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MEU/Th FUEL CYCLE OPTIMIZATION FOR THE LEAD PLANT

by

M. H. MERRILL and R. K. LANE

**Prepared under
Contract EY-76-C-03-0167 \
Project Agreement No. 65
for the San Francisco Operations Office
Department of Energy**

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ABSTRACT

The reference equilibrium cycle fuel composition for the Lead Plant was specified previously by a C/Th ratio of 850 and a fuel rod diameter of 1.17 cm, which is optimal for non-recycle operation and close to optimal for recycle of bred U-233. Subsequent work has emphasized the importance of full recycle of all discharged uranium to maintain the competitive advantage of the MEU/Th cycle. Cycles with full recycle optimize at higher thorium loadings and larger rod diameters. This is an additional benefit for core design and reduces fabrication problems. New optimization studies based on full recycle lead to an equilibrium cycle composition characterized by a C/Th ratio of 600 and a rod diameter of 1.35 cm. The average packing fraction of fuel particles in the rod is 0.43. The C/Th ratio for the initial core is 350, which can also be accommodated with the 1.35 cm rod diameter. Mass flow data for 30 year operation and fuel cycle cost data have been obtained for this cycle and for several other thorium loadings. The 30-year levelized fuel cycle cost is 18.3 mills/kwhr for all-uranium recycle and 19.3 mills/kwhr for recycle of U-233 only. The 30 year U_3O_8 requirements are 3244 and 3750 MT/GWe respectively at 0.70 capacity factor and 0.2 percent tails enrichment.

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1. Summary

The reference equilibrium cycle fuel composition for the Lead Plant was specified previously ⁽¹⁾ by a C/Th ratio of 850 and a fuel rod diameter of 1.17 cm. This composition is optimal for non-recycle operation and close to optimal for recycle of bred U-233. Subsequent work on the Lead Plant and on cycles submitted for government studies (NASAP/INFCE) has emphasized the importance of full recycle of all discharged uranium to maintain the competitive advantage of MEU/Th cycle. Cycles with full recycle optimize at higher thorium loadings and larger rod diameters. This is an additional benefit for core design (easier fuel zoning and better heat transfer) and reduces fabrication problems.

Some new optimization studies based on full uranium recycle have therefore been completed. An additional change in the new studies is the adoption of an enrichment of 12% for recycled denatured U-233 in place of the 15% value used in previous studies.

The new optimized equilibrium cycle composition is characterized by a C/Th ratio of 600 and a rod diameter of 1.35 cm. The average packing fraction of fuel particles in the rod is 0.43. An alternative composition with very slightly lower U_3O_8 requirements would be C/Th=600, $D_{rod}=1.245$ cm (the present FSV size), and an average packing fraction of 0.50. The larger diameter gives greater flexibility in the approach to equilibrium, when the loadings in some segments may exceed those required at equilibrium. If the loadings of these segments can be reduced in the course of more detailed design work, the use of the FSV rod size, for which there is considerable manufacturing and irradiation experience, would be preferable.

The re-optimized C/Th ratio for the initial core is 350, which can also be accommodated with the 1.35 cm rod diameter.

Mass flow data for 30 year operation and fuel cycle cost data have been obtained for the reference cycle and for several other thorium loadings. The 30 year levelized fuel cycle cost is 18.3 mills/kwhr for all-uranium recycle and 19.3 mills/kwhr for recycle of U-233 only. The 30 year U_3O_8 requirements for an 880 Mwe steam cycle plant are 3244 and 3750 MT/GWe respectively, for a capacity factor of 70% and a uranium tails enrichment of 0.2%.

2. Criteria and Assumptions

The general requirements to be met by the MEU/Th fuel cycle in the Lead Plant are listed in Table 1. In essence, they call for an economic optimization within the constraints of current HTGR fuel technology. This reflects the time schedule of the Lead Plant and the desire to preserve the option of returning to the HEU cycle in the future should conditions permit.

More specific criteria derived from the general requirements are listed in Table 2. Many are taken directly from the HEU design, either because of the requirement for commonality or because there have been insufficient multi-dimensional calculations for the MEU cycle on which to base a value.

The power level was fixed by utility preference and does not depend on fuel cycle considerations. The power density was optimized for the HEU cycle, but on the basis of limited parametric studies is probably not far from optional for the MEU cycle.

The cycle length of 4.0 ± 0.5 years was chosen primarily from fuel cycle cost considerations and for allowing for future fuel resource requirement improvements. For example, effective cycle lengths of ~ 3.7 to ~ 4.3 years can be realized with combinations of fuel elements having 3 year and 6 year core residence times. This technique, coupled with some segregation of thorium and MEU by block type, is currently expected to show reduced resource requirements. If 18 month refueling were to become a requirement for certain utilities, a 4.5 year cycle would result if one-third of the core were refueled every 18 months.

Table 1

GENERAL REQUIREMENTS

- ° MEU/Th → cycles interchangeable
- ° Maximum utilization of existing technology
- ° Acceptable fuel performance risk
- ° Cycle extension flexibility comparable to HEU/Th
- ° Favorable incentive for recycle
- ° Near minimum resource requirements for current technology
- ° Favorable resource and cost improvement potential
- ° Near minimum fuel cycle costs averaged over 15 years

Table 2

SPECIFIC CRITERIA

- o Thermal power level 2240 MWt
- o Power density 7.1 w/cc
- o Effective cycle length 4 ± 0.5 EFPYS @ 80% CF
- o Loading capability for $\geq 80\%$ CF
- o Peak fast fluence $\leq 8 \times 10^{21}$ nvt
- o Age peaking factor (APF) ≤ 1.40
- o Present control system (includes power rods)
- o Conservative K_{eff} in mass flow prediction $K_{eff}^{eoc} = 1.008$
- o Feed uranium enrichment 19.9%
- o Uranium separability; 2 particle TRISO/BISO system
- o Recycle U-233 Denatured in-repro to $\epsilon = 12\%$ U-233 in U
- o Cycle cost and U_3O_8 needs optimized for delayed uranium recycle assumption
- o Fuel pin - coolant array and outer dimensions of HEU 8 row block
- o Same or larger coolant hole frontal area as HEU design
- o Fuel-coolant; Fuel-Fuel web thickness $\geq$ HEU fuel block web
- o Fuel rod diameter ≥ 1.20 cm (manufacturing considerations)
- o Fuel rod diameter to accommodate transition cycle loading variations plus nominal cycle extension capability of ~ 30 EFPD's
- o Current reference fissile/fertile particle design
- o Initial core C/Th ratio specified to minimize transition reload power peaking
- o Equilibrium C/Th ratio ≤ 650
- o GCRA/GAC common basis fuel cycle cost parameters to be used for cost optimization

The peak fluence limit is based on the irradiation behavior of graphite and pyrocarbon and is not affected by fuel cycle choice.

The age peaking factor limit of 1.40 is based on comparisons of zero- and two-dimensional calculations for the HEU cycle. Specifically it was verified that for zero-dimensional calculations that gave age peaking factors ≤ 1.40 , the corresponding two-dimensional calculation would have region peaking factors ≤ 1.60 which is the limiting design value. This correspondence will have to be checked for the MEU cycle and the age peaking limit adjusted if necessary.

The end-of-cycle reactivity of 1.008 leaves some margin for uncertainties and for the lumped burnable poison, which is generally not included in the zero-dimensional survey calculations. Some additional conservatism is present in the calculations reported here for the MEU cycle, since the neutron leakages used are based on a larger 3360 MWt core, and a value of 1.01 is used instead of 1.008 for the end-of-cycle reactivity. Comparisons of zero- and two-dimensional calculations for the HEU cycle show little difference in end-of-cycle reactivity, so no specific allowance has been assumed for that effect.

The limiting enrichments of U-235 and U-233 are assumptions, since there have been no government regulations on this point to date for reactors in the United States. A U-235 enrichment of 20% is a limit for foreign export and a U-233 enrichment of 12% is considered equivalent to 20% for U-235 on a bare critical mass basis.

The optimization of the cycle for delayed uranium recycle is based on the assumption that a reprocessing plant would not be economically justifiable until there were several HTGRs committed. It is therefore assumed for the Lead Plant that recycle begins with the seventh reload.

The next 5 criteria relate to the fuel block design. The block dimensions and coolant frontal area (hence pressure drop) of the HEU design are conserved to ensure the feasibility of converting from one cycle to the other. The web thickness limits are based on not exceeding stress limits. The lower limit on rod diameter is based on manufacturing economics and reflects the difficulties of fabricating small diameter rods in the present injection process and drilling long holes of small diameter in the graphite blocks. It should be noted that none of these points have been studied in detail for any proposed alternative design. This would have to be done if more detailed design work turned up significant advantages for a block design that violated these limits.

The fissile particle design is a compromise between the physics requirement to have the largest possible kernel and the thinnest possible coating, and the present limits of the available manufacturing processes and irradiation test experience. The FIMA limit for the current fissile particle is 25% and includes an assumed peak-to-average burnup of 1.2, an assumption taken from the HEU cycle. The fertile particle is taken directly from the HEU cycle since no incentive to modify it has been identified. The fuel particle design data is given in Table 3.

The C/Th ratio at equilibrium is optimized for economics. The specification of a lower limit on thorium loading corresponds to a decision to optimize for recycle of all uranium. Assumption of no recycle or recycle of only the bred U-233 would result in lower optimum thorium loadings. The initial C/Th ratio is chosen to control power peaking during the approach to equilibrium. Since a rather unique loading is required to achieve acceptable peaking factors in later cycles, there is little incentive to attempt to minimize initial core loadings to minimize front-end cash flows to the utility. For this reason such cash flow analysis was not considered a design criteria.

Table 3

FUEL PARTICLE DESIGNS

		<u>Density</u>
<u>Fissile:</u>		
Kernel Dia (UC ₂)	350μ	10.6* gm/cc
Buffer thick.	105	1.05
IPyC thick.	35	1.90
SiC thick.	35	3.2
OPyC thick.	45	1.80
T/D	0.628	
Burnup limit:	25% fima	
<u>Fertile:</u>		
Kernel Dia (ThO ₂)	500μ	9.9 gm/cc
Buffer thick.	85	1.05
PyC	75	1.90
t/D:	0.32	
Burnup limit:	6% fima	

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*More accurate numbers for kernel density would be 10.5 gm/cc for UCO
and 10.8 gm/cc for UC₂.

The criteria discussed above have been used in the studies described below to define the optimum fuel cycle. Because of the limited information available from multi-dimensional calculations, it is likely that some of these criteria will be revised as the design progresses.

3. Equilibrium Cycle Survey Calculations

The equilibrium cycle studies were done with the GAFFEE⁽²⁾ zero-dimensional burnup code and followed the techniques used in numerous previous studies of the MEU/Th cycle.⁽³⁾ The calculations were done for recycle of the bred U-233. The results for the case of all-uranium recycle were then estimated by evaluating the U_3O_8 equivalent in the discharged makeup U-235 and discharged recycle U-233. A parity of 1.3 for U-233 was assumed for this estimate.

These GAFFEE calculations were the first to be done with a recycle U-233 enrichment of 12%. All previous calculations have assumed 15%. Because of code limitations, the recycle uranium contained only U-233 and U-234 and omitted the U-235 and U-236 which are also present. An additional approximation was to use the same U-238 resonance cross sections for both makeup and recycle U-238. This slightly over-estimates U-238 absorptions since the recycle particle with its lower enrichment has greater shielding of the U-238.

Figure 1 shows the GAFFEE results for U_3O_8 requirements with the normal 0.50 particle packing fraction for recycle U-233 enrichments of 15 and 12%. Considering the case of recycling only the U-233, it is seen in the upper curves that the choice of an optimum composition is not strongly affected by the enrichment change. The minimum U_3O_8 requirements occur at a rod diameter of about 1.19 cm in either case. On the lower curves of C/Th ratio versus rod diameter (right hand scale), this diameter is seen to correspond to C/Th ratios of 635 and 715 for enrichments of 15 and 12% respectively.

Fig. 1. Lead Plant: Equilibrium Cycle; Variable Rod Diameter

For the case of all-uranium recycle, the curves of U_3O_8 requirements do not appear to reach their minima within the range of the parametric survey. However the flattening out of the C/Th versus diameter curves indicates that no points above C/Th=500 will be reached (i.e. such loadings are too heavy to satisfy criticality requirements). This is also implied in the sharp rise in the U_3O_8 curves for U-233 only recycle.

For several reasons it is not advisable to choose a reference composition at the indicated minimum of about C/Th=500.

1. The change in uranium loading to produce a given change in reactivity becomes large at this point which could lead to uneconomic performance during the approach to equilibrium as well as frequent necessity to adjust the rod diameter to handle small reactivity adjustments as the design is refined.
2. The concept of recycling all of the uranium is something of an idealization; in practice it will probably not be possible to effectively utilize all of the discharged fuel. The true curve of U_3O_8 requirements versus rod diameter will therefore be between those given here for U-233-only and all-U recycle, and would have its minimum at a lower thorium loading.

For the 12% U-233 enrichment presently assumed, a C/Th ratio of 600 is therefore considered a reasonable choice. For this loading, the rod diameter of 1.245 cm presently used for the FSV fuel elements would be appropriate.

As is discussed below, the approach to equilibrium for C/Th ratios in this range has been studied with GARGOYLE calculations but is not fully optimized. In most of these calculations there occur variations of the annual uranium loadings required even after the thorium loading

has been made constant at the equilibrium value. This leads to total heavy metal requirements in the rod which would require average particle packing fractions greater than the 0.50 value assumed. In order to provide for this problem, we have studied the effect of enlarging the fuel rod diameter and dropping the packing fraction while keeping the C/Th ratio constant. Diluting the uranium in this manner tends to increase the U-238 resonance integral, while increasing the rod diameter increases the Dancoff factor and reduced the resonance integral. The net effect is found to be rather small.

Figure 2 gives data on U_3O_8 requirements at equilibrium as a function of particle packing fraction for a fixed rod diameter of 1.245 cm. The packing fraction of 0.5 corresponds to C/Th=600 as noted above. The data in this figure can be compared to that for smaller rod diameters and full packing fractions given in Figure 1. For example, if C/Th=700 and $D_{rod}=1.195$ cm in Figure 1, the U_3O_8 requirements are 119.7 and 136 ST/GWe-yr for the two recycle modes. If we keep C/Th=700 and raise the rod diameter to 1.245 cm, we find in Figure 2 that the packing fraction drops to 0.46. The U_3O_8 requirements remain unchanged within the accuracy of the curves.

Similar data to that in Figure 2 was generated for a rod diameter of 1.35. For the desired composition of C/Th=600, the critical case is found with a packing fraction of 0.43. In this case the U_3O_8 requirements rise slightly relative to the 1.245 cm diameter case. This is a larger diameter change than that illustrated in the C/Th=700 example.

Fig. 2. Lead Plant: Equilibrium Cycle; Variable Particle Fraction

The two examples are summarized in the table below:

C/Th Ratio	700		600	
Rod Diameter	1.195	1.245	1.245	1.350
Packing Fraction	.50	.46	.50	.43
U ₃ O ₈ : ST/GWe-yr				
U-233 only	136.0	136.0	139.0	143.7
All U	119.7	119.0	115.2	116.2

The small penalty to the reference case in U₃O₈ requirements is considered acceptable in view of the greater margin for loading variations provided by the 1.35 cm diameter.

Alternative methods of accommodating the loading variations in the approach to equilibrium would be dropping the thorium loading on some reloads or allowing the burnup interval between reloads to fluctuate slightly from the constant 292 full power days assumed in the GARGOYLE calculations. The effect of dropping the thorium loading to C/Th=700 can be seen from the table above to be quite small, particularly when it is considered, as discussed before, that the true data for all-U recycle lies between the two values given. The effect of varying the reload interval would have to be evaluated with cost calculations.

Based on these studies, the composition characterized by C/Th=600, rod diameter of 1.35 cm, and particle packing fraction of 0.43 was selected as optimal for the equilibrium cycle.

4. Mass Flow Calculations for 30 Year Operation

The behavior of the initial core and the subsequent reloads has been studied with the zero-dimensional GARGOYLE code.⁽⁴⁾ The calculational model is similar to that used in GAFFEE with the exceptions that the number of groups is reduced from 16 to 9, and the resonance cross sections of U-238 and thorium are varied as functions of the respective concentrations of these materials by means of shielding factors.

Recycle of the bred U-233 begins with Reload 7. Introducing all of the U-233 accumulated up to that point at one time, however, appears to cause undesired fluctuations in the makeup feed requirements. The accumulated recycle material is therefore distributed over a period of 5 reloads. This is an uneconomic procedure, since it prolongs inventory charges on the bred fuel, but the effect is not large. Hopefully, it can be improved on in further design work.

By trial and error, the C/Th ratio in the initial core has been fixed at 350, primarily to meet power peaking limits in subsequent reloads. A heavy initial thorium loading requires more U-235 for criticality in the early years which hurts economics, but produces more U-233 for the later years which maintains the power generation in the older segments and reduces age peaking. A light initial thorium loading has the opposite effects.

The thorium loadings of reload segments are increased gradually over 5 reloads up to the level corresponding to C/Th=600. This again is a matter of trial and error and the selection is made mainly on power peaking criteria rather than economics.

Figure 3 illustrates the variation of thorium, U-235 and U-233 loadings over the operating life of the reactor. The end-of-cycle age peaking factors are also shown for the first six reloads. For a few reloads, the limit of 1.40 is reached and these segments require more design work. All subsequent reloads have values below 1.3. The loading program given is considered adequate for the initial design, since the true extent of the power peaking problems can only be determined from later multi-dimensional calculations.

The fluctuations in U-235 requirements even out to the end of reactor life are a consequence of the fact that the reload segments are not equal quarters of the core. In addition, changes of thorium or U-233 loading are being made out to the 12th reload and the effects of these changes take some time to damp out. The equilibrium values for U-235 and U-233 averaged over the last four reloads are 478 and 86 kgs/year respectively. This compares to 500 and 88.5 kgs/year found in the GAFFEE equilibrium cycle calculations. The differences can be attributed to slight differences in input data and calculational models.

Examining the total uranium loadings (makeup and recycle) throughout the 30 years shows that the maximum concentration occurs in Reload 8 and is 18% greater than the equilibrium value. The volume fraction of fissile particles in the fuel rod at equilibrium is 0.31 and the total particle fraction (fissile and fertile) is 0.43. An 18% increase in fissile particles makes the total about 0.49 which is acceptable. The initial core has a total particle fraction around 0.45 which is also satisfactory. It can be concluded that the 1.35 cm rod diameter provides adequate margin for loading variations.

The sum of U_3O_8 requirements over the 20 year operations lifetime is 3244 MT/GWe for the all-uranium recycle case and 3750 MT/GWe for recycle of only U-233. These values are based on the 70% capacity factor assumed in the cost calculations. (The GAFFEE and GARGOYLE

calculations are run for 80% capacity factor and the results discussed above are based on that value). Further improvement in these numbers will probably be made by additional optimization of the loadings during the approach to equilibrium.

Fig. 3. Approach-to-Equilibrium Mass Flows

5. Fuel Cycle Cost Calculations

Fuel cycle cost calculations have been done with the GACOST code⁽⁵⁾ based on 30 year mass flow data from the GARGOYLE calculation for the reference case. Note that since it is not feasible to run a large number of GARGOYLE calculations for different C/Th ratios and rod diameters, the selection of the optimal composition was based primarily on GAFFEE results with the criteria of minimizing U_3O_8 requirements. In general, this criteria will also ensure low fuel cycle costs, since uranium costs are the dominant factor. To illustrate this in the present case, GARGOYLE and GACOST calculations were also run for C/Th ratios of 850 and 500. The C/Th=850 case was also evaluated for the assumption of no recycle.

The fuel cycle cost assumptions are listed in Table 4, and are based on consultations with GCRA. The results for fuel cycle cost and U_3O_8 requirements are shown in Figure 4 as a function of C/Th ratio. The fuel cycle cost for recycle of all uranium is seen to be relatively insensitive to C/Th ratio, varying by about 2% over the range of C/Th considered. The U_3O_8 minimum is similarly insensitive. As noted in Section 3 above, the true recycle case would lie between the two cases calculated, since not all discharged uranium could be effectively utilized. For a realistic case, the U_3O_8 minimum could be very close to C/Th=600 as was also predicted by the GAFFEE survey for the equilibrium cycle.

The insensitivity of the results to the C/Th ratio indicates that there is some freedom to adjust the thorium loading if necessary to accommodate power peaking or other core design problems without significant economic penalty. A breakdown of the fuel cycle cost components is given in Table 5 and illustrates the dominant contribution of depletion charges.

Table 4

GA/GCRA COST ASSUMPTIONS (1978 \$)

<u>Handling Cost Assumptions</u>	
	<u>HTGR</u>
Handling Costs	\$/FE
Fab	4000
Shipping	1700
Spent Fuel Disposal	3500
Repro	4400
Reprocessed Waste Disposal	2225
Refab	7500
 <u>Economic and Resource Assumptions</u>	
Capacity Factor, %	70
Tails assay, %	0.2
SWU Cost, \$/SWU	100
U ₃ O ₈ Cost, \$/lb U ₃ O ₈	1990 45\$/lb
	2000 55
	2010 80
	2020 120
	2030 200
Conversion cost, \$/Kg	5
Working capital rate, %	15.6
Discount rate, %	10.2
Inflation rate, %	6.0
Startup	1990
Plant Efficiency, %	38.6
Levelizing Period, yrs	15

Fig. 4. Fuel Cycle Cost and U_3O_8

Table 5

FUEL CYCLE COST COMPONENTS

mills/kwhr(e)

<u>C/Th</u>	<u>Recycle Option</u>	<u>Fab.</u>	<u>Refab</u>	<u>Depl</u>	<u>Ship</u>	<u>Waste</u>	<u>Repro</u>	<u>Total</u>
850	None	2.24	0.0	15.28	0.64	1.30	0.0	19.46
	U-233 only	1.54	0.89	13.63	0.64	0.78	1.45	18.93
	All U	1.54	0.89	12.94	0.64	0.78	1.45	18.24
600	U-233 only	1.52	0.92	13.98	0.64	0.78	1.45	19.29
(Ref. Case)	All U	1.52	0.92	12.99	0.64	0.78	1.45	18.30
500	U-233 only	1.54	0.89	14.56	0.64	0.78	1.45	19.85
	All U	1.54	0.89	13.30	0.64	0.78	1.45	18.60

The fabrication and refabrication costs depend on the fraction of the core occupied by makeup and recycle blocks respectively. There is some flexibility here which is not represented in the zero-dimensional burnup calculations used to determine the mass flows. In these calculations we have assumed the C/Th ratio is the same in both block types, although some variation might be desirable to shape the axial power distribution. The GACOST code also assumes uniform thorium loading but divides the U-235 and U-233 between the two block types to meet some empirical power sharing criteria originally derived for the HEU cycle. The validity of these criteria for the MEU cycle remains to be demonstrated. Based on these criteria however, the equilibrium block splits used for the cost calculations are the following:

C/Th	Blocks/Reload Segment	
	Makeup	Recycle
850 No recycle	878	0
850 Recycle	749	129
600 Recycle	708	170
500 Recycle	701	177

The mass flow data by block type on this basis is given in Table 6. For the C/Th=600 case, a split based on equal fissile particle volume fraction in each block type and ignoring the power sharing criteria would give 674 makeup and 204 recycle blocks. The data by particle type in Table 6 could be used to give block loadings on this basis also.

Table 6
Heavy Metal Loadings for Equilibrium Cycle
C/Th=350/600 D_F=1.35 cm. 4 YR Annual Reload 30

ISOTOPE	KGS/ Segment	By Particle Type		KGS/ Block	By Block Type
	Fissile	Fertile	Recycle	Makeup	Recycle
<u>B.O.C.</u>					
Th-232		3115.9		3.548	3.548
U-232			0.04		0.0002
U-233			87.7		0.516
U-234			13.3		0.078
U-235	473.3		2.4	0.669	0.014
U-236			0.27		0.002
U-238	1917.5		657.1	2.708	3.865
<u>E.O.C.</u>					
Th-232		2911.6		3.316	3.316
PA-231		0.02		2x10 ⁻⁵	2x10 ⁻⁵
PA-233		6.8		0.008	0.008
U-232		0.04	0.02	4x10 ⁻⁵	1.6x10 ⁻⁴
U-233		80.0	10.1	0.091	0.151
U-234		13.2	12.2	0.015	0.087
U-235	72.8	2.4	4.5	0.106	0.030
U-236	65.9	0.3	1.5	0.093	0.009
U-238	1745.8		5.9	2.466	0.035
NP-237	7.8	0.01	0.2	0.011	0.001
NP-239	0.6	0.003	0.2	8.5x10 ⁻⁴	0.001
PU-238	2.9	0.0002	0.06	0.004	3.5x10 ⁻⁴
PU-239	20.5	0.00005	6.8	0.029	0.040
PU-240	10.9	0.00003	3.6	0.015	0.021
PU-241	10.3	0.000006	3.5	0.015	0.021
PU-242	8.3		2.8	0.012	0.016
No. of Blocks (GACOST Basis)				708	170

6. Conclusions

1. A thorium loading characterized by $C/Th=600$ gives near-optimal U_3O_8 resource requirements for the assumption of all-uranium recycle. The optimization is relatively insensitive to thorium loading over a practical range.
2. The rod diameter of 1.35 cm provides adequate fuel volume for all anticipated loading variations throughout reactor life.
3. The fuel cycle cost is close to minimum for the assumed economic ground rules.
4. A satisfactory approach-to-equilibrium strategy has been found to use as a basis for the first detailed core design calculations. There is room for further optimization and some improvements may be necessary to reduce power peaking for intermediate reloads.

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