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APPLICATION OF AN LP MODEL TO BREEDER STRATEGY STUDIES

by

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INTRODUCTION

The comparative economics of Fast Breeder Reactors (FBRs) and Light Water Reactors (LWRs) is one of key factors in determining when and if breeders can be successfully deployed. Discussions of breeder economics normally focus on its probable capital cost, and there have been a large number of breeder capital cost estimates published over the years. Their bases differ widely and the estimates themselves differ correspondingly. Almost always, however, the estimates of breeder capital costs are higher than the corresponding costs for an LWR, and breeder economic competitiveness against an LWR involves a tradeoff between a capital cost differential penalty and a fueling cost incentive. As both the capital cost differential and the fueling cost savings are only estimates at this time, there is room for a range of opinion on the point of economic competitiveness.

At least some of the range of opinion is traceable to differences in perceptions of future demand, resource costs and economic environment. Another part is attributable to differing bases for breeder cost estimates, for example, whether for first-of-a-kind, first-few, or for a mature industry. The relationships between the factors of the first kind, however, demand, resources, economic environment can be clarified by analyses based on a mathematical modeling of the nuclear power system. In this analysis, it will be shown that at least four plausible definitions of the capital cost differential allowable for economic breeder introduction are possible. Each one is relevant to a different way of posing allowable cost differential questions. Thus, a further part of the range of opinion on the point of breeder economic competitiveness evidently arises because of such differences in definitions. Once the differences in possible definition are identified, there is still room for discussion about which definition is appropriate for any given purpose. The purpose of this paper, however, is to try to clarify the bases for such discussions by showing the effects of adopting various possible definitions, and demonstrating by example the relationships between them.

This paper, therefore, discusses the relationships between the capital cost differential (FBR-LWR) allowable for economic breeder introduction and energy demand, resource availability (through price-quantity schedule), and economic environment for a range of future projections. The ALPS[1] linear programming reactor systems analysis code, developed by Hanford Engineering Development Laboratory, was used for economic optimizations where they were done, and where they were not it provided a useful tool to compute the discounted total system power cost over the planning horizon for a given set of reactor mix and cost parameters.

For our examples, we have taken the latest OECD-NEA estimates[2] of worldwide nuclear demand for the nuclear power system characteristics. The OECD-NEA report gives two sets of projections; a "present trend" and an "accelerated growth" demand. We used the "present trend" projection, which gives 1000 GWe in the year 2000 and about 45 GWe/yr growth thereafter. For the effects of uranium resource price-quantity schedule, we have used four such schedules, derived from OECD/IAEA estimates,[3] simplified to illustrate the basic effects. In each schedule the U_3O_8 price was assumed to escalate linearly with cumulative consumption, at least to a certain point. As a base case, the price was assumed to be twice the "forward cost" at the "reasonably assured" plus "estimated additional" resource level. For the base case, therefore, the U_3O_8 price is $100/lb at the point 5.6 million short tons are consumed. Beyond this consumption level, the price was assumed to increase linearly with additional uranium consumption, with the long range price bounded by two extremes. At one extreme, it was assumed that when the price reaches $300/lb unlimited uranium resources are available at that constant price. At the other, the price was assumed to go on escalating at the same linear rate.

For a second case, termed the low uranium price case, the price was assumed to be the same as the forward cost, that is, $50/lb at 5.6 million short tons. Another possible interpretation of this assumption is that a much larger resource base turns out to be available within the $100/lb recovery cost.

The range of uranium prices assumed for the analysis is illustrated in Fig. 1. The financial assumptions and the fuel cycle cost assumptions are summarized in Table 1.

BREEDER SYSTEM ECONOMICS

The major parameter affecting the allowable capital cost differential is the uranium price. The uranium price depends on the uranium supply and demand (i.e., the price-quantity relationship), which in turn depends on the interactions between nuclear energy demand, reactor mix, time horizon, etc.

Figure 2 illustrates some of these interactions. With optimization of the reactor mix between the LWR and the FBR (the latter introduced no earlier than year 2000) to minimize the discounted total system cost, the FBR market penetration and the uranium consumption under the assumptions stated are shown as a function of the capital cost differential. The base case uranium price-quantity schedule, leveled at $300/lb was used for this example. If the capital cost differential is zero, the FBR is more economic and achieves maximum market penetration, and minimum uranium consumption results. Up to a capital cost differential of 30% the optimum strategy does not change: Maximum FBR introduction is most economic and uranium consumption stays at the minimum. If the capital cost differential is increased beyond 30%, a tradeoff between the breeder market penetration and the uranium consumption takes place. The breeder penetration starts to decrease as the capital cost differential is increased eventually to the point that the breeder is driven out of the market completely. This point is reached when the capital cost differential is too great to compensate for assumed infinite supply of uranium at the $300/lb figure.

In Fig. 2, not only the optimum reactor mix changes with the capital cost differential -- the total system cost changes as well. This is shown in Fig. 3. In Fig. 3, the differential total discounted system cost is shown as a function of the capital cost differential. (The integrated total system power costs were discounted back to the beginning of the planning horizon, i.e., 1975. In Fig. 3, only the relative differences in total discounted system cost between various cases are plotted.) The solid curve is for the optimum reactor mix case described above. With the LWR only in the system -- no breeder introduction -- the system cost is invariant to breeder capital cost as shown by the dashed curve in Fig. 3. The two curves merge together, defining a limiting allowable capital cost differential, beyond which breeder introduction at any date in the time horizon would not reduce the system cost.

The system cost for forced maximum breeder introduction from the year 2000 without optimization, is shown by the dotted curve in Fig. 3. For small capital cost differential, this case is identical to the optimum reactor mix case (because the maximum breeder penetration is optimum strategy). However, as the capital cost differential is increased, the system cost with maximum breeder penetration is higher than the optimum penetration case and the two curves diverge. However, the total system cost is still lower than for the LWR-only system, and breeder introduction at the maximum rate remains economic. It is not most economic — the solid line gives this case — but it is more economic than staying with LWRs throughout the planning horizon. As the capital cost differential is increased further, the maximum breeder introduction curve crosses the LWR-only curve, at which point maximum breeder introduction is less economic than an all-LWR strategy.

The term "allowable capital cost differential," as used in this report, is defined as the incremental capital cost that can be paid for the fast breeder over the capital cost of the LWR, while maintaining the same power cost.

$$\Delta = \text{Allowable Capital Cost Differential (\%)} = 100 \times \frac{\text{FBR} - \text{LWR}}{\text{LWR}} .$$

The power costs for the LWR and the FBR may be compared in many different ways: power generating cost at a given time, power cost levelized over the plant lifetime (assumed to be 30 years in this study), or as components of a total power system cost instead of the single reactor cost basis. The relevance of each depends on the question being asked. It is instructive to consider the following four approaches in defining an allowable capital cost differential (Δ) for the FBR over the LWR (two of which can be identified from Fig. 3):

1. Limiting Δ: As discussed earlier and indicated in Fig. 3, beyond this limiting Δ the breeder introduction at any date in the time horizon results in a higher system cost than the no breeder introduction case.

2. System Δ: As illustrated in Fig. 3, at this capital cost differential the total system cost is indifferent as to maximum breeder introduction or continued LWRs usage over the time horizon considered. The lower shaded area in Fig. 3 represents the economic benefits derived from maximum breeder introduction for the corresponding range of capital cost differential, and the upper shaded area represents the economic costs if breeders are introduced at the maximum rate at cost differentials above the indifference point.

3. Optimum System Δ: The above definition assumes maximum breeder introduction for a given introduction date (assumed to be the year 2000 in Fig. 3). However, for a given capital cost differential, the system power cost with maximum breeder penetration may be higher than for an optimum penetration strategy. This is shown in Fig. 3, where the dotted area represents the additional economic benefits that would result if breeder introduction (or the reactor mix) were optimized. (The allowable capital cost differential defined for an optimized system cost is not uniquely identifiable from Fig. 3, however, because it is a continuous function of the breeder introduction date, while the other quantities in Fig. 3 are defined by the year 2000 introduction date taken for the example in the figure.)

4. Single Reactor Δ: The three definitions described above are based on considering the total power economy over a specified planning horizon. Another way of defining the allowable capital cost is to compare the 30-year levelized power cost of a single FBR with that of an LWR for a given startup year. Because the uranium price is determined by the cumulative consumption for the total system, the system characteristics must be assumed, implicitly or explicitly, for the 30-year period beyond the decision point in question. There are various ways that this can be done, and at least two different approaches can be employed. One approach is to assign 30-year requirements to each LWR as it comes on-line, so that the LWR fueling cost for the reactor under consideration is determined by the price of uncommitted uranium; after the 30-year requirements for the LWRs currently on line have been accounted for. Another approach is to explicitly assume that the reactor system as a whole remains all-LWR and calculate the levelized costs accordingly. The latter approach is used in this study. The difference between the two is not large. In either case the effect of breeder introduction on uranium prices in the period following the decision is not accounted for.

The allowable capital cost differentials defined by the four different approaches described above are compared in Fig. 4 as a function of the breeder introduction date.

For the early fast breeder introduction, the allowable capital cost differentials defined for the total system are larger than the allowable differential defined for a single plant. As fast breeder introduction is delayed, the allowable differentials defined for the system or for a single plant tend to merge together, because the uranium consumption for the total system is increased and the uranium price is approaching the ceiling price assumed. With further delay in breeder introduction both will approach the limiting capital cost differential.

The large differences in allowable capital cost differential between the single reactor and system approaches shown in Fig. 4, especially for early breeder introduction cases, follow from the definition of the uranium price-quantity schedule. A fixed price-quantity schedule, independent of future price expectations is derived from the production cost (or recovery cost) point of view. Future price expectations might be expected to be influenced by the particular reactor scenario that is being followed and its anticipated effect on uranium consumption and therefore price. The differences in future consumption patterns are substantial between different reactor scenarios. The single-reactor, fixed price-quantity schedule approach implicitly assumes the absence of price effects related to differences in future reactor deployments.

Figure 5 illustrates these considerations. In Fig. 5, the solid curves represent uranium prices as a function of time, which result from the assumed price-quantity schedule. If we consider the year 2000, the uranium price used in the economic analysis for the single reactor approach is independent of the future environment. The dashed curves in Fig. 5 represent "shadow prices" for various scenarios. The "shadow price" is calculated from the LP optimization, and quantifies an intrinsic value of the uranium as a function of time. Obviously, shadow price cannot be interpreted as market price. However, market price will tend to be pushed toward shadow price, and Fig. 5 illustrates the large differences in the effects of future environments on the uranium value at the year 2000. The systems approach, on the other hand, takes into account the effect of future environment as well as the effect of breeder introduction on the system.

The capital costs for commercial-scale breeders are not known with any reasonable certainty at this time. Figure 4 provides a framework in which a target cost can be measured for an assumed breeder introduction date. The same figure can also be used in determining when breeders can compete economically with LWR's for an assumed capital cost differential.

Which approach in Fig. 4 (i.e., the single reactor versus the reactor systems approach) should be used will depend on the situation: whether utility planning, national planning, or global considerations are being discussed. It will also depend on whether the planning is for a first nuclear unit or an addition to a large existing nuclear base; and also whether the near-term (favored in utility decisions) or the long-term (favored in national decisions) is being emphasized.

SENSITIVITY ANALYSIS

The tradeoff between the FBR capital cost penalty and the LWR U_3O_8 cost savings depends on the whole range of input parameters assumed for the analyses — uranium price-quantity schedule, nuclear demand growth rate, fuel cycle cost differential, O&M cost differential, discount rate, planning horizon, and so on. The best values for none of these parameters are known within any degree of certainty, and all of the above definitions of allowable capital cost differential are sensitive to the particular values taken for them. Precise calculations of optima are questionable under these circumstances.

To illustrate the sensitivity of the numerical results to differences in input assumptions, we have calculated sensitivities for the System Δ definition of allowable capital cost differential. The System Δ gives the upper limit of the cost differential allowable for breeder introduction on any given date to be more economic than continued LWR deployment through the time horizon. It pertains to the broadest effect of probable interest, the global decision to introduce or forego the FBR. The approximate range of this capital cost differential is of interest, as is its sensitivity to the values assumed for the input parameters. In the following paragraphs its sensitivity to each of these parameters is examined one by one, to identify the parameters that affect the analyses most.

1. Influence of Uranium Price-Quantity Schedule: Figure 6 shows the allowable capital cost differential, as a function of FBR introduction date, for the two uranium price-quantity schedules. For each price-quantity schedule, the solid curve is based on the ceiling price of $300/lb, (that is, an unlimited amount of uranium is assumed to be available at that price) and the dashed curve shows the situation with further linear price escalation, with additional uranium consumption, beyond $300/lb. (See Fig. 1 for the price assumptions.) The shaded area therefore represent the ranges defined by the two extremes in the assumptions for behavior of the long-term uranium price.

As can be seen from Fig. 6, for the base case ($100/lb at 5.6 million ST), with year 2000 FBR introduction, the allowable capital cost differential is about 100%. That is, the FBR could cost twice as much as the LWR and the total system power cost would be indifferent as to whether the energy was produced by an LWR-only economy or with maximum penetration of FBR's. If the uranium price in the long-term continues to linearly escalate the allowable capital cost differential is substantially higher, as the figure shows. For the low uranium price schedule (i.e., the price is equal to the "forward" cost) the allowable capital cost differential for the 2000 introduction is about 60%. In this case the effect of long-term price escalation is very small because the amount of uranium consumed beyond the ceiling price is small within the planning horizon.

2. Nuclear Demand Growth Rate: For the $300/lb ceiling price, the allowable capital cost differential is rather insensitive to the growth rate. This is because an unlimited amount of uranium is available at that price and the higher energy demand can be met with LWR's using uranium in unlimited amounts at the same price. For the continuous uranium price escalation case, the allowable capital cost differential is very sensitive to the growth rate.

3. FBR Fuel Cycle Costs: The sensitivities with respect to the FBR fuel cycle cost assumptions were analyzed using uncertainties in reprocessing cost as an illustration. The tradeoff between the FBR capital cost penalty and the LWR U_3O_8 cost saving obviously depends as well on the differential that exists between the FBR and the LWR in other components of the fuel cycle cost. But reprocessing cost sensitivities illustrate the effects, and as can be seen from Fig. 7, the effect on the allowable capital cost differential of changing the FBR reprocessing cost from $240/kg to $720/kg ($480/kg for the base case) is not large, considering the cost range assumed was a factor of 3. Similar sensitivities may be expected for the FBR fabrication cost.

4. Improved LWR Fuel Utilization: Various modifications are envisioned to improve the fuel utilization of the present LWR fuel cycle, such as increasing the discharge burnup, reducing tails assay, and other modifications. Increase in the discharge from 30,000 MWD/T range to 50,000 MWD/T results in about 15% savings in annual uranium requirements,[4] and the fuel cycle cost is reduced as well. Lowering the tails assay from 0.2 to 0.05%, results in an additional 20% savings in uranium requirements.

The improvements for the LWR fuel utilization tends to reduce the allowable capital cost differential for breeders, though the effect is partially offset by increased separative work requirements and the reduced plutonium availability for the breeder system. (The increased burnup for the LWR results in a 30% reduction of its plutonium discharge, because more plutonium is burned in-situ. This could cause plutonium shortages and further incentive for earlier breeder introduction, or put another way, for a given breeder introduction a higher capital cost differential for breeders would be allowable.)

For the base case, however, the direct effects of reduced LWR U_3O_8 usage dominate, and the allowable capital cost differential for the year 2000 FBR introduction case is reduced from 98 to 84% by the assumption of increased discharge burnup for the LWR; and further reduced to 66% if both the increased discharge burnup and the tails assay reduction are assumed.

5. Planning Horizon: The choice of planning horizon also affects the system cost. The effect of the planning horizon on the allowable differential is illustrated in Fig. 8. A near-term planning horizon makes the allowable capital cost differential smaller; it increases as the planning horizon is extended behaving somewhat differently for the two different price assumptions. It is useful to keep in mind the long time constant associated with breeder scenarios. For this study, the planning horizon starts from 1975, however, the earliest breeder introduction considered in this study is in the year 2000. For the next 30 years the breeder introduction was constrained. Also about 30 years must be allowed for end effects in the optimization period, because the uranium requirements for the LWR installed during this period cannot otherwise be accounted for entirely. Thus the planning horizon must extend beyond 2075 at least for meaningful results in the study of long-term alternatives. For long term horizons beyond 2075, Fig. 8 indicates the allowable capital cost differential is not affected much, for either case, but particularly little for the $300/lb unlimited supply case.

6. Inflation Effects: The analysis presented in this report was performed on a constant dollar basis (zero inflation rate). If the analysis were performed on a current dollar basis with inflation effect included, in theory the same results should be obtained in terms of the allowable capital cost differential (except for a small discrepancy arising from inflation-related tax effects), if the analysis treats the inflation effects in a consistent manner.[5] For representative cases, the analysis was performed on both constant dollar and current dollar bases, and essentially the same results were obtained.

The allowable capital cost differential analyzed in this section, the System Δ, is not an estimate of fast breeder costs nor is it a target to aim at. It simply states that if the breeder costs that much more than the LWR, under the stated assumptions the breeder economy would give the same power cost as an LWR economy over a given planning horizon. It translates into economic terms the global question of the effect of the presence or absence of the breeder. The magnitudes are sensitive to the host of input assumptions in the manner shown above. All that can be expected from such calculations is some indication of the range in which the allowable cost differentials defined in this way are likely to be. Other definitions of allowable capital cost differential, for example, that for an economically optimum FBR introduction date were displayed in this report and conceptually at least they give more specific information. The uncertainty in the input data, however, does make such specificity questionable.

The analysis in this section indicates that the System Δ capital cost differential is most sensitive to the uranium price schedule as reflected in the difference between the \$50/lb and \$100/lb bases for recovery costs; and whether an unlimited amount of uranium is available at a ceiling price (assumed to be \$300/lb in this study) or whether the price continues to increase with increasing consumption. Combinations of effects for which the sensitivities are shown, however, are also capable of changing the magnitude of such allowable capital cost differentials substantially. Finally, and most importantly, use of the other definitions of the allowable differential, appropriate to particular questions posed, can also give quite numerically different results.

REFERENCES

1. R. W. Hardie, W. E. Black and W. W. Little, "ALPS, A Linear Programming System for Forecasting Optimum Power Growth Patterns," HEDL-THE-72-31, April 1972.

2. "Nuclear Fuel Cycle Requirements and Supply Considerations, Through the Long-Term," OECD Nuclear Energy Agency, February 1978.

3. "Uranium: Resources, Production and Demand," A joint report by OECD NEA and IAEA, December 1977.

4. C. E. Till and Y. I. Chang, "Once-Through Fuel Cycles," Proceedings of the 18th Annual ASME Symposium on Non-Proliferation: Reality and Illusion of a Plutonium-Free Economy, March 1978, p. 113.

5. T. R. Stauffer, R. S. Palmer and H. L. Wyckoff, "Breeder Reactor Economics," Breeder Reactor Corporation (1975).

TABLE 1. Fuel Cycle Cost and Financial Assumptions

	Base Case	Ranges Examined
1. LWR Capital Cost, \$/kWe	665	
2. FBR O&M Cost Differential over LWR, \$ Million/GWe-yr	0.8 (= 0.122 mills/kWhr)	
3. U_3O_8 Price	See Fig. 2	See Fig. 2
4. Enrichment Cost, \$/kg SWU	100	
5. U_3O_8 - UF_6 Conversion, \$/kg U	4	
6. Fabrication Cost, \$/kg HM		
LWR	100	
FBR - Core	950	
- Axial Blanket	25	
- Radial Blanket	150	
7. Reprocessing Cost Including Shipping and Waste Storage, \$/kg HM		
LWR	240	
FBR	480	240-720
8. Inflation Rate, %	0	6
9. Discount Rate, %	4.525	10.8
10. Fixed Charge Rate, %	9.45	17.1

Fig. 1. Uranium Price vs. Quantity Relationship Assumed for the Study

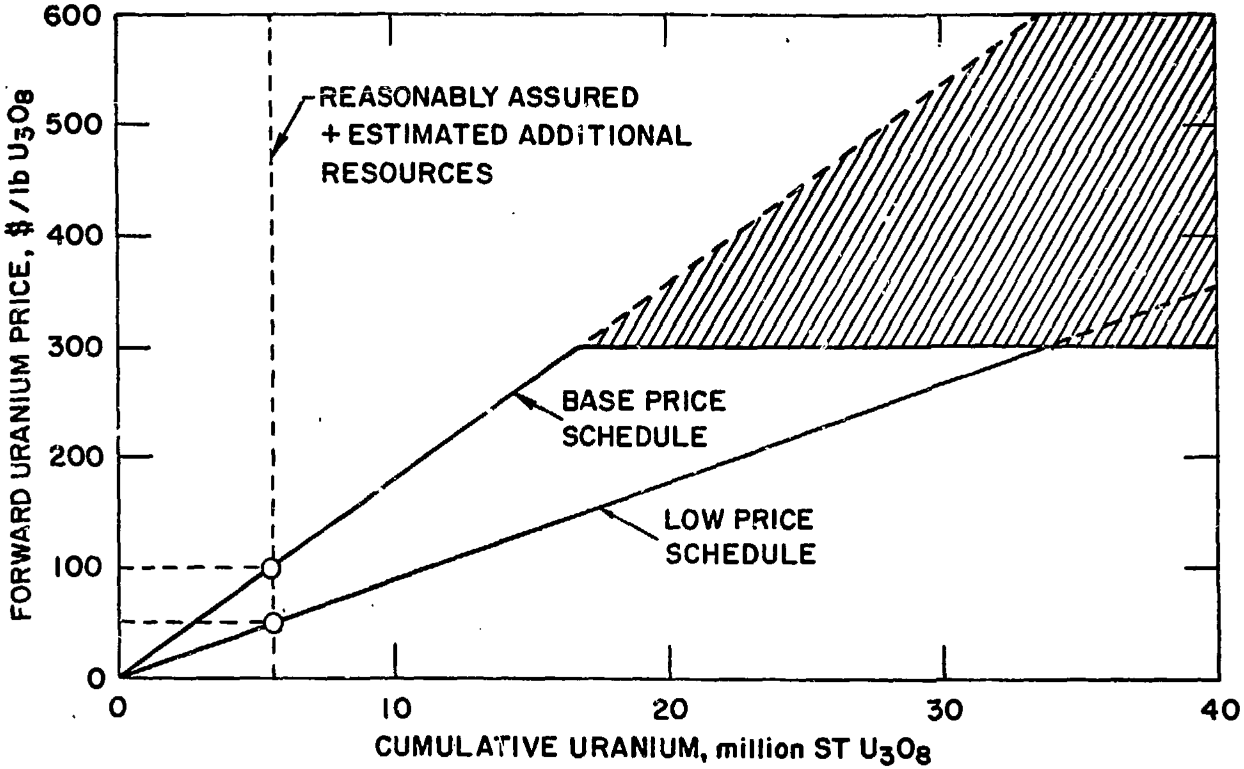

Fig. 2. Illustration of the Effects of Capital Cost Differential (FBR-LWR) on Power System Characteristics Optimized for the Minimum Discounted System Cost over a Planning Horizon

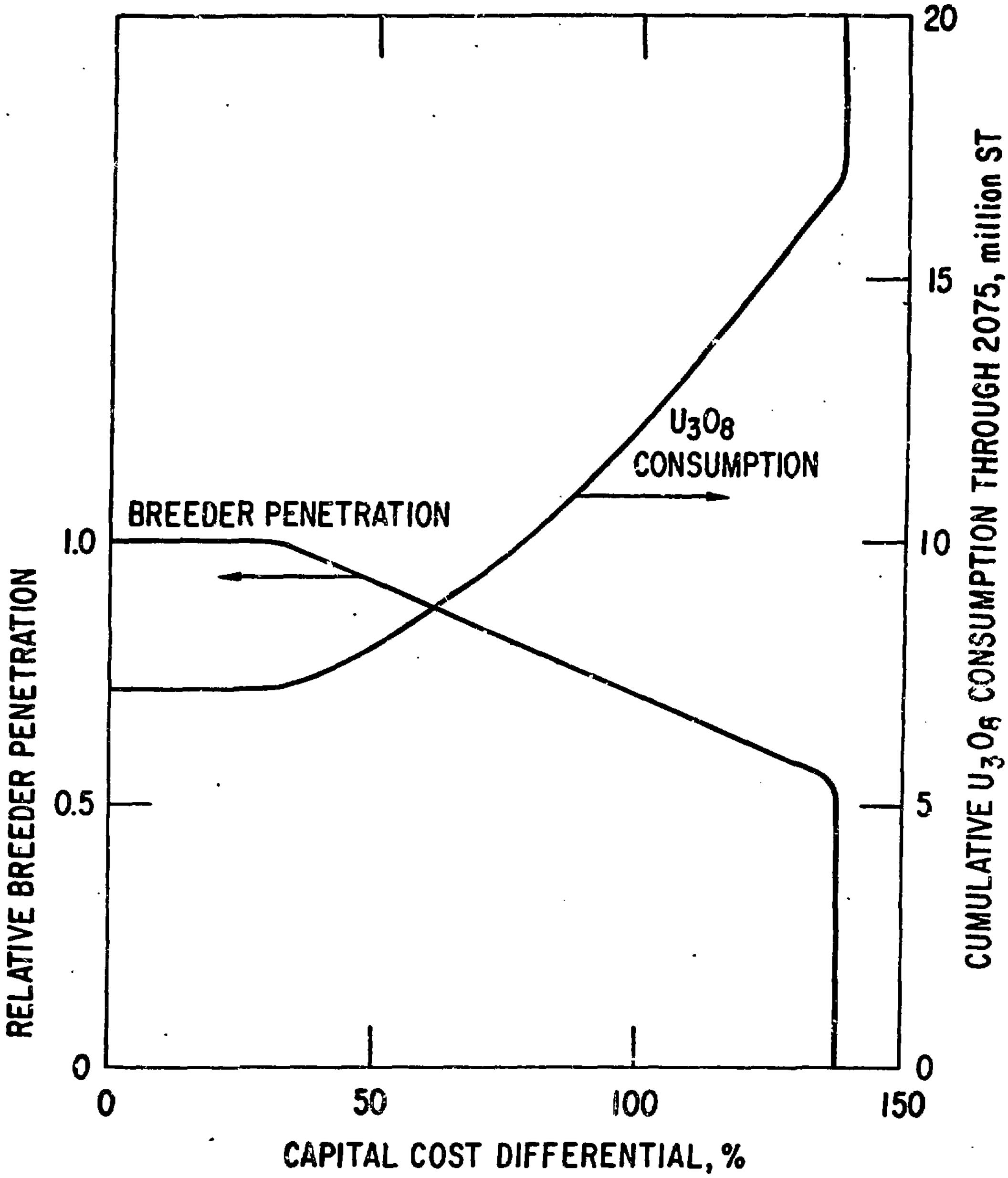

Fig. 3. Relationship between the Discounted System Cost and the Capital Cost Differential (FBR-LWR)

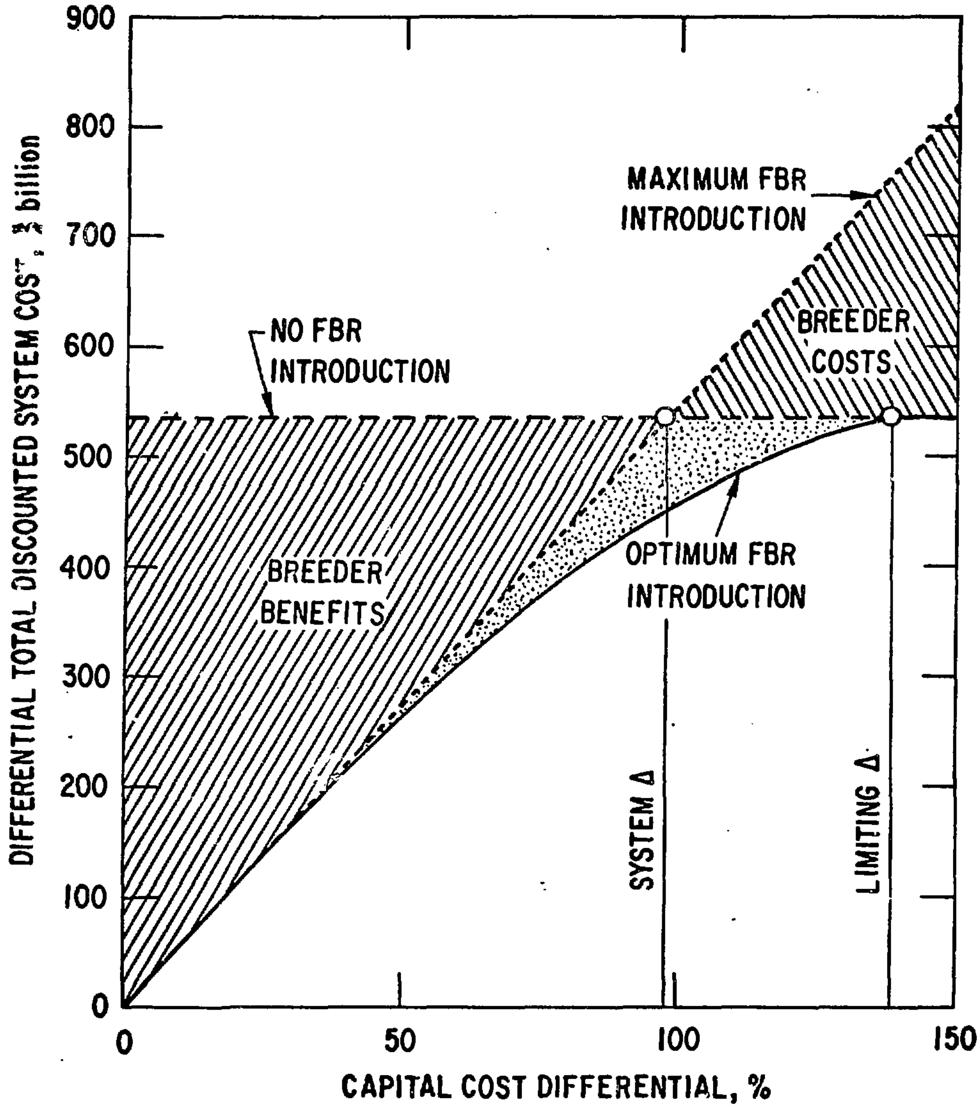

Fig. 4. Comparison of Various Definitions for Allowable Capital Cost Differential as a Function of FBR Introduction Date

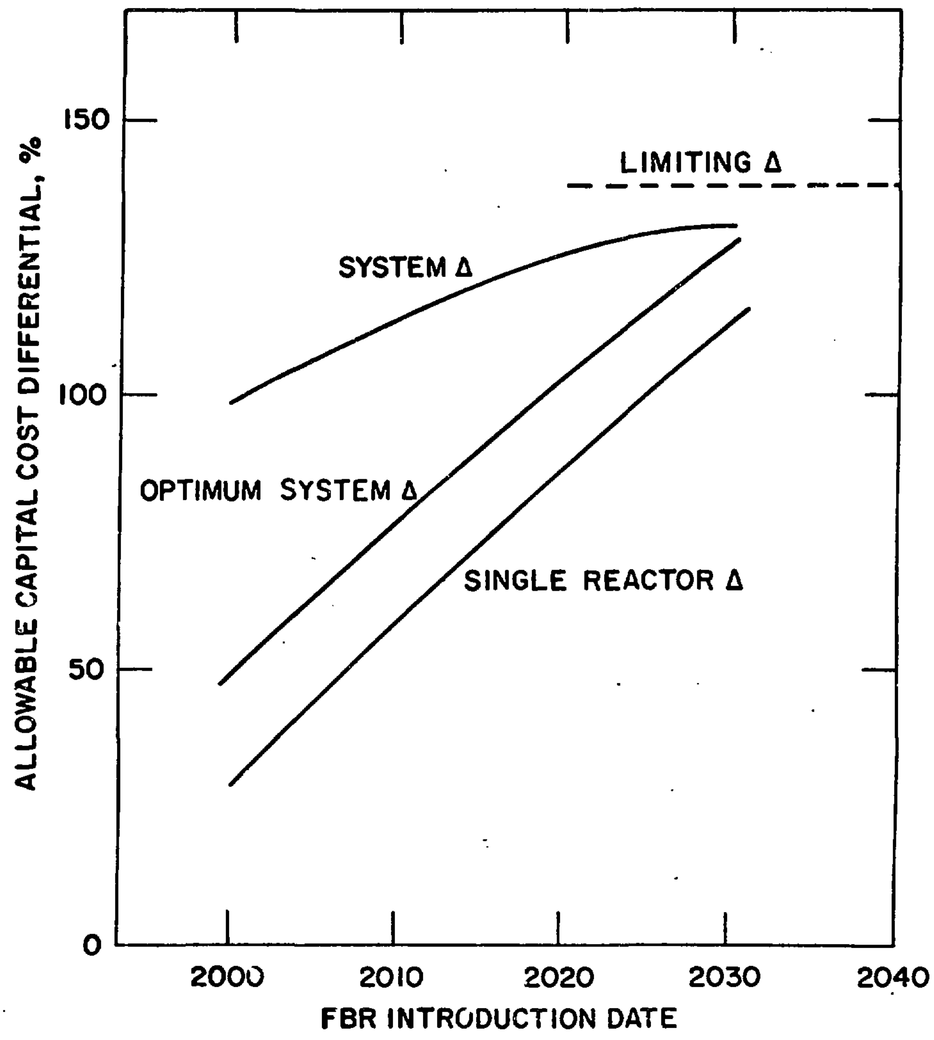

Fig. 5. Uranium Price and "Shadow Price" as a Function of Time for Various Reactor Scenarios

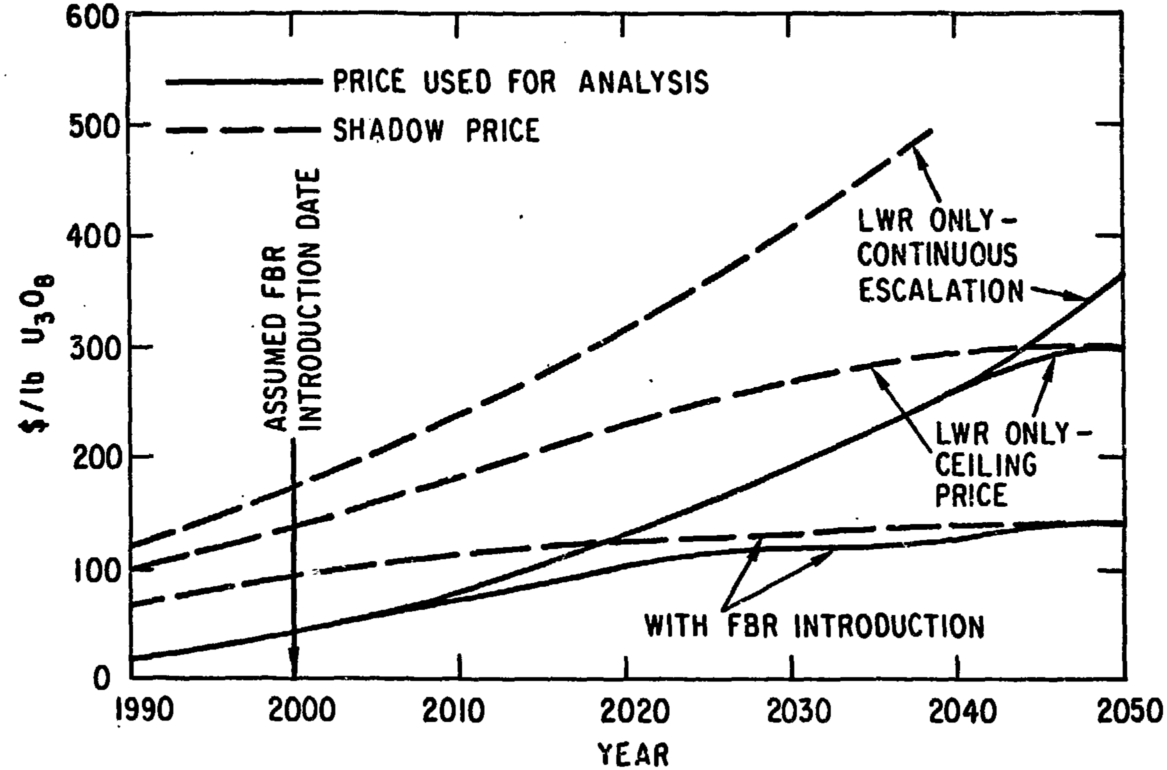

Fig. 6. Comparison of Allowable Capital Cost Cost Differentials for Various Uranium Price Schedules

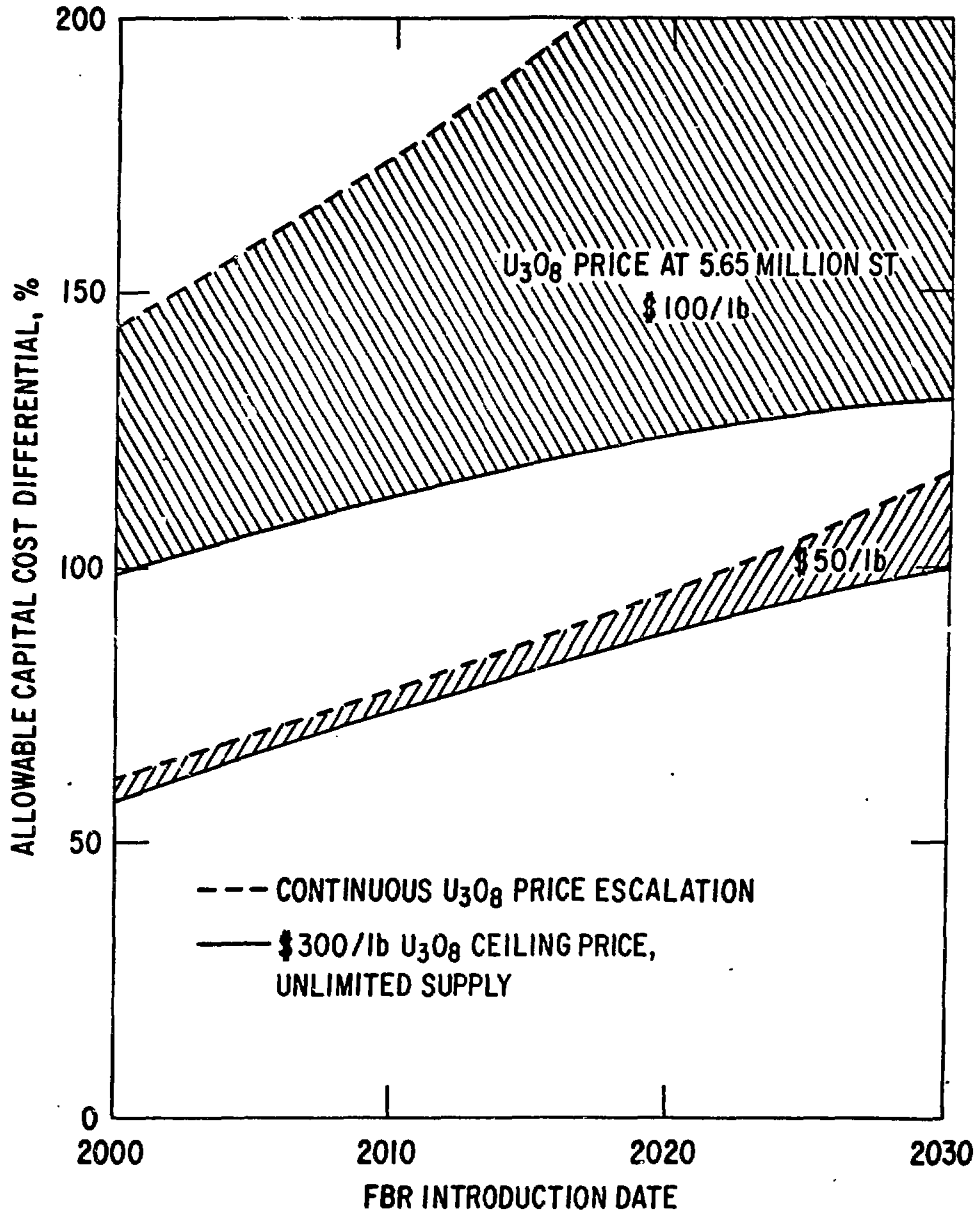

Fig. 7. Comparison of Allowable Capital Cost Differentials for Various FBR Reprocessing Costs

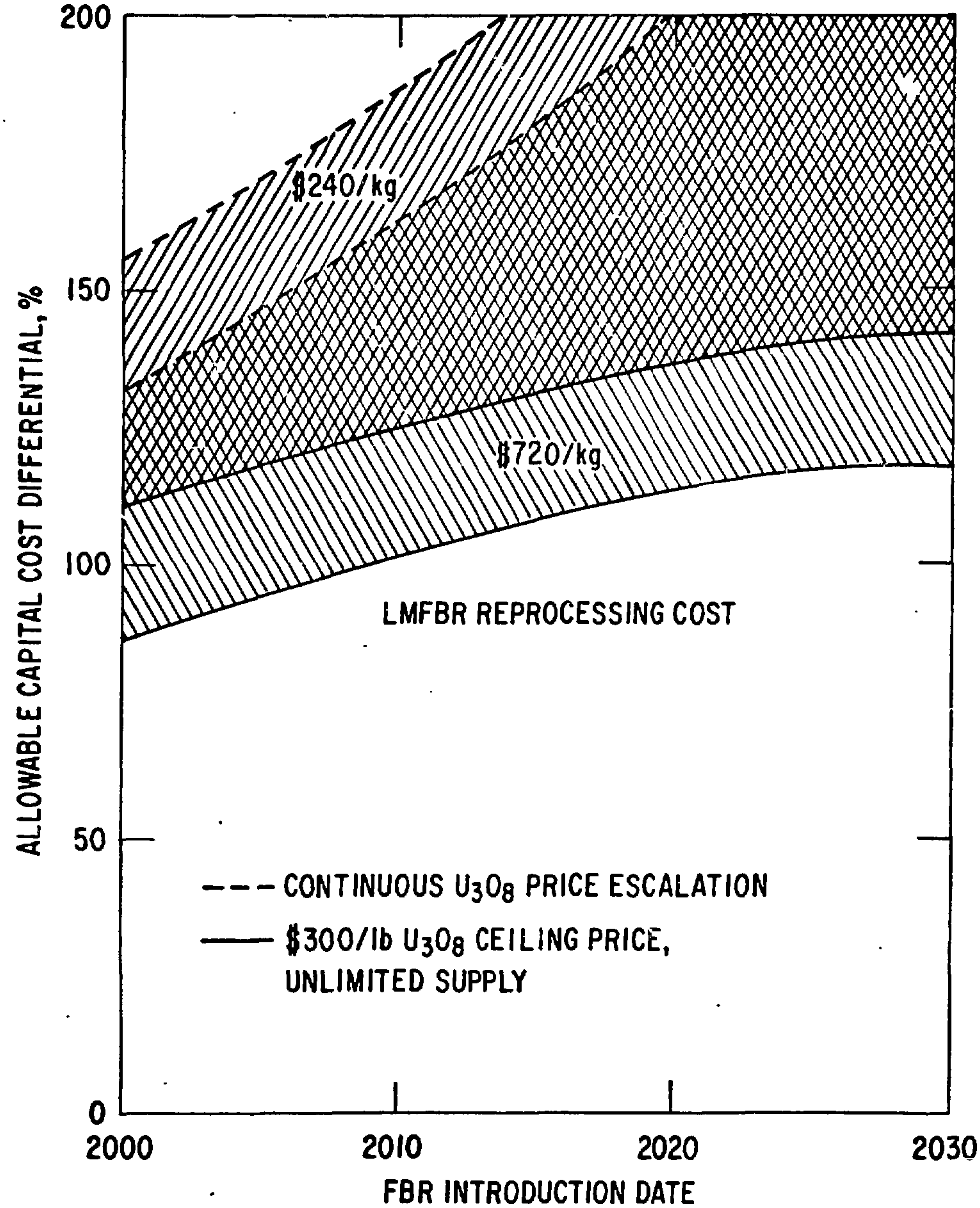

Fig. 8. Sensitivity of Allowable Cost Differential to Planning Horizon