitative systems-oriented observations and then attempt to give some economic quantification of the benefits from fusion-fission hybrids and their allowed capital cost.

II ADVANTAGES OF A FUSION-FISSION OPTION

A preliminary economic analysis such as the one presented below suggests that there are strong incentives to make use of the large amount of heat liberated in a fusion-fission hybrid. However, a closer analysis indicates several advantages for a device that breeds fissile fuel and/or burns fission waste products without generating electricity for external sales. In this regard, breeding U-233 from thorium appears preferable to plutonium production from U-238 due to the lower rates of heat generation in the former case and the consequently reduced penalty for not utilizing heat. In any final commercial decisions, economic considerations will be of major importance, but these other issues could also be of substantial
significance.

In the following, some of these issues are presented with special emphasis on non-electrical fusion-fission systems.

1. Perhaps the most obvious advantage for a basically non-electrical fusion-fission device results from eliminating the constraint of instantaneous reliability. While total on-line hours per year will still be critical for economic feasibility, the impact of a momentary failure, potentially quite serious on an electrical system, would, for this hybrid, be negligible. Such decoupling from electrical power production supports the practicality of very large sized units that seem to be indicated for many fusion systems, because it eliminates the need for a large amount of back-up generation (spinning reserve) which otherwise would be required. The pulsed nature of the Tokamak causes no problems for this concept (the UWM-1 has a burn time of 90 minutes followed by a recharge time of 6.5 minutes). Similarly foregoing electricity production may reduce the reliability constraints upon the laser in laser fusion concepts, as the impact of missing a few shots every now and again would be minimal. Reduced reliability requirements should lower costs in numerous other areas.
2. Optimization of breeding at the expense of electrical production has advantages from the standpoint of handling the heat produced. In particular:

(a) if one is not concerned with surrounding the fission blanket with a superconducting magnet, such as in a laser system, the required power density can be made low enough to reduce safety concerns, e.g., a loss of coolant accident.

(b) Since the principal product is fuel rather than electricity, thermodynamic efficiency has relatively less importance. Therefore a power density and thus a blanket temperature could be selected in either a laser or magnetic confinement system that would permit rejection of heat at temperatures high enough to make dry cooling practical. The independence of a need for cooling water with dry cooling would result in additional flexibility in siting and licensing.

3. There is the strong possibility that a separate business entity would own and operate a fuel producing device. This would be significant in that the price for the fissile fuel produced, or waste products disposed of, would probably not be set by a state regulatory body, although federal regulation as in the case of oil and gas today might still occur. The
company would have a market as broad as the entire fission economy (i.e., worldwide) rather than one strongly tied to a narrow operating area. The business operations would thus be optimized for fuel production and/or waste disposal leaving the utility to concentrate on electricity production.

4. The non-electrical option allows the utilities to optimize for the generation of electricity with the (by then) mature LWR and HTGR nuclear technologies. Increased reliability and efficiency in utility operations would be major results. The approach is the one which changes the electrical utility business least, an advantage for any technology trying to gain utilization and a strong reason to suspect that the time scale of introduction (after commercial demonstration) will be rapid. This, combined with the shorter research program to demonstration that will be probable with a simpler device, means that this concept can be considered to have mid-term (before 2000) relevance. The case for the high priority of fusion research should therefore be strengthened even further.

5. The potential for a device to transmute certain fission waste products, as well as breed fuel, has psychological, sociological, and philosophical significance. It offers a way to lessen the burden on future generations to guard
radioactive wastes for thousands of years, requiring potentially unrealistic assumptions about the longevity of our societal institutions. While recycle of radioactive wastes (principally the actinides which are the longest lived) has been discussed in the case of breeder reactors, such fusion-fission devices with their harder neutron spectrum offer some fundamental advantages. The promise of such transmutation, we believe, could have an immediate impact on the current nuclear energy debate.

6. This concept fits well into the nuclear park arrangement which might consist of several fission reactors, a fusion breeder and waste burner, a fuel reprocessing plant, and a short-term storage facility. The safety and security implications are obvious.

7. A device that does not produce electricity for electrical sales may generate power for on-site consumption (i.e. for neutral beams, lasers, etc.). It may therefore be possible to make use of some of the thermal energy generated without sacrificing the above advantages of a non-electrical fusion-fission breeder. The final design configuration will be determined by system optimizations beyond the scope of this paper.
From a national priorities viewpoint, a fuel producer addresses a more critical problem than electrical power production, namely that of fuel supply. In fact, the motivation for developing the LMFBR is fissile fuel supply in future years, not electrical capacity.

To provide some indication of the need for breeding in a nuclear economy, two scenarios were compared for a projection of nuclear power growth to 2020 AD. The nuclear reactor requirements were assumed met either with LWR's or the mix of converters and breeders shown in Figure 1. The breeders shown could either be commercial LMFBR's and advanced fast breeders, or the advanced breeders could be fusion-fission energy systems. The illustrative discussion below is carried out in terms of plutonium bred from U-238 but the production of U-233 from thorium is an alternative option. It should be emphasized that the plutonium or U-233 production characteristics of fusion-fission hybrids and fast breeders may be substantially different.

A comparison of the mined uranium and enrichment requirements for these two scenarios (all LWR's, or converters and breeders) provides a measure of the economic incentive for breeders. The breeder scenario indicates a strongly advancing breeder technology and hence provides a reasonable basis to assess the maximal fuel cycle savings with breeder development. A less rapid rate of breeder introduction appears more likely.
LWR's are seen to be phased out after 2010 and all new capacity thereafter is provided by commercial and advanced breeders. HTGR's are seen to decline to a significant but modest level. The analysis is terminated arbitrarily at 2020 AD.

Figure 2 shows the U₃O₈ (yellowcake) requirement if the nuclear capacity forecast shown in Figure 1 were met with light water reactors (LWR's) employing plutonium recycle or with the mix of converters and breeders shown.² In the latter case the initial plutonium requirements for the breeders are met with that produced in LWR's; no plutonium recycle in LWR's is assumed although plutonium would be available for the assumed breeder capacity. The depleted uranium for breeders would be available from stockpiled enrichment plant tailings. The U₃O₈ requirements shown in this time frame thus arise from the predicted LWR and HTGR capacities forecast and are not influenced by breeder requirements. Higher breeder performance permits more plutonium to be recycled, however, and reduces U₃O₈ requirements.

The uranium reserves are shown in Figure 3 as a function of the ore concentration levels and the corresponding price as estimated by the AEC.¹,³ The ore costs at a given concentration are less than those currently being paid today (by a factor of 2) but they do provide an indication of ore costs.
The figures shown are thus conservative. There is considerable uncertainty regarding uranium resources and more uranium may exist at lower prices. Figure 4 shows the cumulative ore savings based on the ore prices of Figure 3 without escalation. While the uncertainties in ore cost and nuclear capacity make any detailed economic analysis uncertain, this capacity and ore cost forecast indicates a cumulative savings on ore alone of almost $300 billion between the years 2000-2020.

The use of LWR's, in contrast to breeders, requires enrichment and the amount of enrichment (in separative work units) for the two reactor scenarios (LWR's only, and breeders and converters) are shown in Figure 5. A separative work unit is required to make 1 kg of uranium with twice the U$^{235}$ enrichment of natural uranium.) Corresponding savings for enrichment are shown in Figure 6 and indicate cumulative savings through 2020 of $75 billion. Enrichment costs are based on the current AEC charge of $47.80 per separative work unit, which will certainly increase in the future.

The savings calculated by comparing these two scenarios can be translated into today's dollars, i.e., their present worth can be calculated. This provides an estimate of the maximum cost of a fusion-fission hybrid research program (in 1974 dollars) that one can justify on the basis of anticipated
fissile fuel cost and enrichment savings. To compute this present worth, one calculates the sum of \((1+i)^{-n}\) times the annual expense where \(n\) is the number of years after the reference year, e.g. 1974. For purposes here, let us make the rough assumption that the cumulative savings are all made in the year 2015 AD (c.f., Figures 4,6) and the interest rate \((i)\) is 10%; then the present value of these savings, say in 1974, would be \((300 \times 10^9 + 75 \times 10^9) / (1 + 0.10)^41 = $8\) billion.

The foregoing two scenarios thus suggest that the ore and enrichment savings from a breeding capability (through 2020) could have a value today on the order of $8 billion. This could be taken as an upper limit on what the U.S. should be willing to spend for R&D today in this area provided that breeders cost no more per electrical kilowatt than converters. If breeders have higher capital costs than converters or are not electricity producers, the R&D expenditures justified in the above way would be reduced.

The research program would be spread out over a number of years, however, for example, from now until 2000 AD, when (c.f. Figure 1) advanced breeders are indicated as commercial. For this period, the $8 billion present worth is equivalent to a $900 million annual R&D expenditure for breeders.
Other portions of the fuel cycle will also have somewhat differing costs depending on whether LWR's continue to be used (through 2020) or whether breeders are introduced. Plutonium is more costly to fabricate than uranium but even with only LWR's, plutonium will still be recycled, entailing extensive plutonium fabrication.

IV PLANT ECONOMICS

Clearly, the cost of a production plant must be directly related to minimum cost for which its product can be sold to break even. The cost of the plant is composed of two portions, namely the initial capital cost, and the operating and maintenance cost, which may be quoted on an annual basis. In the case of nuclear fission or fusion plants, the capital cost dominates and we will confine ourselves to considering this major cost component.

For a non-electrical breeder the minimum allowable price of the fuel produced (dollars per gram) is simply related to the unit capital cost of the plant (dollars per gram per year) through a percentage of the capital cost called the carrying charge. This carrying charge is determined as the percentage of the capital cost that must be earned annually to pay for the plant over its lifetime; the principal components are
interest, depreciation, and Federal and local taxes. This relationship is given in Appendix A by setting \( e = 0 \) in the equation.

The relationship for a 15% carrying charge is illustrated in Figure 7. For example, if plutonium (or U-233) can be sold for $30 per gram, the maximum allowed capital cost for the plant is $150 per gram per year (see * on Figure 7). For a capacity of 1.5 tonnes/year of plutonium, as has been discussed, the allowed plant cost would be $225 million.

If the plant produces electricity as well as nuclear fuel, revenue is derived from both products. In this case, a question arises as to how much of the costs should be allocated to each of the products. Furthermore, the capital cost is not accurately reflected by the capital cost per unit of one of the products, i.e., by $/gram/year as presented in Figure 7.

To illustrate the interrelationship of the two products, the cost to produce a unit quantity of plutonium (or U-233)* can be related to total capital cost with electrical revenues as a parameter. In Figure 8 both plutonium production without electricity generation and with 1000 MWe at 75% capacity factor in an electrical breeder are illustrated. For the cases of electrical power generation, electrical power credits of 10 and

*This discussion and Figure 8 are given in terms of plutonium. The same discussion and numerical values are also true for U-233 produced from thorium.
were computed from the capital cost using a carrying charge of 15% as above. The equation for the curves is given in Appendix A.

Two plutonium production capacities are illustrated. The lower annual plutonium production rate is the same as that for a 1000 MWe LMFBR (advanced oxide) and the larger for a production rate 10 times as great, which appears readily achievable in a fusion-fission breeder. A capital cost of $500 million would correspond to a 1000 MWe electrical power-plant unit cost of $500 per KWe, which is roughly what is projected for the LMFBR. The value discussed with regard to no electrical production and shown by a * in Figure 7, is similarly indicated on Figure 8.

The curves indicate that, as expected, the unit cost of plutonium is reduced by the concurrent generation of electricity for a given plant capital cost. Increasing plutonium production capacity also reduces the production cost of plutonium.

The current value of plutonium is about $10 per gram based on the cost of the equivalent reactor fuel as uranium. Assuming a future fissile fuel market value of $30 per gram, the following allowed capital costs for the cases considered obtain (see Figure 8 and Appendix A).
TABLE 1

BREAKEVEN PLANT COST
(MILLIONS OF DOLLARS)

<table>
<thead>
<tr>
<th>Plutonium Production Capacity</th>
<th>LMFBR (15k)</th>
<th>HYB PID (3k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kilograms per year)</td>
<td>0</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>10*</td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td>20*</td>
<td>2000</td>
</tr>
</tbody>
</table>

Electrical Power Cost (mills per kWh)

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>22</th>
<th>225</th>
<th>450</th>
</tr>
</thead>
<tbody>
<tr>
<td>10*</td>
<td>460</td>
<td></td>
<td>660</td>
<td>890</td>
</tr>
<tr>
<td>20*</td>
<td>900</td>
<td></td>
<td>1100</td>
<td>1330</td>
</tr>
</tbody>
</table>

For these electricity and fuel production capacities and prices, the effect of electricity product and credit substantially alters the allowed capital cost for the plant. An electrical capacity of 1000 MWe corresponds to the largest electrical powerplants being built today; clearly for less electrical power production, the effect is also less.

With little or no electrical production, as in the first case, the allowed capital cost is sensitive to plutonium production capacity and plutonium price. However, for 1000 MWe of base-load output, a major portion of the revenue requirements are met through electrical sales so the effect of plutonium production capacity on breakeven capital cost is less (c.f. Table 1).

*1000 MW of electrical generation at 75% capacity factor is assumed.
One can also express the breakeven capital cost of the plant on the basis of unit thermal (or electrical output) and Figure 9 shows this plotted as a function of the ratio of fissile fuel to heat production, $\gamma$. Curves (see Appendix A) are plotted for no electricity production and 1000 MW of electricity generation (75% capacity factor); the electricity is shown at 10 and 20 mills/kWh, and fissile fuel, e.g. plutonium, is taken at $30 per gram.

The vertical lines indicate several values of $\gamma$ discussed in the literature. The values of $\gamma$ shown as Reference 7 are for a lithium and U-238 blanket (larger $\gamma$), and a lithium, U-238 and 4% plutonium blanket (smaller $\gamma$). The capital cost for a beam driven tokamak reactor (TCT) has been estimated to be on the order of $800 million. For power levels with these two blankets in this reactor of 6000 MW thermal (lower $\gamma$) and 2000 MW thermal (higher $\gamma$), the unit capital costs would be $130 per kW thermal and $400 per kW thermal, respectively. The corresponding production costs for electrical power can be seen from Figure 9 to be modest, indicating that such a system appears to have economic potential.

The question can also be raised as to the allowed capital cost of a fusion-fission plant burning up radioactive wastes (e.g. actinides) either with or without electrical generation. Figures 7
through 9 can be directly applied to this case if the words "plutonium production" are replaced with "radioactive waste consumption", i.e. grams (or kilograms) are interpreted as radioactive wastes consumed. For example, with reference to Figures 7 and 8 or Table 1, consider a plant producing no electricity for external sales and burning radioactive wastes for a fee comparable to the price of fissile fuel. Then for a 1500 kilogram per year waste burning capacity at a fee of $30 per gram of waste, the allowed plant cost would be $225 million. The economics of this application will clearly be determined by the methods and the associated price required by society for the disposal of radioactive wastes. The possibility of significant heat production from the burning of actinides in a fusion-fission system would appear to favorably affect the economics of such an approach through the realization of a significant credit for heat or electricity.

CONCLUSION
The above discussion indicates a number of systems incentives for the development of fusion-fission energy systems. In addition, a consideration of fissile resource and enrichment requirements for an expanding nuclear economy suggests substantial funds, on the order of billions of 1974 dollars, can be justified over the next half century for the introduction of high performance breeders. The allowed capital cost of the plant will depend strongly on fissile
fuel and useful heat production rates and the competitive market price of these products, as well as any credits for waste disposal.
References


7. J. D. Lee, UCRL-73952, June 1972; D. Jassby, private communication.


Appendix A

The relationship of product capacities and unit revenue requirements to plant capital cost (neglecting O&M) for the cases of plutonium and electricity production is as follows.

For 15% carrying charges, the annual cost to produce the two products (plutonium and electricity) is 0.15C. If this is set equal to revenues,

\[ 0.15C = n \cdot P_{th} \cdot 8760 \cdot 10^{-3} \cdot e + P_{pu} \cdot g \cdot f \]

where:
- \( C \) - capital cost in $ (15% carrying charges assumed)
- \( n \) - thermal cycle efficiency (1/3 assumed)
- \( P_{th} \) - plant thermal output in kW
- \( g \) - capacity factor, i.e. percentage of the year (8760 hours) that the plant operates (75% assumed)
- \( e \) - electricity price in mills/kWh
- \( P_{pu} \) - plutonium production capacity in grams/year
- \( f \) - price of plutonium in $/gram

This equation can be rewritten as

\[ f = (0.15C - 6.6Pee)/0.75Ppu = f(P_{pu},P_{ee}) \]

Where \( P_{e} = nP_{th} \) kilowatts and subscripts denote parameters.

This curve is plotted as Figure 8 for \( P_{e} = 0, 10^6 \) KWe; \( P_{pu} = 0.15 \times 10^6 \) g/yr, 1.5 \times 10^6 g/yr; \( e = 10, 20 \) mills/kWh.

Alternatively, the equation can be rewritten as

\[ (C/P_{th}) = 15e + 4.4 \times 10^4 \gamma f = G_{ef}(\gamma) \]

Where \( \gamma = P_{pu}/8760P_{th} \) grams/kWh. This curve is plotted as Figure 9 for \( e = 10, 20 \) mills/kWh and \( f = 30 \) $/gram.
US ELECTRICAL GENERATION CAPACITY FORECAST

ESTIMATED FUTURE NUCLEAR GENERATING CAPACITY, IN MILLIONS OF MEGAWATTS (ELECTRIC). AEC FIGURES UNTIL 2000; AFTER THIS, THE TOTAL ELECTRIC GENERATING CAPACITY IS ASSUMED TO DOUBLE EVERY 25 YEARS. ALL NEW CAPACITY IS ASSUMED TO BE NUCLEAR AFTER 2010. CONTRIBUTION OF VARIOUS TYPES OF REACTORS IS SHOWN SEPARATELY.

FIGURE 1
CUMULATIVE MINED URANIUM REQUIREMENTS

Note: Cumulative $U_3O_8$ requirements to year 1990 are $0.7 \times 10^6$ short tons.
REASONABLY ASSURED PLUS ESTIMATED
URANIUM RESERVES

FIGURE 3
CUMULATIVE COST OF MINED URANIUM

CUMULATIVE COST (BILLIONS OF DOLLARS)


FIGURE 4
CUMULATIVE SEPARATIVE WORK REQUIREMENTS

CUMULATIVE SEPARATIVE WORK UNITS (BILLIONS)

YEAR


FIGURE 5
CUMULATIVE COST OF SEPARATIVE WORK

FIGURE 6

CUMULATIVE COST (BILLIONS OF DOLLARS)

YEAR


LWR'S ONLY

BREEDERS AND CONVERTERS
REVENUE REQUIREMENTS
FOR PLUTONIUM
WITHOUT ELECTRICITY PRODUCTION

FIGURE 7
PLUTONIUM PRODUCTION COST AS FUNCTION OF PLANT CAPITAL COST

ANNUAL REVENUE REQUIREMENTS (MILLIONS OF DOLLARS PER YEAR)

CAPITAL COST (MILLIONS OF DOLLARS)

FIGURE 8
BREAKEVEN PLANT COST AS FUNCTION OF RELATIVE HEAT AND PLUTONIUM PRODUCTION

PLUTONIUM AT $30 PER GRAM

CAPITAL COST (DOLLARS PER KW THERMAL)

20 MILLS /KWH

10 MILLS /KWH

NO ELECTRICITY PRODUCTION

*VALUES OF $\gamma$ FROM REFERENCES 5, 6 & 7

PLUTONIUM TO HEAT PRODUCTION RATIO, $\gamma$

(10^-4 GRAMS PER KWH THERMAL)

FIGURE 9
QUESTIONS ABOUT FIRST PRESENTATION

Furth: I'd like to make one comment on the basic strategy. You consider two extreme cases if I understand you right; one where you make power and nuclear fuel and one where you just make nuclear fuel. The latter is nice because you don't have to worry about shutdowns; on the other hand, it has more trouble making the grade economically. I think one should consider also a plant which is making nuclear fuel and at the same time using its power production to make some chemical fuel, hydrogen, for example. That would then be a useful intermediate case. It would have the advantage of not being on line for some consumer and, at the same time, it would get a little bit more boost economically than one would get from nuclear fuel production alone, so that the combination might be viable.

Burger: Another thing you might do is generate electricity for internal use in the power plants. That was the example we used in the paper.

Lotker: If I could make just a comment. The strategy which appeals to me so much is that with a fuel producer alone the utility, which is already thinking on a long timescale as Ray (Huse) pointed out, has the option of continuing with what will be by then mature technology, namely light water reactors and HTGR's. So it doesn't have to take the risk of putting a new device on its system; the utility does its business, namely generating electricity with units of increasing reliability, and the fuel producer does its business.

Furth: In addition the fuel producers could make a little something on the side which you could put in your cars. They have to.

Wolkenhauer: I know you didn't directly, but have you looked at the cost of the electricity for running your "fuel production only facility" and its impact on the whole cost picture? Presumably if you are producing fuel only, there is a considerable consumption of electricity in running the plants. What is the order of magnitude here in your calculations?

Lotker: We really didn't address that point except insofar as the case where we produce no fuel. Those charges could be interpreted as having the cost of electricity production as part of the capital cost of the
plant. I think it's important to note that in this presentation we considered only capital costs. The costs you are talking about are clearly O&M costs and may turn out to be a substantial fraction of the total production costs. The electricity requirements, I think, will vary considerably from one concept to another. The laser has its own special requirements, as do things like neutral beams, power supplies and what-not. One hopefully would try to get around this, even in a plant that is only producing fuel, by generating electricity for onboard consumption.

Wolkenhauer: You may not know what that is (power consumption), but you can establish an envelope into which it must fall, like you have done for your capital costs.

Burger: Yes, one could do it but we didn't.

Holdren: The cumulative savings on the cost of uranium and on the cost of enrichment are quite sensitive to what you assume for the growth rate of electricity in the future. They are also sensitive to how much uranium you believe there is, and the final comparison on savings is quite sensitive to the incremental value of extra breeding ratio, in terms of how much you can afford to pay in capital costs for the plant compared to a converter or a burner of less efficiency. I wonder if you would comment on all three of these things. What did you assume for the growth rate of electricity? Whose numbers did you use for uranium, and how sensitive did you find the results to be if these numbers prove to be in error, as for example, the recent EPRI study suggests they may be? Have you looked at the incremental value of breeding ratio in comparison to, say, light water reactors and HTGR's?

Burger: The philosophy was to take one sort of mean case and see what types of savings you would have in order to get a feel for the order of magnitude, recognizing that there are a lot of uncertainties that are hard to quantify in detail. We took the Cornell workshops, of the past year, which were organized as an input to the recent five year energy budget planning. We took the projection of the growth rate they used which is roughly an electrical doubling time of 25 years. We took this as a typical case. It shows a very strong introduction of breeders and a very rapid phasing out of converter technology so as to give an upper limit on the kind of benefits you
might gain from the introduction of a breeding capability. We didn't make any effort to explore the whole range of parameters with regard to the EPRI study. I think that this is a mean case and not way out on the tails of the probability curve.

Lotker: I think what we were trying to do is to give those of you who are working in the fusion business and in fusion-fission hybrid systems some idea of the way a utility approaches the economics. Jim (Burger) prepared an appendix which gives a broad-brush look at things like what revenue requirements are, what kinds of cost of money we use, and what types of capacity factors we think may be typical. Then I think, using this framework you can go ahead and put in any prediction for uranium supplies or load growth that you care to, and you can come up with an indicated savings.

Burger: What you might do with the curve for the net savings on uranium with a strong breeder scenario versus an all converter scenario is convert those savings which might accumulate over 50 years into what you might be able to spend for a research program over 20 years, by present worth techniques, referring the money to a fixed period of time and then spreading it out over different periods. This could be used to gain an estimate of what you might be willing to spend for a research program. The savings indicated by our curves suggest that you might be able to spend a billion dollars a year between now and the year 2000 for breeder development. That would be sort of an upper limit, the upper limit coming from the assumption that the capital cost per kilowatt electric is the same whether you use fusion-fission hybrid or converter reactors.

Moir: I have been concerned from the point of view of designing one of these hybrids, about the price of plutonium and what it's worth. On some of the slides, you showed $10 per gram up to $100 per gram and, being a spread of about 10, it seems that's a very wide margin. I'm wondering what we need to know to pin it down a little more. I notice that it is quite steep for the case of producing 1500 kilograms per year of plutonium. Our example that we have worked out produces 1300 kilograms per year, essentially the same thing, and even if it would go up to $50 per gram, I think that would change the situation with...
respect to designing for fuel production rather than for electricity. So I'm wondering what you need to know to pin that worth down more accurately? How do the diffusion plants come into that?

Burger: Well, of course, one reason we showed a range is because, in a way, we're dodging that question. It's about $10 a gram today based on parity with uranium. In some of the examples we assumed that $30 per gram might be a reasonable escalation of this. We didn't really go into the details of what future plutonium prices will be other than to take $10 per gram today and expect to double or triple this, based on discussions and detailed analysis by others of future costs.

Lotker: I think the philosophy you can take today is to take it to the price of alternative fissile isotopes. Uranium prices are going to go up. The cost of the fissile isotopes will go up with the yellow cake prices and with the enrichment cost. The factor of the increase is not unreasonable. It is not a very large economic penalty to fission power in that the fuel costs are so low. So that is something that the industry can easily live with. In the future, of course, the price will be pegged on what the plant producing it will cost; namely what a hybrid or LMFBR will cost, and not an arbitrary price.

Burger: Diffusion plus the cost of the yellow cake is a substantial portion of the net fuel costs.

Jassby: There was a remark that Ray Huse made about the value of actinide transmutation, I think. He said that it was worth per gram the same as the value of plutonium. Is that correct?

Burger: There was some discussion of the possibility of transmuting waste; and not knowing what the value or cost would be to transmute waste, we said, just for one case, suppose that society is willing to pay the same to transmute waste, that it's willing to pay for fissile fuel. Then you could use our production curves by just relabeling the axes as radioactive waste consumption.

Jassby: In fact, do you have any idea how much it would be worth?

Burger: At the moment it would be far below what that curve in our paper indicates. People today argue about a fraction of a mill per kwhr(e) as an acceptable cost.

Coffman: The LMFBR people have projected in their impact statement the value of plutonium per gram, starting about $10 per gram, as
showing a peaking up at several 10's of dollars in the late 1980's, and having a very rapid fall off and plateau around the year 2000 to about $2 per gram. I wonder if you would comment on what that would mean to the feasibility of a hybrid system if, indeed, plutonium turned out to be worth between 1 and 5 dollars per gram.

Lotker: I think from the utility point of view that's great; it reduces our fuel cost, but I think realistically the projected cost of plutonium is going down because there will be lots of breeders making lots of plutonium. If that is not the case or if those breeders cost more than people think they'll cost, then the figure of $2 will not stand.

Burger: The hybrid system would have to compete on the same basis. However, it has the capability of maybe producing a great deal more plutonium than the breeder so on the plutonium side it might have an edge, although with a low plutonium price, the value of heat or electricity produced would be more crucial to the economics.

Wolkenhauer: I'd like to respond quickly to Dr. Jassby's question. You referred to actinide transmutation. Your answer referred to what the utilities and the people are going to pay in terms of waste management, and I thought your numbers are quite correct. However, the transmutation process for actinides is fission and thus one can view the actinides as a fuel which they are in the peculiar spectrum of the CTR. You can, at least, hope that the actinides in a CTR have a worth close of that of plutonium. It probably won't be the plutonium worth but it might be like a half or a third of that. So your curves might not be too far off.

Burger: Do you have a credit for the heat in a transmutation device?

Wolkenhauer: Yes, and it is substantial.

Williams: Could you say something about the timing problems with the enrichment services, separative work, and how you think that affects the timing of the need for other fuel processing possibilities.

Lotker: I am not up to date on exactly what diffusion plant is being delayed or the so-called constipation problem of reprocessing facilities, but clearly all these things tend to make options like this more necessary. Although we talk about fissile fuel costs being a certain amount, the very fact that you don't have enrichment facilities may make a need for a breeder like this necessary even though there's plenty of cheap yellow cake.
Burger: You can have it if you pay for it today.
Williams: Clearly, the technology of enrichment is known. The question of timing is will enrichment services be available to satisfy the demand from light water reactors until breeders are available.