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FUEL-CYCLE COST COMPARISONS FOR HIGH-TEMPERATURE GAS-COOLED REACTOR FUELS*

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ABSTRACT

Calculations were made of the burnup, conversion ratio, and fuel-cycle cost over a wide range of fuel compositions and fuel management modes for semi-homogeneous uranium and uranium-thorium fuels. A limited series of heterogeneous lattices was also investigated in connection with low-enrichment uranium fuel. Lowest fuel-cycle cost [0.88 mills/kwhr(e)] for an economy containing large-scale low-cost fabrication and reprocessing facilities was found to be the uranium-thorium recycled fuel. For near-term economics with high fuel fabrication costs, lower fuel-cycle costs may be obtained from a semi-homogeneous partially enriched uranium fuel operated on a throw-away cycle. We have not been able to find any advantage to a heterogeneous low-enrichment uranium fuel cycle in a high-temperature gas-cooled reactor.

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I. Semi-Homogeneous Graphite-Moderated Fuels

We have made calculations of the reactivity lifetimes and the associated conversion ratios and fuel-cycle costs for a wide variety of fuel compositions that might be used in a high-temperature gas-cooled reactor. The results for fully enriched uranium with thorium and for partially enriched uranium are described in this paper. Parallel calculations have also been made for plutonium-thorium fuels, and these results are discussed elsewhere.[1]

For each type of fuel we varied the moderator-to-fuel ratio and fissile-to-fertile ratio and computed the reactivity lifetime. All of the calculations were made for the slightly idealized case of a graded-exposure equilibrium fuel cycle in which the fuel was assumed to be fed continuously into the reactor and discharged at some later time, also continuously. The calculated neutron spectrum for all fuel elements was characteristic of the average composition and did not change with time. Two different types of fuel management were considered. In non-recycle fuel management it was assumed that the fuel discharged from the reactor was to be reprocessed and sold or discarded without reprocessing. In the other type, recycle fuel management, it was assumed that the uranium and plutonium discharged from the reactor were to be reused after reprocessing along with sufficient makeup fuel to maintain the required fissile loading. The isotopic concentrations of the recycled material were calculated to meet the condition that the quantity of each isotope discharged, less the processing losses, should be equal to the quantity fed from the recycle stream. Additional makeup fuel of a specified composition was fed as required.

The lifetimes were computed with a space-independent code in which the leakage was allowed for by the inclusion of a buckling term giving 2.0 to 2.5% neutron leakage. The moderator was carbon (graphite) in all cases, and it was assumed that the moderator and fuel were essentially homogeneous with respect to neutron behavior. The calculations were done with 11 fast and 20 thermal energy groups. Fission-product

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concentrations were calculated explicitly for the 35 most important nuclides, and a pseudoelement was used for the remainder of the fission products.

Earlier studies[2] have indicated that minimum fuel-cycle costs for the ^{235}U-thorium fuel are to be found with a power density of 5–10 w/cm^3. The minimum occurs as a result of the contrasting effects of greater parasitic captures in ^{135}Xe and ^{233}Pa at high power density and larger fuel inventory costs at low power density. In this study we did not vary the power density: a value of 5 w/cm^3 was used for all cases. Some of the other assumptions made in the study are given in Table I.

The conversion ratios and reactivity lifetimes that were obtained are shown in Figs. 1 through 4 as functions of the fuel feed composition. The highest conversion ratios were obtained for the thorium-fully enriched uranium fuel with recycle (Fig. 3). In these cases the conversion ratio can be above 0.9 for burnups of 25,000–30,000 Mwd/T and can approach 1.0 for very short burnup. It should be emphasized that these calculations did not allow for such devices as selected partial recycle, fertile blankets or removal of fission products during irradiation. Such devices could increase the conversion ratio for economically attractive cycles to near unity or perhaps even higher. In the recycled thorium-uranium fuels with high conversion ratio nearly all of the fissions occur in the bred ^{233}U, and it is the high η value of the ^{233}U which is primarily responsible for the superior nuclear performance of these fuels. A concurrent disadvantage of the recycled fuel is the buildup of ^{236}U in the recycled stream which results in neutron absorption in both ^{236}U and ^{237}Np. As the conversion ratio is decreased, the proportion of ^{235}U makeup in the recycled fuel becomes greater, and the buildup of ^{236}U increases. Consequently, at conversion ratios less than about 0.75 the burnup at a given conversion ratio is greater with non-recycled uranium-thorium fuel (Fig. 4) than with recycled uranium-thorium fuel (Fig. 3). The conversion ratios obtained with partially enriched uranium fuels were never greater than about 0.7 at the high burnups required for an economical cycle with this type of fuel. At a given burnup the conversion ratios tended to be lower for the recycled than for the non-recycled partially enriched uranium. The combination

Table I. Fixed Parameters for Fuel-Cycle Calculation

Power density, w/cm^3	5.0
Thermal efficiency, %	40
Reactor plant factor	0.8
Average moderator temperature, °K	900
Buckling, cm^{-2}	2.0×10^{-5}
Isotopic composition of fully enriched uranium, wt %:	
^{234}U	1.04
^{235}U	93.15
^{236}U	0.22
^{238}U	5.59
Graphite matrix density, g/cm^3	1.65
Coolant fraction	0.39
Fixed charges on fuel inventory, %/year	10
Fixed charges on working capital, %/year	10
Fabrication holdup time, days	150
Processing holdup time, days	150
Processing losses, %:	
Uranium and plutonium	1.0
Protactinium	3.1
Fabrication scrap losses, %	0.2
Fuel shipping charges, $/kg of heavy metal:	
To processing plant	6.40
From processing plant	5.05
Cost of ^{235}U, $/g[a]	12.05
Cost of ^{233}U, $/g[a]	12.05
Cost of plutonium, $/g fissile	10.0

[a]This price is for fully enriched material. The USAEC cost schedule was used for lower enrichments.

of high burnup and low conversion ratio in the higher-enrichment fuels gave a very great depletion of the fissile material in a fuel element.

The various assumptions regarding economic parameters are given in Table I and in Fig. 5. It should be noted in Fig. 5 that the costs per unit weight of heavy metal for fabrication and for reprocessing were allowed to vary with throughput. These costs were recently calculated as a part of a comprehensive study of the probable reactor industry in the period following 1970.[3] An industry size of 15 000 Mw(e) was assumed. We used remote fabrication for all recycled fuel, hooded fabrication for the thorium-fully enriched fuel, and direct fabrication for the partially enriched uranium fuel. The cost of ^{235}U of various enrichments follows the current USAEC schedule and appears to be a reasonable projection for a period some time in the future. In mixtures containing ^{233}U, the ^{233}U was treated like ^{235}U which results in a slight under evaluation for most cases. A 10% interest rate was used both for fuel inventory and for working capital for fuel fabrication; this rate is considered representative for private financing.

The fuel-cycle costs are tabulated in Table II for the composition that gave the lowest total cost with each type of fuel. Other data for these same cases are given in Table III and Table IV.

The total fuel-cycle costs including fuel reprocessing are significantly lower for the thorium-fully-enriched uranium fuels than for the partially enriched uranium fuels. The thorium-based fuel gives a cost of 0.88 mills/kwhr(e) for the recycled mixture and essentially the same total when the spent fuel is reprocessed and sold. The partially enriched uranium fuel gives a cost of 1.20 mill/kwhr(e) when the fuel is recycled and 0.96 when the fuel is reprocessed and sold. The better cost of the thorium-based fuel comes principally from the higher conversion ratios that occur when most of the fissions are in ^{233}U, leading to a much lower net cost of fissionable material. The recycled uranium-thorium fuel has the lowest fuel makeup cost and the lowest total fuel cycle cost in spite of high fabrication cost owing to the necessity of remote fabrication.

Table II. Minimum Fuel-Cycle Cost for Uranium-Thorium and Partially Enriched Uranium Homogeneous Fuels

	Minimum Fuel-Cycle Cost, [mills/kwhr(e)]			
	Partially Enriched Uranium Fuel		Uranium-Thorium Fuel	
	Not Recycled	Recycled	Not Recycled	Recycled
Reprocessing	0.155	0.172	0.159	0.177
Fabrication	0.085	0.163	0.098	0.183
Fabrication interest	0.008	0.011	0.014	0.022
Shipping	0.006	0.019	0.007	0.023
Uranium feed	0.740	0.680	0.767	0.219
Uranium credit	(0.021)		(0.334)	
Plutonium credit	(0.100)		(0.000)	
Core inventory	0.057	0.088	0.128	0.189
Fabrication inventory	0.030	0.048	0.032	0.038
Processing inventory	0.005	0.022	0.014	0.029
Total	0.965	1.203	0.885	0.880
Total with spent fuel discarded[a]	0.926		1.013	

[a]Fuel compositions were re-optimized in computing the costs on this line.

Table III. Homogeneous Fuel Compositions Yielding Minimum Cost

	Partially Enriched Uranium Fuel		Uranium-Thorium Fuel	
	Not Recycled	Recycled	Not Recycled	Recycled
Fresh fuel composition:				
Moderator-to-fissile atom ratio	10 000	10 000	7000	7000
Enrichment, % fissile atoms	7.08	6.75	5.31	3.77
Average core composition:				
Moderator-to-fissile atom ratio	20 400	13 800	13 000	8700
Enrichment, % fissile atoms	3.69	5.08	2.97	3.06
Reactivity lifetime:				
Cycle time, full power days	573	349	925	746
Fissions per initial fissionable atom	1.52	0.93	1.72	1.39
Mwd/T (U+Pu+Th)	102 000	59 000	87 000	50 000
Average core specific power, kw/kg fissile	5160	3480	3330	2230
Net conversion ratio	0.63	0.63	0.72	0.86
Plant throughputs, MT/year:				
Processing	96	172	114	207
Fabrication	108	186	126	219
Unit cost for fabrication plus processing, $/kg	265	197	239	178
Ratio of initial to average power density	1.49	1.21	1.84	1.24
Average η of fissile nuclides	1.92	1.93	2.14	2.19

Table IV. Neutron Balance for Minimum Cost of Homogeneous Fuels

	Reactions Per Source Neutron			
	Partially Enriched Uranium Fuel		Uranium-Thorium Fuel	
	Not Recycled	Recycled	Not Recycled	Recycled
Absorptions:				
^{232}Th			0.334	0.353
^{233}Pa			0.010	0.009
^{233}U			0.228	0.341
^{234}U			0.011	0.043
^{235}U	0.223	0.191	0.235	0.109
^{236}U	0.004	0.029	0.007	0.018
^{237}Np	0.001	0.007	0.003	0.007
^{238}U	0.256	0.235	0.003	0.004
^{239}Pu	0.233	0.235	0.002	0.004
^{240}Pu	0.071	0.092	0.001	0.001
^{241}Pu	0.059	0.090	0.001	0.001
^{242}Pu	0.003	0.023	0.000	0.000
Fission products	0.088	0.055	0.103	0.066
Moderator	0.037	0.022	0.037	0.023
Leakage	0.025	0.021	0.025	0.021
Total	1.000	1.000	1.000	1.000
Productions:				
^{233}U			0.519	0.772
^{235}U	0.448	0.379	0.473	0.216
^{239}Pu	0.411	0.412	0.004	0.006
^{241}Pu	0.132	0.203	0.002	0.003
Other	0.009	0.006	0.002	0.003
Total	1.000	1.000	1.000	1.000

In Table II we have also tabulated the total fuel-cycle cost for non-recycled fuels under the assumption that the spent fuel is to be discarded without reprocessing. The total cost for the partially enriched uranium fuel was decreased to 0.93 mills/kwhr(e) in this case, indicating that it is not worthwhile to reprocess such a feed to recover its plutonium even in a very large-scale reprocessing industry. This somewhat surprising result comes about from a combination of the very high burnup with most of the plutonium burned in situ and the high ^{242}Pu content of the spent fuel, along with the fact that reprocessing is inherently more expensive for graphite-matrix fuels than for some other types. The cost for the thorium-uranium fuel was increased to 1.01 mills/kwhr(e) by discarding the spent fuel; the economics of this type of fuel evidently requires that the spent fuel be reprocessed and reused.

Estimates of the probable cost of reprocessing the fuel do not depend strongly on the design of the fuel element or the mode of fuel management. Instead, the reprocessing cost depends primarily on the assumptions made regarding the size of the industry and the size of the reactor complex to be served by a single reprocessing plant. This situation is illustrated in Table II where the reprocessing cost varies only from 0.155 to 0.177 mills/kwhr(e) as the type of fuel and the burnup are changed considerably. The situation with regard to fabrication cost is somewhat different. This item can vary significantly with fuel element design, burnup, and type of fuel. There may also be significant changes brought about by the degree of automation in the fabrication plants. Hence, it seems worthwhile to consider the sensitivity with which the fuel-cycle cost for each type of fuel varies with the unit cost for fuel fabrication. We have considered the fuel fabrication cost as a parameter to be varied independently and have found the fuel compositions which gave lowest cost for each assumed value. The resulting fuel-cycle costs are plotted in Fig. 6 for three of the types of fuel management: recycled uranium-thorium, non-recycled uranium-thorium with the fuel reprocessed and sold, and partially enriched uranium with the spent fuel discarded. The other possibilities for fuel management (recycled partially enriched uranium, non-recycled partially enriched

uranium with the fuel reprocessed and sold, and uranium-thorium with the fuel discarded) are not shown because they never gave costs as low as the types shown. The trend in optimization was toward higher enrichments, higher burnups and lower conversion ratios as the fuel fabrication costs was increased.

The data in Fig. 6 indicate that the recycled fully enriched uranium fuel gives a lower fuel-cycle cost than any of the other fuel types when the fabrication cost is below $100/kg. This fuel is particularly advantageous at low fabrication costs because a low burnup is permitted, thus increasing the conversion ratio. The enhancement in conversion ratio results from the smaller number of neutron captures in fission products and also from a secondary improvement in the η of the fuel when the recycled stream has a higher ratio of ^{233}U to ^{235}U. At fabrication costs above $165/kg, the best costs were obtained with partially enriched uranium fuel in which the spent fuel is discarded. At the very high burnups required by these fabrication costs the low fuel inventory cost for the latter fuel is the decisive factor. There is apparently an area of fabrication costs from $100 to $165/kg in which the non-recycle uranium-thorium fuel gives the lowest cost. However, such a fuel cycle would imply a guaranteed market for the spent fuel in some other reactor type.

It should be kept in mind that the difference in fuel-cycle cost among the various types of fuel is, in all cases, small in comparison with the total power cost. A more complete analysis would be needed, taking into account any differences in thermal performance and core design requirements, before choosing one type of fuel. Nevertheless, the work we have done indicates particular promise for a partially enriched uranium throwaway cycle for near-term use and for recycled uranium-thorium fuel for ultimate large-scale use.

II. Heterogeneous Low-Enrichment Uranium Fuel

In considering the use of partially enriched uranium fuels in graphite-moderated high-temperature gas-cooled reactors a question that arises is whether there would be an advantage in "lumping" the fuel. The heterogeneous lattice can achieve a given burnup at a considerably lower enrichment than the homogeneous reactor core and can thereby use ^{235}U at a lower cost per gram. The principal offsetting disadvantage is that a smaller volume fraction of the core is used for heat generation when the moderator and fuel are segregated and the power density and specific power are simply limited by heat removal considerations.

We have investigated this question by studying a configuration shown schematically in Fig. 7. The fuel element would consist of a hexagonal block of graphite with a cluster of 42 coolant passages and 19 fuel channels at its center. The fuel channels contained UO_2 at 95% of theoretical density. The reactor power was 1000 Mw(e), the core height was 25 ft, the coolant (helium) temperature was 720°F at the inlet and 1470°F at the outlet. The maximum fuel temperature was limited to 3032°F, giving a power output of 2.586 Mw for the maximum power fuel element. The fuel was not recycled. Calculational methods were essentially the same as in the study of the homogeneous fuel with heterogeneous resonance integrals computed by the GAM-II[4] code and thermal cells calculated by the THERMOS[5] code. Costs were computed on the same basis as for the homogeneous fuel.

The principal variables were the lattice pitch between fuel clusters, the size of the fuel channel, and the fuel enrichment. The burnups and conversion ratios are shown in Fig. 8 for the 0.375-in.-diam fuel channel. It can be seen that considerably lower enrichments were obtained than in the case of the homogeneous fuel. Criticality was obtained with enrichments as low as 1%. However, we have not been able to find a configuration which would be critical on natural uranium, largely because the amount of graphite and void space that must be present in the fuel cluster prevent achieving sufficiently small effective resonance integrals for ^{238}U. Calculations were also made for a larger rod, of 0.576 in. diam, with very similar results.

The case that gave lowest fuel-cycle costs is listed in Table V. The fuel-cycle cost was computed on the basis of discarding the spent fuel without reprocessing since the lowest costs were obtained in this way. The optimum case had a 2% feed enrichment in comparison with a 7% enrichment for the homogeneous non-recycle partially enriched optimum. The total fuel-cycle cost for the heterogeneous case was 0.94 mills/kwhr(e) which was almost identical with the 0.93 mills/kwhr(e) calculated for the homogeneous case. However, the power density of the heterogeneous case was only 2.58 w/cm^3, implying that the capital costs for the core and pressure vessel would be high. We conclude from these data that it will be difficult to find a configuration for a heterogeneous fuel element which will give, at the same time, very low enrichment and a combination of fuel costs and capital costs which would be attractive.

Table V. Summary of Optimum Case for Heterogeneous Uranium Fuel

Power density, w/cm^3	2.58
Initial fuel enrichment, %	2
Lattice pitch, in.	13
Reactivity lifetime:	
Cycle time, full power days	1400
Fissions per initial fissile atom	1.44
Mwd/T (total U)	27 300
Average specific power, kw/kg fissile	2220
Net conversion ratio	0.59
Fabrication plant throughput, MT/year	403
Unit cost for fabrication, $/kg	58.5
Fuel-cycle cost, mills/kwhr(e):	
Fabrication	0.224
Fabrication interest	0.046
Shipping + storage	0.022
Uranium feed	0.561
Core inventory	0.066
Fabrication inventory	0.023
Total	0.942

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[2]R. S. Carlsmith, Parametric Study of Fueled-Graphite Reactors, pp. 383–394, "GCRP Semiannual Progress Report September 30, 1963," USAEC Report ORNL-3523, Oak Ridge National Laboratory.

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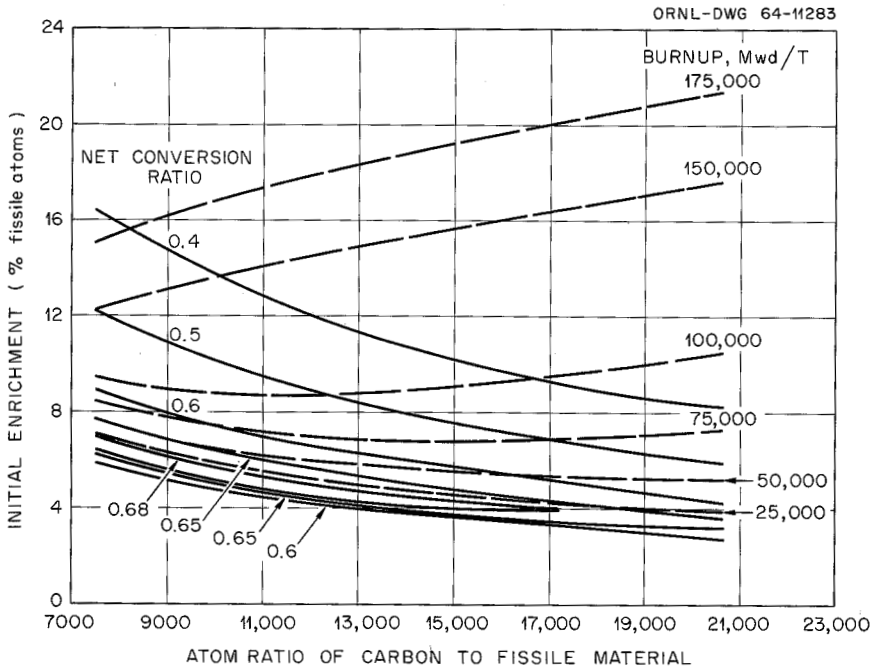

Fig. 1. Burnup and Conversion Ratios for Recycled Partially-Enriched Uranium Fuel.

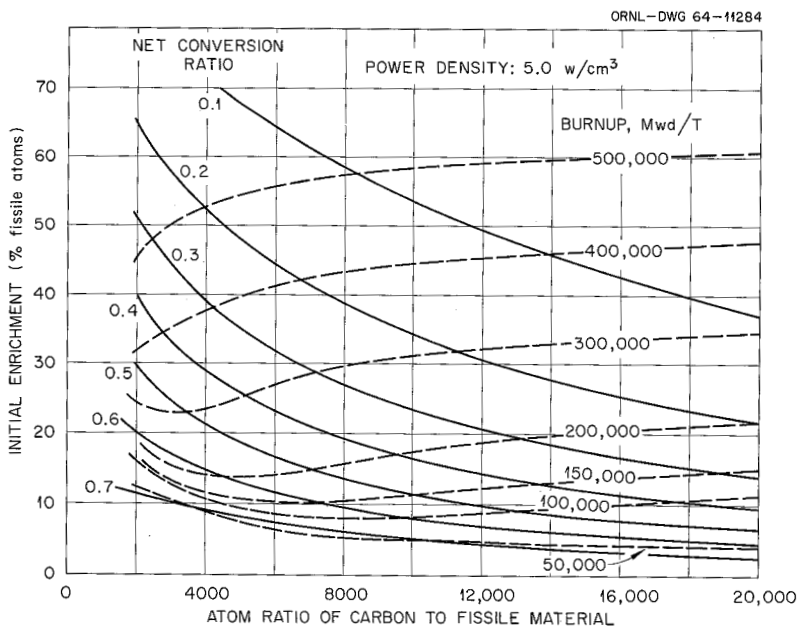

Fig. 2. Burnup and Conversion Ratios for Non-Recycled Partially-Enriched Uranium Fuel.

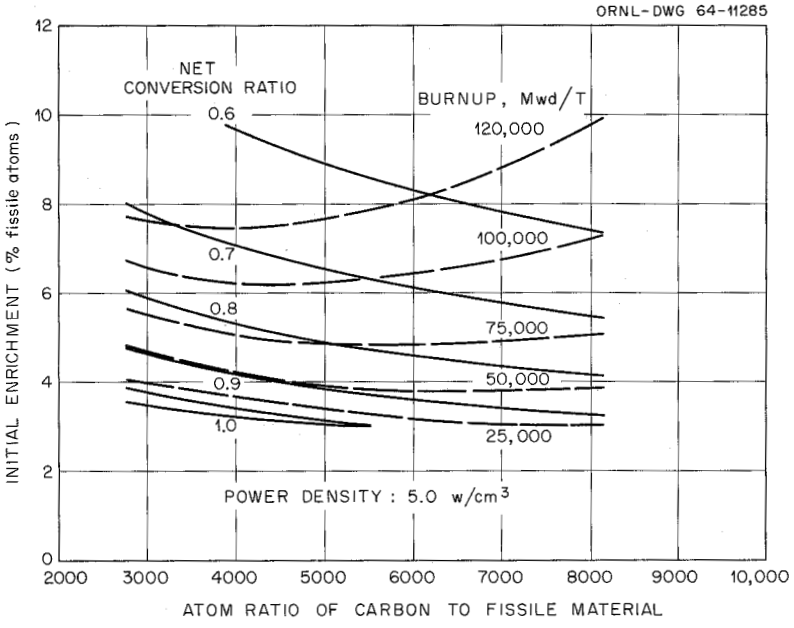

Fig. 3. Burnup and Conversion Ratios for Recycled Uranium-Thorium Fuel.

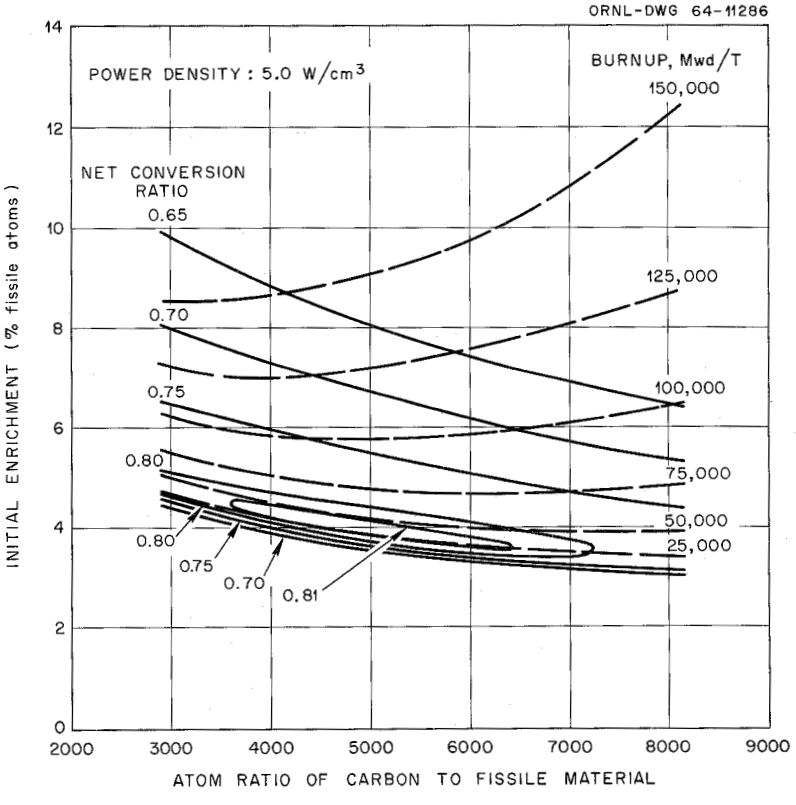

Fig. 4. Burnup and Conversion Ratios for Non-Recycled Uranium-Thorium Fuel.

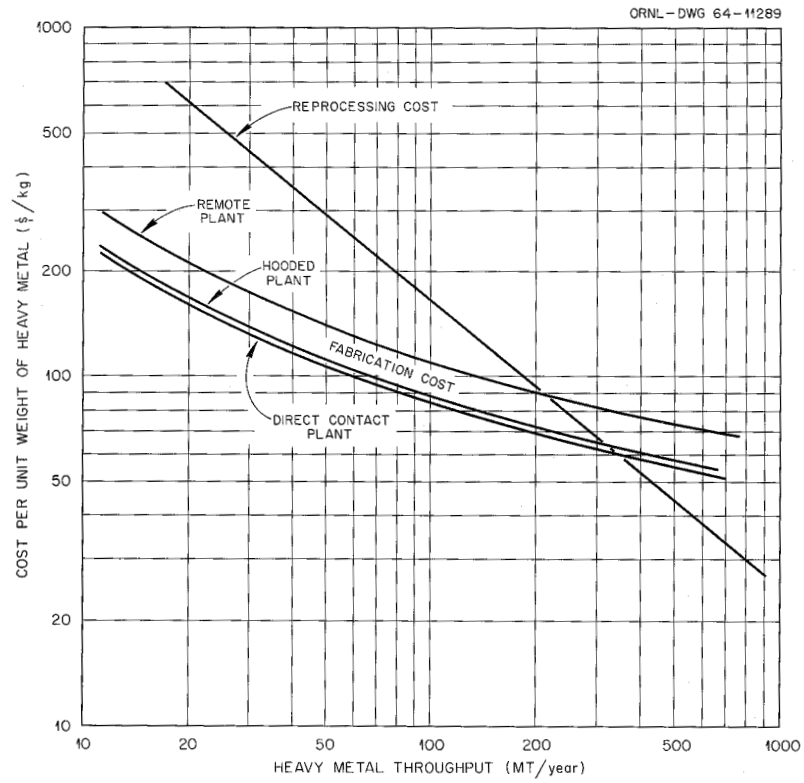

Fig. 5. Unit Cost Estimates for Fabrication and Reprocessing.

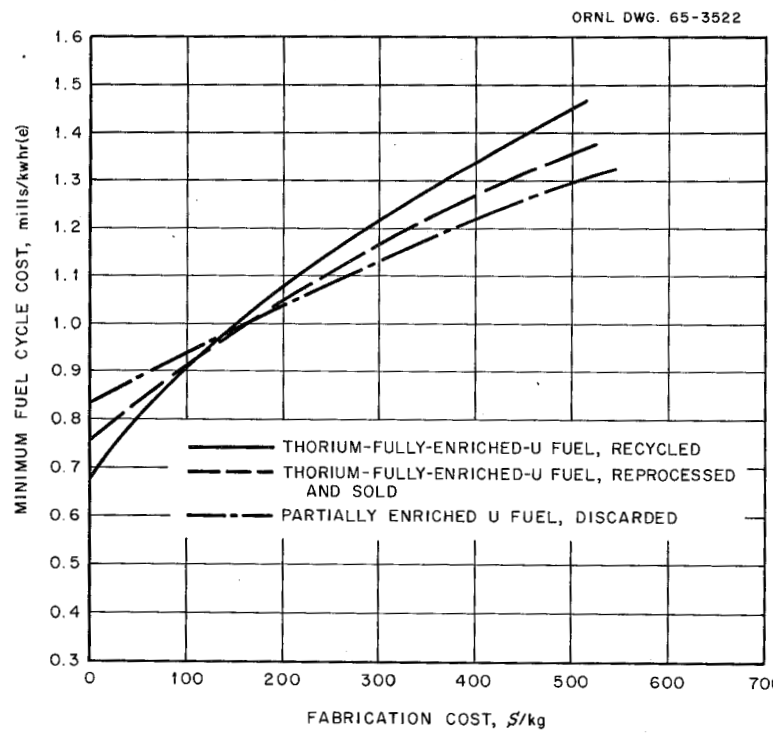

Fig. 6. Variation of Fuel-Cycle Cost with Unit Fabrication Cost.

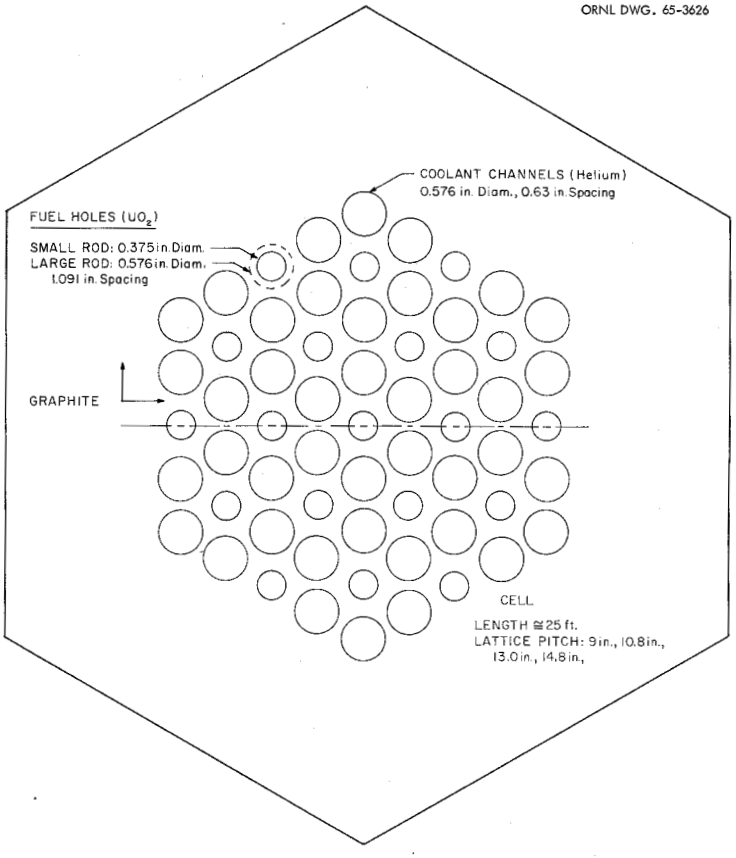

Fig. 7. Cross Section of Heterogeneous Fuel Element.

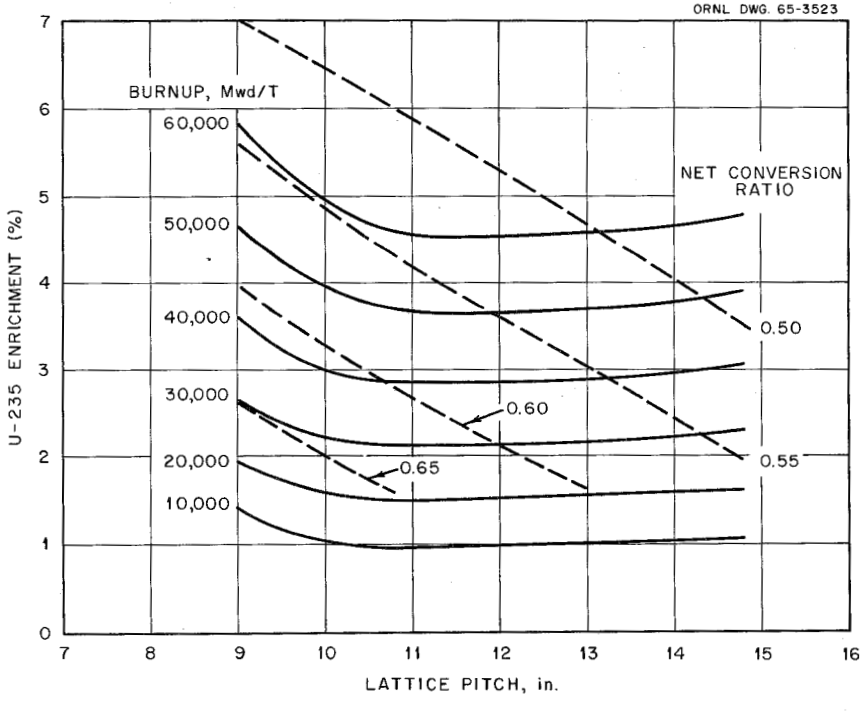

Fig. 8. Burnup and Conversion Ratios for Heterogeneous Low-Enrichment Uranium Fuel.

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