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COST PENALTIES ASSOCIATED WITH CROSS-MIXING OF HTGR PARTICLE TYPES DURING FUEL REPROCESSING

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CONTENTS

Page

Abstract 1
Introduction 2
Analysis and Results 4
  Fuel Cycle Data 4
  Fuel Cycle Costs 4
  Crossover Penalty on Fuel Costs 9
  Fuel Value of ^{233}U 14
References 17

COST PENALTIES ASSOCIATED WITH CROSS-MIXING OF HTGR PARTICLE TYPES DURING FUEL REPROCESSING

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ABSTRACT

In the HTGR, the fertile material (thorium) and the bred fissile material (^{233}U and ^{235}U) are contained in a "fertile" particle, while the makeup fissile material (highly enriched ^{235}U) is contained in a separate "fissile" particle. The reference fuel cycle is a "selective recycle" in which these two particles are separated during the head-end operations at the chemical reprocessing plant. The bred ^{233}U is, of course, recycled. The residual makeup material (^{235}U + ^{236}U) recovered from the fissile particle is retired or sold, and fresh ^{235}U is purchased to provide fissile makeup to the HTGR. In some HTGR fuel management modes, the residual makeup uranium is recycled for a second "burn", and then discarded at zero value. That mode was not treated in this study. Typically, fuel cycle calculations have assumed that complete separation of the fissile and fertile particles is possible in the headend operation. In practice, the separation will be less than perfect, and incomplete separation may result in: (1) some of the fertile particles becoming mixed with the fissile particles, with subsequent retirement of a fraction of the bred fissile material; or (2) some of the fissile particles becoming mixed with the fertile particles, leading to recycle of residual makeup material containing a high fraction of ^{236}U. Either of these situations, termed "crossover" or "cross mixing", can produce a higher fuel cycle cost than the ideal complete separation of the two particles. The objective of this study was to determine the magnitude of the nuclear performance cost penalty associated with cross mixing. Results obtained for 30-year levelized fuel costs indicate that each ten percent crossover of bred fuel (^{233}U) into the retired fuel stream would cause from .003 to .04 mill/kwhe increase in fuel cycle cost, for retired fuel values of 100 to zero percent of "book value", respectively. Ten percent crossover of residual makeup fuel (^{235}U) into the recycle fuel stream causes about 0.006 mill/kwhe increase in fuel cycle cost.

Key words: high temperature gas cooled reactors, HTGR, thorium fuel cycle, fuel recycle, fuel management, economics, fuel value

INTRODUCTION

The reference fuel cycle for the HTGR uses thorium as the fertile material and uranium as the fissile material. The fissile uranium is provided by recycling bred ^{233}U, supplemented by a sufficient amount of highly-enriched uranium as makeup material to satisfy reactivity requirements. The makeup uranium is contained in one type of coated particle (the "fissile" particle), while the thorium and recycled bred uranium is contained in a different type of particle (the "fertile" particle). The two types of particles are designed to enable the discharged makeup fuel to be separated from the remainder of the fuel during reprocessing operations.

The uranium remaining in the discharged fissile particle is approximately 25–30% enriched in ^{235}U. However, it also contains about 50% ^{236}U, which is a significant neutron poison. Also, the gaseous diffusion plants have a much lower efficiency for separating ^{235}U from ^{236}U than for separating ^{235}U from ^{238}U. As a result, while it may have some value, the residual makeup fuel is not as desirable as fresh enriched uranium for use in the HTGR. Consequently, the reference fuel management scheme for the HTGR uses "selective recycle," in which only the bred uranium is recycled. The residual makeup uranium is assumed to be sold (or "retired") at some reduced value.*

In most HTGR fuel cycle studies, complete separation of the two types of particles is assumed. In actual practice, this separation will be less than 100 percent complete, and there will be some fraction of "crossover" or mixing of particle types. This will lead to unintentional recycle of some fraction of the residual makeup uranium, or accidental retirement of some fraction of the bred uranium, or both. These crossmixing situations are shown schematically in Figure 1.

Either direction of crossover will lead to an increase in fuel cost, relative to the ideal selective recycle. Continued recycled of residual makeup uranium leads to significant buildup of ^{236}U, with associated neutron losses. Retirement of bred uranium leads to greater requirements

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*In some fuel management schemes, the residual makeup uranium is recycled for a second "burn" and then is discarded at zero value. This study did not treat that fuel management option.

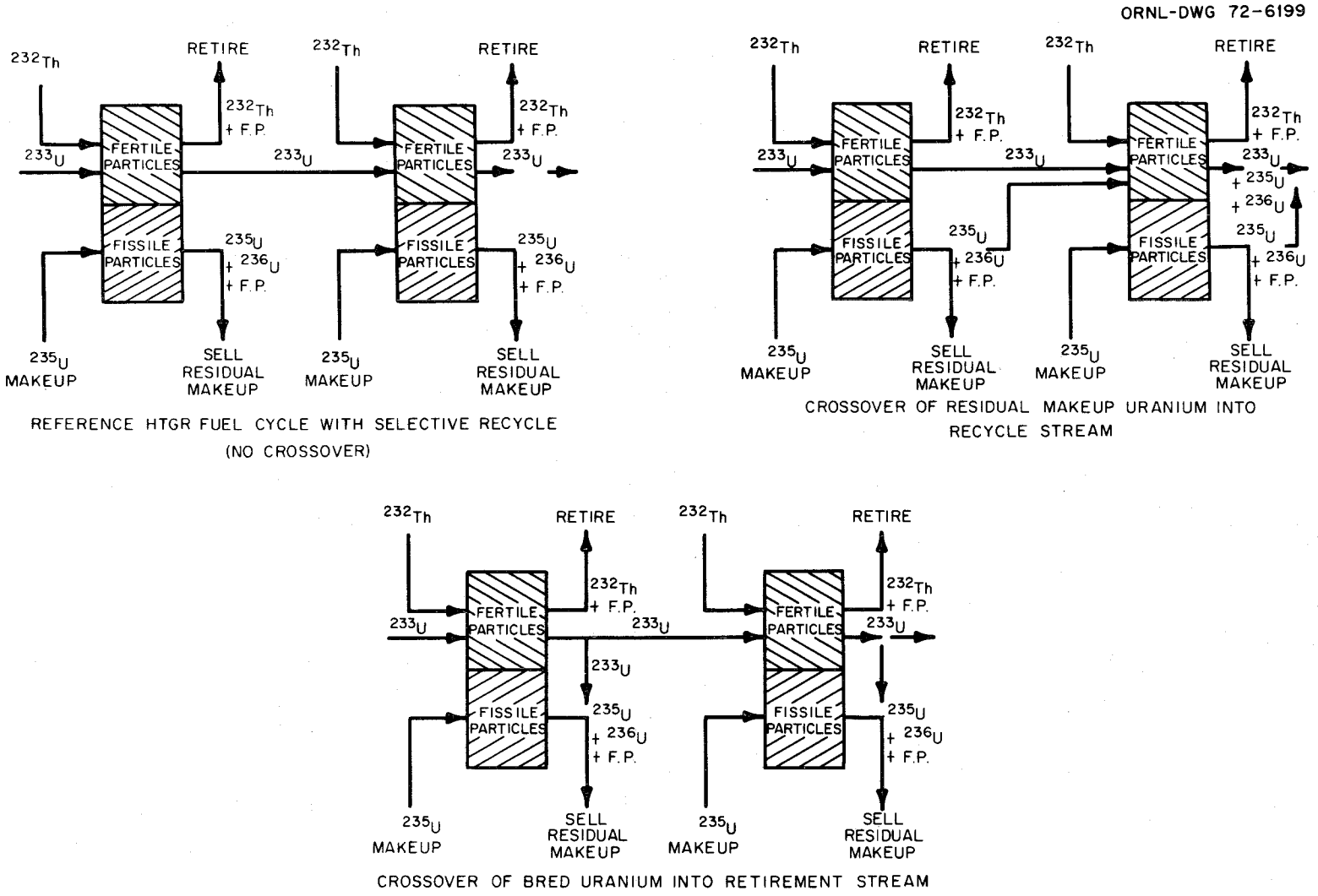

Fig. 1. Schematic Diagram of HTGR Reference Fuel Cycle and Crossover Modes.

for makeup with highly-enriched uranium. Also, mixing of bred uranium with discharged feed uranium leads to a requirement for handling that uranium in a shielded facility, with higher handling costs. Moreover, the value of the ^{233}U will be reduced by presence of ^{236}U. Concurrent crossover in both directions should produce additive penalties.

This study treated both crossover situations, with the fraction of cross mixing (in either direction) as a parameter. The ideal selective recycle case (complete separation) was used as a basis for comparison.

ANALYSIS AND RESULTS

Fuel Cycle Data

Mass balance data were provided by GGA.[1,2] These data included reactor loadings and charge-discharge data for all cycles from reactor startup to end of reactor lifetime. The fuel cycle characteristics of the reference reactor are summarized in Table 1. Fuel cycle mass flows were generated for the 8 cases listed in Table 2, using the GARGOYLE[3] zero-dimensional depletion code. Cumulative fuel consumptions over a 31-year reactor lifetime* are summarized in Table 3. These results show that either mode of cross mixing results in greater net consumption of fissile material (lower conversion ratio) than obtained for the reference case.

Fuel Cycle Costs

The cycle-by-cycle charge and discharge data were input to the economics subroutine of the TONG code.[4] Economic ground rules and fuel handling charges used in this study are presented in Table 4.

Since the main objective of this study was to determine the cost differential between different recycle modes, the absolute value of the fuel handling charges has no effect. Only the differences in fuel handling charges from one case to another are of significance in such comparative

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*Due to the sequence of fuel batches considered in the depletion calculations, it was more convenient to use a 31-year lifetime than to use the "standard" 30-year lifetime.

Table 1. Characteristics of Reference HTGR Fuel Cycle

Reactor Power, MW(t)	3000
MW(e)	1160
Carbon-to-Thorium Ratio	
Initial Core	225
Reload Segments	250
Fuel Residence Time, years at 0.8 plant factor	4
Reload Segment Core Fraction	
Segment A	0.28
Segment B	0.24
Segment C	0.24
Segment D	0.24

Table 2. Description of Cases Considered in Fuel Cross-Mixing Study

Case Number	Description
1	Reference Case. Selective recycle with no accidental cross mixing of particle streams.
2	No recycle, i.e. 100% of bred uranium being retired with the residual makeup uranium.
3	With 2% of bred uranium being retired with residual makeup uranium.
4	With 10% of bred uranium being retired with residual makeup uranium.
5	With 30% of bred uranium being retired with residual makeup uranium.
6	With 10% of residual makeup uranium recycled with the bred uranium.
7	With 20% of residual makeup uranium recycled with the bred uranium.
8	Full recycle; i.e., with 100% of residual makeup uranium recycled with the bred uranium.

Table 3. Cumulative Fuel Consumptions During 31 Years of Reactor Operation (at 80% Plant Factor)

Case Number	Cumulative Fissile Feed, Kilograms		Cumulative Fissile Discharged, kgs		Cumulative Net Consumption of Fissile Material
	^{233}U	^{235}U	^{233}U	^{235}U	
1 (Ref)	5,868	14,800	6,994	2,228	11,446
Crossover of Bred Uranium to Retired Stream					
3 (2%)	5,786	14,972	6,999	2,242	11,517
4 (10%)	5,276	15,546	6,941	2,221	11,660
5 (30%)	4,043	17,010	6,822	2,202	12,029
2 (100%)	0.0	22,091	6,534	2,372	13,185
Crossover of Residual Makeup to Recycle Stream					
6 (10%)	5,922	15,020	7,063	2,314	11,565
7 (20%)	5,959	15,217	7,112	2,383	11,681
8 (100%)	6,277	16,898	7,538	3,055	12,582

Table 4. Economic Ground Rules

Present-worth Discount Rate	7%/year
Fuel Interest Charge Rate	13.2%/year
Fuel Handling Charges:	
Fabrication	\$110/kg
Reprocessing	\$95/kg
Shipping — To Reactor	\$8/kg
From Reactor	\$17/kg
Fuel Material Values	
Thorium	\$5/lb ThO_2
Bred Uranium — ^{233}U	\$14.81/gram
^{235}U	\$12.70/gram
Fissile Plutonium	\$9.28/gram
Makeup Uranium* (93.5% ^{235}U)	\$12.70/gram ^{235}U
Residual Makeup Uranium	0—\$12.70/gram ^{235}U
Fuel Losses	
Fabrication	0.5%
Reprocessing	0.5%
Fuel Holdup Times	
Pre-Irradiation	6 months
Post-Irradiation	6 months

*Based on \$32/kg separative work, \$8/lb U_3O_8 and \$2.70/kg U for conversion from U_3O_8 to UF_6.

calculations. However, the values shown were estimated for a future large industry in order to indicate the magnitude of the total fuel cycle cost, as well as the fuel cost differentials.

As noted, the value of "retired" fissile uranium was varied from zero to 100% of the makeup uranium value. The value of retired ^{233}U was assigned the same fractional value as was used for retired ^{235}U.

The fuel cycle costs levelized over the complete 31-year lifetimes are presented in Table 5. Fuel costs for the final refuelings of the reactor lifetimes are presented in Table 6. These last-cycle costs are identified as "near equilibrium" costs. Attainment of complete equilibrium in ^{236}U would require much longer reactor histories. The contribution which is made by sale of "retired" fuel is noted in the tables. This contribution was multiplied by the fraction of "book value" to determine sensitivity of results to this value. Results are presented in Figure 2 and 3.

Crossover Penalty on Fuel Costs

The 31-year history results indicate that each ten percent crossover of bred uranium into the retired stream increases fuel cycle costs by about 0.003–0.04 mill/kwh(e), depending on whether the retired fuel is sold at full value or zero value, respectively. Ten percent crossover of residual makeup uranium into the recycle stream increases fuel cycle costs by about .006 mill/kwh(e).

The "near-equilibrium" costs yield similar cost penalties for the crossover of bred uranium into the retired stream. However, the penalty for crossover of residual makeup uranium into the recycle stream is higher (about 0.020 mill/kwh(e) penalty from ten percent crossover) than the average penalty over the first 31 years of recycle. This is due to the higher cumulative concentration of ^{236}U in the fertile particle in the near-equilibrium case. That is, during all the years of reactor operation, one has been adding ^{236}U to the fertile particle at each reload (e.g., 10% of discharged ^{236}U is added at each reload). It should be noted that these cycles have not reached complete equilibrium in ^{236}U, so the equilibrium cycle penalty would be even higher than the near-equilibrium values obtained in these calculations.

Table 5. 31-year Lifetime Levelized Fuel Cycle Costs, mills/kWh(e)

	Reference	Bred Uranium Retired				Residual Makeup Recycled		
Case No.	1	3	4	5	2	6	7	8
Net Fuel Consumption*	.578	.578	.582	.592	.621	.583	.589	.630
Fabrication	.131	.131	.131	.131	.131	.131	.131	.134
Reprocessing	.102	.102	.102	.102	.102	.106	.106	.108
Shipping	.029	.029	.028	.028	.028	.029	.029	.030
Fuel Interest Charges	.448	.449	.446	.442	.435	.450	.450	.460
Fab. plus Proc. Interest	.048	.049	.049	.049	.049	.045	.045	.043
Total Fuel Cost	1.336	1.338	1.338	1.344	1.366	1.344	1.350	1.405
Contribution made by sale of retired fuel at 100% value*	-.064	-.072	-.097	-.159	-.377	-.057	-.050	+.010

*With 100% of fresh fuel value ($/gram) assigned to retired fuel.

Table 6. Near-Equilibrium Fuel Cycle Costs, mills/kWh(e)

	Reference	Bred Uranium Retired				Residual Makeup Recycled		
Case No.	1	3	4	5	2	6	7	8
Net Fuel Consumption*	.583	.585	.586	.598	.632	.593	.603	.679
Fabrication	.123	.124	.123	.123	.123	.124	.125	.129
Reprocessing	.096	.096	.096	.095	.095	.096	.096	.100
Shipping	.026	.026	.026	.026	.026	.027	.027	.027
Fuel Interest Charges	.215	.217	.215	.214	.215	.221	.225	.258
Fab. plus Proc. Interest	.006	.006	.006	.006	.006	.006	.006	.006
Total Fuel Cost	1.049	1.054	1.052	1.062	1.097	1.067	1.082	1.199
Contribution made by sale of retired fuel at 100% value*	-.037	-.046	-.077	-.149	-.386	-.040	-.038	-.006

*With 100% of fresh fuel value ($/gram) assigned to retired fuel.

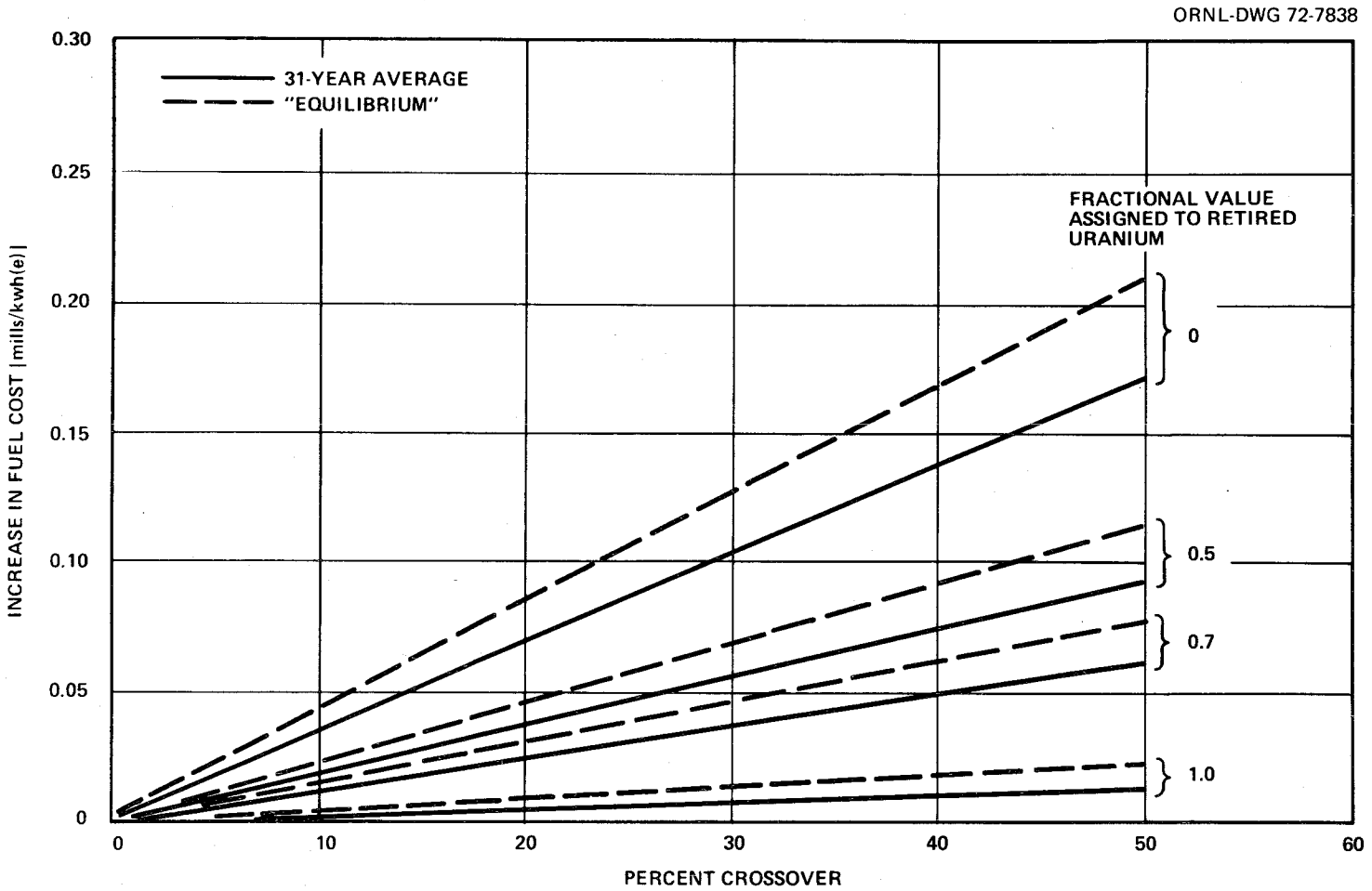

Fig. 2. Fuel Cost Penalty Resulting from Crossover of Bred Fuel into Retired Stream.

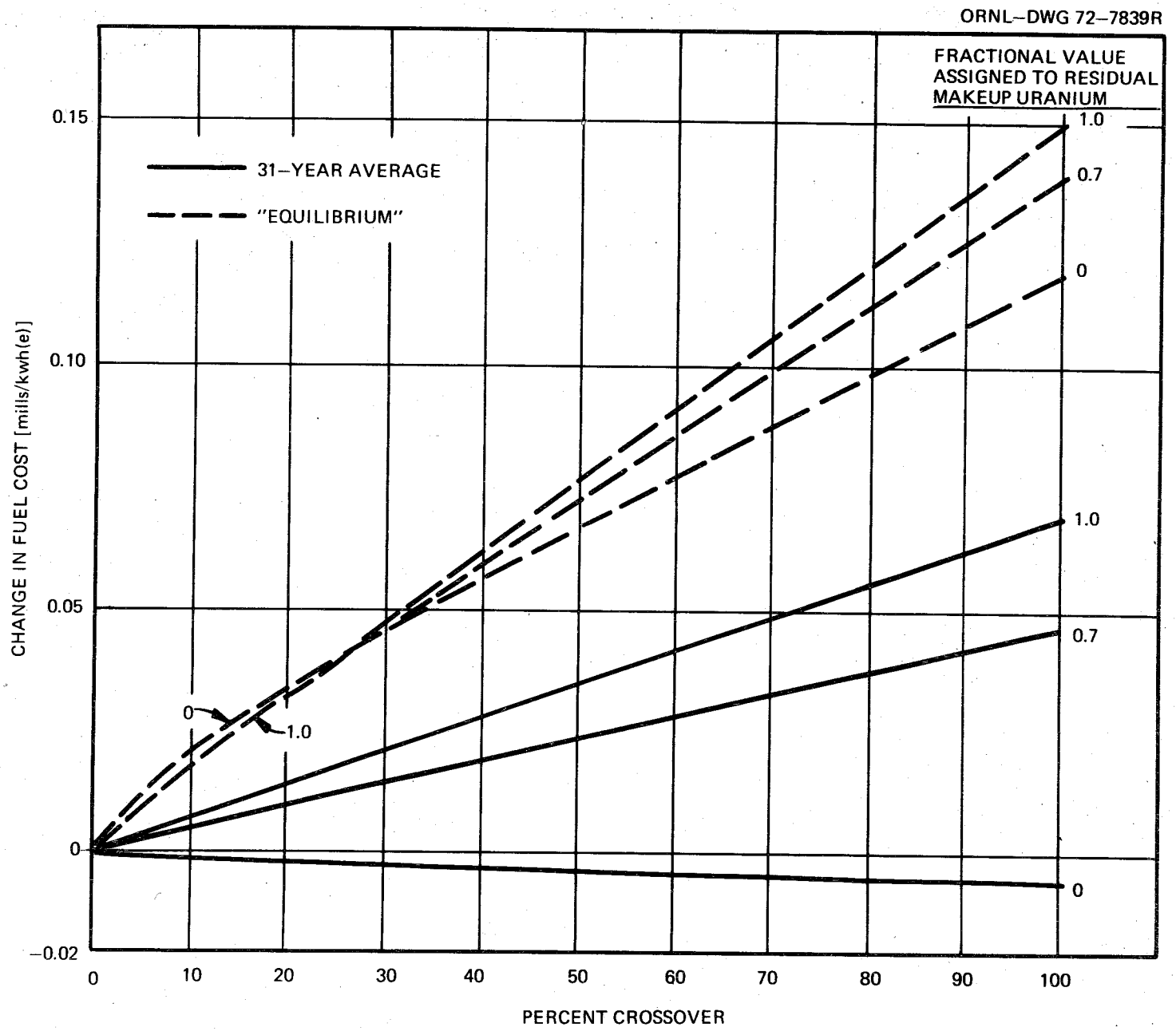

Figure 3 (Revised). Fuel Cost Penalty Resulting from Crossover of Residual Makeup Uranium into Recycle Stream.

The extreme of 100 percent recycle of the residual makeup uranium (not shown on the figures) increases the lifetime average fuel cost by about 0.025–0.065 mill/kwh(e), depending on whether the market value of the residual makeup is zero or near the highly-enriched uranium value. Thus, even if the selective recycle technology were not available, the resulting cost penalty would not be excessively high during the first 30 years of reactor operation. It should be noted that the ^{236}U content in the fuel builds up gradually. Therefore, the penalty is small in the early years, building up to larger values at long exposure times. Thus, the penalty occuring in later years (say, after 10 years of recycle) will be very high. The fact that present value discounting and long-term averaging produces a low average penalty will be of small comfort to the utility when looking at its annual charges.

These cost penalties result from degradation of nuclear performance and give no credit for offsetting savings in fuel handling costs. The crossover cases might have lower fuel handling charges than the reference 100% separation case. For example, acceptance of 10-20 percent crossover might allow a simpler and less expensive headend treatment at the reprocessing plant. Also, the full recycle case might not require separate particles, which could result in lower fabrication and reprocessing costs. Potential savings in fuel handling charges need to be estimated as a function of allowable particle crossmixing. When these data are available, tradeoff studies can be made to determine the optimum mode of operation.

The fuel cost penalties shown here can be translated into breakeven reductions in fuel handling charges. At the reference exposure levels, each 0.01 mill/kwh(e) is equivalent to $10/kg of total heavy metal (U plus Th) on fuel handling charges.

Fuel Value of ^{233}U

The above fuel costs were calculated using $14.81/gram as the reference value of ^{233}U in the HTGR. This value is 14/12 times the value of ^{235}U in 9.35%-enriched uranium ($8/lb U_3O_8 and $32/kg separative work). Subsequently, the value of ^{233}U was treated as a parameter to enable derivation of a

breakeven value for ^{233}U in recycled fuel. Results of this analysis are presented in Figure 4, indicating a value of about \$16.25–16.50/gram.

It should be observed that a zero fuel fabrication cost differential between fresh makeup fuel and recycle fuel was applied in these studies. Also, in this analysis, the same value was assigned to discharged ^{233}U (either recycled or retired) as to feed ^{233}U, whereas, in the crossover penalty analysis, retired ^{233}U value was reduced by the same factor as was used for retired ^{235}U. Thus, the derived ^{233}U value implicitly includes the penalty for the ^{236}U present.

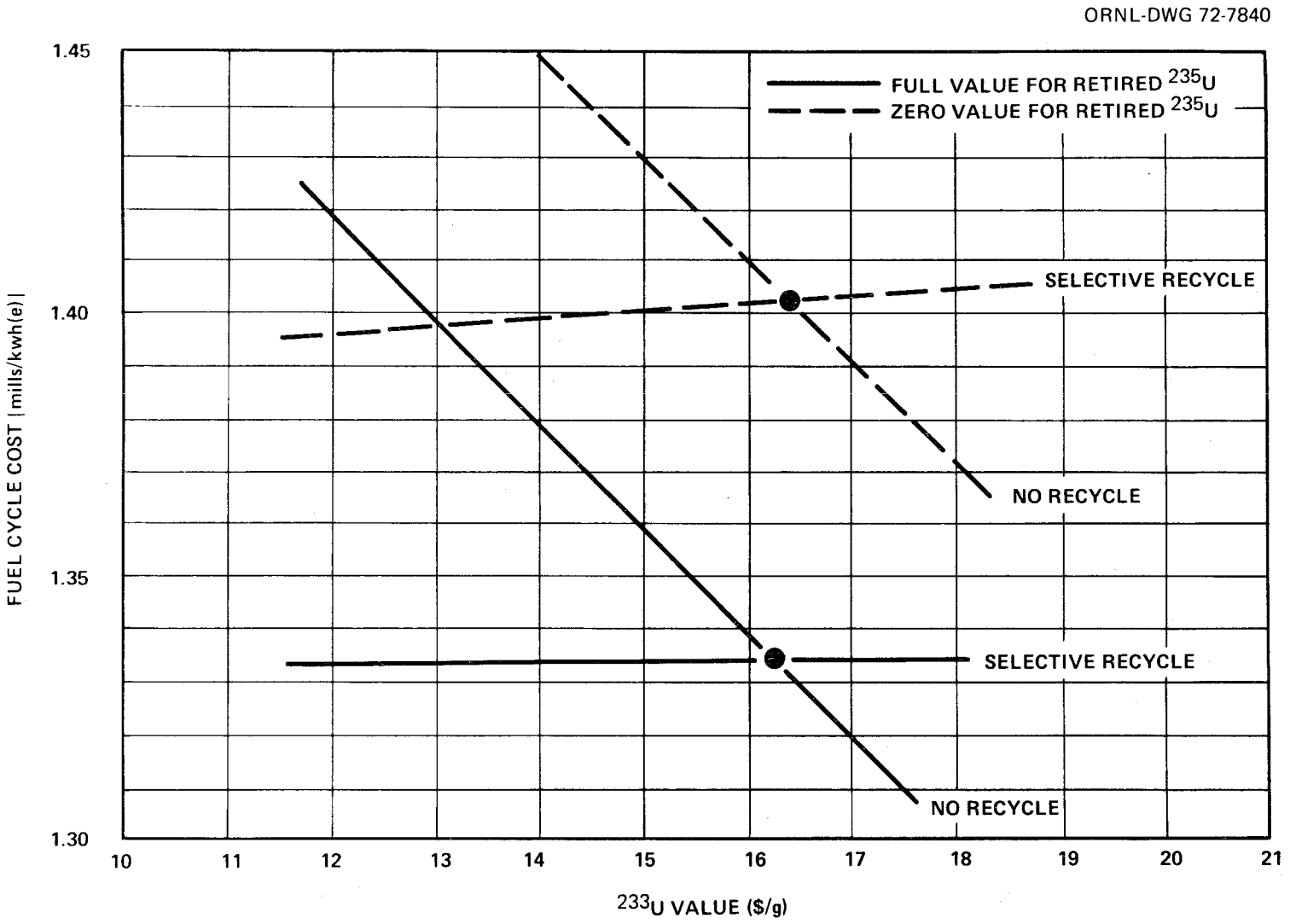

Fig. 4. Fuel Value of ^{233}U in HTGR Recycle Fuel.

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