H 196

ORNL-5484

Pebble Bed Reactor Core Physics and Fuel Cycle Analysis

MASTER

[illegible]
Distribution Category UC-77
Gas-Cooled Reactor Technology

[illegible]

[illegible]

[illegible]

HIGH-TEMPERATURE GAS-COOLED REACTOR [illegible] PROGRAM
(ORNL [illegible] 01441)

Date Published: October 1979

MASTER

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

TABLE OF CONTENTS

ABSTRACT

The Pebble Bed Reactor is a gas-cooled, graphite-moderated high-temperature reactor that is continuously fueled with small spherical fuel elements. The projected performance was studied over a broad range of reactor applicability. Calculations were done for a burner on a throwaway cycle, a converter with recycle, a prebreeder and breeder. The thorium fuel cycle was considered using low, medium (denatured), and highly enriched uranium.

The base calculations were carried out for electrical energy generation in a 1200 MW_e plant. A steady-state, continuous-fueling model was developed and one- and two-dimensional calculations were used to characterize performance. Treating a single point in time effects considerable savings in computer time as opposed to following a long reactor history, permitting evaluation of reactor performance over a broad range of design parameters and operating modes.

The analysis of ore requirements and fuel costs indicates that the concept should be competitive with others. The best performance is achieved with highly enriched uranium recycle, and although fuel breeding is possible, production of fuel at a significant rate is likely uneconomical. The following table summarizes key results of this performance assessment.

This work was performed for DOE under a technical information exchange umbrella agreement between the Federal Republic of Germany and the United States. The effort was primarily intended to produce reliable results independently from those generated with German methods and data.

Table I. Performance Summary for the Pebble Bed Reactor Concept with the Plant Efficiency Dependent on Technology Level

Service and Technology Level	Nominal Carbon to Heavy Metal (Atomic)	Nominal Fueled Pebble Residence (full power yrs)	Average Conversion Ratio	Peak Pebble Power (kW)	Fueled Pebble Exposure (MW$_t$D/kgm)	Fissile Inventory (kgm/Installed MW$_e$) Plant	Fissile Inventory (kgm/Installed MW$_e$) System	External Fissile Feed (kgm/MW$_e$-Yr)	Fissile Commitment (kgm/Installed MW$_e$)	Ore Requirement (ton U_3O_8/Installed MW$_e$) 30 year	Ore Requirement (ton U_3O_8/Installed MW$_e$) Incl. Commitment	Fuel Cost (mill/kWh$_e$-hr) Low Indirect	Fuel Cost (mill/kWh$_e$-hr) Reference
Burner, Low Enriched Uranium													
Reference	575	2.0	.54	2.1	130.	0.9	1.1	.8[illegible]	20.[illegible]	4,360	4,650	5.6	6.2
Burner, Medium Enriched (denatured) Uranium Fuel													
Low Technology	450	2.5	.54	2.3	130.	1.1	1.4	.86	22.2	4,400	4,720	5.8	6.5
Reference	450	2.6	.55	5.1	205.	0.9	1.2	.76	18.2	3,890	4,170	5.0	5.7
High Technology	450	2.9	.55	5.6	270.	0.7	1.0	.65	14.8	3,320	3,560	4.3	5.0
Burner, Fully Enriched Uranium													
Low Technology	250	3.8	.55	2.2	90.	1.4	1.6	.76	18.3	3,960	4,270	5.5	6.3
Reference	250	4.0	.58	5.0	225.	1.3	1.5	.66	10.2	3,480	3,800	4.7	5.6
High Technology	250	4.2	.57	5.5	250.	1.3	1.9	.56	14.2	2,970	3,290	4.1	4.9
Converter, Fully Enriched Uranium Recycle													
Low Cost													
Low Technology	250	3.8	.63	2.2	95.	1.4	2.1	.48	12.8	2,370	2,790	4.8	6.0
Reference	250	4.0	.65	5.0	225.	1.3	2.5	.42	10.8	2,150	2,450	4.2	5.1
High Technology	250	4.2	.67	5.5	250.	1.3	2.0	.38	8.8	1,860	2,190	3.6	4.8
Low Ore													
Low Technology	175	2.0	.75	[illegible]	36.	1.7	2.9	.44	11.8	1,870	2,610	6.1	7.4
Reference	175	2.0	.78	3.[illegible]	40.	1.6	2.7	.36	9.7	1,500	2,200	5.1	6.5
High Technology	175	2.0	.80	[illegible].4	100.	1.6	2.6	.30	8.8	1,290	1,960	8.8	6.0
Prebreeder, Fully Enriched Uranium[b]													
Low Cost	175	2.5	.70	2.2	45.	3.3	3.6	.56	18.3	2,990	3,840	4.3	[illegible]
Reference	175	1.5	.73	2.2	70.	1.8	2.6	[illegible]	17.7	3,480	4,074	4.8	5.5
High Performance	175	3.0	.71	3.9	135.	2.1	2.6	.66	19.8	3,420	4,030	4.5	5.6
Near Breeder, Breeder, [illegible] Fuel													
Low Cost	250	4.2	.710	4.7	250.	1.0	1.9	.28	7.1			3.8	4.8
Low Fuel	150	1.5	.890	2.8	50.	1.0	2.2	.10	4.4			5.2	6.4
High Conversion	110	2.0	.990	3.1	40.	2.8	6.1	.028	1.9			5.1	7.5
Break even	90	1.5	1.023	2.6	26.	3.6	7.6		7.6			7.4	10.6
Breeder	80	1.5	1.036	2.5	24.	4.3	9.2		9.2			8.5	12.2

[a]Burner and converter load factor 0.75; prebreeder, near breeder, breeder are high technology, load factor 0.85; ore enrichment tails .002, 30 year plant life.

[b]Breeder fuel generation for these cases in kgm/MW$_e$-Yr (net): 0.25, 0.32, 0.33; note that increasing the plant efficiency reduces the breeder fuel production.

SECTION 01: INTRODUCTION

This is a report of calculations done to assess the projected performance of pebble bed nuclear reactors. The analysis was done for DOE under the technical information exchange umbrella agreement between the FRG[a] and the US. Local methods and data were used.

There is special interest in the pebble bed reactor concept in the FRG. Their 300 MWe THTR demonstration plant[1] is scheduled to go into operation in 1983. This application is attractive because of the excellent performance of the 15 MWe AVR pilot-type plant[2] which has operated at a high thermal efficiency and has been on line most of the time.[b] There is continuing US interest in developing a gas-cooled reactor concept which would effect a high thermal efficiency. Likely uses are in electric energy generation plants and in process heat applications.

In this report we consider power plant applications with the following types of operation:

1. Fully enriched U^{235} feed with thorium
   a) throwaway cycle (burner),
   b) selective reprocessing and recycle (converter),
2. Medium enriched (~20 percent U^{235} in U^{238} with thorium) and low enriched, throwaway cycle (burner),
3. Denatured U^{233} in U^{238} with thorium, with reprocessing and recycle (converter),
4. U^{233} fuel (from a prebreeder or fast reactor) with thorium (converter, near breeder, or breeder),
5. Converting fully enriched U^{235} fuel with thorium to U^{233} fuel (prebreeder).

A considerable amount of analysis has been done on the pebble bed concept in the FRG.[7,14,16,17,18,19] Calculations have been done by the staff at LASL using the German codes for machine calculations which were imported by them for use in the US.[5] The early effort in the US was an assessment of the performance of an advanced breeder concept fueled with U^{233} proposed by the General Electric Company.[6]

---

[a]Federal Republic of Germany.

[b]But this facility is down due to water entering the core causing iron rust and subsequent catalized carbon, oxygen reaction damaging pebbles.

Emphasis at ORNL in the early effort was on methods to treat the continuously fueled pebble bed reactor concept. An interim document was issued reporting calculations done primarily for an advanced breeder concept.[7] Subsequent effort has shown that for the results reported, the resonance shielding calculations left much to be desired, and the fission product absorptions were overestimated, causing the performance to be underestimated, especially at high exposure. However, the sound conclusions drawn were that the U^{233} inventory of the system associated with a plant must be held down for the concept to be economically attractive and competitive, even for an advanced concept, and that a break even fissile fuel balance is more likely than any significant net production of U^{233} fuel with U^{235} feed.

This analysis effort was a back-up to that done in Germany. We claim originality only regarding some of the methods of analysis and their application. This work was intended to produce reliable results quite independently of those generated with the German methods and data. Primary emphasis in this study was placed on the long-term potential, not on a specific design, and variation in technology level is considered. We consider the FRG arguments supporting the once-through cycle, as opposed to rapid recycle, to be sound.

The results of this study are presented and discussed in the main body of this report. The unit costs used in this study are shown and the economic modeling is discussed in Appendix A. The resonance shielding model is described in Appendix B where certain reference resonance integrals are reported, and the broad group cross section collapse procedure is described in Appendix C, the calculations done with the NITAWL and XSDRNPM models in the AMPX code system.[8] The steady state, continuous fueling model used for the base calculations by application of the VENTURE[9] and BURNER[10] codes is described in Appendix D. The point reactor model survey calculations done with the PREMOR code[11] are discussed in Appendix E.

The drawing in Fig. 1-1 indicates the geometric description used in these calculations. An average core power density of 5 W_{th}/cc was generally used. For a 1,200 MW_e plant 3,000 MW_{th}, this gives a core size of 6×10^8 cm^3 and the dimensions shown in the illustration. We label the two pebble types as "primary pebbles" (those loaded with fuel) and "fertile pebbles" (those loaded without any fuel). Reference is made to "core residence time" which is the time the primary pebbles require to make a single traverse through the core; with varying pebble flow rates the residence time reported may not represent an effective average but only a referencing (small differences from a reference are not reflected in this reference to avoid confusion).

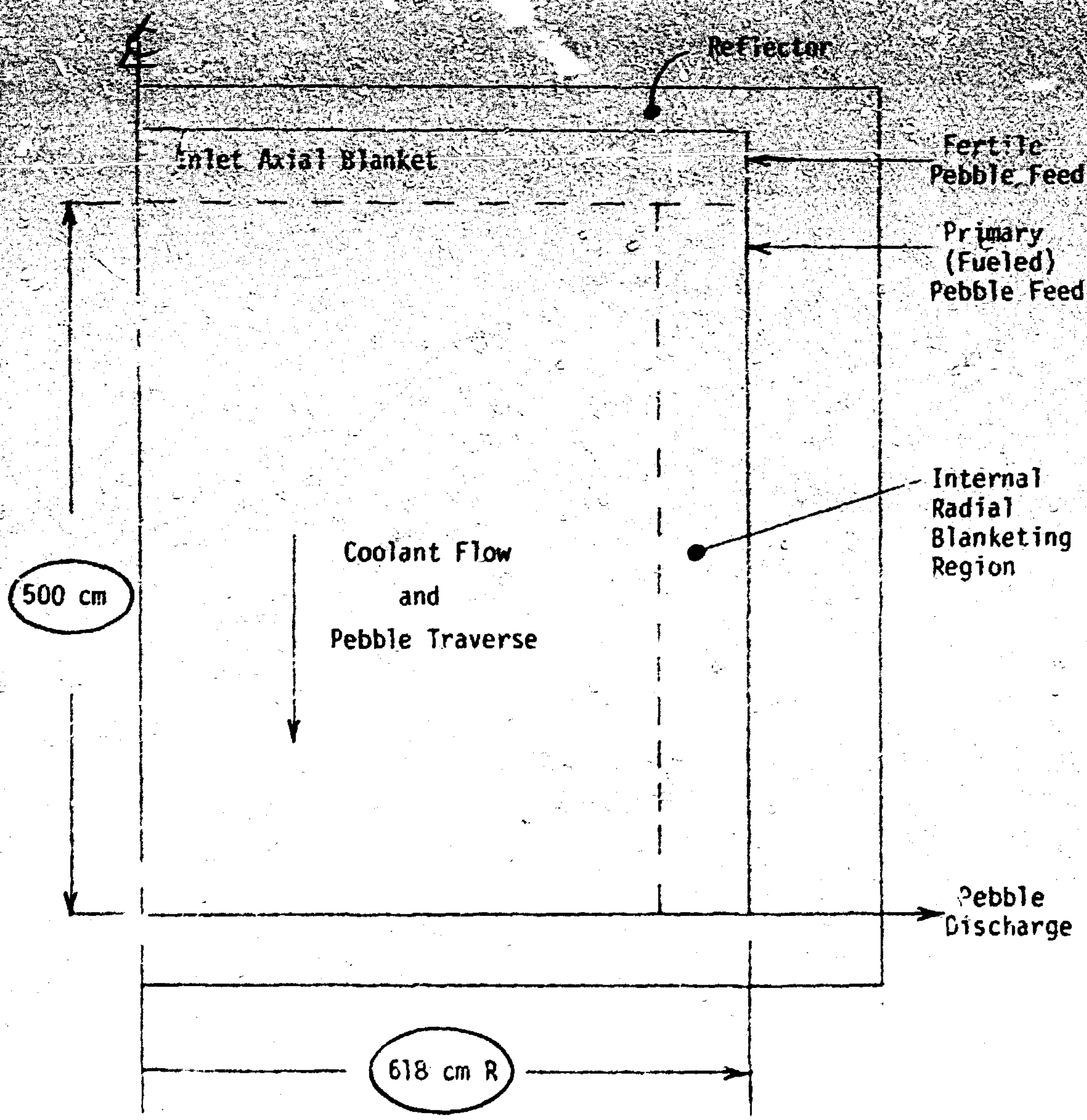


Fig. 1-1. A Simple Representation of a 3,000 MW_{th} Pebble Bed Reactor

A relatively thin inlet blanket region was usually included in the model by considering the introducing of fertile pebbles above the primary pebble feed point. Primary reasons for using an axial blanket were the improved performance possible and our concern about representing a voided region immediately above the fueled core and the possible discrepancy in one and two dimensional calculations when applying diffusion theory. Two-dimensional discrete ordinates calculations have been made to examine the situation. If an axial blanket is used it likely would be thicker than the one considered in the base calculations, and it might be fixed for occasional replacement, but the use of fertile pebbles seems attractive.

For radial blanketing, attention has been focused on the attractive scheme of introducing only fertile pebbles near the outside of the core to effect an internal blanket.

We discuss U_3O_8 ore consumption and commitment. These, of course, depend on the amount of energy produced and the details regarding enrichment from ore. Consumption is estimated directly from the difference between fissile uranium feed and recovered fissile uranium discharge. Commitment is estimated from total external fissile uranium feed, and thus it is the amount of ore required to supply feed to one reactor over its life. These are simple definitions, yet there are complexities, as regarding credit at the end of the reactor life. What constitutes recoverable material on a throwaway cycle after it has been in a reactor?

Regarding Potential Use and Development

The pebble bed gas-cooled reactor concept has the potential for use to generate electrical energy in power plants. For the long term, the direct gas turbine cycle is of interest to eliminate a secondary steam system. The concept has the potential for production of high temperature process heat. Dual service to produce high temperature process heat and electricity has interesting applications which could be of considerable importance.

Operation of the reactor at a high temperature permits energy conversion at a high efficiency. A plant operated at the low conversion efficiency of 0.3 releases 2.33 units of energy to the environment for every unit produced. This is reduced to 1.5 units released at an efficiency of 0.4, a decrease of 36 percent.

The highest possible utilization of fissile fuel from ore is associated with continuous fueling. Decrease in the conversion of fertile material to fissile is associated with operation in a batch mode which requires control rod absorption to offset the reactivity swing associated with net fuel depletion and fission product buildup.

The use of thorium in a thermal reactor shows a neutron economy advantage over uranium because of the more favorable thermal nuclear properties of ^{233}U over ^{239}Pu and the higher isotope mixtures. Short term non-proliferation rules can be satisfied using medium enriched uranium with thorium on a throwaway cycle.

In addition to the considerations above, the pebble bed gas-cooled reactor concept admits use in a variety of roles, from a burner to at least a break-even breeder, and a prebreeder to use ^{235}U fuel to produce ^{233}U breeder fuel. Flexibility of the design and pebble management appear to admit superior performance -- for example, once recycle of fueled pebbles without reprocessing allows high exposure to be achieved while a high rate of breeder fuel production is achieved in fertile pebbles in a single pass. Blanket fertile pebbles may be removed and passed directly through the core to effect a high fissile content reducing reprocessing losses.

Still the concept is not developed, and its development will require a considerable investment of U.S. Government funds and the commitments of private industry and utilities and other possible users. Even with a reasonable level of support, it is a major step to achieve a viable industry. A cooperative development program with the FRG can reduce this cost and is attractive considering the German commitment to develop the concept. Commitments may not be forthcoming considering the problems of the Fort Saint Vrain fixed fuel HTGR demonstration plant, especially if this plant will not operate at the design power level. Still, good performance of the FRG THTR demonstration plant in the early 1980's could then change the situation. The current US effort is oriented toward the development of the fixed fuel concept.

Development of the pebble bed concept faces technical hurdles. These lie in the areas of the requirements for control, heat removal, instrumentation, stability, safety, pebble handling, and materials. The core could be limited to a small and uneconomical size by the requirements. Favorable capital investment and fuel processing costs remain to be demonstrated. Licensing requirements remain to be established. Indeed a preferred design for a large plant considering practical aspects remains to be identified.

The pebble bed concept shows adequate promise for outstanding performance to justify a continuing investment in development. The technical uncertainties must be reduced before the construction of a large plant could be seriously considered.

Pebble Design and Exposure

We believe that continuing development and testing will cause a preferred pebble design to evolve which cannot now be predicted. It appears possible to achieve both the heavy metal loadings assumed in this study and the high exposure (burnup), but this may not prove to be true. Whereas the breeder pebbles need to be loaded heavily to effect a low carbon to heavy metal ratio, up to 35 Kgm HM per pebble, the pebble loadings for the other services are within limits of what has been demonstrated. The THTR reactor has apparently satisfied FRG licensing requirements with a pebble loading up to 16.5 gm and 100 MW_{th}-D/kgm HM exposure with consideration of control and safety as a demonstration plant.[12]

High exposure remains to be proven. The AVR experiment has demonstrated[12] the routine exposure of 180 MW_{th}-D/kgm HM, compared with values up to 250 considered in the calculations at a considerably higher power density. Test experience has shown preferred designs,[21] failure modes and achievable burnup. Actual requirements to contain the fission products and effect a high exposure within an acceptable damage level remain to be established. It is not clear, for example, whether or not a SiC containment shell is required around the heavy metal kernels. Requirements with recycle must be demonstrated.

Cross Sections

The microscopic cross sections used in this study have been used in the past for analysis of gas cooled, graphite moderated reactors. They have a long history of modification to improve results of calculations compared with experiments, especially critical experiments and integral reaction rate measurements. Some of the data originated with the General Atomic Company. Some ENDF-IV data is deemed inadequately evaluated for thermal reactor calculations. Little of the current effort has gone into cross section evaluation, and full documentation of the source of all of the data in use would be a formidable task.

We believe that a modest discrepancy in the thorium resonance integral would not seriously affect the reported results. If the absorption rate in thorium were lower than estimated, the reported results could be obtained by modest changes from the selected pebble designs to increase the resonance integral, or by increasing the thorium loading, or vice versa. We have treated a realistic pebble design with a reasonable modeling scheme to account for resonance shielding, but recognize considerable uncertainty due to the simple methods used.

It is worth noting that the pebble cell (multiple cell for more than one pebble type) presents a challenge for establishing effective reaction rate cross sections. Another challenge yet under study is that of establishing reliable properties for neutron transport across the reactor in the diffusion theory approximation given data for the pebble cell. Generally we have used a homogeneous, infinite medium spectrum obtained by specifying a buckling and representative reactor contents to generate collapsed few-group cross sections. Variations in temperature and nuclide concentrations have been ignored, except for the different thorium loading in two pebble types, in that a single set of microscopic cross sections was used for each reference condition.

We have considered loading the pebbles with ThO_2. Some silicon was included, primarily to produce reaction rate information to allow assessment of the dependence of performance on the amount of SiC used in the kernel coatings, if any. A significant amount of graphite contamination was included.

Modeling

The steady state, continuous fueling model discussed in Appendix D is not a conventional method of calculation. The conventional method used in Germany follows the reactor history from an initial state. For this model we select a point in the reactor history and assume that the feed composition and rate have been fixed for some time, causing the discharge composition and rate also to be fixed at a steady state condition. A solution to the problem is obtained directly by adjusting the fissile feed composition in an iterative process to effect the critical condition and associated neutron flux distribution. This solution for the reactor properties at a point in the operating history is used to characterize performance. It is representative of all but the early history for throwaway of discharged pebbles, but does not account for the effect of fuel recycle after reprocessing and the build up of the higher actinides and the associated change in the reactor characteristics with time. The model was chosen to allow parameter studies to be done with a relatively sophisticated neutronics code at a much lower computation cost than required to follow the operating history.

We note that although the critical reactor state is approximated directly, an iterative process is used to effect a solution. Many but not all of the problems were tightly converged. Extrapolation schemes have been used to approximate converged solutions where necessary, and slight variations in results may be due to incomplete convergence. Long reactor histories were calculated by exploiting a point reactor model which allows survey calculations to be done at low cost. Account could be taken of selective recycle and an economic model applied to predict fuel cost for a single pebble type.

Regarding the calculation of fuel costs for power plant application, there is not a simple result for a situation. Many parameters can take on ranges in values, and the significant indirect costs depend on the details of the economic model. We report reference results based on choices which may or may not allow direct comparisons to be made with results reported in other studies, and selectively explore the effect of changes from the reference calculation.

Primary documentation of the methods of calculation is found in the referenced reports covering the computer codes.

SECTION 02: BURNER PERFORMANCE WITH ENRICHED URANIUM

We elected to make a majority of the needed exploratory calculations with fully enriched U^{235} feed with thorium. There is interest in the performance with this feed as a burner operation, the discharge material being stored or possibly discarded. Complications from changes in the resonance absorption of the plutonium isotopes are not severe as with low or medium enriched uranium fuel, simplifying analysis. The calculations produce information about the early operation with recycle because a plant operated with recycle must start without recycle.

Point model calculations were made to survey long reactor histories; basic fuel cost data for such histories was generated and the effects from variation in the economic data were determined. One-dimensional parameter studies were done by obtaining continuous fueling, steady state solutions. These one-dimensional parameter studies were made primarily for a thick radial blanket (using a small radial buckling). Two-dimensional results were obtained for selected conditions, including the use of fertile pebbles to effect a radial blanket in the reactor, and flattening of the power density by variation in fuel enrichment (increasing it radially). Calculations were made to examine behavior after shutdown and after a power level change. Finally, two-dimensional discrete ordinates calculations were made to assess the core nuclear properties with and without an inlet axial blanket.

At the start of FY 1978, a number of exploratory calculations were done before the calculational procedures had been fine tuned for this effort. An abbreviated fission product representation was used which underestimated neutron losses, overpredicted the conversion ratio and underestimated the fissile feed rate. Conclusions drawn from this early effort served to guide the effort, and some of those, especially applicable to the throwaway cycle, are:

1) Decreasing the core height from that for a nuclear optimum bare reactor decreases the power density peak, an effect observed in the German analysis effort.[12]

2) The fissile feed rate varies slowly with changes in a design (such as change in the carbon to heavy metal ratio) for a given exposure, and this causes the fuel cost and the U_3O_8 ore consumption and commitment to vary slowly with design changes.

BLANK PAGE

3) Once-recycle of the fertile pebbles reduces the fissile feed rate and hence reduces fuel cost and ore consumption (but the effect is less than expected).

4) The economic optimum C/HM ratio was predicted to lie below the value of 325 chosen in Germany, for both throwaway and recycle with enriched uranium feed, using indirect costs representative of US utility companies.

Selected results from these early calculations are shown in Table 2-1 for the steady state, continuous fueling model. These results show, for example, the effect of core height on the power density peak. These results show small inconsistencies reflecting the preliminary nature of the calculations done at the start of this work. Information about power density peaking and exposure by pebble type was made available after such early calculations had been made by enhancing the analysis methods.

Table 2-1. Results of Early Parameter Studies (One-dimensional, axial blanket, 1200 MW_e plant, 5 W_{th}/cc, atomic C/HM 325)

Case		B4A1	B4B1	B4D1	B3C1	B3F2	B4C1	B4E2	B5C1
Core Height (cm)		350	500	900	700	700	700	700	700
Cycle (primary/fertile)		1/1	1/1	1/1	1/1	1/2[a]	1/1	1/2	1/1
Residence time (full power yrs)		4	4	4	3	3	4	4	5
Conversion Ratio		.617	.637	.640	.676	.624	.630	.594	.605
Fissile Inventory (Kgm)		1,267	1,125	1,030	1,019	1,123	1,065	1,122	1,093
Peak Axial Power Density (W_{th}/cc)		11.6	14.5	19.6	14.6	14.7	18.8	18.5	22.7
Core Leakage Fraction		.0855	.0693	.0584	.0555	.0571	.0653	.0702	.0728
Average Exposure (MW_{th} D/Kgm HM)		117.6	116.3	118.1	90.22	141.3	117.8	182.8	142.7
Feed Rates (Kgm/D at full power)									
Primary	Th[illegible]	5.6009	5.6002	5.6000	7.4679	7.4679	5.6009	5.6009	4.5430
	U[illegible]	1.9819	1.8943	1.8930	1.9268	1.6596	1.9375	1.6780	1.9271
	U[illegible]	.1056	.1010	.0999	.1028	.0882	.1030	.0895	.1028
Fertile	Th^{232}	17.817	17.816	17.814	23.756	21.892	17.817	16.099	14.451
	Pa[illegible]					.0021		.0006	
	U[illegible]					.4476		.3329	
	U[illegible]					.1508		.1339	
	U[illegible]					.0292		.0283	
	U[illegible]					.0080		.0101	

[a]Once-recycle of the fertile pebbles without reprocessing.

The initial fissile loading at reactor start up was not usually obtained in this effort. However, it enters the fuel cost calculations. Selected results are shown in Table 2-2 for the clean core with a one-dimensional model assuming radial blanketing.

Table 2-2. Initial Reactor State Conditions (One-dimensional, clean core)

C/HM, nominal	115[a]	115[b]	175[c]	175	250	325	400
Core height (cm)	500	700	500	700	700	700	700
Fuel	U^{233}	U^{233}	U^{235}	U^{235}	U^{235}	U^{235}	U^{235}
Fissile Inventory (Kgm)	2,128	2,162	1,364	1,238	989	766	620
Conversion Ratio	1.098	.916	.856	.861	.851	.824	.793
Peak Axial Power Density (W_{th}/cc)	11.62	7.83	11.41	7.63	7.67	7.66	7.66

[a]Only the upper half of the core fueled.

[b]No axial blanket at the inlet.

[c]Most of the fuel in the upper half of the core.

Primary results of one-dimensional parameter studies are shown in Table 2-3. These results indicate the improved fuel utilization by once recycle of the fertile pebbles without reprocessing. Radial blanketing was assumed in these cases. The "cycle" terminology 1/1 means fresh feed for both streams, while 1/1/2 means fresh feed for both streams, but the fertile pebbles are recycled once (without reprocessing).

The supplemental results in Table 2-4 at a C/HM of 250 display the effect from variation in the inlet design, within the limitations of diffusion theory and the geometric representation. The results for increases in the radial buckling indicate the effect of increased neutron leakage, as would be the consequence of less effective radial blanketing and/or a smaller reactor size. Later two-dimensional

Table 2-3. Results at Several Heavy Metal Loadings (One-Dimensional, Axial Blanket, 1,200 MW_e Plant, 5 W_{th}/cc)

Case	AL41[a]	AL51	AM21	AK41	AM31	AN41	AN31
Core Height (cm)	700	350	500	500	700	700	500
C/Heavy Metal (nom. atomic)	175	175	175	175	250	250	250
Cycle (primary/fertile)	1/2	1/1	1/1	1/1/2	1/1	1/1	1/1/2
Residence Time (full power yrs)	4	5	2	5	3	4	4
Conversion Ratio	.652	.656	.729	.642	.672	.635	.621
Fissile Inventory (kg)	1,858	1,154	1,982	2,123	1,355	1,415	1,561
Fissile Feed Rate (gm/d)	2,183	2,1?9	3,373	1,992	2,224	2,127	1,923
Peak Metal Power Density (W_{th}/cc)	12.2	14.4	7.33	11.3	13.3	16.6	17.8
Core Leakage Fraction	.0423	.0598	.0436	.0557	.0465	.0542	.0614
Fission Product Absorption Fraction	.06[illegible]	.10[illegible]	.0671	.1119	.0932	.1054	.1175
Exposure (MW_{th}D/kg HM)							
Average	77.8	96.2	39.7	131.	73.3	56.3	154.2
Primary/Fertile	119/69.9	144/52.2	67.7/15.8	332/119	177/36.1	229/49.0	205/113
Mass Balances (kg/D at full power)							
Primary Feed Th^{232}	15.837	12.670	31.670	12.668	8.5623	6.4217	6.4210
U^{235}	2.1833	2.1387	3.3732	1.9921	2.2244	2.1266	1.9232
U^{238}	.1163	.1139	.1695	.1051	.1186	.1133	.1033
Fertile Feed Th^{232}	20.376	16.301	47.751	8.1503	36.500	22.500	11.250
Pa^{233}							
U^{233}							
U^{234}							
U^{235}							
U^{236}							
Primary Discharge Th^{232}	14.743	11.646	30.475	11.572	7.9974	5.9014	5.9161
Pa^{233}	.0013	.0006	.0122	.0013	.0019	.0003	.0007
U^{233}	.3417	.2799	.5874	.2794	.1798	.1376	.1367
U^{234}	.0842	.0775	.0848	.0722	.0451	.0410	.0376
U^{235}	.1742	.1289	.7235	.1326	.1245	.0863	.0890
U^{236}	.3171	.3068	.4196	.2890	.3230	.3063	.2785
U^{238}	.0930	.0870	.1509	.0815	.0980	.0887	.0807
Fissile Pu	.0022	.0021	.0036	.0020	.0019	.0017	.0016
Other Pu	.0019	.0019	.0019	.0018	.0019	.0020	.0018
Fertile Discharge Th^{232}	18.908	14.910	43.158	6.8379	28.067	20.696	9.5523
Pa^{233}	.0017	.0008	.0163	.0007	.0031	.0011	.0011
U^{233}	.4380	.3579	.7600	.1689	.5904	.4504	.2115
U^{234}	.1120	.1037	.1130	.0690	.1530	.1397	.0928
U^{235}	.0255	.0262	.0166	.0223	.0297	.0307	.0252
U^{236}	.0048	.0060	.0015	.0114	.0058	.0078	.0143

[a]Note that the pebbles have about the same loading at a C/HM 175.

Table 3-3. (Cont'd.)

A821	A831	A832	[illegible]	AD??	A0??	[illegible]	AD??	[illegible]	AD41	AEX1
700	730	330	[illegible]	[illegible]	[illegible]	[illegible]	330	[illegible]	700	500
325	525	315	[illegible]	[illegible]	[illegible]	[illegible]	430	[illegible]	400	490
[illegible]	[illegible]	1/2	[illegible]	[illegible]	[illegible]	[illegible]	1/1	[illegible]	1/1	1/1/2
2	3	3	[illegible]	[illegible]	[illegible]	[illegible]	2	[illegible]	4	3.75
.664	[illegible]	.583	[illegible]	[illegible]	[illegible]	[illegible]	.698	[illegible]	.525	.558
[illegible]	[illegible]	1.171	[illegible]	[illegible]	[illegible]	[illegible]	875.	91[illegible]	943.	587.
2.42[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.449	[illegible]	2.270	[illegible]
12.4	[illegible]	11.2	[illegible]	[illegible]	[illegible]	[illegible]	36.3	[illegible]	26.6	14.[illegible]
[illegible]	[illegible]	.066[illegible]	[illegible]	[illegible]	[illegible]	.0738	.0620	[illegible]	.0833	.0723
[illegible]	[illegible]	.1223	[illegible]	[illegible]	[illegible]	.0704	.2920	[illegible]	.1230	.1167
[illegible]	64.3	[illegible]	[illegible]	[illegible]	[illegible]	76[illegible]	72.2	[illegible]	138.1	152.7
[illegible]	[illegible]	178/38.9	[illegible]	[illegible]	[illegible]	214/115	177/31.4	[illegible]	292/63.6	211/104
[illegible]	[illegible]	7.4672	5.6925	[illegible]	5.4093	6.4003	9.2222	6.1421	4.6111	6.7062
[illegible]	2.2003	1.8333	2.1597	[illegible]	1.9056	2.0657	2.4401	2.3252	2.2701	2.1156
[illegible]	.1177	.1097	[illegible]	[illegible]	.1016	.1069	.1295	.1247	.1207	.1128
35.432	23.756	22.030	17.817	20.362	18.694	10.1809	29.453	19.635	14.736	10.710
		.0018			.0023					
		.4511			.3794					
		.1439			.1281					
		.0277			.0257					
		.0068			.0073					
10.6015	6.9281	6.5394	5.1097	5.8861	5.9174	5.9012	8.6682	5.6770	4.1847	6.2327
.0026	.0007	.0005	.0002	.0008	.0006	.0007	.0014	.0003	.0001	.0010
.2180	.1503	.1530	.1133	.1265	.1291	.1277	.1784	.1204	.0896	.1284
.0505	.0458	.0428	.0405	.0405	.0378	.0392	.0477	.0416	.0361	.0390
.1926	.0888	.1001	.0542	.0652	.0794	.0711	.1386	.0656	.0399	.0762
.3488	.3217	.2679	.3090	.3077	.2785	.2915	.3576	.3329	.3036	.3101
.1116	.0962	.0829	.0889	.0902	.0814	.0853	.1122	.1006	.0928	.0934
.0018	.0015	.0014	.0014	.0014	.0014	.0014	.0015	.0014	.0013	.0013
.0017	.0019	.0016	.0020	.0019	.0017	.0018	.0017	.0020	.0021	.0017
33.755	22.035	20.524	16.227	18.694	17.256	8.6266	27.740	18.091	13.307	9.2093
.0079	.0018	.0013	.0006	.0023	.0018	.0010	.0042	.0010	.0003	.0014
.6579	.4517	.4405	.3390	.3794	.3640	.1797	.5446	.3653	.2704	.1848
.1576	.1438	.2080	.1276	.1281	.1754	.0680	.1524	.1334	.1160	.0925
.0254	.0277	.0502	.0271	.0257	.0433	.0214	.0246	.0251	.0238	.0204
.0042	.0068	.0276	.0086	.0073	.0275	.0138	.0049	.0073	.0089	.0127

Table 2-4. Supplemental Results for Fully Enriched Feed (One-Dimensional, C/HM 250, 500 cm height, 1,200 MW_e, 5 W_{th}/cc)

Case		ANX1[a]	ANX2	ANX3[a]	ANX4[a]
Reference Conditions					
Core Residence Time (Yrs)		4.0	4.0	4.0	4.0
Fertile Pebble Recycle		Blanket	Core	Core	Core
Axial Blanket (cm)		35.71	35.71	0	0
Top Reflection		Weak	Weak	Weak	Strong
Radial Buckling (cm^{-2})		0.7×10^{-5}	0.7×10^{-5}	0.7×10^{-5}	0.7×10^{-5}
Equivalent Core Radius (cm)[b]		909	909	908	909
Conversion Ratio		.621	.627	.585	.607
Fissile Inventory (Kgm)		1,551	1,508	1,651	1,436
Peak Axial Power Density (W_{th}/cc)		12.8	13.0	12.4	14.7
Core Leakage Fraction		.0614	.0598	.0781	.0696
Fission Product Absorption Fraction		.1175	.1185	.1155	.1169
Exposure (MW_{th}D/Kgm HM)					
Average		154.2	152.6	151.0	151.7
Primary Fertile		205/113	203/114	214/103	212/106
Mass Balances (Kgm/D at full power)					
Primary Feed	Th^{232}	6.4210	6.4210	6.4210	6.4210
	U^{235}	1.9232	1.8897	2.0867	1.9955
	U^{238}	.1033	.1007	.1112	.1064
Fertile Feed	Th^{232}	11.250	11.250	11.249	11.249
Primary Discharge	Th^{232}	5.9161	5.911[illegible]	5.9152	5.9059
	Pa^{233}	.0007	.0007	.0009	.0007
	U^{233}	.1367	.1363	.1381	.1364
	U^{234}	.0376	.0381	.0375	.0385
	U^{235}	.0890	.0842	.1010	.0822
	U^{236}	.2785	.2733	.3034	.2857
	U^{238}	.0807	.0791	.0872	.0836
Fissile	Pu	.0016	.0016	.0018	.0017
Other	Pu	.0018	.0018	.0019	.0019
Fertile Discharge	Th^{232}	9.5523	9.5379	9.6711	9.6392
	Pa^{233}	.0011	.0011	.0014	.0011
	U^{233}	.2115	.2103	.2163	.2122
	U^{234}	.0928	.0935	.0908	.0920
	U^{235}	.0252	.0253	.0244	.0247
	U^{236}	.0143	.0146	.0125	.0133

[a] These cases had about 0.0017 fraction neutron absorptions in silicon while the others had none (inadvertently).
[b] Actual core radius for 600 m^3 is 618 cm (but with power flattening the effective radius may be less than this).
[c] This case treated 13 energy groups instead of 4.

Table 2-4. (Cont'd.)

ANX5	ANX6	ANX7	ANX8	ANX9	ANX10	ANY9[c]
4.0	4.0	4.0	4.0	4.2	4.2	4.2
Core	Core	Core	Core	no	no	no
71.42	35.71	35.71	0	35.71	35.71	35.71
Weak	Weak	Weak	Weak	Weak	Weak	Weak
0.7×10^{-5}	1.6×10^{-5}	3.2×10^{-5}	3.2×10^{-5}	0.7×10^{-5}	3.2×10^{-5}	0.7×10^{-5}
909	601	425	425	909	425	909
.668	.613	.591	.559	.637	.595	.635
1,493	1,559	1,648	1,575	1,493	1,641	1,507
13.5	13.1	13.1	14.7	13.1	13.3	12.9
.0400	.0680	.0818	.0932	.0597	.0819	.0603
.1208	.1163	.1128	.1108	.1071	.1029	.1069
153.9	152.0	150.2	149.3	101.0	100.2	100.9
192/126	206/111	207/106	278/97	225/53	232/48	225/53
6.4210	6.4210	6.4210	6.4210	6.1152	6.1152	6.1152
1.7240	1.9674	2.0894	2.2194	2.0601	2.2813	2.0700
.0919	.1049	.1114	.1183	.1099	.1216	.1104
11.249	11.250	11.250	11.249	21.429	21.429	21.429
5.9227	5.9218	5.9386	5.9384	5.6012	5.6316	5.6016
.0006	.0007	.0006	.0006	.0007	.0006	.0007
.1357	.1378	.1403	.1404	.1282	.1325	.1286
.0374	.0372	.0357	.0360	.0387	.0361	.0386
.0803	.0971	.1216	.1243	.0755	.1133	.0770
.2495	.2854	.3041	.3207	.2955	.3306	.2971
.0727	.0826	.0881	.0938	.0851	.0951	.0854
.0014	.0017	.0019	.0020	.0016	.0020	.0017
.0016	.0018	.0020	.0021	.0019	.0023	.0019
9.3895	9.5725	9.6287	9.7414	19.628	19.737	19.632
.0009	.0010	.0010	.0009	.0022	.0020	.0023
.2062	.2137	.2195	.2217	.4196	.4332	.4208
.0954	.0926	.0909	.0893	.1325	.1239	.1319
.0262	.0252	.0251	.0242	.0293	.0271	.0291
.0168	.0134	.0129	.0115	.0078	.0064	.0077

calculations allow comparison with specific two-dimensional models and generally show less effective in-core radial blanketing than was assumed for these calculations, decreasing the conversion ratio and increasing the fissile feed rate.

Two-Dimensional Calculations

Results of two-dimensional calculations are shown in Table 2-5. The radial feed variation required to reduce the radial power density peak was examined and its effect on performance. Internal radial blanketing was also studied. Additional results are shown in Table 2-6 which consider the reactor without an axial blanket and an annular core discussed later.

The steady state condition with once recycle of the fertile pebbles was treated directly. In this calculation a discrete recycle was considered (lacking direct mixing capability); little effect was found from this approximation by altering the model, but additional results are not reported here.

Neutron balance data accounting for losses are shown in Table 2-7 for selected cases.

The data presented previously allows the assessment of perturbations from the reference cases. A 0.01 fraction increase in neutron loss causes about 0.02 loss in conversion ratio and 0.05 fraction increase in the fissile feed rate. Thus removing the silicon and an associated absorption fraction of 0.0015 would be expected to increase the conversion ratio by 0.003 and reduce the fissile feed rate by less than 0.01 fraction; doubling the silicon content to better contain the fission fragments in the heavy metal kernels would reduce the conversion ratio by 0.003 and increase the fissile feed rate by less than 0.01 fraction.

Blanketing and Power Density Flattening

Regarding power flattening, consider first the core without a radial blanket. By increasing the fissile feed enrichment radially outward, the exposure to a neutron flux which decreases radially outward can effect a nearly flat radial power density. Flattening reduces the peak to average power density maximizing the power level for a given limiting heavy metal temperature.

Variation in the radial power density directly causes the efficiency of heat removal to be reduced. To limit the peak heavy metal temperature, the mass flow rate of coolant must be increased along a path of high power density. The situation is aggravated by the low flow rate in areas of high gas temperature and low density, and high in areas of low gas temperature. The net result is higher flow rate, higher pressure drop through the core, and lower average exit coolant temperature, reducing the efficiency of heat removal. (Natural remixing in a pebble bed helps some of course.)

If the pebble residence time were constant over the core, the energy produced in each pebble (exposure) would be the same with a fixed heavy metal feed rate and flat radial power density. Thus there would be uniform exposure, avoiding a distribution about an average, which maximizes the allowable exposure before severe pebble damage. With a longer residence time at the edge of the core, exposure increases. To effect the same exposure with a 25 percent variation in the residence time would require a peak to average power density of about 15 percent neglecting axial effects, while with a flat power density the exposure would vary approximately as the reciprocal of the residence time. (Axial depletion of fuel reduces the effect.)

Disadvantages of power flattening include increased neutron leakage decreasing the fuel conversion ratio and increasing the fissile inventory and feed rate, increased power density near the reflector which may exceed that inward due to neutron flux peaking in and return from the reflector, and elevated flux level in the reflector increasing the damage rate. The increased fuel requirement can be held tolerable by incomplete flattening, holding down the feed enrichment toward the outer edge of the core. This holds down the power density peaking near the reflector and reduces the flux level in the reflector. (However, the power density peak is not reduced as much as it could be.) The effect of the condition near the reflector is especially important because of the large volume

Table 2-5. Two-Dimensional Results for Fully Enriched U^{235} Feed With and Without Internal Radial Blanket ($5\ W_{th}/cc$, 500 cm height, 1,200 MW_e)[a]

Case		MR210	MR236	MR237	MR238	MR248[b]
C/N		250	250	250	250	250
Cycle		1/1	1/1	1/1	1/1	1/1
Radial Blanket Fraction of Core		0.2	0.2	[illegible]	0.2	0.2
Core Residence Time (full power yrs)		4.0	4.3	4.0	4.0	4.0
Conversion Ratio		.617	.619	.629	.620	.626
Fissile Inventory (Kgm)		1,575	1,583	[illegible]	1,632	1,621
Power Density, Peak (W_{th}/cc)		22.3	19.5	[illegible]	18.6	17.7
Pebble Peak, Primary/Fertile[e]		57/18	51/18	47/17	45/16	44/16
External Leakage Fraction		.0617	.0616	.0620	.0620	.0623
Fission Product Absorption Fraction		.1086	.1082	.1070	.1065	.1058
U^{235} Feed Density by zone (A/Bn-cm in pebble)						
(1)		5.202-5	5.292-5	5.014-5	4.900-5	4.943-5
(2)		—	5.582-5	5.314-5	5.260-5	5.243-5
(3)		—	5.982-5	5.714-5	5.600-5	5.643-5
(4)		—	5.982-5	7.014-5	7.500-5	7.543-5
(5)		fertile	fertile	fertile	fertile	fertile
(6)		fertile	fertile	fertile	fertile	fertile
Exposure (MW_{th} D/Kgm HM)						
Average		91.3	92.2	91.3	92.1	91.2
Primary/Fertile by zone path						
(1)		257/62	255/60	246/57	241/56	242/56
(2)		257/62	264/62	260/61	253/60	253/60
(3)		260/56	268/58	263/58	260/58	260/58
(4)		231/36	239/37	263/40	273/40	270/39
(5)		- /16	- /17	- /19	- /20	- /20
(6)		- / 8	- / 9	- /10	- /11	- /11
Mass Balances (Kgm/D at full power)						
Primary Feed	Th^{232}	5.1218	5.1218	5.1218	5.1218	5.1218
	U^{235}	2.2243	2.2166	2.2243	2.2321	2.2487
	U^{238}	.1186	.1182	.1186	.1190	.1199
Fertile Feed	Th^{232}	25.409	25.409	25.409	25.409	25.409
Primary Discharge	Th^{232}	4.6766	4.6762	4.6787	4.6800	4.6794
	Pa^{233}	.0005	.0005	.0005	.0006	.0006
	U^{233}	.1134	.1135	.1137	.1138	.1151
	U^{234}	.0337	.0337	.0335	.0333	.0336
	U^{235}	.1044	.1036	.1092	.1124	.1207
	U^{236}	.3175	.3168	.3188	.3203	.3233
	U^{238}	.0899	.0897	.0904	.0908	.0912
Fissile	Pu	.0019	.0019	.0020	.0020	.0021
Other	Pu	.0022	.0022	.0022	.0022	.0023
Fertile Discharge	Th^{232}	23.611	23.601	23.591	23.587	23.587
	Pa^{233}	.0020	.0021	.0021	.0021	.0023
	U^{233}	.4818	.4844	.4903	.4932	.4970
	U^{234}	.1279	.1286	.1294	.1296	.1308
	U^{235}	.0286	.0287	.0286	.0286	.0289
	U^{236}	.0078	.0078	.0076	.0075	.0074

[a] Core fraction of radial zones (outward) and relative primary pebble residence times: 1/5, .85; 1/5, .925; 1/5, 1.0; 1/5, 1.075; 1/10, 1.1125; 1/10, 1.1875; half primary, half fertile pebbles.
[b] Thirteen neutron energy groups instead of 4.
[c] Fertile streams recycled individually to the next outer channel, the fourth one back to the central channel; radial blanket pebbles not recycled.
[d] No axial blanket.
[e] Multiply by $\frac{4}{3}\pi r^3 = 113.1\ cm^3$ for the power level per pebble of 6 cm. diameter pebbles.

Table 2-5. (Cont'd.)

MR256	MR310	MR311	MR312	MR313	MR314	MR326	MR336
256	325	325	325	325	325	325	325
1/1/2[c]	1/1	1/1	1/1	1/1	1/1	1/1	1/1
0.2	0	0	0	0	0	0.1	0.2
4.0	3.5	3.5	3.5	3.5	3.5	3.4	3.3
.597	.571	.569	.564	.562	.564	.583	.592
1,726	1,289	1,302	1,333	1,329	1,326	1,282	1,241
19.0	9.4	16.2	18.3	16.7	16.1	17.9	21.1
44/20	51/15	42/13	45/13	41/13	41/13	46/14	55/16
.0656	.0849	.0872	.0910	.0893	.0688	.0776	.0710
.1176	.1049	.1035	.1030	.1033	.1034	.1055	.1084
4.726-5	4.122-5	3.356-5	2.645-5	3.407-5	3.560-5	3.913-5	4.340-5
5.027-5	"	3.736-5	3.475-5	3.744-5	3.762-5	4.113-5	4.490-5
5.427-5	"	4.176-5	4.305-5	4.157-5	4.132-5	4.313-5	4.740-5
7.327-5	"	4.586-5	5.136-5	4.747-5	4.458-5	4.813-5	6.340-5
fertile	"	4.996-5	5.965-5	5.347-5	5.322-5	5.813-5	fertile
fertile	"	4.996-5	5.065-5	5.347-5	5.322-5	fertile	fertile
125.5	101.6	101.6	101.6	101.4	101.5	97.3	94.1
233/106	239/56	200/43	166/39	207/47	215/50	228/52	246/57
242/107	238/55	223/51	209/49	221/51	223/52	238/55	253/59
250/93	234/52	240/55	243/56	237/53	235/52	244/55	253/57
262/92	223/43	246/51	262/54	248/44	238/47	246/46	263/45
-/32	127/30	238/37	264/40	243/35	240/34	241/29	-/19
-/17	183/20	220/27	245/29	224/25	221/24	-/18	-/10
5.1218	6.4749	6.4749	6.4749	6.4749	6.4749	5.9358	5.3605
2.1644	2.3250	2.3261	2.3629	2.3771	2.3666	2.2601	2.2501
.1154	.1239	.1240	.1260	.1267	.1261	.1219	.1179
16.392	20.599	20.599	20.599	20.599	20.599	22.319	24.144
4.5966	5.9867	5.9890	5.9914	5.9910	5.9900	5.4691	4.3151
.0005	.0007	.0008	.0008	.0007	.0008	.0007	.0006
.1151	.1296	.1303	.1305	.1315	.1304	.1208	.1107
.0330	.0384	.0379	.0376	.0379	.0379	.0370	.0358
.1355	.1153	.1130	.1215	.1220	.1230	.1049	.0884
.3134	.3349	.3366	.3425	.3443	.3474	.3300	.3244
.0885	.0996	.0997	.1012	.1021	.1017	.0969	.0937
.0620	.0017	.0017	.0018	.0017	.0017	.0017	.0017
.0021	.0020	[illegible]	.0021	.0021	.0021	.0021	.0021
14.697	19.018	19.029	19.038	19.034	[illegible]	20.661	[illegible]
.0019	.0022	.0023	.0024	.0022	.0023	.0023	.0023
.2973	.3832	.3913	.3919	.3920	.3917	.4189	.4404
.0942	.1215	.1200	.1190	.1200	.1202	.1257	.1278
.0255	.0242	.0237	.0235	.0237	.0247	.0260	[illegible]
.0136	.0066	.0062	.0061	.0062		.0068	.0073

Table 2-6. Additional Two-Dimensional Results for Fully Enriched U^{235}
($5\ W_{th}/cc$, 500 cm height, 1,200 MW_e)

Case		MR280[b]	MR281[b]	MR283[c]	MR285[d]	MR286[b]	MR293[b]
C/HM		250	250	250	250	250	250
Cycle		1/1	1/1	2/1	3/1	3/1	[illegible]
Radial Blanket Fraction of Core		0	0	0	0.2	0.2	0
Core Residence Time (full power yrs)		3.5	4.2	4.2	4.0	4.3	4.2
Conversion Ratio		.573	.549	.540	.572	.567	.544
Fissile Inventory (kgm)		1,351	1,918	2,027	1,778	1,806	1,908
Power Density, Peak (W_{th}/cc)		13.2	14.1	14.0	18.2	17.7	14.2
Pebble Peak, Primary/Fertile		34/12	36/13	37/12	43/15	44/15	33/16
External Leakage Fraction		.0943	.0983	.0953	.0835	.0835	.0992
Fission Product Absorption Fraction		.0944	.1019	.0985	.1066	.1067	.1120
U^{235} Feed Density by zone (A/Bn-cm in pebble							
(1)		4.119-5	4.802-5	4.676-5	5.428-5	5.524-5	4.293-5
(2)		4.319-5	5.002-5	4.87[illegible]-5	5.723-5	5.824-5	4.493-5
(3)		4.689-5	5.372-5	5.246-5	6.128-5	6.224-5	4.863-5
(4)		5.019-5	5.702-5	5.576-5	8.028-5	8.174-5	5.193-5
(5)		5.879-5	6.562-5	6.476-6	fertile	fertile	6.053-5
(6)		5.879-5	6.562-5	6.476-6	fertile	fertile	6.053-5
Exposure (MW_{th} D/kgm HM)							
Average		82.4	97.8	96.4	90.6	90.5	154.2
Primary/Fertile by zone path							
(1)		200/35	230/44	223/41	253/79	255/45	242/104
(2)		209/38	239/46	231/44	265/53	265/52	251/108
(3)		220/39	248/47	240/45	272/52	272/51	262/110
(4)		220/33	247/40	238/39	279/35	278/34	262/100
(5)		213/23	238/28	227/27	/17	/16	254/36
(6)		189/15	214/19	202/18	/8	/8	228/26
Mass Balance (kgm/D at full power)							
Primary Feed	Th^{232}	7.4241	6.1867	6.1867	5.1218	5.1218	6.1867
	U^{235}	2.6816	2.5564	2.5002[e]	2.4380	2.4757	2.3167
	U^{238}	.1429	.1363	.2306	.1300	.1325	.1235
Fertile Feed	Th^{232}	26.144	21.787	21.678	25.407	25.407	10.3384
Primary Discharge	Th^{232}	6.9268	5.7102	5.7263	4.6816	4.6836	5.4147
	Pa^{233}	.0013	.0009	.0008	.0007	.0007	.0008
	U^{233}	.1587	.1343	.1448	.1155	.1150	.1359
	U^{234}	.0381	.0359	.0562	.0328	.0336	.0345
	U^{235}	.2506	.1835	.2162	.1330	.1433	.1688
	U^{236}	.3863	.3690	.6324	.3519	.3581	.3347
	U^{238}	.1166	.1072	.1824	.0988	.1003	.0974
Fissile	Pu	.0025	.0023	.0042	.0023	.0023	.0022
Other	Pu	.0023	.0023	.0040	.0025	.0024	.0023
Fertile Discharge	Th^{232}	24.535	20.247	20.193	23.758	23.768	9.3689
	Pa^{233}	.0042	.0027	.0026	.0027	.0027	.0012
	U^{233}	.5185	.4389	.4441	.4911	.4883	.2165
	U^{234}	.1232	.1159	.1106	.1182	.1209	.0847
	U^{235}	.0240	.0244	.0232	.0253	.0260	.0232
	U^{236}	.0044	.0053	.0047	.0058	.0059	.0113

[a] Also refer to notes in Table 2-5.
[b] No inlet axial blanket.
[c] Annular core, outer internal blanket, radial zone fractions 0.04, four at 0.215, 0.1.
[d] Annular core, inner and outer internal blanket, radial zone fractions 0.04, four at 0.215, 0.1.
[e] See case MR281 for feed rates of other uranium isotopes (primary discharge).
[f] Somewhat different modeling.
[g] Modeling different, more reflection reduces core losses.
[h] Modeling different, large reflectors.

Table 2-6. (Cont'd.)

MR294[b]	MR294A[b,f]	ANC010[f,g]	ANC012[f,g]	ANC014[f,g]	ANC016[f,g]	MR238A[f]	MR256A[f]	MS250[g]	MS251[f,g]
250	250	250	250	250	250	250	250	250	250
1/1/2	1/1/2	1/1	1/1	1/1	1/1	1/1	1/1/2	1/1	1/1
5.2	5.2	0.1	[illegible]	0.14	0.14	[illegible]	[illegible]	[illegible]	0
4.2	4.4	4.2	4.2	4.2	4.2	4.0	4.0	4.1	4.15
.556	.550	.543	.581	.589	.685	.530	.592	.551	.572
1.833	1.819	1.846	1.683	1.637	1.746	1.505	1.666	1.628	1.670
18.1	17.9	15.6	16.6	16.7	18.0	27.6	15.5	16.6	13.2
42/19	37/19	40/13	41/16	47/16	42/15	62/17	41/19	49/15	56/53
.0838	.0958	.0898	.0756	.0745	.0752	.3526	.0683	.0560	.0238
.1166	.1163	.1063	.1052	.1057	.1562	.1074	.1179	.1093	.1036
5.395-5	5.273-5	6.727-5	6.241-5	fertile	fertile	4.819-5	6.686-5	3.925-5	4.580-5
5.396-5	5.413-5	5.621-5	5.147-5	5.862-5	5.860-5	6.079-5	4.986-5	3.925-5	4.730-5
5.796-5	5.913-5	5.721-5	5.241-5	5.862-5	5.360-5	5.479-5	5.386-5	4.025-5	4.680-5
7.628-5	7.713-4	6.027-5	5.541-5	[illegible]	[illegible]	6.079-5	7.286-5	[illegible]	5.270-5
fertile	fertile	7.121-5	6.641-5	5.867-5	7.390-5	fertile	fertile	7.025-5	5.680-5
fertile	fertile	fertile	fertile	fertile	fertile	fertile	fertile	fertile	6.580-5
125.2	125.2	97.[illegible]	97.[illegible]	96.[illegible]	96.[illegible]	97.5	126.[illegible]	97.4	96.[illegible]
244/112	246/112	269/41	251/46	[illegible]/26	[illegible]/36	243/60	[illegible]	233/60	226/4[illegible]
252/[illegible]	252/116	256/53	2[illegible]/57	278/59	264/54	251/63	2[illegible]	[illegible]/59	230/4[illegible]
259/[illegible]	259/[illegible]	259/52	249/[illegible]	279/64	2[illegible]/59	252/61	249/[illegible]	233/5[illegible]	2[illegible]/44
266/[illegible]	267/114	2[illegible]/4[illegible]	2[illegible]/54	274/54	2[illegible]/53	261/41	2[illegible]/112	[illegible]	2[illegible]/44
[illegible] 30	[illegible] 30	253/30	250/[illegible]	236/34	2[illegible]/35	[illegible] 18	[illegible] 19	264/12	[illegible]/36
[illegible] 16	[illegible] 16	[illegible]	[illegible]16	[illegible]	[illegible]	[illegible] 9	[illegible] 13	14	2[illegible]/47
5.7216	5.1216	5.4435	5.4440	5.7[illegible]	5.2106	[illegible]	[illegible]	[illegible]	[illegible]
2.3149	2.3261	2.5386	2.1391	[illegible]	2.1444	[illegible]	[illegible]1464	[illegible]	[illegible]
.[illegible]34	.1786	.1963	.2247	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
16.[illegible]	16.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	16.[illegible]	[illegible]	[illegible]
4.[illegible]	4.[illegible]	4.[illegible]	5.[illegible]	[illegible]	5.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	.0007	.0007	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	.3136	[illegible]	.0984	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.[illegible]	.1466	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.[illegible]64	.[illegible]	.3702	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.[illegible]	.0944	.1941	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.[illegible]	.0012	.0012	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	.0023	.0004	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
14.8337	14.4426	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	14.[illegible]	[illegible]	[illegible]
.0014	.0014	.0024	[illegible]	[illegible]	[illegible]	.0014	[illegible]	[illegible]	[illegible]
[illegible]	.2787	.4374	.4159	.4414	[illegible]	[illegible]	[illegible]	[illegible]	.4155
.3897	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	.0054	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.0054

Table 2-7. Distribution of Neutron Losses

Reference Case	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	1	[illegible]	2	1	1	1	1	1
Groups	[illegible]	[illegible]	4	4	5	4	4	8
[illegible]	250	250	250	375	250	250	250	230
Residence time (yr)	4.5	4.8	4.5	7.3	4.2	4.2	4.2	4.2
[illegible] recycle fertile	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]					3.5	3.6	3.24	
Actinides								
[illegible]	.27875	.28776	.26949	.27840	[illegible]	[illegible]	[illegible]	.27749
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Pu	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	9.96-5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	3.52-5	3.89-5	1.56-5	3.50-5	3.51-5	3.52-5	3.16-5	4.76-5
Fission Product								
[illegible]	.00635	[illegible]	.00069	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	.00148	[illegible]	[illegible]	.00156	.00156	.00141	.00143
[illegible]	[illegible]	.00612	.00650	[illegible]	[illegible]	[illegible]	[illegible]	.00658
[illegible]	[illegible]	.00044	.00041	[illegible]	.00042	[illegible]	.00040	.00040
Ag	[illegible]	[illegible]	.00012	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Xe	.00574	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.00614
[illegible]	[illegible]	[illegible]	.00012	[illegible]	[illegible]	[illegible]	.00017	.00017
Cs	[illegible]	[illegible]	.00739	.00588	[illegible]	[illegible]	.00585	.00610
[illegible]	.00114	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.00107	[illegible]
[illegible]	[illegible]	.02134	[illegible]	.02236	[illegible]	[illegible]	.02115	.02074
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.00015	[illegible]
Nd	[illegible]	[illegible]	.01445	[illegible]	[illegible]	.01385	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	.00491	[illegible]	[illegible]	[illegible]	.00410	[illegible]
Pm	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.00573	.00567	[illegible]
Pm	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Pm	[illegible]	[illegible]	.00257	.00256	[illegible]	[illegible]	[illegible]	[illegible]
Sm	.00750	.00755	.00764	[illegible]	[illegible]	[illegible]	[illegible]	.00744
Sm	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.00213	.00222
Sm	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.00362	.00368	.00375
Sm	.00325	[illegible]	.00370	[illegible]	[illegible]	.00323	.00308	.00717
Eu	.00208	[illegible]	[illegible]	.00210	.00211	.00211	.00197	.00205
Eu	.00166	.00169	.00209	.00173	[illegible]	.00171	.00156	.00163
Eu	.00177	.00174	.00213	[illegible]	.00176	.00176	.00151	.00167
SSFP[a]	.00972	.00964	.01221	.00976	.00980	.00977	.00919	.00955
NSFP[b]	.00396	.00396	.00495	.00382	.00389	[illegible]	.00368	.00387
Other								.00170[c]
C	.02160	.02187	[illegible]	[illegible]	.02275	[illegible]	.02139	.02111
He	8.17-5	8.30-5	7.67-5	[illegible]	9.28-5	9.36-	8.36-5	7.96-5
Si	.00143	.00146	.00135	[illegible]				.00215
O	9.84-5	1.29-4	9.81-5	9.02-5	1.48-4	1.48-4	1.45-4	1.01-4
Leakage	.06299	[illegible]	[illegible]	.07107	.06033	.05967	.08189	.07596
Total	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

[a]Slowly saturating lumped fission products.
[b]Non-saturating lumped fission products.
[c]Concrete [illegible]

involved (volume proportional to r^2). Flattening may significantly aggravate xenon driven flux oscillation increasing control requirements for stabilizing the flux distribution.

Radial blanketing with fertile pebbles appears to be very desirable, in spite of reducing the efficiency of energy removal. It shields the reflector, and reduces the core leakage, increasing the conversion ratio and reducing the fissile inventory (U^{233} vs U^{235}) and feed rate. However, with a fixed core size, internal blanketing increases the power density at a given power level by reducing the radius of the core containing fueled pebbles. Dedication of 10 percent of a 328 cm radius core involves a thickness of 32.8 cm and an increased power density of about 10 percent; 5 percent would be 16.2 cm. As the thickness of a radial layer of fertile pebbles is increased, likely the more practical it is to effect a nearly flat power density over the fueled pebble zone, up to some thickness. (A minimum thickness may be found to be desirable to limit the damage rate to the graphite reflector.) Radial blanketing can also effect a bottom blanket with ported pebble exit due to natural pebble flow. The use of fertile pebbles for the radial blanket is attractive because they can be continuously removed and then passed through the core without processing to effect sufficient fissile content to avoid both uneconomical processing and high loss. A radial blanket likely disallows the location of control rods in the reflector.

Blanketing the top of the core with fertile pebbles seems desirable, preferably allowing them to pass on through the core to avoid a fixed blanket requiring removal and avoiding low build up of fissile material in fixed outer pebbles. The core leakage would be reduced, increasing the conversion ratio and reducing the fissile inventory and feed rate. A 50 cm blanket above a 500 cm high core adds 10 percent pebble loading, but these are unfueled pebbles. For effective blanketing, these pebbles should stack above the others. This would increase the coolant pressure drop, but less than by a factor of the relative height increase since the inlet gas temperture at the top of the core is low.

The means to effect a near flat zone of pebbles at the top of the bed, with introduction of pebbles below it, would have to be invented and demonstrated. Shorter residence time of pebbles near the center tends to cause a voided inverted cone at the top which may be a severe impact. Indeed the requirements for control and shutdown rods may be severely impacted by an inlet blanket of moving pebbles. At least there would be increased requirements for structural support to maintain free rod passages, if these are required. The requirements for a demonstration of satisfactory rod positioning capability and associated core instrumentation appear to be impacted. With this study has come the feeling that fissile pebbles can not be fed under a fertile pebble blanket and an adequate distribution be effected unless the blanket is suspended above the core, which would require structure and the removal, replacement and reinsertion of the blanket pebbles into the core some way, hopefully without plant shutdown.

Effect of Pebble Packing

The dependence of performance on the pebble packing fraction was calculated with the following results:

	Reference	10 Percent Packing Increase
Pebble Packing Fraction	0.61	0.671
Coolant Fraction	0.39	0.329
Conversion Ratio	0.6298	0.6523
Fissile Inventory (Kgm)	1,562	1,628
Fissile Feed (Kgm/D)	2.160	2.133
Peak Power Density		
Core	19.6	18.6
Primary Pebble	53.5	48.6
Fertile Pebble	15.5	15.3
Fission Product Absorption Fraction	.1037	.1003
Core Leakage Fraction	.0572	.0500

Increased Problem Size

More meshpoints and exposure regions would be used for design support calculations than were used for these survey calculations. A few problems were solved to test the capability. The number of axial regions was increased from 14 to 30 for the fueled pebbles (34 including an axial blanket), and the radial from 5 to 11, making 644 compositions to treat for exposure compared with 136 typically used in the analysis. The number of (R,Z) meshpoints was increased from 50 × 52 = 2,600 to 53 × 88 = 4,664, 18,656 space energy points. The computer time was increased by a factor of 3. The results indicated that the reference calculations were adequate for survey; a lower power density peak was found at a small increase in the fissile feed rate, and relatively good flattening was found to be possible with only two feed enrichments.

Annular Core

An annular core design is worth consideration. Above some core size, such design could be necessary; the control of pebbles appears to present problems for a large core requiring multi-porting, but an annular design is likely not desirable below some plant size, perhaps as large as 3,000 Mw_{th}. By incorporating a central column of concrete axial steel ties can be used to reduce the load on and significantly ease the structural requirements of the concrete pressure vessel heads. This concrete must be shielded, so an internal graphite reflector is necessary which would be subject to a higher damage rate than the external reflector, inviting adjacent blanketing with fertile pebbles. It may prove feasible to locate control rods in this internal reflector and also associated instrumentation, possibly attractive for control of xenon driven flux oscillation. A 75 cm radius concrete column and 36 cm reflector has an area of 3.87 m^2 compared to 120 m^2 for a 618 cm radius cylindrical core, an increase of only 3 percent and an outside core radius increase to 628 cm, not very significant in considering such aspects as capital costs. However, shielding of the concrete may require considerably more material than considered here.

Significant reduction in the variation of the pebble residence time may result with an annular design without significant impact on the requirements for distributing the feed pebbles. This could reduce the variation in pebble exposure allowing increase in the average. The requirements for power flattening do not appear to be changed much, but the neutron flux which peaks in the annulus may not be as stable. The tendency for xenon driven radial flux oscillation within the annulus section is reduced but across the whole core (azimuthal) is greater.

Requirements in the thermal, hydraulics area appear to be no more difficult to satisfy, although multiple coolant entrance and exit ports may be even more attractive with the central plug ... ing through the reactor.

Results for an annular core with a 75 cm concrete plug and a 36 cm internal reflector were shown in Table 2-6.

After Shutdown

After reactor shutdown, the level of ^{135}Xe poisoning passes through a maximum due to ^{135}I decay and discontinued absorption loss, and then decreases to zero due to decay. Also, the decay of ^{233}Pa to ^{233}U fuel adds excess neutrons in a neutron balance. With load change there are changes in the neutron balance. Here we are interested in such effects and the dependence of these on the core design. Of special interest are how long the plant would stay shut down before startup is possible (Xe override requirements), and when the multiplication factor increases above unity requiring rod insertion, and how much control worth is needed to effect the subcritical state after a long time.

The history of the multiplication factor after shutdown and following load change was determined by treating the reactor as a fixed bed. Selected one-dimensional results are shown in Table 2-°. These calculations treat the full set of chain equations used in the continuous fueling model explicitly is considered including ^{233}Pa$\rightarrow$^{233}U, ^{135}I $\rightarrow$^{135}Xe, and the route to ^{149}Sm involving ^{148}Pm and ^{148m}Pm, at operating temperature. Note the significant effect of the loading on behavior.

Additional calculations were done for a reference two-dimensional case having a C/HM of 250 (MR256). The results obtained at shutdown and following it for the reactor at power (hot) and cold are shown below:

Time After Shutdown (Hours)	Multiplication Factor Hot	Multiplication Factor Cold
0	1.0	1.0297
6	.9516	.9799
12	.9483	.9765
18	.9591	.9876
24	.9735	1.0024
30	.9871	1.0164
36	.9984	1.0281
42	1.0071	1.0370
13,140	1.0729	1.1047

Table 2-8. Multiplication Factor After Shutdown

Case Description	^{233}U Feed C/HM 175 Once Recycle 3 Year Residence	^{235}U Feed C/HM 325 Once Recycle 3.5 Year Residence	^{235}U Feed C/HM 175 Once Through 1.5 Year Residence
Time After Shutdown (Hrs)			
0	1.0	1.0	1.0
3	.9761	.9587	.9772
6	.9654	.9404	.9671
9	.9623	.9341	.9643
12	.9636	.9349	.9658
15	.9676	.9398	.9699
18	.9728	.9468	.9753
21	.9786	.9549	.9811
24	.9845	.9633	.9870
27	.9901	.9714	.9926
30	.9953	.9789	.9978
33	1.0000	.9858	1.0025
36	1.0042	.9919	1.0066
39	1.0078	.9973	1.0102
42	1.0109	1.0018	1.0132
45	1.0136	1.0057	1.0158
Time After Renewed Operation with Fixed Bed (Days)			
1	1.0032	1.0013	1.0034
2	1.0013	1.0002	1.0014
3	1.0011	1.0002	1.0015
4	1.0007	.9998	1.0015
5	1.0003	.9991	1.0013
Time After Power Level Reduced to Half (Days)			
.5		.9986	1.0012
1.		.9981	1.0011
1.5		.9976	1.0010
2.		.9971	1.0008
2.5		.9965	1.0006
3.		.9960	1.0005
Time After Power Level Increased to Full (Days)			
.5		.9955	1.0003
1.		.9950	1.0001
1.5		.9945	1.0001
2.		.9940	.9998
2.5		.9935	.9996
3.		.9931	.9995

The prompt reactivity temperature coefficient was also calculated for this case at power as -2.9×10^{-5} per °C (without change in the graphite temperature), where the temperature rise would be the average in all of the heavy metal (considering fissile and fertile content).

The after-shutdown situation may be examined for partial override capability. The following results are based on the two-dimensional calculation for shutdown with a C/HM of 250 without any allowance for delay in effecting power or temperature changes:

Fraction Override Capability	Worth in k_{eff}	Time in Hours: Restart Allowed	Restart not Allowed	Restart reallowed to $k_{eff}>1$
0	0	0	37.4	0
0.40	0.0224	1.9	24.5	11.0
0.60	0.0336	3.1	18.7	15.6
0.80	0.0448	4.8	12.4	20.2
1.00	0.0560	always	0	37.4

Note that if peak load occurred once daily and is assumed to persist over a period of 4 hours, and with shutdown at the end of one period, it would be desirable to be back to power in 20 hours. Allowing 3 hours to bring up power, restart in 17 hours is desirable which would require a worth of 0.0456 in k_{eff} or just over 80% total override capability.

This is an appreciable amount of neutron loss to tie up, amounting to about 0.09 loss in conversion ratio compared to absorption in thorium. Analysis of the requirements on a distribution grid would be required to show that such override is not needed or is not justified based on costs (with energy purchase or trading allowed), probability distributions of plants down, capability to maintain a viable supply at a low supply level, and assessment of the probability of rapid startup. There is a basic difference between a core with an axial blanket and one without regarding override. Without the blanket the required reactivity can possibly be tied up in control rods in place of axial leakage without degrading performance. The analysis here is incomplete; a careful study must be made of the situation involving a selected control rod and core design and control rod role, with sophisticated treatment of neutron transport and consideration of startup at a temperature below normal operation and operation for a period at below design level.

From the viewpoint of Xe override and control requirements (and others such as stability from tighter coupling), a low C/HM is attractive. However, the worth of an individual control rod decreases with decrease in the C/HM and associated higher fissile loading, so many aspects must be considered.

Flux Oscillation Driven by Xenon and Its Control

A large reactor would be expected to exhibit neutron flux level oscillation on a period of several hours, driven by the Xe^{135} concentration changes. Increase in the flux level locally causes an increase in the destruction rate relative to the production rate due to the lag in the concentration of the I^{135} precursor, and an equilibrium concentration of Xe^{135} is approached only after several hours delay. The long-time equilibrium concentration of Xe^{135} is higher at the elevated flux level and acts as a poison reducing the flux level locally. Thus the flux level would be expected to roll around the core along the azmuthal coordinate, oscillate in the coordinate of weakest coupling. This behavior is associated with a weakly coupled core and would require compensation by slow local changes in the neutron loss rate, increases and decreases, as with control rods, for cores above some size to avoid excessive local power densities and unstable appearance in operation. The condition would be expected to be aggravated by increasing the carbon to heavy metal ratio, increasing the power density for a given core size, and flattening the power density. If cores above some size are to be used, flux tilting must be sensed with instruments and the driving force compensated.

It is unlikely that axial flux oscillation could be tolerated due to the complexity associated with effecting local axial compensation and the requirement to measure flux level changes in three dimensions. To test for stability, (R-Z) two-dimensional problems were solved for the reactor with and without axial and radial blankets and the once-recycle of fertile pebbles without reprocessing, for a 500 cm high fueled core, a C/HM of 250, and a power level of 3000 Mw_{th} (not the worst design conditions). The bed was fixed. The multiplication factor was calculated following short exposure steps over an operating period of several hours treating the full set of chain equations used for evaluating performance. Initially a perturbation was introduced to excite the oscillation mode: setting the Xe^{135} concentration to zero in a few zones having high power densities. The peak power density approached an asymptotic stable value exhibiting dampened oscillation, and there is stronger dampening with blankets than without. We conclude that the core is stable in the (R-Z) plane and will not exhibit axial oscillation driven by the Xe^{135}. The calculation was done without temperature feedback and hence is conservative: temperature feedback would be a dampening effect through the increase in the Th^{232} resonance integral from Doppler broadening with increase in temperature adding local absorption with increase in the local flux level, power density and temperature.

Examination of azmuthal stability is left to be done in the continuing effort with temperature feedback to produce meaningful information. Assessing stability is, however, impacted by such complexities as two types of pebbles which have quite different power densities and temperature feedback. We note that only a small amount of neutron absorption would be required, even for a large core, considering the small change required in the neutron balance. The required instrumentation and mechanism for control remain to be established as well as the maximum core size for a specific design and operating conditions for which control is not needed. The location of movable absorber in the reflector or in a radial blanket may well prove feasible as well as out-of-core instrumentation.

Explicit Modeling of the Core Inlet

Discrete Ordinates and Monte Carlo calculations were made to explicitly model the core inlet region. A reference (R-Z) case was chosen that had a thin axial blanket and 20 percent of the reference core area as an outer radial blanket. Nuclide concentrations were taken from a steady state, continuous fueling model calculation treating two dimensions but without representation of the core inlet region. Essentially the same four group cross section data were used for all calculations. Calculations were made with the DOT-IV code[13] using P_3

cross sections and S_4 quadrature (16 directions). Results are shown in Table 2-9 for the original diffusion theory case, and for a DOT diffusion theory case (transport corrected) and for the discrete ordinates formulation with the inlet region represented (modest gas space and reflector). Results are also shown with the axial blanket removed and a thicker axial reflector, with no control absorber and with control absorber in the axial reflector, and also for the latter situation with a thicker radial reflector. The amount of absorber material included is apparently excessive, so a smaller perturbation is more realistic. Note that the net axial and total external neutron leakage and hence the conversion ratio are dependent on the reactor inlet design. Increased reflection reduces the leakage. Poisoning from control rods located in the axial reflector causes a spacial shift in the neutron flux that significantly affects reaction rates.

The information generated allows assessment of the results obtained to characterize performance. The flux shape in the core depends directly on the design of the top of the reactor and the position of the control rods. The reactor contents depend on this flux shape, and therefore the peak power density and peak temperatures. Careful modeling will be essential to support design effort on a specific plant.

To test the Monte Carlo method, case TX2TA was also modeled with the KENO code.[22] It was found that after following a reasonable number of neutron histories, the results were sensitive to the spacial fission source distribution. Without a good initial source, early histories had to be discarded to obtain reliable results, so it is desirable to supply a Monte Carlo calculation with a reasonable initial source distribution. Results are shown below for comparison providing a reliability check of the base discrete ordinates results:

Method	Discrete Ordinates	Monte Carlo
k_{eff}	1.0071	0.9964 $\pm$ .0051
External Leakage	0.0757	0.0731

More histories would have to be followed to reduce the statistical uncertainty, a one standard deviation level estimate shown.

Table 2-9. Two-Dimensional Results with the Reactor Top Modeled

Case	TXO[a]	TX1DA	TX1TA	TX2TA	TX2TB	TX2TC
Axial Reflector (cm)	–	30.	30.	60.	60.	60.
Axial Gas Space (cm)	–	46.	46.	100.	100.	100.
Axial Blanket (cm)	36.	36.	36.	0.	0.	0.
Radial Reflector (cm)	30.	30	30.	30.	30.	60.
Radial Blanket Fraction	0.2	0.2	0.2	0.2	0.2	0.2
Rods in Axial Reflector	No	No	No	No	Yes	Yes
Neutronics Theory	Diffusion	Diffusion	Transport	Transport	Transport	Transport
k_{eff}	1.0	1.0155	1.0073	1.0071	.9596	.9619
Net Top Axial Leakage						
From Core			.0648	.0621	.0620	.0606
From Blanket	.0456		.0327	–	–	–
External Leakage Fraction						
Top	.0456	.0381	.0285	.0342	.0030	.0036
Radial	.0130	.0225	.0185	.0384	.0249	.0178
Bottom	.0036	.0021	.0028	.0031	.0049	.0057
Total	.0622	.0627	.0498	.0757	.0328	.0271
Peak-to-Average Fission Source[b]						
Internal	3.24	3.19	3.15	3.06	2.54	2.55
Core Top			2.67	3.27	0.71	0.80
Integrated Reaction Rates by Key Nuclides						
U^{233} Absorption	.1980	.1888	.1913	.1901	.2156	.2191
U^{235} Absorption	.2799	.2968	.2898	.2906	.2376	.2347
Pa^{233} Absorption	.0109	.0115	.0112	.0107	.0106	.0104
Th^{232} Capture	.2876	.3015	.2961	.2671	.2753	.2795
U^{234} Capture	.0115	.0107	.0109	.0110	.0132	.0132
Simple Conversion Ratio	.6119	.6280	.6236	.5659	.6220	.6305
Critical Conversion Ratio[c]	.6119	.6433	.6309	.5730	.5799	.5909
Peak Total Neutron Flux Above 200 keV (n/cm^2-sec × 10^{-12})						
Radial Reflector	5.66	5.73	6.07	6.84	7.53	9.85
Axial Reflector	–	9.59	9.90	50.8	23.1	19.9

[a]Original case omitting inlet detail, supplied nuclide densities.
[b]Point peak relative to the average for total power generation in the fueled core (80 percent of core volume).
[c]Estimated from reaction rates for a change in the core contents.

The axial cell associated with one of the bank of control rods was modeled and various analysis methods are being applied to this problem in the continuing effort. Shown in Fig. 2-1 is the change in multiplication associated with incremental insertion of the bank of control rods as calculated by the discrete ordinates method.[a] The calculations were of a survey nature to test methods and several aspects were ignored including the effects associated with radial reflection at the top of the reactor. A detailed design of a control rod was not represented, rather a solid cylinder of absorption, and it displaced material so that the core contents were not conserved. Still the shape of the curve should be representative and considerable variation in worth is expected with position.

The results we have obtained indicate that the full reactor and control rods in detail can be modeled by the Monte Carlo method to determine the control rod bank insertion worth, but not the individual rod worth. A direct calculation of the reactivity importance of specific position changes appears feasible applying a perturbation Monte Carlo method; since a significant number of events of interest would have to occur for acceptable statistics, however, there are lower limits on the change in rod position and the number of rods that can be considered. Adequate capability to describe the geometry of many rods (and the pebbles explicitly toward the top of the core if desired) is not available in the production versions of the local Monte Carlo codes.

Regarding Temperatures

Local capability for solving the thermal hydraulics problem is yet under development. Shown in Fig. 2-2 are the key fissile nuclide concentrations and pebble power densities as a function of axial position from a one-dimensional calculation for a relatively short core residence time. Shown in Fig. 2-3 are primary temperatures with the coolant flow downward and also upward. Favorable temperature peaking with downward coolant flow is indicated.

[a]Monte Carlo results are also shown (also for discrete changes) for a modest number of histories.

ORNL-DWG 79-8356

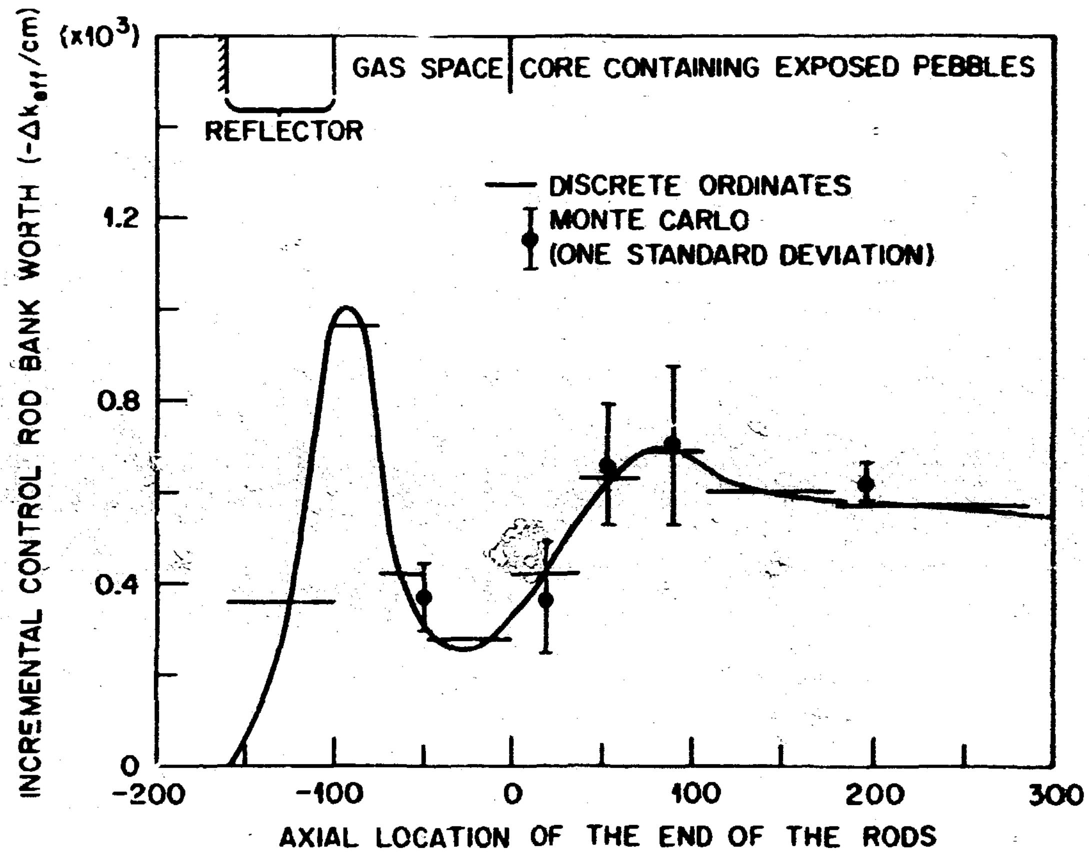


Fig. 2-1. Incremental Control Rod Bank Insertion Worth

The local effort on thermal hydraulics calculations continues. Of special concern is the dependence of the thermal conductivity on the high energy neutron flux exposure and the degree of annealing out of associated defects over the temperature history. Special considerations are involved for an adequate treatment of such details as a radial blanket and radial variation in the power density, and to assess the effects of flow blockage and the spacial distributions of more than one pebble type. The calculations that have been done show that to hold down the temperature at the pebble center, it is necessary to effect distribution of the heat source over as much of the pebble as possible, requiring distributio. of the heavy metal over all but an outer protective shell some 0.5 cm thick (say 2.5 cm radius meat in a 3.0 cm radius pebble rather than smaller).

ORNL-DWG 78-22398

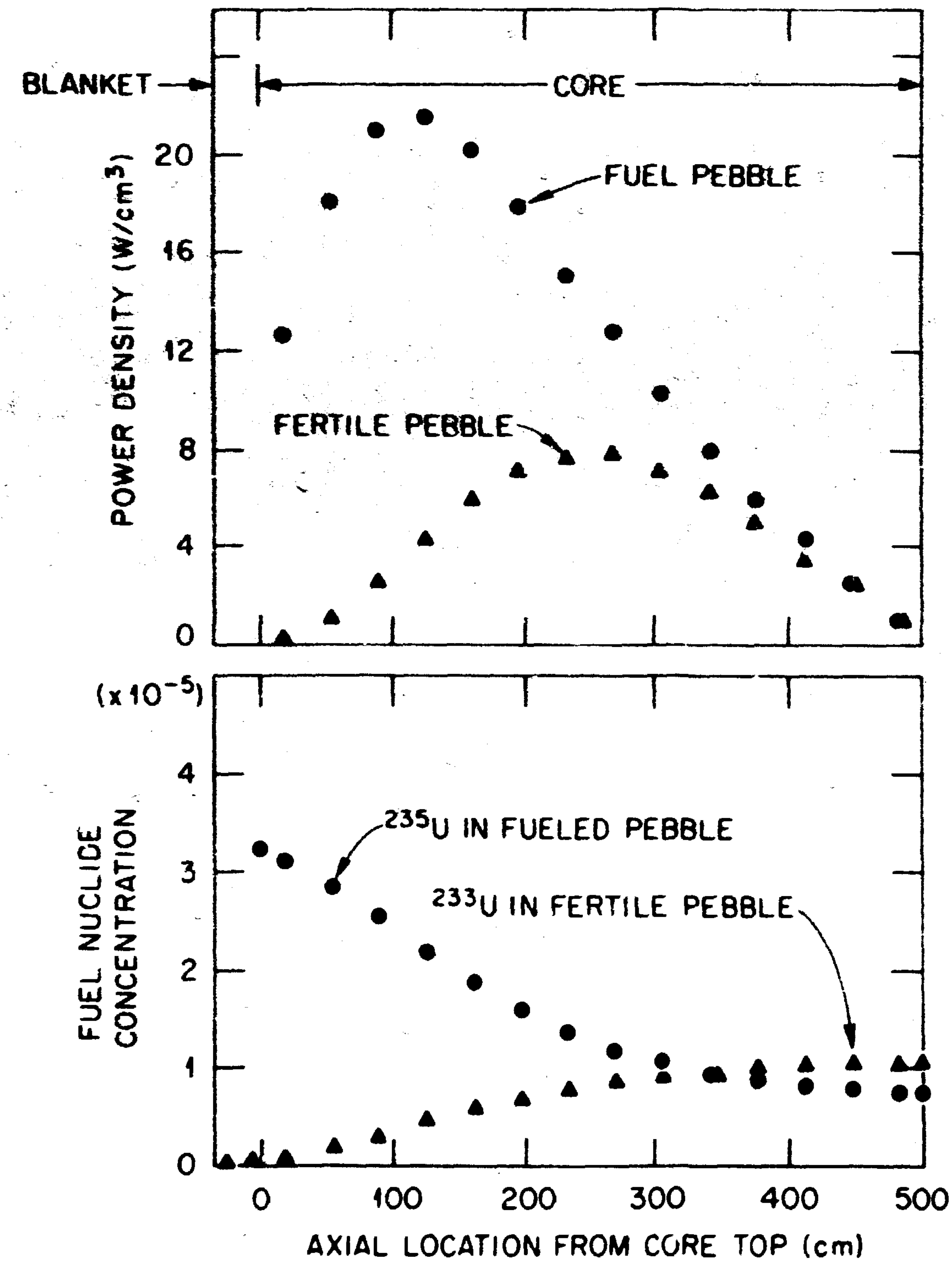


Fig. 2-2. Illustration of Fuel Concentrations and Pebble Power Density

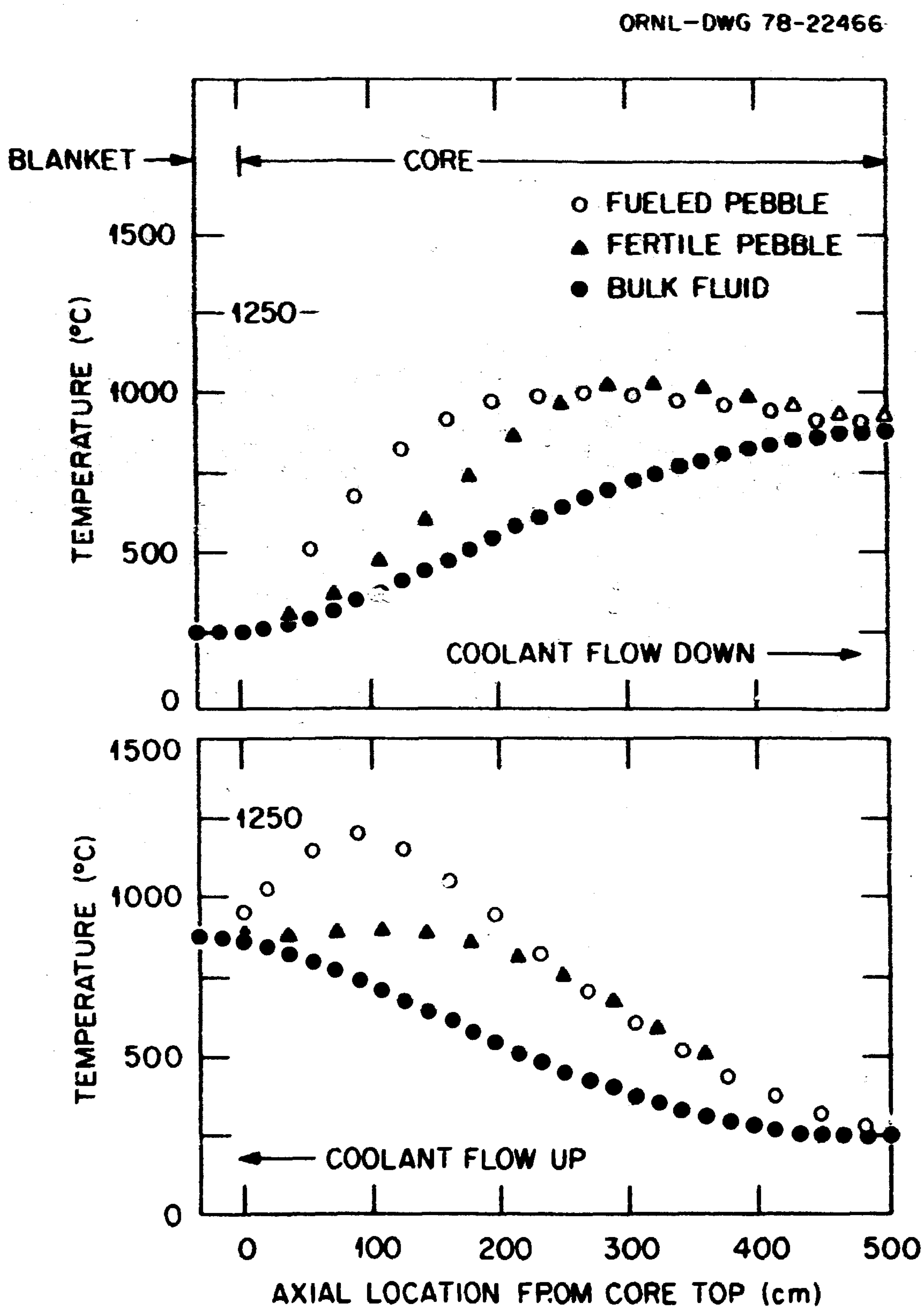


Fig. 2-3. Temperatures with Coolant Flow Upward and Downward

Point Model Results

Point model calculations were used to model the pebble bed reactor and predict performance over a thirty year operating history. The model considers a single pebble type. Results of calculations made for the throwaway cycle are shown in Table 2-10. Shown are estimates of the fissile feed, ore consumption and fuel cost for a representative cycle and for thirty year operation. The neutron loss fraction of 0.05 was selected to represent a blanketed core, while the 0.08 fraction is more representative of a reactor without a blanket at a C/HM of 250, or a plant of lower capacity. The neutron loss fraction tends to increase as the heavy metal loading is decreased increasing the C/HM, so a 0.08 fraction loss at a C/HM of 400 represents some blanketing.

Point model results for a fixed fuel reactor with only partial refueling are shown in Table 2-11. These calculations with 1/3 reactor refueled are identical with those done for the pebble bed reactor results in Table 2-10 except that account was taken in the model of the requirement for control rod losses to offset the loss in reactivity, and a scheme was used which causes the flux levels to be batch dependent. As the refueling fraction is made smaller, the approximation approaches continuous fueling (but we do not credit the pebble bed reactor with the advantage of flux levels dependent on the batch). Comparing the results, we estimate the required fissile feed to a pebble bed reactor and the ore consumption to be nearly 15 percent less than for a fixed fuel reactor, and fuel cost to be 10 percent less, if the fraction core neutron loss is about the same. Accounting for the lower coolant fraction and associated lower core neutron leakage of the fixed fuel design, and allowing some excess reactivity (in control rods) for Xe override and control, reduce this gain by perhaps 50 percent.

Economics

Shown in Table 2-12 are the calculated fuel costs for selected two-dimensional cases. The calculations involved a direct treatment of the steady state cycle and extension to estimate the effective fuel

Table 2-10. Point Model Results for the Continuously Fueled Reactor Throwaway Cycle (1,200 MW_e plant at 0.75 load factor, .002 tails)

Residence Time yrs at full power)	Exposure (MW_{th}-D/Kgm HM)	Fissile Loading (Kgm)	Conversion Ratio	Cycle Data			30 Year History		
				U_3O_8 Feed (Kgm/D)	Ore Consumption (Kgm/MW_e Yr)	Fuel Cost (Mill/KW_e Hr)	U_3O_8 Feed[a] (Kgm/D)	Ore Consumption[b] (Kgm/MW_e)	Fuel Cost (Mill/KW_e Hr)
C/HM 150, 5 W_{th}/cc, .05 neutron loss fraction									
3	73.2	1,342	.684	1.564	146	4.825	1.637	3,283	5.211
4	96.3	[illegible]	655	1.471	138	4.620	1,536	3,066	[illegible]
5	118.5	[illegible]	.624	1.459	137	4.692	1.514	3,014	[illegible]
C/HM 250, 5 W_{th}/cc, .08 neutron loss fraction									
3	72.7	1,501	.631	1.766	165	5.360	1.849	3,709	5.775
4	95.5	1,595	.603	1.655	155	5.132	1.731	3,464	5.380
4[c]	98.7	1,539	.596	1.649	154	5.097	1.722	3,444	5.339
5	117.4	1,716	.575	1.631	153	5,191	1.697	3,376	5.243
C/HM 250, 7.5 W_{th}/cc, .08 neutron loss fraction									
2	72.4	1,074	.607	1.885	176	5.397	1.945	3,964	5.760
3	106.1	1,179	.569	[illegible]	[illegible]	[illegible]	1.760	3,610	5.216
4	137.5	1,310	.531	1.717	161	5.124	1.762	3,561	5.126
C/HM 400, 5 W_{th}/cc, .05 neutron loss fraction									
2	72.7	862	.629	1.661	155	5.095	1.708	3,493	5.439
3	106.7	924	.590	1.550	145	4.741	1.590	3,242	4.918
4	138.6	1,001	.552	1.559	146	4.834	1.588	3,236	4.824
C/HM 400, 5 W_{th}/cc, .08 neutron loss fraction									
2	72.3	943	.584	1.822	170	5.498	1.874	3,831	5.862
3	105.9	1,019	.548	1.641	153	5,114	1.737	3,540	5.306
4	137.4	1,110	.512	1.686	158	5.191	1.723	3,507	5.192

[a] Includes initial inventory
[b] Installed capacity basis, U_3O_8
[c] Heavy metal feed fixed

Table 2-11. Point Model Results for the Fully Enriched Throwaway Cycle, Fixed Fuel Reactor ($1,200\ MW_e$ plant at 0.75 load factor, .002 tails)

Residence Time (yrs at full power)	Fraction Reactor Refueled	Exposure (MW_{th}-D/kgm HM)	Fissile[a] Loading (kgm)	Conversion Ratio	Cycle Data: Feed (kgm/D)	Cycle Data: Ore Consumption (kgm/MW_e Yr)	Cycle Data: Fuel Cost (Mills/kW_e hr)	30 Year History: U Feed (kgm/D)[b]	30 Year History: Ore Consumption[c] (kgm/MW_e)	30 Year History: Fuel Cost (Mills/kW_e hr)
C/HM 250, 5 W_{th}/cc, .05 neutron loss fraction										
3	1/3	72.7	1,357	.615	1.779	166	5.394	1,866	3,734	5.702
4	1/3	95.3	1,459	.578	1.707	160	5.274	1.794	3,564	5.444
5	1/3	116.9	1,560	.542	1.702	159	5.404	1.792	3,538	5.410
3	1/4	72.9	1,349	.637	1.704	159	5.197	1,800	3,577	5.529
4	1/4	95.6	1,435	.601	1.622	152	5.040	1.716	3,384	5.212
5	1/4	117.5	1,538	.567	1.612	151	5.138	1.705	3,341	5.141
4	1/6	96.0	1,420	.627	1.533	143	4.793	1.634	3,198	4.987
C/HM 250, 5 W_{th}/cc, .08 neutron loss fraction										
3	1/3	72.1	1,523	.568	1.994	187	5.962	2.094	4,188	6.308
4	1/3	94.5	1,638	.531	1.896	177	5.804	2.000	3,967	6.072
5	1/3	115.4	1,772	.498	1.878	176	5.916	1.995	3,910	5.959
3	1/4	72.3	1,512	.556	1.914	179	5.750	2.023	4,019	6.139
4	1/4	94.8	1,618	.552	1.808	169	5.560	1.919	3,778	5.766
5	1/4	116.4	1,742	.521	1.784	167	5.641	1.896	3,706	5.679
4	1/6	95.2	1,598	.576	1.717	161	5.303	1.834	3,585	5.526
C/HM 250, 7.5 W_{th}/cc, .08 neutron loss fraction										
2	1/3	71.9	1,089	.547	2.112	199	5.964	2.185	4,423	6.292
3	1/3	104.9	1,213	.497	1.970	184	5.662	2.047	4,127	5.849
4	1/3	135.4	1,369	[illegible]	1.969	184	5.823	2.051	4,103	5.957
2	1/4	72.0	1,081	.564	2.032	190	5.767	2.086	4,220	6.103
3	1/4	105.3	1,196	.519	1.879	176	5.423	1.961	3,933	5.608
4	1/4	136.2	1,339	.476	1.871	175	5.553	1.955	3,893	5.559
3	1/6	105.8	1,180	.542	1.785	167	5.173	1.870	3,732	5.357
C/HM 400, 5 W_{th}/cc, .08 neutron loss fraction										
2	1/3	71.8	951	.516	2.055	192	6.084	2.120	4,325	6.403
3	1/3	104.7	1,037	.471	1.928	180	5.742	1.996	4,047	5.919
4	1/3	135.4	1,139	.434	1.917	179	5.934	1.990	4,012	5.613
2	1/4	72.0	946	.535	1.974	185	5.881	2.045	4,154	6.208
3	1/4	105.2	1,026	.495	1.838	172	5.505	1.911	3,855	5.676
4	1/4	136.2	1,121	.459	1.823	171	5.575	1.896	3,808	5.567
3	1/6	105.7	1,016	.522	1.742	163	5.351	1.915	3,651	5.419

[a] Determined at end of cycle
[b] Includes initial inventory
[c] Installed capacity basis

cost for a thirty year operating history. The costs are shown for the throwaway burner cycle, and also for reprocessing. Reprocessing of the fueled primary pebbles may be uneconomical considering an additional penalty for refabrication. A net thermal to electrical energy conversion efficiency at 0.4 was assumed, $3000\ MW_{th}$ for a $1200\ MW_e$ plant.

Table 2-12. Fuel Costs for the High Enriched ^{235}U Feed Burner Cases
(30 year life, 0.75 plant load factor, 0.4 plant efficiency)

Schedule 1 Unit Costs, 0.10 Interest, 0.07 Discount

CASE	MR280	MR280*	MR281	MR281*	MR286	MR291	MR256A	MR236	MR238	MR256	MR310	MR311	MR314	[illegible]	[illegible]
THROWAWAY BOTH															
COST OF FUEL	4.2450	4.2450	4.0424	4.0424	3.9186	3.6551	3.3958	3.5117	3.5351	3.8206	3.6785	3.7174	3.7414	[illegible]	[illegible]
FABRICATION	0.4369	0.4957	0.3805	0.4240	0.3359	0.3051	0.2569	0.3296	0.3301	0.2711	0.4650	0.4661	0.4661	0.4177	[illegible]
REPROC/WASTE	0.2126	0.2126	0.1759	0.1759	0.1455	0.1321	0.0746	0.1443	0.1484	0.0876	0.1688	0.1690	0.1690	0.1567	[illegible]
INDIRECTCOST	1.9976	1.9168	2.0253	2.0535	1.9167	1.3207	1.7115	1.7201	1.7426	1.7892	1.5789	1.5495	[illegible]	1.5426	[illegible]
TOTAL COST	6.7820	6.8697	6.6250	6.7301	6.3169	5.4612	5.4408	5.7758	5.7531	5.8193	5.4915	[illegible]	[illegible]	[illegible]	[illegible]
REPROCESS BOTH															
COST OF FUEL	2.5535	2.5535	2.6785	2.6785	2.5823	2.7852	2.4733	2.3477	2.1808	2.4562	2.5252	2.5330	2.5760	2.4116	[illegible]
FABRICATION	0.4369	0.4957	0.3805	0.4240	0.3359	0.3051	0.2569	0.3296	0.3301	0.2711	0.4650	0.4661	0.4661	0.4177	[illegible]
REPROC/WASTE	0.7639	0.7771	0.6325	0.6829	0.5282	0.4231	0.3256	0.5181	0.5198	0.3625	0.7373	0.7147	0.7186	[illegible]	[illegible]
INDIRECTCOST	2.2575	2.2835	2.3594	2.3426	2.2898	2.2383	1.9880	2.2765	2.1104	2.1277	1.7424	1.8774	1.8174	1.7613	[illegible]
TOTAL COST	6.2112	6.3977	6.2509	6.1323	5.6913	5.7146	4.9969	5.5129	5.1156	5.2172	5.5131	5.5826	[illegible]	[illegible]	[illegible]
REPROCESS FERTILE															
COST OF FUEL	3.0855	4.2850	3.0611	4.0424	2.4256	3.1662	2.7511	2.4278	2.4330	2.7508	2.8092	2.8619	2.8691	2.5911	[illegible]
FABRICATION	0.4369	0.4957	0.3805	0.4240	0.3359	0.3051	0.2569	0.3296	0.3301	0.2711	0.4650	0.4661	0.4661	0.4177	[illegible]
REPROC/WASTE	0.4997	0.2126	0.4132	0.1759	0.3419	0.2127	0.1856	0.3393	0.3393	0.1816	0.4558	0.4559	0.4558	0.4217	[illegible]
INDIRECTCOST	2.1703	1.9168	2.3302	2.0535	2.2588	2.1483	1.9049	2.0549	2.0453	2.0876	1.7841	1.8070	1.8118	1.7656	[illegible]
TOTAL COST	6.1923	6.8697	6.1587	6.7321	5.7574	5.8249	5.1628	5.1512	5.1877	5.2913	5.5138	5.5913	[illegible]	[illegible]	[illegible]

Schedule 1 Unit Costs, 0.05 Interest, 0.35 Discount

CASE	MR280	MR280*	MR281	MR281*	MR286	MR291	MR256A	MR236	MR238	MR256	MR310	MR311	MR314	[illegible]	[illegible]
THROWAWAY BOTH															
COST OF FUEL	4.2450	4.2450	4.0424	4.0424	3.9186	3.6551	3.3958	3.5117	3.5351	3.8206	3.6786	3.7174	3.7414	3.6146	3.5611
FABRICATION	0.4369	0.4957	0.3805	0.4240	0.3359	0.3051	0.2569	0.3296	0.3301	0.2711	0.4650	0.4661	0.4661	0.4177	[illegible]
REPROC/WASTE	0.2126	0.2126	0.1759	0.1759	0.145	0.1321	0.0746	0.1443	0.1484	0.2876	0.1688	0.1690	0.1604	0.1567	0.1434
INDIRECTCOST	0.9335	0.9170	0.9716	0.9443	0.9184	0.3333	0.8192	0.4203	0.8161	0.8336	0.7592	0.7692	0.7111	0.7412	0.7196
TOTAL COST	5.7980	5.8703	5.5737	5.6309	5.3186	4.3115	4.5451	4.9049	4.8451	4.6112	5.0711	5.1417	.1526	4.9641	[illegible]
REPROCESS BOTH															
COST OF FUEL	2.5535	2.5535	2.6785	2.6785	2.5823	2.7452	2.4733	2.3477	2.1804	2.4562	2.5252	2.5300	2.5760	2.4114	[illegible]
FABRICATION	0.4369	0.4957	0.3805	0.4240	0.3359	0.3051	0.2569	0.3296	0.3301	0.2711	0.4650	0.4661	0.4661	0.4177	[illegible]
REPROC/WASTE	0.7639	0.7771	0.6325	0.6423	0.5282	0.4231	0.3256	0.5181	0.5188	0.3620	0.7373	0.7383	0.7186	0.6820	[illegible]
INDIRECTCOST	1.0992	1.0995	1.1141	1.1499	1.1049	1.2624	0.9341	1.0020	1.0185	1.0254	0.8611	0.8714	0.8797	0.8504	0.8290
TOTAL COST	4.8824	4.9258	4.8296	4.8492	4.5073	4.5712	3.9872	4.3374	4.0470	4.1149	4.5986	4.6482	4.6576	4.4326	[illegible]
REPROCESS FERTILE															
COST OF FUEL	3.0855	4.2850	3.0611	4.0424	2.9256	3.1662	2.7511	2.4278	2.4330	2.7508	2.8092	2.8619	2.8691	2.5911	[illegible]
FABRICATION	0.4369	0.4957	0.3805	0.4280	0.3359	0.3051	0.2569	0.3296	0.3301	0.2711	0.4650	0.4661	0.4661	0.4177	[illegible]
REPROC/WASTE	0.4997	0.2126	0.4132	0.1759	0.3419	0.2127	0.3856	0.3393	0.3393	0.1815	0.4554	0.4559	0.4558	0.4217	0.3788
INDIRECTCOST	1.0449	0.9170	1.1584	0.9443	1.0472	1.3111	0.9367	0.9917	1.0360	1.0051	0.8619	0.8712	0.8770	0.8526	0.8151
TOTAL COST	5.0669	5.9703	4.9632	5.6309	4.5906	4.7151	4.3733	4.0080	4.1083	4.2089	4.5918	4.6564	4.6691	4.3971	4.1978

*The two pebble case was treated as if single pebble to show the gain (cases MR280 and MR281), the assumption being there is no fertile pebble. For these cases the recovery of all fuel would seem to be economical, but for some cases it is not, and additional flexibility of the two pebble operation.

Table 2-12. (Cont'd.)

Schedule 2 Unit Costs, 0.10 Interest, 0.07 Discount

CASE	MR280	MR280*	MR281	MR281*	MR286	MR293	MR256A	MR236	MR238	MR256	MR310	MR311	MR314	MR326	MR336
THROWAWAY BOTH															
COST OF FUEL	4.2450	4.2450	4.0428	4.0428	3.9186	3.6557	3.3958	3.5117	3.5361	3.8206	3.6785	3.7374	3.7438	3.6186	3.5633
FABRICATION	0.4925	0.4559	0.4199	0.3936	0.3712	0.3314	0.2789	0.3646	0.3651	0.2959	0.5104	0.5115	0.5117	0.4810	0.4445
REPROC/WASTE	0.2126	0.2126	0.1759	0.1759	0.1456	0.1021	0.0786	0.1443	0.1444	0.0976	0.1688	0.1690	0.1690	0.1567	0.1403
INDIRECTCOST	1.9390	1.9987	2.0864	2.0360	1.9413	1.9230	1.7380	1.7446	1.7671	1.7662	1.6012	1.6218	1.6309	1.5670	1.5240
TOTAL COST	6.8491	6.8122	6.6849	6.6482	6.3768	6.0388	5.4833	5.7652	5.8126	5.5702	5.9588	6.0397	6.0554	5.8232	5.6722
REPROCESS BOTH															
COST OF FUEL	2.5535	2.5535	2.6785	2.6785	2.5420	2.7852	2.4703	2.1877	2.1804	2.4562	2.5252	2.5750	2.5750	2.4319	2.3730
FABRICATION	0.4925	0.4559	0.4199	0.3936	0.3712	0.3314	0.2789	0.3646	0.3651	0.2958	0.5104	0.5115	0.5117	0.4810	0.4445
REPROC/WASTE	0.9838	0.9921	0.8147	0.8209	0.6753	0.5486	0.4276	0.6673	0.6682	0.4729	0.9627	0.9641	0.9640	0.8806	0.8000
INDIRECTCOST	2.2041	2.1920	2.3108	2.2981	2.2413	2.1674	1.9091	2.0277	2.0625	2.0793	1.7274	1.7523	1.7618	1.7076	1.6673
TOTAL COST	6.2239	6.1935	6.2239	6.1911	5.8297	5.8326	5.0860	5.2473	5.2762	5.3043	5.7253	5.7979	5.8126	5.5112	5.2848
REPROCESS FERTILE															
COST OF FUEL	3.0855	4.2450	3.0611	4.0428	2.8256	3.1662	2.7511	2.4274	2.4330	2.7508	2.8092	2.8619	2.8691	2.6831	2.5792
FABRICATION	0.4925	0.4559	0.4199	0.3936	0.3712	0.3314	0.2789	0.3646	0.3651	0.2958	0.5104	0.5115	0.5117	0.4810	0.4445
REPROC/WASTE	0.6102	0.2126	0.5045	0.1759	0.4175	0.2552	0.1729	0.4144	0.4144	0.2176	0.5586	0.5590	0.5589	0.5196	0.4405
INDIRECTCOST	2.1539	1.9987	2.2856	2.0360	2.2336	2.1363	1.9013	2.0383	2.0647	2.0666	1.7692	1.7919	1.8007	1.7487	1.7106
TOTAL COST	6.3321	6.9122	6.2711	6.6482	5.8479	5.8892	5.1042	5.2406	5.2772	5.3309	5.6471	5.7240	5.7404	5.4327	5.1799

Schedule 2 Unit Costs, 0.05 Interest, 0.035 Discount

CASE	MR280	MR280*	MR281	MR281*	MR286	MR293	MR256A	MR236	MR238	MR256	MR310	MR311	MR314	MR326	MR336
THROWAWAY BOTH															
COST OF FUEL	4.2450	4.2450	4.0429	4.0428	3.9186	3.6553	3.3958	3.5117	3.5361	3.4206	3.6785	3.7374	3.7438	3.6186	3.5633
FABRICATION	0.4925	0.4559	0.4199	0.3936	0.3712	0.3314	0.2789	0.3646	0.3651	0.2958	0.5104	0.5115	0.5117	0.4810	0.4445
REPROC/WASTE	0.2126	0.2126	0.1759	0.1759	0.1456	0.1021	0.0786	0.1443	0.1444	0.0876	0.1688	0.1690	0.1690	0.1567	0.1403
INDIRECTCOST	0.9131	0.9096	0.9811	0.9760	0.9300	0.9181	0.8286	0.8358	0.8461	0.8439	0.7697	0.7798	0.7838	0.7526	0.7310
TOTAL COST	5.8532	5.8221	5.6196	5.5882	5.3654	5.0069	4.5779	4.8564	4.8916	4.6480	5.1273	5.1976	5.2083	5.0089	4.8803
REPROCESS BOTH															
COST OF FUEL	2.5535	2.5535	2.6785	2.6785	2.5420	2.7852	2.4703	2.1877	2.1804	2.4562	2.5252	2.5700	2.5700	2.4119	2.3730
FABRICATION	0.4825	0.4559	0.4199	0.3936	0.3712	0.3314	0.2799	0.3646	0.3651	0.2958	0.5104	0.5115	0.5117	0.4810	0.4445
REPROC/WASTE	0.9938	0.9921	0.8147	0.8209	0.6753	0.5486	0.4276	0.6673	0.6602	0.4729	0.9622	0.9641	0.9640	0.8806	0.8000
INDIRECTCOST	1.0632	1.0553	1.1133	1.1071	1.0800	1.0418	0.9161	0.9774	0.9939	1.0005	0.8328	0.8450	0.8493	0.8229	0.8035
TOTAL COST	5.0940	5.0568	5.0261	5.0000	4.6688	4.7970	4.0930	4.1969	4.2075	4.2259	4.8307	4.8906	4.9001	4.6265	4.4210
REPROCESS FERTILE															
COST OF FUEL	3.0855	4.2450	3.0611	4.0428	2.8256	3.1662	2.7511	2.4274	2.4330	2.7508	2.8092	2.8619	2.8691	2.6831	2.5792
FABRICATION	0.4825	0.4559	0.4199	0.3936	0.3712	0.3314	0.2789	0.3646	0.3651	0.2958	0.5104	0.5115	0.5117	0.4810	0.4445
REPROC/WASTE	0.6102	0.2126	0.5045	0.1759	0.4175	0.2552	0.1729	0.4144	0.4144	0.2176	0.5584	0.5590	0.5589	0.5196	0.4445
INDIRECTCOST	1.0361	0.9095	1.1057	0.9760	1.0761	1.0263	0.9122	0.9707	0.9949	0.9941	0.8537	0.8648	0.8688	0.8435	0.8252
TOTAL COST	5.2143	5.8221	5.0862	5.5882	4.6904	4.7792	4.1151	4.1870	4.2074	4.2584	4.7316	4.7973	4.8094	4.5272	4.3135

Ore Commitment and Consumption

Calculated requirements of ore, the commitment and the consumption for operation of a plant, are shown for selected cases in Table 2-13. The subject is discussed further in section 10.

Recapitulation on Modeling

In reviewing the results of this analysis, comment is in order about the modeling. Such survey calculations tend to be idealized in that many design details are ignored. Still an attempt was made to produce realistic results. For an example, less side reflection was generally assumed than could be considered possible. There is uncertainty about the axial leakage at the inlet and more detailed analysis will be required for a specific design and control rod positioning scheme.

Under certain conditions, an unusually high power density peaking was found, so careful assessment will be essential for a specific design with accurate modeling.

Table 2-13. Estimated Ore Requirements Without Fuel Reprocessing (Basis kgms U_3O_8/MW_e installed, operated 30 yrs at 0.75 plant factor, 0.4 thermal efficiency, and 0.002 enrichment tails)

Case	AL51	AM31	AM41	AB31	AD31	MR314	MR326	MR281	MR293	ANCQ16	MR238A	MR256A	MS250	MS251	MS250A[a]
C/HM	175	250	250	325	400	325	325	250	250	250	250	250	250	250	250
Residence Time (yrs)	5	3	4	3	3	3.5	3.4	4.2	4.2	4.2	4	4	4.1	4.15	4.1
Recycle Fertile	No	No	No	No	No	No	No	No	Yes	No	No	Yes	No	No	No
Radial Power Density flattening	1-D	1-D	1-D	1-D	1-D	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Radial Blanket Fraction	--	--	--	--	--	0	0.1	0	0	0.14	0.2	0.2	0.1	0	0.1
Axial Blanket[b]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	No	Yes
Fissile Inventory															
Initial reactor	238	190	190	148	119	148	148	190	190	190	190	190	190	190	190
Steady state reactor	376	260	272	209	176	255	246	369	367	336	289	324	313	321	319
Steady state system[c]	432	319	328	267	237	317	306	436	428	390	346	381	36[illegible]	383	379
Net Consumption[d]	3,377	3,512	3,358	3,474	3,671	3,737	3,609	4,036	3,85[illegible]	3,734	3,399	3,392	3,367	3,712	3,624
Gross Commitment	3,809	3,831	3,686	3,741	3,908	4,054	3,915	4,[illegible]72	4,056	4,132	3,745	2,773	3,736	4,095	4,003

[a]Case MS250 was modeled in much more detail and the exposure and power density were better flattened, reducing the peak from 18.6 to 15.7 W_{th}/cc at an apparent penalty of 7.6 percent in the fissile feed rate; the actual fissile burnup accounts for 2,469 kgms U_3O_8/MW_e installed, throwaway for 1,155; without power density flattening the ore for the initial inventory was 171 but the peak power density 22.7 W_{th}/cc.

[b]Axial blanket used was only 35.7 cm high.

[c]Inventory in the feed stream is charged to the system.

[d]Consumption was calculated directly from the feed rate at steady state.

SECTION 03: CONVERTER PERFORMANCE WITH HIGH ENRICHED URANIUM

The incentives for reprocessing and recycle of fuel are to lower the fuel cost and to reduce ore requirements. Note that the performance at a point in the early history is approximated by the throwaway cycle treated in the previous section.

The converter performance was examined by solving successive steady state, continuous fueling problems with feed of material available for recycle. Two basic designs and modes of operation were considered:

1) High ore utilization with a short residence time and a C/HM of 175,

2) Low fuel cost with a long residence time and C/HM of 250.

The results of calculations are shown in Table 3-1. Note that with delay in availability of fuel for recycle and a load factor well below unity, the full power results cover about half of a thirty year operating history.

This data was processed and the following estimate is given for the performance over a thirty year history:

C/HM	175		250	
Nominal Residence Time (full power yrs)	2		4	
Conversion Ratio	0.78		0.66	
Fissile Inventory (kgm)	1,960		1,600	
Average Exposure (MW_{th}-D/kgm)	35		94	
Total U^{235} feed (kgm/MW_e installed at .75 LF)	9.707		10.850	
Core Fissile Consumption (kgm/MW_e-Yr)	1.162		1.167	
Ore Requirements (kgm U_3O_8/MW_e installed)				
Load Factor	.75	.70	.75	.70
Commitment	2,240	2,150	2,500	2,360
Consumption	1,540	1,450	2,120	1,980
Fuel Cost (mill/kW_e-hr at 0.75 load factor)				
Fuel	1.567		2.072	
Fabrication	.926		.452	
Reprocessing	1.634		.540	
Indirect	2.364		2.214	
Total	6.491		5.278	
Total at Half Indirect Charge	5.309		4.171	
Fuel Cost with Fuel Component Doubled (direct and indirect)				
Total	10.474		9.511	
Total at Half Indirect Charge	8.446		7.324	

Note that the cost penalty for effecting lower ore consumption by increasing the conversion ratio is rather high, about 23 percent for the base case, and even 10 percent for higher fuel unit cost (relative to

BLANK PAGE

Table 3-1. Two-Dimensional Results for High Enriched Feed with Full Recycle (5 W_{th}/cc, 500 cm height, 1,200 MW_e, 0.015 Processing Loss)

Case		JC11	JC12	JC13	JC14	JC15	JE11	JE12	JE13
C/HM		175	175	175	175	175	250	250	250
Cycle		1/1	2/1	3/1	4/1	5/1	1/1	1/1	1/1
Residence Time (full power yrs)		2	2	2	2	2	4.1	4.1	4.1
Axial Blanket (cm)		53.6	53.6	53.6	53.6	53.6	[illegible]	35.2	35.2
Radial Blanket (cm)		31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2
Conversion Ratio		.713	.774	.786	.789	.788	.630	.661	.661
Fissile Inventory (kgm)		2,172	1,948	1,9[illegible]	2,02[illegible]	2,066	1,562	1,560	1,61[illegible]
Power Density (W_{th}/cc)									
Core peak		10.5	10.4	10.3	10.8	10.8	19.6	20.1	19.2
Primary pebble peak		21.7	27.4	29.3	29.5	29.6	53.5	55.5	53.6
Fertile pebble peak		9.4	9.0	9.[illegible]	8.9	8.7	15.5	15.0	14.4
Exposure (MW_{th}-D/kgm)									
Primary pebbles		92.4	90.6	90.4	90.1	89.9	235.4	226.4	225.1
Fertile pebbles		12.2	12.[illegible]	12.2	11.9	11.6	48.1	46.0	44.1
Average		35.6	35.5	35.3	35.[illegible]	35.0	95.5	94.2	93.1
Fission Product Absorption Fraction		.0641	.0608	.0597	.0588	.0583	.1047	.0996	.0972
Core Leakage Fraction		.0473	.0505	.0483	.0475	.0470	.0572	.0559	.0535
Mass Balance (kgm/D at full power)									
Primary Make up Feed	Th-232	20.591	20.591	20.591	20.591	20.591	5.6714	5.6714	5.6714
	U-235	1.2323	.7091	.9148	.9115	.9121	2.1604	1.3412	1.3603
	U-238	.1972	.0362	.0487	.0490	.0487	.1152	.0716	.0720
Primary Recycle Feed	U-233		1.4029	1.6931	1.7704	1.8015		.5594	.6050
	U-234		.1977	.4163	.5661	.6605		.1121	.2592
	U-235		1.1563	.6254	.6012	.6435		.1428	.1526
	U-236		.4546	.6319	.7126	.7481		.3141	.4661
	U-238		.1712	.1749	.1990	.2160		.0886	.1232
Fertile Feed	Th-232	59.928	59.928	59.928	59.928	59.928	23.483	23.483	23.483
Primary Discharge	Th-232	19.796	19.755	19.407	19.819	19.829	5.2093	5.2211	5.2312
	Pa-233	.0043	.0038	.0060	.0029	.0029	.0006	.0006	.0006
	U-233	.4051	.7031	.7802	.8133	.8338	.1184	.1402	.1460
	U-234	.0642	.2296	.4330	.5333	.5962	.0364	.1291	.1648
	U-235	1.1123	.60[illegible]	.5918	.6320	.6745	.1193	.1249	.1516
	U-236	.4597	.6143	.7217	.9086	.8869	.3107	.4552	.5664
	U-238	.1730	.1826	.2020	.2193	.2470	.0899	.1251	.1531
Fissile	Pu	.0048	.0049	.0055	.0061	.0068	.0016	.0023	.0022
Other	Pu	.0022	.0023	.0026	.0028	.0031	.0020	.0027	.0033
Fertile Discharge	Th-232	57.869	57.894	57.870	57.903	57.927	21.651	21.701	21.747
	Pa-233	.0214	.0188	.0184	.0183	.0182	.0220	.0019	.0018
	U-233	.9836	.9961	.9938	.9894	.9884	.4469	.4514	.4581
	U-234	.1416	.1459	.1417	.1373	.1339	.1385	.1338	.1294
	U-235	.0213	.0218	.0211	.0203	.0197	.0308	.0300	.0290
	U-236	.0017	.0019	.0018	.0017	.0016	.0084	.0078	.0072

processing costs) at a lower indirect charge. The penalty does decrease the higher the unit fuel cost relative to processing charges.

Selected results of point model calculations considering a single pebble are shown in Table 3-2 with recycle delayed 1/3 the real residence time. The predicted performance of a fixed fuel reactor is shown in Table 3-3 with one cycle delay in recycle, unless noted, for comparison. The effect on performance of several variables in the fuel cycle are explored in Table 3-4 for a single pebble, fixed fuel reactor with 1/4 core refueling, and when considered, one cycle delay in recycle. Only small changes in performance characteristics are associated with a wide variation in the recycle of material. Selective or partial recycle may be the optimum due to the relative high cost associated with refabrication of fuel.

Information has been developed herein that allows an assessment to be made of the cost penalty associated with reducing the ore requirements by reducing the exposure of the fuel and increasing the conversion ratio. Shown below is a summary of data selected to present a composite picture:

Exposure (MW_{th}-D/kgm)	Conversion Ratio	Ore Requirement (kgm U_3O_8/MW_e Installed) Consumption	Commitment	Fuel Cost (mill/kW_e-Hr) Low Indirect	Reference
128	.60	2,450	2,700	4.3	5.4
113	.63	2,290	2,600	4.2	5.3
97	.66	2,120	2,500	4.2	5.3
82	.69	1,950	2,410	4.3	5.4
66	.72	1,780	2,320	4.4	5.5
51	.75	1,610	2,230	4.7	5.9
36	.78	1,450	2,150	5.3	6.5
20	.81	1,280	2,080	7.0	8.3

Note that the ore commitment to operate the reactor through its life is reduced much less by decreasing the exposure than is the consumption. The cost penalty to reduce the ore consumption 34 percent is estimated at 23 percent, but to reduce it 27 percent the cost would be increased only 12 percent.

Table 3-2. Point Model Results for Delayed Recycle with Continuous Fueling ($1,200\ MW_e$ plant at 0.75 load factor, 0.002 tails, 0.015 recycle loss)

				Cycle Data			30 Year History		
Residence Time (yrs at full power)	Exposure (MW_{th}-D/kgm HM)	Fissile Loading (kgm)	Conversion Ratio	U^{235} Feed (kgm/D)	Ore Consumption (kgm/MW_eYr)	Fuel Cost (Mill/KW_e Hr)	U^{235} Feed[a] (kgm/D)	Ore Consumption[b] (kgm/MW_e)	Fuel Cost (Mill/KW_e Hr)
C/HM 250, 5 W_{th}/cc, .05 neutron loss fraction									
1	24.4	1,201	.803	.567	48	7.60	.718	1,207	7.966
2	48.4	1,303	.757	.701	61	5.16	.837	1,447	5.385
3	71.7	1,393	.718	.805	72	4.61	.943	1,600	4.704
4	94.6	1,464	.683	.917	82	4.53	1,041	1,864	4.494
5	116.7	1,545	.651	1.017	92	4.70	1.134	2,052	4.466
C/HM 250, 5 W_{th}/cc, .08 neutron loss fraction									
3	71.3	1,536	.661	.980	92	5.10	1.126	2,012	5.221
4	93.6	1,653	.628	1.086	102	5.06	1.220	2,202	5.004
4[c]	99.3	1,558	.615	1.110	104	5.00	1.243	2,279	4.961
5	115.4	1,751	.599	1.178	110	5.21	1.309	2,376	4.966
C/HM 250, 7.5 W_{th}/cc, .08 neutron loss fraction									
2	70.2	1,154	.635	1.042	97	4.98	1.158	2,174	5.128
3	101.6	1,352	.589	1.197	112	4.87	1.294	2,448	4.845
4	133.6	1,416	.549	1.325	124	5.06	1,417	2,689	4.866
C/HM 400, 5 W_{th}/cc, .05 neutron loss fraction									
2	70.7	[illegible]	.663	.943	88	5.37	1,038	1,983	5.454
3	104.1	970	.615	1,085	102	4.97	1.169	2,257	[illegible]
4	135.2	1,054	.575	1.211	113	5.07	1.287	2,500	4.781
C/HM 400, 5 W_{th}/cc, .08 neutron loss fraction									
[illegible]	70.[illegible]	999	.613	1,097	102	5.77	1.190	2,285	5.855
3	103.0	1,075	.564	1.[illegible]24	115	5.36	1,313	2,539	[illegible]285
4	133.7	1,176	.533	1.236	125	5.44	1.4[illegible]1	2,761	5.345

[a] Includes initial inventory
[b] Installed capacity basis, [illegible]
[c] Heavy metal feed fixed

Table 3-3. Point Model Results for Fully Enriched Delayed Recycle, Fixed Fuel Reactor ($1,200\ MW_e$ [illegible]ant at 0.75 load factor, 0.002 tails, 0.015 recycle loss)

[illegible]	[illegible]	[illegible]	[illegible] Loading	[illegible] Ratio	[illegible]	Cycle Data Ore Consumption [illegible]	Fuel Cost [illegible]	30 Year History Feed (kg/D)	30 Year History Ore Consumption (kg/MW_e)	30 Year History Fuel Cost (Mill/kWe Hr)
[illegible]										
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2,094	5.188
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2,342	5.065
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.392	1.476	2,561	5.139
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.996	1.096	1,966	5.038
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.961	1.220	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.184	[illegible]	5.157	1.325	2,397	4.895
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.761	[illegible]	2,049	4.674
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2,034	4.657
[illegible]										
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.669	1.349	2,419	5.709
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.477	[illegible]	5.597
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.569	2,861	5.649
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.284	[illegible]	5.056
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2,528	5.394
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.398
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.183
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.155
[illegible]										
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.604
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.449
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.576
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1,442	5.462
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.249
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.015
[illegible]										
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

Table 3-4. Point Model Results Which Display the Effect of Fuel Management for a Fixed Fuel Reactor
(1,200 MW_e plant at 0.75 load factor)

Recycle Reference			Exposure	Conversion Ratio	U^{235} Feed ($Kgm\ U^{235}$/D/MW_e)	Ore Commitment[a] ($Kgm\ U_3O_8$/MW_e for 30 yr at .75)	Fuel Cost[b] (mill/KW_e hr)
Delayed	Material	Fraction					
C/HM 250, 0.05 fraction neutron loss							
	Throwaway		101.2	.5968	1.424	3,597	5.176
No	U	1.0	98.7	.6160	1.017	2,570	4.635
Yes	U	1.0	99.0	.6170	1.035	2,615	4.855
Yes	U	.98	99.0	.6167	1.043	2,634	4.854
Yes	U	.90	99.2	.6157	1.073	2,710	4.848
Yes	U	.80	99.4	.6143	1.111	2,806	4.841
Yes	U,Pu	1.0	99.0	.6163	1.034	2,615	4.856
Yes	U,Pu	.98	99.1	.6163	1.043	2,634	4.854
C/HM 400, 0.05 fraction neutron loss							
	Throwaway		105.9	.5380	1.469	3,710	5.277
No	U	1.0	101.8	.5548	1.114	2,813	5.020
Yes	U	1.0	102.5	.5557	1.125	2,836	5.418
Yes	U	.98	102.6	.5555	1.129	2,852	5.417
Yes	U	.90	102.9	.5547	1.156	2,920	5.415
Yes	U	.80	103.4	.5536	1.190	3,005	5.412
Yes	U,Pu	1.0	102.5	.5553	1.122	2,835	5.418
Yes	U,Pu	.98	102.6	.5551	1.129	2,852	5.417

[a] Installed capacity basis.
[b] Cost accounting considers lead and lag and therefore does not directly reflect the effect of no recycle delay.

It should be noted that if the size of the processing facilities for a developed industry depend on the throughput causing the unit costs to decrease with increase in the throughput, the economic optimum shifts toward higher throughput, lower exposure.

Cost calculations shown in Table 3-5 were made using the data from specific cases, several of these cases discussed in the previous section.

Table 3-5. Fuel Costs for the High Enriched ^{235}U Feed Converter Cases
(30-year life, 0.75 plant load factor, 0.4 plant efficiency)

Schedule 1 Unit Costs, 0.10 Interest, 0.07 Discount

CASE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
THROWAWAY BOTH																
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INDIRECTCOST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROCESS BOTH																
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INDIRECTCOST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROCESS FISSILE																
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INDIRECTCOST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Schedule 1 Unit Costs, 0.05 Interest, 0.07 Discount

CASE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
THROWAWAY BOTH																
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INDIRECTCOST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROCESS BOTH																
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INDIRECTCOST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROCESS FISSILE																
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INDIRECTCOST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

SECTION 04: BURNER PERFORMANCE WITH MEDIUM AND LOW ENRICHED URANIUM

The recent concern with proliferation risk has brought about an interest in medium enriched uranium fuel as reactor feed. For non-proliferation purposes the enrichment must be less than a predescribed lower limit needed for practical weapon production. Although opinions differ, the limit on enrichment is in the range of 0.20 for a U^{235}-U^{238} mixture and lower for U^{233}-U^{238} based on the quantity of material required for a weapon.

The fuel cycle of most practical concern is the throwaway cycle in which the discharged fuel is not reprocessed (in which case the fissile uranium discharge is isolated along the fuel cycle path, a possible proliferation risk). The discharged fuel from the reactor does contain fissile Pu, but the quantity is small and the fuel is "hot" due to its high activity at that time.

Note on Calculational Procedure

The continuous flow, steady state model requires iteration between a neutronics module and a fuel-depletion (burnup) module. In the neutronics module, a search procedure is performed to adjust the U^{235} (or any nuclide if desired) atom density in order to achieve criticality. The global iterative process converges quite well when the fissile U^{235} content is adjusted but may not converge if the U^{238} content is also adjusted to maintain a fixed feed enrichment (for high-enriched feed this problem does not occur). The medium and low enriched feed calculations were therefore performed for a fixed U^{238} and Th^{232} feed and the U^{235} was adjusted to achieve criticality. The exact feed enrichments therefore vary slightly about the designed enrichments and are reported for each case.

Reactor and Pebble Designs for LEU, MEU Study

The effect of changes in overall reactor design on reactor performance was studied for high enriched feed cases (Sec. 02) and was not repeated for LEU, MEU feed. The reactor design is fixed: 1200 MW_e, 3000 MW_{th} power rating; an average of 5 W_{th}/cc in the core and a fixed "active" core height (not including the axial blanket) of 500 cm.

BLANK PAGE

The pebbles were designed to achieve the desired heavy metal loadings. Shown below are the nominal specifications for the LEU and MEU pebble designs:

Low Enriched and Medium Enriched Pebble Designs,
One Feed Stream, Single Oxide (Uranium)

Nominal C/HM		300	450	600	850
Heavy Metal Loading (gm)		9.87	6.56	4.92	3.47
Fuel Grains Kernel Diameter (cm)		.0800	.0800	.0800	.0800
Coating Thickness (cm)		.0190	.0190	.0190	.0190
Pebble Meat Radius (cm)		2.500	2.500	2.500	2.500
Packing Fraction		.0578	.0384	.028[illegible]	.0203
Pebble Densities	U^{238}	1.987-4	1.351-4	1.013-4	7.143-5
(atoms/bn-cm)	Th^{232}	0.0	0.0	0.0	0.0
	C	6.605-2	6.608-2	6.607-2	6.607-2

Medium Enriched Pebble Designs, Two Feed Streams

Nominal C/HM		325		450		550	
Pebble		Primary	Fertile	Primary	Fertile	Primary	Fertile
C/HM for Pebble		330	320	455	445	556	544
Heavy Metal Loading (gm)		9.36	9.58	6.78	6.93	5.5[illegible]	5.67
Fuel Grains Kernel Diameter (cm)		.0400	.0300	.0400	.0300	.040[illegible]	.0300
Coating Thickness (cm)		.0130	.0130	.0130	.0130	.0130	.0130
Pebble Meat Radius (cm)		2.381	2.356	2.381	2.332	2.381	2.324
Packing Fraction		.0888	.1364	.0642	.1015	.0526	.0840
Pebble Densities	$U^{[illegible]}$	1.676-4	–	1.213-4	–	9.927-5	–
(atoms/bn-cm)	Th^{232}	–	2.200-4	–	1.590-4	–	1.301-4
	C	6.932-2	7.043-2	6.922-2	7.074-2	6.917-2	7.081-2

The cross sections were input as a single set of four-group, microscopic cross section for a set of 13 actinides, 29 fission products, and the remaining structure and coolant. Details concerning resonance integrals and group collapsing are discussed in Appendices B and C.

Medium Enriched Uranium Feed One-Dimensional Parameter Studies

The one-dimensional MEU feed parameter studies were performed for a fixed burnup of approximately 200 $MW_{th}D/Kg\text{-}HM$ in the primary pebble (pebble with fissile feed) over a range of C/HM ratios. Variation in axial blanket thickness was also studied to ascertain axial leakage loss effects.

Results obtained for the steady-state continuous fueling model in one-dimension are shown in Table 4-1 for medium enriched U^{235} feed over a range of parameters. The optimal performance from an ore conservation standpoint is obtained at C/HM of 450. An axial blanket of fertile pebbles fed above the fueled core region and flowing through the reactor was included in the modeling and the effect of axial blanket thickness is demonstrated. An increase of blanket thickness decreases the leakage fraction resulting in an associated decrease in fissile inventory and fissile feed rate.

After an initial pass of the fertile pebbles through the core there is a considerable amount of U^{233} present and the fertile pebble exposure is low in comparison to the primary pebbles, warranting recycle without reprocessing (or holdup) of the fertile pebble for throwaway cycles. The "cycle" reference number represents one pass of the fertile pebbles (1) or recycle to the top of the core (2). The results indicate a decrease by about six percent in the required fissile feed rate for fertile pebble recycle versus no recycle.

The parameter studies are for a nominal feed enrichment of 0.20, the actual enrichment varying slightly about the nominal. Supplementary one-dimensional results for medium enriched U^{235} feed are listed in Table 4-2; included in the table are cases with the U^{235} feed at enrichments varying slightly about 0.20 to access performance sensitivity to small changes in the feed enrichment and residence time.

A change in the pebble packing fraction within the core in a PBR affects performance due to resulting changes in neutron leakage. From a modeling standpoint, the buckling used to approximate the radial leakage in a one-dimensional, axial calculation is also important.

Table 4-1. Results for Medium-Enriched Uranium Feed
(One-dimensional two pebble types, 1200 MW_e, 5 W_{th}/cc, core height = 500 cm)[a]

CASE		AX0	AX1	AX2	BX0	BX1	BX2
Core Height (cm)		500	500	500	500	500	500
Axial Blanket Thickness (cm)		0.0	35.7	71.4	0.0	35.7	71.4
Carbon/Heavy Metal (atom ratio)		325	325	325	450	450	450
Cycle (1 or 2 passes of fertile pebbles)		1	1	1	1	1	1
Resident Time at Full Power (yrs)		3.5	3.5	3.5	2.5	2.5	2.5
Feed Enrichment		.221	.211	.198	.206	.197	.188
Conversion Ratio		.592	.613	.643	.559	.581	.607
Fissile Inventory (kg)		1994	1785	1641	1137	1001	932
Average Peak Power Density (watts/cc)		9.85	10.05	10.71	10.77	11.13	11.97
Peak Power Density in Primary Pebble (watts/cc)		28.84	29.06	31.31	29.25	32.07	35.30
Peak Power Density in Fertile Pebble (watts/cc)		4.51	4.88	5.45	4.99	5.11	5.68
Leakage Loss		.0698	.0590	.0445	.0845	.0727	.0556
Fission Product Absorption Loss		.0840	.0851	.0862	.0906	.0916	.0924
Average Burnup (MW_{th} D/KgHM)		123	124	125	123	124	125
Burnup in Primary Pebble (MW_{th}D/KgHM)		210	208	203	211	208	202
Burnup in Fertile Pebble (MW_{th}D/KgHM)		36	42	50	36	42	49
Mass Flows (Kg/Day)							
Primary Feed	U-[illegible]	2.6905	2.5296	2.3382	2.4941	2.[illegible]570	2.2183
	U-[illegible]	9.4864	9.4864	9.4864	9.6113	9.6113	9.6113
Fertile Feed	Th-[illegible]	12.1384	12.1398	12.1398	12.2819	12.2832	12.2833
Primary Discharge	U-[illegible]	.4249	.3661	.3124	.2432	.2049	.1814
	U-[illegible]	.3834	.3607	.3329	.3610	.3411	.3206
	U-[illegible]	8.3236	8.3233	8.3333	8.5501	8.5502	8.5672
	Pu (fissile)	.1800	.1708	.1631	.1164	.1106	.1056
	Pu (nonfissile)	.1010	.0998	.0987	.0976	.0964	.0921
Fertile Discharge	Th-[illegible]	11.2102	11.1369	1.0196	11.4112	11.3352	11.2219
	Pa-[illegible]	.0029	.0023	.0019	.0040	.0031	.0026
	U-[illegible]	.3721	.3699	.3667	.3082	.3057	.3005
	U-[illegible]	.0687	.0751	.0852	.0711	.0780	.0904
	U-[illegible]	.0145	.0165	.0202	.0126	.0144	.0177
	U-[illegible]	.0019	.0023	.0033	.0019	.0025	.0037

[a] Radial buckling = 3.2-5 in all cases except case BY3 which has a buckling of 7.0-6.

Table 4-1. (Cont'd.)

AY0	AY1	AY2	SY0	BY1	BY2	BY3[a]	CY2
500	500	500	500	500	500	500	500
0.0	35.7	71.4	0.0	35.7	71.4	71.4	71.4
325	325	325	450	450	450	450	550
2	2	2	2	2	2	2	2
3.5	3.5	3.5	2.5	2.5	2.5	2.5	2.0
.207	.197	.187	.196	.187	.178	.197	.177
.591	.611	.635	.556	.575	.600	.564	.573
1969	1774	1661	1138	.017	943	1123	706
9.93	10.14	10.81	10.86	11.23	12.20	11.77	13.09
27.36	27.48	29.43	29.85	30.37	33.56	32.85	36.20
6.73	6.88	7.15	6.56	6.70	6.90	6.37	6.64
.0703	.0601	.0467	.0849	.0664	.0576	.0861	.0654
.0886	.0907	.0933	.0945	.0969	.0995	.0910	.1007
166	[illegible]	169	166	167	168	160	165
202	[illegible]	194	204	201	196	196	192
95	106	172	92	102	118	106	112
2.4739	[illegible]	2.1755	2.3396	2.2161	2.0785	2.8615	2.1199
9.4864	9.4864	9.4864	9.6113	9.6115	9.6113	9.6113	9.8330
6.0692	6.0709	6.0709	6.1410	6.1427	6.1427	6.1427	6.2827
.3940	.3433	.3070	.2346	.2021	.1786	.2850	.1476
.3534	.3320	.3093	.3384	.3204	.2998	.3360	.3077
8.3251	8.3266	8.3478	8.5536	8.5564	8.5769	8.6160	8.8644
.1798	.1719	[illegible]	.1175	.1122	.1082	.1266	.0902
.1009	.0998	.0978	.0976	.0964	.0945	.0955	.0932
5.1779	5.1110	5.0066	5.5057	5.2381	5.1308	5.2014	5.3082
.0013	.0010	.0008	.0018	.0014	.0011	.0011	.0015
.1977	.1864	.1790	.1558	.1509	[illegible]	.1582	.1356
.0598	.0623	.0656	.0598	.0625	.0663	.0626	.0673
.0188	.0200	.0218	.0148	.0157	.0170	.0166	.0151
.0052	.0062	.0080	.0051	.0062	.0081	.0065	.0078

Table 4-2. Supplemental Results for Medium-Enriched U^{235} Feed (One-dimensional, two pebble types, 1200 MW_e, 5 W_{th}/cc, core height = 500 cm)

CASE		BY2AE	BY2BE	BY2CE[a]	BY2EE
Core Height (cm)		500	500	500	500
Axial Blanket Thickness (cm)		71.4	71.4	71.4	71.4
Carbon/Heavy Metal (atom ratio)		450	450	450	450
Cycle (1 or 2 passes of fertile pebbles)		2	2	2	2
Resident Time at Full Power (yrs)		1.75	2.50	2.3	2.[illegible]
Feed Enrichment		.156	.202	.226	.190
Conversion Ratio		.632	.601	.571	.609
Fissile Inventory (Kg)		861	935	922	916
Average Peak Power Density (watts/cc)		10.36	12.31	11.02	11.67
Peak Power Density in Primary Pebble (watts/cc)		26.62	32.73	34.87	30.74
Peak Power Density in Fertile Pebble (watts/cc)		8.03	8.15	8.36	8.14
Leakage Loss		.0541	.0572	.0722	.0563
Fission Product Absorption Loss		.0887	.1034	.1035	.0999
Average Burnup (MW_{th} D/KgHM)		126	175	185	162
Burnup in Primary Pebble (MW_{th}D/KgHM)		158	213	230	199
Burnup in Fertile Pebble (MW_{th}D/KgHM)		84	121	121	111
Mass Flows (Kg/Day)					
Primary Feed	U^{235}	2.1258	2.0340	2.1729	2.0439
	U^{238}	11.4822	8.0376	7.4475	8.7365
Fertile Feed	Th^{232}	10.1373	7.0961	6.5752	7.7132
Primary Discharge	U^{235}	.2574	.1539	.1762	.1728
	U^{236}	.3001	.2949	.3150	.2953
	U^{238}	10.5520	7.1649	6.5979	7.8493
	Pu (fissile)	.1219	.0844	.0847	.0922
	Pu (nonfissile)	.0919	.0783	.0762	.0815
Fertile Discharge	Th^{232}	8.8648	5.9104	5.4674	6.5063
	Pa^{233}	.0038	.0014	.0019	.0017
	U^{233}	.2348	.1617	.1568	.1768
	U^{234}	.0966	.0776	.0730	.0822
	U^{235}	.0217	.0195	.0190	.0201
	U^{236}	.0077	.0098	.0091	.0093

[a]Same as case BY2EE except the pebble packing fraction is smaller, 0.52 compared to 0.61.

The effects of variation in buckling and pebble packing fraction are indicated in Tables 4-1 and 4-2.

The throwaway cycle has an economic optimum at C/HM = 450. Fuel cycle costs for the one-dimensional cases are listed in Table 4-3.

MEU Feed Two-Dimensional Cases

The two-dimensional cases for medium enriched feed (U^{235} $-U^{238}$ primary feed and Th^{232} fertile feed) were restricted to a C/HM ratio of 450, the optimum ratio as determined from the one-dimensional parameter studies. Three technology performances were assessed: (1) a low technology — mixed oxide, single pebble feed; no radial or axial blankets; no immediate recycling of pebbles; a moderate burnup level (<140 $MW_{th}D/Kg/HM$); (2) a reference technology — two pebble types; an axial blanket thickness of 35.71 cm; no immediate recycling of pebbles; a burnup less than 210 $MW_{th}D/Kg/HM$; and (3) a high technology — two pebble types; a 71.43 cm axial blanket; immediate recycle of thorium pebbles; a burnup less than 240 $MW_{th}D/Kg/HM$.

The following summary indicates the 2-D MEU studies as identified by the case title. The cases were selected to examine the effects of variation in residence time, variation in radial reflector density and

Summary of Two-Dimensional MEU Cases

Case	Technology Level	Average Pebble Residence Time, Full Power Yrs	Radial Reflector Graphite Density (gm/cc)	Radial Reflector Thickness (cm)	Nominal U/TH Loadings (gms/pebble)	Number of Enrichment Zones
TDCLC1	Low	2.00	1.0	35.0	4.4,2.47	1
TDCLC2	Low	2.35	1.0	100.0	4.4,2.47	1
TECLC	Low	2.50	1.0	100.0	4.4,2.47	1
TDRLA	Low	2.50	1.0	100.0	3.4,3.47	1
TDRLB	Low	2.50	1.6	100.0	3.4,3.47	1
TDRLC	Low	2.50	1.6	100.0	4.4,2.47	2
TDCRD	Reference	2.50	1.0	100.0	6.8/6.93	1
TECRD	Reference	2.65	1.0	100.0	8.7/4.94	1
TDRRA	Reference	2.65	1.6	100.0	6.8/6.93	1
TDRRB	Reference	2.65	1.6	100.0	8.7/4.94	2
TDCHC	High	3.00	1.0	35.0	8.7/4.94	1
TDCHD	High	2.65	1.0	100.0	8.7/4.94	1
TDRHA	High	2.90	1.6	100.0	6.8/6.93	1
TDRHB	High	2.90	1.6	100.0	8.7/4.94	3

Table 4-3. Fuel Costs for MEU One-Dimensional, Two Feed Stream Cases
(1200 MW_e, 0.75 Load Factor, 30 Year Lifetime)

Linear Interest Rate = 0.1, Discount Rate = 0.07

CASE	AX0	AX1	AX2	BX0	BX1	BX2	AY0	AY1	AY2	BY0	BY1	BY2	CY2
THROWAWAY BOTH													
COST OF FUEL	4.2415	3.9802	3.6689	3.9203	3.6976	3.4726	3.8923	3.6481	3.3988	3.6629	3.4610	3.2389	3.3019
FABRICATION	0.3575	0.3574	0.3545	0.4427	0.4422	0.4418	0.2888	0.2875	0.2886	0.3551	0.3547	0.3540	0.4199
REPROC/WASTE	0.1354	0.1344	0.1332	0.1360	0.1352	0.1343	0.0951	0.0942	0.0932	0.0950	0.0948	0.0940	0.0966
INDIRECTCOST	1.9082	1.7785	1.6531	1.3052	1.2273	1.1627	1.8008	1.5003	1.5797	1.2469	1.1898	1.1074	0.9442
TOTAL COST	6.6426	6.2505	5.8097	5.8042	5.4962	5.2114	6.0771	5.5301	5.3598	5.3605	5.0807	4.9943	4.7625
REPROCESS BOTH													
COST OF FUEL	3.0115	2.8331	2.5956	3.0837	2.9157	2.7277	3.0694	2.9042	2.7133	3.1497	2.9986	2.8146	2.9482
FABRICATION	0.3575	0.3574	0.3545	0.4427	0.4422	0.4418	0.2888	0.2875	0.2886	0.3551	0.3547	0.3540	0.4199
REPROC/WASTE	0.5969	0.5928	0.5871	0.7632	0.7588	0.7534	0.4185	0.4143	0.4100	0.5335	0.5291	0.5241	0.6299
INDIRECTCOST	2.1576	2.0192	1.9227	1.3542	1.2630	1.2167	2.0316	1.7124	1.7967	1.2901	1.2022	1.1398	0.9134
TOTAL COST	6.1235	5.8020	5.4600	5.6439	5.3801	5.1395	5.8083	5.3184	5.2085	5.3284	5.0855	4.8326	4.9134
REPROCESS FERTILE													
COST OF FUEL	3.4507	3.1957	2.8918	3.2647	3.0498	2.8370	3.4764	3.2462	3.0123	3.3287	3.1394	2.9297	3.0180
FABRICATION	0.3575	0.3574	0.3545	0.4427	0.4422	0.4418	0.2888	0.2875	0.2886	0.3551	0.3547	0.3540	0.4199
REPROC/WASTE	0.3924	0.3899	0.3863	0.4914	0.4884	0.4845	0.2152	0.2128	0.2095	0.2624	0.2596	0.2595	0.2986
INDIRECTCOST	2.0824	1.9688	1.8939	1.3815	1.3030	1.2623	1.9666	1.6686	1.7669	1.3176	1.2397	1.1837	0.9804
TOTAL COST	6.2829	5.9117	5.5266	5.5803	5.2835	5.0255	5.9471	5.4151	5.2772	5.2639	4.9836	4.7229	4.7129

Linear Interest Rates = 0.05, Discount Rate = 0.035

CASE	AX0	AX1	AX2	BX0	BX1	BX2	AY0	AY1	AY2	BY0	BY1	BY2	CY2
THROWAWAY BOTH													
COST OF FUEL	4.2415	3.9802	3.6689	3.9203	3.6976	3.4726	3.8923	3.6481	3.3988	3.6629	3.4610	3.2389	3.3019
FABRICATION	0.3575	0.3574	0.3545	0.4427	0.4422	0.4418	0.2888	0.2875	0.2886	0.3551	0.3547	0.3540	0.4199
REPROC/WASTE	0.1354	0.1344	0.1332	0.1360	0.1352	0.1343	0.0951	0.0942	0.0932	0.0956	0.0948	0.0940	0.0966
INDIRECTCOST	0.9126	0.8514	0.7915	0.6274	0.5878	0.5596	0.8595	0.7239	0.7541	0.5984	0.5619	0.5319	0.4549
TOTAL COST	5.6470	5.3234	4.9481	5.1265	4.8628	4.6083	5.1357	4.7538	4.5345	4.7120	4.4731	4.2188	4.2732
REPROCESS BOTH													
COST OF FUEL	3.0115	2.8331	2.5956	3.0837	2.9157	2.7277	3.0694	2.9042	2.7133	3.1497	2.9986	2.8146	2.9482
FABRICATION	0.3575	0.3574	0.3545	0.4427	0.4422	0.4418	0.2888	0.2875	0.2886	0.3551	0.3547	0.3540	0.4199
REPROC/WASTE	0.5969	0.5928	0.5871	0.7632	0.7588	0.7534	0.4185	0.4143	0.4100	0.5335	0.5251	0.5241	0.6299
INDIRECTCOST	1.0373	0.9717	0.9263	0.6519	0.6091	0.5867	0.9749	0.8300	0.8629	0.6200	0.5782	0.5481	0.4409
TOTAL COST	5.0032	4.7545	4.4635	4.9416	4.7254	4.5095	4.7515	4.4360	4.2747	4.6583	4.4616	4.2409	4.4385
REPROCESS FERTILE													
COST OF FUEL	3.4507	3.1957	2.8918	3.2647	3.0498	2.8370	3.4764	3.2462	3.0123	3.3287	3.1394	2.9297	3.0180
FABRICATION	0.3575	0.3574	0.3545	0.4427	0.4422	0.4418	0.2888	0.2875	0.2886	0.3551	0.3547	0.3540	0.4199
REPROC/WASTE	0.3924	0.3899	0.3863	0.4914	0.4884	0.4845	0.2152	0.2128	0.2095	0.2624	0.2596	0.2555	0.2986
INDIRECTCOST	0.9997	0.9465	0.9119	0.6656	0.6287	0.6094	0.9424	0.8081	0.8479	0.6337	0.5970	0.5701	0.4730
TOTAL COST	5.2002	4.8895	4.5445	4.8644	4.6092	4.3727	4.9229	4.5546	4.3582	4.5800	4.3506	4.1093	4.2095

thickness, variation in pebble loadings, and the effect of power flattening by varying the feed enrichment across the core.

The cases reflecting a low level of technology have a single pebble type (mixed-oxide U-Th fuel). The uranium and thorium loadings of 3.4 and 3.47 gms/pebble in the mixed-oxide fuel correspond to the 6.8 gms of U/fissile pebble and the 6.93 gms of Th/fertile pebble when two pebble types are used. These heavy metal loadings are those given in the pebble design summary for MEU, C/HM = 450. Given a residence time, the feed enrichment may be reduced by increasing the U^{238} loading (at the expense of decreasing the Th^{232} loading in the fertile pebble for a fixed average C/HM ratio). The U/Th loadings (gms/pebble) of 4.4, 2.47 (mixed-oxide) and the corresponding 8.7/4.94 (separate pebble types) were examined for cases representing all three technology levels.

The results of the two-dimensional, MEU cases are shown in Table 4-4. Indicated in the results is the increase in enrichment but decrease in fertile feed rate due to an increase in the residence time for a fixed U^{238} loading. Also the cases representing pebble feed designs with the higher Th^{232} loading have a slightly lower fissile feed rate and fissile inventory but a higher enrichment. Nevertheless, use of the pebble designs with the higher U^{238} fueled-pebble loading is more desirable since a longer residence time can be obtained while keeping the fissile feed enrichment (or maximum enrichment for cases with varying feed enrichments) below the "non-proliferation" limit of 0.2.

Comparison of the low technology cases indicates that an increase in the reflector thickness from 36 to 100 cm can result in a decrease in fissile feed by as much as nine percent and in fissile inventory by four percent. An increase in reflector graphite density from 1.0 gm/cc (representing a reflector with channels for structure) to 1.6 gm/cc results in a savings of only a few percent in fissile feed rate and fissile inventory (for a 100 cm reflector).

The cases chosen as the best representative for each of the three technology levels (low, reference and high) are cases TDRLC, TDRRB,

Table 4-4. Results for Medium-Enriched U^{235} Feed (Two-Dimensional, 1200 MW_e, 5 W_{th}/cc, core height = 500 cm)

Case		TDCLC1	TDCLC2	[illegible]	[illegible]	[illegible]
Radial Reflector Thickness (cm)		36.0	100.0	100.0	100.0	100.0
Inlet Axial Blanket Thickness (cm)		0.0	0.0	0.0	0.0	0.0
Core Radius, Fueled (cm)		618.04	618.04	618.04	618.04	618.04
Radial Blanket Thickness (cm)		0.0	0.0	0.0	0.0	0.0
Cycle (1 or 2 passes of fertile pebbles)		1	1	1	1	[illegible]
Residence Time, Full Power (yrs)[a]		2.00	2.35	2.50	[illegible]	[illegible]
Fissile Feed Enrichment		.164	.169	.176	.216	[illegible]
Fissile Inventory (Kgm)		1312	1232	1259	1225	1185
Peak Power in Fissile Pebble (Kw/pebble)		2.42	2.33	2.35	2.36	2.33
Leakage Loss, fractional		.0986	.0904	.0909	.0942	.0827
Fission Product Loss, fractional		.0782	.0847	.0861	.0898	[illegible]
Conversion Ratio		.539	.543	.539	.531	.534
Average Burnup (MW_{th}-D/Kg HM)		103	118	125	122	122
Burnup by Zones (Primary/Fertile)						
1		115	125	132	128	[illegible]
2		116	125	132	129	[illegible]
3		112	120	130	[illegible]	[illegible]
4		97	114	122	[illegible]	[illegible]
5		77	102	104	106	[illegible]
6		62	98	105	102	[illegible]
Feed Rates (Kg/full power day)						
Primary	U^{235}	3.0072	2.7071	2.6734	[illegible]	[illegible]
	U^{238}	15.3537	13.3363	12.5361	[illegible]	[illegible]
Fertile	Th^{232}	10.7283	9.3187	8.7695	[illegible]	[illegible]
Discharge Rates (Kg/full power day)						
Primary	U^{235}	.6087	.3958	.3654	[illegible]	[illegible]
	U^{236}	.4047	.3831	.3613	.3247	[illegible]
	U^{238}	14.1106	12.1007	11.1312	8.6604	[illegible]
	Pu(f)	.2049	.1679	.1582	.1071	[illegible]
	Pu(n)	.1210	.1141	.1112	.0841	[illegible]
Fertile	Th^{232}	10.7072	8.6978	8.1468	11.3342	[illegible]
	Pa^{233}	.0046	.0034	.0030	.0042	[illegible]
	U^{233}	.2762	.2469	.2355	.3155	[illegible]
	U^{234}	.0504	.0512	.0506	[illegible]	[illegible]
	U^{235}					
	U^{236}					

[a]There are six feed paths bounded by r(cm) = 276.40, 390.98, 478.73, 552.79, 586.32, 618.04. The relative path flow rates are 1.0, 1.09, 1.18, 1.26, 1.31, and 1.40.

[b]Feed enrichments: inner three paths = .167, outer three paths = .186.

[c]Feed enrichment: inner three paths = .187, outer two paths = .197.

[d]Feed enrichments: inner two paths = .179, third path = .194, outer two paths = [illegible].

Table 4-4. (Cont'd.)

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	100.0	100.0
[illegible]	35.7	[illegible]	[illegible]	35.7	[illegible]	[illegible]	77.4	77.4
[illegible]	586.32	586.32	586.32	586.32	586.32	586.32	586.32	[illegible]
[illegible]	31.72	31.72	31.72	31.72	31.72	31.72	31.72	31.72
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	.224	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.1897
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.39	[illegible]	[illegible]	[illegible]
[illegible]	.0783	.0793	.0738	.0787	[illegible]	.0693	.0619	.0641
[illegible]	[illegible]	.0919	.0954	.0929	.1078	.0984	.1031	[illegible]
[illegible]	[illegible]	.524	.555	.599	[illegible]	.553	.557	[illegible]
[illegible]	[illegible]	[illegible]	151	[illegible]	163	167	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 4-5. Fraction of Total Neutron Losses for Selected Actinides for Two-Dimensional MEU Cases

Case	Th^{232}	U^{233}	U^{234}	U^{235}	U^{236}	U^{238}	Pu^{239}	Pu^{240}	Pu^{241}	Pu^{242}
TDCLC1	.07262	.03926	.00166	.30218	.00617	.15340	.13510	.04446	.03519	.00173
TDCLC2	.07829	.04293	.00191	.29056	.00678	.15187	.13694	.0464[illegible]	.03844	.00212
TECLC	.07721	.04345	.00198	.29008	.00718	.15044	.13634	.04657	.03889	.00226
TDRLA	.11219	.06598	.00315	.29746	.00744	.11725	.10762	.03734	.03208	.00194
TDRLB	.11398	.06712	.00321	.29515	.00732	.11745	.10807	.03762	.03250	.00197
TDRLC	.07764	.04412	.00199	.28857	.00707	.15027	.13655	.04680	.03932	.00226
TDCRD	.12803	.07985	.00420	.28497	.00720	.1[illegible]346	.10453	.03684	.03213	.00211
TECRC	.08779	.05405	.00279	.29164	.00807	.14439	.13196	.04611	.03948	.00260
TDRRA	.12224	.08239	.00444	.28167	.00813	.11234	.10399	.03688	.03249	.00223
TDRRB	.08898	.05531	.00283	.28040	.00796	.14411	.13188	.04615	.03961	.00259
TDCHC	.08876	.079[illegible]	.00725	.28852	.00890	.12677	.11314	.03919	.03292	.00234
TDCHD	.09064	.07200	.00671	.26665	.00748	.14081	.12787	.04522	.03881	.00252
TDRHA	.12795	.10450	.01025	.26125	.00804	.10764	.09935	.03584	.03188	.00230
TDRHB	.09031	.07310	.00702	.26371	.00800	.13870	.12676	.04582	.03954	.00274

and TDRHB respectively. In each of these cases the power is moderately flattened across the core by use of radial feed zones with varying enrichment. The reference technology represents a design comparable with seed and breed PBR concepts currently being investigated in Germany. Compared to the reference technology, the lower technology concept requires an increase in external fissile feed of approximately six percent; a higher technology level could reduce the fissile feed by about nine percent.

The fraction of total neutron losses due to absorption in the thorium, uranium, and plutonium actinides are listed in Table 4-5 for all MEU two-dimensional cases. A detailed accounting of all neutron losses are listed in Table 4-6 for the representative case of each technology level.

Fuel cycle costs are shown in Table 4-7 for all MEU 2-D cases. Note that there is not a separate fertile pebble for the low technology cases and "reprocess fertile" is identical to the "throwaway case", whereas "both" refers to the primary pebble (mixed-oxide pebble). In all cases, it pays to recover the U^{233} from the fertile pebble, but it may not be economical to recover the spent U^{235} in the fissile pebble.

Table 4-6. Detailed Account of Neutron Losses for Selected Two-Dimensional MEU Feed Cases

Case	TDRLC	TDRRB	TDRHB
Actinide			
Th^{232}	.07764	.08898	.09031
Pa^{233}	.00358	.00425	.00473
U^{233}	.04412	.05531	.07310
U^{234}	.00199	.00283	.00702
U^{235}	.28857	.28040	.26371
U^{236}	.00707	.00796	.00800
U^{238}	.15027	.14411	.13870
Np^{239}	.00038	.00041	.00042
Pu^{239}	.13655	.13188	.12676
Pu^{240}	.04680	.04615	.04532
Pu^{241}	.03932	.03961	.03954
Pu^{242}	.00226	.00259	.00274
Am^{243}	.00069	.00087	.00099
Fission Product			
Kr^{82}	.00015	.00018	.00028
Kr^{83}	.00068	.00077	.00110
Rh^{103}	.00736	.00773	.00820
Rh^{105}	.00013	.00013	.00014
Ag^{109}	.00082	.00089	.00092
Xe^{131}	.00455	.00501	.00590
Xe^{133}	.00017	.00019	.00020
Cs^{133}	.00403	.00454	.00552
Cs^{134}	.00052	.00064	.00095
Xe^{135}	.02160	.02123	.02079
Cs^{135}	.00011	.00011	.00012
Nd^{143}	.00908	.00979	.01142
Nd^{145}	.00278	.00310	.00375
Pm^{147}	.00480	.00509	.00541
Pm^{148}	.00081	.00092	.00101
Pm^{148m}	.00201	.00214	.00228
Sm^{149}	.00731	.00736	.00742
Sm^{150}	.00146	.00168	.00206
Sm^{151}	.00331	.00350	.00384
Sm^{152}	.00251	.00278	.00325
Eu^{153}	.00154	.00174	.00214
Eu^{154}	.00105	.00125	.00164
Eu^{155}	.00123	.00141	.00179
SSFP	.00611	.00691	.00888
NSFP	.00254	.00290	.00368
Other			
C	.02664	.02657	.02946
He	.00006	.00006	.00007
Si	.00196	.00181	.00180
O	.00004	.00004	.00004
Leakage	.08539	.07418	.06460
Total	1.0	1.0	1.0

Table 4-7. Fuel Costs for MEU Two-Dimensional, Two Feed Stream Cases
(1200 MW_e, 0.75 load factor, 30-year lifetime)

Linear Interest Rate = 0.1, Discount Factor = 0.07

CASE	TDCLC1	TDCLC2	TDCLC	TDRLA	TDRLB	TDRLC	TDCRD	TECRD	TDRRA	TDRRB	TDCHC	TDCHD	TDRHA	TDRHB
THROWAWAY BOTH														
COST OF FUEL	4.6672	4.2081	4.1680	4.1929	4.1140	4.1030	3.9110	3.9317	3.8385	3.8965	4.1397	3.6362	3.4246	3.5296
FABRICATION	0.6055	0.5330	0.5065	0.5189	0.5179	0.5057	0.4003	0.3858	0.3908	0.3858	0.2914	0.3180	0.2955	0.2957
REPROC/WASTE	0.1663	0.1020	0.1322	0.1370	0.1360	0.1331	0.1231	0.1124	0.1155	0.1122	0.0729	0.0836	0.0682	0.0755
INTERESTCOST	1.3813	1.3713	1.4122	1.4138	1.3867	1.3860	1.2911	1.3003	1.3092	1.3277	1.5670	1.2953	1.2607	1.2863
TOTAL COST	6.8203	6.2551	6.2156	6.2527	6.1556	6.1290	5.7976	5.7702	5.6501	5.7219	6.0516	5.2931	5.0531	5.1071
REPROCESS BOTH														
COST OF FUEL	3.4070	3.3097	3.3114	3.2652	3.2360	3.3109	3.0679	3.2232	3.0612	3.2060	3.5402	3.2193	3.0873	3.2069
FABRICATION	0.6055	0.5330	0.5065	0.5169	0.5179	0.5057	0.4103	0.3858	0.3908	0.3858	0.2914	0.3180	0.2955	0.2957
REPROC/WASTE	0.9990	0.7789	0.7235	0.7498	0.7683	0.7285	0.6516	0.6494	0.6092	0.6487	0.3797	0.8386	0.3789	0.3922
INTERESTCOST	1.4936	1.4311	1.4705	1.4483	1.4509	1.4338	1.1540	1.3718	1.3638	1.3581	1.6073	1.2810	1.2993	1.2959
TOTAL COST	6.4160	6.0538	6.0115	6.0222	5.9532	5.9789	5.5280	5.6300	5.4651	5.5983	5.8627	5.2529	5.0609	5.1903
REPROCESS FERTILE														
COST OF FUEL	4.6672	4.2081	4.1680	4.1829	4.1140	4.1030	3.2394	3.4429	3.1858	3.4109	3.9287	3.6156	3.1625	3.3125
FABRICATION	0.6055	0.5330	0.5065	0.5189	0.5179	0.5057	0.4103	0.3858	0.3908	0.3854	0.2914	0.3180	0.2955	0.2957
REPROC/WASTE	0.1663	0.1020	0.1122	0.0370	0.1360	0.1331	0.4082	0.4115	0.4208	0.4115	0.1739	0.1978	0.1724	0.1776
INTERESTCOST	1.3813	1.3713	1.4122	1.4138	1.3867	1.3890	1.3800	1.3800	1.3952	1.3685	1.5966	1.2958	1.3003	1.3248
TOTAL COST	6.8203	6.2551	6.2156	6.2527	6.1556	6.1298	5.4778	5.6201	5.3925	5.5739	5.9906	5.4268	4.9705	5.1306

Linear Interest Rate = 0.05, Discount Factor = 0.035

CASE	TDCLC1	TDCLC2	TDCLC	TDRLA	TDRLB	TDRLC	TDCRD	TECRD	TDRRA	TDRRB	TDCHC	TDCHD	TDRHA	TDRHB
THROWAWAY BOTH														
COST OF FUEL	4.6672	4.2081	4.1680	4.1829	4.1140	4.1030	3.9110	3.9317	3.8305	3.8965	4.1393	3.6362	3.4246	3.5296
FABRICATION	0.6055	0.5330	0.5065	0.5189	0.5179	0.5057	0.4101	0.3858	0.3908	0.3858	0.2914	0.3180	0.2955	0.2957
REPROC/WASTE	0.1663	0.1020	0.1322	0.1370	0.1360	0.1331	0.1231	0.1124	0.1155	0.1122	0.0729	0.0836	0.0682	0.0755
INTERESTCOST	0.6620	0.6580	0.6788	0.6790	0.6666	0.6664	0.6221	0.6455	0.6306	[illegible]	0.7859	0.6067	0.6055	0.6218
TOTAL COST	6.1010	5.5022	5.4815	5.5183	5.4353	5.4087	5.0857	5.0753	4.9754	5.0336	5.2895	4.6425	4.3978	4.5212
REPROCESS BOTH														
COST OF FUEL	3.4079	3.3097	3.3114	3.2652	3.2360	3.3139	3.0679	3.2232	3.0612	3.2060	3.5402	3.2193	3.0873	3.2065
FABRICATION	0.6055	0.5330	0.5065	0.5189	0.5179	0.5057	0.4103	0.3858	0.3908	0.3858	0.2914	0.3180	0.2955	0.2957
REPROC/WASTE	0.9099	0.7789	0.7235	0.7498	0.7683	0.7285	0.6919	0.6494	0.6092	0.6487	0.3797	0.8386	0.3789	0.3922
INTERESTCOST	0.7181	0.6885	0.7071	0.7166	0.6987	0.6898	0.6548	0.6611	0.6579	0.6527	0.5957	0.6175	0.6267	0.6252
TOTAL COST	5.4805	5.3105	5.2607	5.2505	5.2010	5.2149	4.8288	4.9196	4.7591	4.6929	5.2111	4.5096	4.3886	4.5196
REPROCESS FERTILE														
COST OF FUEL	4.6672	4.2081	4.1680	4.1829	4.1140	4.1030	3.2394	3.4429	3.1858	3.4109	3.9287	3.6156	3.1625	3.3125
FABRICATION	0.6055	0.5330	0.5065	0.5189	0.5179	0.5057	0.4103	0.3858	0.3908	0.3854	0.2914	0.3180	0.2955	0.2957
REPROC/WASTE	0.1663	0.1020	0.1122	0.1370	0.1360	0.1331	0.4085	0.4115	0.4208	0.4110	0.1739	0.1978	0.1724	0.1776
INTERESTCOST	0.6620	0.6500	0.6788	0.6794	0.6666	0.6669	0.6658	0.6653	0.6738	0.6589	0.7703	0.6248	0.6071	0.6197
TOTAL COST	6.1010	5.5022	5.4815	5.5183	5.4353	5.4087	4.7617	4.9055	4.6709	4.8602	5.1683	4.5558	4.2776	4.4495

LEU/MEU Single Pebble Type One-Dimensional Parameter Study

One effect of putting the uranium feed into "primary" pebble and the thorium feed into a "fertile" pebble is a significant increase in the peak pebble power density since a large amount of the power is being produced in the primary pebble alone. The benefit in keeping the fissile and fertile fuels separated is to achieve internal radial blanketing with fertile pebbles and then recycle them back to the core immediately. For a low level of technology, immediate selective, recycling of pebbles may not be achievable and one pebble type (mixed oxide or uranium) might be used. One-dimensional parameter studies were performed for a single pebble feed stream over a range of C/HM ratios, burnups, and enrichments.

For a fixed amount of U^{238} in the feed pebble and for a given C/HM ratio, the fissile enrichment varies as the residence time changes. A short residence time requires a large throughput of U^{235}. The relationship is not proportional due to the buildup of the plutonium and the fission products. Thus, for a given C/HM and burnup (which increases as residence time increases) there is a fixed fissile enrichment needed to achieve criticality.

The cases listed in Table 4-8 cover a range of C/HM ratios and residence times. All cores are for enriched uranium feed with no thorium. The cases with enrichments less than $\sim$ 15% are considered low-enriched. Note that low enrichments are achievable only at short residence times, and the optimum C/HM from an ore conservation standpoint is 600 - 800. The neutron losses are itemized as fractional total absorption rate by nuclide in Table 4-9.

The fuel costs for these cases are shown in Table 4-10. Note that a low cost leads to the selection of a high C/HM and a longer residence time.

The effect of putting thorium into the feed stream - at the expense of a higher enrichment - is indicated by the results in Table 4-11 upon examination of cases 45004 to 45008. In these cases, the heavy metal content is fixed and thorium is gradually substituted for uranium. Note that case 45009 gives essentially the same results of case BXO in Table 4-1. This is expected since the calculations are one-dimensional

Table 4-8. One-Dimensional Results for Single Pebble, Low to Medium Enriched Uranium Feed, Power Density = 5 W_{th}/cc, 1200 MW_e, Core Height = 500 cm, No Axial Blanket, Radial Buckling = 3.2-5.

	300A	300B	300C	300D	450A	450B	450C	450D	600A	600B	600C	600D	850A	850B	850C	850D
Nominal C/HM (atom ratio)	300	300	300	300	450	450	450	450	600	600	600	600	850	850	850	850
Residence Time at Full Power (yrs)	1.0	2.0	3.0	4.0	1.0	2.0	3.0	4.0	1.0	2.0	3.0	4.0	1.0	2.0	3.0	4.0
Feed Enrichment	.102	.141	.175	.206	.100	.144	.184	.222	.094	.142	.188	.233	.108	.170	.230	.287
Conversion Ratio	.624	.586	.554	.526	.593	.563	.533	.506	.552	.527	.500	.473	.491	.463	.437	.411
Fissile Inventory (kg)	2925	3925	4755	5491	1794	2428	2988	3516	1113	1481	1839	2202	765	1008	1265	1507
Peak Power Density in Pebble (watts/cc)	13.76	14.51	15.29	15.92	13.90	14.68	15.59	16.25	14.19	15.46	16.53	17.24	14.79	17.02	18.58	20.08
Fraction Loss Due to:																
Leakage	.0888	.0876	.0880	.0887	.1014	.0985	.0981	.0986	.1150	.1110	.1104	.1109	.1344	.1303	.1298	.1300
Fission Product Absorption	.0388	.0465	.0526	.0579	.0467	.0570	.0648	.0712	.0553	.0693	.0794	.0871	.0651	.0838	.0962	.1053
Burnup (MW_{th}D/kg/HM)	34	65	94	121	50	96	137	174	68	128	182	229	95	176	245	302
U^{235} Atom Density in Feed Pebble (atoms/bn-cm)	2.28-5	3.31-5	4.28-5	5.23-5	1.51-5	2.20-5	3.09-5	3.91-5	1.07-5	1.69-5	2.38-5	3.12-5	8.72-6	1.48-5	2.16-5	2.91-5
Feed Rates (kg/D)																
U^{235}	8.9366	6.4741	5.5752	5.1129	5.9252	4.4922	4.0255	3.8228	4.1752	3.3133	3.0997	3.0506	3.4111	2.8912	2.8206	2.8469
U^{238}	78.7272	39.3636	26.2424	19.6818	53.5282	26.7641	17.8[illegible]	[illegible].3820	40.1362	20.0681	13.3787	10.0341	28.3014	14.1507	9.4338	7.0754
Discharge Rates (kg/D)																
U^{235}	5.9976	3.6149	2.7150	2.2249	3.2471	1.9018	1.4235	1.1757	1.6739	.8953	.6512	.5371	.9260	.4413	.3068	.2488
U^{236}	.6014	.6060	.6142	.6220	.5051	.4906	.5037	.5119	.4390	.4253	.4273	.4355	.4169	.4056	.4110	.4200
U^{238}	76.3204	37.1307	24.1415	17.6915	51.3650	24.7550	15.9539	11.5963	39.2156	18.2874	11.7093	8.4605	26.6749	12.6582	8.0472	5.7774
Pu (fissile)	1.3546	1.0797	.9216	.8107	.9663	.7250	.5956	.5098	.6271	.4197	.3227	.2654	.3695	.2103	.1482	.0795
Pu (nonfissile)	.2504	.2368	.2212	.2071	.2313	.2049	.1844	.1678	.2147	.1800	.1565	.1387	.1743	.1397	.1179	.1022

Table 4-9. Fractional Neutron Loss Rates for Single Pebble, One-Dimensional, Uranium Feed Cases

Case	300A	300B	300C	300D	450A	450B	450C	450D	600A	600B	600C	600D	850A	850B	850C	850D
Actinides																
U-235	.37170	.35980	.35915	.36226	.33645	.32396	.32494	.33047	.31264	.30116	.30488	.31321	.31016	.30540	.31384	.32498
U-236	.00334	.00655	.00974	.01289	.00325	.00632	.00944	.01262	.00319	.00613	.00919	.01237	.00337	.00652	.00980	.01317
U-238	.30052	.27736	.26037	.24635	.26826	.24794	.23269	.21985	.23688	.21867	.20481	.19308	.20016	.18316	.17018	.15942
Np-237	.00053	.00045	.00041	.00037	.00057	.00048	.00043	.00039	.00060	.00050	.00044	.00040	.00061	.00051	.00045	.00040
Pu-239	.14874	.16263	.16485	.16346	.16955	.17840	.17690	.17253	.17773	.18125	.17632	.16959	.16747	.16497	.15725	.14923
Pu-240	.02870	.03718	.04066	.04220	.04123	.04971	.05220	.05261	.04853	.05601	.05710	.05627	.05132	.05562	.05468	.05265
Pu-241	.00827	.01403	.01743	.01955	.01729	.02620	.03036	.03233	.02765	.03862	.04228	.04316	.03619	.04546	.04684	.04603
Pu-242	.00013	.00041	.00070	.00097	.00034	.00095	.00151	.00197	.00064	.00166	.00248	.00307	.00098	.00225	.00312	.00368
Am-243	.00001	.00004	.00009	.00014	.00004	.00014	.00028	.00041	.00008	.00033	.00060	.00084	.00018	.00062	.00105	.00138
Total	.86194	.85845	.85340	.84819	.83698	.83410	.82875	.82318	.80794	.80433	.79810	.79199	.77044	.76451	.75721	.75094
Fission Products																
Xe-135	.01662	.01427	.01271	.01155	.01920	.01728	.01589	.01478	.02139	.02017	.01920	.01834	.02285	.02224	.02167	.02107
Others	.02216	.03220	.03990	.04631	.02751	.03973	.04895	.05644	.03395	.04918	.06021	.06881	.04228	.06152	.07458	.08423
Total	.03878	.04647	.05261	.05786	.04671	.05701	.06484	.07122	.05534	.06935	.07941	.08715	.06513	.08376	.09625	.10530
Other Losses																
C	.00834	.00595	.00483	.00416	.01271	.00888	.00707	.00596	.01928	.01360	.01072	.00889	.02759	.01970	.01542	.01266
He	.00003	.00002	.00001	.00001	.00004	.00003	.00002	.00002	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
Si	.00201	.00141	.00112	.00096	.00207	.00143	.00112	.00094	.00238	.00167	.00130	.00107	.00242	.00172	.00133	.00109
O	.00008	.00008	.00008	.00008	.00006	.00006	.00006	.00006	.0000[illegible]	.00004	.00004	.00003	.00003	.00003	.00003	.00003
Leakage	.08882	.08762	.08795	.08874	.10143	.09849	.09814	.09862	.11502	.11101	.11043	.11086	.13439	.13028	.12976	.12998
Total	.09928	.09508	.09399	.09395	.11631	.10889	.10641	.10560	.13672	.12632	.12249	.12086	.16443	.15173	.14654	.14376
Total	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 4-10. Fuel Costs for LEU/MEU Single Pebble Feed Cases
(1200 MW_e, 0.75 Load Factor, 30 Year Lifetime)

Linear Interest Rate = 0.1, Discount Factor = 0.07

CASE	300A	300B	300C	300D	450A	450B	450D	600A	600B	600C	600D	850A	850B	850C
THROWAWAY BOTH														
COST OF FUEL	10.3196	7.7713	6.9104	6.5206	8.1415	6.0747	5.6729	5.9451	4.8846	4.6796	4.6728	4.9991	4.4198	4.3958
FABRICATION	1.4291	0.7677	0.5473	0.4375	1.1822	0.5361	0.3760	1.1626	0.6351	0.4611	0.3758	1.2407	0.6891	0.5090
REPROC/WASTE	0.6032	0.3018	0.2011	0.1508	0.3589	0.1424	0.0884	0.2632	0.1290	0.0846	0.0627	0.1829	0.0887	0.0578
INDIRECTCOST	1.9974	2.4288	2.9246	3.4424	1.5690	2.1775	2.8914	1.1570	1.4480	1.8262	2.2436	0.9808	1.2651	1.6308
TOTAL COST	14.3492	11.2696	10.5834	10.5513	11.2516	8.9306	9.0286	8.5278	7.0967	7.0516	7.3549	7.4035	6.4627	6.5934
REPROCESS BOTH														
COST OF FUEL	4.5890	4.4172	4.4343	4.5099	4.3804	4.2676	4.4019	4.0368	3.9416	4.0410	4.1813	3.9978	4.0327	4.1873
FABRICATION	1.4291	0.7677	0.5473	0.4375	1.1822	0.5361	0.3760	1.1626	0.6351	0.4611	0.3758	1.2407	0.6891	0.5090
REPROC/WASTE	2.4793	1.2404	0.8265	0.6197	1.9636	0.7789	0.4836	1.7941	0.8794	0.5769	0.4273	1.6618	0.8062	0.5255
INDIRECTCOST	2.6096	2.9774	3.4697	4.0002	1.9105	2.4825	3.2081	1.2067	1.4860	1.8659	2.2871	0.8921	1.1835	1.5502
TOTAL COST	11.1070	9.4027	9.2779	9.5673	9.4366	8.0651	8.4695	8.2002	6.9426	6.9448	7.2714	7.7923	6.7116	6.7719
REPROCESS FERTILE														
COST OF FUEL	10.3196	7.7713	6.9104	6.5206	8.1415	6.0747	5.6729	5.9451	4.8846	4.6796	4.6728	4.9991	4.4198	4.3958
FABRICATION	1.4291	0.7677	0.5473	0.4375	1.1822	0.5361	0.3760	1.1626	0.6351	0.4611	0.3758	1.2407	0.6891	0.5090
REPROC/WASTE	0.6032	0.3018	0.2011	0.1508	0.3589	0.1424	0.0884	0.2632	0.1290	0.0846	0.0627	0.1829	0.0887	0.0578
INDIRECTCOST	1.9974	2.4288	2.9246	3.4424	1.5690	2.1775	2.8914	1.1570	1.4480	1.8262	2.2436	0.9808	1.2651	1.6308
TOTAL COST	14.3492	11.2696	10.5834	10.5513	11.2516	8.9306	9.0286	8.5278	7.0967	7.0516	7.3549	7.4035	6.4627	6.5934

Linear Interest Rate = 0.05, Discount Factor = 0.035

CASE	300A	300B	300C	300D	450A	450B	450D	600A	600B	600C	600D	850A	850B	850C
THROWAWAY BOTH														
COST OF FUEL	10.3196	7.7713	6.9104	6.5206	8.1415	6.0747	5.6729	5.9451	4.8846	4.6796	4.6728	4.9991	4.4198	4.3958
FABRICATION	1.4291	0.7677	0.5473	0.4375	1.1822	0.5361	0.3760	1.1626	0.6351	0.4611	0.3758	1.2407	0.6891	0.5090
REPROC/WASTE	0.6032	0.3018	0.2011	0.1508	0.3589	0.1424	0.0884	0.2632	0.1290	0.0846	0.0627	0.1829	0.0887	0.0578
INDIRECTCOST	0.9541	1.1556	1.3911	1.6386	0.7511	1.0390	1.3812	0.5555	0.6944	0.8768	1.0788	0.4727	0.6102	0.7881
TOTAL COST	13.3060	9.9964	9.0499	8.7475	10.4336	7.7921	7.5185	7.9263	6.3431	6.1021	6.1901	6.8954	5.8078	5.7508
REPROCESS BOTH														
COST OF FUEL	4.5890	4.4172	4.4343	4.5099	4.3804	4.2676	4.4019	4.0368	3.9416	4.0410	4.1813	3.9978	4.0327	4.1873
FABRICATION	1.4291	0.7677	0.5473	0.4375	1.1822	0.5361	0.3760	1.1626	0.6351	0.4611	0.3758	1.2407	0.6891	0.5090
REPROC/WASTE	2.4793	1.2404	0.8265	0.6197	1.9636	0.7789	0.4836	1.7941	0.8794	0.5769	0.4273	1.6618	0.8062	0.5255
INDIRECTCOST	1.2603	1.4299	1.6637	1.9175	0.9218	1.1915	1.5396	0.5803	0.7136	0.8967	1.1005	0.4283	0.5694	0.7478
TOTAL COST	9.7577	7.8552	7.4718	7.4846	8.4480	6.7741	6.8010	7.5738	6.1697	5.9756	6.0848	7.3286	6.0975	5.9695
REPROCESS FERTILE														
COST OF FUEL	10.3196	7.7713	6.9104	6.5206	8.1415	6.0747	5.6729	5.9451	4.8846	4.6796	4.6728	4.9991	4.4198	4.3958
FABRICATION	1.4291	0.7677	0.5473	0.4375	1.1822	0.5361	0.3760	1.1626	0.6351	0.4611	0.3758	1.2407	0.6891	0.5090
REPROC/WASTE	0.6032	0.3018	0.2011	0.1508	0.3589	0.1424	0.0884	0.2632	0.1290	0.0846	0.0627	0.1829	0.0887	0.0578
INDIRECTCOST	0.9541	1.1556	1.3911	1.6386	0.7511	1.0390	1.3812	0.5555	0.6944	0.8768	1.0788	0.4727	0.6102	0.7881
TOTAL COST	13.3060	9.9964	9.0499	8.7475	10.4336	7.7921	7.5185	7.9263	6.3431	6.1021	6.1901	6.8954	5.8078	5.7508

Table 4-11. One-Dimensional Results for Single Pebble Type, C/HM = 450, Full Power Residence Time = 2.5 Years, 1200 MW_e, No Axial Blanket, Core Height = 500 cm, Average Power Density = 5 W_{th}/cc

	45001[a]	45002[a]	45003[a]	45004	45005	45006	45007	45008	45009
Radial Buckling	3.2-5	3.2-5	3.2-5	3.2-5	3.2-5	3.2-5	3.2-5	3.2-5	7.0-6
Feed Enrichment	.155	.155	.148	.143	.151	.164	.187	.226	.206
Conversion Ratio	.548	.549	.547	.574	.566	.556	.542	.524	.558
Fissile Inventory (kg)	2465	2470	2249	2300	1987	1724	1514	1356	1141
Peak Power in Pebble	15.33	15.33	15.51	15.83	15.89	16.03	16.30	16.73	16.92
Leakage Loss	.0989	.0989	.1000	.0899	.0933	.0975	.1029	.1096	.0844
Fission Product Loss	.0629	.0629	.0648	.0620	.0666	.0719	.0779	.0843	.0906
Burnup (MW_{th}D/kgHM)	118	118	119	116	118	119	120	121	123
Feed Rates (kg/D)									
U-235	3.9364	3.9417	3.7094	3.7026	3.3799	3.1184	2.9284	2.8112	2.5014
U-238	21.4113	21.4113	21.4113	22.2195	19.0657	15.9119	12.7628	9.6121	9.6121
Th-232	0.0	0.0	0.0	0.0	3.0712	6.1409	9.2122	12.2819	12.2819
Discharge Rates (kg/D)									
Th-232	0.0	0.0	0.0	0.0	2.9028	5.7830	8.6425	11.4737	11.4127
Pa-233	0.0	0.0	0.0	0.0	.0009	.0018	.0028	.0038	.0040
U-233	0.0	0.0	0.0	0.0	.0927	.1794	.2567	.3229	.3083
U-234	0.0	0.0	0.0	0.0	.0105	.0240	.0411	.0624	.0709
U-235	1.4042	1.4086	1.2206	1.2708	.9816	.7372	.5420	.3946	.2582
U-236	.4773	.4777	.4594	.4477	.4289	.4141	.4047	.4012	.3639
U-238	19.4725	19.4735	19.4869	20.1574	17.2345	14.3310	11.4532	8.5956	8.5521
Pu (fissile)	.6034	.6044	.5575	.6144	.4663	.3333	.2224	.1368	.1166
Pu (nonfissile)	.2040	.2024	.2113	.2586	.2171	.1754	.1356	.0987	.0976
Averaged Pebble Atom Densities (atoms)/bn-cm									
U-235	2.5155-5	2.5189-5	2.3704-5	2.3661-5	2.1598-5	1.9928-5	1.8714-5	1.7964-5	1.5985-5
U-238	1.3510-4	1.3510-4	1.3510-4	1.4020-4	1.2030-4	1.0040-4	8.0530-5	6.0650-5	6.0650-5
Th-232	0	0	0	0	1.9880-5	3.9750-5	5.9630-5	7.9500-5	7.9500-5
C	6.6080-2	6.6080-2	6.6080-2	6.9980-2	6.9980-2	6.9980-2	6.9980-2	6.9980-2	6.9980-2

[a] Identical cases with the exception of the cross section library used in the calculation.

and unblanketed and the only effect of separate feed streams is the difference in peak power density. Cases 45001 —45003 are identical except for the use of different cross section sets. Case 45004 has a higher heavy metal loading than does 45003.

Note on One-Dimensional LEU Calculations

The one-dimensional LEU calculations cover a wide range of residence times and carbon to heavy metal ratios. These calculations are geared for a scoping-type evaluation to determine trends over these important parameters. More detailed calculations are performed in two-dimensions over a limited range of feasible fuel designs and residence times as indicated by the 1-D results. Thus, the 1-D results are qualified: uncertainty exists in the radial buckling chosen to approximate the effects of radial leakage, and the choice of a single set of cross-sections limits the availability to account for burnup-dependent spectrum effects caused by the depletion of U^{235} and the buildup of the plutonium isotopes. This limitation is much more severe for the LEU single oxide cases than the MEU and HEU mixed oxide cases.

LEU Feed Two-Dimensional Cases

The low-enriched uranium feed cases are represented by case title in the following summary:

Summary of Two-Dimensional LEU Cases

Case	Average Pebble Residence Time, Full Power Yrs	Radial Reflector Graphite Density (gm/cc)	Radial Reflector Thickness (cm)	Number of Enrichment Zones
B21	3.0	1.0	36.0	1
TD450	2.0	1.0	100.0	1
TD451	2.0	1.6	100.0	1
TD452	2.0	1.6	100.0	2
TD600	2.0	1.C	100.0	1
TD601	2.0	1.6	100.0	1
TD602	2.0	1.6	100.0	2

The results of the LEU 2-D cases are listed in Table 4-12. Note that increasing the graphite density decreases the fissile feed rate approximately five percent. Cases TD452 and TD602 have two feed-enrichment zones. With two zones, the power density is fairly flat across the core. The results indicate that the fissile feed rate is less than that predicted in the 1-D cases, but there is still a large decrease in the fissile feed requirement at a C/HM of 575 compared to C/HM of 435 or 276. Case TD602 is representative of the preferred LEU fuel cycle.

A detailed account of neutron losses is listed for cases TD452 and TD602 in Table 4-13.

Fuel cycle costs for the LEU two-dimensional cases are given in Table 4-14. As was the case for the MEU low technology cases, the LEU cases have a single pebble type and in Table 4-14 "Both" will refer only to the feed pebble.

Summary of Ore Requirements and Fuel Cycle Costs for LEU and MEU Two-Dimensional Cases

The ore requirements and throwaway fuel cycle costs for the LEU and MEU two-dimensional cases are shown in Table 4-15. Consumption for a throwaway cycle refers to fissile feed required for the reactor after the initial loading. Commitment refers to consumption, initial loading, and fissile inventory of fabricated fuel committed to the reactor at any given time.

Comparing cases TDRLC, TDRRB, TDRHB, and TD602 will indicate the relative ore and cost requirements for the representative MEU technology levels and the LEU feed. Compared to the reference MEU technology, low technology MEU feed will result in a six percent increase in U_3O_8 ore at an increase in cost of eight percent; a high technology MEU will decrease the ore required by nine percent while reducing the cost by nine percent; a LEU feed cycle would increase the U_3O_8 requirement by twelve percent at an increase in cost of nine percent.

Table 4-12. Two-Dimensional Results for LEU Feed (Core Radius, Fueled = 618.04 cm, Core Height = 500 cm, No Radial Blanket, Power Density = 5 W_{th}/cc, Single Pebble Type, 1200 MW_e)

Case	821	TD450	TD451	TD452	TD600	TD601	TD602
Radial Reflector Thickness (cm)	36.0	100.0	100.0	100.0	100.0	100.0	100.0
C/HM (atom ratio)	276	432	433	568	568	572	575
Residence Time, Full Power (yrs)[a]	3.0	2.0	2.0	2.0	2.0	2.0	2.0
Fissile Feed Enrichment	.168	.118	.113	.113[b]	.127	.122	.123[c]
Fissile Inventory (Kgm)	4494	1758	1678	1686	1200	1118	1128
Peak Power in Pebble (Kw/pebble)	2.47	2.12	2.04	1.92	2.24	2.22	2.06
Leakage Loss, fractional	.07895	.08169	.07571	.07645	.09399	.08665	.087[illegible]
Fission Product Loss, fractional	.05560	.06325	.06397	.06385	.07500	.07634	.07607
Conversion Ratio	.567	.584	.588	.586	.534	.545	.543
Average Burnup (MW_{th}-D/KgHM)	95	99	99	99	131	131	131
Burnup by Feed Paths							
1	115	106	103	90	137	138	130
2	108	105	102	99	138	137	132
3	99	102	100	99	136	134	132
4	83	93	95	101	126	126	134
5	65	84	91	97	113	117	127
6	57	87	97	105	111	117	129
Feed Rates (Kg/full power day)							
U^{235}	5.2852	3.5787	3.4160	3.4233	2.9278	2.7947	2.8065
U^{238}	26.2424	26.7641	26.7641	26.7641	20.0681	20.0681	20.0681
Discharge Rates (kg/full power day)							
U^{235}	2.5188	1.1679	1.0876	1.0899	.6181	.5435	.5475
U^{236}	.5824	.4254	.4174	.4181	.3914	.3781	.3797
U^{238}	24.1169	24.7186	24.7144	24.7205	18.2866	18.2589	18.2657
Pu(f)	.8871	.5913	.5772	.5756	.4387	.3304	.3301
Pu(n)	.2186	.2253	.2239	.2234	.1836	.1838	.1834

[a]There are six feed paths bounded by r(cm) = 276.40, 390.98, 478.73, 552.79, 586.32 and 618.04. The relative path flow rates are 1.0, 1.09, 1.18, 1.26, 1.31 and 1.40.
[b]Feed enrichments: inner three paths = 0.109, outer three paths = 0.121.
[c]Feed enrichments: inner three paths = 0.117, outer three paths = 0.133.

Table 4-13. Detailed Account of Neutron Losses for Selected Two-Dimensional LEU Feed Cases

Case	TD452	TD602
Actinide		
Th^{232}	—	—
Pa^{233}	—	—
U^{233}	—	—
U^{234}	—	—
U^{235}	.29043	.28065
U^{236}	.00558	.00572
U^{238}	.25987	.22061
Np^{239}	.00058	.00056
Pu^{239}	.19732	.19135
Pu^{240}	.05632	.06079
Pu^{241}	.03541	.04631
Pu^{242}	.00139	.00212
Am^{243}	.00023	.00047
Fission Product		
Kr	.00009	.00011
Kr^{83}	.00034	.00047
Rh^{103}	.00476	.00629
Rh^{105}	.00010	.00015
Ag^{109}	.00074	.00089
Xe^{131}	.00327	.00385
Xe^{133}	.00011	.00017
Cs^{133}	.00285	.00330
Cs^{134}	.00018	.00033
Xe^{135}	.01935	.02135
Cs^{135}	.00010	.00009
Nd^{143}	.00492	.00707
Nd^{145}	.00181	.00222
Pm^{147}	.00377	.00424
Pm^{148}	.00060	.00071
Pm^{148m}	.00146	.00174
Sm^{149}	.00652	.00699
Sm^{150}	.00084	.00113
Sm^{151}	.00267	.00306
Sm^{152}	.00178	.00217
Eu^{153}	.00092	.00123
Eu^{154}	.00044	.00075
Eu^{155}	.00066	.00096
SSFP	.00389	.00481
NSFP	.00172	.00204
Other		
C	.01955	.02562
He	.00004	.00006
Si	.00193	.00210
O	.00006	.00004
Leakage	.07645	.08750
Total	1.0	1.0

Table 4-14. Fuel Costs for LEU Two-Dimensional Cases
(30-year lifetime, 0.75 load factor, 1200 MW_e)

Linear Interest Rate = 0.1, Discount Factor = 0.07

CASE	B21	TD450	TD451	TD452	TD600	TD601	TD602
THROWAWAY BOTH							
COST OF FUEL	8.1937	5.4250	5.1627	5.1728	4.4611	4.2466	4.2670
FABRICATION	0.4708	0.6107	0.6086	0.6109	0.5895	0.5908	0.5947
REPROC/WASTE	0.1819	0.1743	0.1736	0.1736	0.1273	0.1265	0.1266
INDIRECTCOST	3.4923	1.6365	1.5638	1.5686	1.3041	1.2410	1.2889
TOTAL COST	12.3387	7.8464	7.5086	7.5259	6.4820	6.2050	6.2372
REPROCESS BOTH							
COST OF FUEL	4.8042	3.9621	3.8148	3.8220	3.7622	3.6503	3.6651
FABRICATION	0.4708	0.6107	0.6086	0.6109	0.5895	0.5908	0.5947
REPROC/WASTE	0.7081	0.9250	0.9229	0.9263	0.8318	0.8311	0.8350
INDIRECTCOST	4.3422	1.7939	1.6947	1.6994	1.2964	1.2094	1.2177
TOTAL COST	10.3253	7.2917	7.0410	7.0587	6.4799	6.2817	6.3125

Linear Interest Rate = 0.05, Discount Factor = 0.035

CASE	B21	TD450	TD451	TD452	TD600	TD601	TD602
THROWAWAY BOTH							
COST OF FUEL	8.1937	5.4250	5.1627	5.1728	4.4611	4.2466	4.2670
FABRICATION	0.4708	0.6107	0.6086	0.6109	0.5895	0.5908	0.5947
REPROC/WASTE	0.1819	0.1743	0.1736	0.1736	0.1273	0.1265	0.1266
INDIRECTCOST	1.6586	0.7822	0.7473	0.7496	0.6262	0.5961	0.5998
TOTAL COST	10.5050	6.9921	6.6922	6.7070	5.8040	5.5601	5.5881
REPROCESS BOTH							
COST OF FUEL	4.8042	3.9621	3.8148	3.8220	3.7622	3.6503	3.6651
FABRICATION	0.4708	0.6107	0.6086	0.6109	0.5895	0.5908	0.5947
REPROC/WASTE	0.7081	0.9250	0.9229	0.9263	0.8318	0.8311	0.8350
INDIRECTCOST	2.0835	0.8609	0.8128	0.8150	0.6223	0.5803	0.5843
TOTAL COST	8.0666	6.3587	6.1591	6.1743	5.8058	5.6526	5.6790

Table 4-15. Ore Requirements and Feed Costs Summary for LEU and MEU Two-Dimensional Cases

Case	Fissile Inventory (kgm/Installed MW_e) Plant	System	External Fissile Feed (kgm/MW_e-Yr)	Fissile Commitment (kgm/Installed MW_e)	Ore Requirement (kgm U_3O_8/Installed MW_e) Consumption	Commitment	Fuel Cost (mills/kWh) (Throwaway) Low Indirect	Reference
MEU								
TDCLC1	1.093	1.436	0.915	22.017	[illegible]	5,019	[illegible]	[illegible]
TDCLC2	1.027	1.335	0.823	19.562	4,225	[illegible]	[illegible]	[illegible]
TECLC	1.049	1.354	0.813	19.650	[illegible]	[illegible]	[illegible]	[illegible]
TDRLA	1.021	1.324	0.808	19.500	4,156	4,453	[illegible]	[illegible]
TDRLB	0.988	1.286	0.795	19.169	4,089	4,383	[illegible]	[illegible]
TDRLC	1.020	1.321	0.802	19.358	4,115	4,414	[illegible]	[illegible]
TDCRD	0.892	1.176	0.758	18.222	3,899	4,164	[illegible]	[illegible]
TECRD	0.926	1.212	0.764	18.411	3,928	4,204	[illegible]	[illegible]
TDRRA	0.886	1.163	0.739	17.791	3,804	4,070	[illegible]	[illegible]
TDRRB	0.913	1.197	0.758	18.246	3,893	4,167	[illegible]	[illegible]
TDCHC	1.073	1.372	0.799	19.356	4,114	[illegible]	[illegible]	[illegible]
TDCHD	0.854	1.120	0.710	17.089	3,644	3,989	[illegible]	[illegible]
TDRHA	0.838	1.086	0.661	15.954	3,401	3,640	[illegible]	[illegible]
TDRHB	0.843	1.101	0.687	16.564	3,531	[illegible]	[illegible]	[illegible]
LEU								
B21	3.745	4.348	1.608	40.519	9,246	9,240	[illegible]	[illegible]
TD450	1.465	1.873	1.089	26.365	5,656	[illegible]	[illegible]	[illegible]
TD451	1.398	1.788	1.039	25.171	5,301	5,726	[illegible]	[illegible]
TD452	1.405	1.795	1.041	25.224	5,311	5,719	[illegible]	[illegible]
TD600	1.000	1.334	0.890	21.370	4,551	4,854	[illegible]	[illegible]
TD601	0.932	1.250	0.850	20.377	4,342	4,626	[illegible]	[illegible]
TD602	0.940	1.260	0.854	20.467	4,361	4,647	[illegible]	[illegible]

[illegible]

Reprocessing centers having a high level of security against access to highly-enriched fissile material would promote the possibility of medium enriched U^{233} feed to a number of "outside" reactors. However, more useful purposes of the U^{233} fuel would be as feed to converters and breeders as discussed in later sections.

The performance with medium-enriched U^{233} feed is summarized in Table 5-1, showing a better neutron utilization than the corresponding denatured U^{235} feed results. The results listed are from one-dimensional calculations; a low buckling is assumed to account for a large radial blanket. Fuel cost information is shown in Table 5-2.

Table 5-1. Results of One-Dimensional Calculations for Medium-Enriched U^{233} Feed

		[illegible]	[illegible]
[illegible]			
[illegible]		[illegible]	[illegible]
[illegible]		[illegible]	[illegible]
[illegible]			
[illegible]		[illegible]	
[illegible]		[illegible]	[illegible]
[illegible]		[illegible]	
[illegible]		[illegible]	[illegible]
Average Core Power Density (watts/[illegible])		[illegible]	[illegible]
Peak Power Density in Primary Pebble (watts/[illegible])		4[illegible]	[illegible]
[illegible] Power Density in Fertile Pebble (watts/[illegible])		[illegible]	[illegible].62
[illegible]		[illegible]	.[illegible]4
Fission Product Absorption [illegible]		[illegible]	[illegible]
Average Burnup (MW_{th} D/[illegible])		[illegible]	[illegible]
Burnup in Primary Pebble (MW_{th} D/[illegible])		[illegible]	[illegible]4
Burnup in Fertile Pebble (MW_{th} D/[illegible])		[illegible]	9[illegible]
Mass Flows (kg/Day)			
Primary Feed	[illegible]	[illegible]	1.[illegible]
	[illegible]	0	0
	[illegible]	0	0
	[illegible]	0	0
	[illegible]	[illegible]4610	9.0587
Fertile Feed	Th[illegible]	[illegible].2542	1[illegible].2203
Primary Discharge	[illegible]	.0418	.0860
	[illegible]	.0918	.1032
	[illegible]	.0192	.0191
	[illegible]	.0077	.0051
	[illegible]	[illegible]	[illegible].4977
	Pu (fissile)	[illegible]	.0551
	Pu (nonfissile)	.0462	.0551
Fertile Discharge	Th[illegible]	7.601[illegible]	[illegible].4474
	[illegible]	.061[illegible]	.0040
	[illegible]	[illegible]	.2614
	[illegible]	.111[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]

BLANK PAGE

CASE	T1Y2A	T2Y2A

THROWAWAY BOTH

COST OF FUEL	3.4003	3.4437
FABRICATION	0.4353	0.5778
REPROC/WASTE	0.0899	0.1330
INDIRECTCOST	1.1923	1.0121
------------	-------	-------
TOTAL COST	5.1177	5.1666

REPROCESS BOTH

COST OF FUEL	2.9455	2.7221
FABRICATION	0.4353	0.5778
REPROC/WASTE	0.5580	0.8212
INDIRECTCOST	1.2390	1.0697
------------	-------	-------
TOTAL COST	5.1778	5.1907

REPROCESS FERTILE

COST OF FUEL	3.0337	2.8967
FABRICATION	0.4353	0.5778
REPROC/WASTE	0.2475	0.3693
INDIRECTCOST	1.3003	1.1326
------------	-------	-------
TOTAL COST	5.0167	4.9764

CASE	T1Y2A	T2Y2A

THROWAWAY BOTH

COST OF FUEL	3.4003	3.4437
FABRICATION	0.4353	0.5778
REPROC/WASTE	0.0899	0.1330
INDIRECTCOST	0.5722	0.4833
------------	-------	-------
TOTAL COST	4.4976	4.6378

REPROCESS BOTH

COST OF FUEL	2.9455	2.7221
FABRICATION	0.4353	0.5778
REPROC/WASTE	0.5580	0.8212
INDIRECTCOST	0.5955	0.5121
------------	-------	-------
TOTAL COST	4.5343	4.6331

REPROCESS FERTILE

COST OF FUEL	3.0337	2.8967
FABRICATION	0.4353	0.5778
REPROC/WASTE	0.2475	0.3693
INDIRECTCOST	0.6262	0.5435
------------	-------	-------
TOTAL COST	4.3426	4.3873

SECTION 6: CONVERTER PERFORMANCE WITH U^{233} FEED

In the event that U^{233} fuel became available, then operation as a converter with fuel recycle could be the economic optimum in a mixed reactor system. The fast breeder reactors with high capital costs could produce fuel for thermal converter reactors having lower capital costs.

Data for reactor histories generated with the point reactor model are shown in Table 6-1. These calculations are idealized in that pure U^{233} feed material was assumed to be available, no recycle loss was considered (although the loss was taken in the fuel cost calculation), and recycle was delayed 1/3 the real core residence time. Relatively long residence time is needed to reduce the fuel cost while this results in high fissile consumption. Relatively large blankets would be required to reduce the core neutron leakage to the lower valves used.

One-dimensional parameter studies with the steady state, continuous fueling model produced the results shown in Table 6-2 for a core with a large radial blanket. Two-dimensional results are shown in Table 6-3.

Table 6-1. Point Model Results for U^{233} Feed
([illegible] MW_e plant at [illegible] load factor, three subzone model, 30-year life with delayed recycle)

Residence Time (yrs at full power)	Exposure (MW_t d/kg HM)	Feed ([illegible])	Fissile Loading (kg)	Conversion Ratio	Fissile Consumption (kg/MW_e yr)	Fuel Cost (mill/kWe hr) Cycle	Fuel Cost (mill/kWe hr) 30 year
[illegible] W_{th}/cc, C/HM [illegible], [illegible] fraction core neutron leakage							
[illegible]	[illegible]	.4946	1,119	.866	.1461	7.63	7.801
1.5	[illegible]	.5512	1,154	.846	.1681	5.93	6.110
[illegible]	[illegible]	[illegible]	1,177	.829	.1872	[illegible]	5.340
3	[illegible]	.6821	1,229	.797	.2218	4.63	4.719
4	[illegible]	.7539	1,283	.768	.2538	4.59	4.563
5	120.3	[illegible]	1,329	.740	.2845	4.77	4.588
5 W_{th}/cc, C/HM 250, 0.025 fraction core neutron leakage							
1	24.8	.3796	1,060	.907	.1018	7.19	7.369
1.5	37.3	.4374	1,091	.886	.1245	5.51	5.696
2	49.6	.4854	1,111	.868	.1441	4.76	4.931
3	73.6	.5714	1,157	.836	.1794	4.21	4.313
4	97.3	.6556	1,202	.806	.2125	4.17	4.157
5	120.6	.7322	1,243	.776	.2448	4.35	4.184
5 W_{th}/cc, C/HM 400, 0.075 fraction core neutron leakage							
1	36.9	.7534	809	.753	.2682	8.03	8.175
2	72.4	.8767	862	.708	.3164	5.86	5.947
3	106.7	.9797	914	.669	.3607	5.51	5.471
4	139.4	1.0742	970	.634	.3983	5.63	5.419
5	171.4	1.1551	1,023	.604	.4316	5.93	5.519
5 W_{th}/cc, C/HM 400, 0.0375 fraction core neutron leakage							
1	36.8	.6015	748	.808	.2090	7.47	7.627
1.5	54.9	.6717	773	.782	.2373	5.96	6.096
2	72.9	.7325	793	.759	.2623	5.33	5.433
3	107.5	.8432	834	.717	.3074	5.00	4.973
4	140.7	.9465	880	.680	.3491	[illegible]	4.941
5	172.4	1.0364	922	.646	.3862	[illegible]	[illegible]

Table 6-2. Results for U^{233} Feed

Case		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Core Height (cm)		500	500	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
C/Heavy Metal (nom. atomic)		175	175	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Cycle (primary/fertile)		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Residence Time (full power yrs)		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Conversion Ratio		.871	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Fissile Inventory (kgm)		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Peak Axial Power Density (kW_{th}/cc)		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Core Leakage Fraction		[illegible]	.0546	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Fission Product Absorption Fraction		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Exposure (MW_{th}D/kgm HM)								
Average		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Primary/Fertile		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Mass Balances (kgm/D at full power)								
Primary Feed	Th^{232}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	U^{233}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	U^{234}							
	U^{235}							
Fertile Feed	Th^{232}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Pa^{233}							
	U^{233}							
	U^{234}							
	U^{235}							
	U^{236}							
Primary Discharge	Th^{232}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Pa^{233}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	U^{233}	[illegible]	.5447	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	U^{234}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	U^{235}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	U^{236}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Fertile Discharge	Th^{232}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Pa^{233}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	U^{233}	.4174	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	U^{234}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	U^{235}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	U^{236}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[a] Holdup of the fertile pebble [illegible] days outside reactor before [illegible]

[b] Fertile pebble recycled to the top of the core instead of to the [illegible]

Table [illegible]-2. (Cont'd)

0102	0108	0103	0104	0105	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
500	500	500	500	500	500	[illegible]	[illegible]	[illegible]	[illegible]
250	250	250	250	250	250	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	2	3	4	[illegible]	4	[illegible]	[illegible]	[illegible]	[illegible]
.812	.832	.774	.744	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1.129	1.242	1.133	1.281	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9.81	9.15	[illegible]	14.6	17.5	24.4	24.5	[illegible]	[illegible]	[illegible]
.0546	.0456	.0616	.0694	.0758	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.0731	.0770	.0882	.1016	.1120	.1160	[illegible]	[illegible]	[illegible]	[illegible]
50.1	44.5	74.4	99.3	121.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
128/24.5	130/21.9	173/40.6	217/55.5	258/70.6	234/112	[illegible]	[illegible]	[illegible]	[illegible]
12.842	12.842	8.5613	6.4210	5.1366	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2.0264	2.0253	[illegible]	1.6116	1.5671	1.4889	[illegible]	[illegible]	[illegible]	[illegible]
	.6102								
	.0812								
45.000	45.000	30.000	22.500	18.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
12.199	12.735	7.9688	5.9214	4.6290	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.0046	.0048	.0016	.0007	[illegible]	.0007	[illegible]	[illegible]	[illegible]	[illegible]
.4169	.4614	.2333	.1597	.1202	.1645	[illegible]	[illegible]	[illegible]	[illegible]
.1791	.5159	.1415	.1169	[illegible]	.1144	[illegible]	[illegible]	[illegible]	[illegible]
.0367	.1465	.0349	.0325	.0299	.0310	[illegible]	[illegible]	[illegible]	[illegible]
.0072	.0458	.0106	.0134	.0153	.0118	[illegible]	[illegible]	[illegible]	[illegible]
42.773	42.913	27.918	20.541	16.179	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.0150	.0157	.0052	.0023	.0012	.0010	[illegible]	[illegible]	[illegible]	[illegible]
.8267	.8332	.5727	.4098	.3411	.2024	[illegible]	[illegible]	[illegible]	[illegible]
.1756	.1576	.1620	.1456	.1262	.0964	[illegible]	[illegible]	[illegible]	[illegible]
.0292	.0247	.0319	.0322	.0333	.0256	[illegible]	[illegible]	[illegible]	[illegible]
.0041	.0032	.0070	.0094	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 6-[illegible] Two Dimensional Results with [illegible] Feed
([illegible] W/cc, 600 cm height, 1,2[illegible] MW(e), 0.01[illegible] processing loss)

Case		[illegible]	SA21	[illegible]	[illegible]
C/HM		175	175	175	175
Cycle		[illegible]	[illegible]	[illegible]	[illegible]
Residence Time (full power yrs)		7.5	5.6	5.5	5.6
Axial Blanket (cm)		[illegible]	53.6	53.6	53.5
Radial Blanket (cm)		31.7	[illegible]	31.7	31.7
Conversion Ratio		[illegible]	.759	.779	.768
Fissile Inventory ([illegible]gm)		[illegible]	[illegible]	2,[illegible]	[illegible]
Power Density (W_{th}/cc)					
Core Peak		[illegible]	39.5	17.5	16.4
Primary Pebbles		29.4	40.4	44.8	43.8
Fertile Pebbles		10.4	17.1	15.4	14.9
Exposure (MW_{th}-D/kgm)					
Primary Pebbles		109.	199.	200.	200.
Fertile Pebbles		18.4	54.4	50.7	49.3
Average		44.6	97.3	96.[illegible]	95.8
Fission Product Absorption Fraction		.0655	.0988	.0953	.0941
Core Leakage Fraction		.0515	.0674	.0621	.0605
Mass Balance (kgm/D at full power)					
Primary Make-up Feed	Th^{232}	16.4725	7.4875	7.4875	7.4875
	U^{233}		1.6355	.9498	.9080
Recycle/Contaminated Feed	U^{233}	2.1997		.6444	.6763
	U^{234}	.5915		.2689	.3478
	U^{235}	.1782		.0810	.1274
	U^{236}	.0550		.0250	.0718
Fertile Feed	Th^{232}	47.737	21.699	21.699	21.699
Primary Discharge	Th^{232}	15.6900	6.7932	6.8156	6.8252
	Pa^{233}	.0047	.0006	.0007	.0007
	U^{233}	.6880	.2221	.2402	.2481
	U^{234}	.5398	.1352	.2232	.2514
	U^{235}	.1983	.0448	.0940	.1124
	U^{236}	.1001	.0151	.0641	.1075
Fertile Discharge	Th^{232}	45.751	19.820	19.904	19.936
	Pa^{233}	.0108	.0014	.0015	.0016
	U^{233}	.8575	.4301	.4442	.4494
	U^{234}	.1515	.1378	.1299	.1270
	U^{235}	.0267	.0374	.0353	.0345
	U^{236}	.0030	.0103	.0088	.0083

SECTION 07: BREEDER, NEAR BREEDER

The pebble bed reactor concept has the capability of producing more fuel than it burns. Unfortunately to effect such net fuel production requires large blankets which add cost and short residence time which leads to high fabrication and reprocessing costs. At a low C/HM needed for breeding and short residence time the total fissile inventory is high and the associated indirect fuel cost is a distinct disadvantage as is the demand on an external source to inventory the system. When lead and lag times sum to equal the real residence time in the reactor, the system inventory is twice that of the reactor, for example.

We have considered that the economic driving force causes operation at only near the breeding state. Perhaps the required conditions for producing enough excess fuel to make up for reprocessing and refabrication losses are of special interest.

Reference parameter studies were done at a nominal C/HM of 110. A lower ratio significantly increases the fissile inventory. Results of one-dimensional parameter studies are shown in Table 7-1.

Special consideration was given to feed of pebbles produced in a prebreeder (or perhaps a fast reactor blanket) without reprocessing. Calculations indicate that a sufficient build up of fissile content for primary pebble feed is unlikely. A very long exposure would be required causing high contamination and serious degrading of the breeder performance by neutron absorption. The pebbles could be used to reduce the fresh fertile feed and take advantage of a low fissile content.

Two-dimensional calculations were done with primary consideration given to in-core radial blanketing and power density flattening. The results are shown in Table 7-2. Primary calculations were done with pure U^{233} feed and as high a C/HM value as would permit breeding at a significant but short residence time. Note that reducing the blanketing or increasing the power density (reducing the fueled core size) reduce the breeding ratio. Results over a narrow range in C/HM are shown assuming that a 0.5 cm coating of graphite is required for the outer shell and that the kernel packing fraction can be increased to reduce the C/HM.

Table I-1. Results for the Breeder, Near Breeder with U^{233} Feed (One-Dimensional, 1,200 MWe, 5 Kw/cc)

Case	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Core Axial Blanket (cm)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Outer Axial Blanket (cm)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Cycle	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Breeding/Conversion Ratio	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Fissile Inventory (kg)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Power Density (kW/cc)						
Peak Axial	7.46	7.64	[illegible]	7.50	[illegible]	[illegible]
Pebble Peak (Primary/Fertile)	24.[illegible]	23.3/[illegible]	22.[illegible]	[illegible]	22.[illegible]	21.[illegible]
Core Leakage Fraction	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Fission Product Absorption Fraction	[illegible]	.0282	.0655	.0815	.0145	[illegible]
Exposure (MWD/T)						
Average	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Primary/Fertile	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Mass Balances (Kg/d at full power)						
Primary Feed Th	[illegible]	253.[illegible]	104.[illegible]	65.[illegible]	108.34	[illegible]
[illegible]	[illegible]	12.73	6.7167	4.6[illegible]	[illegible]	5.0[illegible]
$U^{[illegible]}$						
$U^{[illegible]}$						
Fertile Feed Th^{232}	478.97	[illegible].47	[illegible].74	[illegible].925	[illegible]	92.[illegible]
Primary Discharge Th^{232}	415.47	206.[illegible]	102.66	67.931	106.51	76.49[illegible]
Pa^{233}	.5268	.2197	.0671	.0311	.0661	.0397
U^{233}	23.89[illegible]	10.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
U^{234}	.4314	.4764	[illegible]	.1591	.1824	[illegible]
U^{235}	.0106	.0198	.0345	.0445	[illegible]	.04[illegible]
U^{236}	.0002	.0003	[illegible]	.0023	[illegible]	.0021
Fertile Discharge Th	476.97	237.50	137.[illegible]	77.345	[illegible]	[illegible]
Pa	.6149	.2454	.0764	.0354	[illegible]	.0352
U^{233}	1.2771	1.4928	1.4176	[illegible]	1.5004	1.3416
U^{234}	.0452	.0651	.0985	.1015	.0909	.1041
U^{235}	.0008	.0024	.0063	.0102	.0064	.0105
U^{236}			.0002	.0064	.0002	.0004

[a] Bottom blanket fresh fertile pebbles.
[b] Bottom blanket exposed fertile pebbles.
[c] Case treats 13 neutron groups instead of 4.
[d] Total U recycle, makeup U^{233}.
[e] Prebreeder fertile discharge reprocessed as feed (total feed shown), Prebreeder fertile discharge as fertile feed (0.162 fraction total U^{233} as fertile).

Table 7-1. (Cont'd.)

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.61	6.25
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.0247
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.0437	[illegible]
[illegible]	[illegible]	[illegible]	18.5	[illegible]	[illegible]	25.5	25.3	26.9
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	27.9/21.8	28.4/19.7	[illegible]
72.095	[illegible]	[illegible]	72.095	[illegible]	72.095	72.095	72.095	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.8646	[illegible]	[illegible]
							[illegible]	[illegible]
							[illegible]	[illegible]
							.0049	[illegible]
83.691	83.691	125.537	83.691	62.768	41.846	41.846	41.846	[illegible]
75.491	75.490	[illegible]	75.504	106.524	70.516	70.527	70.555	[illegible]
[illegible]	.0456	[illegible]	.0564	.1522	.0579	.0562	.0564	.0537
[illegible]	[illegible]	[illegible]	[illegible]	4.6257	2.8668	2.7747	3.0603	[illegible]
.3459	[illegible]	[illegible]	[illegible]	.3324	.2963	.2929	.6250	.4601
.0430	[illegible]	[illegible]	[illegible]	[illegible]	.0360	.0361	.1417	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.0017	.0018	.0153	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	60.776	39.868	39.872	39.916	33.635
.0359	[illegible]	.0285	[illegible]	.0147	.0066	.0065	.0066	[illegible]
1.3570	1.3467	1.5878	1.3873	1.2155	.9621	.9429	.9649	.8914
.1067	[illegible]	.0947	[illegible]	[illegible]	.1330	.1336	.1275	.1856
[illegible]	[illegible]	.0076	.0114	.0163	.0242	.0247	.0228	.0465
[illegible]	[illegible]	.0002	.0005	[illegible]	.0022	.0023	.0020	.0076

Table 7-2. Results of Two-Dimensional Calculations for a Breeder, Near Breeder

Case		BB010	BB015	BB205	BB210	BB215	BB415	BB410[c]	BB510
C/HM, atomic, nominal		110	110	110	110	110	110	[illegible]	110
Residence Time (yr)		1.0	1.5	.5	1.0	[illegible]	[illegible]	[illegible]	[illegible]
Cycle		[illegible]	1	1	1	1	[illegible]	1	[illegible]
Core Diameter, fueled (cm)		1,106	1,106	1,106	1,106	1,106	2,236	2,236	[illegible]
Radial Blanket (cm)		66.25	66.25	87.84	87.88	[illegible]	[illegible]	[illegible]	[illegible]
Breeding Ratio		.9925	.9793	1.0246	1.0037	.9898	1.0201	1.0241	1.0253
Fissile Inventory (kgm)		2,443	2,553	2,308	2,454	2,560	[illegible]	3,308	[illegible]
Power Density, Peak (W/cc)[a]									
Average		10.17	10.30	10.31	10.11	10.[illegible]	[illegible]	[illegible]	[illegible]
Primary Pebble		29.6	29.0	31.1	29.5	29.[illegible]	[illegible]	[illegible]	[illegible]
Fertile Pebble		4.12	6.16	[illegible]	4.12	6.15	[illegible]	[illegible]	[illegible]
Exposure (MW$_{th}$-D kgm HM)[b]									
Average		12.14	18.26	6.57	11.32	[illegible]	9.302	[illegible]	[illegible]
Primary Pebble		27.19	36.47	14.60	27.14	18.39	[illegible]	[illegible]	[illegible]
Fertile Pebbles		2.35	5.26	0.44	2.06	4.31	1.51	[illegible]	[illegible]
Leakage Loss Fraction		.01442	.02434	.01413	.01931	.01815	[illegible]	.00854	[illegible]
Fission Product Absorption Fraction		.03615	.04273	.03384	.03613	.04250	.03480	.03156	[illegible]
Mass Balance (kgm/D)									
Primary Feed	Th232	40.542	60.30	141.344	30.547	60.365	[illegible]	[illegible]	[illegible]
	U233	6.7454	4.6131	12.7476	6.1470	4.5553	[illegible]	8.2467	[illegible]
	U234								[illegible]
	U235								[illegible]
	U236								[illegible]
Fertile Feed	Th232	148.826	94.239	344.97	170.483	114.434	206.031	206.031	[illegible]
Primary Discharge	Th232	[illegible]	58.895	129.541	80.040	55.836	[illegible]	[illegible]	111.681
	Pa233	.0763	.0376	.0280	.0763	[illegible]	.0290	[illegible]	[illegible]
	U233	4.9375	3.0692	10.6137	4.9394	3.0114	[illegible]	6.4831	[illegible]
	U234	[illegible]	.3434	.4202	.3800	.3434	[illegible]	[illegible]	[illegible]
	U235	.0366	.0468	.0239	.0365	[illegible]	[illegible]	.1909	[illegible]
	U236	[illegible]	.0025	.0004	.0013	[illegible]	[illegible]	.0009	[illegible]
Fertile Discharge	Th232	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Pa233	.0649	.0257	[illegible]	.0615	[illegible]	.0663	.0663	[illegible]
	U233	1.6034	1.4249	1.7516	1.6433	[illegible]	1.7004	1.7198	1.6638
	U234	.0986	.1127	.0241	.0956	[illegible]	.0859	.0840	[illegible]
	U235	.0027	.0126	.0031	.0027	[illegible]	.0056	.0056	.0050
	U236	.0002	.0006		.0002	[illegible]	.0001	.0001	.0001
Net Fissile Gain (kgm/MW$_e$-yr)									
No reprocessing loss		-.0073	-.0234	.0286	.0046	[illegible]	.0234	.0274	[illegible]
0.015 fraction reprocessing loss		-.0380	-.0445	.0302	-.0203	[illegible]	[illegible]	[illegible]	[illegible]

[a] Power density could be flattened more in cases BB010 - BB215
[b] Blanket pebbles included
[c] High estimate of the thorium resonance integral
[d] Thirteen groups instead of four
[e] No axial blanket but reflected

Table 7-2. (Cont'd.)

[illegible]	88518	[illegible]	8040[d]	[illegible]	88615	88415	8C410	8H410	[illegible]	[illegible]	81410	81420	81120[e]
[illegible]	[illegible]	110	[illegible]	110	110	[illegible]	100	90	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	1.5	1.5	1.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	3	4	4	1	2	1	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	1.236	1.236	1.236	1.236	1.236	1.236	1.236	1.236	[illegible]	[illegible]	[illegible]	[illegible]	1.236
[illegible]	97.88	97.88	97.88	97.88	98.41	97.98	97.98	97.98	[illegible]	[illegible]	[illegible]	[illegible]	97.98
[illegible]	1.0207	1.0132	1.0175	[illegible]	.9930	1.0380	1.0181	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	3.211	3.294	3.38	[illegible]	3.171	2.329	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	8.04	[illegible]	[illegible]	[illegible]	8.20	8.33	8.41	[illegible]	[illegible]	[illegible]	[illegible]	8.91
[illegible]	[illegible]	24.4	26.5	[illegible]	22.8	23.4	23.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	4.34	[illegible]	4.63	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	4.38	4.03	9.06	[illegible]	[illegible]	13.71	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	22.38	22.06	22.02	[illegible]	31.6	31.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	1.32	1.27	1.27	[illegible]	3.69	[illegible]	2.69	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.01564	.01355	.01547	.01566	[illegible]	.02442	.02479	.01353	.01631	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.03142	[illegible]	.03093	.03090	[illegible]	.03714	.03852	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
113.184	113.184	113.184	113.184	[illegible]	75.4562	75.356	83.002	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	3.5469	3.6252	3.7426	3.7445	3.2265	3.4211	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	1.5440	1.8440	1.8691	.6815	.6797								
.2513	.3516	.5039	.5108	.0465	.0985								
.0243	.0464	.0760	.0770	.0066	.0066								
[illegible]	[illegible]	206.077	206.077	137.385	111.538	137.385	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	111.734	111.736	73.947	73.958	73.920	81.447	136.83	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	.0503	.0298	.0298	[illegible]	.0413	.0419	.0437	.0891	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6.6368	6.7319	6.8205	6.3353	4.0789	4.0618	3.7499	4.4900	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	1.7446	1.9542	1.9795	.9395	.9874	.3529	.3679	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	.4424	.6088	.6153	.2073	.2067	[illegible]	.0401	.0293	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.0463	.0744	.1113	.1114	[illegible]	.0225	.0014	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	204.041	204.044	135.305	119.551	135.234	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
.0636	[illegible]	.0628	.0629	.0278	.0273	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	1.6239	1.6201	1.5191	[illegible]	1.5402	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	.0744	.0732	.0735	.0929	.0931	[illegible]	.0953	.0749	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	.0045	.0046	.0285	.0064	[illegible]	.0086	.0044	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	.0001	-.0001	[illegible]	.0003	.0004	.0003	.0001	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	.0234	.0217	.0149	[illegible]	.0023	.0090	.0205	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	-.0177	-.0202	[illegible]	-.0148	-.0298	.0558	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Neutron accounting is shown in Table 7-3 for selected cases.

Fuel cost results are shown in Table 7-4. There is a significant increase in fuel cost associated with increasing the core size and operating at a reduced power density. Contamination from the higher uranium isotopes in the feed initially and upon recycle increases the fuel cost.

Reactor history calculations were made with the point model to account for the effect of recycle and build up of the higher actinides, and selected results are shown in Table 7-5 for the ideal situation of no recycle loss. Accounting for a recycle loss and fixing the recycle delay at 1.5 years yields the results in Table 7-6. Note that the external source passes through a minimum as the exposure is increased when a recycle loss is considered.

If we consider that the fissile material in the system, total inventory, at the end of the plant life is of secondary importance, then we seek that operation which minimizes the fissile feed to the reactor. (Presumably that material at the end of plant life would inventory another plant.) The results shown in Table 7-6 indicate that minimum external feed occurs at an exposure of about 24 MW_{th}-D/Kgm for the single pebble treatment and a C/HM of 110. To effect a conversion ratio above unity over the life requires a reactor design which has a very low effective neutron loss fraction which possibly would cost more than justified by the small reduction in external feed.

Steady state conditions without recycle were also calculated for a series of cases to allow comparison with results discussed earlier and with results treating two and three dimensions. These results are shown in Table 7-7.

Table 7-3. Neutron Accounting for Selected Breeder, Near Breeder Cases

Reference Case	B351C	B355C	BB415	BG410	BH410	BH415	BH420	BI410	BI420
Groups	4	13	4	4	4	4	4	4	4
C/HM	110	110	110	100	90	90	90	80	80
Residence Time (Yrs)	1.0	1.0	1.5	1.5	1.0	1.5	2.0	1.0	2.0
Actinide									
Th	.43651	.43585	.45960	.46539	.47820	.47131	.46531	.48616	.47192
Pa	.00927	.00931	.01104	.01048	.00974	.00974	.00959	.00792	.00884
U	.43038	.43049	.44952	.45087	.45237	.45216	.45181	.45309	.45369
U	.03767	.03777	.00766	.00720	.00464	.00675	.00872	.00410	.00812
U	.02385	.02387	.00135	.00113	.00045	.00092	.00151	.00053	.00118
U	.00078	.00078	.00001	.0001		.00001	.00001		.00001
Fission Products									
Xe	.01460	.01454	.01519	.01416	.01327	.01307	.01290	.01223	.01131
All other	.01633	.01636	.02333	.02171	.01503	.02009	.02464	.01336	.02238
Other									
C	.01075	.01077	.01199	.01013	.00877	.00860	.00838	.00711	.00675
He	.00004	.00004	.00005	.00004	.00004	.00004	.00003	.00003	.00003
Si	.00108	.00107	.00121	.00103	.00089	.00087	.00084	.00073	.00068
O	.00027	.00029	.00027	[illegible]	.00024	.00024	.00024	.00027	.00120
Leakage	.01647	.01805	.01875	.01753	.01637	.01628	.01602	.01467	.01499
Total	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 7-4. Fuel Costs for the Breeder, Near Breeder Cases
(30 year life, 0.85 plant load factor, 0.4 plant efficiency)

Schedule 1 Unit Costs, 0.10 Interest, 0.07 Discount

TYPE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]																
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INTERESTCOST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]																
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INTERESTCOST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]																
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INTERESTCOST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Schedule 1 Unit Costs, 0.05 Interest, 0.035 Discount

TYPE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]																
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INTERESTCOST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]																
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INTERESTCOST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]																
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INTERESTCOST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 7-6. Point Model Results for the Breeder, Near Breeder with U-233 Feed (1,200 MW_e plant at 0.85 load factor, 30 year life 5 %/yr, recycle delayed one cycle, three subzone model), nominal C/HM 110

Residence Time (yrs at Full power)	Exposure (MW_{th}-D/kgm HM)	U-233 Feed Gross (kg/yr)	U-233 Feed External (Kgs)	Breeding (Conversion) Ratio Initial*	Breeding (Conversion) Ratio Average	Breeding (Conversion) Ratio Final	Fuel Cost (mill/kWe hr) Cycle	Fuel Cost (mill/kWe hr) 30 yr
Core Neutron Leakage Fraction 0.010								
.5	6.4	11.827	2,951	1.073	1.035	1.023	16.6	16.63
.75	9.6	8.290	3,059	1.057	1.021	1.008	11.6	11.69
1.0	12.8	6.199	3,336	1.047	1.012	1.000	9.4	9.54
1.25	16.0	5.056	3,636	1.039	1.004	.994	7.9	[illegible]
1.5	19.1	4.356	3,895	1.033	.997	.985	7.0	7.24
2.	25	3.334	4,374	1.025	.986	.973	5.9	6.11
2.5	31.9	2.762	4,780	1.019	.975	.963	5.3	5.50
3.	38.2	2.346	5,165	1.014	.964	.953	4.9	5.11
Core Neutron Leakage Fraction 0.015								
.25	3.2	21.03	2,754	1.084	1.042	1.029	31.0	31.13
.50	6.4	11.85	2,864	1.063	1.023	1.010	16.7	16.80
.75	9.6	8.212	3,300	1.048	1.012	.999	11.9	12.06
1.0	12.8	6.300	3,695	1.038	1.003	.990	9.5	9.67
1.25	16.0	5.142	3,998	1.030	.995	.983	8.1	8.28
1.5	19.1	4.364	4,251	1.024	.988	.976	7.2	7.36
2.	25.5	3.397	4,735	1.016	.976	.964	6.0	6.25
Core Neutron Leakage Fraction 0.025								
.25	3.2	23.36	2,836	1.063	1.023	1.009	31.0	31.61
.50	6.4	12.37	3,679	1.043	.995	1.007	17.1	17.14
.75	9.6	8.479	4,081	1.029	.993	.981	12.3	12.33
1.0	12.8	6.509	4,423	1.019	.985	.972	9.8	9.95
1.25	15.9	5.319	4,728	1.012	.977	.965	8.4	8.54
1.5	19.1	4.519	4,970	1.006	.970	.958	7.4	7.61
2.	25.5	3.576	5,466	.998	.958	.946	6.3	6.49

*Calculated for a period of 1/3 the residence time.

Table 7-6. Point Model Breeder, Near Breeder Thirty-Year History (1200 MW plant, 0.80 plant factor, nominal C/HM 110, 30-year life, .015 recycle loss, 1.5 year recycle delay)

Residence Time (yrs at full power)	Exposure (MW_{th}-D/kg HM)	Fissile Loading (kg)	Average Conversion Ratio	Fissile Balance (kg/MWe-Yr) External Source	Total Feed	Recovered Discharge	Net Production	Fuel Cost (Mill/kWe Hr)
5 W_{th}/cc, .01 neutron loss fraction, U-233 feed								
.765	9.8	2,310	1.025	.2324	2.6637	2.6545	-.0092	11.469
.95625	12.2	2,456	1.020	.2106	2.1904	2.1794	-.0111	9.658
1.275	16.3	2,581	1.008	.1923	1.7073	1.6907	-.0166	7.952
1.275[b]	18.5	2,508	1.007	.1890	1.6795	1.6617	-.0178	7.775
1.9125	24.5	2,357	.990	.1820	1.2098	1.1811	-.0287	6.087
3.825	48.8	2,281	.951	.1924	.7095	.6449	-.0546	4.522
5 W_{th}/cc, .015 neutron loss fraction, U-233 feed								
.765	9.8	2,442	1.019	.2457	2.7040	2.6842	-.0198	11.625
.95625	12.3	2,532	1.011	.2216	2.2248	2.2032	-.0215	9.790
1.275	16.3	2,582	1.000	.2049	1.7345	1.7079	-.0266	7.972
1.9125	24.4	2,691	.981	.1920	1.2321	1.1934	-.0387	6.206
3.825	48.6	2,929	.942	.2039	.7258	.6513	-.0745	4.637
5 W_{th}/cc, .025 neutron loss fraction, U-233 feed								
.765	9.8	2,506	1.003	.2726	2.7873	2.7462	-.0411	11.913
.95625	12.3	2,603	.993	.2496	2.2959	2.2534	-.0425	10.059
1.275	16.3	2,652	.983	.2295	1.7930	1.7458	-.0472	8.081
1.9125	24.4	2,767	.964	.2162	1.2780	1.2191	-.0589	6.446
3.825	46.5	3,194	.924	.2273	.7591	.6646	-.0945	4.868
7.5 W_{th}/cc, .015 neutron loss fraction, U-233 feed								
.54643	10.5	1,804	.994	.2411	2.7014	2.6537	-.0477	10.836
.6375	12.2	1,813	.987	.2346	2.3705	2.3203	-.0502	9.606
.765	14.6	1,859	.978	.2214	2.0322	1.9780	-.0542	8.292
.95625	18.2	1,910	.967	.2101	1.6858	1.6253	-.0605	7.170
1.275	24.3	1,954	.953	.2022	1.3309	1.2598	-.0710	5.987
1.9125	36.5	2,053	.930	.2042	.9688	.8781	-.0906	4.875
3.825	71.9	2,272	.879	.2378	.6180	.4762	-.1418	4.307
5 W_{th}/cc, .015 neutron loss fraction, U-233 + higher feed[a]								
.765	9.8	2,575	1.017	.2551	2.8148	2.7911	-.0237	11.819
.95625	12.2	2,624	1.009	.2310	2.3052	2.2860	-.0252	9.926
1.275	16.3	2,672	.997	.2110	1.7952	1.7652	-.0300	8.085
1.275[b]	16.5	2,632	.996	.2078	1.7693	1.7384	-.0308	8.015
1.9125	24.3	2,794	.960	.1961	1.2786	1.2370	-.0415	6.314
3.825	48.3	3,045	.940	.2102	.7547	.6778	-.0769	4.724
7.5 W_{th}/cc, .015 neutron loss fraction, U-233 + higher feed								
.6375	12.2	1,874	.985	.2419	2.4580	2.4044	-.0536	9.728
.765	14.6	1,919	.976	.2281	2.1054	2.0481	-.0573	8.489
.95625	18.2	1,971	.966	.2163	1.7456	1.6822	-.0634	7.262
1.275	24.2	2,022	.952	.2085	1.3779	1.3042	-.0737	6.064
1.275[b]	24.6	1,977	.949	.2061	1.3504	1.2748	-.0756	5.993
1.9125	36.2	2,129	.924	.2098	1.0042	.9110	-.0933	4.940
3.825	71.5	2,376	.878	.2439	.6424	.4986	-.1438	4.092

[a] U-233, U-234, U-235, U-236 fractions .880, .104, .015, .001.
[b] Fix total heavy metal feed.

Table 7-7. Point Model Breeder, Near Breeder Results Without Recycle ($1{,}200\ MW_e$ plant, 0.85 plant factor, 30-year life, 0.015 reprocessing loss, $5\ W_{th}/cc$, 0.015 neutron loss fraction, U^{233} + higher feed)

Residence Time (yrs at full power)	Exposure (MW_{th}-D/ Kgm HM)	Fissile Loading (kgm)	Conversion Ratio: Average	Conversion Ratio: Steady State	Fissile Balance (Kgm/MW_e-Yr): 30 Year Feed	Steady State: Feed	Steady State: Recovered Discharge	Steady State: Net Production	Fuel Cost* (mill/kW_e Hr): 30 Year	Fuel Cost*: Steady State
.54643	7.56	2,272	1.0337	1.0335	3.4946	3.4479	3.4323	-.0155	11.967	11.548
.765	9.87	2,316	1.0232	1.0230	2.5594	2.5118	2.4990	-.0128	10.669	10.476
.9562	12.34	2,349	1.0158	1.0154	2.0872	2.0397	2.0566	-.0169	9.035	8.904
1.275	16.4	2,397	1.0053	1.0048	1.6138	1.5651	1.5468	-.0183	7.431	7.361
1.9125	24.6	2,479	.9883	.9873	1.1394	1.0897	1.0596	-.0301	5.888	5.891
3.825	49.0	2,597	.9491	.9456	.6774	.6275	.5586	-.0689	4.567	3.720

*Includes first core indirect costs for 30-year history.

Regarding Breeder Optimization

The conditions which satisfy some objective function may be determined from the results. Fortunately these two-dimensional problems were well converged so that the results do not display a significant variation from precise solutions for the situations treated. The results which consider only variation in the kernel packing fraction will be considered subject to constraints on such packing.

Consider the reactor operation and associated fissile mass balances. Using effective values,

$$R = (1-\alpha)\,[F + Q(C-1)] \tag{7-1}$$

where R is the recovery rate

α is the reprocessing loss fraction

F is the feed rate

C is the conversion (breeding) ratio

Q is the rate of fuel consumption per unit time, i.e.

$Q = P(dF^{-}/dE)$,

where P is the thermal power level,

$\frac{dF^{-}}{dE}$ is the amount of fuel consumed to produce a unit amount of thermal energy, and $P = dE/dT$.

We seek to maximize the number of reactors which can be supplied fuel, or minimize the amount of make-up fuel. Ignoring the inventory requirement (considering it to be a small factor relative to the feed component), we seek the maximum of the excess fuel produced relative to the feed,

$$X = \frac{R}{F} = \frac{Q}{F}(C-1)(1-\alpha) - \alpha \tag{7-2}$$

This maximum occurs at the point where

$$\frac{FdC}{(C-1)\,dF} = 1, \tag{7-3}$$

independent of the reprocessing loss α.

The optimum so defined was estimated at different C/HM ratios from the data for clean U^{233} feed as follows:

C/HM	Nominal Residence Time (yrs)	Primary Exposure (MW_{th}-D/Kgm)	Breeding Ratio	Feed (Kgm/D)	Net Productions, no loss (Kgm/MW_e -Yr)
80	2.0	30.8	1.0305	6.4	.0346
90	1.5	26.5	1.0287	7.0	.0325
100	1.1	21.5	1.0257	7.7	.0297
110	0.9	19.0	1.0232	8.5	.0256

Considering the C/HM variable, the primary variables are

Y = carbon to heavy metal ratio, and

Z = Pe/F, the exposure,

where e is the fissile enrichment of the feed and P the associated power (for the primary if desired, but total for consistency with the earlier equations). Setting the partial derivations of X equal to zero leads to the desired optimum

$$\frac{\partial F}{F\partial Y} = \frac{\partial C}{(C-1)\partial Y}, \text{ and}$$

$$\frac{\partial F}{F\partial Z} = \frac{\partial C}{(C-1)\partial Z}, \text{ or}$$

$$\frac{\partial C}{\partial Y}\,\frac{\partial Z}{\partial Z} = \frac{\partial C}{\partial Z}\,\frac{\partial F}{\partial Y}\,. \tag{7-4}$$

This result is independent of the reprocessing losses.

Unfortunately, these partial derivatives are far from constant. Using a change in variables

$$X = \frac{QZ}{Pe} (C-1)(1-\alpha) - \alpha . \tag{7-5}$$

Fixing P as the total power, the apparent optimum occurs at

$$\frac{\partial e}{e\partial Y} = \frac{\partial C}{(C-1)\partial Y} , \text{ and}$$

$$\frac{Z\partial e}{e\partial Z} = 1 + \left(\frac{Z}{C-1}\right) \frac{\partial C}{\partial Z} , \text{ or} \tag{7-6}$$

$$Z \left\{ \frac{\partial e}{\partial Z} \left[\frac{\partial C/\partial Y}{\partial e/\partial Y}\right] - \frac{\partial C}{\partial Z} \right\} = C-1. \tag{7-7}$$

The result of processing the data available indicates that as much thorium should be packed into the inner part of the pebble as possible to optimize as defined. Lowering the C/HM below 80 or even this low may not prove practical. At a C/HM of 80, the effect of reprocessing loss on the net fissile production with clean feed is shown below:

Reprocessing Loss (fraction)	Net Fissile Production kgm/MW_e-yr
0.000	.0346
0.005	.0246
0.010	.0146
0.015	.0046
0.020	-.0053
0.025	-.0153

Another view is that the optimum desired is the condition for which the total external feed is minimized, which is approximately the system inventory. For a residence time of T in the reactor and delay for recycle of time H, the system and reactor inventories are related by

$$I_S = \left(\frac{T+H}{T}\right) I_R . \tag{7-8}$$

Approximating the reactor inventory from the feed and discharge rates,

$$I_s = \frac{T}{2} (F + D) \left(1 + \frac{H}{T}\right) \quad . \tag{7-9}$$

At a given C/HM, the last term is the most important, so the driving force is to a long residence time (high exposure), and resulting low breeding ratio. The driving force is also toward a high C/HM to reduce the inventory.

Summary

The results which have been presented indicate that the pebble bed reactor can be operated as a breeder with fuel which is primarily U^{233}. The fuel production rate decreases from the peak for an initial clean core and with recycle of reprocessed fuel due to buildup of the higher uranium actinides. After considering a reasonable processing loss, a break even fuel history is more likely than any significant fuel production. The amount of external fuel required to fuel the system (reactor and associated fuel cycle system) through a plant life is an important consideration, along with fuel cost. The optimum design and operation considering the requirements and costs may well result in performance below the point of net breeding. A high C/HM ratio, high power density and long exposure are forced by these considerations.

Large blankets are needed for a high breeding ratio, and elaborate reactor design analysis with consideration of control requirements is required for thorough assessment. The use of fertile pebbles in blankets will reduce the heat removal capability below that achievable, reducing the energy conversion efficiency. A short out-of-core recycle delay is needed to reduce the system inventory. Fuel loss in processing significantly impacts the fuel balance because of the relatively high feed rate (short residence time and low power level per unit fissile material). The ability to hold down this loss and the cost of holding it down remain to be demonstrated considering that the fissile content of much of the heavy metal will be low. Special handling of the pebbles is desirable to increase the fissile content, especially cycling fertile pebbles from the blanket back to the core without reprocessing. The pebble removal, separation and feed requirements will have to be established and a practical design and mode of operation developed.

SECTION 08: PREBREEDER

The purpose of a prebreeder is the use of U^{235} feed, primarily from ore, to produce a U^{233} product which has sufficiently low content of the higher uranium isotopes that this discharged material will serve adequately as fuel for a thermal breeder or near breeder. Calculations were done to assess the performance including the fuel production at a selected C/HM of 175. Results of one-dimensional parameter studies are shown in Table 8-1 for two pebbles having about the same heavy metal loadings and a core with a large radial blanket.

A special advantage was found for once recycle of the fueled primary pebbles. A short residence time of the fertile pebbles is needed to effect a high rate of U^{233} fuel production (rather than consume it in place). But fuel cost considerations force a long residence time of the primary pebbles. Both needs are met by once recycle of the primary pebbles without reprocessing. The pebble bed concept has unique capability for prebreeder application if such recycle proves to be practical. As shown by the results, a disadvantage of such operation is the increased power density in the primary pebbles on their first pass. It may be desirable to reduce this power density peak by only partial recycle. With recycle, selective separation of pebbles would be most desirable to avoid long exposure, but this might prove to be costly.

More of the U^{233} product can be made available (without high contamination from U^{235} and U^{236}) by loading the fertile pebble with a larger fraction of the total thorium. Results are displayed in Table 8-2 for a selected distribution. Once recycle of the primary pebble is also considered and a second cycle using reprocessed primary pebble discharge from a first cycle as feed.

Results of two-dimensional calculations are shown in Table 8-3. Neutron accounting is shown in Table 8-4 for selected cases.

Fuel costs were determined for the prebreeder. Selected results are shown in Table 8-5 .

Table 8-1. Prebreeder Results for Fully Enriched U^{235} Feed to Produce U^{233} (One-dimensional, axial blanket, 1,200 MW_e plant, 5 W_{th}/cc, C/HM 175, 500 CM height)

Case		PB05A	PB10A	PB15A	PB20A	PB10C
Cycle (primary/fertile)		1/1	1/1	1/1	1/1	1/2[a]
Residence Time (full power yrs)		.5	1	1.5	2	1
Conversion Ratio		.742	.738	.735	.729	[illegible]
Fissile Inventory (Kgm)		1,835	1,837	1,833	1,842	1,791
Peak Axial Power Density (W_{th}/cc)						
Average		7.41	7.42	7.57	7.93	7.41
Zone Pebble Peak (primary/fertile)		23/1.8	22/3.7	22/5.0	22/6.0	19/7.4
Core Leakage Fraction		.0431	.0434	.0437	.0436	.0456
Fission Product Absorption Fraction		.0390	.0497	.0590	.0671	.0518
Exposure (MW_{th} D/Kgm HM)						
Average		9.97	19.9	29.8	39.7	27.5
primary/fertile		20.4/1.11	37.8/4.67	53.2/9.81	67.7/15.8	33.8/16.8
Mass Balances (Kgm/D at full power)						
Primary Feed	Th^{232}	126.68	63.341	42.227	31.670	63.341
	U^{233}					
	U^{234}					
	U^{235}	10.620	5.6237	3.9658	3.1792	4.8193
	U^{236}					
	U^{238}	.5661	.2597	.2114	.1695	.2569
Fertile Feed	Th^{232}	163.005	81.502	54.335	40.751	40.751
Primary Discharge	Th^{232}	125.42	62.098	41.007	30.475	62.089
	Pa^{233}	.1664	.0518	.0236	.0128	.0510
	U^{233}	.9091	.8203	.6940	.5874	.8230
	U^{234}	.0524	.0711	.0806	.0848	.0725
	U^{235}	7.0945	2.5619	1.2563	.7209	2.1647
	U^{236}	.6410	.5452	.4723	.4196	.4716
	U^{238}	.5495	.2825	.1936	.1509	.2422
Fissile	Pu	.0085	.0059	.0045	.0036	.0050
Other	Pu	.0021	.0021	.0020	.0019	.0018
Fertile Discharge	Th^{232}	161.32	79.854	52.714	39.158	39.108
	Pa^{233}	.2126	.0661	.0300	.0163	.0319
	U^{233}	1.1946	1.0691	.9007	.7600	.7456
	U^{234}	.0699	.0946	.1072	.1130	.1173
	U^{235}	.0032	.0081	.0128	.0166	.0175
	U^{236}	.0001	.0004	.0009	.0015	.0017
U^{233} Product (Fertile pebble stream)						
Fraction of U		.951	.917	.885	.856	.851
Kgm/Kgm Fissile Feed		.1325	.2019	.2347	.2442	.1613
Kgm/Kgm Fissile consumed		1.3536	1.0854	.8979	.7288	.7889

[a] Once recycle fertile pebbles, steady state condition.
[b] Once recycle primary pebbles, steady state condition.
[c] First recycle reprocessed primary pebble discharge plus makeup.
[d] Second recycle reprocessed primary pebble discharge plus makeup.

Table 8-1. (Cont'd.)

42.272	31.670	63.340	[illegible]	21.113	15.835	31.670	21.113	31.670
						.6067	.4576	.7190
						.4827	.3821	.1700
3.3665	2.7206	6.2083	3.7503	2.9660	2.6056	3.0646	2.4981	3.0191
						.4895	.4195	.9141
.1795	.1450	.3309	.1999	.1581	.1369	.2715	.2457	.3878
27.167	20.376	163.065	81.502	54.335	40.751	81.502	54.335	81.502
41.004	30.480	62.169	30.490	19.979	14.746	30.561	20.006	30.525
.0278	.0122	.0820	.0243	.0106	.0066	.0234	.0101	.0229
.6931	.5058	.7851	.5814	.4418	.3502	.6969	.4898	.5550
.0812	.0944	.0676	.0809	.0821	.0746	.1700	.1093	.2702
1.0572	.6202	2.0661	.8918	.7891	.2067	.7580	.2784	.8070
.4023	.3591	.5962	.4896	.4195	.3717	.6141	.6852	1.0335
.1644	.1292	.3120	.1780	.1332	.1110	.2621	.2077	.3417
.0038	.0031	.0067	.0045	.0035	.0030	.0067	.0056	.0083
.0017	.0016	.0023	.0023	.0022	.0022	.0033	.0035	.0042
25.566	18.818	161.358	79.922	52.807	39.271	79.937	52.841	79.971
.0141	.0075	.2098	.0631	.0279	.0149	.0607	.0264	.0594
.5524	.4287	1.1733	1.0510	.8917	.7616	1.0461	.8859	1.0352
.1192	.1136	.0662	.0864	.0952	.0985	.0959	.0921	.0819
.0231	.0259	.0030	.0072	.0109	.0139	.0071	.0104	.0066
.0035	.0053	.0001	.0003	.0007	.0011	.0003	.0006	.0003
.795	.751	.952	.922	.896	.872	.922	.898	.925
.1683	.1603	.2228	.2971	.3100	.2980	.3024	.3092	.2928
.5645	.4193	1.2701	.9760	.7702	.6210	1.0352	.7859	1.0118

Table [illegible]. Results for the Prebreeder With a Higher Fertile Loading in the Fertile Pebble

(One-dimensional, [illegible] blanket, 1200 MW_{e}, 5 W_{th}/cc, [illegible] 1800)

[illegible]

Table 8-4. Neutron Accounting for Selected Prebreeder Cases

Case	PBA015	PBA020	PBB015	PBC015	PBC115	PBC215	PBB13	PBC11	PBC1	PBD12[a]	PBC13
Fuel Cycle	1	1	1	1	2	3	1/1	1/2/1	1/2/1	1/2/1	1/2/1
Dimensions	2	2	2	2	2	2	1	1	1	1	1
Actinides											
Th	.37578	.37000	.36809	.36358	.35989	.35381	.36090	.35681	.34410	.34300	.33313
Pa	.01398	.01385	.01382	.01249	.01237	.01190	.01223	.01115	.01072	.01071	.01238
U	.14123	.17000	.13535	.12930	.16992	.17805	.16227	.10670	.13982	.13827	.15932
U	.00460	.00654	.00439	.00371	.00653	.00903	.00521	.00267	.00430	.00429	.00560
U	.34508	.31177	.35128	.35822	.31134	.30163	.31991	.36296	.34663	.34692	.32292
U	.00525	.00635	.00535	.00490	.01153	.01723	.00577	.00694	.00964	.00962	.01247
U	.00250	.00256	.00250	.00249	.00352	.00452	.00240	.00292	.00329	.00327	.00365
Np	5.8-6	5.9-6	5.9-6	5.1-6	7.2-6	9.1-6	4.7-6	5.4-6	6.0-6	6.0-6	6.6-6
Pu	.00201	.00218	.00206	.00196	.00277	.00353	.00204	.00246	.00293	.00291	.00334
Pu	.00059	.00069	.00060	.00056	.00076	.00099	.00064	.00076	.00091	.00097	.00116
Pu-241	.00034	.00050	.00040	.00035	.00049	.00061	.00047	.00053	.00078	.00078	.00098
Pu	1.4-5	2.4-5	1.4-5	1.1-5	1.5-5	1.9-5	1.9-5	2.2-5	4.9-5	4.9-5	8.1-6
Am	2.2-6	5.2-6	2.3-6	1.6-6	2.3-6	2.7-6	2.7-6	4.1-6	1.3-5	1.3-5	2.8-6
Fission Products											
Xe	.02020	.01993	.02023	.01990	.01964	.01948	.01992	.02003	.01965	.01968	.01933
Others	.03973	.04802	.03969	.03693	.03510	.03540	.04485	.04501	.05841	.05852	.06947
Other											
C	.01952	.01907	.01898	.01912	.01889	.01835	.01922	.01851	.01759	.01761	.01662
He	.00008	.00008	.00008	.00008	.00007	.00007	.00007	.00007	.00007	.00007	.00007
Si	.00192	.00185	.00191	.00197	.00194	.00188	.00215	.00208	.00196	.00196	.00134
O	.00018	.00018	.00018	.00018	.00018	.00018	.00018	.00017	.00017	.00017	.00017
Leakage	.02689	.02640	.03501	.04424	.04371	.04322	.04169	.04039	.03996	.04118	.03977
Total	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

[a] 13 groups rather than 4.

Table 8-5. Fuel Costs for the Prebreeder Cases
(30-year life, 0.85 plant load factor, 0.4 plant efficiency)

Schedule 1 Unit Costs, 0.10 Interest, 0.07 Discount

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]															
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INVENTORY COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]															
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INVENTORY COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]															
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INVENTORY COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Schedule 1 Unit Costs, 0.05 Interest, 0.035 Discount

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]															
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INVENTORY COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]															
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INVENTORY COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]															
COST OF FUEL	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FABRICATION	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
REPROC/WASTE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
INVENTORY COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TOTAL COST	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Regarding the Prebreeder Optimum

We seek an optimum design and mode of operation of a prebreeder. An economic optimum and an ore utilization optimum for a system of prebreeders and breeders (or near breeders) are possible objectives here and a symbiosis calculation is in order. But what can be done with a simple analysis?

Let us assume indeed that if fuel is available, installation of breeders is economically attractive. Then the question comes down to what is optimum for the prebreeder. The approximation may be made that only the prebreeder fuel costs make significant incremental contribution and the associated electrical energy production from the combined system is of interest. Assume that the system fuel inventory associated with each breeder plant must be available as an external source at the time it is placed in operation, perhaps representative of a young industry, and that there is no additional external feed required nor excess fuel produced. Assume further that once in operation, a breeder continues to operate thereafter, although a new plant would have to be built to replace one removed from service at the end of its life. With discounting, the "present amount of energy" for perpetual operation is given by 1/i with periodic compounding at the period rate of i. Thus a plant operated at a load factor of 0.85 produces the associated present amount of energy relative to the time of installation of

i	kWe-hr/Installed kWe
.02	372,300
.04	186,150
.06	124,100
.08	93,075
.10	74,460

A prebreeder also operated at a 0.85 load factor and a thirty year life has an associated present amount of energy relative to the time of its installation of

i	kWe-hr/Installed kWe
.02	167,000
.04	129,000
.06	102,500
.08	83,500
.10	70,200

Note that while there is little difference between the worth of 30-year service and perpetuity at a discount rate of 0.1, there is a large difference at a low rate.

Assume that the amount of fissile material available from a prebreeder is the steady state discharge rate D times a period of time L after a recovery loss fraction α. If the external fuel supply required for a breeder plant is S_B, a breeder plant may be installed at the end each time interval L,

$$S_B = D\,L\,(1-\alpha). \qquad (8\text{-}1)$$

The total present amount of energy associated with the system of reactors is given by

$$E_T = E_P + Y\,E_B \sum_{n=1}^{30/L} (1+i)^{-nL}, \qquad (8\text{-}2)$$

Where Y is the delay in availability, and E_P and E_B are present amounts discussed above,

$$E_P = 8{,}760\,U_P \left[\frac{1-(1+i)^{-30}}{i}\right],$$

$$E_B = 8{,}760\,U_B \left[\frac{1}{i}\right]; \qquad (8\text{-}3)$$

where the load factor is shown as U.

A "present amount" of the ore commitment for a prebreeder plant may be determined as the initial associated system inventory S_p plus a periodic make up,

$$O_p = 8,760 \; Q \left\{ S_p + F_p \left[\frac{1-(1+i)^{-30}}{i} \right] \right\} , \qquad (8\text{-}4)$$

where F_p is the annual fissile feed rate at the load factor per unit installed energy, and Q the conversion from U^{235} to U_3O_8 ore. The ratio of ore commitment to total energy generation on a present worth basis is

$$\frac{O_p}{E_T} = \frac{Q \left\{ S_p + F_p \left[\frac{1-(1+i)^{-30}}{i} \right] \right\}}{\left\{ U_p \left[\frac{1-(1+i)^{-30}}{i} \right] + \frac{YU_B}{i} \sum_{n=1}^{30/L} (1+i)^{-nL} \right\}} \qquad (8\text{-}5)$$

Argument can be made that the ore should not be discounted because it is committed initially. This is removed from Eq. 8-5 by replacing the discounting term in the numerator by 30 annual periods.

Results are obtained for a reference set of data. Assuming $U_p = U_B = 0.85$, $S_B = 4.6$ kgm/MW$_e$, $Q = 231$ Kgm U_3O_8/kgm U^{235}, and using a simple term for the delay of

$$Y = (1+i)^{-(H+1.0)} ,$$

where H is the processing delay time, Eq. 8-5 becomes for $i = 0.08$ and $H = 1.5$

$$\frac{O_p}{E_T} = \frac{0.231 \; S_p + 2.60 \; F_p}{9.57 + 8.76 \sum_{n=1}^{30/L} (1+i)^{-nL}} , \text{ and} \qquad (8\text{-}6)$$

$$\sum_{n=1}^{30/L} (1+i)^{-nL} = \frac{1-(1+i)^{-(30+L)}}{1-(1+i)^{-L}} , \tag{8-7}$$

with account for satisfying part of the fuel for a last plant to produce a continuous result rather than one with discontinuities for whole plants. Results are shown below for two discount rates and with and without ore discounting, estimating an initial inventory requirement for the prebreeder with delay in recycle:

Prebreeder					Ore per Unit Electrical Energy (kgm U_3O_8/kWe - Hr) x 10^6			
Residence Time (yrs at full power)	System Inventory (kgm/Installed MW_e)	Annual Fissile Feed (kgm/yr/Installed MW_e)	Annual Breeder Fuel Recovery (kgm/yr/Installed MW_e)	Delay Time to Accumulate Breeder Feed L	Ore Discounted		Ore Not Discounted	
					i = .04	i = .08	i = .04	i = .08
0.5	5.60	0.96	0.460	10.0	.0871	.151	.129	.325
1.0	3.58	0.85	0.366	12.57	.0796	.136	.127	.295
1.5	3.02	0.76	0.301	15.26	.0743	.122	.116	.273
2.0	2.90	0.70	0.258	17.82	[illegible]	.118	.117	.263
1.0PT[a]	1.79	1.06	0.363	12.67	.0850	.137	.142	.336
1.5PT[a]	1.83	0.90	0.305	15.09	.0796	.136	.132	.304
2.0PT[a]	1.90	0.79	0.261	17.62	.0769	.118	.125	.281

[a]Once recycle of primary pebble without reprocessing and then throwaway.

Thus the optimum considering ore utilization occurs at a relatively long fuel residence time for the prebreeder and a low rate of installation of breakeven breeder plants. Parameter changes that reduce the ore commitment may be noted.

It is difficult to assess primary aspects by examining the discount form of the equations. For such study, an operating period of T will be examined with delay in breeder startup of period L. The resulting equation without discounting for the ratio of ore committed to the energy production rate at T is

$$\frac{O_P}{P(T)} = \frac{Q[TF_P + (S_P/U_P)]}{1 + (1-\alpha)\ D(T-L)\ (U_B/S_B)} , \tag{8-8}$$

and for T large this reduces to

$$\frac{O_P}{P(T)} = \frac{Q\ F_P\ S_B}{(1-\alpha)\ D\ U_B[(1-(L/T)]} \quad . \tag{8-9}$$

Integrating the denominator of Eq. (8-8) to place the result in the basis of energy produced,

$$\frac{O_P}{E_T} = \frac{Q\ [T\ F_P + (S_P/U_P)]}{T + (\frac{1}{2S_B})\ (1-\alpha)\ D\ \ U_B(T-L)^2} \quad . \tag{8-10}$$

The amount of ore required to supply the prebreeder fuel relative to the energy produced is smaller:

- The longer the period in time considered;
- The higher the production rate of recoverable breeder fuel (but there is impact from increase in the feed rate to the prebreeder);
- The lower the breeder inventory;
- The lower the prebreeder inventory;
- The higher the breeder plant load factor;
- The higher the prebreeder plant load factor (but of less importance than that for the breeder except for short time);
- The shorter the delay time in use of the breeder fuel.

Given the fuel cost for the prebreeder without credit for breeder fuel production, the cost associated with total energy production is given without considering the value of U^{233} (except for indirect costs) by

$$C_{T,P} = C_P \left[\frac{E_P}{E_T}\right] \quad . \tag{8-11}$$

Accounting for total costs, the two components may be added without considering breeder fuel direct costs:

$$C_{T,T} = \frac{C_P U_P \left[1-(1+i)^{-30}\right] + C_B Y U_B \sum_{n=1}^{30/L} (1+i)^{-nL}}{U_P \left[1-(1+i)^{-30}\right] + Y U_B \sum_{n=1}^{30/L} (1+i)^{-nL}} \quad . \tag{8-12}$$

Results are shown below for the data displayed using a reference cost for the breeder of C_B = 8.5 mills/kW_e:

Prebreeder		Fuel Cost Component for the Complex			
Reference Residence Time (Full Power Yrs)	Cost Component (mills/kW_eHr)	Prebreeder Only		Prebreeder and Breeder	
		i=.04	i=.08	i=.04	i=.08
0.5	19.0	6.64	6.46	11.00	12.50
1.0	11.2	4.32	4.16	9.22	9.61
1.5	8.2	3.41	3.24	8.41	8.37
2.0	7.0	3.06	2.89	8.03	7.82
1.0R1	8.2	3.17	3.05	8.42	8.38
1.5R1[a]	6.8	2.81	2.68	8.22	7.76
2.0R1	5.8	2.53	2.38	8.22	7.27

The apparent economic optimum occurs at a relatively long residence time for the prebreeder (high exposure). Parameter changes that reduce the cost may be noted.

Now let us assume that a breeder is to be installed every year over 30 years in a mature economy. If sufficient prebreeders are installed initially to inventory the system associated with each of these breeders, the delay in use of produced fuel that was included above is avoided. Given the rate of fuel production of the prebreeder D, and the system external fissile feed associated with a breeder plant of S_B, the required number of prebreeders is

$$N_P = \frac{S_B}{D(1-\alpha)} \quad . \tag{8-13}$$

(N_p is the same as L above.) A delay for the first breeder after start up of the prebreeders of U=H + 1.0 years will be assumed, so over a 30 year life of the prebreeders, 30 breeders will be installed, the first at time H + 1.0 and the last at H + 31. The resulting equation for the ore requirement per unit total energy produced is

[a]Once recycle of primary pebbles without reprocessing.

$$\frac{O_P}{E_T} = \frac{Q\left[S_P + F_P \sum_{n=1}^{30} (1+i)^{-n}\right]}{U_P \sum_{n=1}^{30} (1+i)^{-n} + \frac{YU_B}{iN_P} \sum_{n=1}^{30} (1+i)^{-n}} ,$$

$$\frac{O_P}{E_T} = \frac{Q\left[\left\{\frac{i\, S_P}{1-(1+i)^{-30}}\right\} + F_P\right]}{\left[U_P + \frac{YU_B}{iN_P}\right]} . \tag{8-14}$$

Results for the reference data used above are shown below:

Prebreeder		Ore Per Unit Electrical Energy ($kgm\ U_3O_8/kW_e$ -Hr)			
		Ore Discounted		Ore Not Discounted	
Residence Time (Yrs)	Number Installed	i=0.4	i=0.8	i=0.4	i=0.8
0.5	10.0	.107	.195	.176	.409
1.0	12.57	.106	.180	.170	.402
1.5	15.28	.102	.167	.163	.372
2.0	17.82	.104	.165	.165	.366
1.0R1	12.67	.113	.183	.189	.447
1.5R1	15.08	.109	.171	.181	.413
2.0R1	17.62	.107	.164	.176	.390

The optimum so defined occurs at a relatively long prebreeder residence time, but evidently shorter for the developed industry than for the early industry treated above, and a large number of prebreeders installed per breeder introduced annually. Note that the results are rather sensitive to the assumptions.

The economic optimum for the situation treated may be determined by selective application of the appropriate equations:

Prebreeder		Fuel Cost Component for the Complex			
		Prebreeder Only		Prebreeder and Breeder	
Residence Time (Yr)	Cost Component (mills/kW_e Hr)	i=.04	i=.08	i=.04	i=.08
0.5	19.0	5.82	9.35	11.93	14.17
1.0	11.2	4.00	6.15	9.52	10.11
1.5	8.2	3.30	4.90	8.37	8.31
2.0	7.0	3.08	4.43	7.80	7.48
1.0R1	8.2	2.94	4.52	8.39	8.32
1.5R1	6.8	2.72	4.11	7.78	7.41
2.0R1	5.8	2.54	3.66	7.25	6.68

The economic driving force for the developed industry is shown to be toward a long residence time in the prebreeder and a large number of prebreeders for each breeder installed annually.

SECTION 09: THE COMPETITIVE POSITION

The pebble bed reactor concept shows advantage over a fixed fuel gas cooled, graphite moderated reactor. Operation with lower control rod absorptions and higher availability without the need to shut down for refueling are distinct advantages of this concept. A higher outlet coolant temperature should be possible, important in both process heat and power plant applications. Low ore requirements and hence conservation of the fuel resource are indicated for the throwaway cycle, and especially so with fuel reprocessing and recycle in high technology reactor designs, relative to the light water reactor. Although specific data are not reported, fuel cycle costs for the concept were found to compare favorably with the costs for other concepts. Therefore the concept must be assigned a high competitive position.

Any study in which ore costs play a dominant role will show that this concept would be installed rather than most others, excluding the possibility of a lower cost breeder concept.

The primary difficulty in projecting the competitive position of this concept is the lack of accurate cost data. High capital and/or fuel handling costs would prevent the concept from competing economically.

Symbiosis study of the future has been done. The results are quite dependent on the assumptions. Consider that any of the possible fission reactor concepts may be installed, and that a realistic set of rules and mass balances are used. Without showing the details the following rather obvious conclusions may be drawn.

A. Lacking a continuing supply of economic fuel from ore and given a breeder reactor concept which has a fissile inventory doubling capability less than an expanding demand for energy from fission reactors, only breeder reactors (fast rather than thermal) would be installed without economic considerations or if the breeder had lower costs than other concepts (not now considered to be true).

B. If the inventory doubling time of the selected (best) breeder reactor exceeds the energy demand doubling time, then breeder plants and plants of a second type of converter reactor having lower costs would be installed.

C. If in the distant future the demand for energy from fission reactors increases slowly and economic fuel from ore is not

BLANK PAGE

available, then a high ratio of installed low cost converters to installed higher cost breeders would be predicted, this ratio depending on not only the differences in costs between the two concepts but also on the dependence of performance on on the cost and mode of operation of each type of reactor which admits selection to fit the conditions. A distinct possibility is many converter reactors for each breeder if the former have significantly lower costs, and the economic driving force tends to move the costs of the two types of reactors toward each other: spend less on the breeder lowering the breeding ratio and more on the converter increasing its conversion ratio.

D. The potential for a direct cycle design with gas turbine generator is obvious. Say that the net plant efficiency can be increased from 0.40 to 0.50.[a] A plant with the same size reactor would produce 25 percent more electricity and the ore requirement and fuel cost would be reduced 20 percent on a per unit electricity basis. The technology is not yet available, but the requirements for the direct cycle appear to be a reasonable extrapolation of current technology, considering the operating temperature of the FRG AVR facility and developments on turbine technology. Costs are uncertain but the steam system would have a high capital cost, and its elimination would be expected to offset the incremental cost of the gas turbine.

E. A prebreeder concept to produce breeder fuel using fuel from ore shows economic potential if it has a lower cost than the breeder, over a period where economic ore is available to fuel the prebreeder. The prebreeder, breeder combination on one fuel cycle (U^{233}) can be more economical than breeder, converters on another fuel cycle (Pu) if costs of the former are lower.

F. The smaller the size of the system considered (consider part or all of the grid of a utility, an area, national and multi-national levels) the more difficult it is to satisfy the requirements in a self-contained system, the more variety to be expected (differences between systems), and the more significant the effect of the conditions unique to the situation on the best choices.

G. Accurate cost estimates are needed for assessing the future and to justify investment in development effort, hard though it may be to predict these.

The above summary presupposes that the total cost of electrical energy from nuclear reactor power plants is competitive with that from other sources.

---

[a] Costs and other considerations including complexity could result in no significant increase in the plant efficiency with a direct cycle.

SECTION 10: ORE USE

We summarize here predictions of the U_3O_8 ore requirements to fuel power plant reactors of the gas cooled pebble bed type, and compare these with the requirements for other types of reactors. Performance of plants with enriched U^{235} fuel, with or without fuel recovery by processing, is of primary interest.

Difficulties are presented by such analysis. Just what should be credited from the core and out of-core inventories at the end of the reactor life is a matter of judgement. The fissile mass balances depend on the assumptions made regarding the core design, the fuel management, etc. Fissile nuclides have individual importance values associated with their use in a given reactor and fuel cycle, and contaminants degrade performance. Given an economic model, cost data, and mass balances, an economic optimum can be determined and ore requirements predicted for these conditions. However, the optimum depends on the economic data and also on the practical considerations taken into account regarding requirements for operation, delay in recycle, etc.

At only a small economic penalty, ore requirements can be reduced from those for the economic optimum. This reduction is more significant for some reactor concepts than others, as indeed is the magnitude of the associated economic penalty.

[illegible] t fissile consumption required to produce a quantity of electrical energy with fuel recovery (not throwaway) can be expressed as

$$Q = \frac{A}{\eta}(1-C) \quad , \tag{10-1}$$

where η is the thermal efficiency and C the conversion ratio.

Hence the associated ore consumption is given by

$$O = \frac{B}{\eta}(1-C) \quad . \tag{10-2}$$

Note that C should be an effective value with allowance for losses. Thus for two similar situations, the ratio of ore requirements is simply the ratios of the differences from unity of the conversion ratios.

For a thermal efficiency of 0.4, operation of a 1,000 MWe plant for a period of 30 years at 0.7 load factor, fully enriched U^{235} fuel and 0.002 enrichment tails (231 gms U_3O_8/gm fissile consumed), we estimate consumption for typical pebble bed reactor conditions at

$$
O = \begin{cases} 5{,}294(1-C)\ , & U^{233} \\ 5{,}884(1-C)\ , & U^{235} \\ 7{,}552(1-C)\ , & Pu^{239} \\ 6{,}318(1-C)\ , & Pu^{241} \end{cases} \qquad (10\text{-}3)
$$

where O is in Kgm, no contribution from high energy fission in other actinides is included, and fissile nuclides are assumed to be of equivalent worth to U^{235} from ore. Note that the data above could be interpreted as relative worths of these nuclides, but only if associated differences in conversion ratio were included; a penalty of 28 percent for Pu^{239} relative to U^{235} is indicated neglecting any difference in the conversion ratio.

This data may be used to approximate the ore requirement for a pressurized water reactor with recycle. For 3 percent enriched U^{235} feed, a fast effect of 0.08, a thermal efficiency of 0.3, a conversion ratio of 0.6, energy from $U^{235}/Pu^{239}/Pu^{241}$ as .5/.3/.2, and a conversion ratio of 0.55, the ore for a plant is estimated at 3,400.

Using an average of the data for U^{233} and U^{235}, the dependence of ore consumption of a pebble bed reactor on the conversion ratio is shown below with an allowance for processing losses.[a]

Conversion Ratio: Reference	Conversion Ratio: (Net after processing)	Ore (kgm)
.5	(.491)	2,840
.6	(.588)	2,300
.7	(.685)	1,760
.8	(.780)	1,230
.9	(.860)	790

[a]See also the results of more detailed analysis in Chapter 3.

Whereas the ore requirement (consumption) associated with the economic optimum may be about 2,000 kgm, this can be reduced to about 1,000 kgm by achieving a high conversion ratio. Such would require a low exposure (low burn up) which significantly increases the required capacity for fuel processing and increases the fuel cost by 25 percent or possibly much more. Relative cost increase is lower the higher the fuel cost component, and there is a significant indirect cost component, which would be expected to increase with increase in exposure when viewed as relative to the direct cost (although the amount decreases due to decrease in the out-of-core inventory). The conversion ratio is increased by reducing the carbon to heavy metal loading, increasing the size of the blankets, and reducing the power density, which increases the cost of energy generation relative to the economic optimum.

The results obtained from point reactor history calculations may be examined in detail. Shown below is a summary for a set of assumptions[a] using a carbon to heavy metal ratio of 250:

Residence Time (yrs)	1	2	4
Exposure (Mw_{th}-D/kgm)	24	48	95
Conversion Ratio	.803	.757	.683
Fuel Cost (mill/kw_e-hr)			
Fuel	1.186	1.433	1.864
Fabrication	2.232	1.140	.596
Reprocessing	2.790	1.411	.726
Subtotal Direct	6.208	3.984	3.186
Indirect	1.758	1.400	1.309
Total	7.966	5.384	4.495

Variations in the Total Fuel Cost:

Total at half the indirect charges	7.087	4.684	3.841
Total with processing cost fixed	6.687	5.384	5.130
Total doubling cost of fuel and fixing the processing cost	9.633	8.209	8.283

[a]The results of two-dimensional calculations show higher costs; here we consider the costs estimates be accurate only in the relative sense.

A special case is made of the reprocessing cost, so the effect of fixing it is shown (the total amount of fission products to be handled is essentially fixed), somewhat extreme. Then the cost of fuel is doubled. The results show not only that the location of the optimum is shifted, but also the economic penalty of operation at below the optimum exposure is sensitive to the data. The optimum conditions are indeed shifted by appreciable change in the cost of fuel (relative to other costs); the optimum exposure decreases with increased cost of fuel.

Comparison of the ore requirements for various reactor concepts has been difficult. There is a large variation in the results reported in the literature. We cite certain information in what follows as judged to be the best information available from private communications or information transmissions not documented in the literature. Recent data has been reported in a thorium utilization study[14] and extracted results are shown in Table 10-1. Note the dependence on conversion ratio for the HTGR and the possibility of effecting a self-sustaining condition with the HWR.

A summary of ore consumption for several reactor concepts is presented in Table 10-2. To provide information on a consistent basis we have reached back to data generated at ORNL in 1964.[14] This old data should be qualified in several respects, especially regarding the low cost data used at that time. The ore requirement then estimated for the PWR, however, was considerably lower than indicated in the literature, and this estimate seems to have been reliable; (see for comparison the data shown in Table 10-1.) Lower requirements were shown in this report for the prismatic HTGR than for the HWR(Th), using beryllium, results which are not used here. The HWR(U) requirements can be reduced considerably; what is not clear is where the economic optimum lies for this concept, but it may well be below the result shown. The HWR(Th) result is for an advanced concept which could have relatively high capital and fuel costs inviting further study.

Table 10-1. Ore Requirements for Several Concepts
(Kg U_3O_8/MW_e at .75 Plant Factor 30 Year Operation, .002 Tails)

Reactor Concept	LWR	SSR	HWR	HTGR*
Commitment				
Uranium Cycle				
Natural throwaway			4,757	
Throwaway	5,943	4,979	3,374	
Full Recycle	3,902			
Thorium Cycle				
Fully Enriched, Recycle	3,369	2,104	1,724	
Denatured, Recycle	3,637	2,214		
Self-sustaining			1,334	
Consumption				
Uranium Cycle				
Natural, throwaway			4,327	
Throwaway	5,443	4,545	3,075	3,901
Full Recycle	3,719		1,838	
Thorium Cycle				
Fully Enriched, Recycle	3,130	1,982	1,624	2,404
Denatured, Recycle	3,402	1,996	1,735	3,719

*Fully enriched U recycle data for a C.R. = 0.66; at a C.R. = 0.90, commitment 1,600, consumption 1,429.

Of course the data shown is for advanced concepts and sophisticated operation with partial refueling. The data we attribute to KFA is an interpretation of their results reported in 1977 and more recent assessment,[12] and yet subject to revision in their ongoing evaluation. The new ORNL estimates for the prismatic HTGR are from point model calculations, not as sophisticated as the analysis done by GA. The gas cooled reactor data shown, and that for the other systems loaded with thorium, consider fully enriched U^{235} fuel.

Table 10-2. Estimates of Ore Consumption for Several Reactor Concepts

Reactor Type	Data Source	Initial Inventory (Kgm/MW_e)	Fissile Make-up (Kgm U^{235}/MW_e Yr)	Ore Consumption[a] (Kgm U_3O_8/MW_e For 30 yr at 0.70)
				Low Cost (Low Ore)
Throwaway Cycle				
PWR (U)	ORNL-3686[b]	2.06	1.16	5,480 (4,990)
	CE			5,090 (4,330)[c]
HWR (U)	ORNL-3686	.58	1.29	5,400
HTGR (U)	GA			3,900
HTGR (Th)	GA			3,730
	ORNL			3,790 (3,470)
PBR (Th)	KFA		.66	3,200
	ORNL	1.00	.68	3,400 (3,100)
Fuel Reprocessing and Recycle				
PWR (U)	ORNL-3686	2.06	.78	3,490[d]
	CE			3,220
SSCR (Th)	ORNL-3686	3.34	.66	2,810
HWR (Th)	ORNL-3686	1.44	.39	1,170
HTGR (Th)	ORNL-3686	2.60	.45	1,930
	GA			2,360 (1,940)
	ORNL	1.44	.48	2,300 (1,900)
PBR (Th)	KFA			2,040 (1,000)
	ORNL	1.00	.45	2,150 (1,500)

[a]Ore enrichment tails 0.002.

[b]Calculations done in 1964.

[c]A 15 percent reduction from the apparent economic optimum is allowed here.

[d]Not calculated, 85 percent discharge fissile credit, requires highly enriched make-up.

SECTION 11: SUMMARY OF PROJECTED PERFORMANCE

An assessment was made of the requirements and performance to predict the effect from the level of technology. In any event, the basic assumption is made that the concept is technically feasible regarding control, safety, and performance of materials. Three levels of technology are assumed:

- Low Technology - single pebble, no axial blanket, modest if any radial blanket, exposure limited to 180 MW_{th}-D/kgm HM for high enriched fuel, lower than reference (desirable) operating temperature and power density.
- Reference - two pebble types, radial and modest axial blankets, 225 MW_{th}-D/kgm fueled pebble exposure for high enriched fuel.
- High Technology - axial and radial blanketing, complicated pebble management, fueled pebble exposure to 260 MW_{th}-D/kgm HM for high enriched fuel, higher than reference power density and temperature.

The data selected from the results of the reported calculations at ORNL to summarize the projected performance of the pebble bed gas cooled thermal reactor concept are shown in Table 11-1 for a reference net energy conversion efficiency of 0.4 after allowance for plant requirements. Note that there are different conditions for the basis of costs and ore requirements (even different from the previous section).

In projecting performance, we also consider that the net energy conversion efficiency will depend on the technology level. The Fort Saint Vrain plant was designed with a superheater to yield a net efficiency of 0.392 with a coolant gas outlet temperature of 785° C. Studies of the pebble bed reactor in the FRG consider an efficiency of 0.40 with an outlet gas temperature of 985° C. Clearly the higher the gas outlet temperature, the higher the efficiency that can be achieved. Still, holding down the capital cost of a plant is of major concern and the optimum efficiency may be lowered by elevated costs. Thus we consider an economic driving force which reduces the heat exchanger surface areas and sophistication of the steam system. Although use of a direct gas turbine cycle could increase the efficiency of plants, we do not consider here the effect of a large increase from this source. A primary attraction of the direct cycle is the associated easier siting because

Table 11-1. Performance Summary for the Pebble Bed Reactor Concept at a Net Plant Efficiency of 0.4[a]

Service and Technology Level	Nominal Carbon to Heavy Metal (Atomic)	Nominal Fueled Pebble Residence (Full power yrs)	Average Conversion Ratio	Peak Pebble Power (kW)	Fueled Pebble Exposure (MW_{th} D/kgm HM)	Fissile Inventory (kgm/Installed MW_e) Plant	Fissile Inventory (kgm/Installed MW_e) System	External Fissile Feed (kgm/MW_e-Yr)	Fissile Commitment (kgm/Installed MW_e)	Ore Requirement (kgm U_3O_8/Installed MW_e) Consumption	Ore Requirement (kgm U_3O_8/Installed MW_e) Commitment	Fuel Cost (mill/kW_e-Hr) Low Indirect	Fuel Cost (mill/kW_e-Hr) Reference
Burner, Low Enriched Uranium													
Reference Technology	575	2.0	.54	2.1	130.	0.9	1.3	.85	20.5	4,360	4,650	5.6	6.2
Burner, Medium Enriched (denatured) Uranium Fuel													
Low Technology	450	2.5	.54	2.2	130.	1.0	1.3	.80	19.4	4,120	4,420	5.4	6.1
Reference	450	2.6	.55	5.1	205.	0.9	1.2	.76	18.2	3,890	4,170	5.0	5.7
High Technology	450	2.9	.55	5.9	220.	0.8	[illegible]	.69	16.6	3,630	3,780	4.6	5.3
Burner, Fully Enriched Uranium													
Low Technology	250	3.8	.55	2.1	90.	1.3	1.5	.71	17.9	3,700	4,000	5.2	5.9
Reference	250	4.0	.58	5.0	225.	1.3	1.5	.66	16.8	3,400	3,800	4.7	5.6
High Technology	250	4.2	.57	5.8	250.	1.4	1.6	.60	15.1	3,100	3,500	4.4	5.2
Converter, Fully Enriched Uranium, Recycle													
Low Cost													
Low Technology	250	3.8	.63	2.1	95.	1.3	2.0	.45	11.4	2,220	2,620	4.5	5.6
Reference	250	4.0	.65	5.0	225.	1.3	2.0	.42	10.8	2,150	2,550	4.2	5.3
High Technology	250	4.2	.67	5.8	250.	1.4	2.1	.40	10.4	1,980	2,430	4.0	5.1
Low Ore													
Low Technology	175	2.0	.75	2.2	36.	1.6	2.7	.41	10.8	1,750	2,450	5.7	6.9
Reference	175	2.0	.78	3.3	90.	1.6	2.7	.36	9.7	1,500	2,200	5.3	6.5
High Technology	175	2.0	.80	3.6	100.	1.7	2.8	.32	8.7	1,330	2,080	5.1	6.4
Prebreeder, Fully Enriched Uranium[b]													
Low Cost	175	2.5	.70	2.9	110.	2.0	2.8	.60	16.3	3,110	3,760	4.6	5.8
Reference	175	1.5	.73	2.9	74.	1.9	3.0	.70	18.8	3,630	4,330	5.1	6.3
High Performance	175	3.0	.71	4.1	135.	2.2	2.8	.70	18.6	3,630	4,280	4.8	5.9
Near Breeder, Breeder, U-233 Fuel													
Low Cost	250	4.2	.710	5.0	220.	1.1	1.6	.28	7.6			4.0	5.1
Intermediate	[illegible]	1.5	.890	3.0	50.	1.1	2.3	.11	4.7			5.5	6.8
High Conversion	110	2.0	.990	3.3	40.	3.0	5.6	.030	6.3			5.6	8.0
Break even	90	1.5	1.023	2.8	26.	3.8	9.1	—	8.1			7.9	11.3
Breeder	80	1.5	1.036	2.7	24.	4.6	[illegible]	—	9.8			9.0	13.0

[a] Burner and converter load factor 0.75; prebreeder, near breeder, breeder are high technology, load factor 0.85; ore enrichment tails .002, 30 year plant life.

[b] Breeder fuel generation for these cases in kgm/MW_e-Yr (net); 0.28, 0.36, 0.38.

of limited locations where cooling water is available. However, a thermal efficiency of 0.5 could be achieved with the penalty of higher cost and increased complexity. The following net energy conversion efficiencies are arbitrarily assumed which could have a wider band of variation:

Technology Level	Outlet Gas Coolant Temperature (°C)	Net Energy Conversion Efficiency
Low	900	.375
Reference	950	.400
High	1000	.425

Results obtained using these efficiencies are shown in Table 11-2 to present a summary of the projected performance.

If the capital cost of a power plant were $600/MW$_e$ capacity, the associated cost component of the product at a plant load factor of 0.75 and an annual charge rate of 0.16 would be 14.6 mill/kW$_e$-hr. A fuel cost of 5.3 then contributes 27 percent of the total. A 10 percent uncertainty in the fuel cost reduces to a 2.7 percent uncertainty in the total.

There are a large number of possible alternative designs and modes operation. An attempt would be made to select the economic optimum with constraints satisfied and some penalty included for uncertainty regarding technical feasibility. A significant contribution to the total cost is the cost of the reactor core. Assuming a reference capital charge component of 1.6 mill/kW$_e$-hr for the core and a power of 0.7 dependence on size, this cost component amounts to:

Relative Core Size	Capital Charge (mill/kW(e)-hr)
0.5	0.98
0.75	1.31
1.0	1.60
1.25	1.87
1.50	2.13

Table 11-2. Performance Summary for the Pebble Bed Reactor Concept with the Plant Efficiency Dependent on Technology Level[a]

Service and Technology Level	Nominal Carbon to Heavy Metal (Atomic)	Nominal Fueled Pebble Residence (Full power yrs)	Average Conversion Ratio	Peak Pebble Power (KW)	Fueled Pebble Exposure (MW_{th} D/kgm HM)	Fissile Inventory (kgm/Installed MW_e) Plant	Fissile Inventory (kgm/Installed MW_e) System	External Fissile Feed (kgm/MW_e-Yr)	Fissile Commitment (kgm/Installed MW_e)	Ore Requirement (kgm U_3O_8/Installed MW_e) Consumption	Ore Requirement (kgm U_3O_8/Installed MW_e) Commitment	Fuel Cost (mill/kW_e-Hr) Low Indirect	Fuel Cost (mill/kW_e-Hr) Reference
Burner, Low Enriched Uranium													
Reference	575	2.0	.54	2.1	130.	0.9	1.3	.85	20.5	4,360	4,6[illegible]0	5.6	6.2
Burner, Medium Enriched (denatured) Uranium Fuel													
Low Technology	450	2.5	.54	2.3	130.	1.1	1.4	.85	20.7	4,400	4,720	5.8	6.5
Reference	450	2.6	.55	5.1	205.	0.9	1.2	.76	18.2	3,890	4,170	5.0	5.7
High Technology	450	2.9	.55	5.6	220.	0.7	1.0	.65	15.6	3,320	3,560	4.3	5.0
Burner, Fully Enriched Uranium													
Low Technology	250	3.8	.55	2.2	90.	1.4	1.6	.76	19.1	3,950	4,270	5.5	6.3
Reference	250	4.0	.58	5.0	225.	1.3	1.5	.66	16.8	3,400	3,800	4.7	5.6
High Technology	250	4.2	.57	5.5	250.	1.3	1.5	.56	14.2	2,920	3,290	4.1	4.9
Converter, Fully Enriched Uranium Recycle													
Low Cost													
Low Technology	250	3.8	.63	2.2	95.	1.4	2.1	.48	12.2	2,370	2,790	4.8	6.0
Reference	250	4.0	.65	5.0	225.	1.3	2.0	.42	10.8	2,150	2,550	4.2	5.3
High Technology	250	4.2	.67	5.5	250.	1.3	2.0	.38	9.8	1,860	2,290	3.8	4.8
Low Ore													
Low Technology	175	2.0	.75	2.3	36.	1.7	2.9	.44	11.5	1,870	2,610	6.1	7.4
Reference	175	2.0	.78	3.3	90.	1.6	2.7	.36	9.7	1,500	2,200	5.3	6.5
High Technology	175	2.0	.80	3.4	100.	1.6	2.6	.30	8.2	1,250	1,[illegible]80	4.8	6.0
Prebreeder, Fully Enriched Uranium[b]													
Low Cost	175	2.5	.70	2.7	45.	1.9	2.6	.56	15.3	2,930	3,540	4.3	5.5
Reference	175	1.5	.73	2.0	79.	1.8	2.8	.66	17.7	3,420	4,075	4.8	5.9
High Performance	175	3.0	.71	3.9	135.	2.1	2.6	.66	19.8	3,420	4,030	4.5	5.6
Near Breeder, Breeder, U-233 Fuel													
Low Cost	250	4.2	.710	4.7	250.	1.0	1.5	.26	7.1			3.8	4.8
Low Fuel	150	1.5	.890	2.9	50.	1.0	2.2	.10	4.4			5.2	6.4
High Conversion	110	2.0	.990	3.1	40.	2.8	5.3	.028	5.9			5.3	7.5
Break even	90	1.5	1.023	2.6	26.	3.6	7.6		7.6			7.4	10.6
Breeder	80	1.5	1.036	2.5	24.	4.3	9.2		9.2			8.5	12.2

[a]Burner and converter load factor 0.75; prebreeder, near breeder, breeder are high technology, load factor 0.85; ore enrichment tails .002, 30 year plant life.

[b]Breeder fuel generation for these cases in kgm/MW_e-Yr (net): 0.25, 0.32, 0.33; note that increasing the plant efficiency reduces the breeder fuel production.

Consider the use of some carbon pebbles containing no heavy metal, perhaps attractive to reduce processing costs. To effect the same temperature peaking conditions with 10 percent of the pebbles carbon, the capital cost penalty is estimated at 0.12 mill/kW_e-hr, a significant penalty likely making such use uneconomical.

Consider the use of fueled and unfueled pebbles, instead of only one. It appears possible to effect nearly the same temperature peaking conditions with selective distribution of heavy metal and choice in the fraction of each type of pebble used as with a single pebble, if the residence time is relatively long, incurring no significant penalty. However, deviation of the pebble distribution from the ideal would cause increased temperature peaking and an associated penalty which should be assessed. In the case of a relatively short residence time, as would be necessary to effect a high breeding ratio, there seems to be significant penalty, as much as 0.4 mill/kW_e-hr, offsetting the fuel cost economic incentive.

Once-recycle of fertile pebbles from the core or from a radial blanket does not appear to incur significant penalty. However an internal radial blanket does increase the power density for a given core size, and use of 10 percent of the cross sectional area for blanket is estimated to add 0.10 mill/kW_e-hr. A lower bulk coolant temperature would also be expected to incur further penalty.

Once-recycle of fueled pebbles without reprocessing shows advantage for a prebreeder, but the cost penalty is estimated at 0.25 mill/kW_e-hr.

Radial power density flattening shows clear advantage. Considering a reasonable degree of flattening, the penalty without flattening is estimated at 0.27 mill/kW_e-hr, plus the contribution from a lower bulk outlet coolant temperature.

Assuming that the plant efficiency depends directly on the difference between the coolant outlet and inlet temperatures, and only 10 percent of the flow was ineffective in removing heat, the associated penalty is estimated to be a reduction in the efficiency of energy conversion from 0.4 to

$$(0.4)\ \frac{1000 - 250}{925 - 250} = 0.36\ ,$$

and this incurs a total capital cost penalty of 1.62 mill/kW_e-hr, a most important aspect to consider.

Additional information would be required to determine if there is economic justification for the development of this concept. The analysis depends on capital costs, processing costs, the effective worth of money (the discount factor), the likelihood of timely introduction with the necessary commitment of the industry, and the eventual use in process heat and electric power services.

SECTION 12: REGARDING THE CAPABILITY FOR CORE DESIGN ANALYSIS

Many different computer codes are used to support the design and licensing of a nuclear plant, and one code may be used in different ways for different purposes. In the design phase, usual practice is to enhance the available capability for analysis to satisfy the needs as identified during the effort. In this section we address the major requirements for analysis of a pebble bed reactor core to support design and operation with emphasis on the core performance. Extension of the analysis capability now used to project performance of this reactor concept is considered.

Power Density (Local Temperature)

The peak pebble power density must be kept below some design value to hold the limiting temperature of the fuel below an acceptable value. Coolant flow and properties are involved as are the pebble properties. Thus a thermal hydraulics calculation is needed coupled to a neutronics exposure calculation to assess conditions over the reactor history. The effects from and requirements for the control of xenon oscillation and to provide override after shutdown must be examined. If two pebble types are involved, the situation is further complicated by feedback from the distribution of the pebbles according to some probability functon. Further complication comes from the variation in residence time of pebbles across the reactor, pebble redistribution and changing pebble packing fraction. In a large reactor, severe roll of the flux around the reactor (azmuthal) is expected without control.

Reliable two-dimensional neutronics calculations are required with exposure treated and the thermal hydraulics problems solved. Three-dimensional neutronics calculations will be required to assess the short time xenon oscillation behavior with its control, and adequacy of this control and the associated instrumentation, and solution of the thermal hydraulics problems in three dimensions with feedback to the core nuclear properties. Such three-dimensional calculations can be avoided only if judged to be prohibitive in cost, as they once were. Much supporting analysis can be done treating only two dimensions, but a rather large uncertainty factor would have to be assigned to results of such analysis requiring lowering the core average power density, either reducing the capacity of the plant or increasing the reactor size. There may well be a practical limit on the core size. Three-dimensional diffusion theory neutronics capability is available but not thermal hydraulics and feedback. Even the adequacy of two-dimensional steady state thermal hydraulics to account for the fine scale remixing of coolant flowing over pebbles when modeling a large core remains to be demonstrated.

Control

Control of the reactor must be demonstrated by reliable calculations, through start up, the operating history, load changes, and following shutdown. The amount of control to be vested in pebble management must be carefully confirmed by thorough analysis. The amount of control to be vested in control rods must be confirmed by thorough analysis. Undoubtedly some three dimensional calculations must be made and likely some of these will have to be done with the Monte Carlo approach for accurate representation of control rods in three dimensions to effect a high level of reliability, capability which exists.

Short time behavior must be assessed which requires coupled neutronic kinetics, thermal hydraulics calculations. Primary concern are the response to possible neutron balance perturbations, self-regulation capability, control requirements and the necessary rates of reactivity removal and required instrumentation for this. Three-dimensional calculations may be required. If fuel is loaded in only one of two pebble types, then the behavior will be quite different than if a full temperature rise were sensed by the fertile material (decreased Doppler coefficient). Behavior of an initial core will differ from that later in life as U^{233} builds in. The calculations which will be required depend on the design and mode of operation and the considerations of most importance. Methods development is needed to treat the three-dimensional problems, specifically for the thermal hydraulics and also the neutronics at a lower cost than even finite-difference diffusion theory capability available. Close coupling of the neutronics thermal hydraulics calculation is needed with feed-back for analysis at reasonable cost.

Exposure Effects and Activity Levels

Exposure effects must be analyzed. Here the basic information is experimental measurement of such effects as caused by atom displacement from nuclear reactions including fission and generation of helium and fission products. Exposure information is generated by nuclear calculations which provide sufficient detail for assessment of the amount of exposure. Then analysis of stress, creep, nuclide transport, etc. is done as necessary to establish suitable performance of the components over the design life and to show activity levels will be below design level. Enhanced capability is needed to produce information about fission product behavior and uclide transport in general.

Reactor Shutdown

The requirements for safe shutdown must be satisfied and analysis must be done to demonstrate this. Short time thermal hydraulics analysis is required to demonstrate the absence of problems after shutdown. Insurance against recriticality from $Pa^{233} \rightarrow U^{233}$, Xe^{135} decay must be demonstrated. Some of the required effort can be done treating two dimensions, but basic three-dimensional capability is needed to assess such effects as localized reduction in coolant flow.

Resonance Shielding

A reliable calculation of resonance shielding is needed which will account for such primary aspects as more than one pebble type, lumping of the actinides in kernels within the core of the pebble, and resonance overlap. Feed-back of temperature and nuclide concentration changes is needed to account for variations over the core to produce accurate results. Enhancing available methods is desirable.

The Neutron Transport Approximation

The methods used in design must be able to produce an accurate estimate of neutron transport. The capability to generate reliable transport data and then use it to produce accurate solutions remains to be demonstrated. Methods development and extensive proof testing is needed.

Local Criticality

Analysis of design and operation with available advanced methods is required to assess any possibility for criticality to occur in locations near the core or in the core in the shutdown mode with consideration of possible severe damage configurations.

Radiation Shielding

Sophisticated analysis with available advanced methods is required to establish adequacy of the design for shielding considering neutron transport over the energy range and gamma ray production and transport regarding local heating and exposure.

Pebble Management

More sophisticated capability will be needed to model the management of the pebbles, especially if pebbles are recycled. An adequate scheme of modeling would seem to depend on the details of pebble flow, control, feed variation, and any procedure for recycle (such as selection by activity for partial recycle without reprocessing). Further assessment of available neutronics capability is needed to establish development needs. Not only is an accurate representation of neutron transport necessary but also at least one scheme which has a low application cost and yet produces results of reasonable accuracy. Methods development must be supported by testing against experimental measurements and also against results obtained with sophisticated methods which accurately model neutron transport effects.

Demand Load and Selective Plant Operation

Additional capability is needed to assess specific applications. For process heat generation, the likely variation in demand with time would be followed, with special consideration of the events of maximums and minimums. Impact to analysis comes from multiple services of a plant and a network of process heat loads.

For electrical power application, added sophistication is needed for analysis of a distribution grid with several reactors on line. Careful accounting of actinide mass flow rates in a system is needed to assess the inventory requirements, lead of feed material, and the effects of plant additions, outages and deletions. Of special concern is moving toward a near self-sustaining operation regarding the nuclear fuel. With different types of plants in operation on the grid, assessment must be made of the effects of different fixed and variable costs for operating different reactors, selected loading causing different load factors, and preferential operation to satisfy needs somewhat in the future.

Operation Support

Special capability will undoubtedly evolve for supporting operation to account for the reactor contents, to aid in decision making and to produce such needed information as required to interpret operating data.

German vs. ORNL Methods for Predicting Performance

Both the FRG and the ORNL methods of calculation appear sound for surveying projected performance. The German methods have rather severe limitations and available methods presently lack sophistication in treating the resonance problem. The ORNL methods lack the capability to treat temperature, nuclide density feedback and the recycle history (fuel management). Costs of both methods are high for a sophisticated calculation, and both lack automation to treat the operating history of a reactor with it held critical. The capability to perform analysis with independent methods is very nice, but is not needed by a single design group. We would expect extensions to be made in Germany to the German methods to support design effort there, and likely extensions in the US to the ORNL methods to support design effort here. (This report does not cover the assessment of the available thermal hydraulic capability made in this study.)

Quality Assurance

A reasonably high level of quality assurance must be established for the methods and data used. Qualifying these involves applying them to situations for which there are experimental results and demonstrating reliable analysis capability. Bias factors may be required, as to adjust estimated worth of central rods and pebble management to control the reactivity. Improvements to the analysis methods and adjustments in basic data may be found necessary, as well as the application of selected, perhaps special calculational procedures.

Summary

In summary there are specific calculations which are required to support design. Available methods should be extended to satisfy the requirements. Special needs lie in microscopic cross section processing and in history calculations. Effort must go into the requirements for raising the level of quality assurance in analysis to improve reliability. Major development is needed for neutronics, thermal hydraulic calculations to assess short time and very short time effects in three dimensions.

ACKNOWLEDGEMENTS

This work was done under D. E. Bartine in the Engineering Physics Division and P. R. Kasten, director of the HTGR Base Program, both of whom contributed, especially regarding strategy in analysis. J. V. Pace helped with the discrete ordinates calculations, G. E. Whitesides, and T. J. Hoffman with the Monte Carlo calculations, T. J. Burns and R. P. Renier made multiplant symbiosis calculations, and T. E. Mott and others of the Technology for Energy Corporation contributed in the thermal hydraulics area. This manuscript was typed by Ann Houston.

REFERENCES

1. K. Wirtz, "Development of Advanced Power Reactors in the Federal Republic of Germany," 1974 Advanced Reactors Conference Proceedings, Atlanta; Pergamon Press (1975).

2. G. Ivens, "AVR - HTR Operating Experience," Proceedings of the 1974 Gas Cooled Reactor Conference, Gatlinburg.

3. E. Teuchert, H. J. Rutten, K. A. Hass, "Pebble Bed HTR with Once Through Fuel Cycle," KFA Julich Report 25.4., Germany (1977).

4. E. Teuchert, H. J. Rutten and H. Werner, "Performance of Thorium Fuel Cycles in the Pebble Bed Reactor," NT 38 374 (May 1978).

5. C. Lee and L. Carruthers, private communication.

6. "Pebble Bed Thermal Breeder Fuel Cycle Considerations," GE Report (COO-4057-1, ESTD 76-08 (1977).

7. D. R. Vondy, "Interim Report on Core Physics and Fuel Cycle Analysis of the Pebble Bed Reactor Power Plant Concept," DOE Report ORNL/TM-6142 (December 1977).

8. N. M. Green, et. al., "AMPX - A Modular Code System to Generate Coupled Multigroup Neutron-Gamma Cross Sections from ENDF/B," Oak Ridge National Laboratory report ORNL/TM-3706 (1976).

9. D. R. Vondy, T. B. Fowler, G. W. Cunningham, "VENTURE: A Code Block for Solving Multigroup Neutronics Problems Applying the Finite-Difference Diffusion-Theory Approximation to Neutron Transport, Version II," Oak Ridge National Laboratory report ORNL-5062 (1977).

10. D. R. Vondy and G. W. Cunningham, "Exposure Calculation Code Module for Reactor Core Analysis: BURNER," Oak Ridge National Laboratory report ORNL-5180 (1979).

11. D. R. Vondy, "PREMOR, A Point Reactor Exposure Model Computer Code for Survey Analysis of Power Plant Performance," DOE report ORNL-5580 (to be published).

12. E. Teuchert, FRG, private communication.

13. W. A. Rhoades, et. al., "The DOT IV Two-Dimensional Discrete Ordinates Transport Code with Space-Dependent Mesh and Quadrature," DOE report ORNL/TM-6529 (January 1979).

14. M. W. Rosenthal, et. al., "A Comparative Evaluation of Advanced Converters," USAEC report ORNL-3686 (1965).

15. Resource Planning Associates, Inc., ERDA report ORNL/TM-6332 (1978).

16. E. Teuchert, "Once Through Cycles in the Pebble Bed HTR," KFA, FRG Report Jul-1470 (December 1977).

17. E. Teuchert, et. al., "The Pebble Bed High Temperature Reactor as a Source of Nuclear Process Heat," KFA, FRG Report Jül-1114-RG, V2 Core Physics Studies, (October 1974).

18. E. Teuchert, et. al., "Performance of Thorium Fuel Cycles in the Pebble-Bed Reactor," Nuc. Tech. 38 p. 374 (May 1978).

19. H. J. Rütten, C. E. Lee and E. Teuchert, "The Pebble-Bed HTR as a Net-Breeding Reactor System," KFA, FRG Report Jül-1521 (July 1978).

20. C. H. Adams, "SYN3D: A Single-Channel Flux Synthesis Code for Diffusion Theory Calculations," ERDA Report ANL-76-21 (July, 1976).

21. T. D. Gulden, et. al., "Present Thorium-Cycle Concepts and Performance Limitations," ANS Topical Meeting, Report CONF-740501 (1974).

22. L. M. Petrie and N. F. Cross, "KENO IV an Improved Monte Carlo Criticality Program," USAEC Report ORNL-4938 (November 1975).

23. A. P. Fraas et. al., "Design Study of a Pebble Bed Reactor Power Plant," ORNL-CF-60-12-5 (May 1961).

Appendix A: UNIT COSTS AND ECONOMIC MODELING

In this section we document the data used and discuss the modeling applied in determining fuel costs for economic analysis. Two basic sets of unit costs have been used called Schedule 1 shown in Table A-1 and Schedule 2 shown in Table A-2. These costs are approximately 1978 basis. Schedule 2 costs are estimates of what we expect would be used in the NASAP study. Schedule 1 costs may be more realistic, somewhat lower and reflecting an estimate of the difference between fabricating both fueled pebbles and fertile pebbles containing no fuel separately, but the refabrication cost estimate may be low. The break downs by pebble type were needed to treat two pebble types. For single pebbles we have selected data consistent with that shown.

In Table A-1, reference unit values of individual nuclides are shown for fully enriched fuel. The reference of \$45/Kgm for U^{235} was chosen arbitrarily, the U^{233} value was arbitrarily set at 1.4 times the U^{235} value, and other values were selected to reflect worths. On the throwaway cycle, the ratio of U^{235} feed rate to U^{233} feed rate is estimated at 1.32 from data in this report without recycle of the fertile pebble, and 1.29 with once recycle of it without reprocessing, for the same reactor design. Simple importance data indicates a much higher ratio, and the effect of feedback with recycle appears to increase the ratio. A source of uncertainty is the requirement for comparative conditions of exposure. With the economics model usually applied in this study (see discussion below), involving sale and repurchase of fuel discharged and recycled, and linear interest rate, the worth of produced fuel enters the calculation directly. Only with straight discounting would the results depend only on the worth of the material at the end of the reactor life and have a small impact due to remoteness in time.

Given low enriched feed, the unit worth of U^{235} was determined from the diffusion plant separation equations with fixed tails. Given ore and separative work costs, worth of fully enriched U^{235} was determined directly and worth of the other actinides, expecting Th^{232} and C, were made proportional to the values in Table A-1.

BLANK PAGE

Table A-1. Schedule I Unit Costs
(Including Shipping and Waste Disposal)

Nuclide	$/gm
Th^{232}	.029
U^{233}	63.
U^{234}	-7.5
U^{235}	45.[a]
U^{236}	-15.
Pu	0
C	.001

Nominal C/HM[b]	110	175	175	250	325	400
Primary Pebbles[c]						
[C/HM]	110	175	273	532	685	832
Fabrication ($/Kgm)	210	270	361	602	804	1006
Refabrication ($/Kgm)	420	540	722	1204	1608	2012
Throwaway ($/Kgm)[d]	185	185	185	185	185	185
Reprocess ($/Kgm)	370	550	715	1150	1400	1650
Fertile Pebbles						
[C/HM]	110	175	110	156	206	256
Fabrication ($/Kgm)	160	200	160	183	217	250
Throwaway ($/Kgm)[d]	185	185	185	185	185	185
Reprocess ($/Kgm)	370	550	370	513	607	700

[a] For low enriched, $104/kgm ore, $80/kgm eq. separative work, $3.5/kgm treatment, 0.002 fn. tails.

[b] Nominal carbon to heavy metal ratio based on 50 percent of each of the two pebble types.

[c] Note that the C/HM is made the same in the two pebbles in one case at a nominal value of 175 and lower C/HM.

[d] This number may be low by as much as a factor of 2.

Table A-2. Schedule II Unit Costs

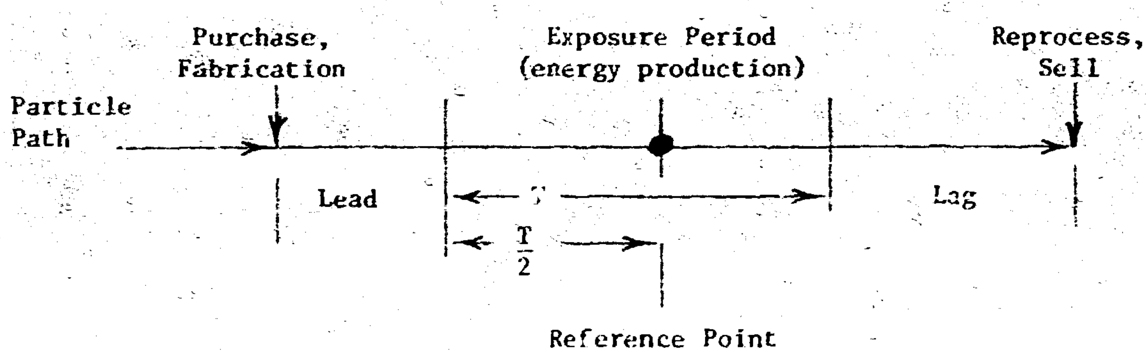
Nominal C/HM	110	175	250	325	400
Primary Pebbles					
[C/HM]	110	273	532	685	832
Fabrication ($/Kgm)	171	318	628	812	988
Refabrication ($/Kgm)	652	770	1443	1841	2223
Throwaway ($/Kgm)	185	185	185	185	185
Reprocess ($/Kgm)	345	735	1535	1899	2249
Fertile Pebbles					
[C/HM]	110	110	156	206	256
Fabrication ($/Kgm)	171	171	177	262	297
Throwaway ($/Kgm)	185	185	185	185	185
Reprocess ($/Kgm)	345	345	639	759	878

The Economic Modeling

In these calculations, the cost of produced electrical energy associated with the fuel (fuel cycle) are estimated. This is for power plant application. Results are reported in mills per Kilowatt-hr electrical which is identical to US 1978 dollars per Megawatt-hr electrical. A number of assumptions have been made in the calculations including recoverable thermal energy per fission for each of the nuclides involved, and a conversion efficiency of 0.4 electrical to thermal. Generally a plant factor, ratio of average power level to design level, of 0.75 was used except 0.85 for a breeder or a prebreeder.

Consider that the fuel cost is to be determined for a single cycle out of the reactor history. For the pebble bed reactor this means treating directly the steady state condition with continuous fueling and discharge at fixed rates. A particle of feed material is followed through its history and account is taken of feed and discharge contents of this particle. Costs of feed purchase, fabrication, reprocessing (or waste disposal) and the value of the reprocessed material are determined. Direct costs in terms of money per unit produced electrical energy are determined for each component by dividing cost or return by energy. Such secondary components as shipping are included with the primary costs.

Indirect costs were determined with an interest charge rate applied linearly. The calculation considers the time displacement between when the cost or return occurred and the midpoint of the exposure period associated with the particle, referencing to the midpoint of energy production:



Recycle after reprocessing was treated in the same way, with purchase of recycle material and make up feed, and sale of recovered material. For two particles with different reactor residence times, indirect costs were calculated separately modeling the individual histories. Throwaway fuel costs reported include waste disposal.

Long reactor histories were treated by levelizing the individual fuel cycle costs using a discount factor. Some calculations were also done with direct discounting for comparison (and elimination of the need for applying the unit costs to material recycled). Discounting was done on an annual basis implying annual collection of revenue from energy sale, not on a shorter time scale. Often the early operating history had not been calculated in this study, so the required information was approximated from available data.

Results of exploratory calculations done to study the economic modeling are shown in Appendix E.

The reference calculations were made with a simple interest rate of 0.10 and discounting at rate 0.07. Indirect costs at a different rate may be approximated by multiplying the estimated indirect cost for the interest rate of 0.10 by the ratio of a desired rate divided by 0.10. We consider these reference values for indirect costs to be representative of, or on the low side of data appropriate for utility economic evaluation in terms of today's dollars. Somewhat higher values might well be used for the operation of a private utility, especially if the calculation were to treat the decrease in buying power of and produce results in inflated dollars. However, no consideration has been given to the rate fixing aspects of utility economics nor the impacts from a burden of high investment and uncertain future of the economic history.

Point model calculations do not account for blanket material and one-dimensional calculations don't account for radial blanket material. Simple adjustments can easily be made and were made in this assessment, but the uncorrected, raw information is reported consistent with the mass balance data.

Fuel Cycle Cost Calculations

Optimal reactor performance is based upon a combination of economic feasibility and attractive neutronic characteristics (low ore requirement and/or high conversion ratio, etc). Reactor designs ranging over a variety of design parameters are compared in the base one- and two-dimensional steady-state, continuous flow reactor calculations. In order to evaluate the relative economic feasibility among various designs, apart from symbiosis studies, the mass flow data resulting from these calculations was used to determine fuel cycle costs and to identify an economic optimum.

Given equilibrium mass flow data, fuel cycle costs (direct and indirect) for a single equilibrium cycle are calculated directly as outlined in the previous section. Reported fuel cycle costs, however, are average cycle cost for the entire reactor lifetime. Account is taken for: (1) charges for initial reactor inventory (indirect fuel costs and fabrication costs); (2) credit for radial blanket (fertile pebbles) recycle to the active core without reprocessing (thus reducing the amount of fertile feed to the core); and (3) charges for an increased fabrication unit cost for recycle with reprocessing. For throwaway cycles a fuel cost for reprocessing and selling burned fuel is calculated, but the fuel is not recycled, and clean fuel fabrication costs are used for the entire reactor lifetime.

The charges associated with initial inventory include direct and indirect charges for fabrication of the first core pebbles and an indirect charge for the cost of fuel in the first core. Thus, for

F = unit fabrication cost, \$/KgHM

I = BOL heavy metal inventory, Kg

P = electric power rating (1200 MWe)

L = plant load factor

B = plant lifetime, yrs (30 yrs)

X = fabrication loss fabrication,

then

$$C = \frac{FI}{8760\ PBL(1-X)} \qquad \text{(A-1)}$$

where C is the additional direct charge, added to the equilibrium costs associated with the fabrication of the initial inventory. An indirect charge factor for both the initial fuel cost and fabrication cost, R, is determined by

$$R = (1+ST)(BQ)/[1-(1+Q)^{-B}] - 1.0, \qquad \text{(A-2)}$$

where

S = linear interest rate

T = fabrication lead time, yrs

Q = discount factor associated with worth of money (0.7 for example).

The extra indirect fabrication cost of the initial core over equilibrium costs is CR.

The extra indirect fuel cost associated with core fissile loading (inventory) over reactor lifetime is denoted by K where

$$K = \frac{\sum_i a_i b_i}{8760\ PBL(1-X)} \cdot R; \qquad \text{(A-3)}$$

a_i is the cost associated with actinide i in \$/Kg, b_i is the feed rate of actinide i in Kg/D, and R is given by Eq. (A-2).

Two-dimensional reactor problems with a radial blanket consisting of fertile pebbles flowing down alongside the core were analyzed. An economic advantage results from recycling the fertile pebbles in the blanket through the active core because of the reduced external feed requirements. Thus, for the steady-state, continuous flow condition in which the fraction of the total number of discharged fertile pebbles (core and blanket) available for recycle is denoted by X, the fabrication and reprocessing direct costs without recycle are reduced by a factor of (1-X) when recycle is considered. The indirect charges associated with average residence times in the core and blanket of T_c and T_b respectively are proportional to $X(T_b+T_c) + (1-2X)T_c$ with recycle and to $X\ T_b+(1-X)T_c$ without recycle; the expressions are identical and indirect costs are essentially the same whether or not recycle is considered.

For closed reactor cycles the fuel is reprocessed and recycled. The refabrication cost of recycled material is higher than the fabrication cost of fresh material because of the remote handling requirement. The recycled material is unavailable for a certain time period after reactor startup as fuel is reprocessed and refabricated. For a time lag period of L and a fabrication direct cost for clean fuel calculated at equilibrium of C_c^d (mills/Kwhr), the fabrication direct cost averaged over reactor history, C_t^d, is given by

$$C_t^d = [1 + (\frac{B-L}{B})(\frac{U_r}{U_c} - 1)] \cdot C_c^d, \qquad \text{(A-4)}$$

where B = reactor lifetime in years

U_r = unit cost of fabricating recycled fuel, \$/KgHM

U_c = unit cost of fabricating clean fuel, \$/KgHM.

The indirect charge averaged over life, C_t^i (mills/Kwhr), is

$$C_t^i = (C_c^d + C_c^i) \cdot \frac{1-(1+Q)^{-L}}{1-(1+Q)^{-B}} + (1+SL) \cdot \frac{1-(1+Q)^{-(B-L)}}{1-(1+Q)^{-B}} \cdot \frac{U_r}{U_c} - C_t^d, \qquad \text{(A-5)}$$

where C_c^i = indirect cost for fabricating clean fuel

Q = discount factor

S = linear interest rate.

Note that C_c^d and C_c^i are calculated directly from the equilibrium mass flow rates, and the fabrication costs for closed cycles using recycled fuel is adjusted using Eqs. (A-4) and (A-5).

Appendix B: RESONANCE SHIELDING MODEL

The resonance shielding model is a single-level, Nordheim Integral treatment.[23] The calculations are performed using the NITAWL module of the AMPX code system 8. The NITAWL code reads as input a master library of cross-section data; for the PBR analysis, the master library has a 123 energy-group structure for all nuclides. For each nuclide with resonance data, the code selects the range of energy groups containing resonance parameters and produces energy and spatially shielded cross sections for fine groups in the resonance range. Each nuclide with resonance data is treated individually; all remaining fine group cross sections are passed through NITAWL unchanged.

As input the code requires a Dancoff Factor for each nuclide with resonance data. The Dancoff Factor is the probability that a neutron leaving the surface of lumped absorber containing nuclide i will have its next interaction with another lumped absorber containing nuclide i. For a bed of pebbles cooled by a non-absorbing gas, an expression for the Dancoff Factor was developed based upon transmission probabilities for spherical shells, the transmission probabilities being calculated analytically as a function of sphere shell thickness and total cross section of each shell. For pebbles of lumped absorber coated with a graphite shell, the transmission probabilities through the graphite coating are defined as follows:

T_k^{OI} ≡ the probability that a neutron leaving the lumped absorber of pebble k with a random angular distribution will reach the outer surface of the pebble without interacting with the graphite coating.

T_k^{IC} ≡ the probability that a neutron entering the outer surface of pebble k with a random angular distribution will reach the lumped absorber in that pebble without interacting with the graphite coating.

T_k^{OO} ≡ the probability that a neutron entering the outer surface of pebble k with a random angular distribution will escape from the pebble without interacting with the graphite coating and without entering the lumped absorber in pebble k.

These transmission probabilities are a function of the absorber radius and total cross section of the graphite shell. For Pebble Bed calculations, the graphite coating density is fixed and T^{IO}, T^{OI}, and T^{OO} can be calculated as a function of absorber radius alone.

For the two-pebble-type reactor designs studied, there exist two distinct absorber lump designs: the primary pebble meat and the fertile meat. Once the primary and fertile meat radii are known, the graphite-coating transmission probabilities are calculated for the primary and fertile pebbles. The Dancoff Factor can be expressed in terms of the graphite-coating transmission probabilities and transmission probabilities of the absorber lumps. However, a simpler and more useful expression for the Dancoff Factor results if the lumped absorber is assumed to be black (all neutrons entering the lumped absorber with an energy near a resonance peak will interact with the lumped absorber) in which case the problem of calculating the Dancoff Factor for nuclide i is then reduced to a geometrical problem of determining the probability that a neutron escaping from the absorber lump containing nuclide i will pass through the pebble graphite coating without interacting with the coating and will reach another absorber lump containing nuclide i. This probability can be expressed solely in terms of the graphite-coating transmission probabilities of the primary and fertile pebbles; two cases exist, the Dancoff Factor for nuclide i, F_i, being expressed for each case as follows, with the additional assumption that there is a random distribution of the two pebble types about a reference pebble:

Case 1 - Nuclide i is found only in the primary fertile pebble

$$F_i = X_k T_k^{OI} T_k^{IO} \left[\frac{1}{1-(X_k T_k^{OO} + (1-X_k) T_c^{OO})} \right] \tag{B-1}$$

where k represents the pebble type (primary or fertile) containing nuclide i; T_c^{OO} is the transmission probability through a solid graphite ball [resulting from the assumption that a neutron passing through a pebble not containing i will react on the average with the graphite in the meat or coating; note that $T_c^{00} = T_k^{00}$ (r=o)]; X_k is the type k pebble fraction of all pebbles in the reactor. For most applications X_k = 0.5.

Case 2 - Nuclide i is found in both the primary and fertile pebbles.

$$F_i^k = T_k^{OI}(X_p T_p^{IO} + (1-X_p)T_f^{IO}) \cdot \left[\frac{1}{1-(X_p T_p^{00}+(1-X_p)T_f^{00})}\right] \quad \text{(B-2)}$$

where p and f subscripts represent primary and fertile pebbles respectively; F_i^k is the Dancoff Factor associated with nuclide i in pebbles of type k. Dancoff Factors for various reactor pebble designs are listed in Table B-1. The results shown in Table B-2 indicate that the black absorber assumption is accurate.

The NITAWL code also requires as input the temperature of each resonance nuclide. Resonance data for Th^{232} is shown in Table B-3 as dependent on temperatures used in the calculation. Values of the multiplication factor are also shown as obtained with a buckled point spectrum model for fixed nuclide concentrations. This data indicates the temperature coefficients and the decrease in keff with increase in temperature. An uncertainty lies in the use of a low temperature in the calculational model to account for shielding in the kernals since the kernals and graphite matrix are being treated as a homogeneous absorber lump (the pebble meat).

The resonance nuclides for the PBR are listed in Table B-4. The resonance integrals associated with the pebble designs of various reactor types are also listed.

The use of constant temperature cross sections causes the effective thickness of a blanket to be smaller than the actual thickness used. Consider the inlet axial blanket to be at 500° C instead of 900° C. Considering only the Th^{232} fertile pebble epithermal cross section, the ratio of thorium cross sections for the lower to higher temperature is .93. (The actual difference in macroscopic removal cross sections considering

Table B-1. Dancoff Factors for Various Pebble Designs

	Nominal C/HM	Primary Pebble		Fertile Pebble	
		Meat Radius (cm)	Dancoff Factor	Meat Radius (cm)	Dancoff Factor
Low Enriched Feed	300	2.500	.444	--	--
(Single Pebble)	450	2.500	.444	--	--
Medium Enriched Feed	325	2.381	.183	2.356	.174
(Two Pebbles)	450	2.381	.183	2.332	.167
	550	2.381	.183	2.324	.166
High Enriched Feed (Two Pebbles)					
Breeder	90	2.5	.444	2.5	.444
Burner/Converter	175	2.0	.273	2.500	.345
	250	1.627	.175	2.347	.240
	325	1.505	.134	2.170	.178

scattering is, however, small.) Account should be taken of the temperature differences in more refined calculations, but the discrepancy is acceptably small for survey calculations since the effect and magnitude are known to first order.

Note on Fuel Packing

After the local capability to perform thermal hydraulics calculations became available, it was found that concentrating the fuel toward the center of a pebble seriously increased the peak temperature in the pebble. Thus it is desirable to effect a distribution of the heat source over as large a volume as possible within the constraint of maintaining a center graphite shell of required thickness to effectively contain the products of fission.

Table B-2. Effective Transmission Probabilities and Dancoff Factor as a Function of Fuel Absorption Cross Section[a,b]

	Σ_a (barns)	T_X^{00}	T_{XI}^{00}	T_X^{00E}	Dancoff Factor[c]
r = 1.50	1000	.2082	.5040	.2373	.0375
	10000	.2082	.0171	.2092	.0717
	∞	.2082	0.0	.2082	.0729
r = 2.00	1000	.1813	.4070	.2443	.1214
	10000	.1813	.0096	.1828	.1875
	∞	.1813	0.0	.1813	.1890
4 = 2.50	1000	.1306	.3320	.2588	.3480
	10000	.1306	.0062	.1330	.4453
	∞	.1306	0.0	.1306	.4441

[a] If the absorber lumps are not assumed to be black, Eqs. (B-1) and (B-2) still apply if (1) $T_i^{00} \equiv T_i^{00E} = T_i^{00} + T_i^{IO} T_{iI}^{00} T_i^{OI}$ where T_{iI}^{00} is the transmission probability through the absorber, and if (2) $T_i^{IO} \equiv T_i^{IO}$ $(1 - T_{iI}^{00})$ in the numerators of the expressions. Note that by definition $T_C^{00E} = T_C^{00}$.

[b] Pebble radius equals 3.0 cm, heavy metal atom density in the meat is 3.6×10^{-4} atoms/bn-cm. The notation "r" refers to meat radius. The outer carbon shell has an atom density of .0878 atoms/bn-cm and a total cross section of 4.66 barns.

[c] Assume Eq. (B-1) applies and $X_K = 1.0$.

Table B-3. Point (infinite medium) Spectrum Calculation

Temperatures (°K)			Th^{232} Resonance Integral		k_{eff}
Graphite kernel	Thermal	Resonance	Primary pebble	Fertile pebble	
1273	1273	1273	44.85	38.25	0.97974
1000	1100	1100	43.77	37.24	0.98479
1000	900	1100	43.77	37.24	0.98479
900	900	1100	43.77	37.24	0.98501
900	900	900	42.34	35.91	0.99158
573	573	573	39.29	33.14	1.00725
573	500	500	38.42	32.37	1.01117
293	293	293	35.31	29.64	1.03082
293	900	293	35.31	29.64	1.03082

Table B-4. Resonance Nuclides and Resonance Integrals of Interest

Nuclides with Resonance Data:

Th^{232}	Pa^{233}	U^{234}	U^{236}	U^{238}	Eu^{153}
Pu^{234}	Pu^{240}	Pu^{241}	Pu^{242}	$Am^{[illegible]}$	Sm^{151}

	Resonance Integral[a]	
	U^{238}	Th^{232}
LEU — Single Oxide		
C/HM = 300	102	—
C/HM = 450	124	—
C/HM = 600	139	—
C/HM = 850	160	—
MEU — Separate Pebble Types		
C/HM = 325	119	53
C/HM = 450	137	58
C/HM = 550	150	60
HEU — Separate Pebble Types		
Breeder C/HM = 80	—	30.3
C/HM = 90	—	31.3
C/HM = 100	—	32.1
C/HM = 110	—	32.9
Converter C/HM = 250	227	44 (fissile pebble)
	—	37 (fertile pebble)
C/HM = 400	245	47 (fissile pebble)
	—	41 (fertile pebble)

[a]The effective resonance integral associated with the actual cross sections used was generally somewhat higher than the values shown as calculated directly due to the flux weighting.

APPENDIX C: Broad Group Cross Section Collapse Procedure

The master library with a 123 energy-group structure and with energy and spatially shielded cross sections for fine groups in the resonance range is collapsed to a few-group structure in the XSDRNPM module of the AMPX code system.[5] The XSDRNPM module is a one-dimensional discrete ordinates code which computes the spatially dependent energy spectrum and collapses all cross sections to a desired few-group structure. An option is available to perform an infinite medium (point) calculation over the entire energy range or for any number of energy groups.

The master library contains shielded resonance cross sections as output from NITAWL (see previous section), and in NITAWL the cross-sections for fine groups covering the resonances of a nuclide are spatially smeared over the pebble volume. An infinite-medium calculation is performed in XSDRNPM for groups in the resonance range to prevent double shielding the resonance cross sections over the space variable.

Most of the cross section collapsing was carried out using a point calculation over the entire energy range because of an error in the XSDRNPM code that caused an erroneous calculation of few-group transport cross sections when the one-dimensional spherical geometry was treated explicitly. This problem was later resolved and cross sections resulting from point and one-dimensional calculations were compared for otherwise identical reactor core analysis.

Appendix D: THE STEADY STATE, CONTINUOUS FUELING MODEL

When the effort on the analysis of the pebble bed reactor started in 1977 at ORNL, we had inadequate local capability to directly characterize the reactor performance. Although some analysis capability had been developed under fluid fuel projects, our base methods development has been directed at fixed fuel concepts. The old CITATION code could have been used, but not effectively, and the newer VENTURE diffusion theory code would not be very useful even given depletion capability, lacking fuel management capability. Whereas considerable methods development may often be justified to support design and operation, only a modest effort could be supported on this project. We rejected the possible course of action of using the German methods being imported by the staff at LASL, because the contribution would be small. Application of independent methods would make a more worthwhile contribution.

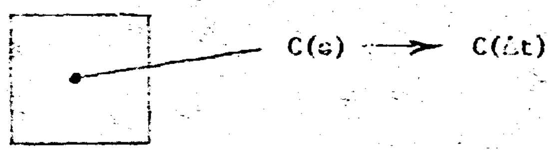
The most important information needed was a one-dimensional axial multigroup neutron flux distribution for a critical reactor at steady state given the necessary continuous feed composition; next important would be the two-dimensional flux distribution. This solution would be for a point in time adequately representing a throwaway cycle (recycle could be considered with successive passes of reprocessed material). An iteration process would be required to effect the solution by adjusting the fuel enrichment from an initial estimate and simultaneous resolution of the flux distribution.

We elected to implement the capability to solve this problem in the computation system incorporating the VENTURE finite-difference diffusion theory neutronics code. This code and the companion exposure code BURNER have been developed with DOE funding primarily for three-dimensional fast breeder calculations. These codes are modules in a flexible system, admitting use in a global iterative scheme. Further, the VENTURE code has effective capability for solving the criticality search problem by adjusting the fissile loading, and would require no major changes. (A few minor changes were found to be desirable and the criticality search procedures have been improved by feedback from pebble bed and other types of problems.) Capability is available to solve one, two and three-dimensional problems.

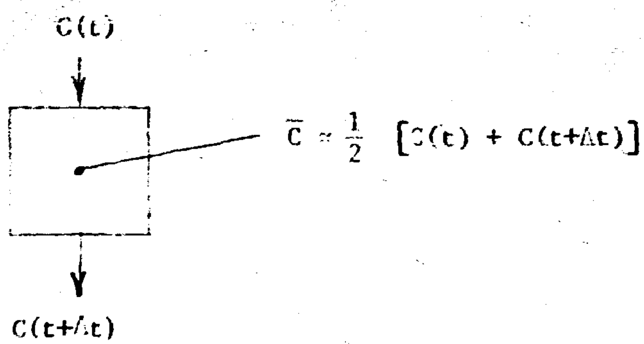
BLANK PAGE

Changes were required to the exposure code BURNER, and the fixed fuel expsoure procedure was paralleled with one for continuous fueling.

Consider that material in a zone is to be exposed for some interval of time in the fixed fuel model,



The continuous fueling model involves exposure of material entering to determine what leaves,



That is, the nuclide concentrations entering a zone are exposed to the zone average flux for the zone resonance time to produce exit concentrations, and hence those entering the next zone along the flow path, and a simple estimate is made of the average zone concentrations. The fixed fuel and the continuous fueling calculations are very similar.

A natural scheme was already imbedded in the codes to treat two pebbles in that zone compositions can be treated and also a subzone scale of compositions. As the development effort and application continued it was found to be readily possible to model complicated situations including

- Different residence times for two different size pebbles,
- Blanketing with one pebble type,
- Flexible pebble recycle without reprocessing,

- Fixed fuel blankets.
- Variation in radial residence time and feed enrichment and also internal radial blanketing with thorium pebbles containing no fuel as feed,
- Subsequent behavior on a short time scale as a fixed bed, as to examine control rod worth, Xe override, the effect of change in power level, and stability.

Consider one difficulty. The neutronics code produces only zone power density without addressing the subzone scale separately. Zone and subzone power density peaks are now edited by the BURNER code as well as the cumulative power along each flow path, allowing interpretation by pebble type when two are involved. The capability to write an interface data file with power densities for each pebble type was added to BURNER to support thermal hydraulic and temperature peaking analysis.

Comments are in order about the global iteration process loop over successive neutronics, exposure calculations. The after-exposure average nuclide concentrations produced by BURNER go to the neutronics code. It adjusts the fuel contents in selected zones as instructed to satisfy the critical state. Simultaneously the fuel contents of feed boxes, false zones not in the geometric mesh, are adjusted in accordance with instructions. Thus the reactor contents as determined by BURNER depend only on the feed material and the latter is adjusted by the neutronics code in the process of producing a new estimate of the flux distribution. Complete convergence of the problem would occur when no change in the fuel density is required in the neutronics calculation.

A number of options are available to accelerate the rate of convergence or to stabilize oscillatory behavior, but these are not now automatically changed during a calculation. The criticality search specifications are flexible; more fuel may be added to the feed boxes than to the reactor zones, or less. The nuclide concentrations produced by BURNER may be weighted with those supplied to it, and a weighting may be made between two successive flux distributions for use in BURNER. The most effective step of acceleration was identified in tests with the point model discussed in Appendix E: the average reactor power is often poor after the exposure calculation (usually low).

so the flux level can be renormalized and the exposure calculation repeated to improve the results. Finally, the closer the initial nuclide concentrations are to the solution, the faster an acceptable solution can be effected, so we try to start with a reasonable set of nuclide concentrations. This is simple to do in some parameter studies, but not when the geometric description is altered, as to change a blanket size. It generally helps to put more fuel in the top of the core (near the inlet) rather than use a uniform distribution for the initial estimate of the fissile loading.

One-dimensional problems generally converge quite rapidly with no need for taking special action other than repeating the exposure calculation once each pass to improve the power level.

Two-dimensional problems do not converge rapidly when the core has a relatively large radius causing weak neutronic coupling. Severe radial flux oscillation occurs which must be dampened: a high local flux level causes high burnup which results in a low flux level the next pass. A combination of reexposure to effect the desired power level, weighting of successive flux distributions, and weighting between after-exposure and before-exposure nuclide concentrations effects acceleration. Selected search specifications for the neutronics calculation help, but unfortunately driving is often required in the early iterative history and dampening in the later history (of the feed box fuel concentration changes). We continue to seek a needed improvement in the procedure and may have to implement a major change to reduce the cost of calculations and improve reliability by effecting better convergence.

A number of tests have been made to prove that the iterative procedure converges to a correct solution. Some of these are reported in reference 1. The use of dampening schemes impacts the assessment of convergence toward a true solution, especially when there is an oscillation involved. Typically in a computer run, a final pass has been made without dampening and without a criticality search (to determine k_{eff}). Experience in the interpretation of results has come from this effort improving our ability to judge the adequacy of results.

The results of successive iterations do not usually display a simple dominating error vector decay, but the results of alternate sets often do. This behavior is not well understood, but it appears to be driven by a feedback effect, and recognizing it allows an extrapolation procedure to be used which is reasonably reliable. In vector notation, we consider a linearly independent set of error vectors, with the dominant one behaving iteration n as

$$E_n = \phi_n - \phi_\infty = A\mu^n ,$$

where μ is the eigenvalue of the error vector, hopefully <1 for a convergent process. Taking any integral result such as the fissile loading f, the recursion relationship above yields (not matrix notation now, but the scalar integral),

$$\mu = \frac{f_n - f_{n-1}}{f_{n-1} - f_{n-2}} ,$$

and extrapolation to the apparent solution is given by

$$f_\infty = f_n + \left(\frac{\mu}{1-\mu}\right)\left(f_n - f_{n-1}\right) .$$

Hopefully one value of μ may be used for all of the key results including power density peak and nuclide feed and discharge rates. The use of alternate iterative results involves the application of

$$\gamma = \frac{f_n - f_{n-2}}{f_{n-2} - f_{n-4}} .$$

$$f_\infty = f_n + \left(\frac{\gamma}{1-\gamma}\right)\left(f_n - f_{n-2}\right) .$$

Results from the iterative history for a problem are shown below. The iterative process was stopped below a usual level of convergence and extrapolation of results for alternate iterations is shown:

Iteration	Fissile Material Feed (Kgm/D)	Fissile Material Loading (Kgm)	Conversion Ratio	Peak Pebble Power Density (W_{th}/cc)
0		Unknown		
1	1.9065	1,288	.6201	29.01
2	2.1041	1,490	.5800	41.43
3	2.1990	1,581	.5625	37.79
4	2.1722	1,544	.5678	40.65
5	2.2086	1,576	.5609	39.22
6	2.1988	1,562	.5628	40.36
7	2.2139	1,575	.5600	39.81
8	2.2104	1,569	.5607	40.21
Extrapolated (n=7)	2.220	1,574	.5589	40.54
Extrapolated (n=8)	2.215	1,572	.5598	40.14

Note that the examples of extrapolation shown above for different alternate sets of data leave something to be desired in this case as the results are yet not very close to a solution. The extrapolated data shown are likely within the accuracy of the calculation, but might not admit assessment of the effect of parameter changes.

In summary, the steady state, continuous fueling model is applied by a direct iteration process to establish the critical reactor state representing a point in time, and the results are used to characterize the nuclear performance.

Other Neutronics Methods

The synthesis code SYN3D[24] from ANL has been incorporated into the local computation system containing the VENTURE code. The latter is used to generate one-dimensional trial functions for two-dimensional problems and two-dimensional trial functions for three-dimensional problems. At the time this is written only a few test calculations have been made and the modest level of effort continues on proofing the method and exploring its utility. It appears that there is serious difficulty from data file proliferation using this synthesis code.

A scheme which appears very attractive for survey calculations would generate importance data for subsequent use. If the importance to the neutron accounting of each nuclide in the feed stream could be established, such data would allow a direct treatment of fueling and recycle at low cost. Sophistication would be required to produce discharge mass balances, power density peaking and exposure, and to account for variation in feed rate, carbon to heavy metal, and resident time. It is not clear that reliable results could be obtained over a wide range of values for the parameters, nor that all the desired results could be obtained. However, the continuously fueled reactor appears especially amenable to the generation and the use of such data. Further investigation and testing are recommended because the return would appear to justify the effort in a continuing program.

Appendix E: THE POINT REACTOR MODEL FOR SURVEY CALCULATIONS

A severe challenge is presented by the problem of estimating the reactor performance over a long operating history. Drastic compromises must be made to allow the calculation to be done at all. Any sophistication in the neutronics model significantly adds to the cost of calculation. There are so many parameters involved when the fuel management possibilities are explored that some scheme of simple modeling is needed for survey calculations. In this effort the results obtained with the point model were used to infer behavior and fuel costs considering the results obtained with the steady state, continuous fueling model treating one or two dimensions. Of special interest here are the predictions of core behavior and the fuel cost calculation.

A procedure of calculation was implemented to follow long operating periods, the code PREMOR.[11] Minimum requirements for reasonable results were satisfied to minimize computation cost. Between successive fuelings a single point, two-group neutronics problem is solved, but the average power level is determined by integration over the interval. Selective, delayed recycle of reprocessed fuel is accounted for and makeup requirements are satisfied by an iteration procedure which effects a critical state at a reference point. One or several batches of material are considered to be resident, each discharged and refueled successively to model either a reactor with continuous fueling or a fixed fuel reactor partially refueled. Thirteen actinide nuclides are treated (Th, U, Pu systems), a fixed structure, moderator, coolant pseudo nuclide, and ten fission product nuclides. Flexibility is allowed regarding the estimate of and variation in the fast-to-thermal flux ratio, an approximation is used to allow the thermal flux to be batch dependent, and a microscopic cross section correlation is available. Fuel cost calculations are done for the mass balance histories with account for low uranium enrichments when applicable. Elaborate edits range from ore requirements, exposure, conversion ratio and doubling time, to nuclide importance, the distribution of neutron absorptions and effective eta values.

BLANK PAGE

The code has been enlightening regarding effective direct iteration procedures and fuel cost evaluation. It was used in this study for thirty year reactor survey calculations. Much effort has gone into its development and testing of the modeling.

The challenge in application of a simple model is to effect reliable results compared with sophisticated calculations. Not only are reliable results needed for some reference situation, but also reasonable accuracy over a range of interest in the many primary variables. Model selection has not been as easy as anticipated. Key input numbers include a core neutron leakage fraction and fast-to-thermal slowing down data.

Results for a reference two-dimensional problem are shown in Table E-1. This case treats two pebbles with an axial blanket and internal radial blanket. The feed is graded to flatten the power density (which increases the required fissile feed rate). Addition of blankets tends to increase the fissile loading. Results of one-dimensional calculations are also shown with two values of the radial buckling. Silicon was left out of the one-dimensional calculations inadvertently, slightly improving the calculated performance. Results with the point model are shown over a range in values of the key variable parameters. These cases were run a sufficient number of cycles to establish the quasi steady state condition for the throwaway cycle. Note that the fissile consumption to produce the desired amount of energy depends on the model because U^{235} and U^{233} fuel are involved.

It should be noted that for the continuous fueling pebble bed simulation, conditions are estimated midway between successive batch fuelings to approximate the critical state without use of control rods. The thermal flux level could be assumed to depend on the batch, but it is not in the calculations done. Early emphasis was on applying the one batch approximation, but this model proved inadequate, so the three batch approximation has received primary emphasis. The use of more than one batch is especially desirable to reduce the exposure time between successive fuelings making the application of a single neutron balance to establish feed requirements more realistic. Also the early history of operation is more realistic and varied enrichment may be

Table E-1. Results Obtained With Parameter Variation
(1,200 MW_e plant, 5 W_{th}/cc, .95 U^{235} feed, C/HM 250, 500 cm high, 4.2 yr. residence)

Model Parameters			Fission Product Absorption Fraction	Conversion Ratio From Mass Balances	Fissile Inventory (Kg)	Fissile Mass Balance (Kg/D)	
Batches Resident	Downscatter Cross Section	Core Leakage Fraction				Feed	Discharge
Two-dimensional Reference			.1065	.620	1,632	2.232	.753
One-dimensional, B^2=0.7x10^{-5}			.1071	.637	1,493	2.060	.657
One-dimensional, B^2=3.2x10^{-5}			.1029	.595	1,641	2.281	.711
Point model cases follow:							
1	.00175	.05	.1192	.534	1,537	2.433	.692
1	.00175	.07	.1179	.516[a]	1,663	2.566	.728
2	.00175	.07	.1073	.606	1,577	2.356	.690
[illegible]	.00175	.05	.1079	.647	1,442	1.951	.634
[illegible]	.00175	.06	.1063	.630	1,498	2.029	.645
3	.00175	.07	.1045	.613	1,560	2.110	.659
3	.00175	.08	.1027	.596	1,626	2.192	.674
3	.00175	.09	.1008	.579	1,698	2.276	.692
3	.0015	.07	.1019	.614	1,722	2.188	.734
3	.0020	.07	.1065	.617	1,450	2.062	.608
4	.00175	.07	.1033	.619	1,552	2.084	.654
6	.00175	.07	.1022	.628	1,545	2.064	.651
12	.00175	.07	.1015	.627	1,539	2.048	.648
18	.00175	.07	.1013	.628	1,533	2.044	.648

[a]This is from mass balances for the simple model; reaction rates give 0.600

considered over the initial feed batches to reduce the amount of the initially loaded fuel removed during early operation (increasing the fuel exposure on the average before removal).

It should be noted that much of the data may be adjusted to effect desired results. Individual microscopic cross sections may be changed from what is produced directly by collapse over a selected fine group spectrum, but this has been avoided. The same procedures were used for these calculations. However, such data as the properties of the two lumped fission products need to be tailored such that the fission product poisoning is realistic, not only for a reference case but also for usual parameter changes. The data must be tailored to produce realistic results and the required adjustments depend on the model to be applied. It may be possible to treat the situations with and without blankets directly through the values of the core neutron leakage fractions specified, but the model is rather coarse for a fully blanketed core.

Regarding economic analysis, the fuel costs depend on the model[a] as well as the data used. Typical results are shown in Table E-2 for the economic models applied. The "cycle" results are for the quasi steady state with throwaway, and near half way through the thirty year life for recycle. The data shown indicates the direct component is different when straight discounting is done than with a linear indirect charge. The reason is that a processing loss was not taken in the mass balance accounting but was in the economics model with the indirect charge and not with straight discounting, a slight discrepancy in the data for the different models as used in this demonstration.

The base calculation applying a simple interest charge shows that the indirect cost decreases as the discount factor is increased. This is a direct consequence of the accounting for costs and return at the terminal point of the interest charges in discounting -- a lag in time for fuel purchase and fabrication and a lead in time for fuel reprocessing and sale. Increasing the discount factor has more effect on the contribution from the energy than it does on the cost factors.

Table E-2. The Effect of the Economic Model on Fuel Cost ($mill/Kw_e$ hr)

Cycle Type	Throwaway				Delayed Recycle			
History Reference	Cycle	30 Year			Cycle	30 Year		
Discount Factor		0.07	0.10	0.14		0.07	0.10	0.14
Component								
Simple Interest Charges at rate 0.10								
1 Cost (fuel, fabrication)	3.7667	3.9579	3.9579	3.9579	4.1187	4.2406	4.2406	4.2406
2 Return after Reprocessing	-.1656	-.1878	-.1878	-.1878	.5976	.7369	.7369	.7369
3 Direct (1-2)	3.9323	4.1457	4.1457	4.1457	3.5210	3.5037	3.5037	3.5037
4 Indirect	1.1900	1.0464	1.0111	.9717	1.6020	1.3377	1.2934	1.1168
5 Total (3+4)	5.1223	5.1921	5.1568	5.1174	5.1230	4.8414	4.7431	4.6205
Straight Discounting (purchase only make up fuel, annual energy accounting)								
3 Direct		4.1457	4.1457	4.1457		3.4856	3.4856	3.4856
4 Indirect		.7778	1.1587	1.6975		.9492	1.3707	1.9473
5 Total		4.9235	5.3044	5.8432		4.4348	4.8563	5.4329
Straight Discounting with Energy Discounted on a One-Quarter Year Basis								
4 Indirect		.7407	1.1276	1.6771		.9158	1.3422	1.9283
5 Total		4.8864	5.2733	5.8228		4.4014	4.8278	5.4139

[a] A more precise accounting of the linear indirect changes for discrete costs and returns was adopted after the results reported here were obtained, including adjustments to the cycle costs to approximate the long history average cost.

Results for additional variations in the model are shown in Table E-3. The number of cycles that recycle material is delayed was varied, and a recovery loss fraction was also considered in generating the mass balances.

Table E-3. Additional Effects of Modeling on the Fuel Cost (mill/Kw_e-hr)

Cycles Recycle Delay	0	1	2	1
Neutronics Recycle Loss Fraction	0	0	0	0.015
<u>Use of simple interest rate 0.10, discount at rate 0.07</u>				
Direct	3.3103	3.5037	3.4747	3.4985
Indirect	1.3330	1.3377	1.3210	1.3369
Total	4.6433	4.8414	4.7957	4.8354
<u>Only discounting at rate 0.07</u>				
Direct	3.2911	3.4856	3.4579	3.4968
Indirect	.8100	.9492	1.0580	.9486
Total	4.1011	4.4348	4.5159	4.4454
<u>Only discounting at rate 0.10</u>				
Direct	3.2911	3.4856	3.4579	3.4968
Indirect	1.1805	1.3707	1.5166	1.3696
Total	4.4716	4.8563	4.9745	4.8664
<u>Only discounting at rate 0.14</u>				
Direct	3.2911	3.4856	3.4579	3.4968
Indirect	1.6961	1.9473	2.1332	1.9455
Total	4.9872	5.4329	5.5911	5.4423

It is of interest to note that the scheme used to apply a simple interest charge and then levelizing by discounting does not accurately reflect the increase in fuel cost associated with increase in delay time and out-of-core inventory. This effect is properly reflected in the costs calculated by only discounting. There is the major difficulty that with a discrete batch fueling model, a constraint is imposed in recycle of integer cycle numbers. This is of course realistic for a partially refueled, fixed fuel reactor (one reactor system), but it may not accurately account for the delay time desired in approximating the continuously fueled reactor. The accounting is consistent with the actual mass balances when only discounting is done. The actual recycle delay time was 1.889 years per cycle delayed compared with 1.5 years considered in the cost calculation.

A value of the discount factor may be estimated from the data which produces the same indirect charges as the simple interest rate of 0.10 and discounting at a rate of 0.07. The effective discount rate is estimated at 0.091 for throwaway using data from Table E-2 and at 0.097 for one cycle delay in recycle using the data from Table E-2 which accounts for processing loss in the mass balances (three batch model). These values are reasonably close to the reference interest rate of 0.10, and indeed this value is essentially what is obtained by interpolating between the results for no delay and one cycle delay to estimate a 1.5 year real time delay.

The dependence of cost on the discount factor was illustrated in Tables E-1 and E-2. Shown below is the effect of varying the interest rate with simple interest charges and discounting at rate 0.07 (indirect charges are linear with the interest rate):

Interest Rate	0.05	0.10	0.15
Throwaway Cycle			
Indirect Charges	.7388	1.4777	2.2165
Total	5.0523	5.7912	6.5300
Delayed Recycle			
Indirect Charges	.6300	1.2600	1.8900
Total	3.6803	4.3103	4.9403

The effect on the fuel cost of a declining load factor was determined. Comparing results for a decline from an initial factor of 0.75 to 0.5 at 30 years relative to the cost for a fixed factor of 0.75, the indirect charges increased 30 percent and the total fuel cost 8 percent with discounting at 0.07.

Consider the effect of the value of the discount factor on the indirect cost associated with the initial reactor core (not capitalized). Assuming a unit cost relative to the total amount of generated electrical energy for thirty years, and discounting annually (revenue available at the end of each year) the results obtained for a 30 year life are:

Discount Factor	Relative Initial Core Fuel Cost	
	Indirect	Total
0	0	1.
0.035	0.631	1.631
0.07	1.418	2.418
0.105	2.316	3.316
0.14	3.284	4.284

Clearly the indirect cost associated with the initial fueling is significant and must [illegible] considered. The higher the discount factor the larger the indirect contribution. (Allowing for the availability of revenue from energy sale on a shorter period than annually only slightly reduces the estimate of indirect costs - for example at rate 0.07 and continuous discounting the relative indirect cost is reduced to 1.393 compared with 1.418 with annual accounting.)

[illegible] conclusion we draw from these results is that there is actually a relatively small variation in the estimated fuel cost due to possible variations in the economic model when a specific situation is treated given reference [illegible]. However, the indirect charges must be determined carefully and a [illegible] procedure for levelizing [illegible] by cycle costs is not obvious, [illegible] scheme of only discounting is apparently superior to one of simple interest charges, because the worth of produced fuel enters only for nonrecycled material late in the history, but the equivalence of rates appears to depend on the situation. The multi-batch model has been found to be far superior to the single batch model for predicting performance, but the economic modeling is significantly impacted if one attempts to apply a simple indirect interest charge and levelize cycle costs.