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FROM: S. Jaye, L. L. Bennett, and M. P. Lietzke

ABSTRACT

The fuel value of U^{233} was calculated for five thermal reactors (Dresden, Yankee, Carolinas-Virginia, Hallam, GCR-II). Relative to a U^{235} value of $17 per gram, pure U^{233} had a value that varied from $18.2 to $20.2 per gram. U^{233} contained in once- and twice-recycle uranium from an initial U^{233}-Th cycle had a value slightly in excess of the value of pure U^{233}. The value of U^{233} in recycle uranium from an initial U^{235}-Th cycle was less than that for pure U^{233} and decreased with each succeeding cycle.

A STUDY OF THE FUEL VALUE OF U^{233}

S. Jaye, L. L. Bennett, and M. P. Lietzke

Introduction

The value of a nuclear fuel can be determined by its usefulness in a reactor; a measure of its usefulness is its influence on fuel cost. With fuel cost as the criterion, fuel value must be treated as a parameter in reactor fuel-cost studies in order to arrive at a logical conclusion. In this study, the fuel value of U^{233} was defined as that value which resulted in the same fuel cost for a given reactor independent of whether U^{235} or U^{233} was used as the enriching material (thorium was the fertile material in all cases). This procedure determines the fuel value of U^{233} relative to that of U^{235}. While this method allows one to calculate the fuel value of U^{233} on a logical basis, the picture becomes somewhat clouded when several different reactor types and fuels utilizing recycled uranium are considered. Thus the fuel value of U^{233} will be a function not only of the isotopic composition of the uranium but also of the reactor in which it is placed. For example, the introduction of U^{233} in a reactor with a high conversion ratio when operating on U^{235} can cause a marked improvement in the conversion ratio and a corresponding increase in reactivity lifetime. On the other hand, if the reactor was initially a poor converter when fueled with U^{235}, the addition of U^{233}, while still improving the conversion ratio, would not increase the reactivity lifetime markedly. Since there will undoubtedly be an economic penalty to be paid for the use of U^{233}, use of U^{233} would not be economical in the latter case.

In this study, the fuel value of U^{233} was calculated in five particular reactors which are representative of the power reactors being considered for early construction. The reactors chosen were the Dresden boiling water reactor; the Yankee pressurized water reactor; the Carolinas-Virginia heavy water moderated reactor; the Hallam sodium-graphite reactor and the GCR-II[1] gas cooled reactor. The fuel value of U^{233} was calculated in a manner similar to that used by Jaye[2] in calculating the fuel value of plutonium. In all cases, the fuel was assumed to be a mixture of thorium and uranium oxides; the basic design of the reactors was not altered except for the isotopic composition of the fuel. For each reactor, two initial fuel loadings were considered: in one case U^{235} was the enriching material while in the other it was U^{233}. The reactivity lifetime and the fuel cost was calculated as a function of fissile enrichment and U^{233} value for both initial fuels. The minimum fuel costs were then determined as a function of U^{233} value. That particular U^{233} value which yielded equal minimum fuel costs independent of the initial enriching material was designated as the U^{233} fuel value. The associated fuel cycles were termed the break-even cycles for U^{233} and U^{235}. The enrichments and reactivity lifetimes for the break-even cycles determined the isotopic compositions at the end of the irradiations for both fuels. Various amounts of uranium from the break-even cycles (an adequate supply of those materials was assumed to be available) were then mixed with thorium and the entire calculation was repeated in order to determine the fuel value of U^{233} in once- and twice-recycle uranium.

Summary of Results

The value of U^{233} relative to that of U^{235} has been calculated for three complete cycles in each of five reactors. The value of U^{233} varied from $18.2 per gram in the Carolinas-Virginia reactor to $20.2 per gram in the Hallam reactor. The value of U^{233} in uranium recycled from an initial U^{233}-Th cycle was somewhat greater than that of pure U^{233}. This increase in U^{233} value was due to an increase in conversion ratio effected by the presence of U^{234} and amounted to at most $2.2 per gram. The value of U^{233} in uranium recycled from an initial U^{235}-Th cycle was less than that of pure U^{233} and decreased with each succeeding cycle. This decrease was a consequence of the buildup of U^{236} which acts as a neutron poison. In general, the value of U^{233} in the pure form and in uranium recycled from an initial U^{233}-Th cycle had a value greater than that of U^{235}. The value of U^{233} in uranium recycled from an initial U^{235}-Th cycle varied from slightly more than that of U^{235} down to $10 per gram. With the exception of the GCR-II, the net fuel costs split into the following three roughly-equal parts: burnup, interest and inventory, and handling (conversion, fabrication, shipping, etc.) costs. The fuel fabrication charge made the largest contribution to the handling costs. In the case of the GCR-II, the low specific power led to low enrichments, relatively short cycles, and high inventory costs which amounted to approximately half the net fuel cost. The handling costs were relatively high (considering the low fabrication charges) due to the brevity of the break-even cycle.

For all the reactors an economic penalty (increased handling charges) was associated with the use of U^{233} and thorium due to radioactivity accompanying these materials. The daughter products of U^{232} were assumed to be removed from recycled uranium prior to its conversion from nitrate to oxide.* In all cases, the thorium oxide was assumed to have Th^{228} associated with it. This necessitated the use of shielded fabrication methods. The penalty associated with the use of an U^{233}-Th rather than an enriched uranium cycle in the Dresden reactor amounted to $32 per kg. The fabrication charge was increased by $60 per kg but the chemical conversion charges were lower due to differences in the economic ground rules.

The results of the break-even fuel cycles for the Dresden reactor are shown in Table 1. The value of U^{233} was $19 per gram in the pure form, $19.9 per gram and $20.3 per gram, respectively, in once- and twice-recycled uranium from an initial U^{233}-Th cycle. The value of U^{233} in once- and twice-recycled uranium from an initial U^{235}-Th cycle was $16.3 per gram and $15.2 per gram, respectively. The fuel costs for the various cycles varied from 4.36 to 4.57 mills/EKwh; the breakdown of these fuel costs are also shown in Table 1. Tables 2, 3, 4, and 5 show the equivalent results for the Yankee reactor, Carolinas-Virginia reactor, Hallam reactor, and GCR-II, respectively. The details of the various cycles are presented in Appendices A through E.

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*Prior to irradiation, thorium was considered to be available as the oxide; after irradiation, uranium was assumed to be marketable as the nitrate insofar as any particular fuel cycle was concerned.

Table 1. Break-even Fuel Costs for Dresden Reactor

Cycle	First	First	Second	Second	Third	Third
Initial Fuel Material	U^{235}	U^{233}	U^{235}	U^{233}	U^{235}	U^{233}
Fissile Enrichment, w/o	3.6	2.9	3.7	3.2	4.0	3.2
Uranium Enrichment, w/o	3.6	2.9	5.0	4.0	7.1	4.7
Reactivity Lifetime, MWD/t	30,500	28,600	30,100	32,800	29,100	31,300
U^{233} Fuel Value, $/gm	19.0	19.0	16.3	19.9	15.2	20.3
Feed Uranium Value, $/gm	17.0	19.0	12.2	16.0	8.97	13.7
Cost of Conversion to Oxide, mills/Ekwh	0.06	0.06	0.08	0.06	0.10	0.07
Cost of Fuel Fabrication, mills/Ekwh	1.01	1.08	1.03	0.94	1.06	0.99
Cost of Shipping, mills/Ekwh	0.09	0.10	0.09	0.09	0.10	0.09
Cost of Chemical Processing,* mills/Ekwh	0.15	0.14	0.15	0.13	0.17	0.14
Cost of Conversion from Nitrate, mills/Ekwh	0.02	0.02	0.02	0.02	0.02	0.02
Cost of Inventory and Interest, mills/Ekwh	1.94	1.80	1.93	1.96	1.99	1.97
Cost of Thorium Burnup, mills/Ekwh	-	-	-	-	-	-
Cost of Uranium Burnup, mills/Ekwh	1.09	1.16	1.19	1.12	1.13	1.00
Net Fuel Cost,** mills/Ekwh	4.36	4.36	4.49	4.32	4.57	4.28

* Complete core loading, 51.5 metric tons

** Thermal efficiency, 0.29

Table 2. Break-even Fuel Costs for the Yankee Reactor

Cycle	First	First	Second	Second	Third	Third
Initial Fuel Material	U^{235}	U^{233}	U^{235}	U^{233}	U^{235}	U^{233}
Fissile Enrichment, w/o	5.7	4.6	5.5	4.4	6.0	4.7
Uranium Enrichment, w/o	5.7	4.6	7.2	5.4	10.0	6.7
Reactivity Lifetime, MWD/t	35,800	35,600	32,400	32,400	31,700	33,200
U^{233} Value, $/gm	19.0	19.0	16.6	20.4	15.3	20.7
Feed Uranium Value, $/gm	17.0	19.0	13.0	16.5	9.8	14.1
Cost of Conversion to Oxide, mills/Ekwh	0.09	0.08	0.11	0.09	0.14	0.10
Cost of Fuel Fabrication, mills/Ekwh	0.46	0.46	0.50	0.50	0.52	0.49
Cost of Shipping, mills/Ekwh	0.08	0.08	0.09	0.09	0.09	0.09
Cost of Chemical Processing,* mills/Ekwh	0.20	0.17	0.22	0.19	0.24	0.20
Cost of Conversion from Nitrate, mills/Ekwh	0.02	0.02	0.02	0.02	0.02	0.02
Cost of Inventory and Interest, mills/Ekwh	1.58	1.45	1.57	1.50	1.65	1.57
Cost of Thorium Burnup, mills/Ekwh	-	-	-	-	-	-
Cost of Uranium Burnup, mills/Ekwh	1.57	1.74	1.62	1.59	1.55	1.45
Net Fuel Cost,** mills/Ekwh	4.00	4.00	4.13	3.98	4.21	3.92

* Complete core loading, 20.1 metric tons

** Thermal efficiency, 0.28

Table 3. Break-even Fuel Costs for Carolinas-Virginia Reactor

Cycle	First	First	Second	Second	Third	Third
Initial Fuel Material	U^{235}	U^{233}	U^{235}	U^{233}	U^{235}	U^{233}
Fissile Enrichment, w/o	5.1	4.4	5.7	4.3	7.5	4.8
Uranium Enrichment, w/o	5.1	4.4	8.0	5.5	14.9	7.5
Reactivity Lifetime, MWD/t	33,700	32,900	35,100	32,200	31,900	34,000
U^{233} Fuel Value, $/gm	18.2	18.2	14.8	19.6	10.0	20.5
Feed Uranium Value, $/gm	17.0	18.2	11.6	15.0	7.1	12.4
Cost of Conversion to Oxide, mills/Ekwh	0.08	0.07	0.11	0.09	0.19	0.11
Cost of Fuel Fabrication, mills/Ekwh	0.88	0.90	0.84	0.92	0.93	0.87
Cost of Shipping, mills/Ekwh	0.11	0.11	0.10	0.11	0.11	0.10
Cost of Chemical Processing,* mills/Ekwh	0.34	0.28	0.33	0.29	0.42	0.30
Cost of Conversion from Nitrate, mills/Ekwh	0.02	0.02	0.02	0.02	0.02	0.02
Cost of Inventory and Interest, mills/Ekwh	1.69	1.61	1.81	1.68	2.07	1.84
Cost of Thorium Burnup, mills/Ekwh	-	-	-	-	-	-
Cost of Uranium Burnup, mills/Ekwh	1.92	2.05	1.94	1.87	1.61	1.71
Net Fuel Cost,** mills/Ekwh	5.04	5.04	5.15	4.98	5.35	4.95

* Complete core loading, 3.43 metric tons

** Thermal efficiency, 0.28

Table 4. Break-even Fuel Cost for Hallam Reactor

Cycle	First	First	Second	Second	Third	Third
Initial Fuel Material	U^{235}	U^{233}	U^{235}	U^{233}	U^{235}	U^{233}
Fissile Enrichment, w/o	4.3	3.4	4.3	3.4	4.6	3.8
Uranium Enrichment, w/o	4.3	3.4	5.3	4.0	7.2	5.0
Reactivity Lifetime, MWD/t	21,200	21,000	21,700	21,300	23,700	24,300
U^{233} Fuel Value, $/gm	20.2	20.2	18.1	20.6	16.8	21.3
Feed Uranium Value, $/gm	17.0	20.2	14.0	17.7	10.7	15.8
Cost of Conversion to Oxide, mills/Ekwh	0.10	0.09	0.11	0.09	0.13	0.10
Cost of Fuel Fabrication, mills/Ekwh	0.57	0.57	0.56	0.57	0.53	0.49
Cost of Shipping, mills/Ekwh	0.14	0.14	0.13	0.14	0.13	0.12
Cost of Chemical Processing,* mills/Ekwh	0.25	0.21	0.24	0.21	0.24	0.20
Cost of Conversion from Nitrate, mills/Ekwh	0.03	0.03	0.03	0.03	0.03	0.03
Cost of Interest and Inventory, millw/Ekwh	1.87	1.72	1.88	1.81	1.95	1.94
Cost of Thorium Burnup, mills/Ekwh	-	-	-	-	-	-
Cost of Uranium Burnup, mills/Ekwh	1.66	1.86	1.79	1.77	1.78	1.73
Net Fuel Cost,** mills/Ekwh	4.62	4.62	4.74	4.61	4.79	4.61

* Complete core loading, 22.2 metric tons

** Thermal efficiency, 0.31

Table 5. Break-even Fuel Cost for GCR-II

Cycle	First	First	Second	Second	Third	Third
Initial Fuel Material	U^{235}	U^{233}	U^{235}	U^{233}	U^{235}	U^{233}
Fissile Enrichment, w/o	2.0	1.6	2.0	1.6	2.0	1.8
Uranium Enrichment, w/o	2.0	1.6	2.5	1.8	3.0	2.2
Reactivity Lifetime, MWD/t	15,700	15,500	17,600	13,300	17,000	16,900
U^{233} Fuel Value, $/gm	19.6	19.6	17.5	19.9	16.9	19.7
Feed Uranium Value, $/gm	17.0	19.6	14.0	17.1	11.5	15.6
Cost of Conversion to Oxide, mills/Ekwh	0.05	0.05	0.06	0.06	0.06	0.05
Cost of Fuel Fabrication, mill/Ekwh	0.63	0.64	0.56	0.73	0.58	0.58
Cost of Shipping, mills/Ekwh	0.15	0.15	0.14	0.18	0.14	0.14
Cost of Chemical Processing,* mills/Ekwh	0.15	0.14	0.13	0.16	0.13	0.13
Cost of Conversion from Nitrate, mills/Ekwh	0.04	0.04	0.03	0.04	0.03	0.03
Cost of Inventory and Interest, mills/Ekwh	1.99	1.90	2.00	1.88	2.02	2.00
Cost of Thorium Burnup, mills/Ekwh	-	-	-	-	-	-
Cost of Uranium Burnup, mills/Ekwh	0.33	0.42	0.55	0.29	0.53	0.38
Net Fuel Cost,** mills/Ekwh	3.34	3.34	3.47	3.34	3.49	3.31

* Complete core loading, 146 metric tons

** Thermal efficiency, 0.36

Discussion of Results

The attainable reactivity lifetimes influence the value of U^{233} to a great extent. Clearly, if the fuel lifetime is limited by fuel element damage to exposures less than 35,000 MWD/T,* the optimum enrichment to use would be the lowest enrichment which could achieve the "damage lifetime." Most of the break-even cycles in this study required less than 35,000 MWD/T; however, the results presented here assume that reactivity lifetime is the only limitation on fuel exposure. For a radiation-damage-limited fuel lifetime, the U^{233} value can be estimated from the information presented in Appendices A through E.

The reactivity-lifetime calculation[3] is based on a spatially uniform flux model in which the flux changes over the lifetime of a fuel loading. This calculational model will overestimate the average exposure for a reactor whose entire core is reloaded at one time, and underestimates the average exposure for a continuously fueled reactor. Although improved fueling methods may significantly increase reactivity lifetimes and therefore decrease fuel costs, the value of U^{233} relative to that for U^{235} should not change markedly.

Basic Steps in the Calculation

Each of the following calculations draws on the information generated in previous calculations:

1. The basic reactor-lattice design is approximated by an idealized cylindrical lattice of up to six regions. The first region contains all fuel isotopes, fission products, and other required materials. Each of the succeeding five regions contains one material (not a fuel material). The average flux in each region is calculated as a function of the macroscopic absorption cross section of region one using a P_3 expansion[4] of the single-energy Boltzmann equation.

*MWD/T is defined as thermal megawatt days per metric ton of fissile plus fertile material.

2. The effective thermal-neutron temperature is calculated[5] as a function of the initial fuel composition.

3. The effective multiplication constant and fuel isotopic densities are calculated[3] as a function of exposure for a spacially uniform-flux distribution. The reactivity lifetime, defined as that exposure at which the effective multiplication constant becomes less than unity, is calculated.

4. The fuel costs are calculated[3] as a function of U^{233} value for the initial fuel composition. The value of U^{234}, U^{235}, U^{236}, and Th^{232} were assumed to be constant and independent of composition.

5. The value of U^{233} is defined as that value for which the minimum fuel costs are equal whether initially fueled with U^{235} or U^{233} mixed with thorium.

6. The isotopic composition of the uranium removed from the reactor at the termination of the break-even cycle is determined. Steps two through six are repeated for various amounts of uranium of this composition added to thorium.

Fuel Cycle Charges

The fuel cost calculations are based on the following set of assumptions:

1. A complete core loading progresses through the various steps in the cycle as an integral unit.

2. The reactor operates at an 80% load factor.

3. Inventory on the fuel is charged from the time of conversion to the oxide until it is returned to the AEC in its proper chemical form.

4. Mixtures of uranium isotopes are borrowed from and returned to the AEC only as the nitrate; thorium only as the oxide.

5. Fabrication charges were estimated separately for each of the five fuel elements assuming shielded manufacturing methods.

6. Due to the criticality hazard, processes which are continuous in nature have costs which depend on the fissile enrichment.

7. The basic design of the reactor was not altered with the exception of the fuel composition.

The individual charges for each step in the fuel cycle were estimated[6] in the following manner:

1. <u>Conversion to the Oxides</u>

Since thorium will be stored as the oxide, there is no necessity to convert it. Uranium which is not associated with the gaseous diffusion plants will be stored as the nitrate. However, before it can be converted to the oxide in a normal chemical operation, the gamma activity from the daughter products of U^{232} must be removed. It was estimated that the chemical separation and conversion would cost $200 per kg of uranium. A 1% loss of uranium is associated with the conversion.

2. <u>Fabrication of Fuel Elements</u>

Although the gamma activity of the uranium is reduced in the conversion operation, any delay between conversion and fabrication will allow this activity to build up again. Since the thorium will have been stored for fairly long periods of time after having been in a reactor, there will be a gamma activity associated with the daughter products of Th^{228}. Due to the presence of this gamma activity, the fuel element fabrication must be performed with shielded manufacturing methods. The estimated fabrication charges,[7] including scrap recovery, for the five different fuel elements are given in Table 6. The fabrication charges shown in Table 6 are roughly \$60 per kg higher than those associated with enriched uranium.[2]

The differences in the fabrication charges were primarily associated with the cladding material and the specific design of the fuel element. The use of Zircaloy rather than stainless steel added roughly \$100 per kg; simple element design was associated with the lower fabrication charges.

Table 6. Uranium-Thorium Fuel Element Fabrication Charges

Reactor	Fabrication Charges, \$/kg
Dresden	\$215
Yankee	110
C-V	200
Hallam	90
GCR-II	85

3. Shipping

The cost of shipping the fuel to the reactor site from the fuel fabrication plant and from the reactor site to the chemical processing plant was assumed to be \$20/kg fuel.

4. Chemical Processing

The fuel processing cost for a one ton per day multipurpose radiochemical plant was calculated by the following equation:

$$\text{cost, \$/kg} = \frac{15.3}{(\text{CPR})} + \frac{15.3\ T}{W} \qquad (3)$$

$$\text{where } T = \begin{cases} 3 & \text{if } W/(CPR) \leq 3 \\ W/(CPR) & \text{if } 3 \leq W/(CPR) < 8 \\ 8 & \text{if } W/(CPR) \geq 8 \end{cases}$$

W = metric tons of fuel in a complete core loading

(CPR) = chemical plant processing rate, tons/day

The value of (CPR) is given in Table 7 as a function of the fissile enrichment of the initial thorium-uranium mixture. A 1% loss of uranium and thorium was associated with chemical processing.

Table 7. Permissible Chemical-Plant Processing Rate

Fissile Enrichment, %	Processing Rate, tons/day
1	1.0
2	0.96
3	0.70
5	0.46
7	0.34
10	0.25
15	0.17
25	0.11

The values of CPR given in Table 7 are equal to those used for plutonium in depleted uranium.[6] This should be a conservative estimate since the thermal absorption cross section of thorium is more than twice that of U^{238}.

5. Conversion from the Nitrate

Since the uranium would be stored as the nitrate at the end of processing, it is not necessary to convert it. The cost of converting thorium from the nitrate to the oxide was taken as $5 per kg. This value is based on the assumption that the thorium will not contain significant gamma activity from the decay products of Th^{228}; this requires that the conversion operation follow within a few weeks of chemical processing. A 1% loss of thorium was associated with chemical conversions.

6. Interest and Inventory

Inventory charges on fuel were taken at 4% per year and interest on borrowed monies at 6% per year.

7. Burnup

The value of the thorium consumed in the reactor or lost in the various handling operations was taken at $22 per kg. The value of the uranium was determined by its isotopic composition; U^{235} was assigned a value of $17 per gram, U^{234} and U^{236} were assigned a zero value.

8. Time Steps in Fuel Cycle

The times required for the different operations during a fuel cycle were those given in Table 8.

Table 8. Time Required for Each Step of the Fuel Cycle

Operation	Time, days
Conversion to oxide	60
Fabrication	275
Shipping	60
Irradiation	determined by the reactivity lifetime and the power density
Cooling	120
Chemical processing	determined by core size and enrichment of fuel
Conversion from nitrate	60

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Appendix A. Results Concerning the Dresden Reactor

The detailed results of the calculations concerning the Dresden reactor are presented in graphical form in Figs. 1A through 16A. Figure 1A summarizes these results and shows the minimum fuel costs (in mills per thermal kwh) as a function of U^{233} value for three complete cycles and two initial fuels. Since the reactor has a conversion ratio less than unity, only the U^{235} fuel exhibits a decreasing fuel cost with increasing U^{233} value. The value of U^{233} in recycle uranium increases slightly with each succeeding cycle after an initial U^{233} cycle. This increase in U^{233} value is the consequence of a slight increase in the conversion ratio due to the presence of U^{234} in recycle uranium. The value of U^{233} in uranium recycled from an initial U^{235} loading decreases with each succeeding cycle as a consequence of the build-up of U^{236}. Since the variation of the break-even fuel costs for the six cycles shown in Fig. 1 is less than 0.1 mills/TKwh and the fuel value of U^{233} varies by only $5 per gram, they may all be considered feasible cycles. Figure 2A shows the initial reactivity and reactivity lifetime as a function of fissile enrichment for both U^{235} and U^{233}. Both the reactivity lifetime and the initial reactivity increase continuously with enrichment. The effects of spectral hardening from the addition of U^{233} are not as pronounced as those associated with plutonium[2] since U^{233} has both a smaller resonance integral and a less energy dependent capture to fission ratio. This lack of similarity with the plutonium systems is even more pronounced in the succeeding cycles. In all cases of uranium recycle, the reactivity lifetime continuously increases with fissile enrichment whereas recycle plutonium exhibited definite reactivity-lifetime maxima.

Figure 3A shows the fuel cost for a U^{235} loading as a function of fissile enrichment for various U^{233} values. Below an enrichment of 3% the fuel costs rise rapidly because of decreasing reactivity lifetimes which lead to large handling costs; for enrichments in excess of 5%, the inventory charges become excessive. Figure 4A presents similar information for U^{233} loadings which exhibit the same general behavior.

Figure 5A gives the densities of the various fuel isotopes as a function of exposure for the U^{235} break-even cycle. While the total uranium content of the reactor drops less than 20%, the fissile uranium drops more than 40%. By the end of the cycle, U^{233} is involved in more than half of the fissions and the poisoning effect of the U^{236} is becoming significant. Figure 6A shows densities of the various fuel isotopes as a function of exposure for the U^{233} break-even cycle. The behavior is similar to the U^{235} break-even cycle except that U^{233} is involved in nearly all the fissions throughout the cycle and U^{236} is present but in very small concentrations.

Figures 7A through 11A present the pertinent information concerning once-recycle uranium and are analogous to Figs. 2A through 6A, respectively. Figures 12A through 16A present the pertinent information concerning twice-recycle uranium and are analogous to Figs. 2A through 6A, respectively.

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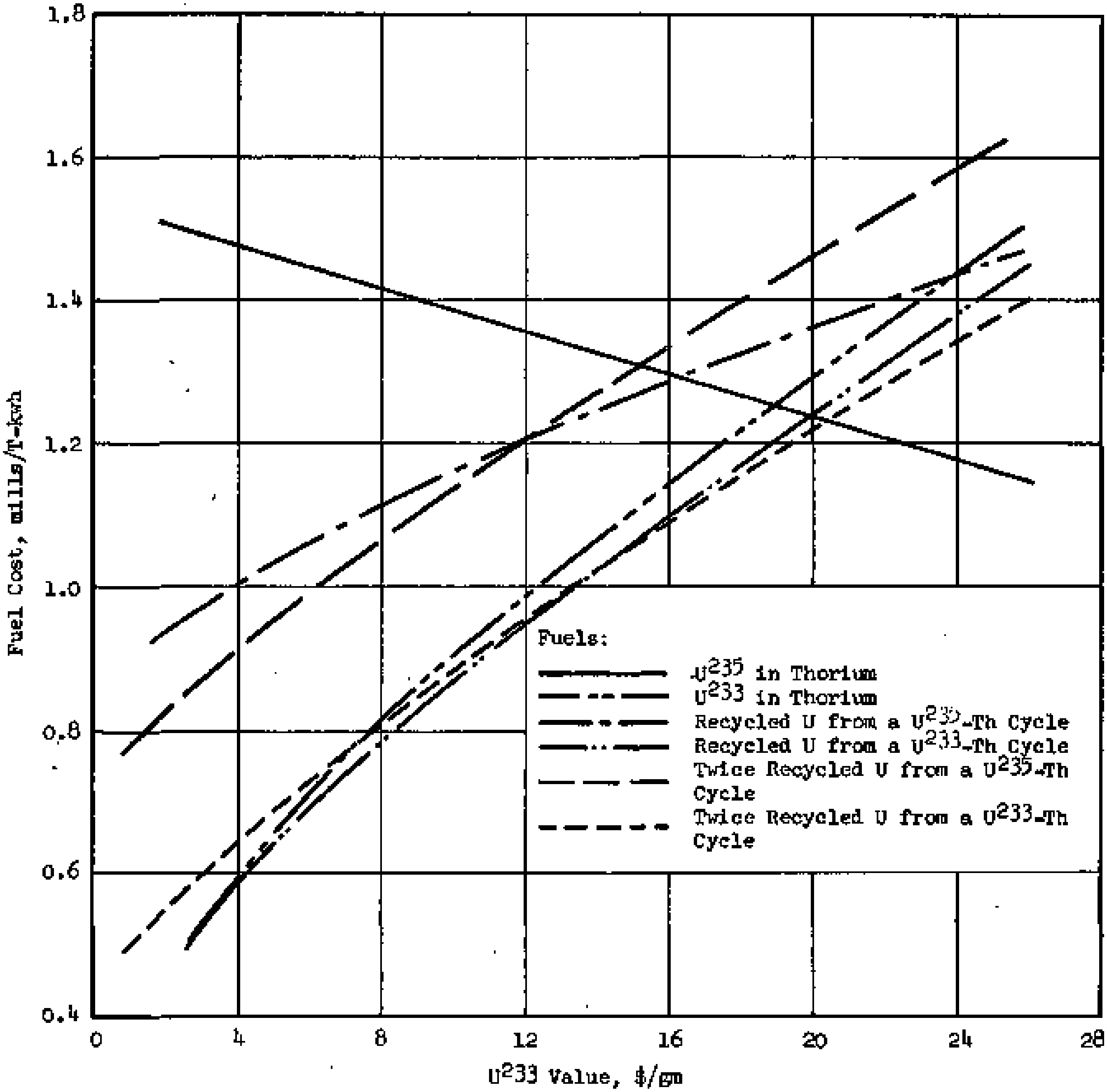

Fig. 1A. Minimum Fuel Cost Vs. U^{233} Value for Dresden Reactor.

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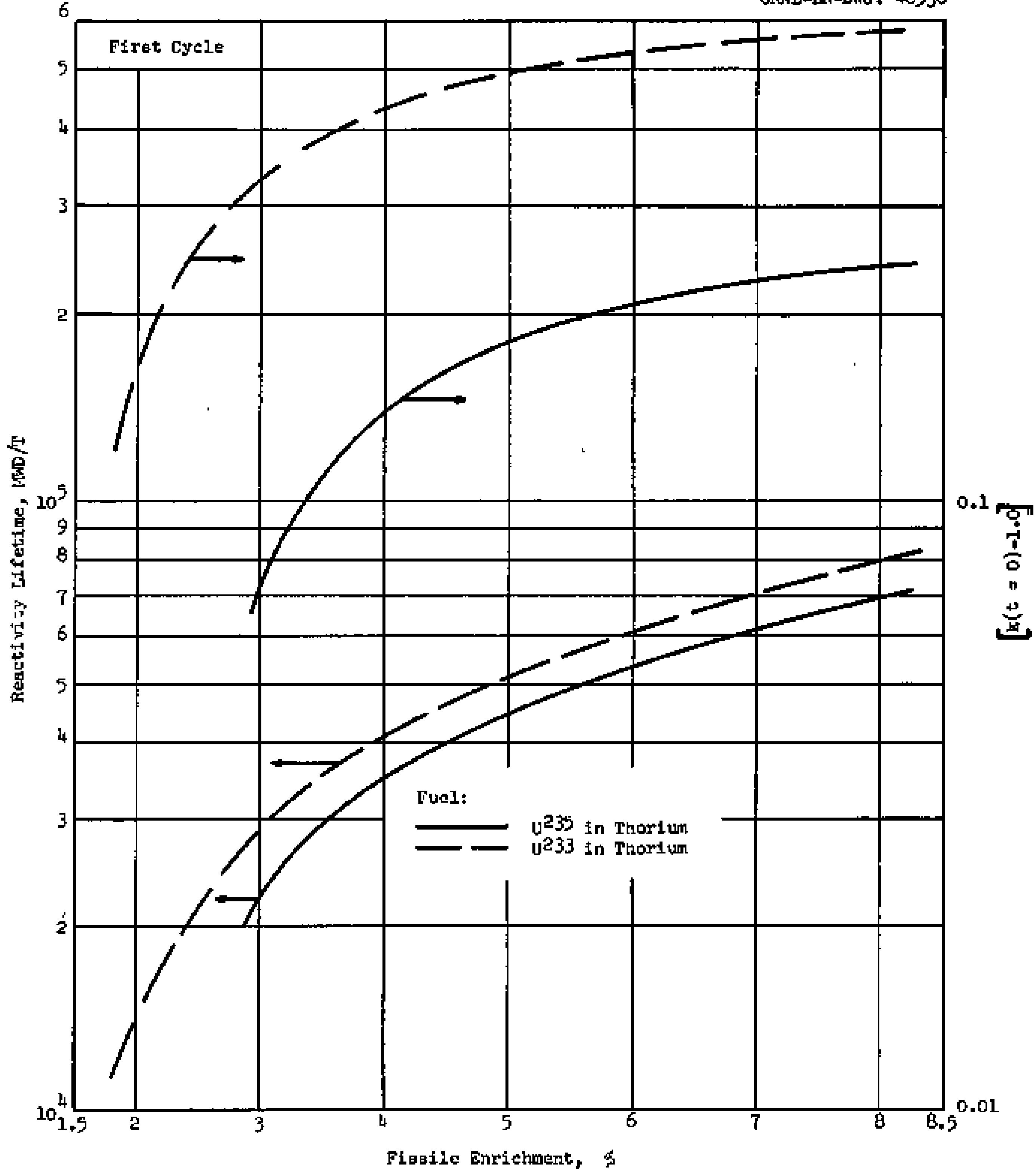

Fig. 2A. Reactivity Lifetime and Initial Reactivity Vs. Fissile Enrichment for Dresden Reactor.

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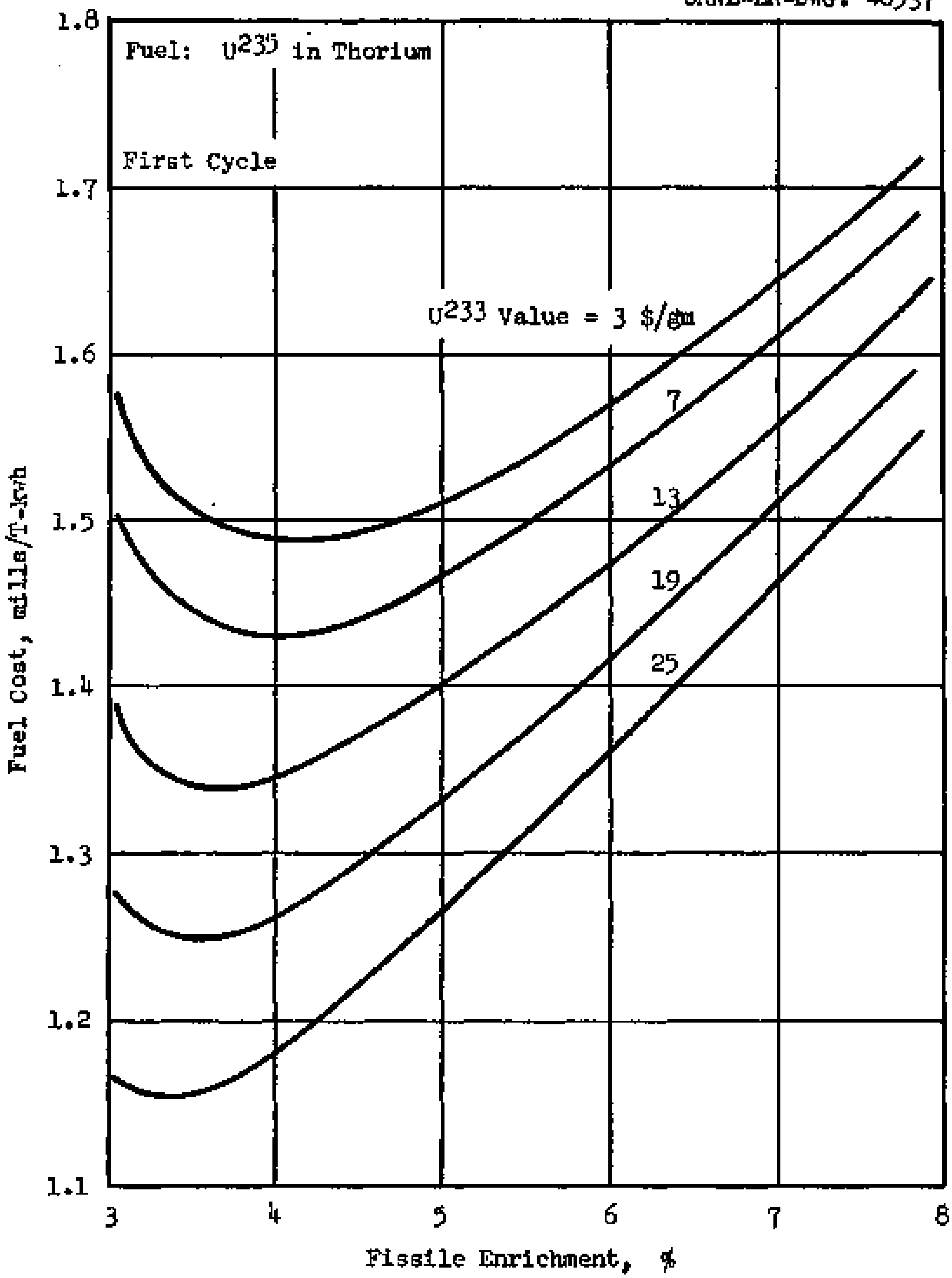

Fig. 3A. Fuel Cost Vs. Fissile Enrichment for Dresden Reactor.

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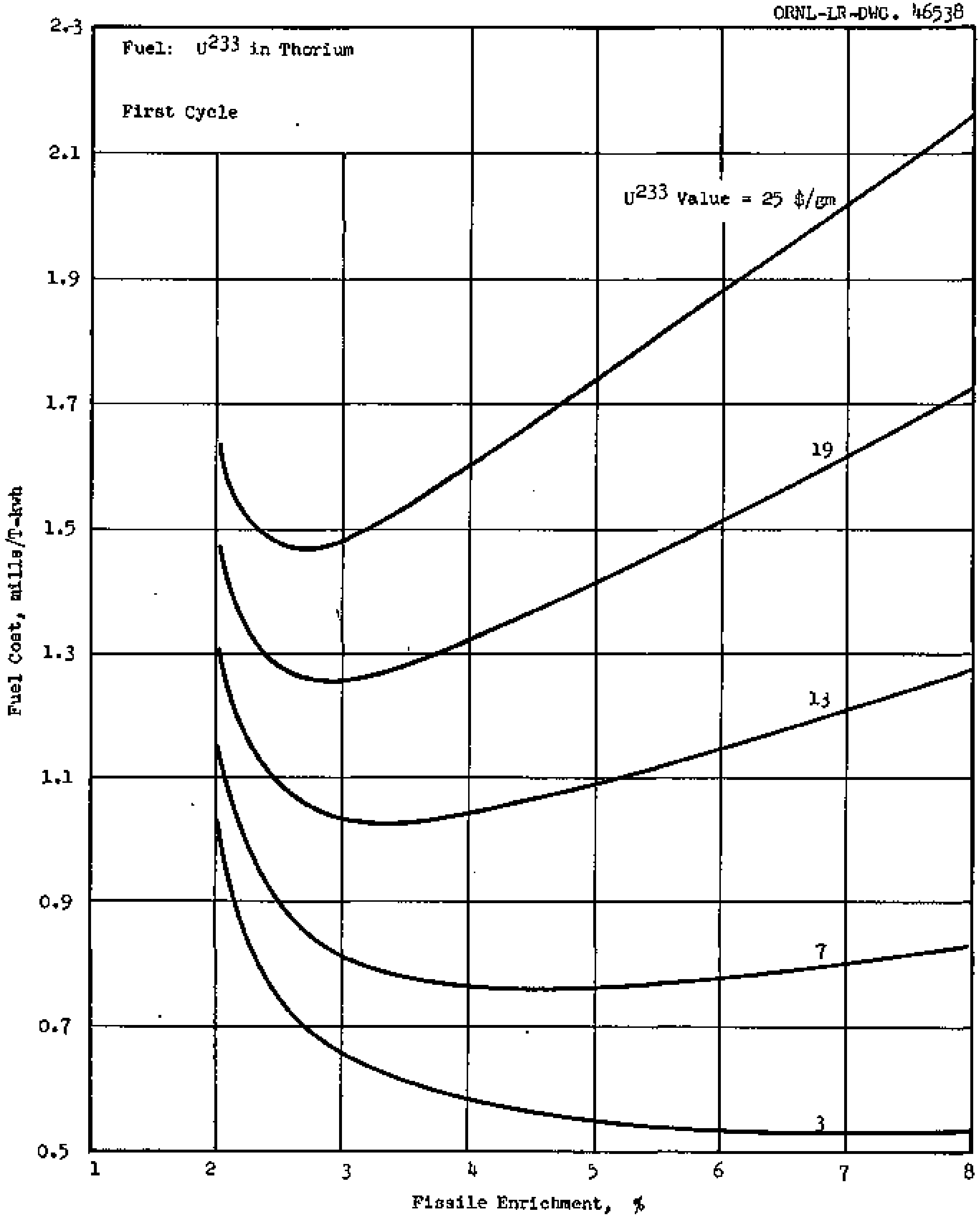

Fig. 4A. Fuel Cost Vs. Fissile Enrichment for Dresden Reactor.

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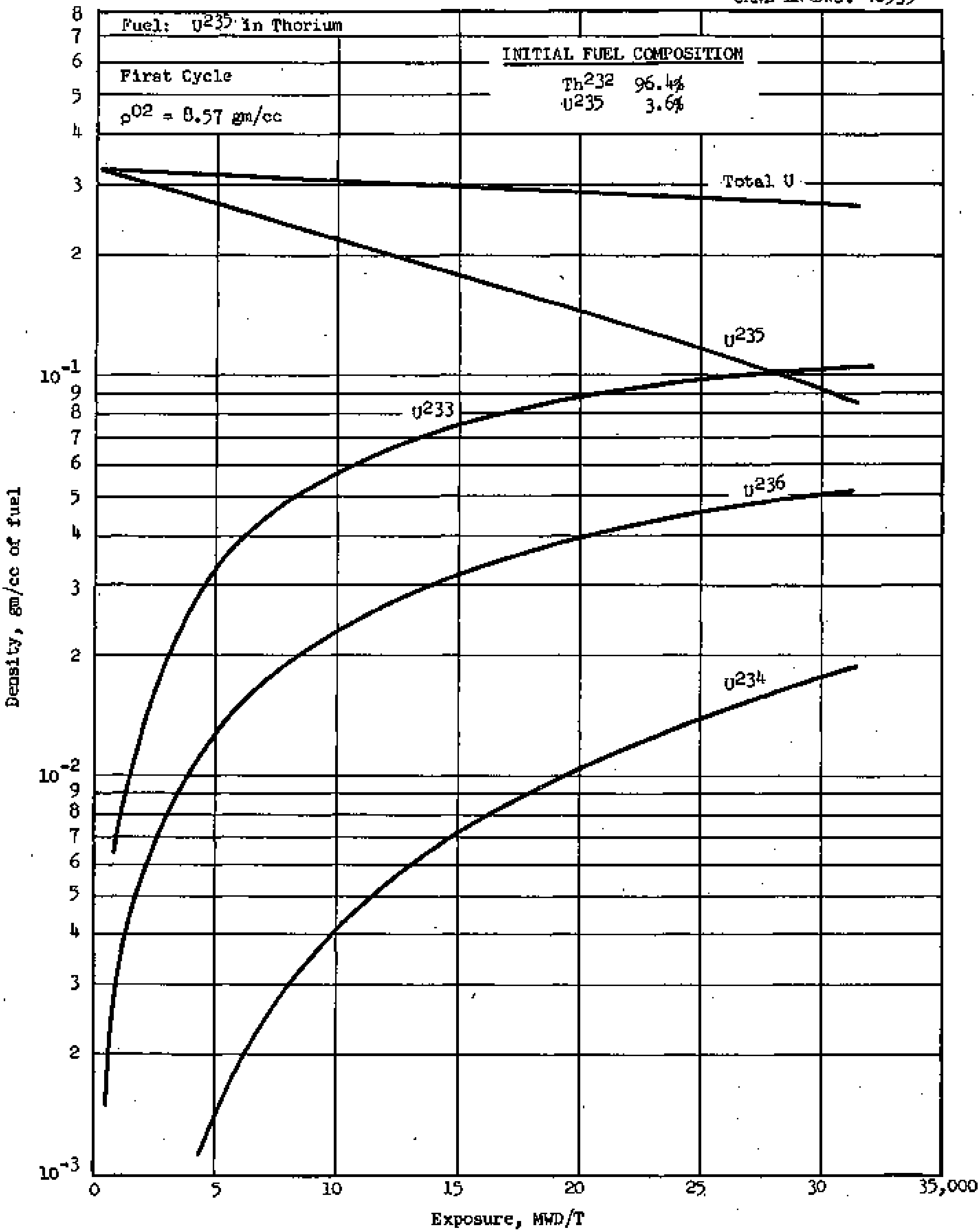

Fig. 5A. Fuel Isotopic Densities Vs. Exposure for Dresden Reactor.

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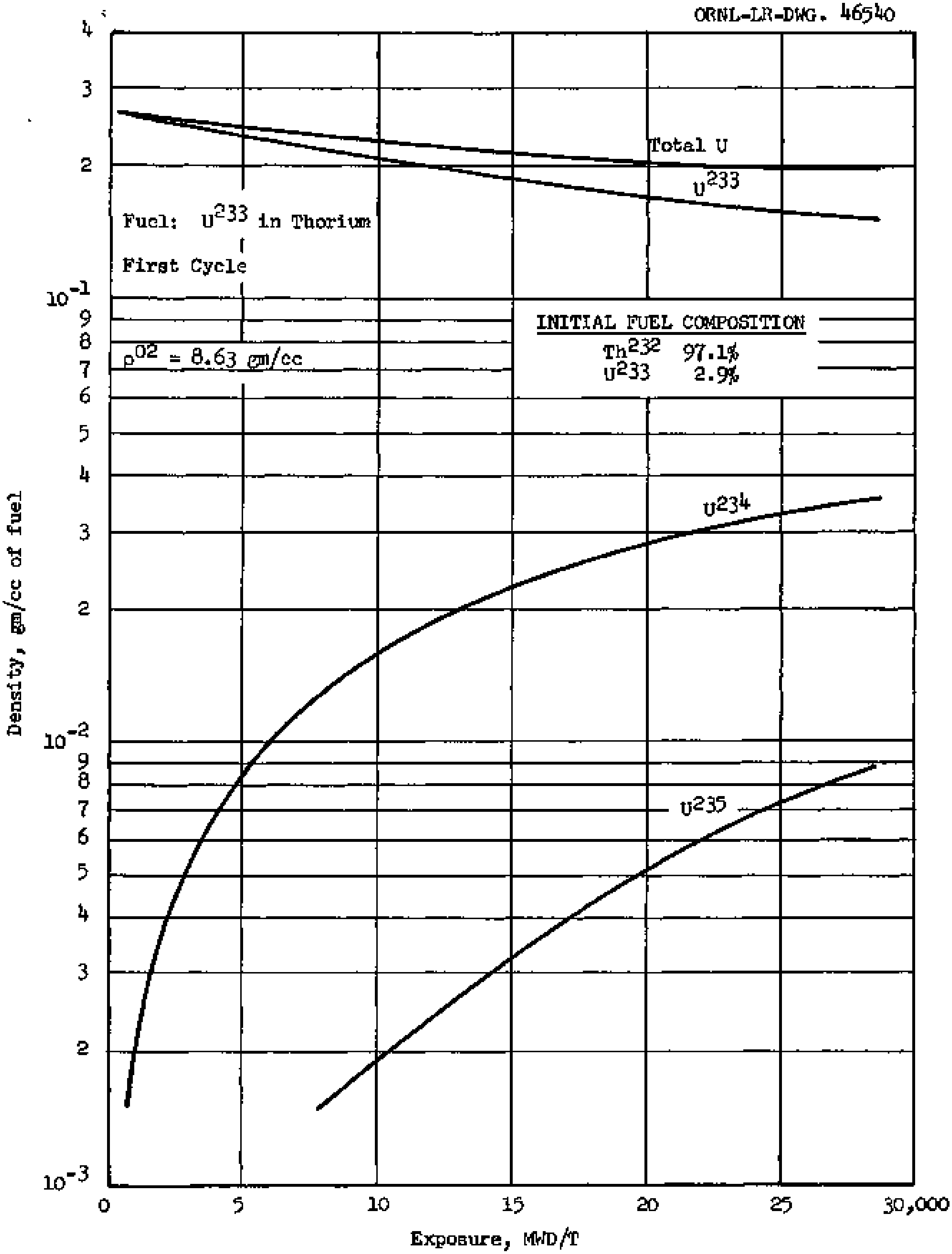

Fig. 6A. Fuel Isotopic Densities Vs. Exposure for Dresden Reactor.

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ORNL-LR-DWG. 46541

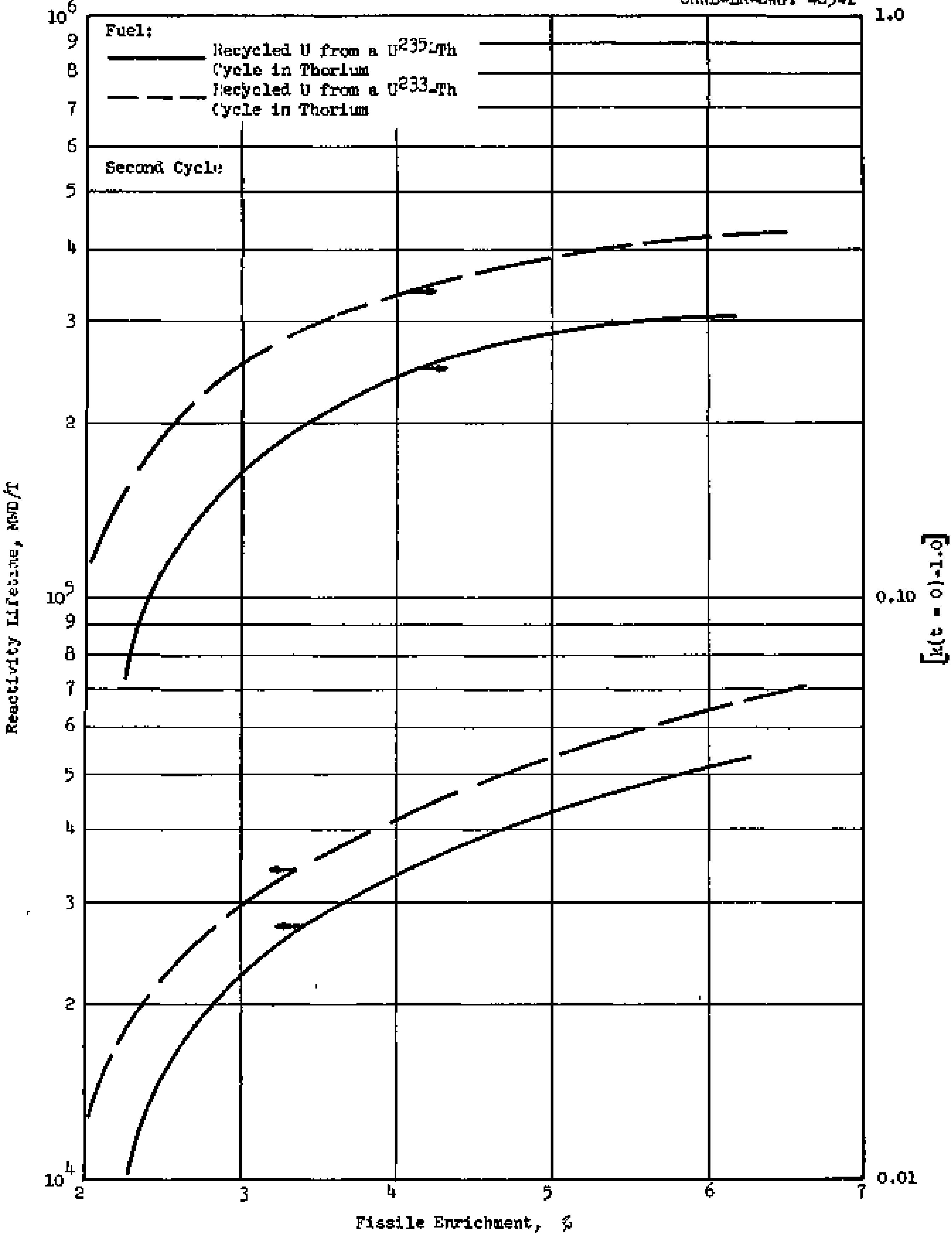

Fig. 7A. Reactivity Lifetime and Initial Reactivity Vs. Fissile Enrichment for Dresden Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46542

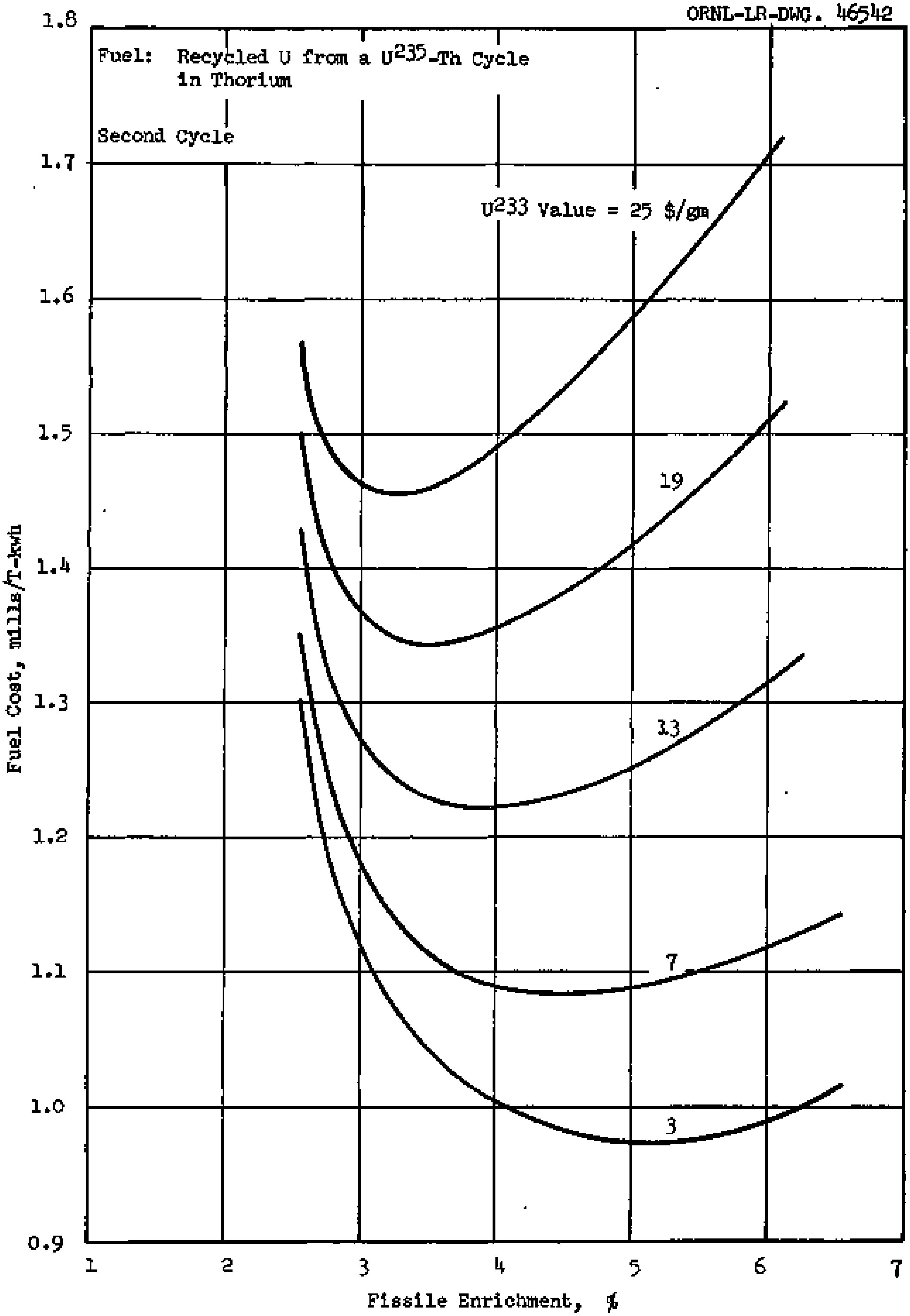

Fig. 8A. Fuel Cost Vs. Fissile Enrichment for Dresden Reactor

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ORNL-LR-DWG. 46543

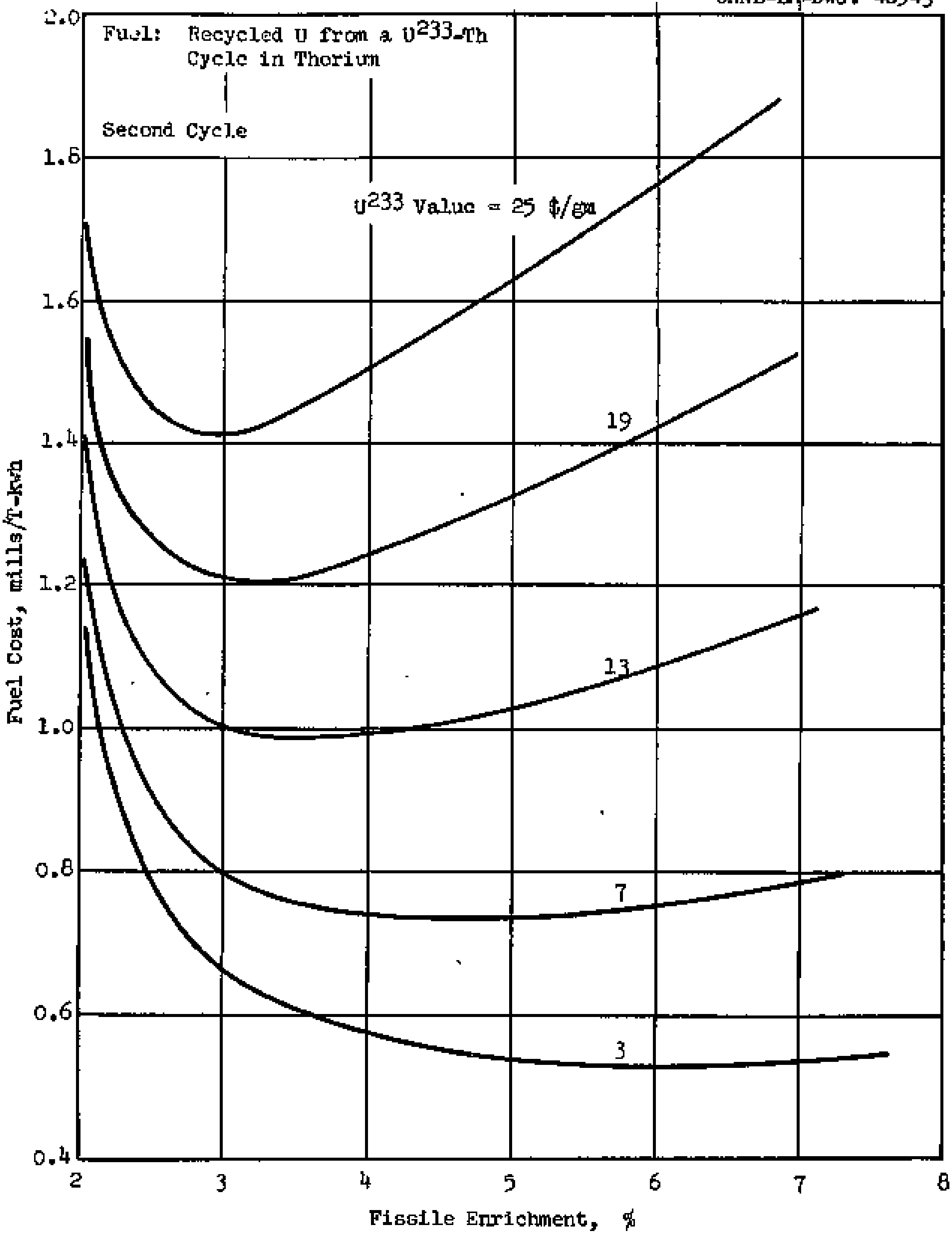

Fig. 9A. Fuel Cost Vs. Fissile Enrichment for Dresden Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46544

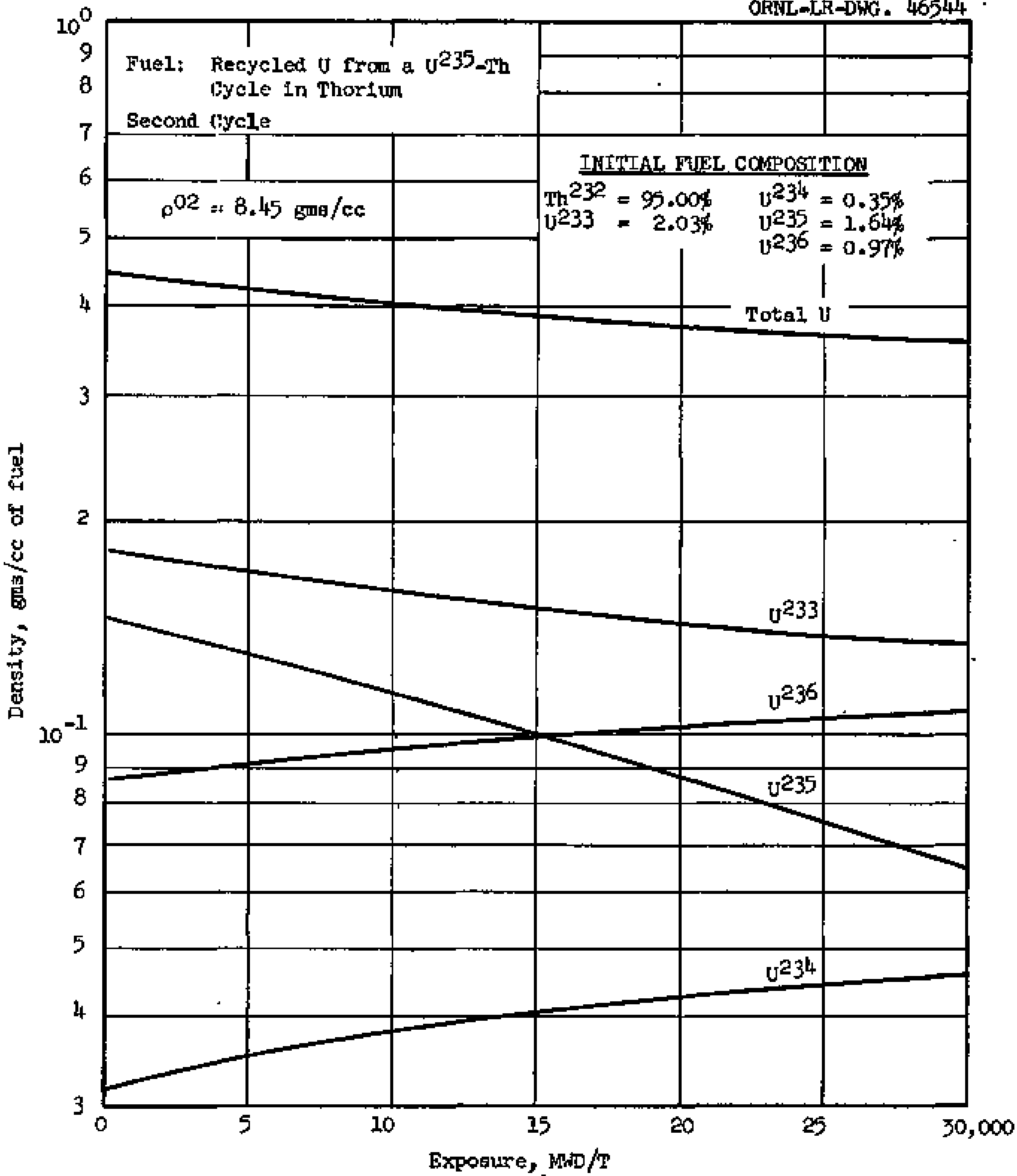

Fig. 10A. Fuel Isotopic Densities Vs. Exposure for Dresden Reactor.

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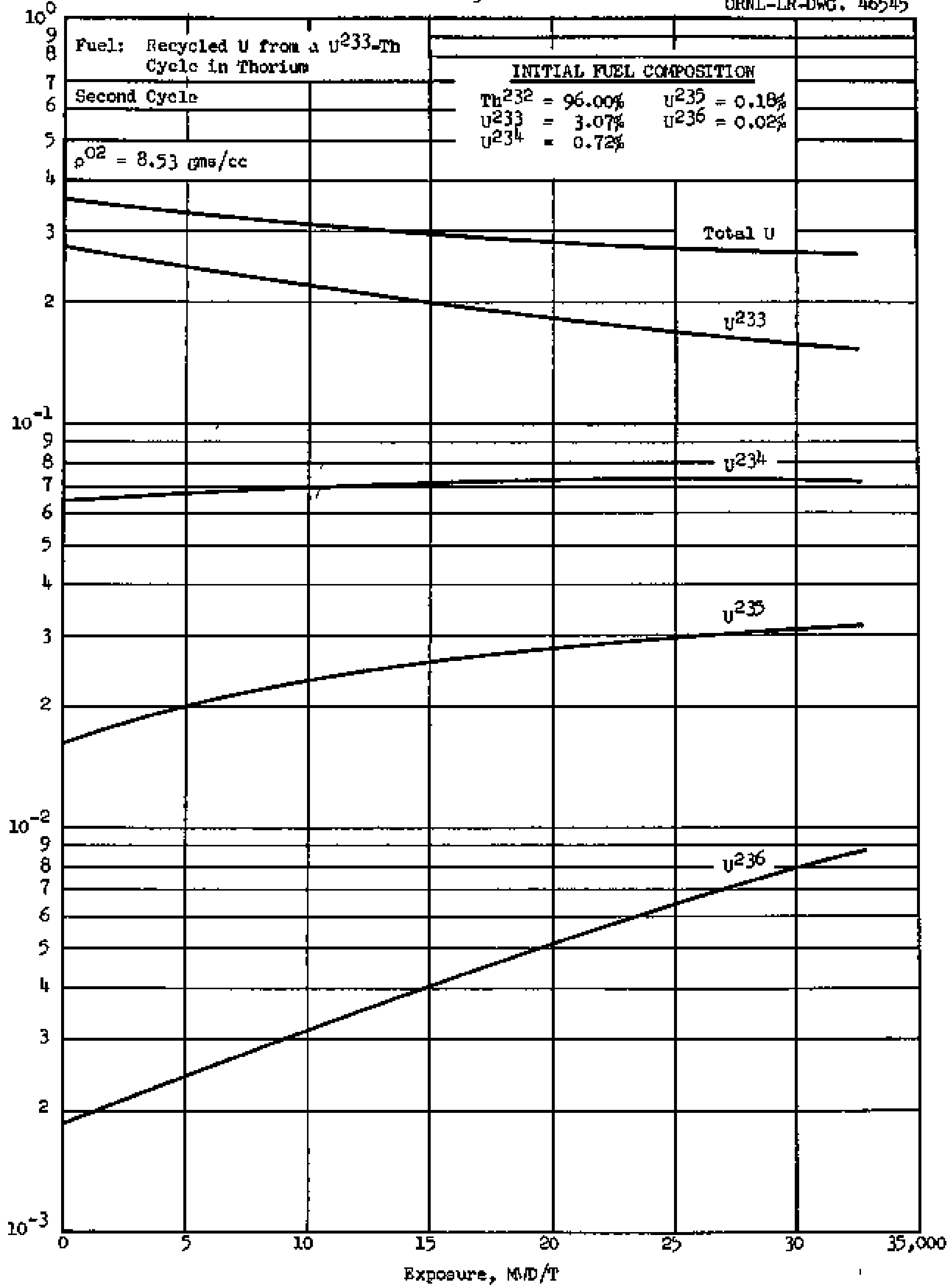

Fig. 11A. Fuel Isotopic Densities Vs. Exposure for Dresden Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46546

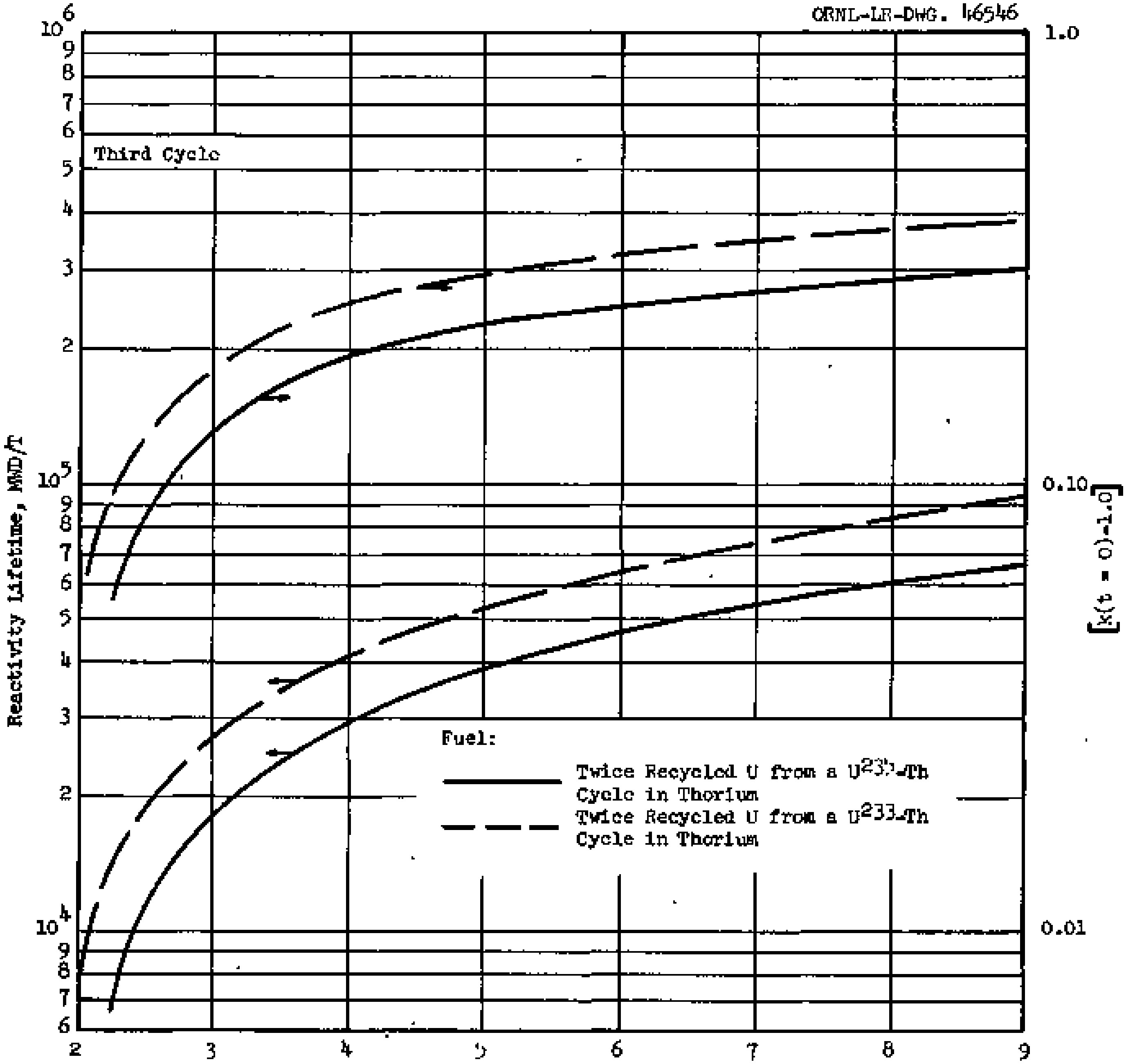

Fig. 12A. Reactivity Lifetime and Initial Reactivity Vs. Fissile Enrichment for Dresden Reactor.

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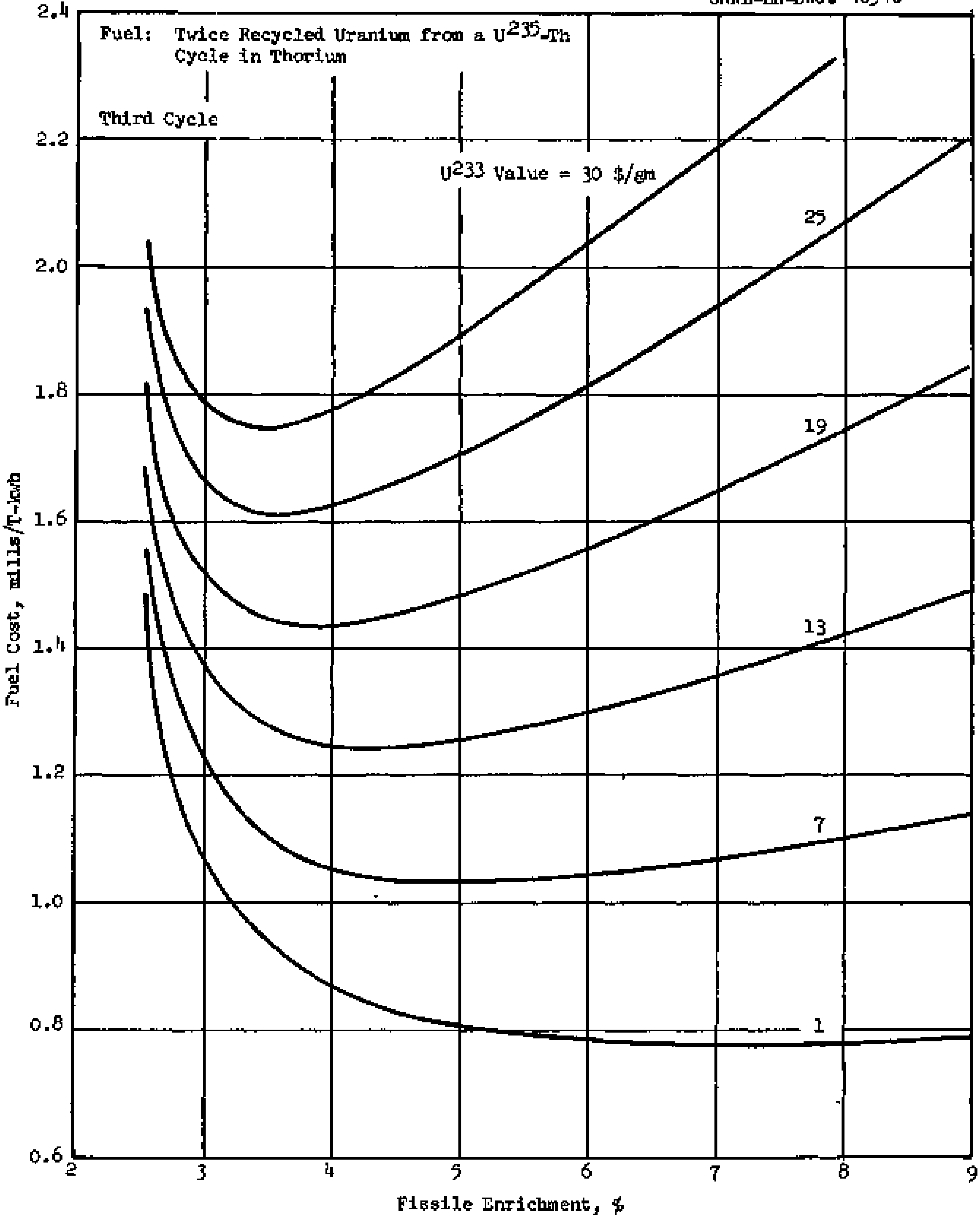

Fig. 13A. Fuel Cost Vs. Fissile Enrichment for Dresden Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46547

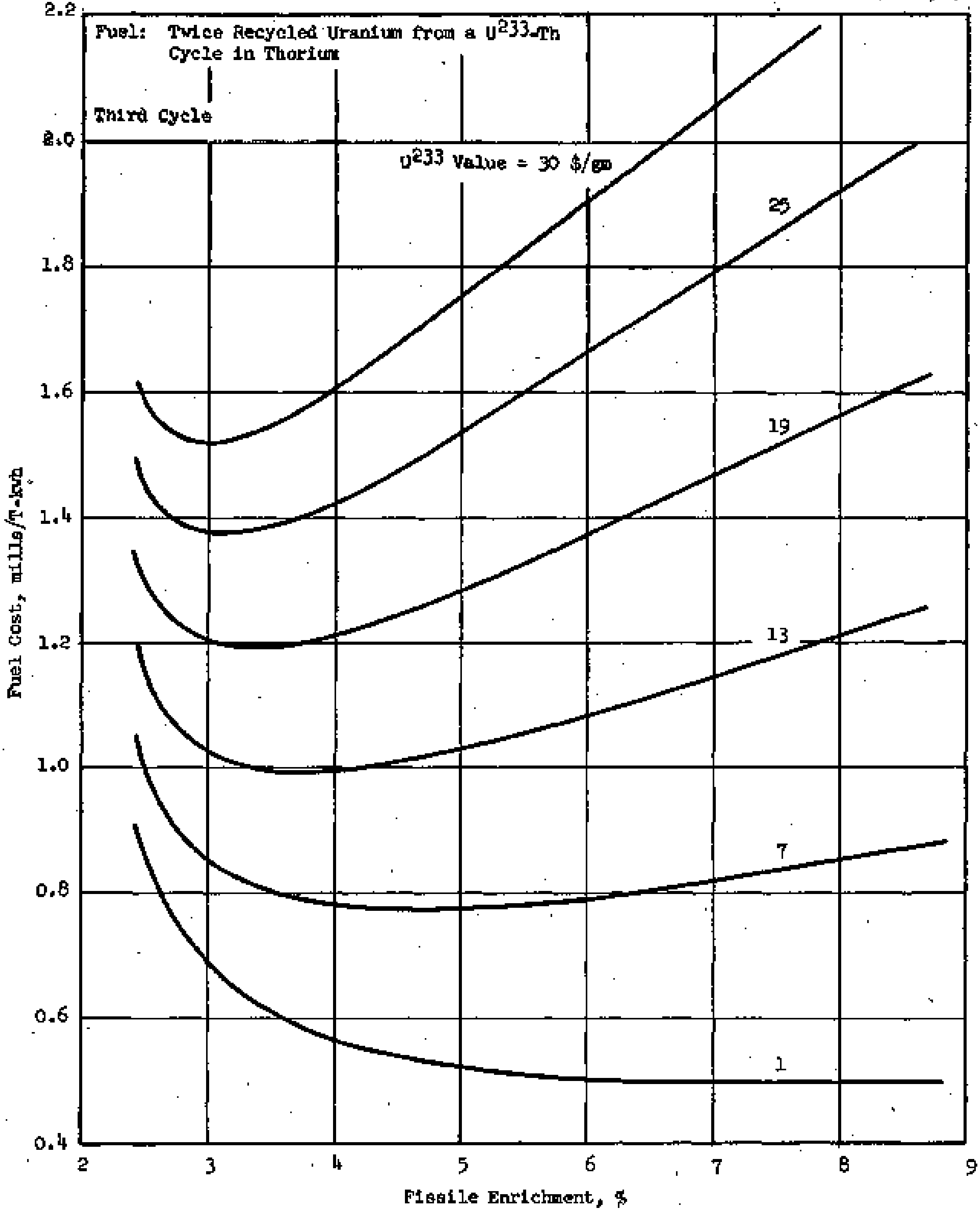

Fig. 14A. Fuel Cost Vs. Fissile Enrichment for Dresden Reactor.

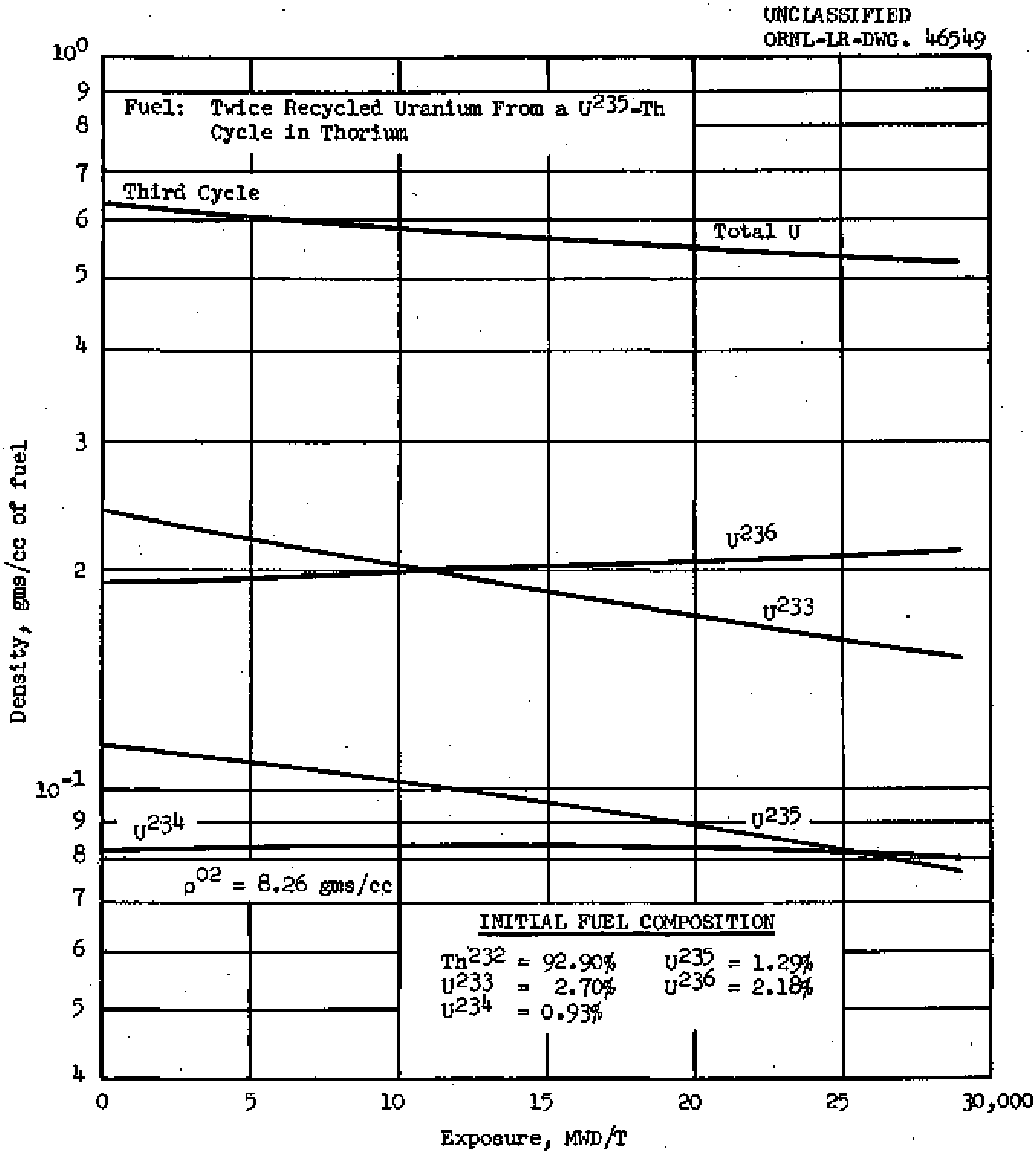

Fig. 15A. Fuel Isotopic Densities Vs. Exposure for Dresden Reactor.

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ORNL-LR-Dwg. 46550

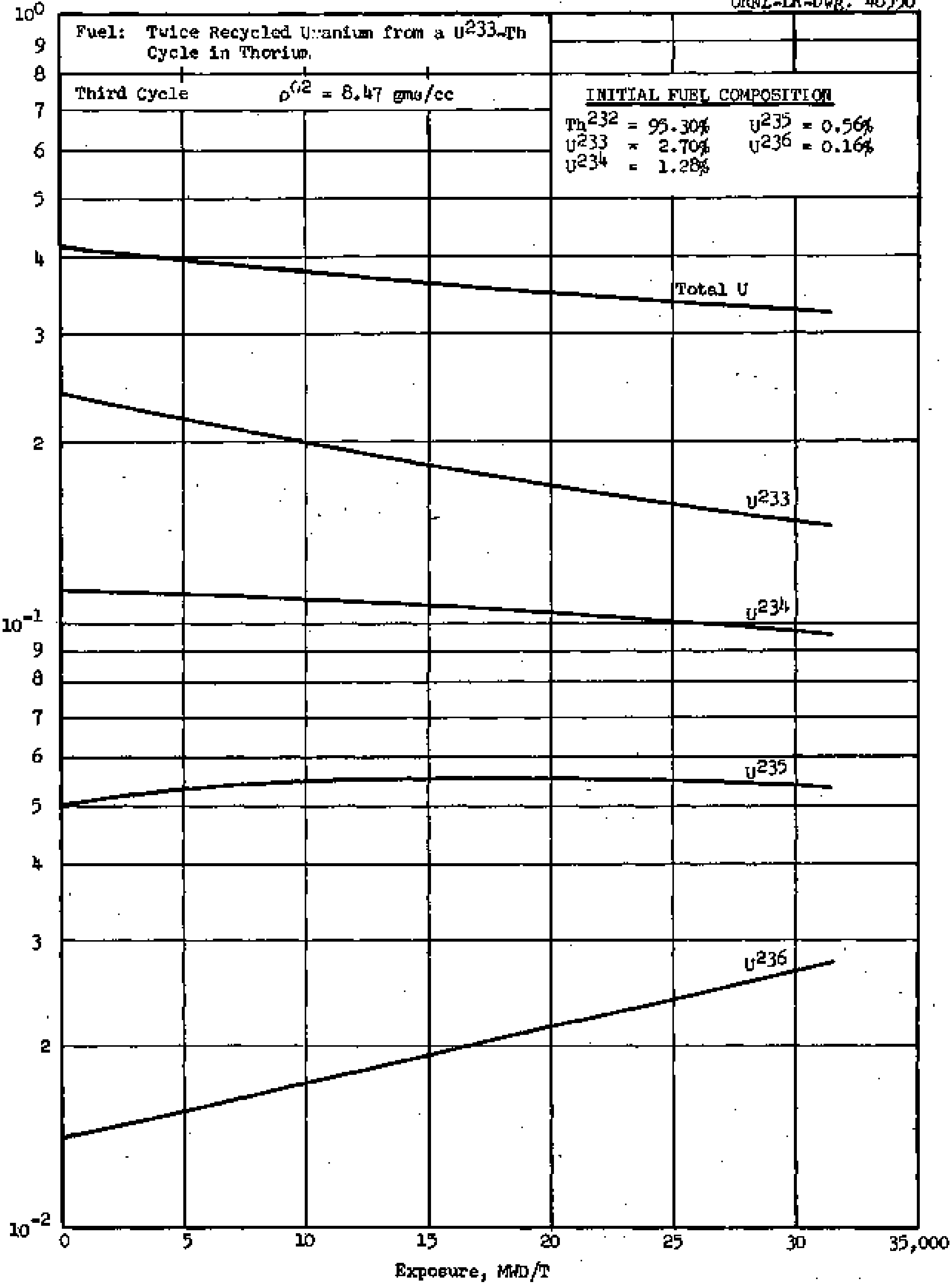

Fig. 16A. Fuel Isotopic Densities Vs. Exposure for Dresden Reactor.

Appendix B. Results Concerning the Yankee Reactor

The detailed results of the calculations concerning the Yankee reactor are presented in graphical form in Figs. 1B through 16B. Figure 1B summarizes these results and shows the minimum fuel costs (in mills per thermal Kwh) as a function of U^{233} value for three complete cycles and two initial fuels. Recycle uranium from an initial U^{235} cycle may be used with only a small increase in fuel costs and a decrease in U^{233} value of less than $4 per gram. Recycle uranium from an initial U^{233} cycle exhibits slightly lower fuel costs and slightly higher U^{233} values than the initial cycle. Figures 2B through 16B are analogous to Figs. 2A through 16A, respectively.

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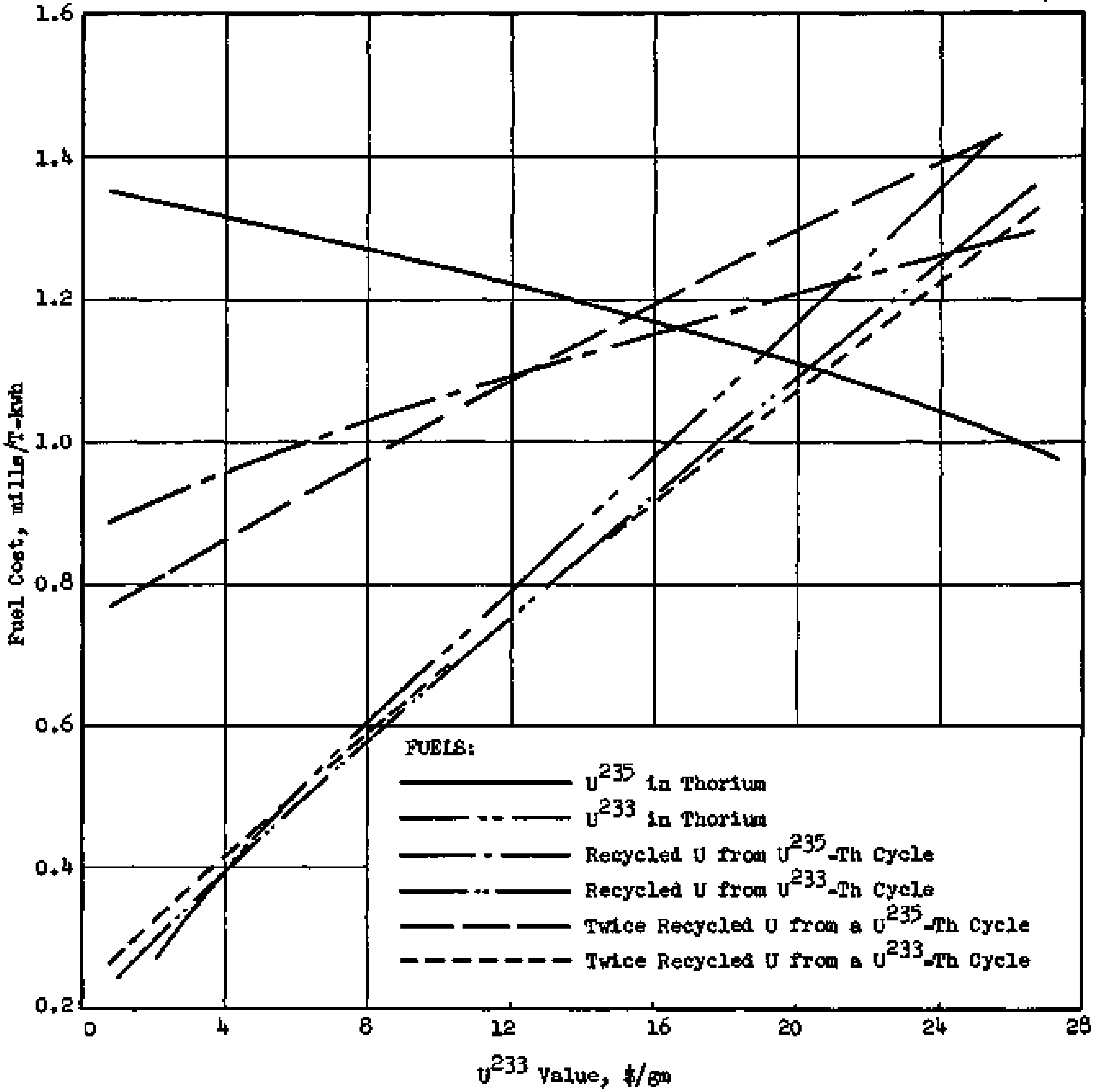

Fig. 1B. Minimum Fuel Cost vs. U^{233} Value for Yankee Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46497

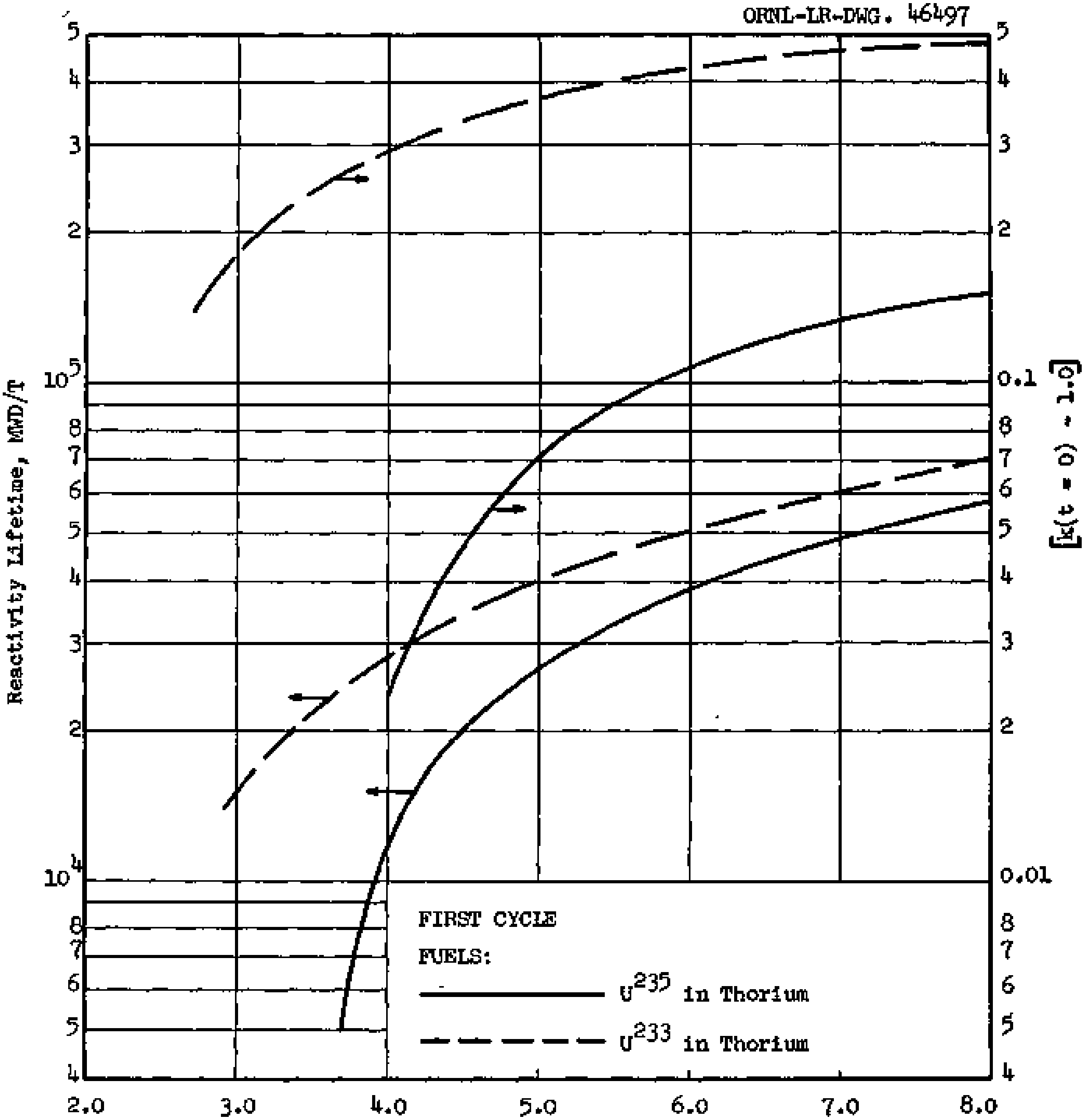

Fig. 2B. Reactivity Lifetime and Initial Reactivity vs. Fissile Enrichment for Yankee Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46498

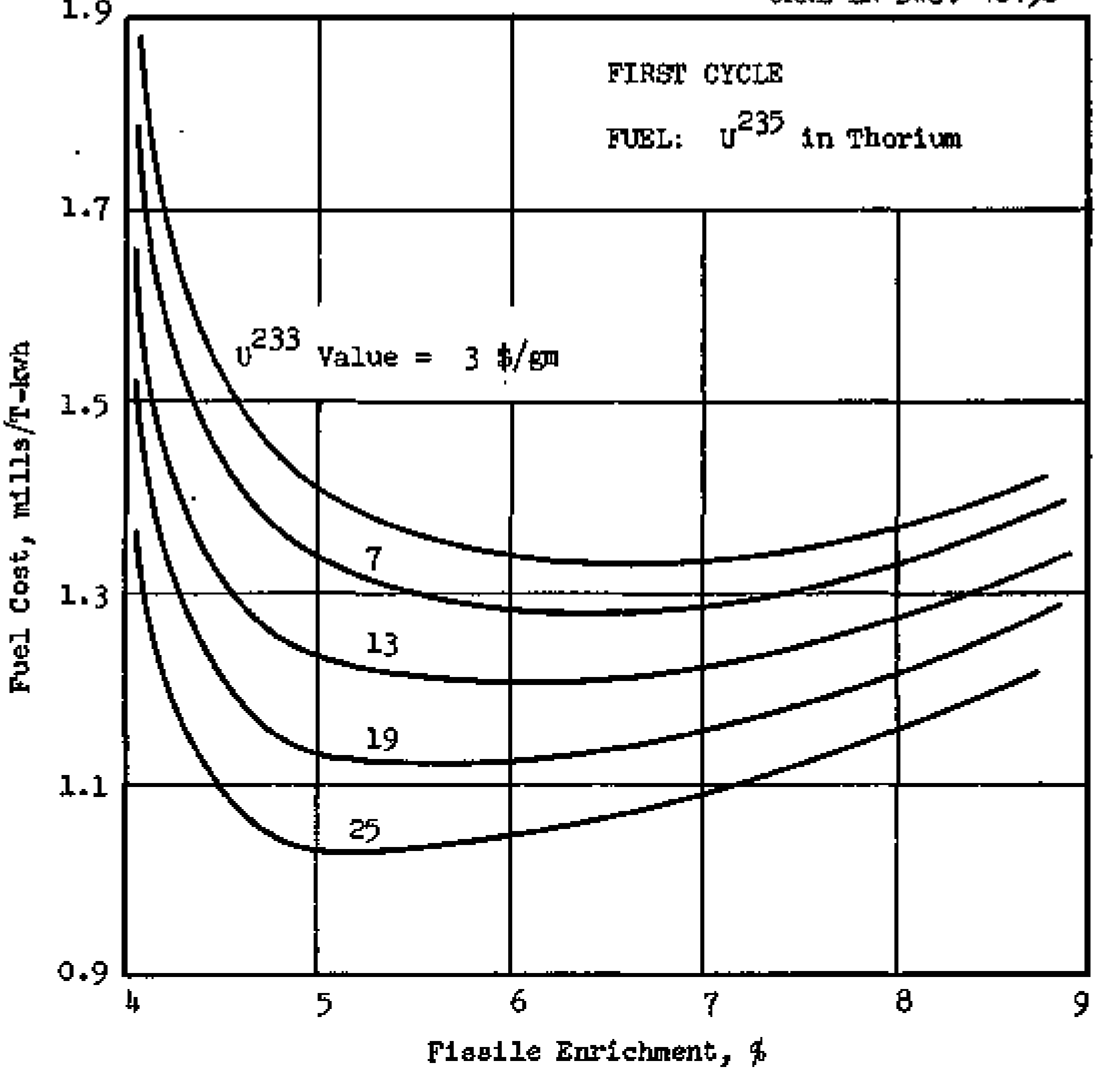

Fig. 3B. Fuel Cost vs. Fissile Enrichment for Yankee Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46499

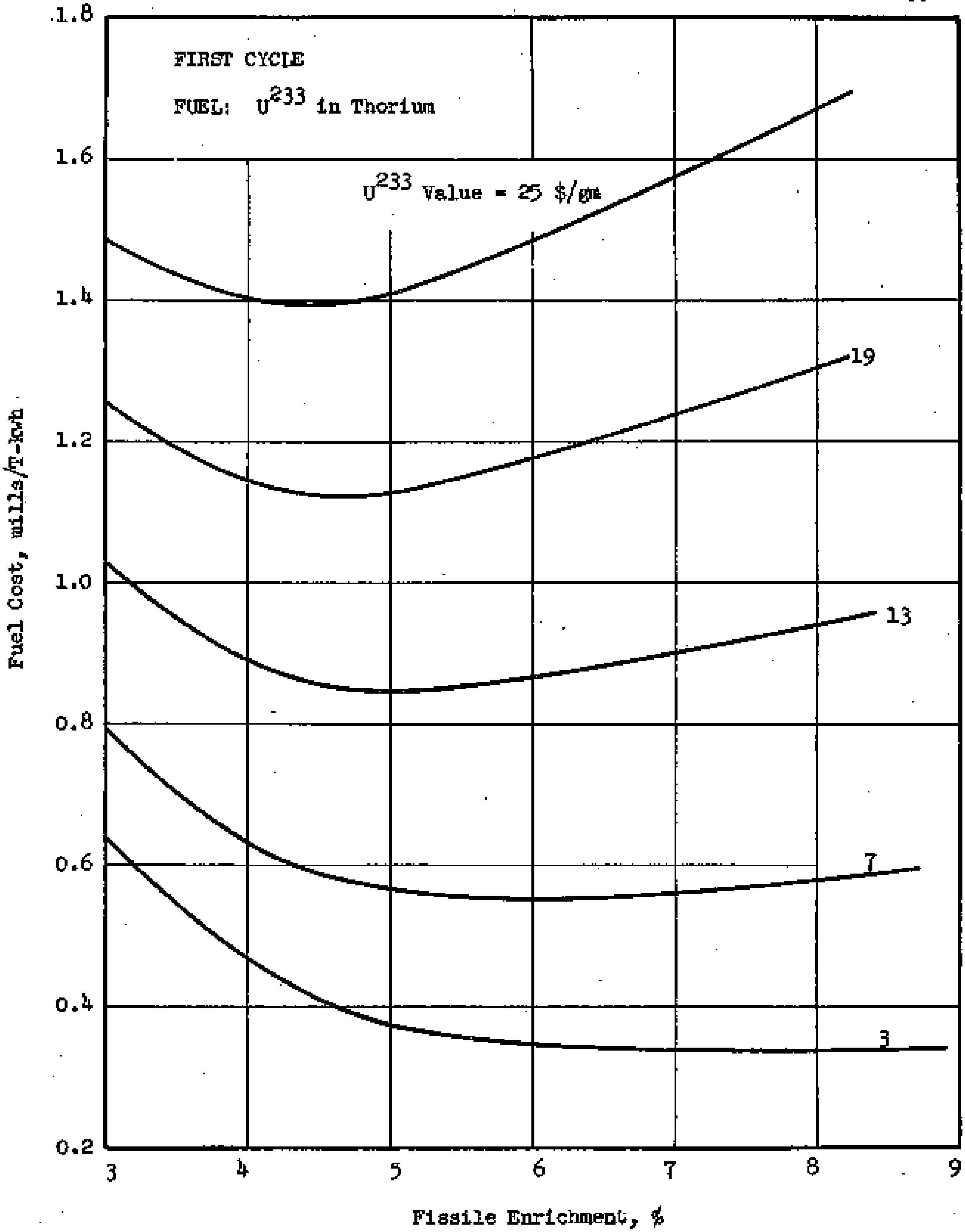

Fig. 4B. Fuel Cost vs. Fissile Enrichment for Yankee Reactor.

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ORNL-LR-DWG. 46500

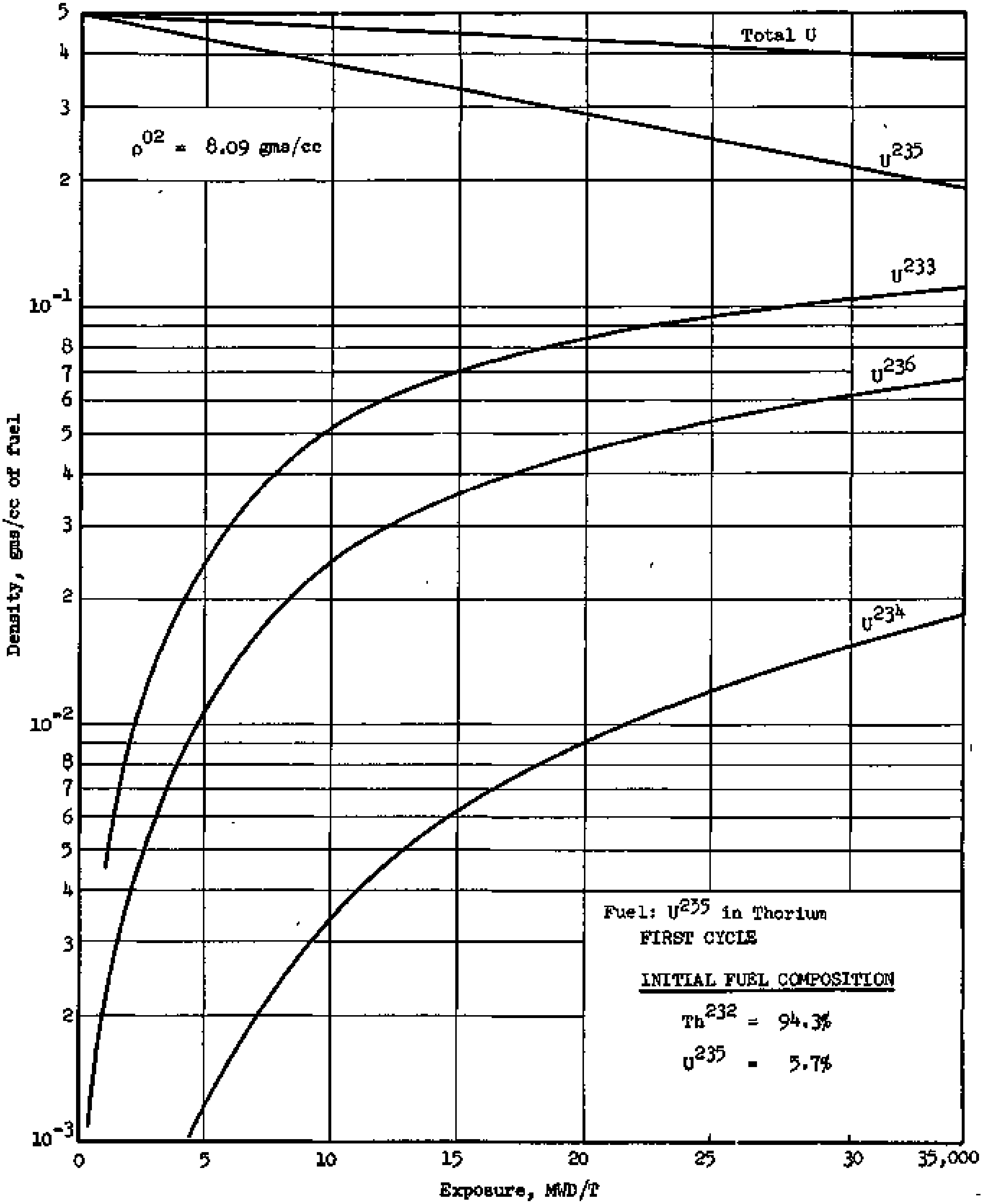

Fig. 5B. Fuel Isotopic Densities vs. Exposure for Yankee Reactor.

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ORNL-LR-DWG. 46501

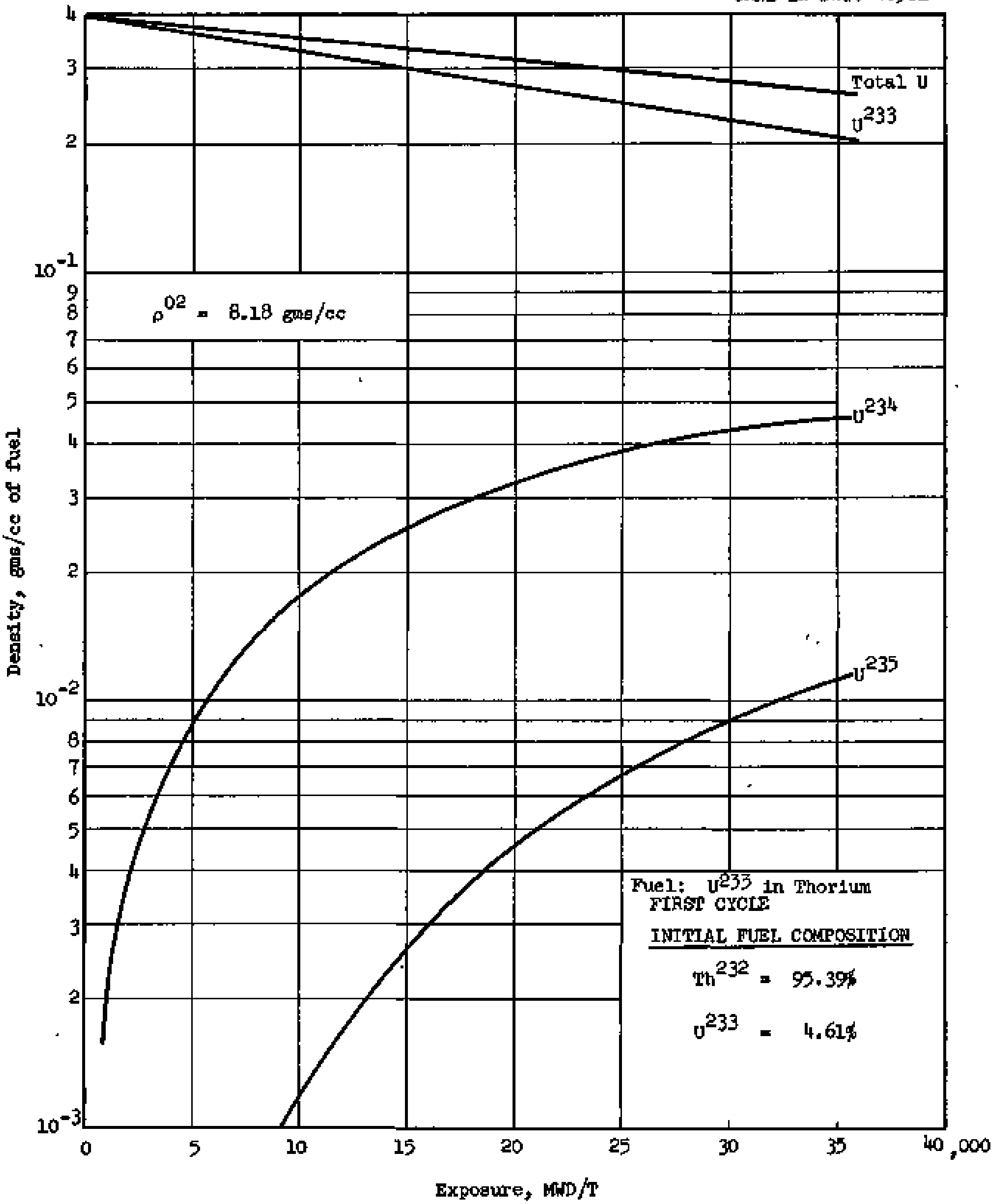

Fig. 68. Fuel Isotopic Densities vs. Exposure for Yankee Reactor.

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ORNL-LR-DWG. 46502

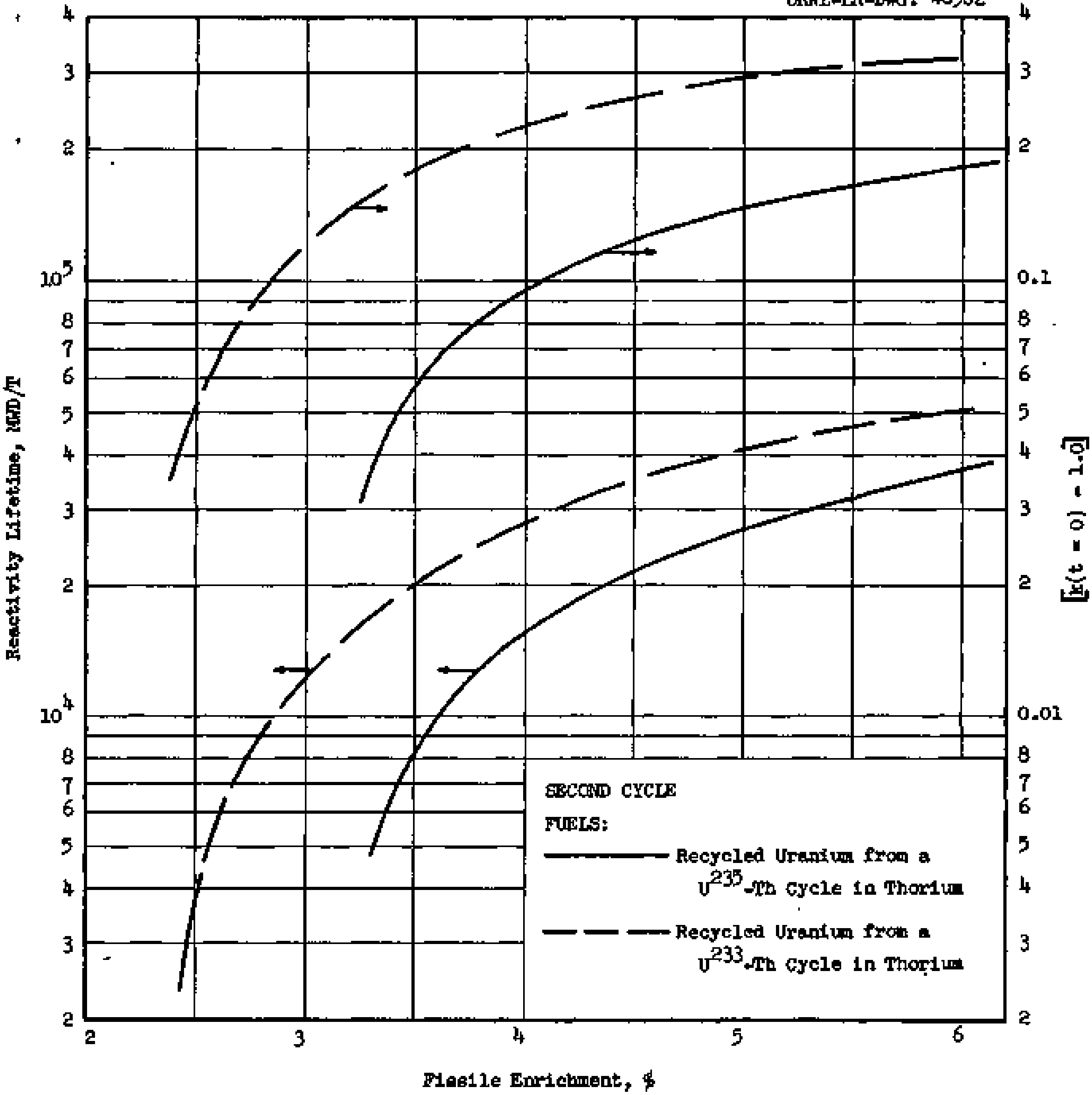

Fig. 7B. Reactivity Lifetime and Initial Reactivity vs. Fissile Enrichment for Yankee Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46503

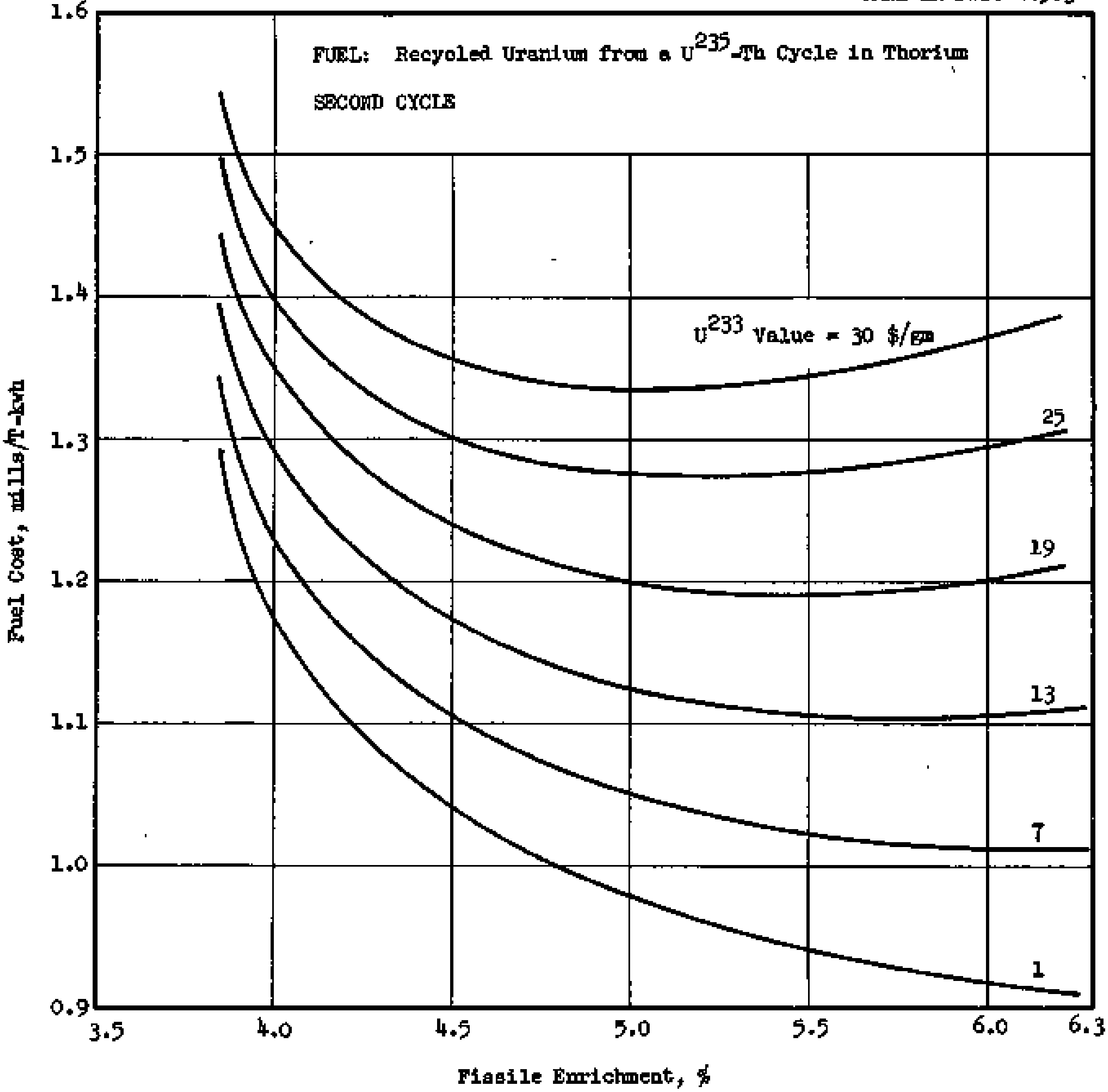

Fig. 8B. Fuel Cost vs. Fissile Enrichment for Yankee Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46504

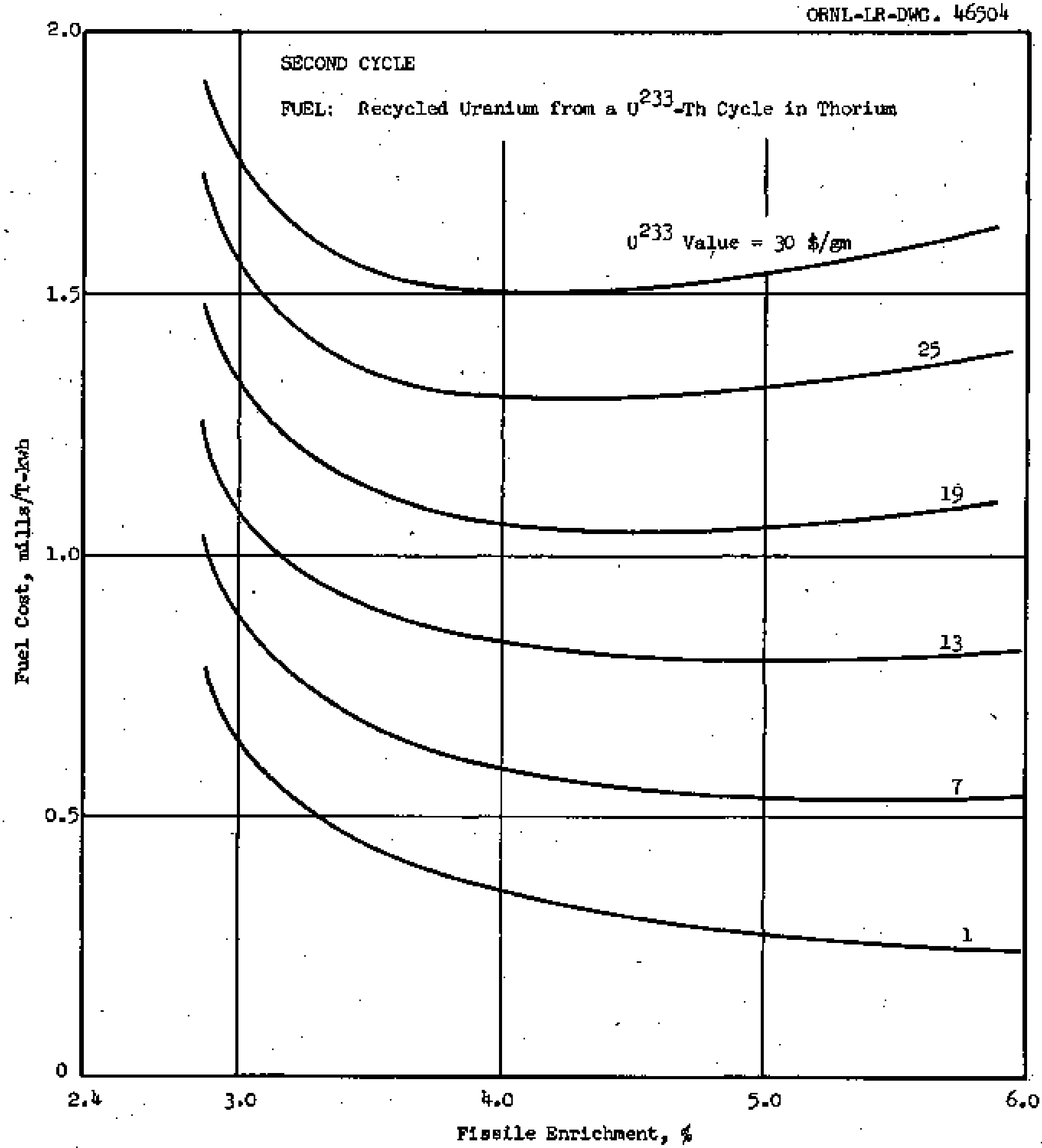

Fig. 9B. Fuel Cost vs. Fissile Enrichment for Yankee Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46505

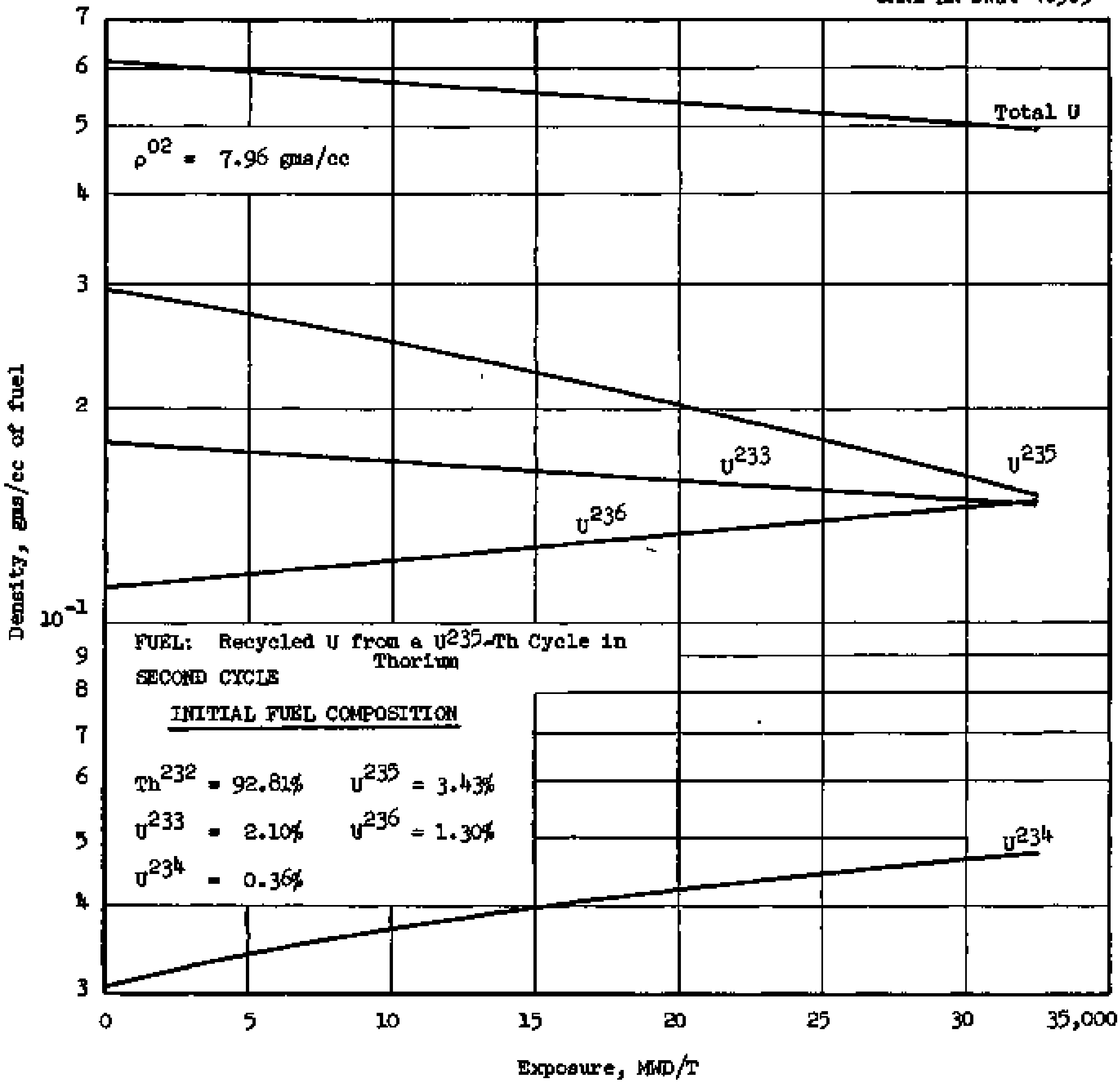

Fig. 10B. Fuel Isotopic Densities vs. Exposure for Yankee Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46506

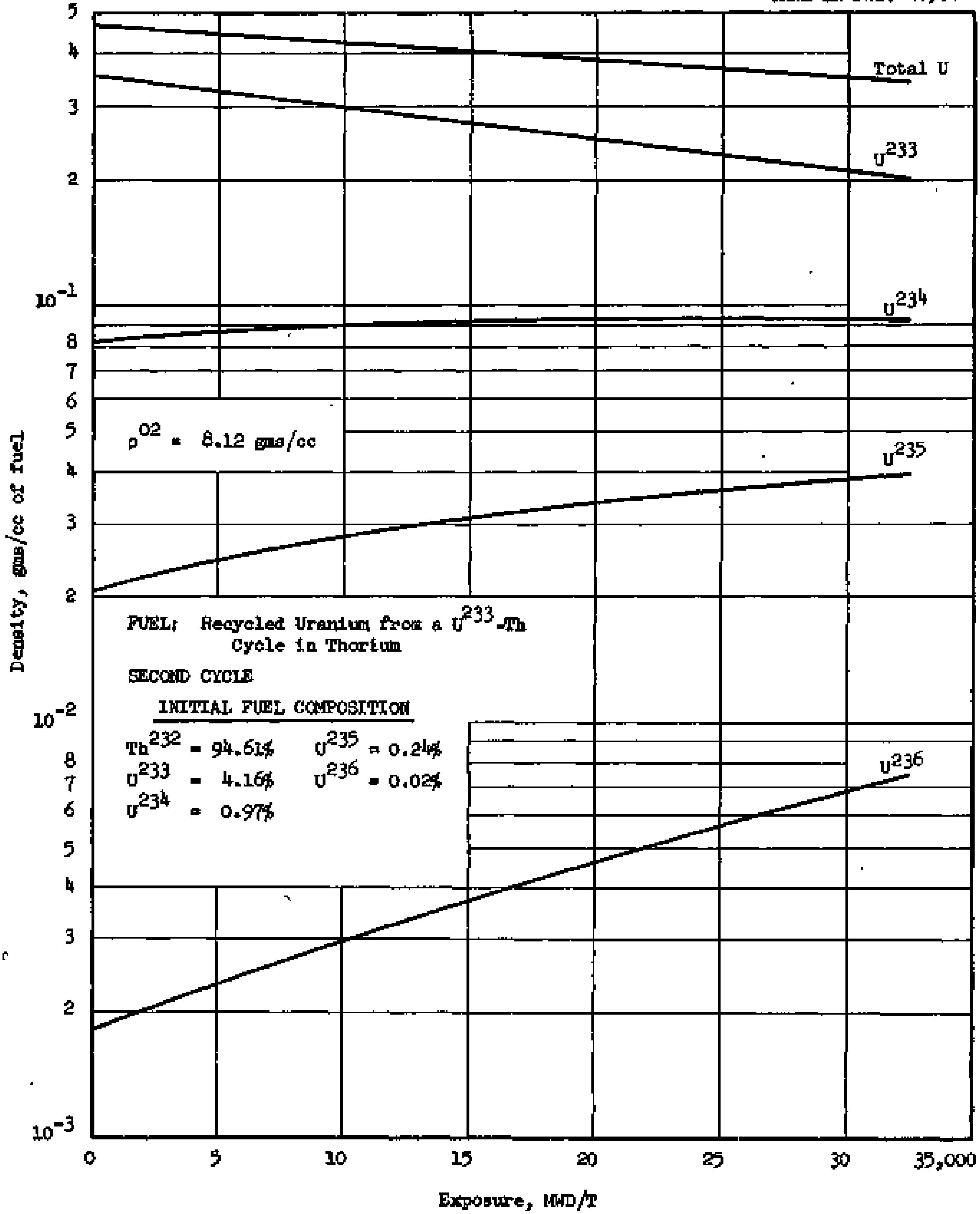

Fig. 11B. Fuel Isotopic Densities vs. Exposure for Yankee Reactor.

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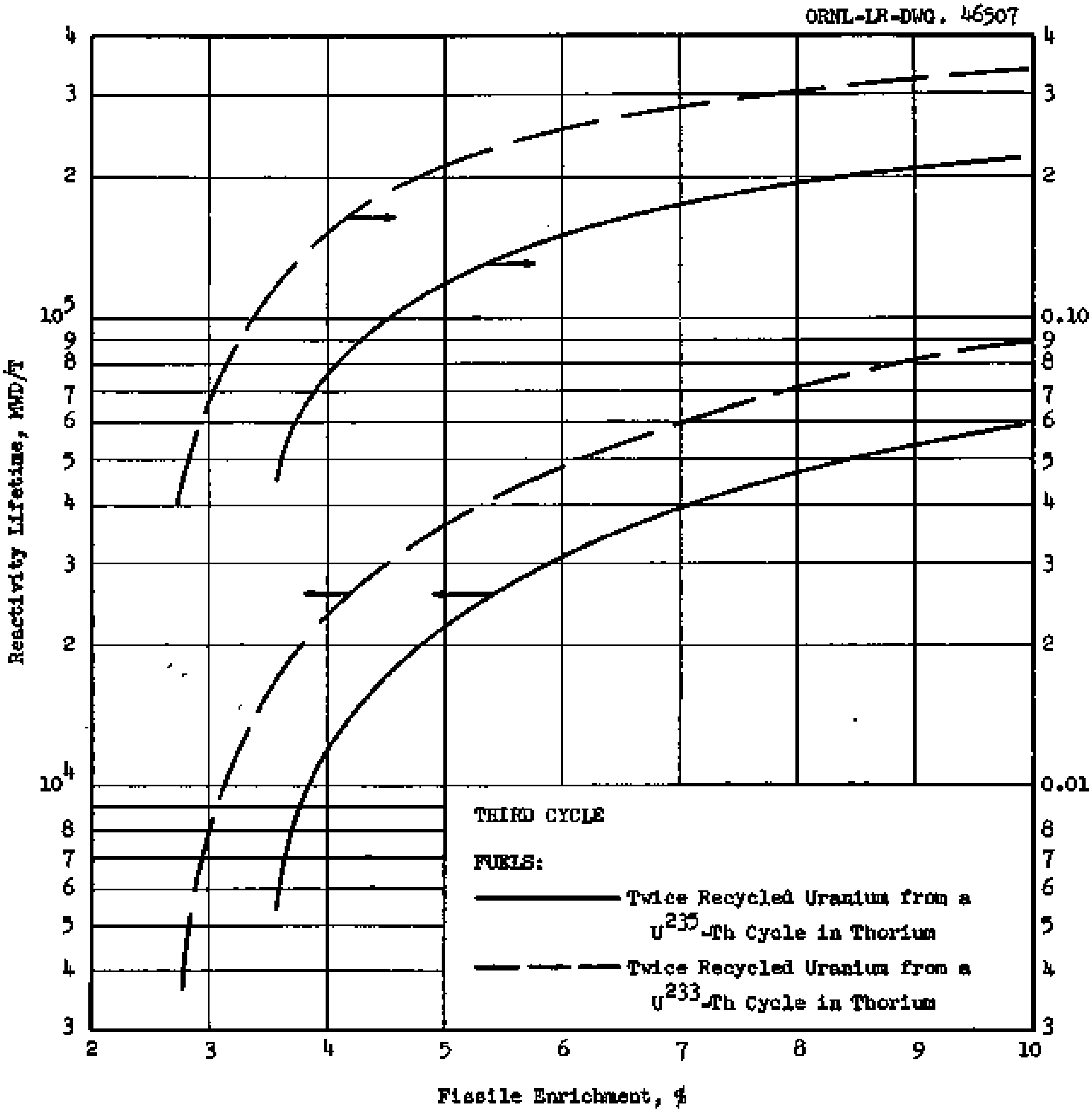

Fig. 12B. Reactivity Lifetime and Initial Reactivity vs. Fissile Enrichment for Yankee Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46508

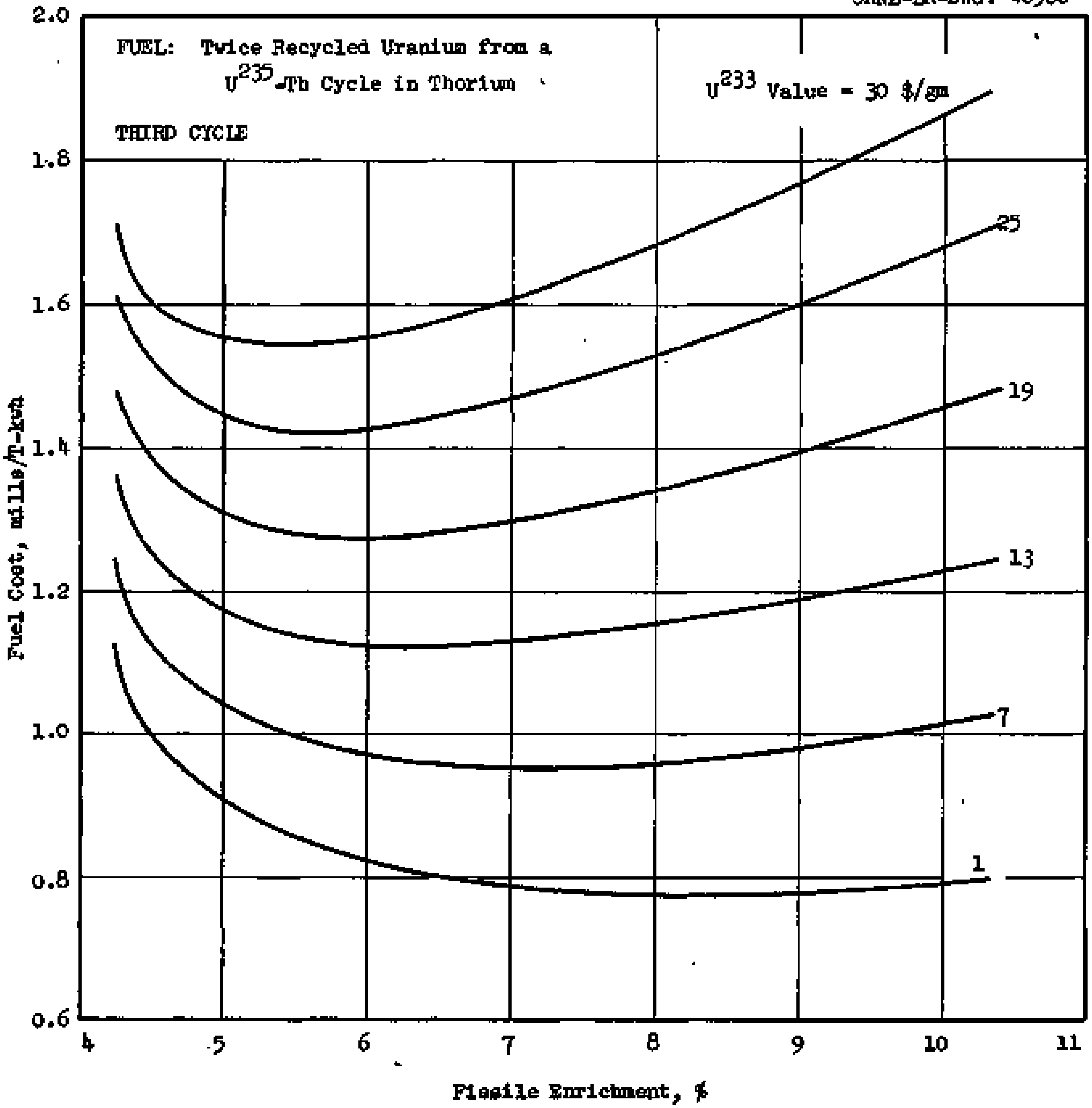

Fig. 13B. Fuel Cost vs. Fissile Enrichment for Yankee Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46509

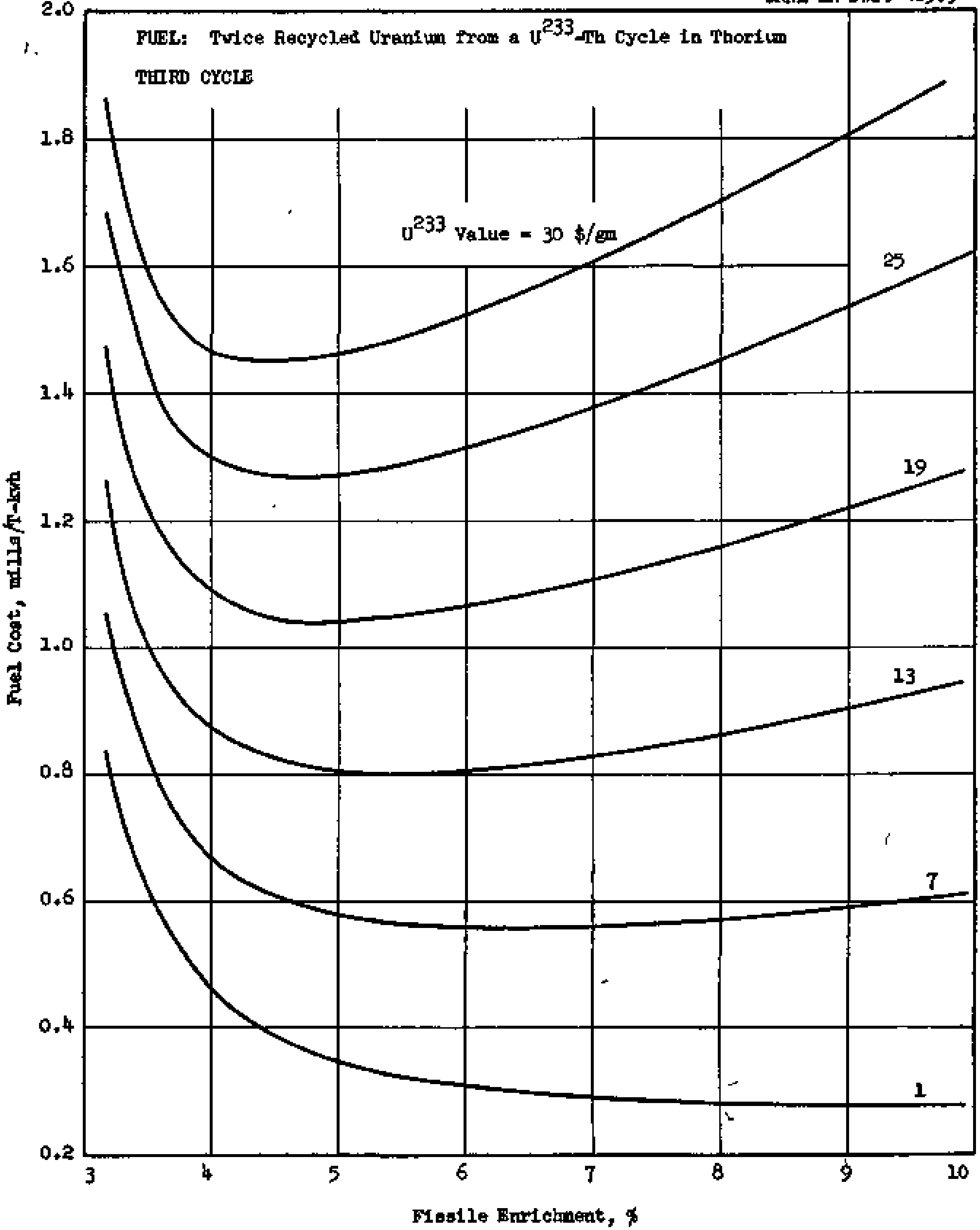

Fig. 14B. Fuel Cost vs. Fissile Enrichment for Yankee Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46510

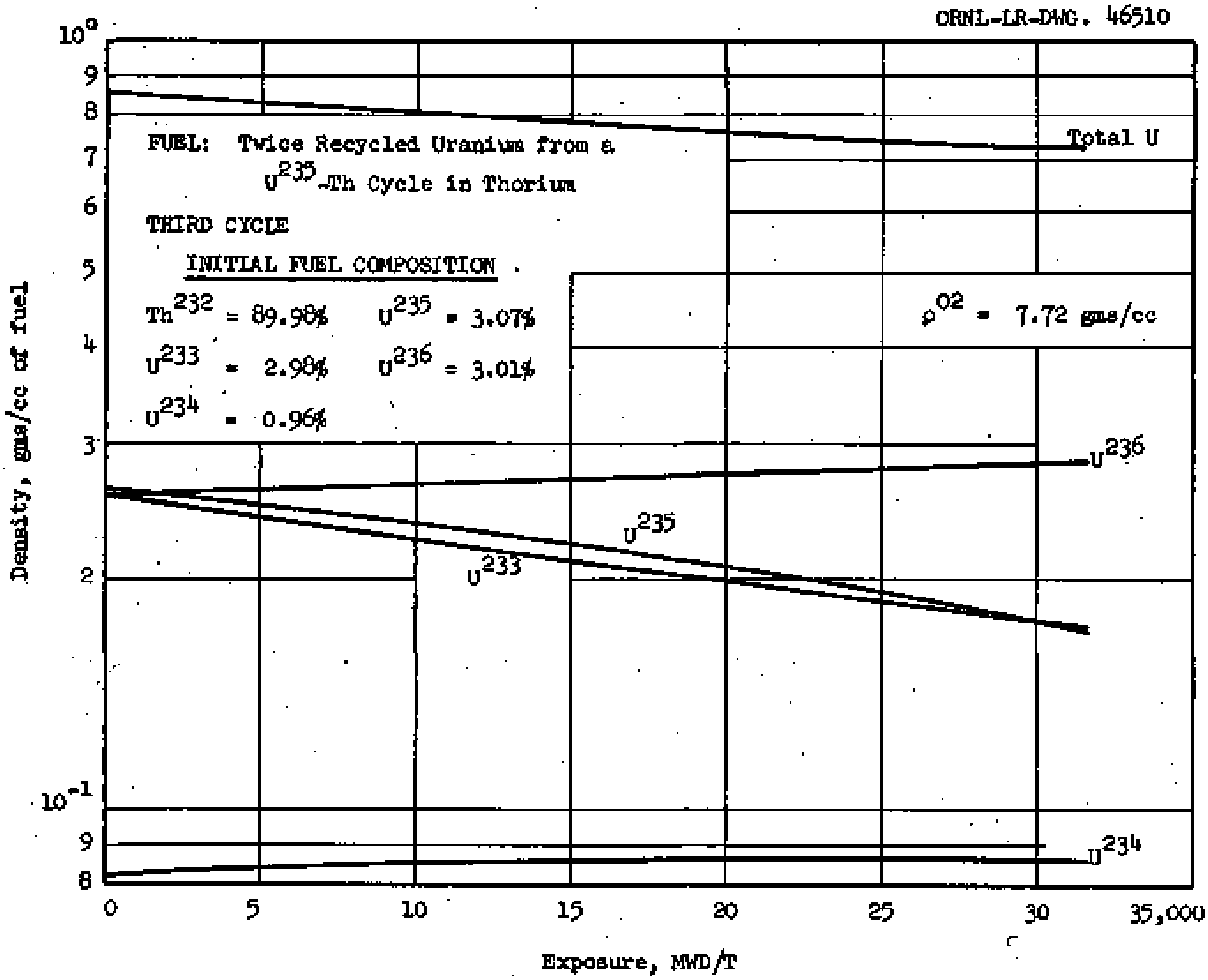

Fig. 15B. Fuel Isotopic Densities vs. Exposure for Yankee Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46511

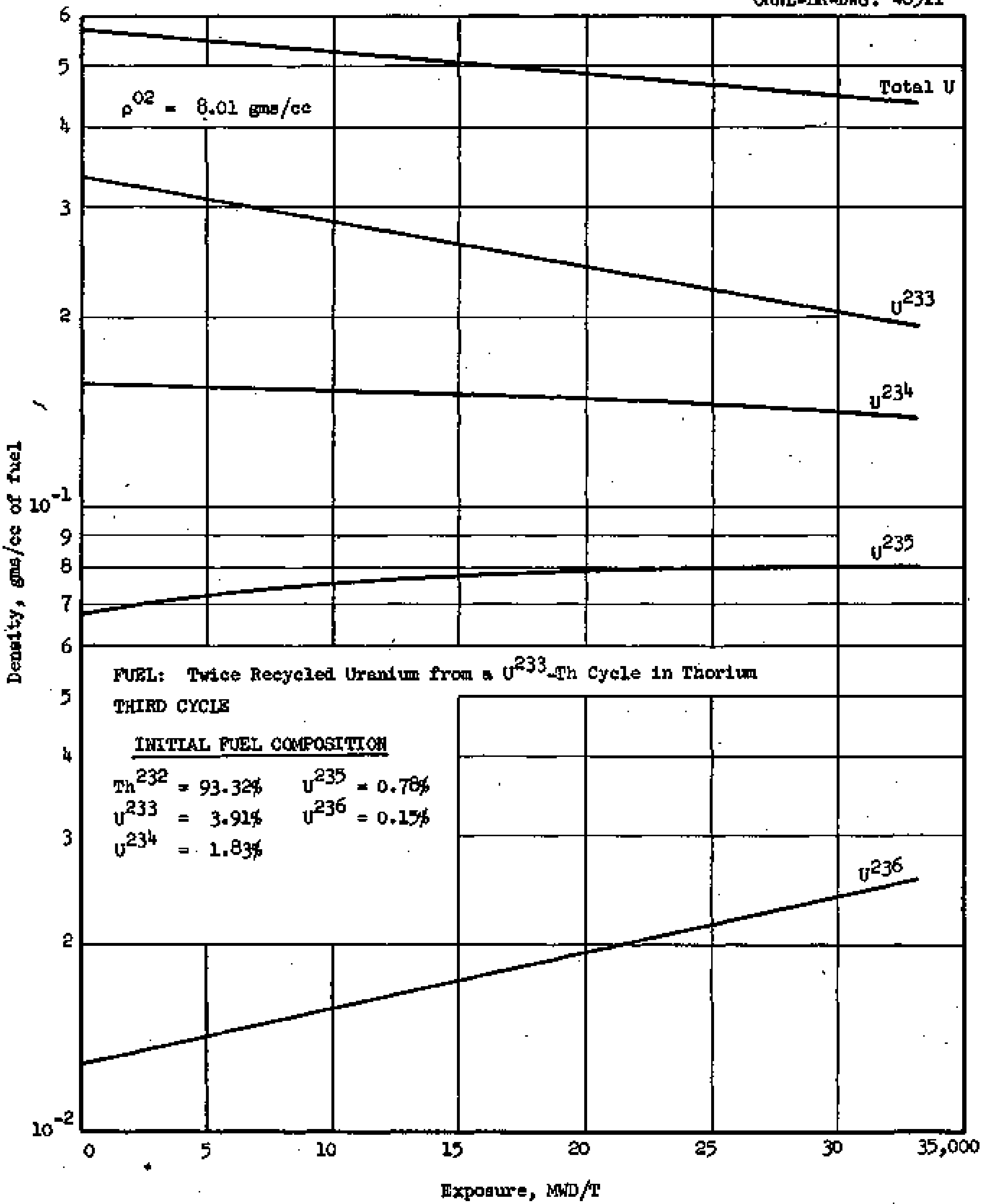

Fig. 16B. Fuel Isotopic Densities vs. Exposure for Yankee Reactor.

Appendix C. Results Concerning the Carolinas-Virginia Reactor

The detailed results of the calculations concerning the Carolinas-Virginia reactor are presented in graphical form in Figs. 1C through 16C. Figure 1C summarizes these results and shows the minimum fuel costs (in mills per thermal Kwh) as a function of U^{233} value for three complete cycles and two initial fuels. Once-recycle uranium from an initial U^{235} cycle is a feasible fuel and may be used with only a small increase in fuel costs and a decrease in U^{233} value of $3 per gram. Twice-recycle uranium from an initial U^{235} cycle requires twice as large an increase in fuel costs and an $8 per gram decrease in U^{233} value making its use more marginal. Recycle uranium from an initial U^{233} cycle has slightly lower fuel costs and slightly higher U^{233} values than the initial fuel. Figures 2C through 16C are analogous to Figs. 2A through 16A, respectively.

UNCLASSIFIED
ORNL-LR-DWG. 46512

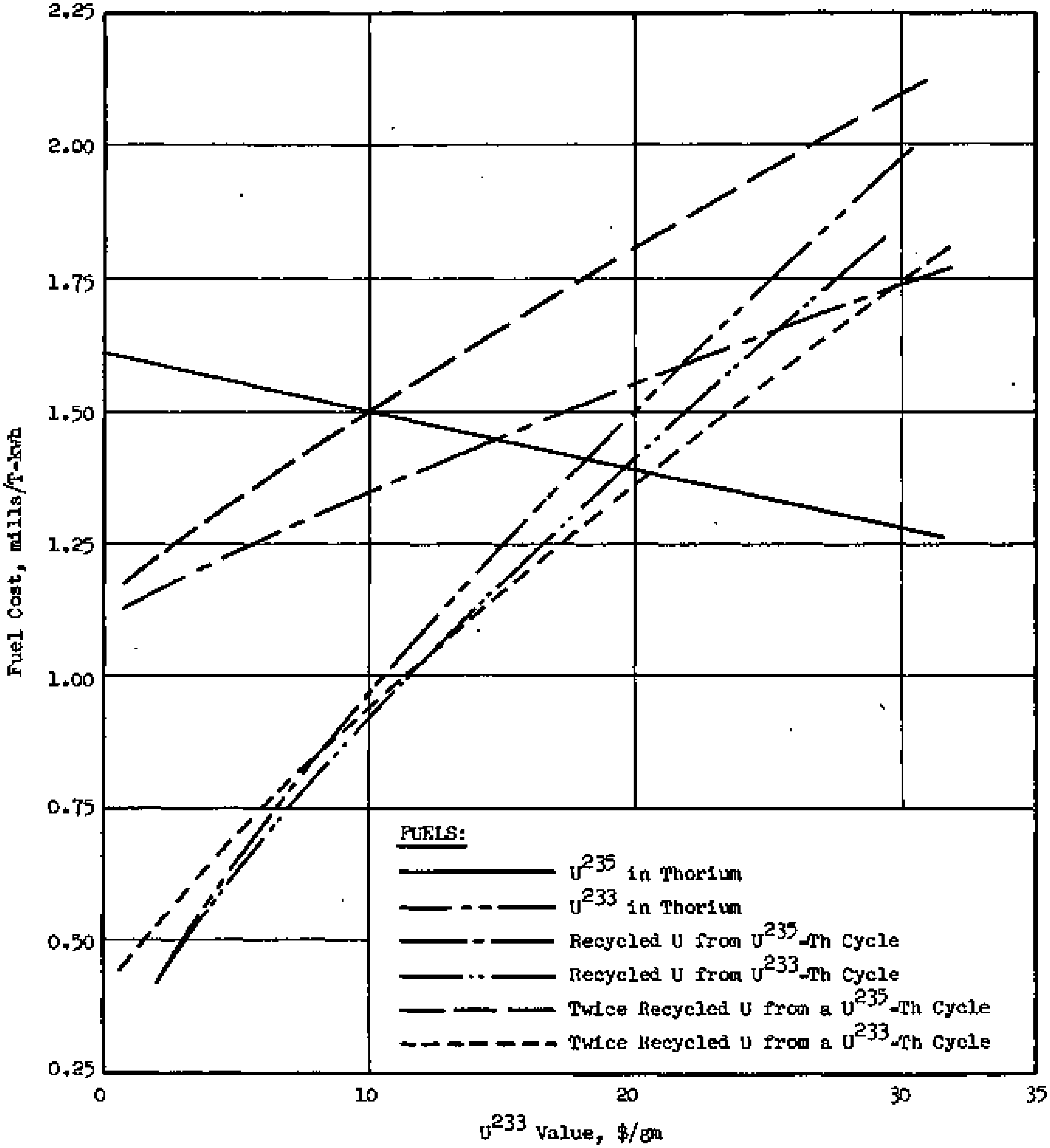

Fig. 1C. Minimum Fuel Cost vs. U^{233} Value for Carolinas-Virginia Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46513

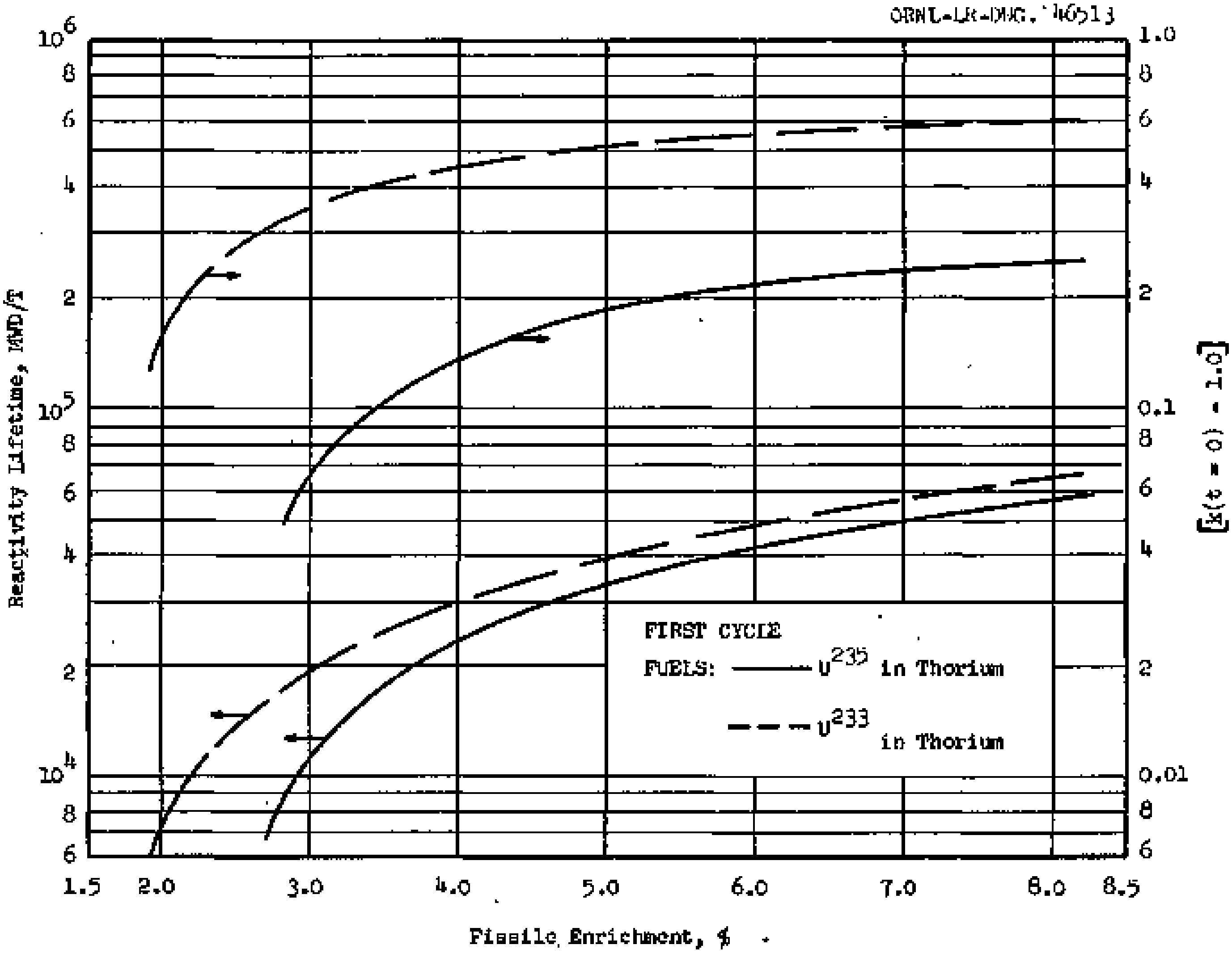

Fig. 2C. Reactivity Lifetime and Initial Reactivity vs. Fissile Enrichment for Carolinas-Virginia Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46514

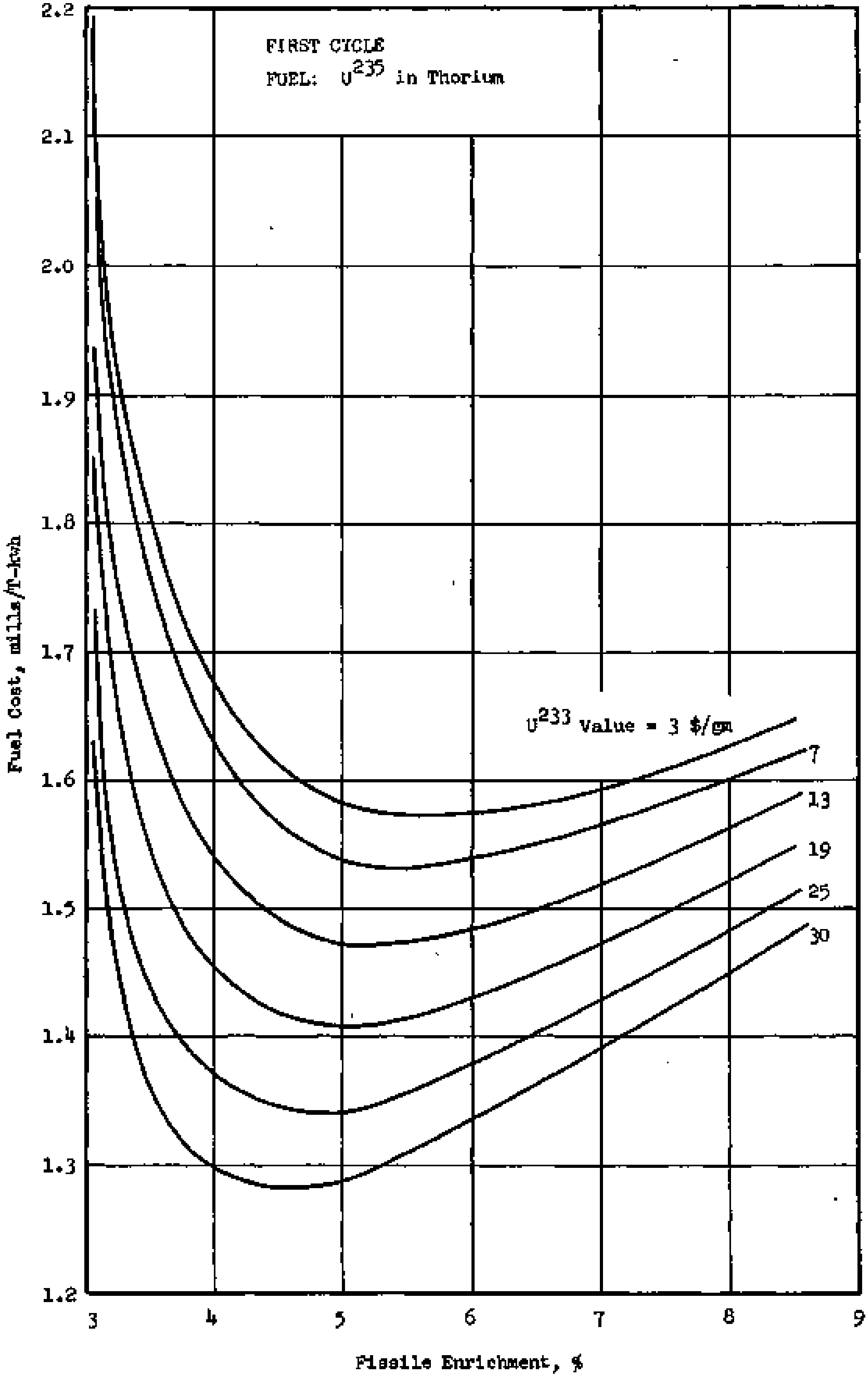

Fig. 3C. Fuel Cost vs. Fissile Enrichment for Carolinas-Virginia Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46515

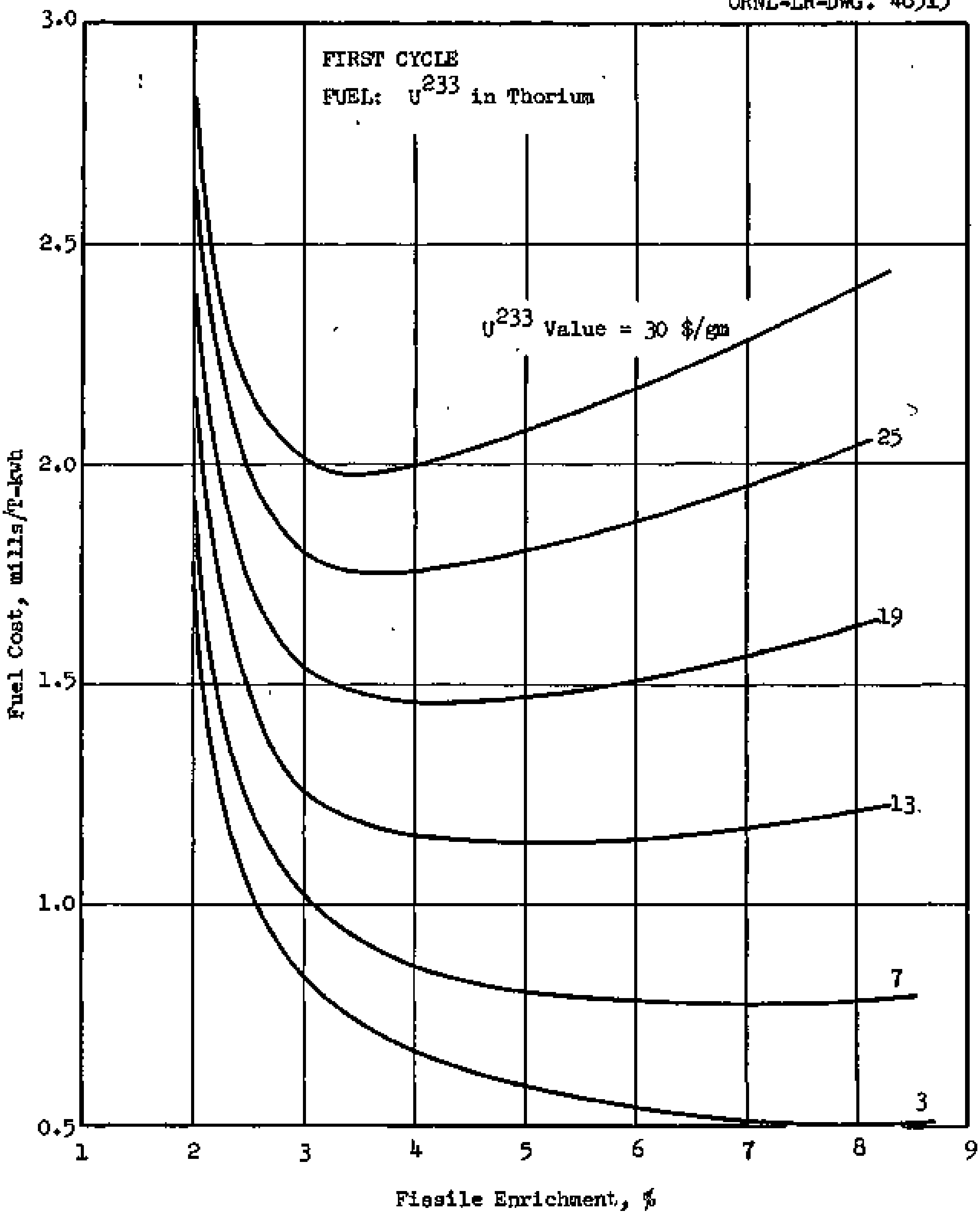

Fig. 4C. Fuel Cost vs. Fissile Enrichment for Carolinas-Virginia Reactor.

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ORNL-LR-DWG. 46516

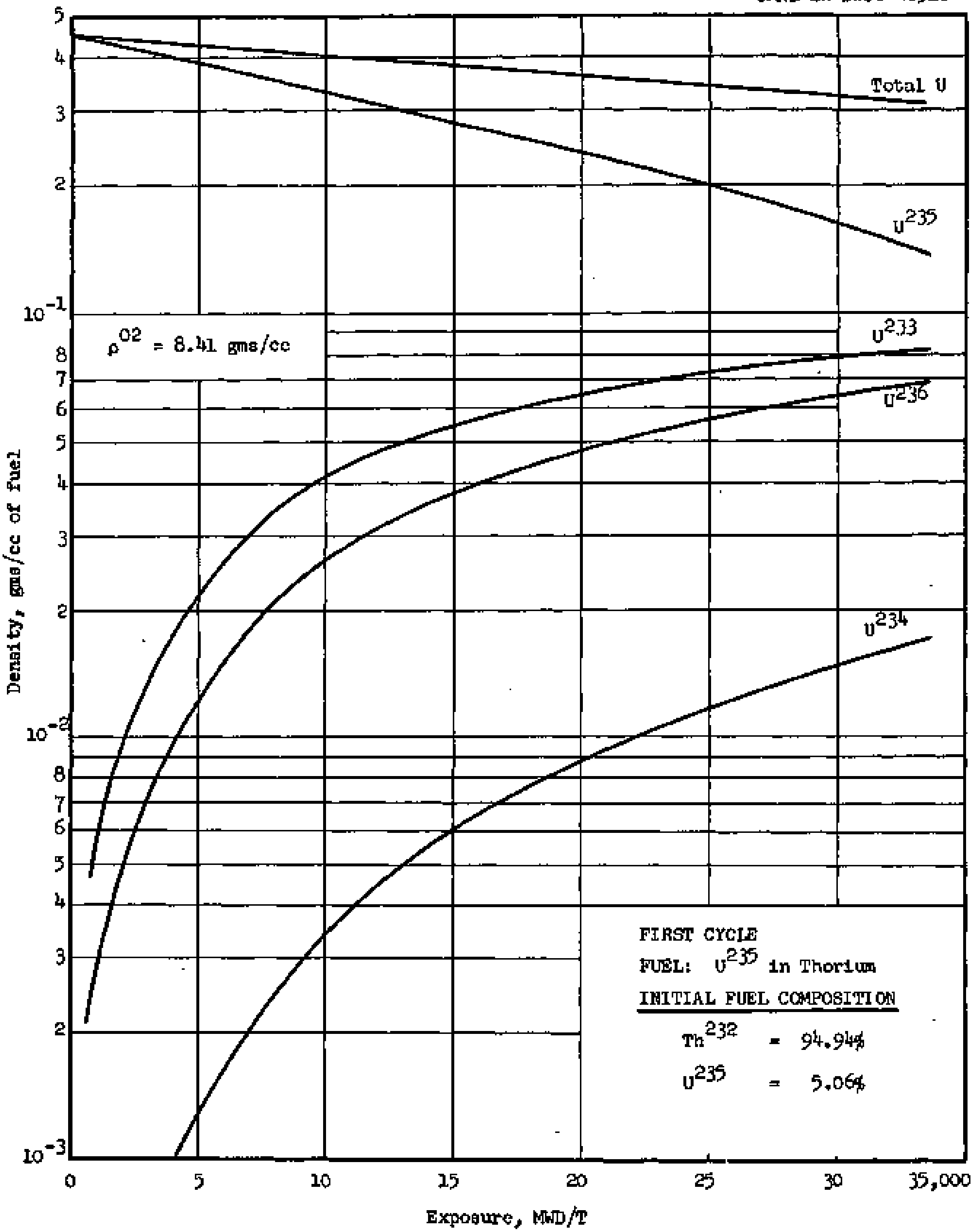

Fig. 5C. Fuel Isotopic Densities vs. Exposure for Carolinas-Virginia Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46517

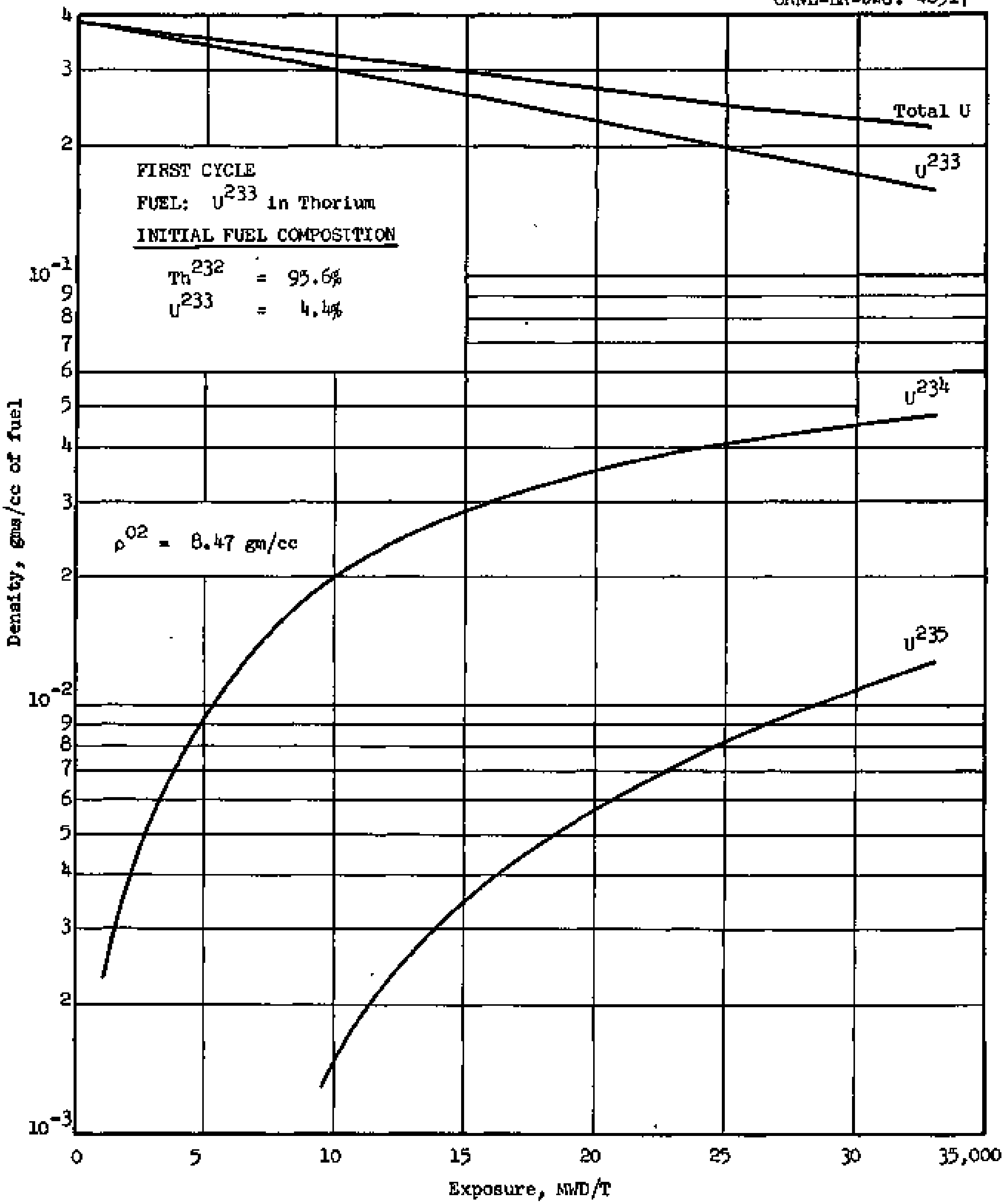

Fig. 6C. Fuel Isotopic Densities vs. Exposure for Carolinas-Virginia Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46518

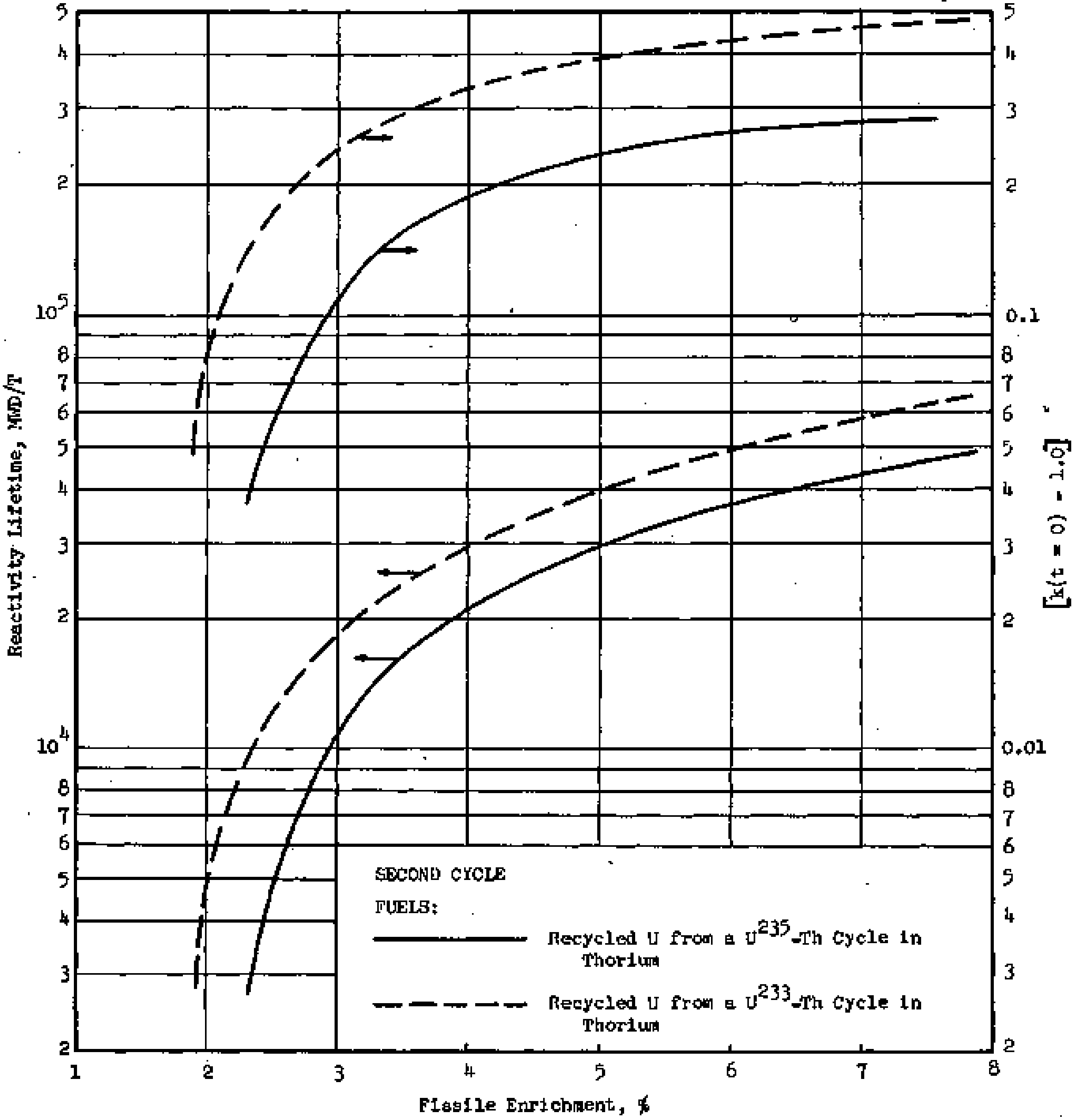

Fig. 7C. Reactivity Lifetime and Initial Reactivity vs. Fissile Enrichment for Carolinas-Virginia Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46519

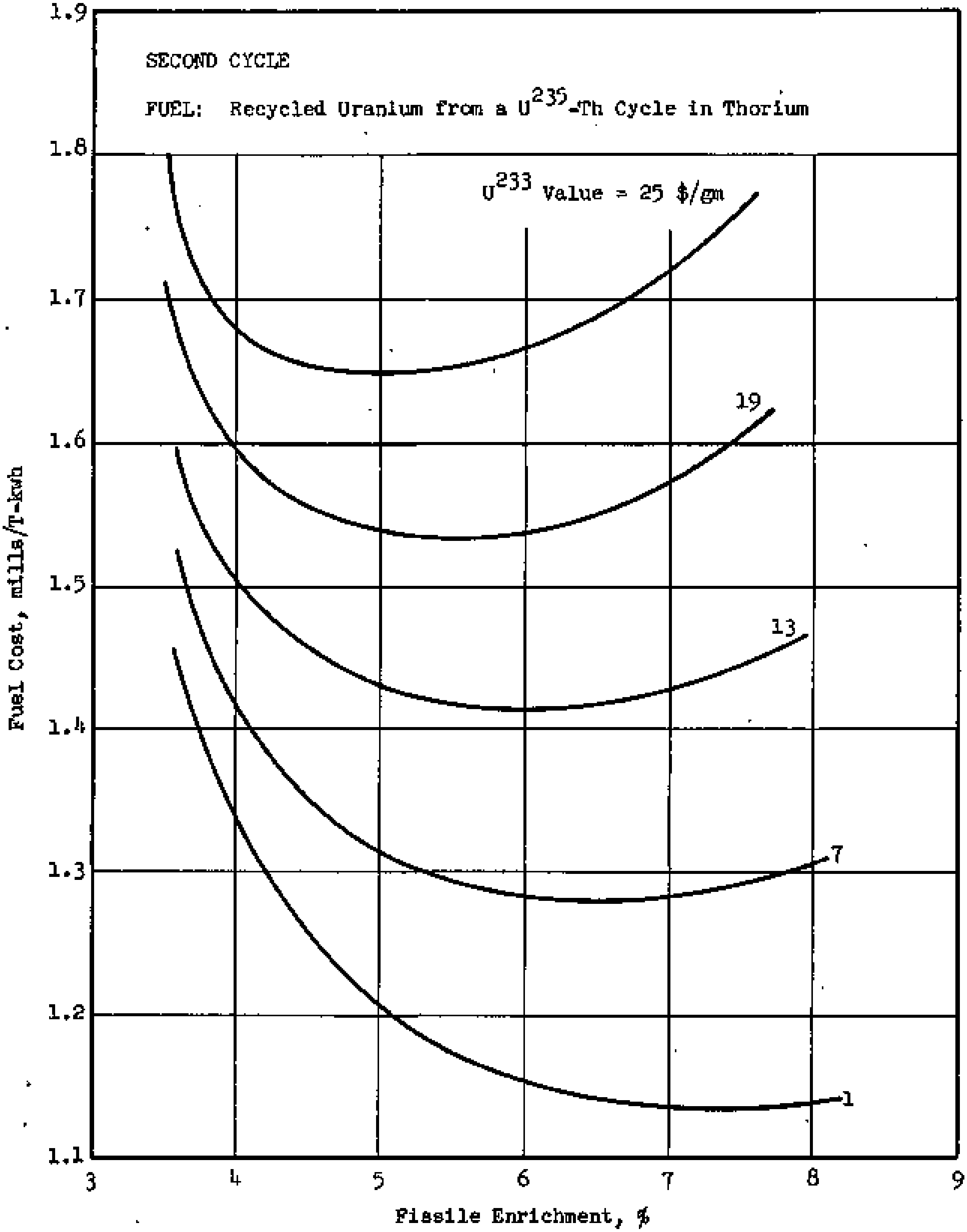

Fig. 8C. Fuel Cost vs. Fissile Enrichment for Carolinas-Virginia Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46520

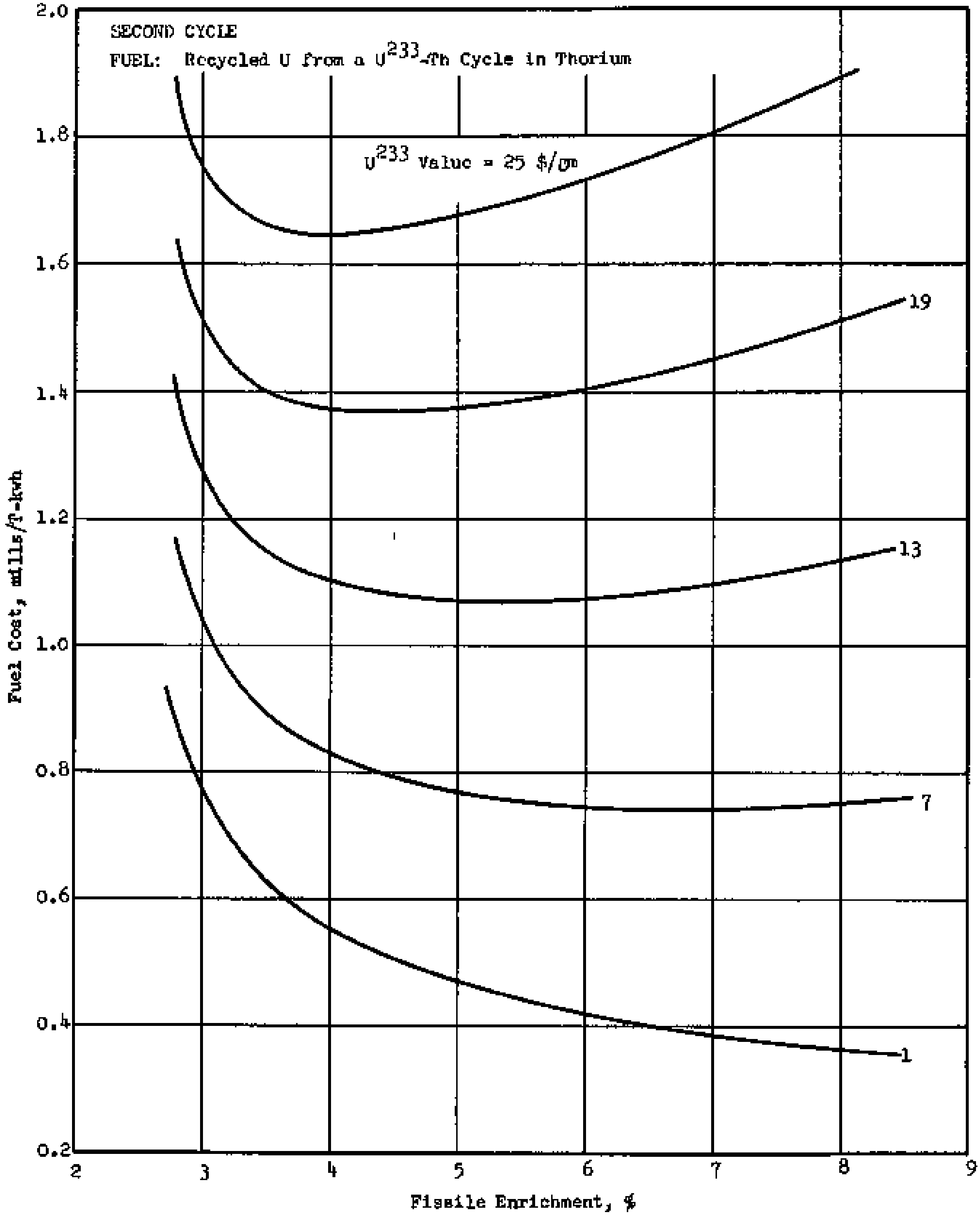

Fig. 9C. Fuel Cost vs. Fissile Enrichment for Carolinas-Virginia Reactor.

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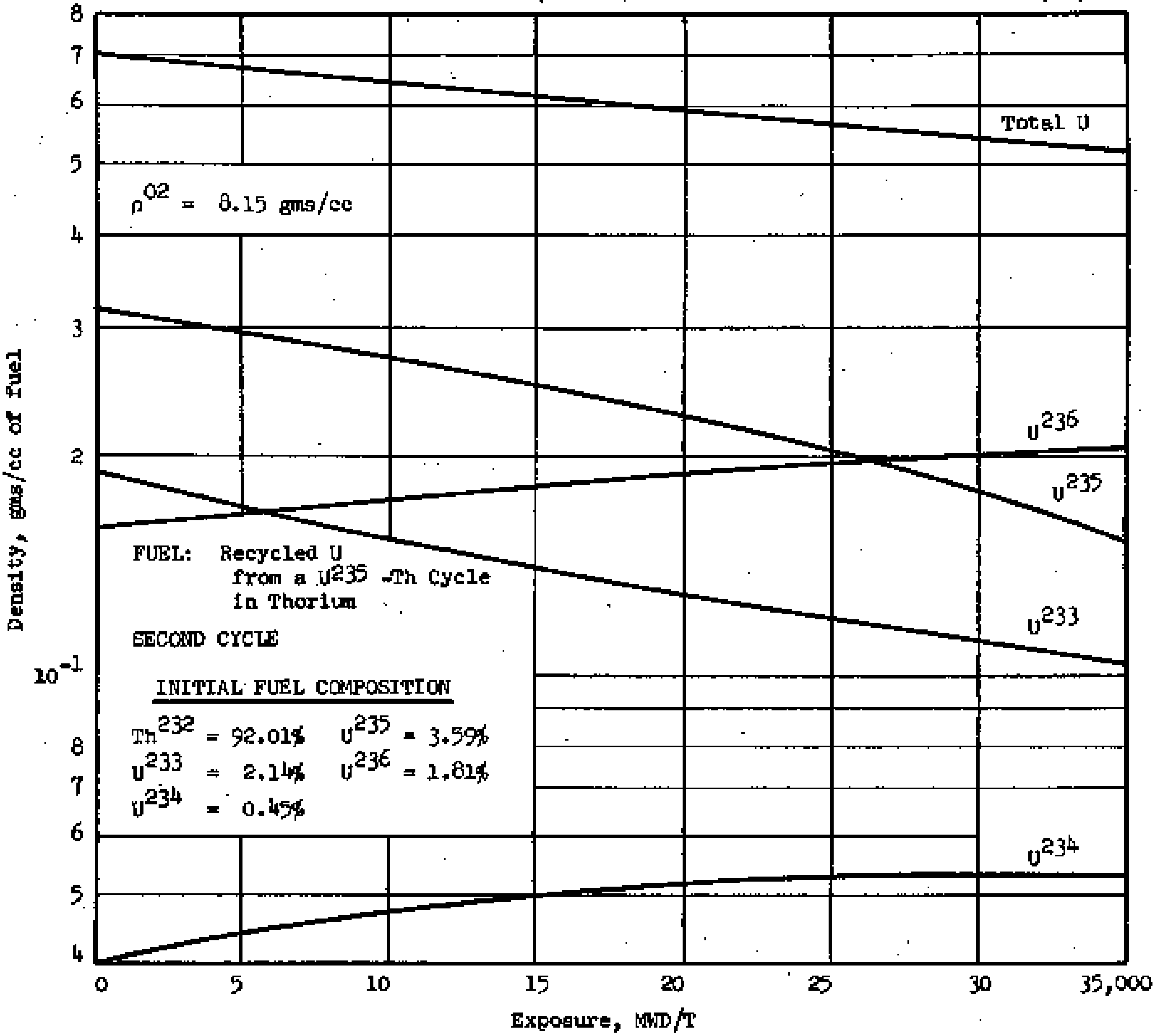

Fig. 10C. Fuel Isotopic Densities vs. Exposure for Carolinas-Virginia Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46522

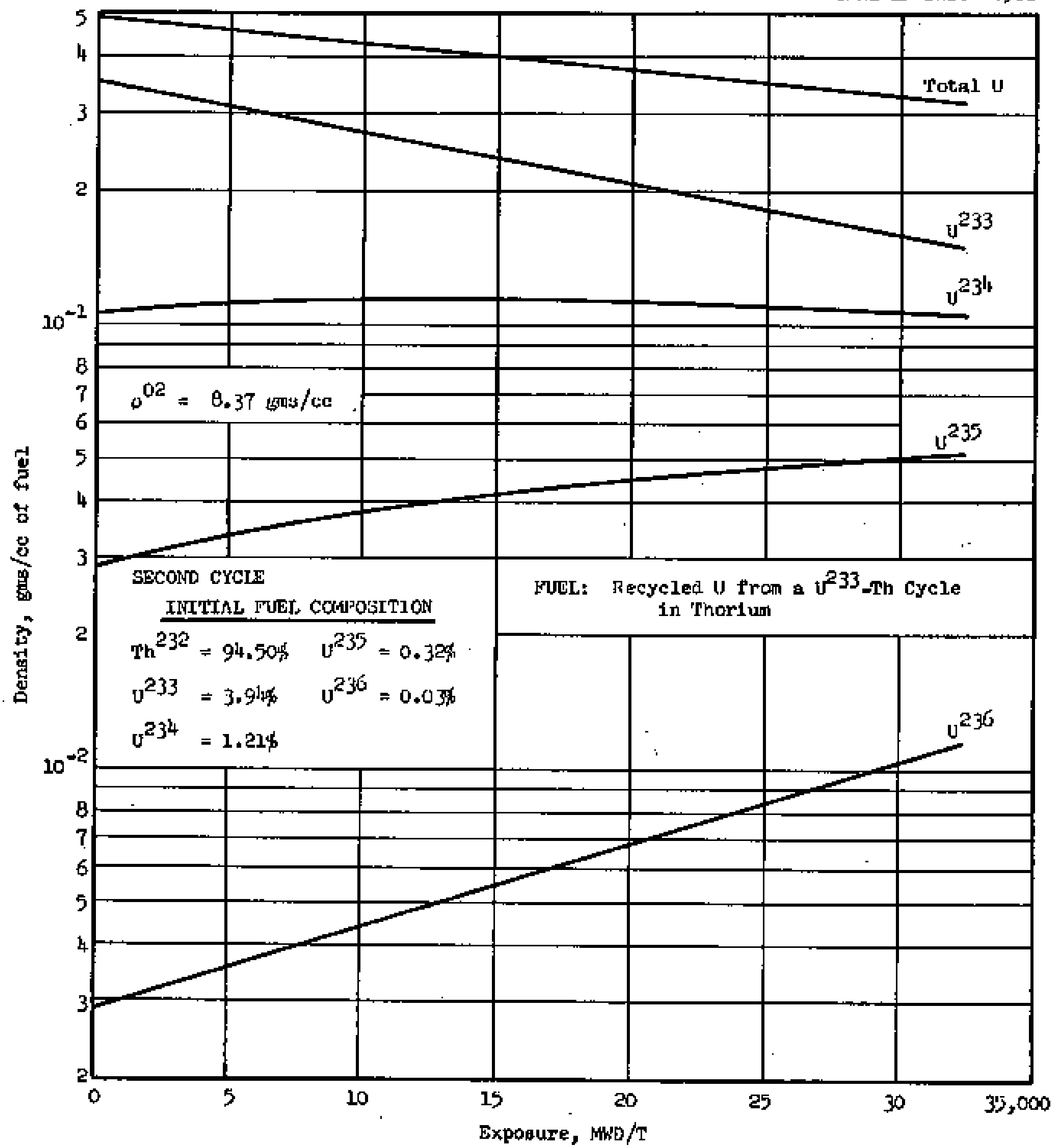

Fig. 11C. Fuel Isotopic Densities vs. Exposure for Carolinas-Virginia Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46523

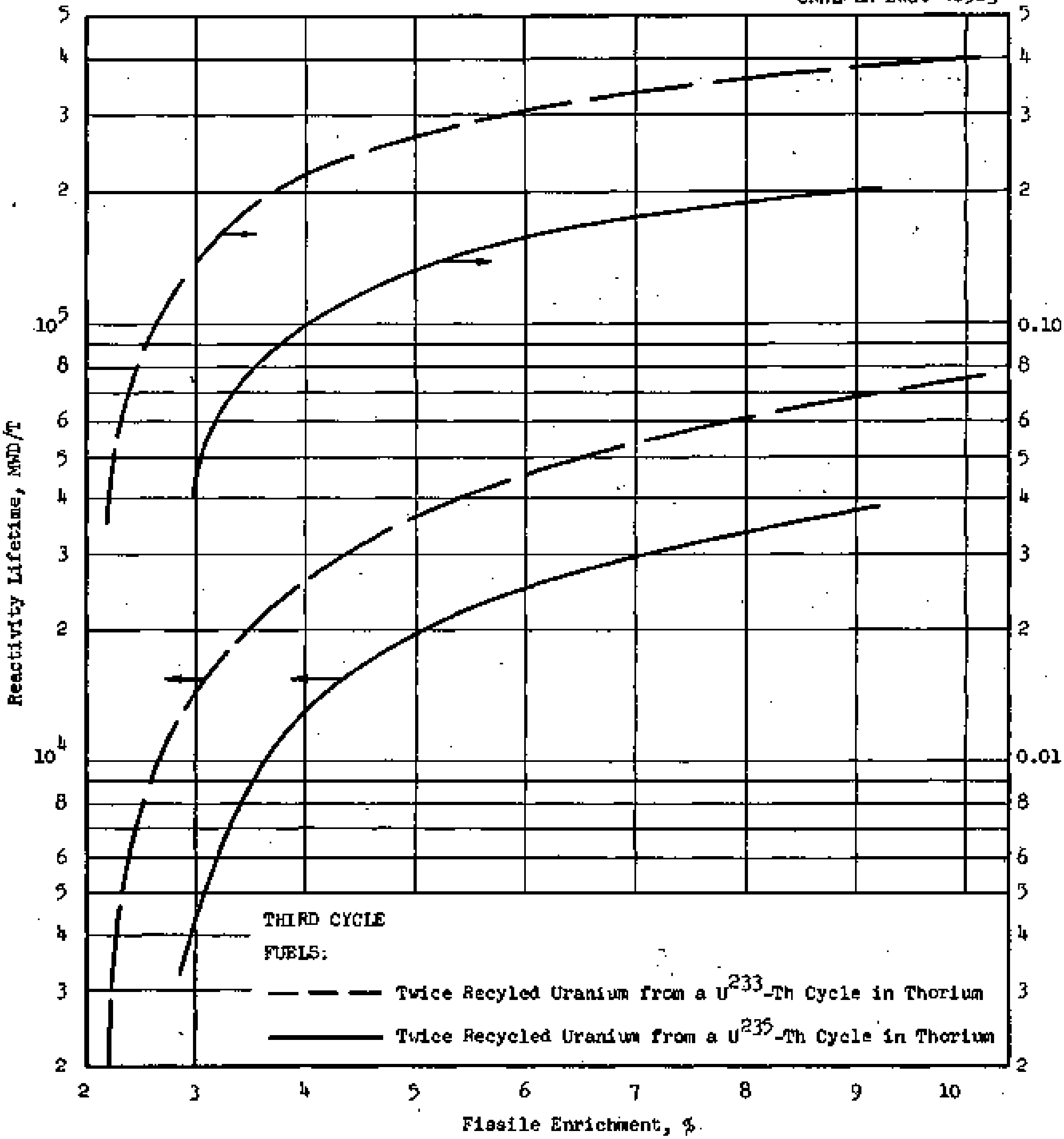

Fig. 12C. Reactivity Lifetime and Initial Reactivity vs. Fissile Enrichment for Carolinas-Virginia Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46524

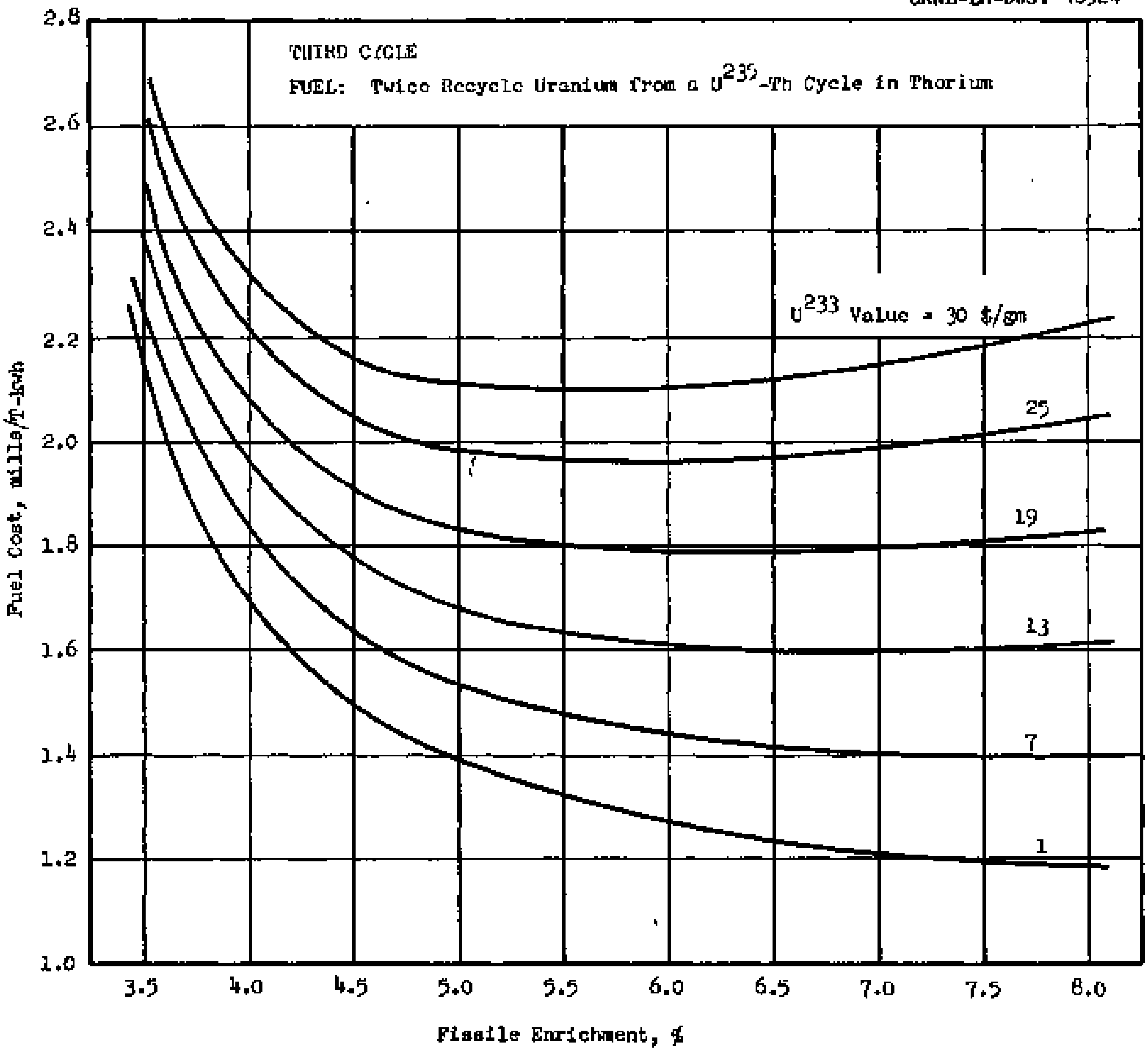

Fig. 13C. Fuel Cost vs. Fissile Enrichment for Carolinas-Virginia Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46525

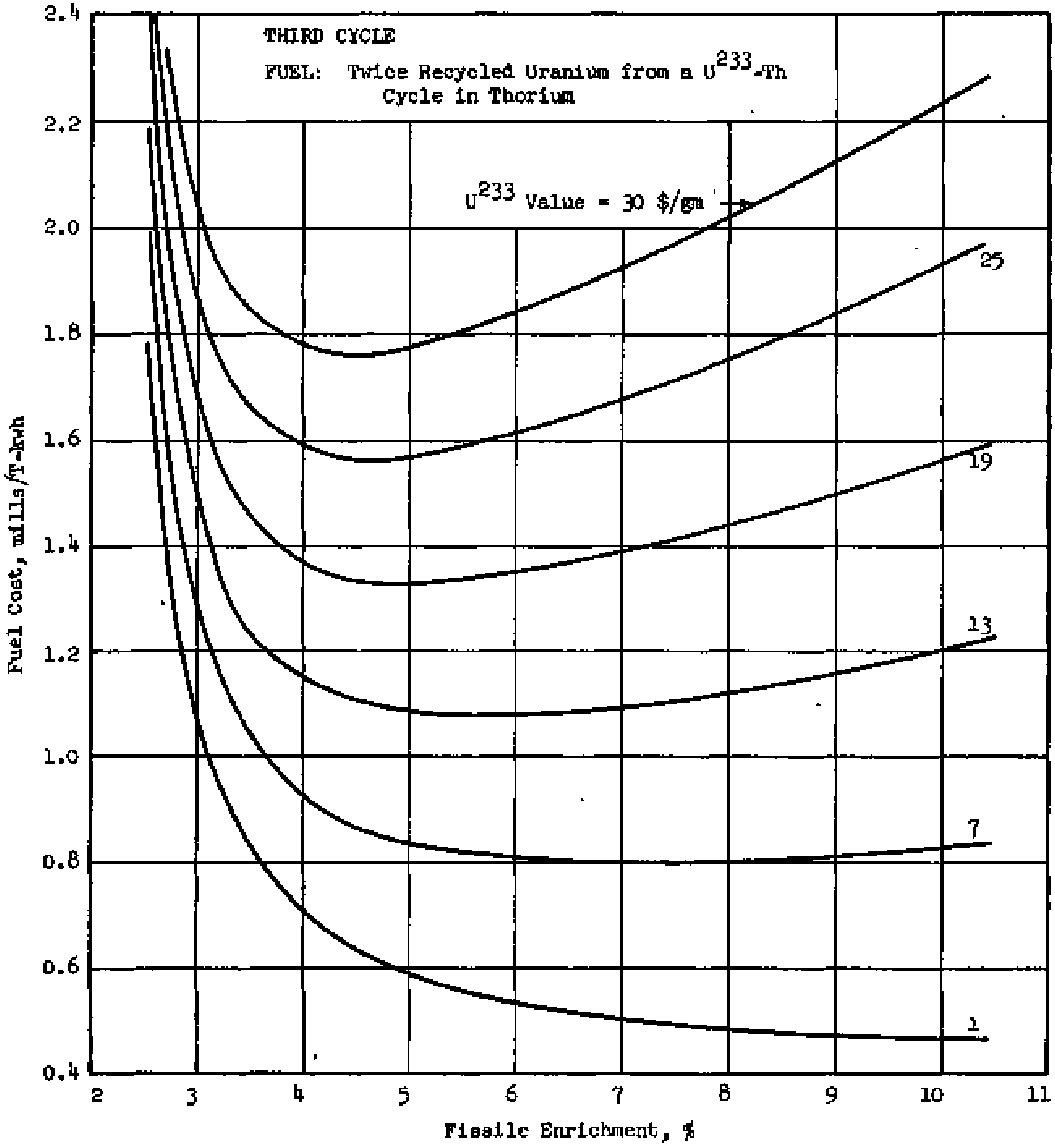

Fig. 14C. Fuel Cost vs. Fissile Enrichment for Carolinas Virginia Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46526

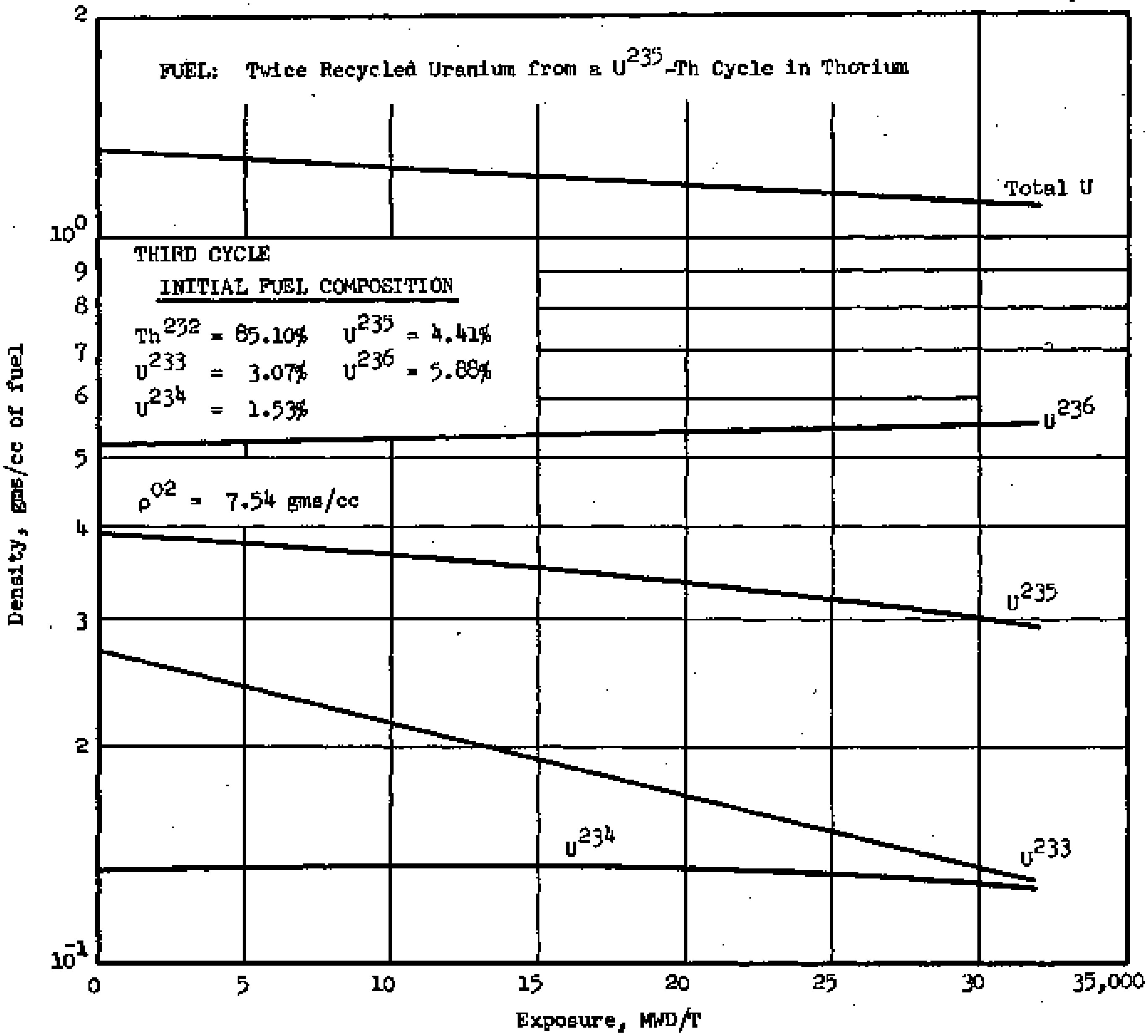

Fig. 15C. Fuel Isotopic Densities vs. Exposure for Carolinas-Virginia Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46527

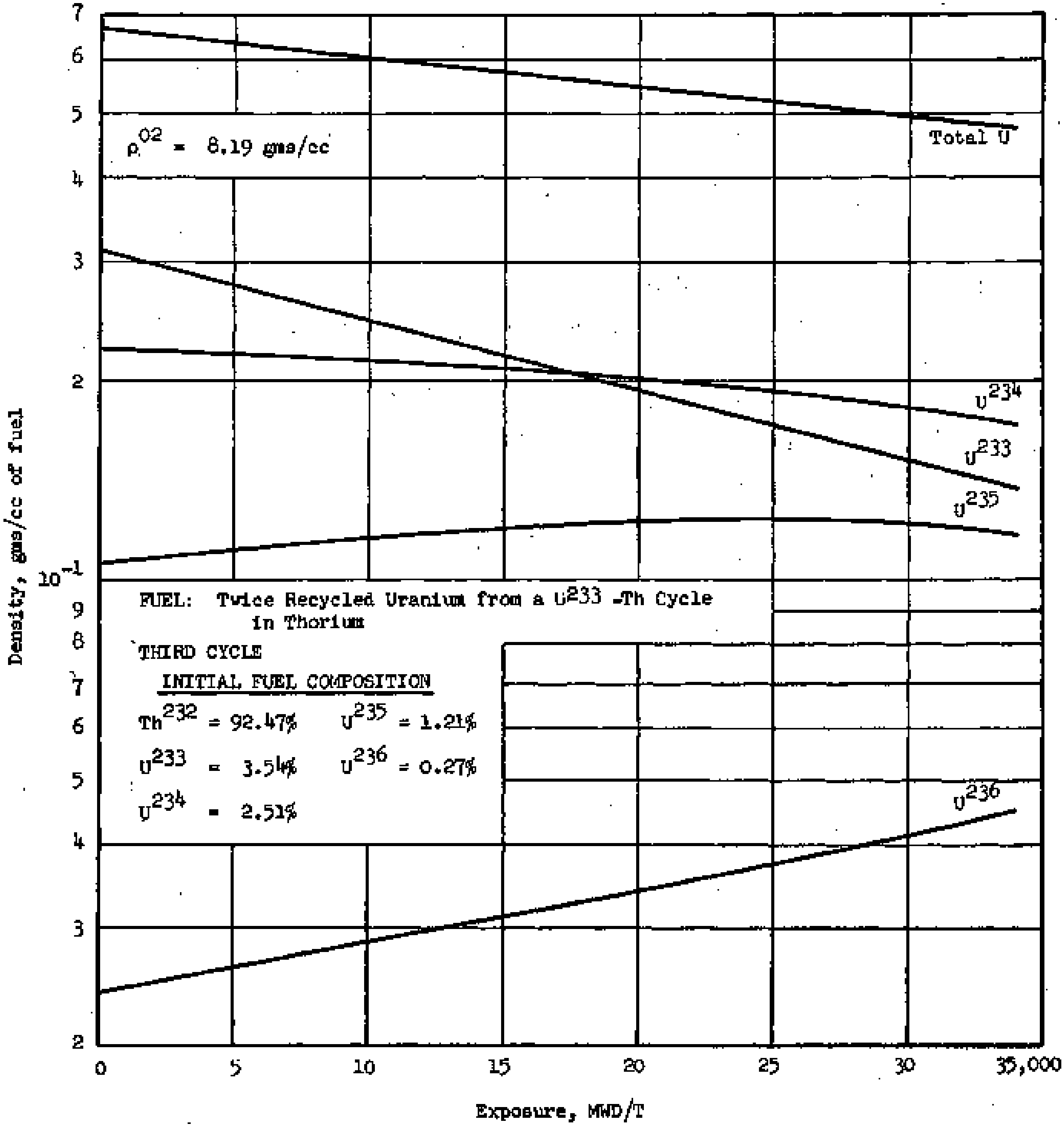

Fig. 16C. Fuel Isotopic Densities vs. Exposure for Carolinas-Virginia Reactor.

Appendix D. Results Concerning the Hallam Reactor

The detailed results of the calculations concerning the Hallam reactor are presented in graphical form in Figs. 1D through 16D. Figure 1D summarizes these results and shows the minimum fuel costs (in mills per thermal Kwh) as a function of U^{233} value for three complete cycles and two initial fuels. Recycle uranium from an initial U^{235} cycle may be used with only a small increase in fuel costs and a decrease in U^{233} value of less than $4 per gram. Recycle uranium from an initial U^{233} cycle exhibits slightly lower fuel costs and slightly higher U^{233} values than the initial cycle. Figures 2D through 16D are analogous to Figs. 2A through 16A, respectively.

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ORNL-LR-DWG. 46644

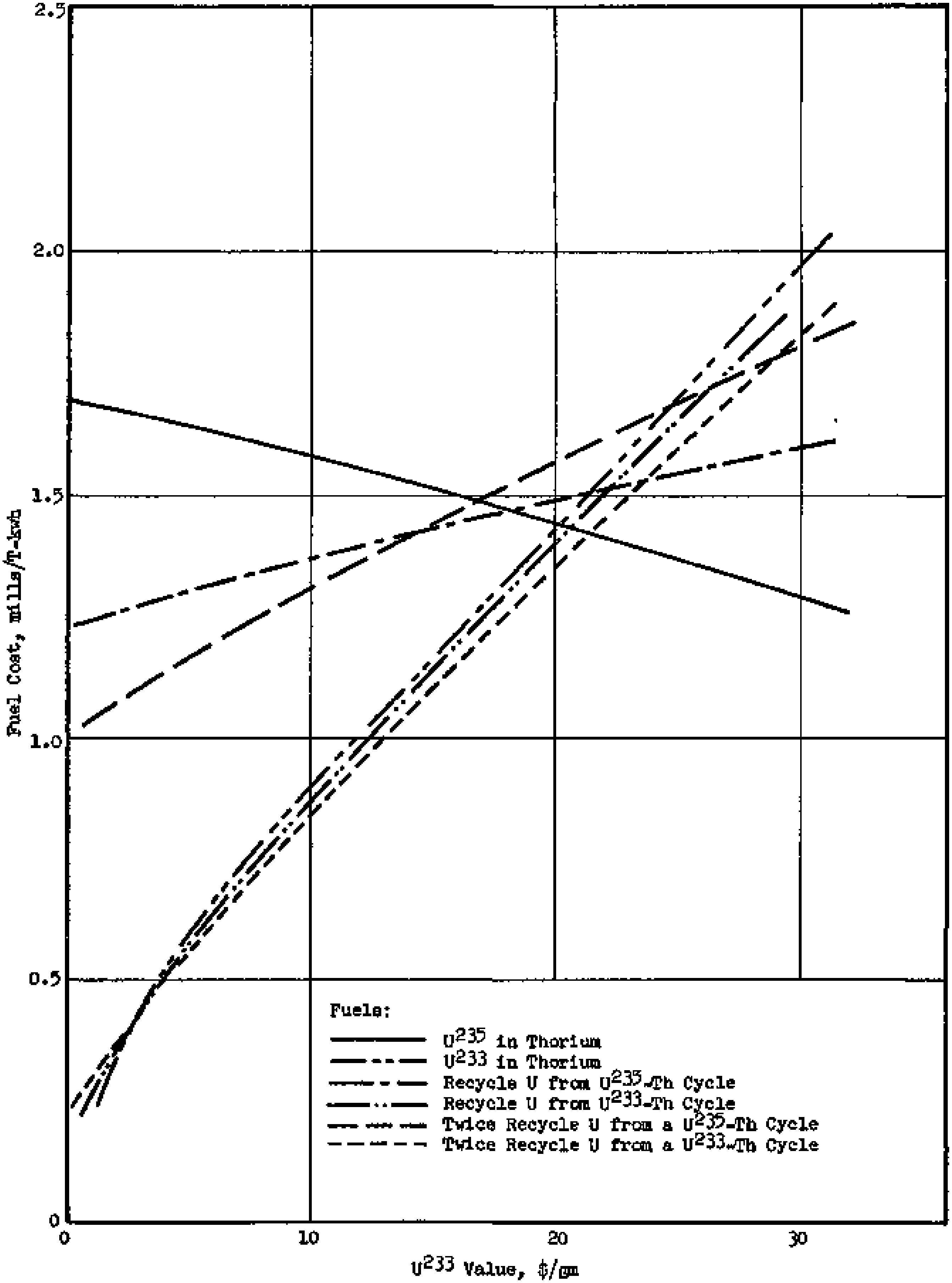

Fig. 1D. Minimum Fuel Cost Vs. U^{233} Value for Hallam Reactor.

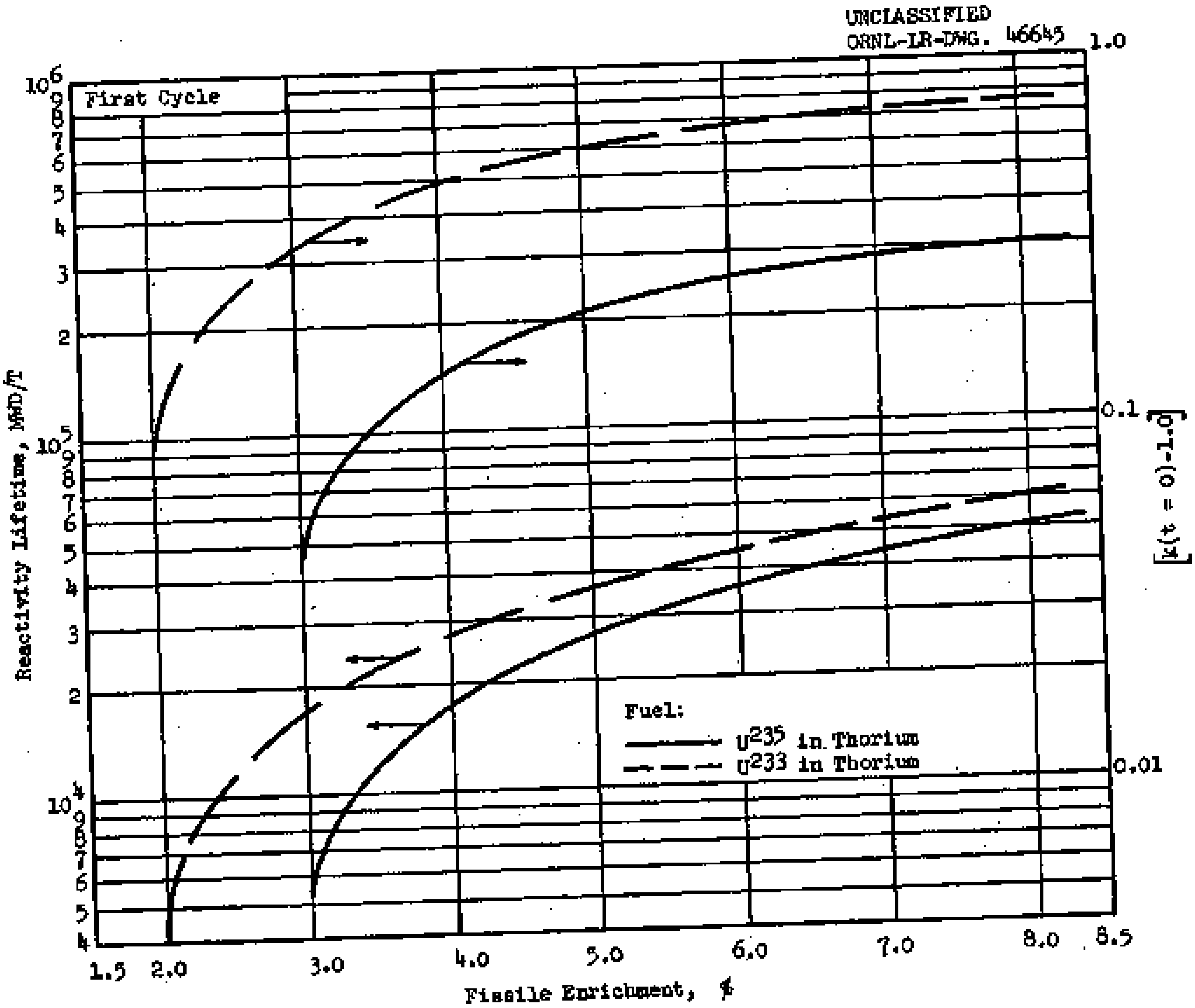

Fig. 20. Reactivity Lifetime and Initial Reactivity Vs. Fissile Enrichment for Hallam Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46646

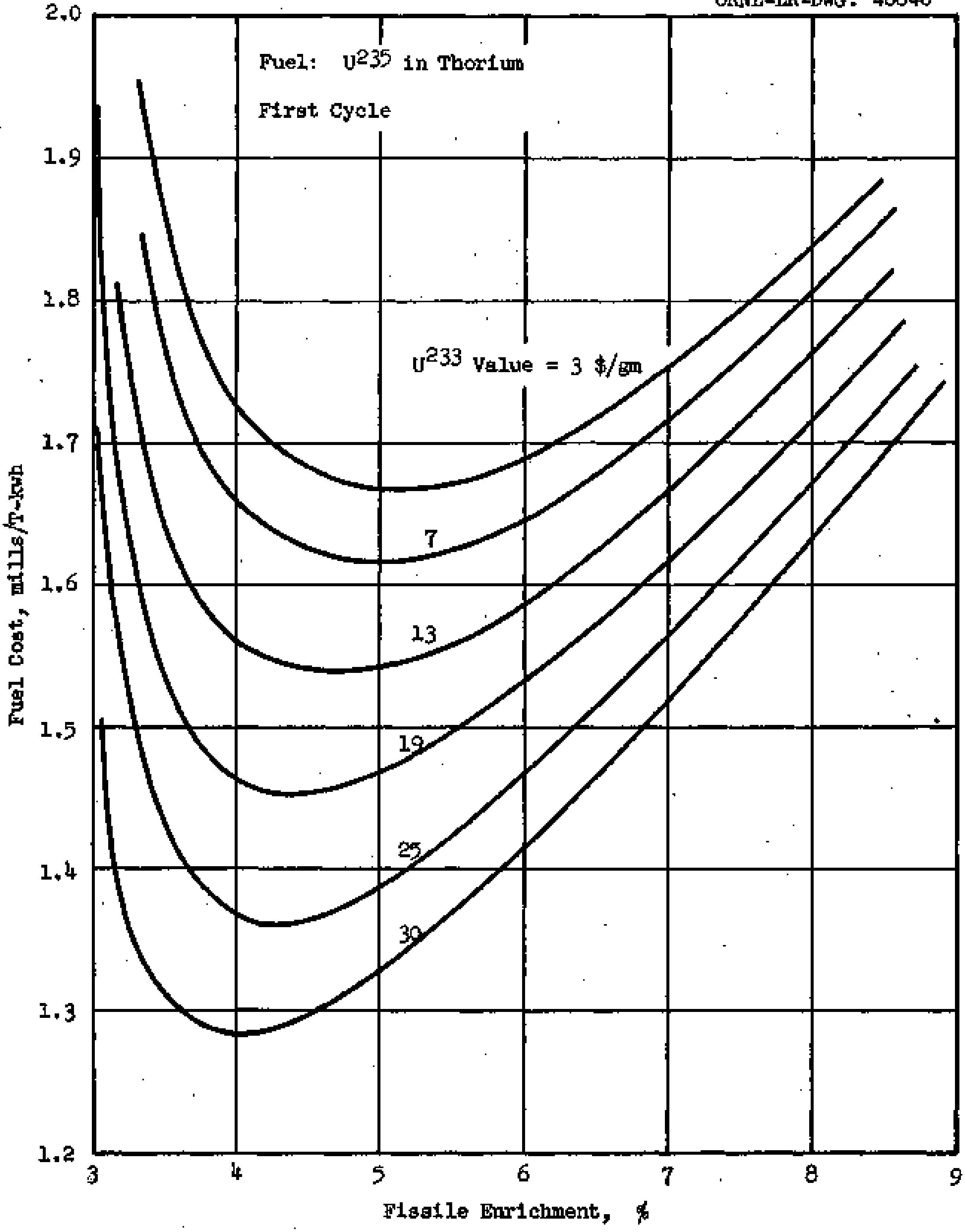

Fig. 3D. Fuel Cost Vs. Fissile Enrichment for Hallam Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46647

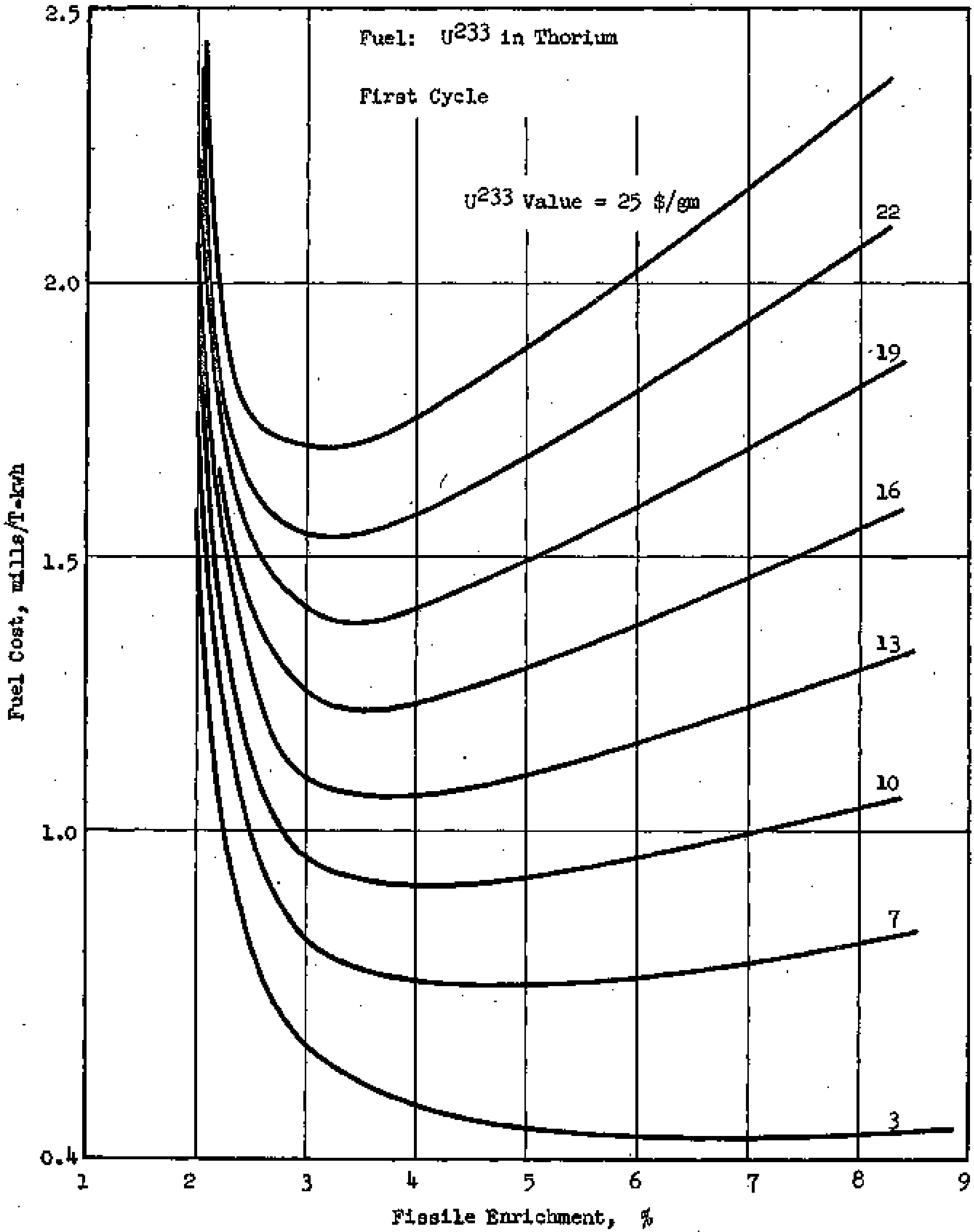

Fig. 4D. Fuel Cost Vs. Fissile Enrichment for Hallam Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46648

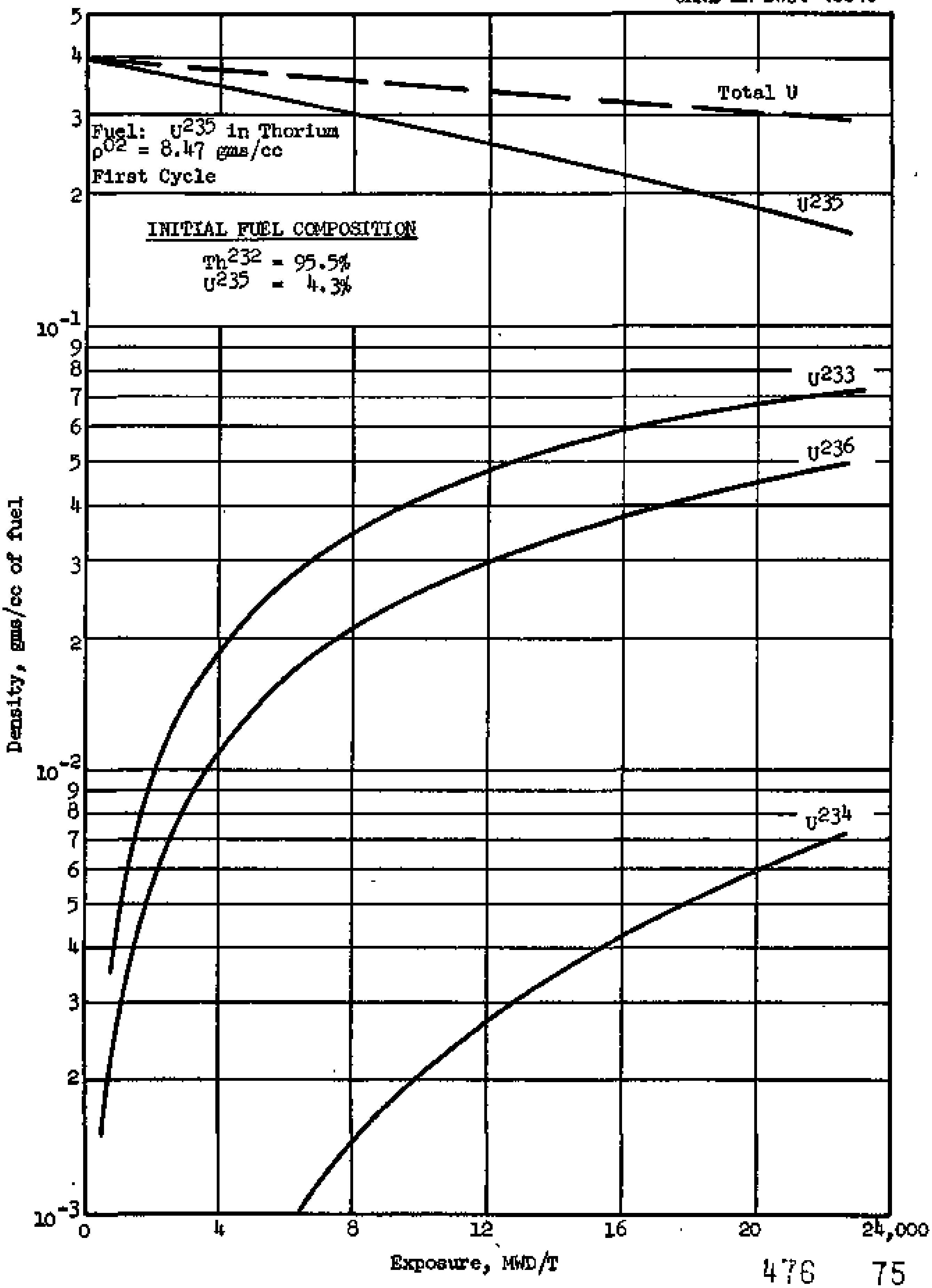

Fig. 5D. Fuel Isotopic Densities Vs. Exposure for Hallam Reactor.

UNCLASSIFIED
ORNL-LR-DWG. 46649

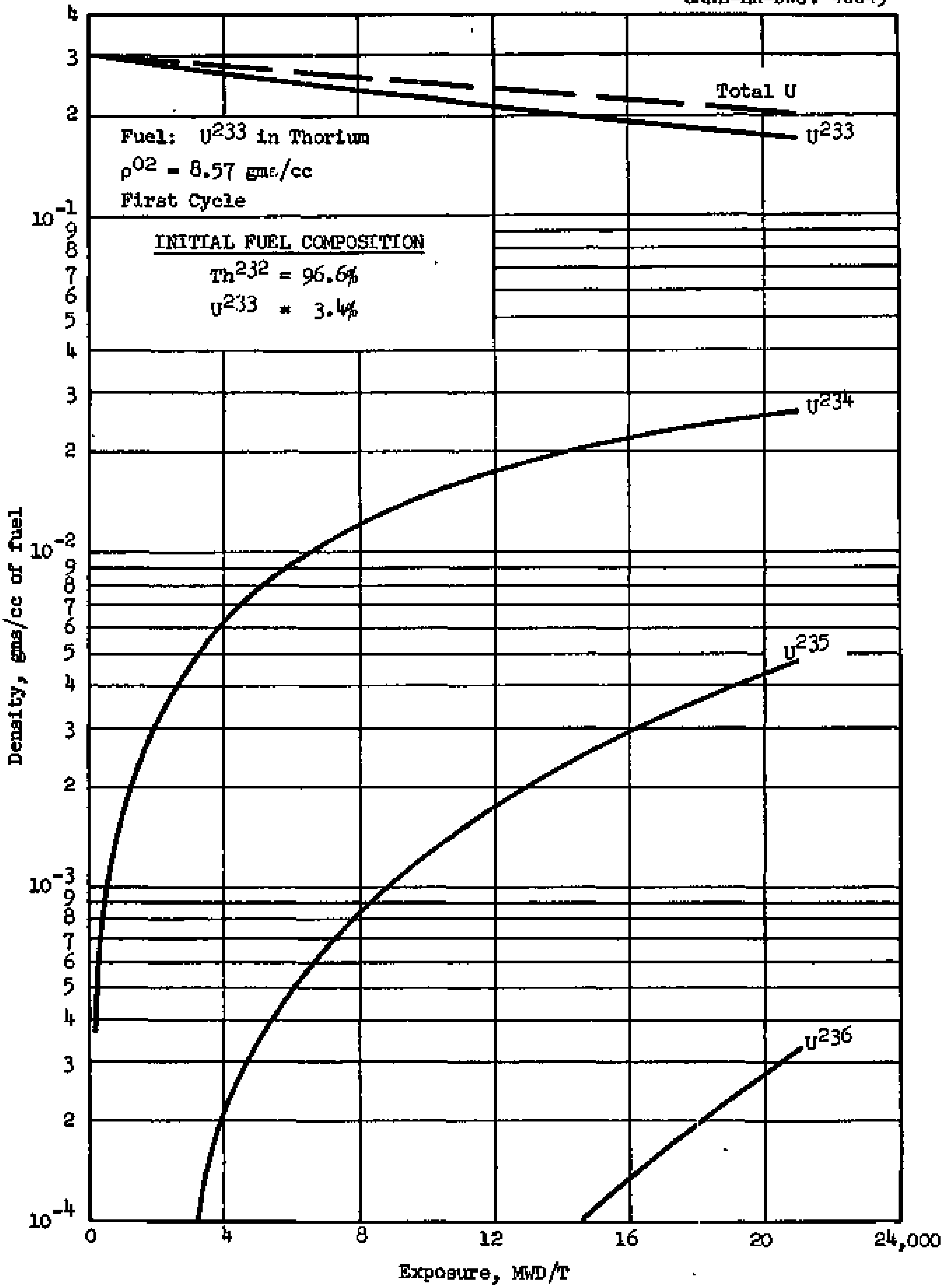

Fig. 6D. Fuel Isotopic Densities Vs. Exposure for Hallam Reactor.

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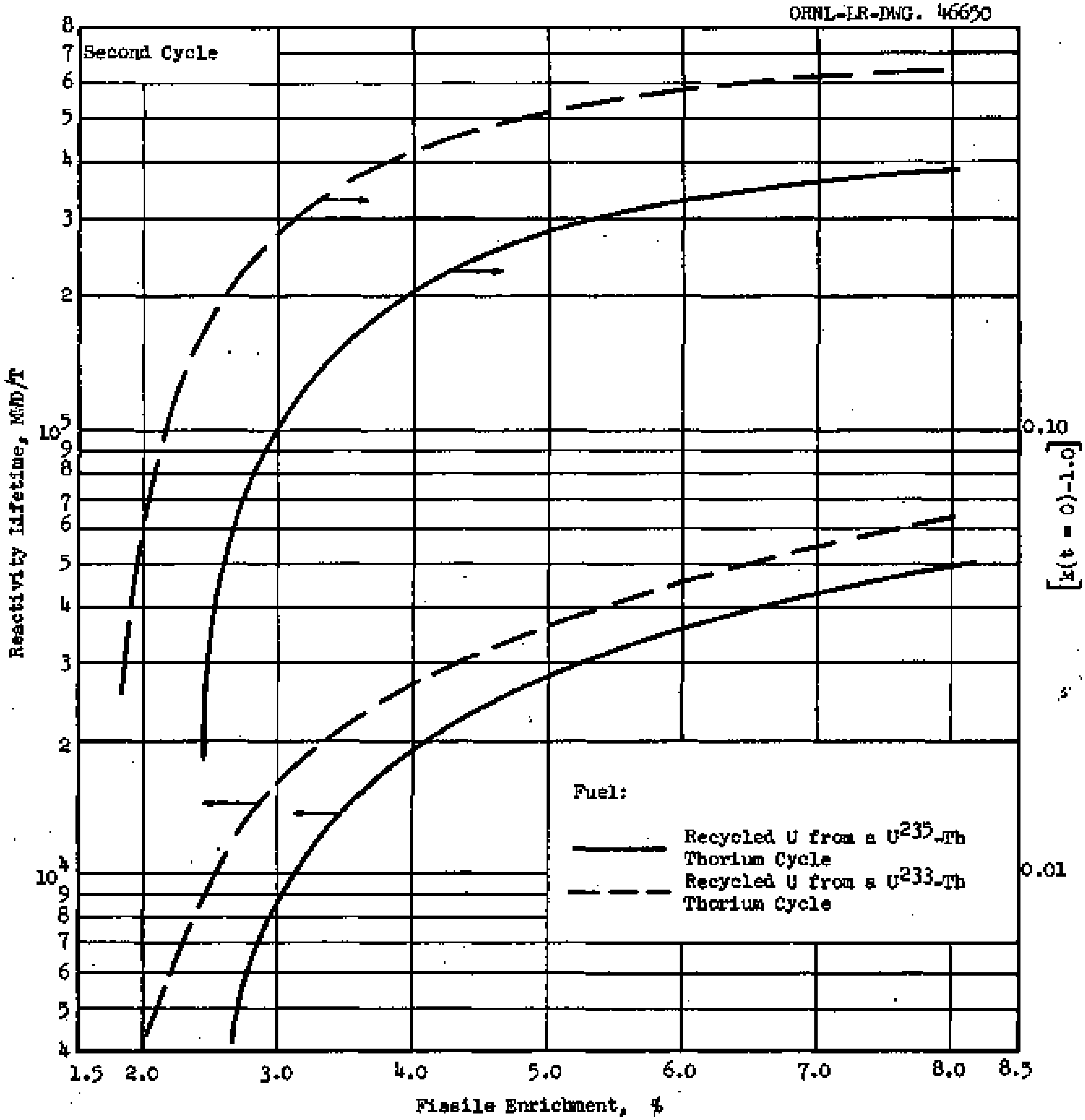

Fig. 7D. Reactivity Lifetime and Initial Reactivity Vs. Fissile Enrichment for Hallam Reactor.

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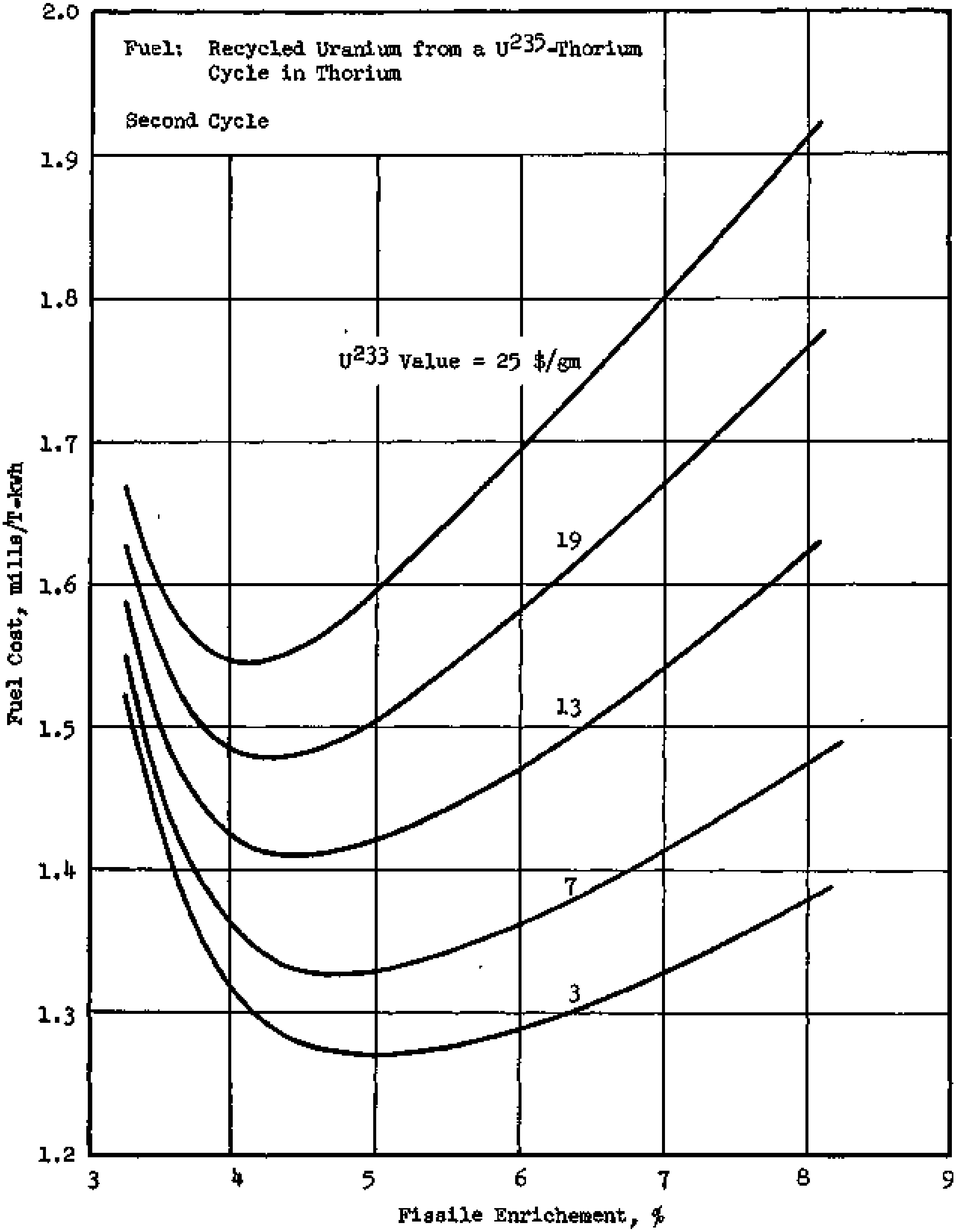

Fig. 8D. Fuel Cost Vs. Fissile Enrichment for Hallam Reactor.

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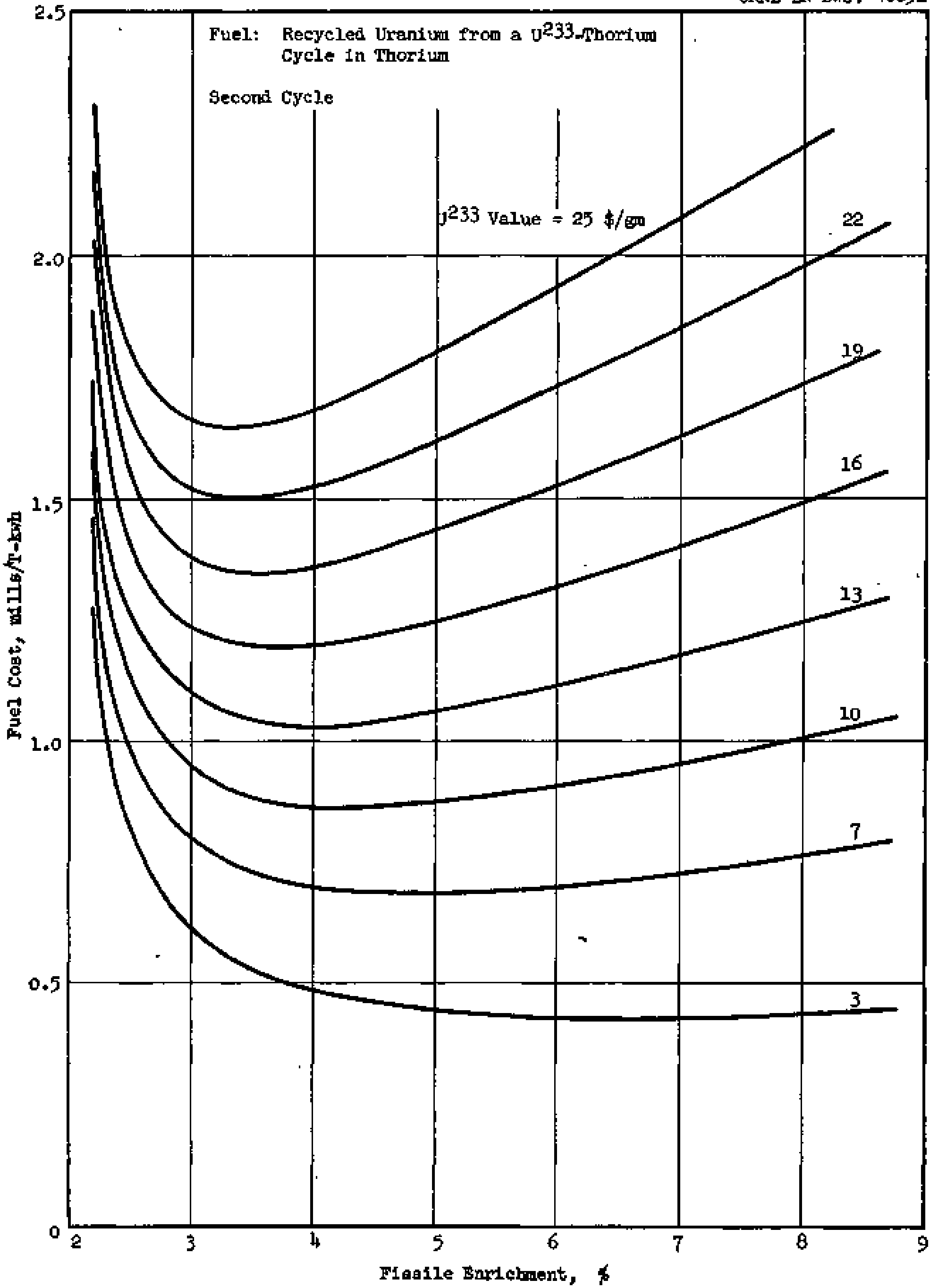

Fig. 9D. Fuel Cost Vs. Fissile Enrichment for Hallam Reactor.

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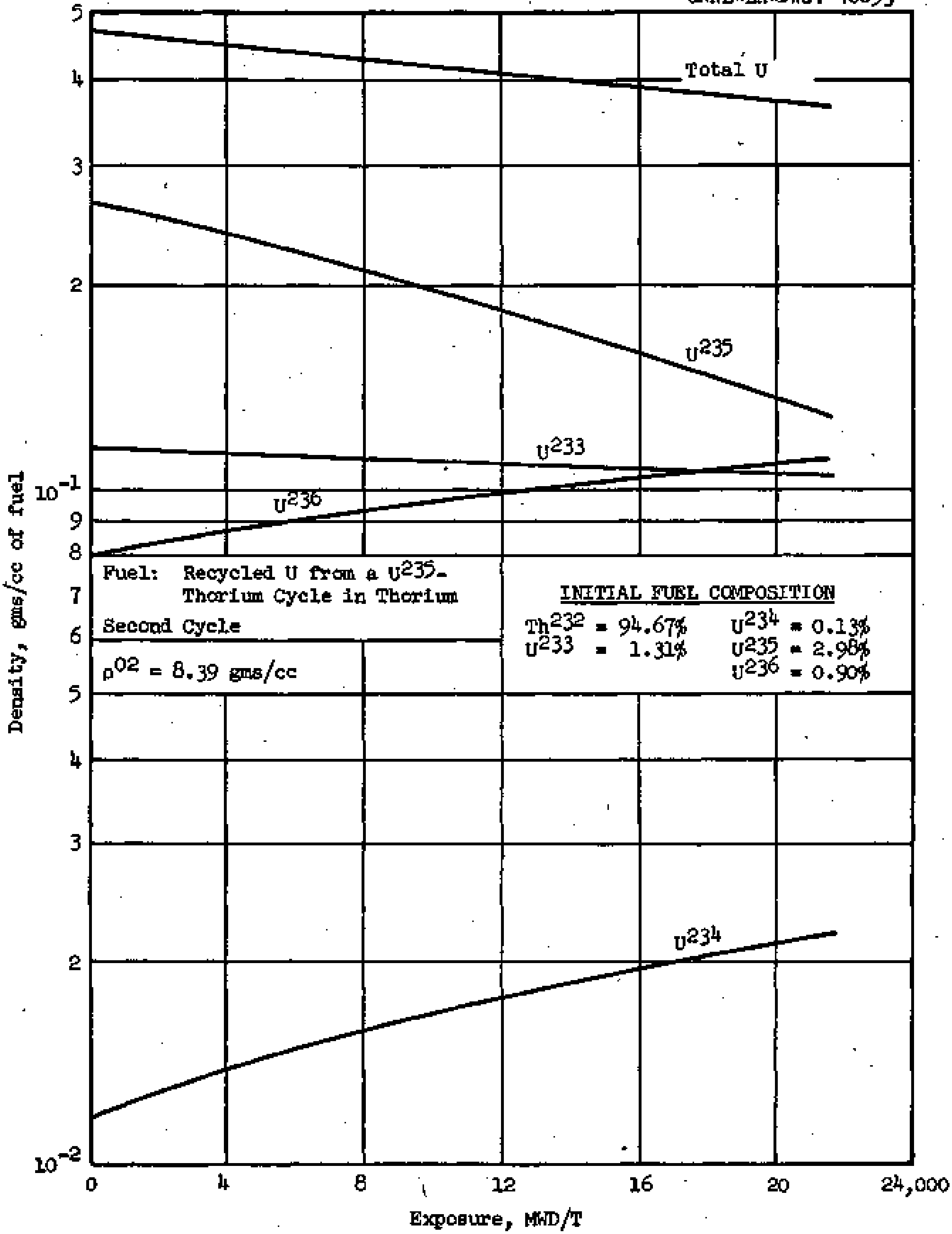

Fig. 10D. Fuel Isotopic Densities Vs. Exposure for Hallam Reactor.

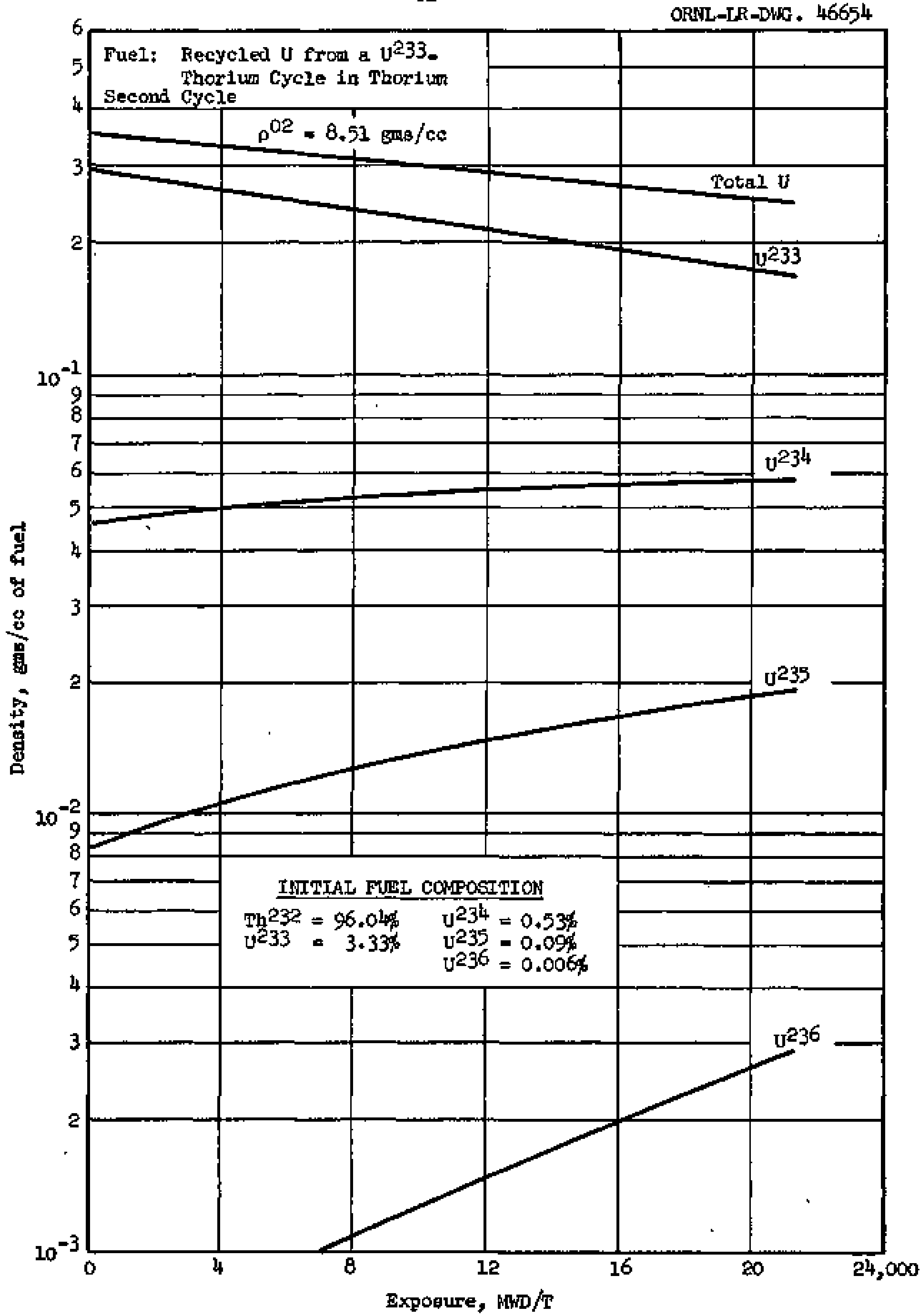

Fig. 11D. Fuel Isotopic Densities Vs. Exposure for Hallam Reactor.

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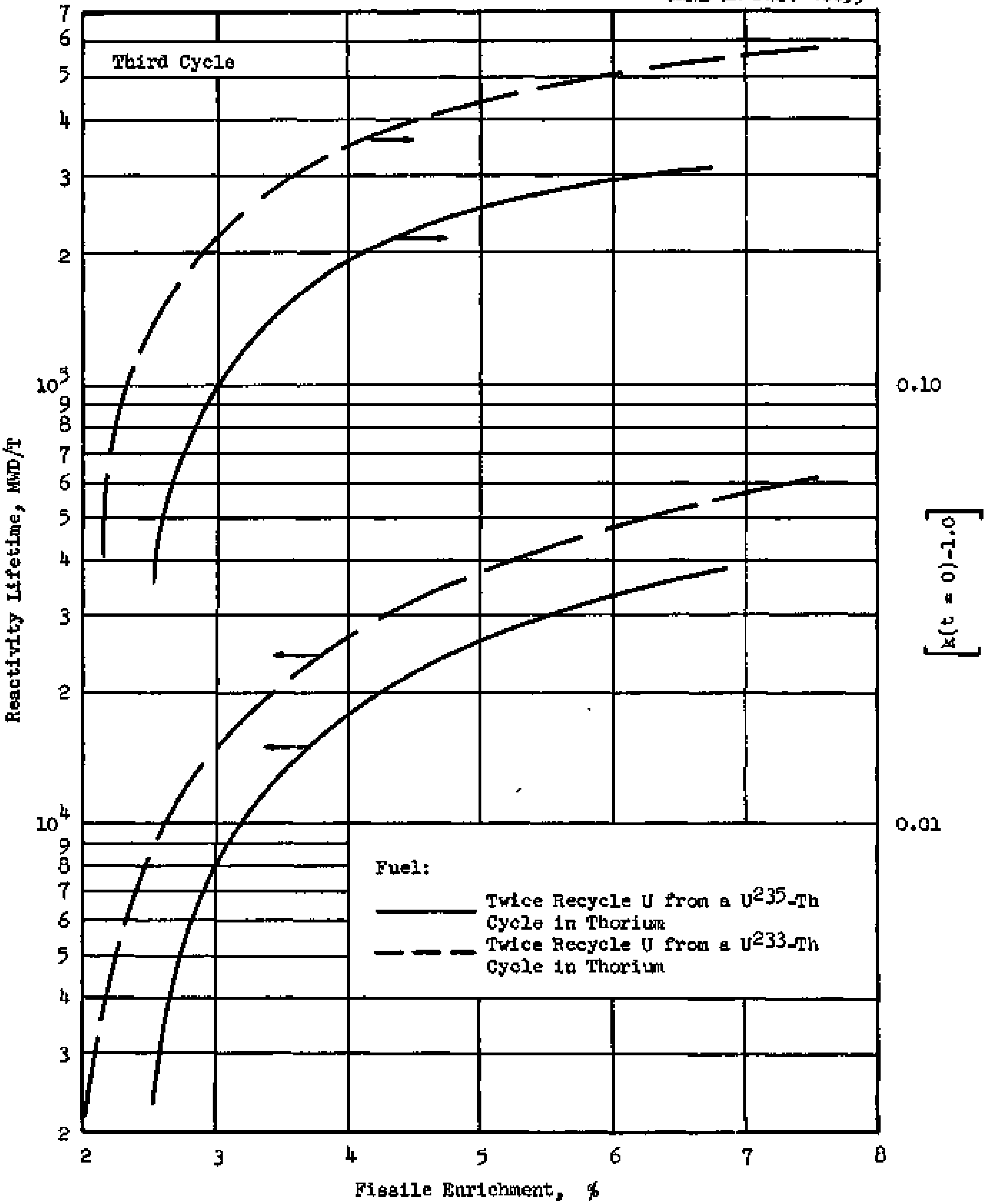

Fig. 12D. Reactivity Lifetime and Initial Reactivity Vs. Fissile Enrichment for Hallam Reactor.

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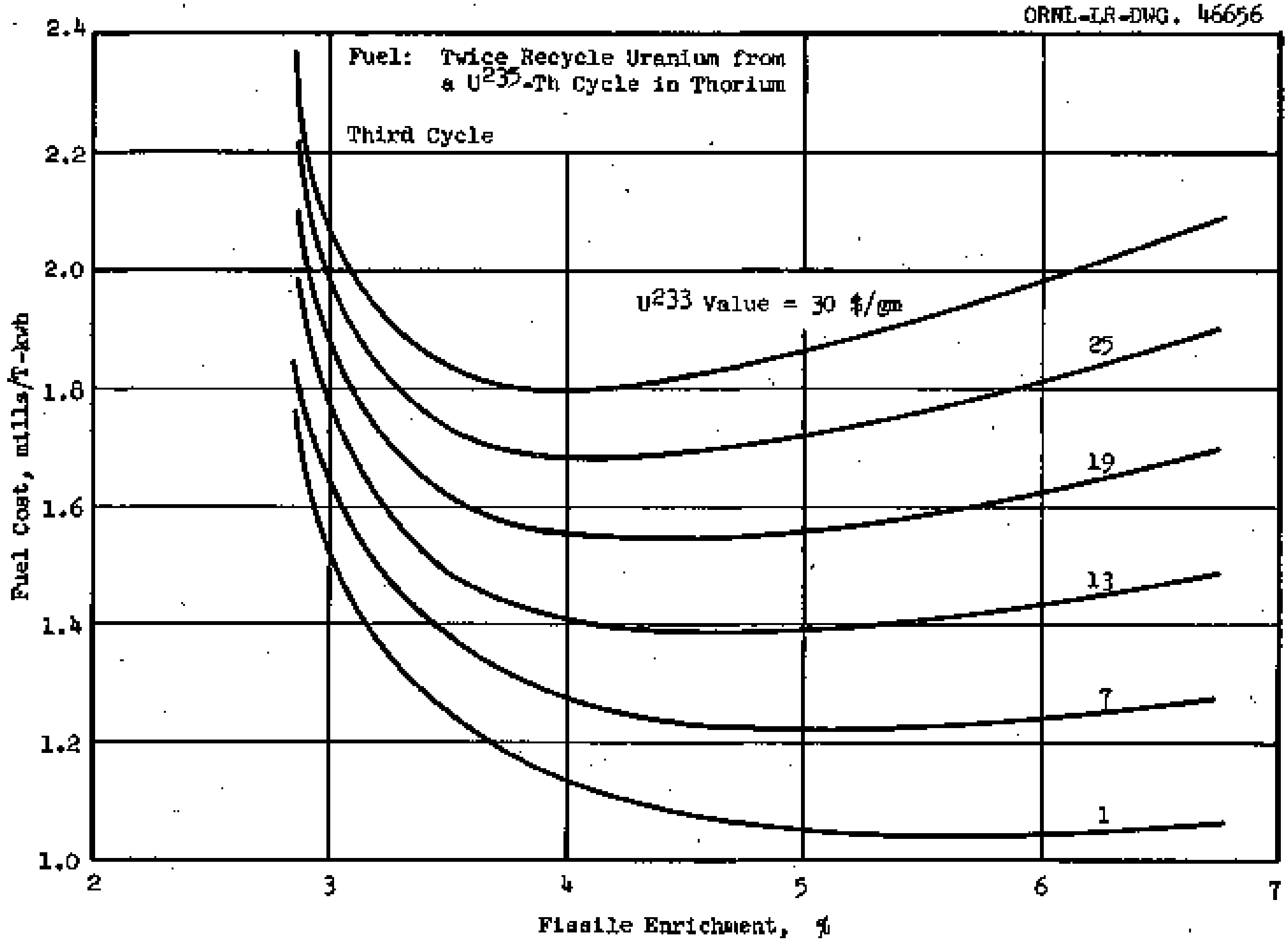

Fig. 13D. Fuel Cost Vs. Fissile Enrichment for Hallam Reactor.

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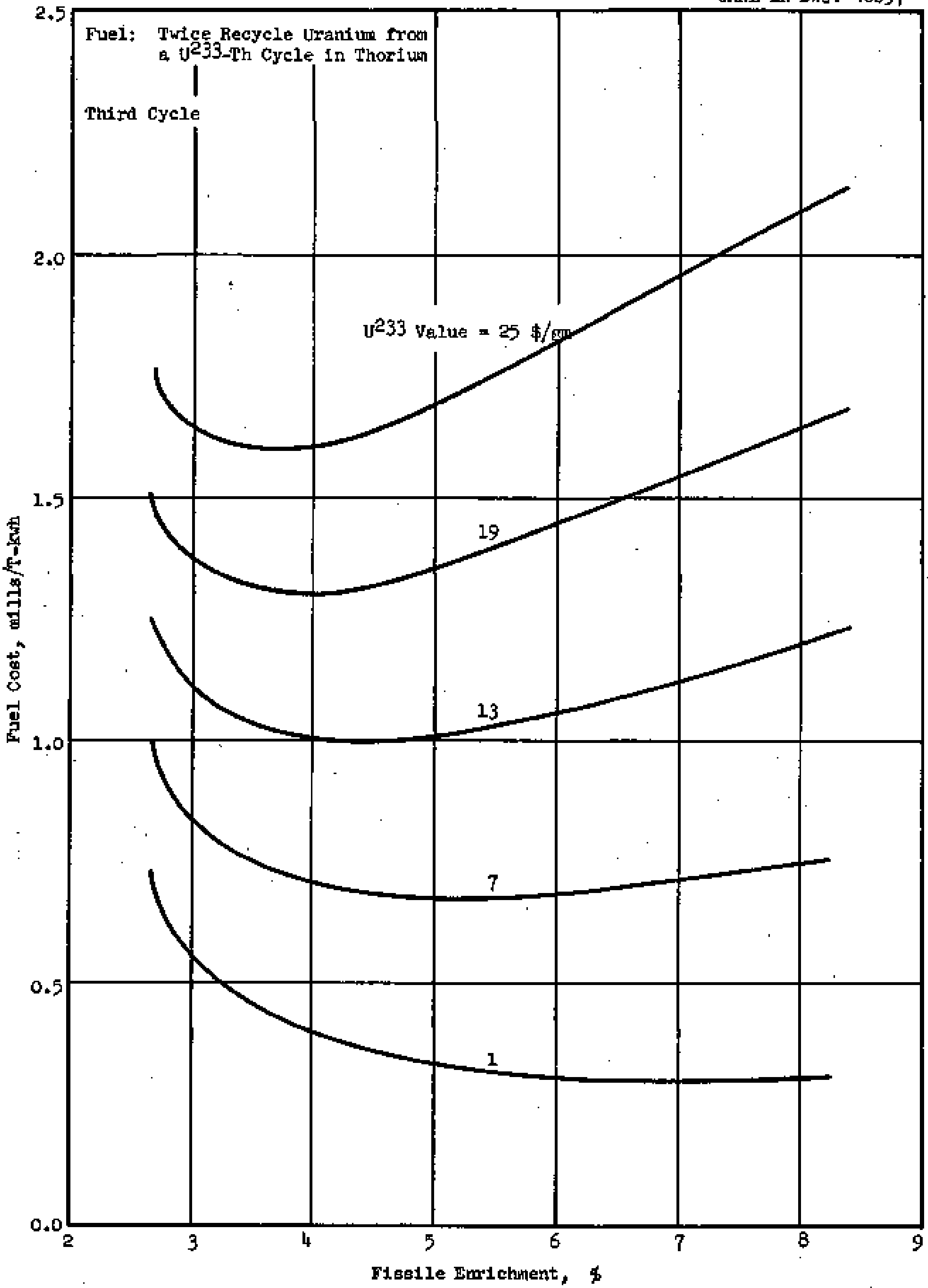

Fig. 14D. Fuel Cost Vs. Fissile Enrichment for Hallam Reactor.

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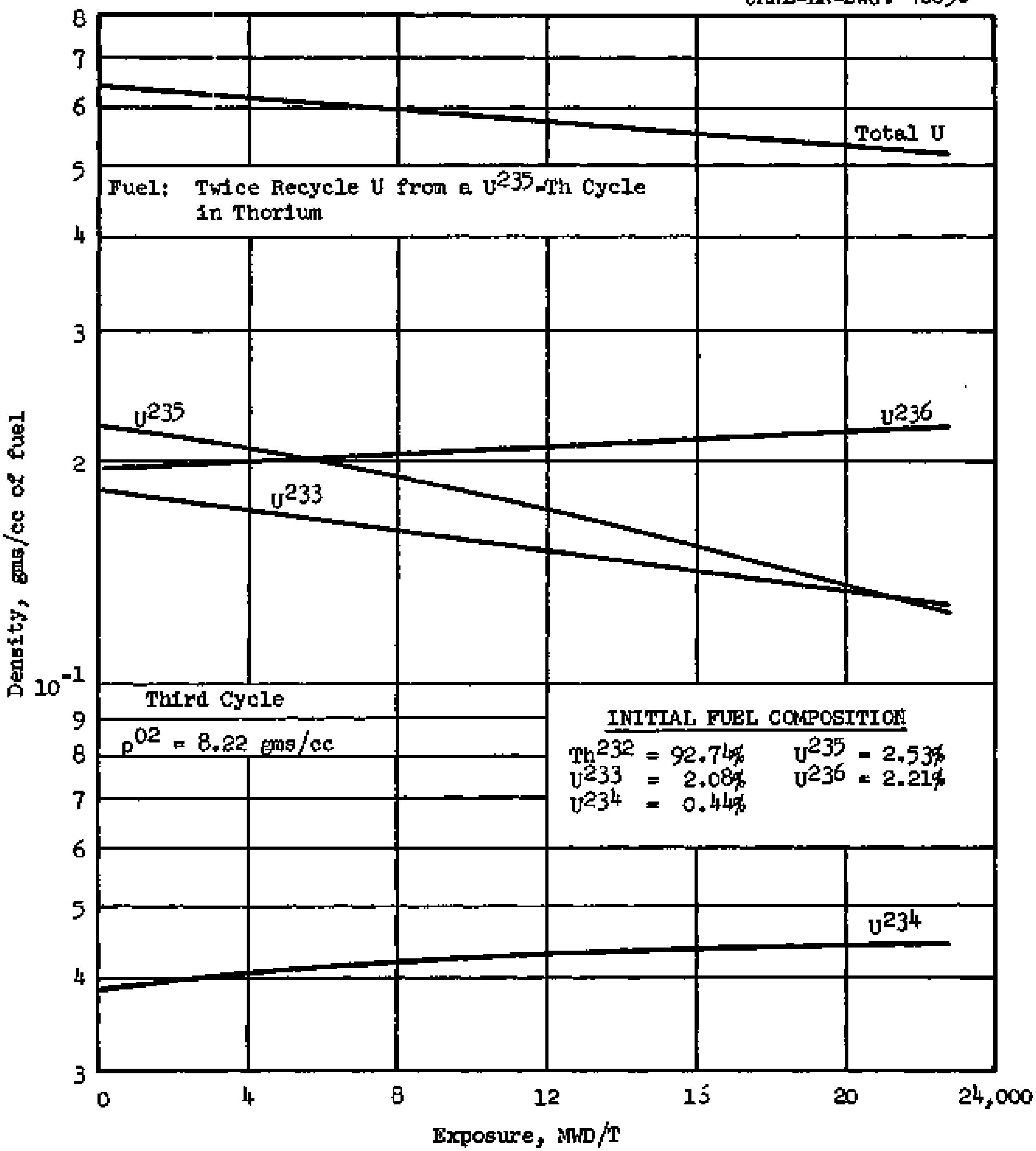

Fig. 15D. Fuel Isotopic Densities Vs. Exposure for Hallam Reactor.

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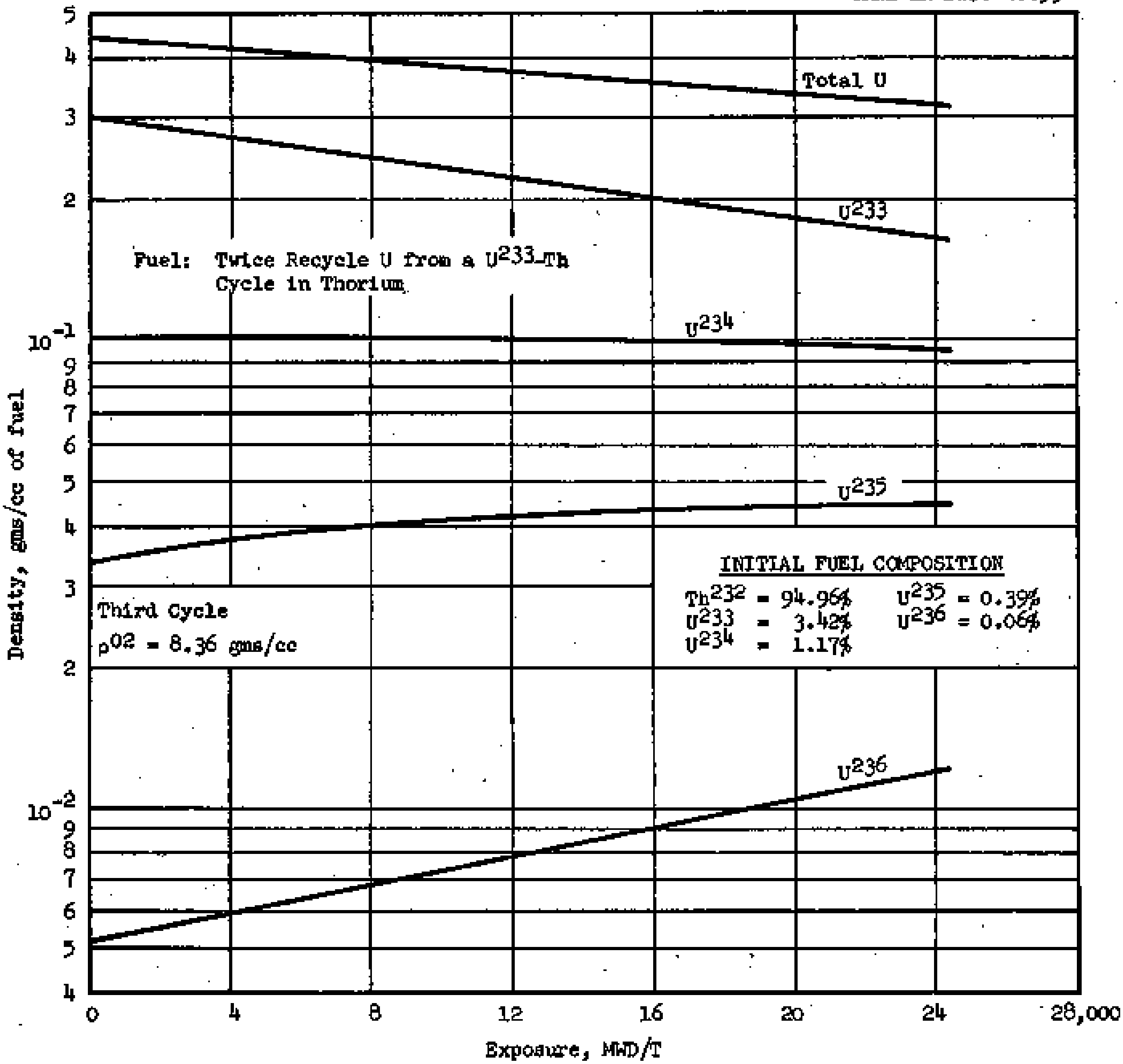

Fig. 16D. Isotopic Densities Vs. Exposure for Hallam Reactor.

Appendix E. Results Concerning the GCR-II

The detailed results of the calculations concerning the GCR-II are presented in graphical form in Figs. 1E through 16E. Figure 1E summarizes these results and shows the minimum fuel costs (in mills per thermal Kwh) as a function of U^{233} value for three complete cycles and two initial fuels. Recycle uranium from an initial U^{235} cycle may be used with only a small increase in fuel costs and a decrease in U^{233} value of less than $4 per gram. Recycle uranium from an initial U^{233} cycle may be used with almost no change in either fuel cost or U^{233} value. Figures 2E through 16E are analogous to Figs. 2A through 16A, respectively.

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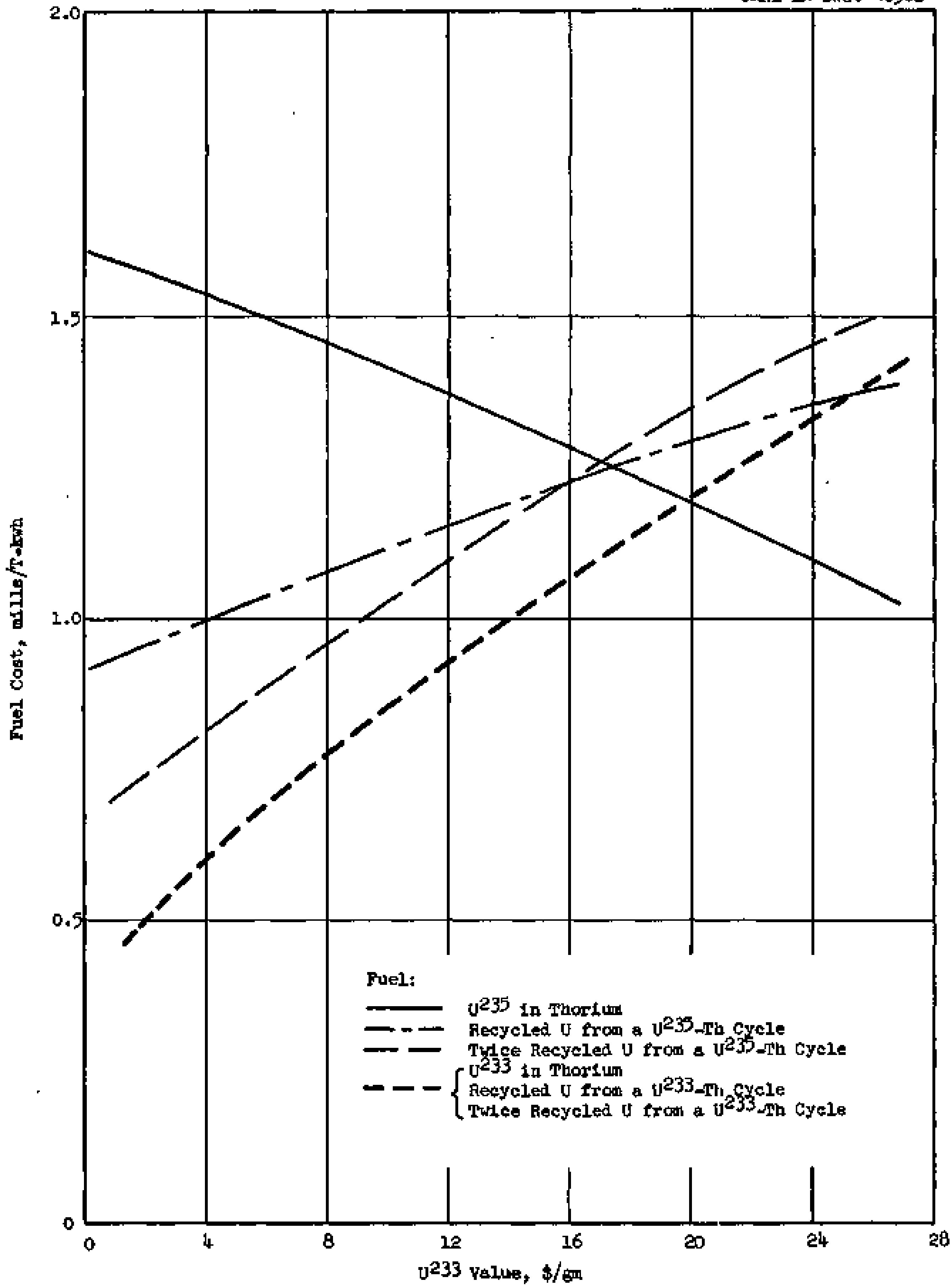

Fig. 1E. Minimum Fuel Cost Vs. U^{233} Value for GCR-II.

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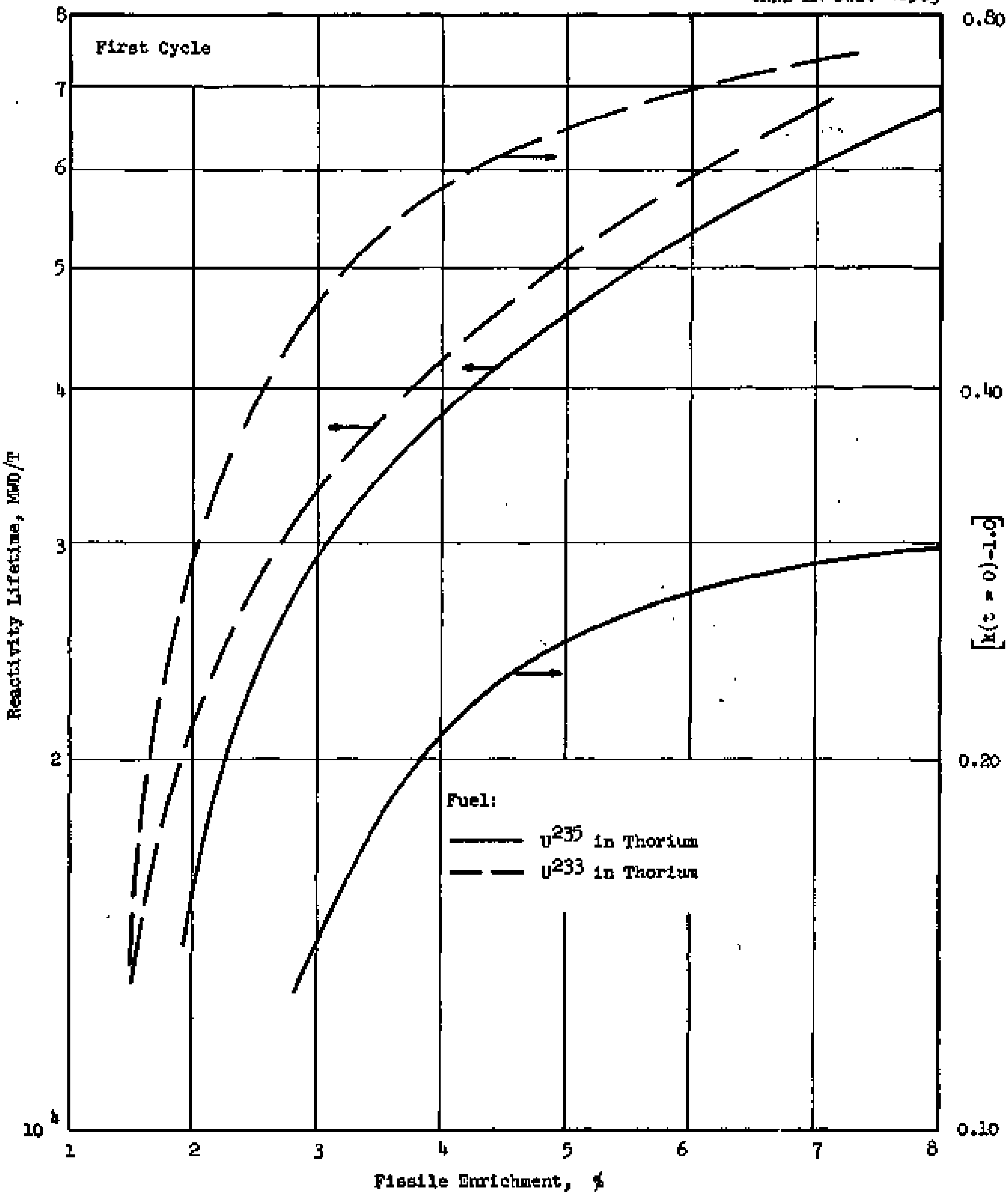

Fig. 2E. Reactivity Lifetime and Initial Reactivity Vs. Fissile Enrichment for GCR-II.

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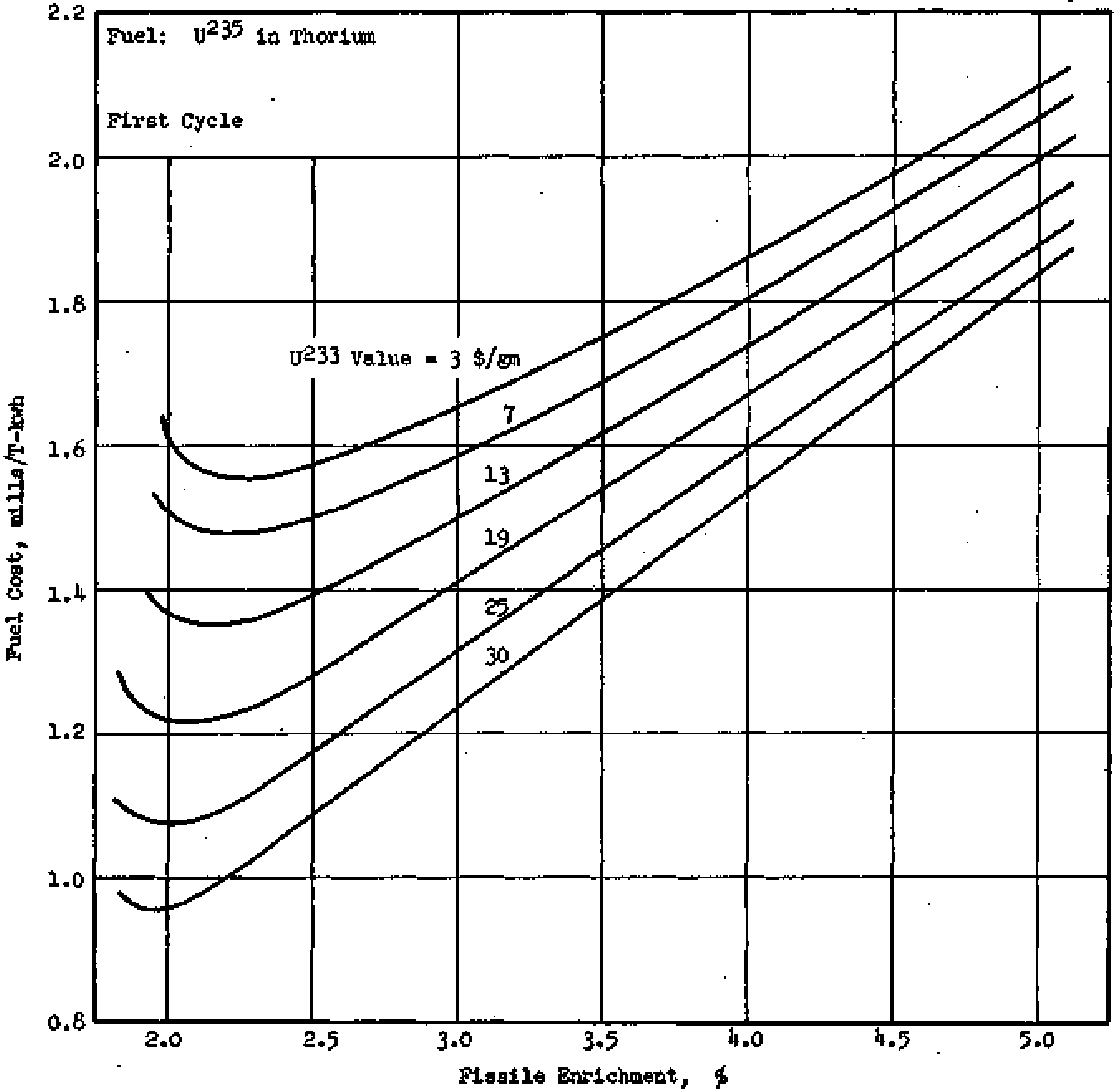

Fig. 3E. Fuel Cost Vs. Fissile Enrichment for GCR-II.

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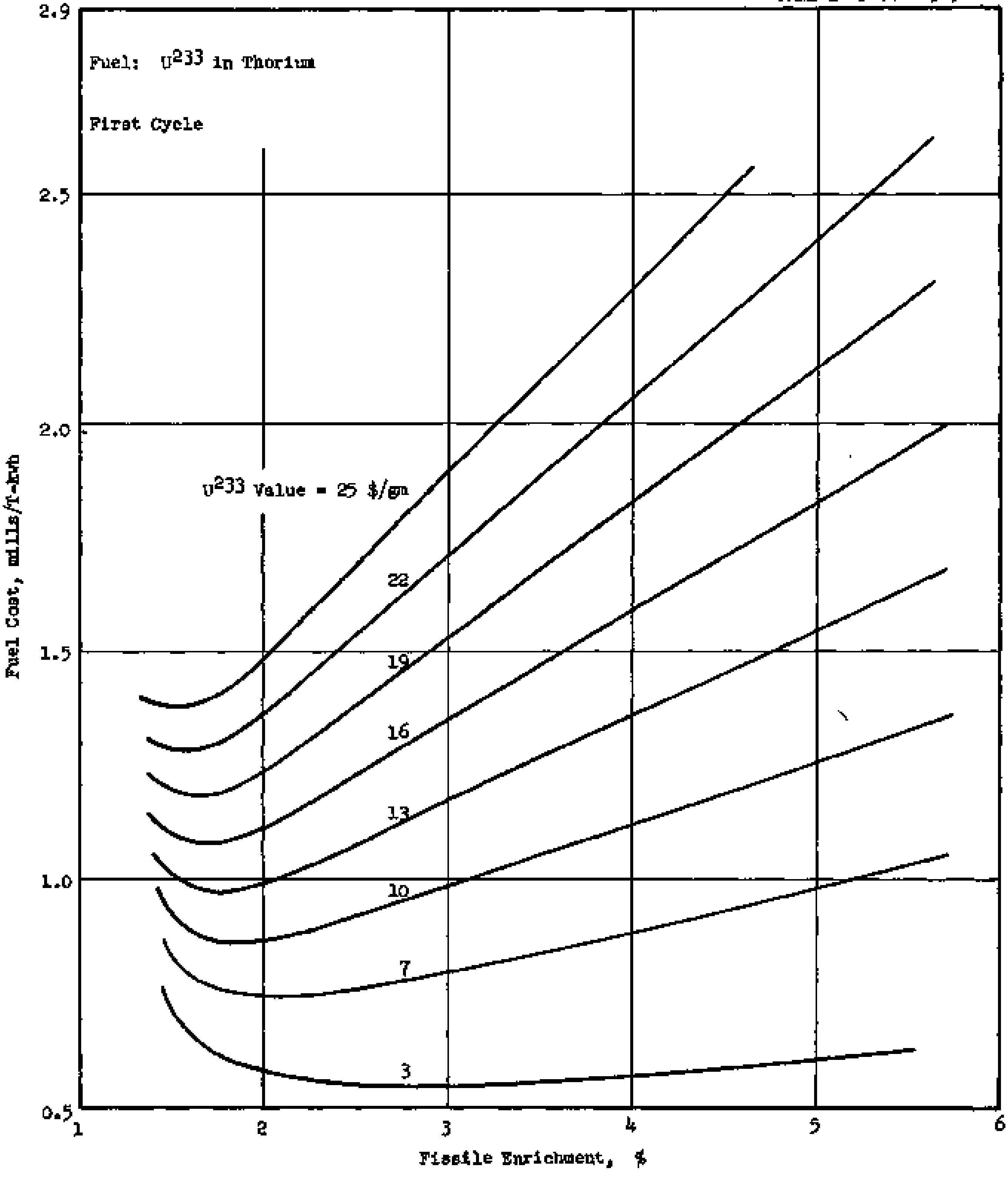

Fig. 4E. Fuel Cost Vs. Fissile Enrichment for GCR-II.

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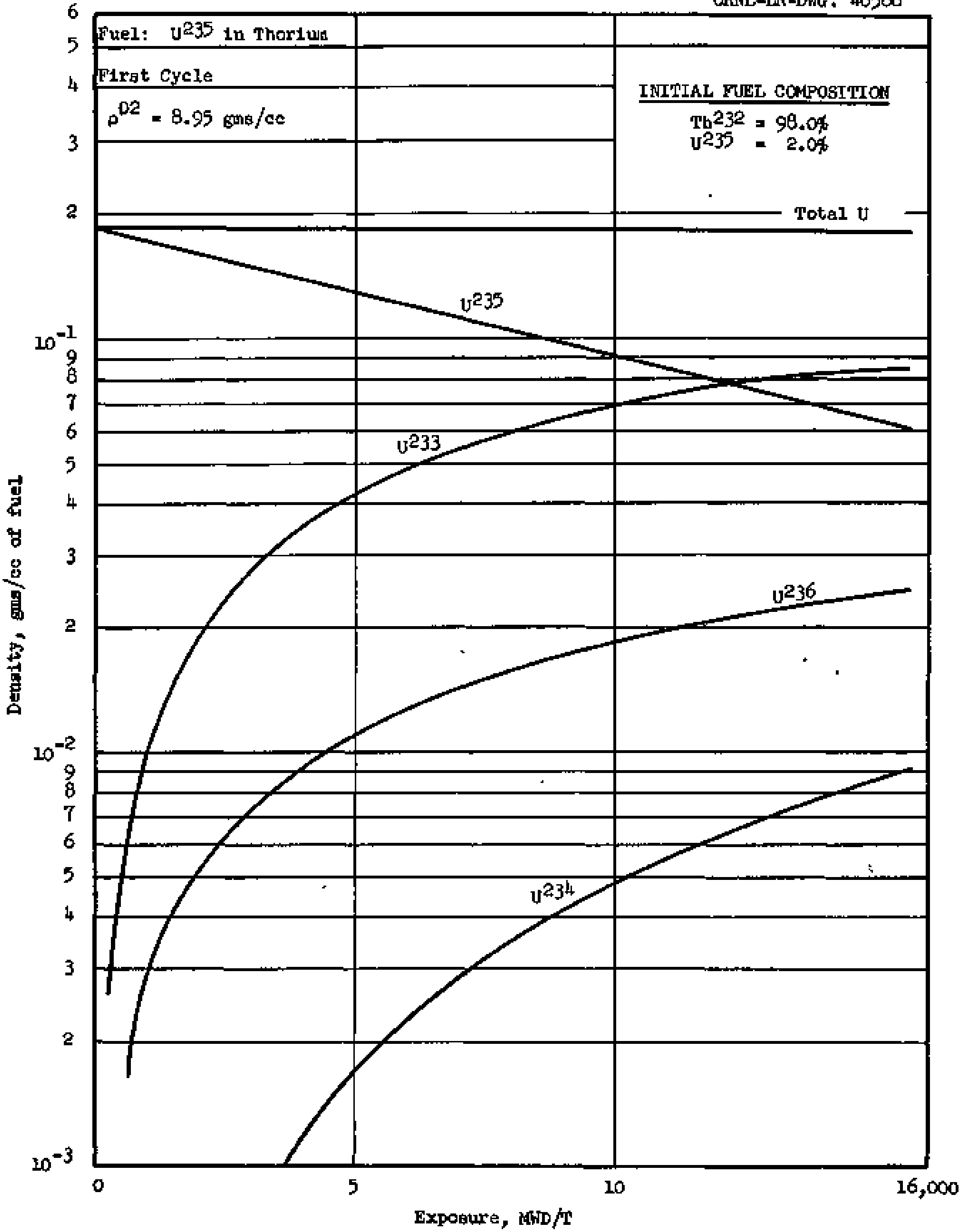

Fig. 5E. Fuel Isotopic Densities Vs. Exposure for GCR-II.

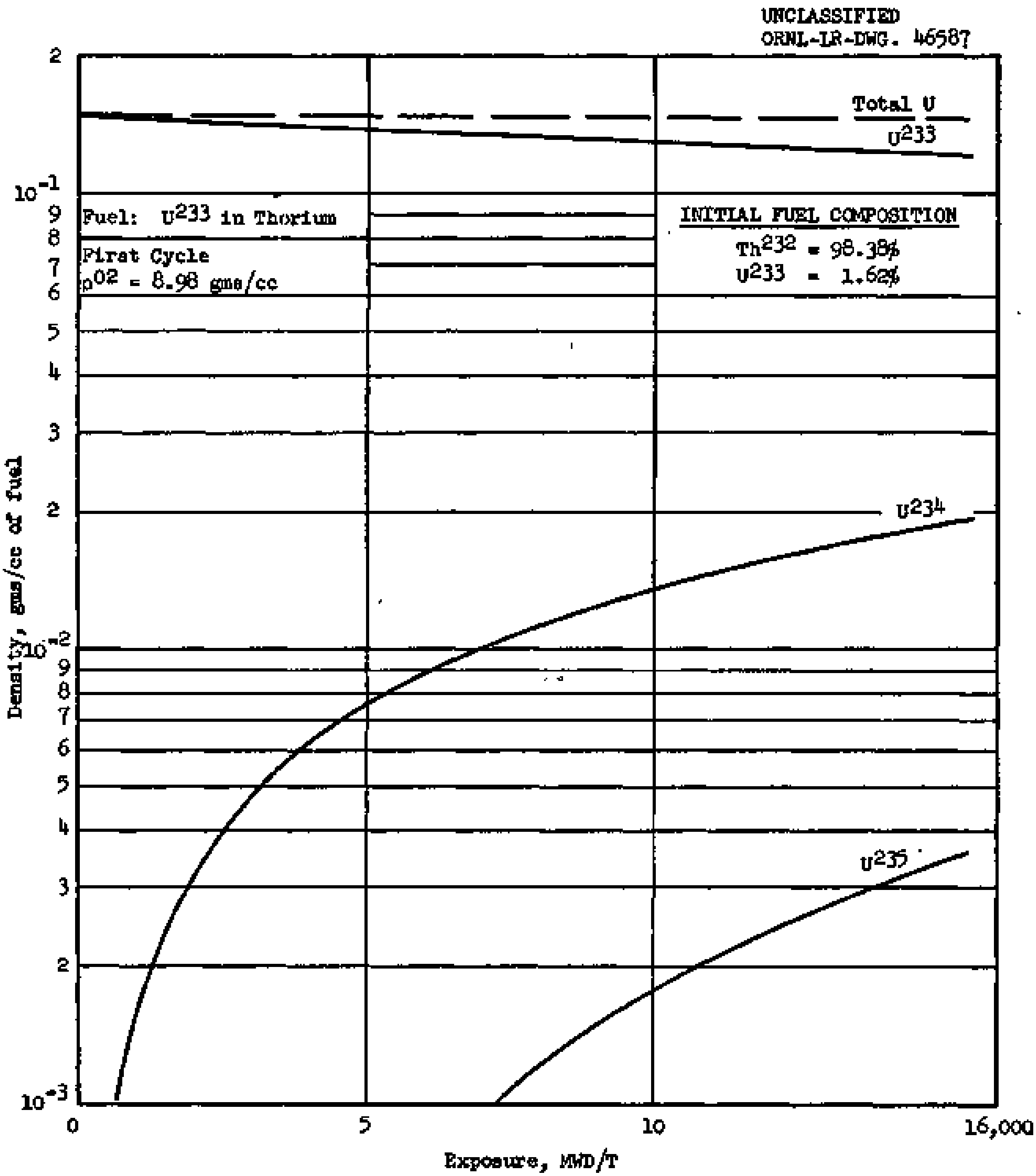

Fig. 6E. Fuel Isotopic Densities Vs. Exposure for GCR-II.

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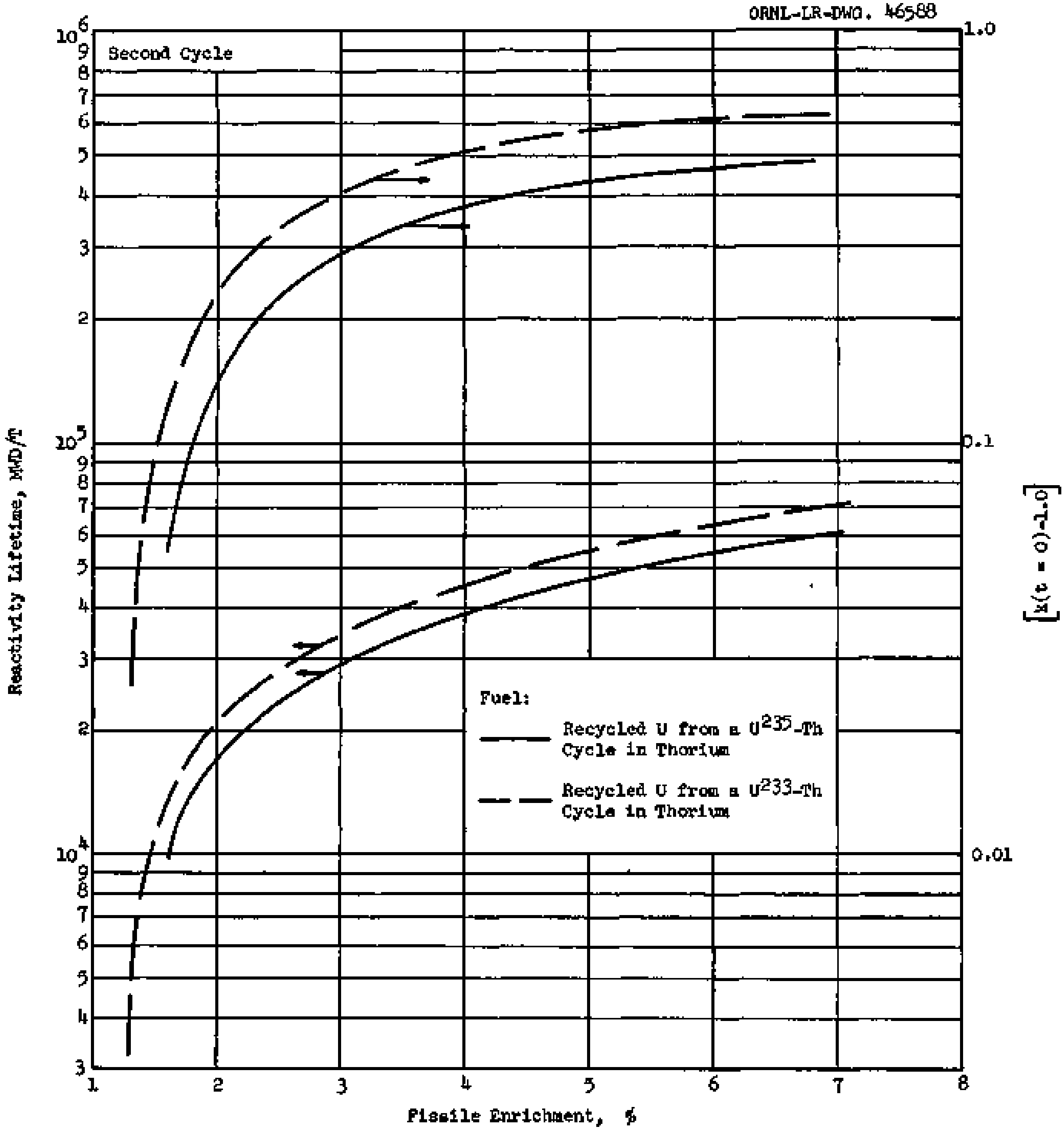

Fig. 7E. Reactivity Lifetime and Initial Reactivity Vs. Fissile Enrichment for GCR-II.

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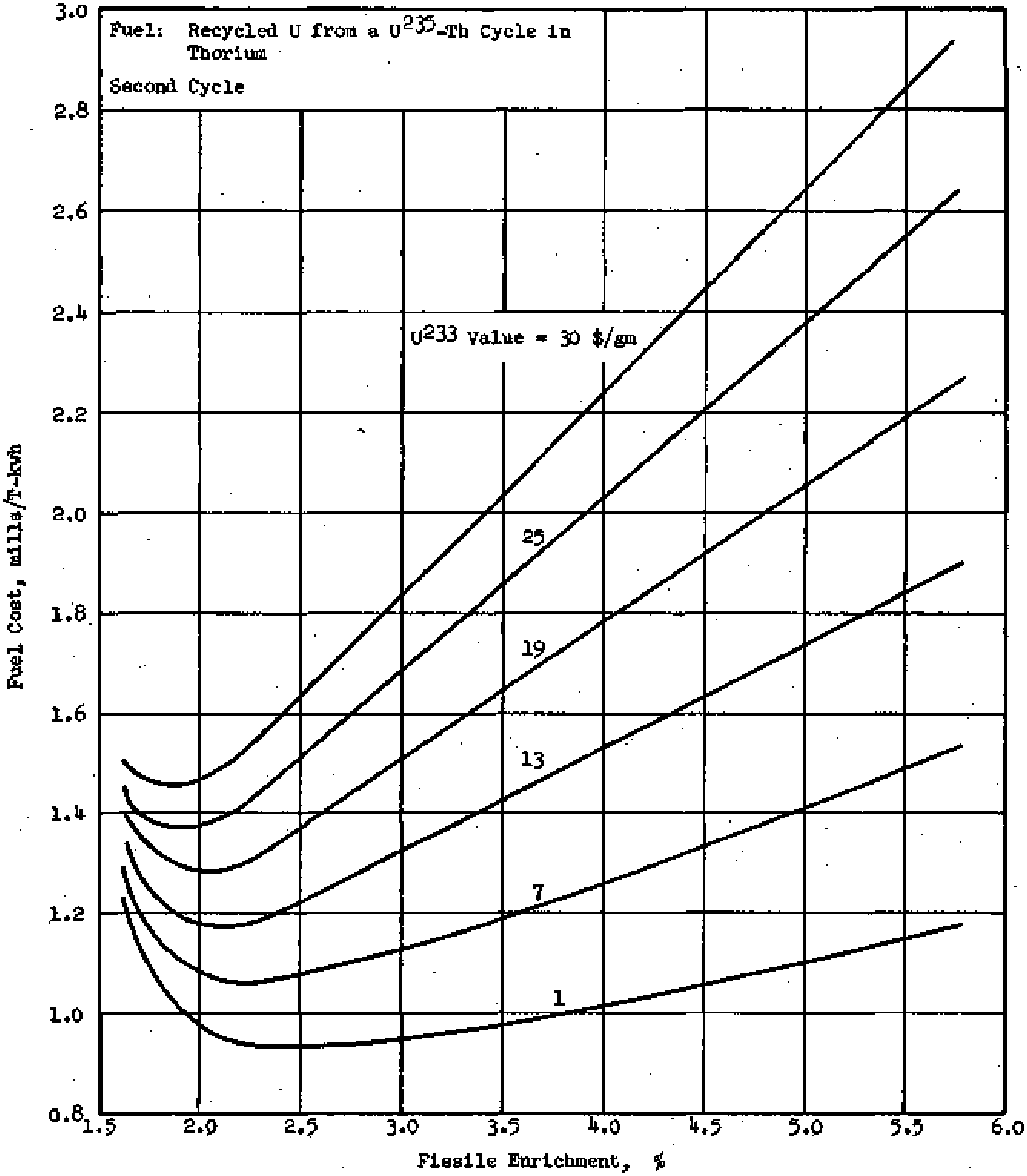

Fig. 8E. Fuel Cost Vs. Fissile Enrichment for GCR-II.

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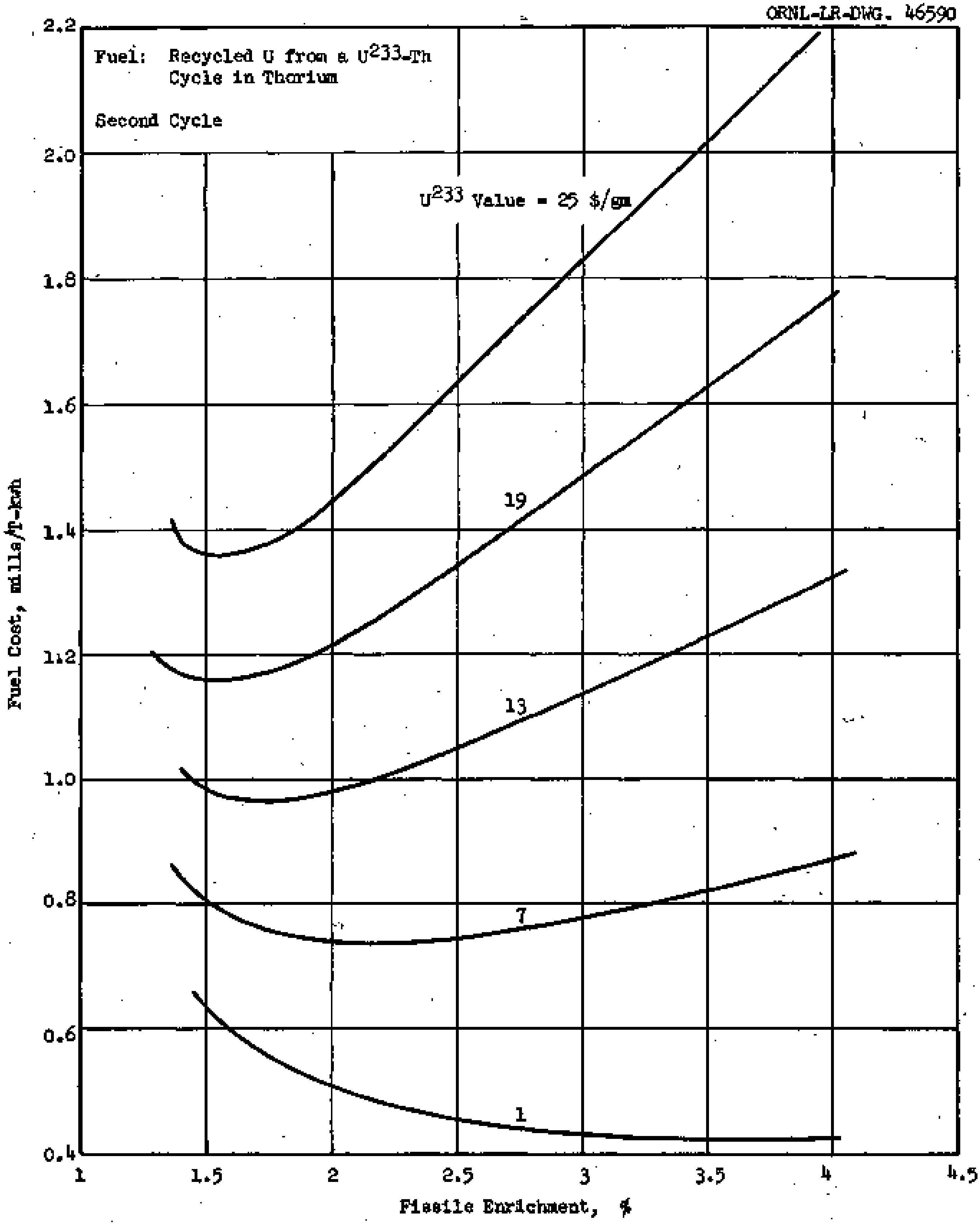

Fig. 9E. Fuel Cost Vs. Fissile Enrichment for GCR-II.

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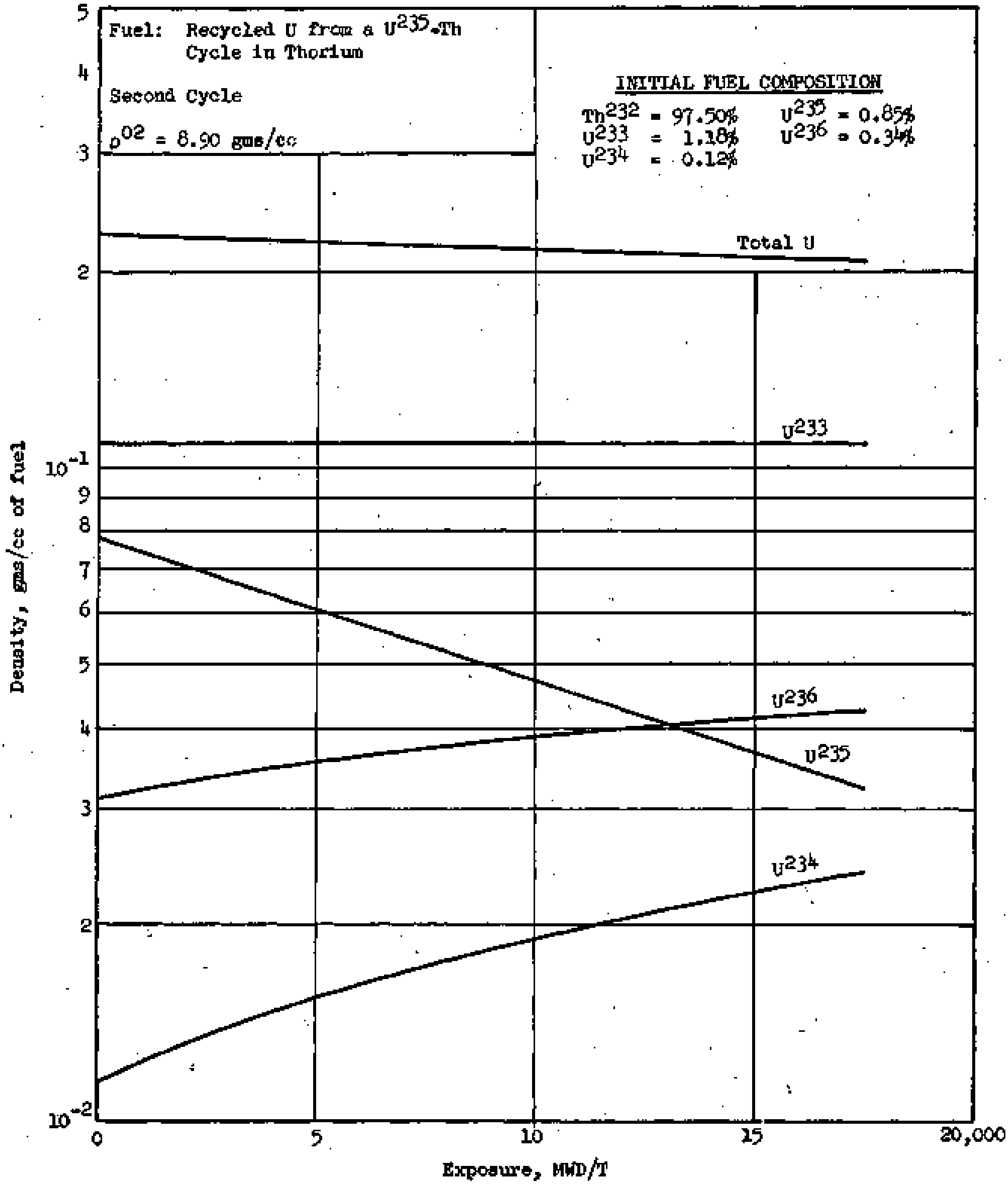

Fig. 10E. Fuel Isotopic Densities Vs. Exposure for GCR-II.

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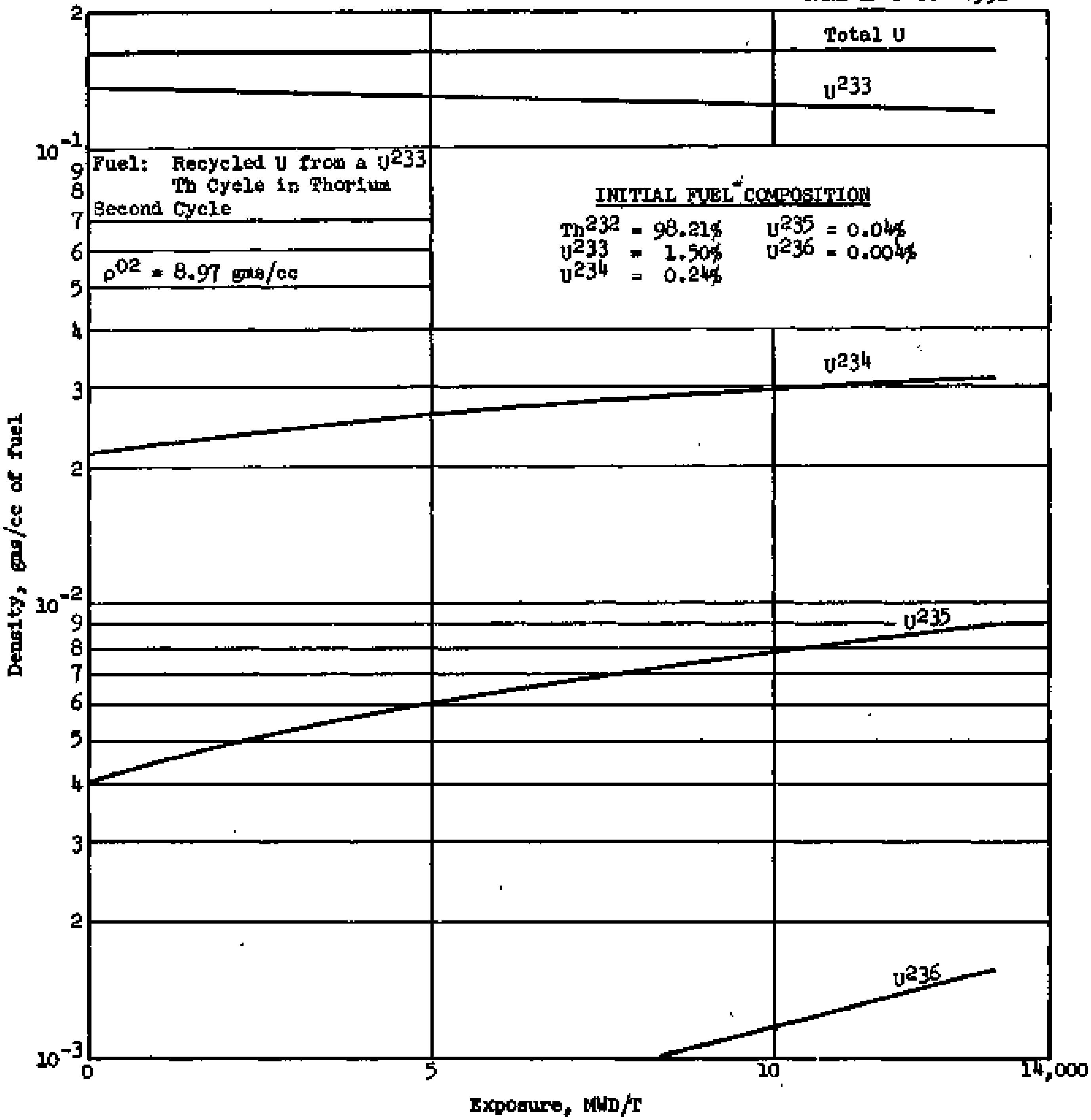

Fig. 11E. Fuel Isotopic Densities Vs. Exposure for GCR-II.

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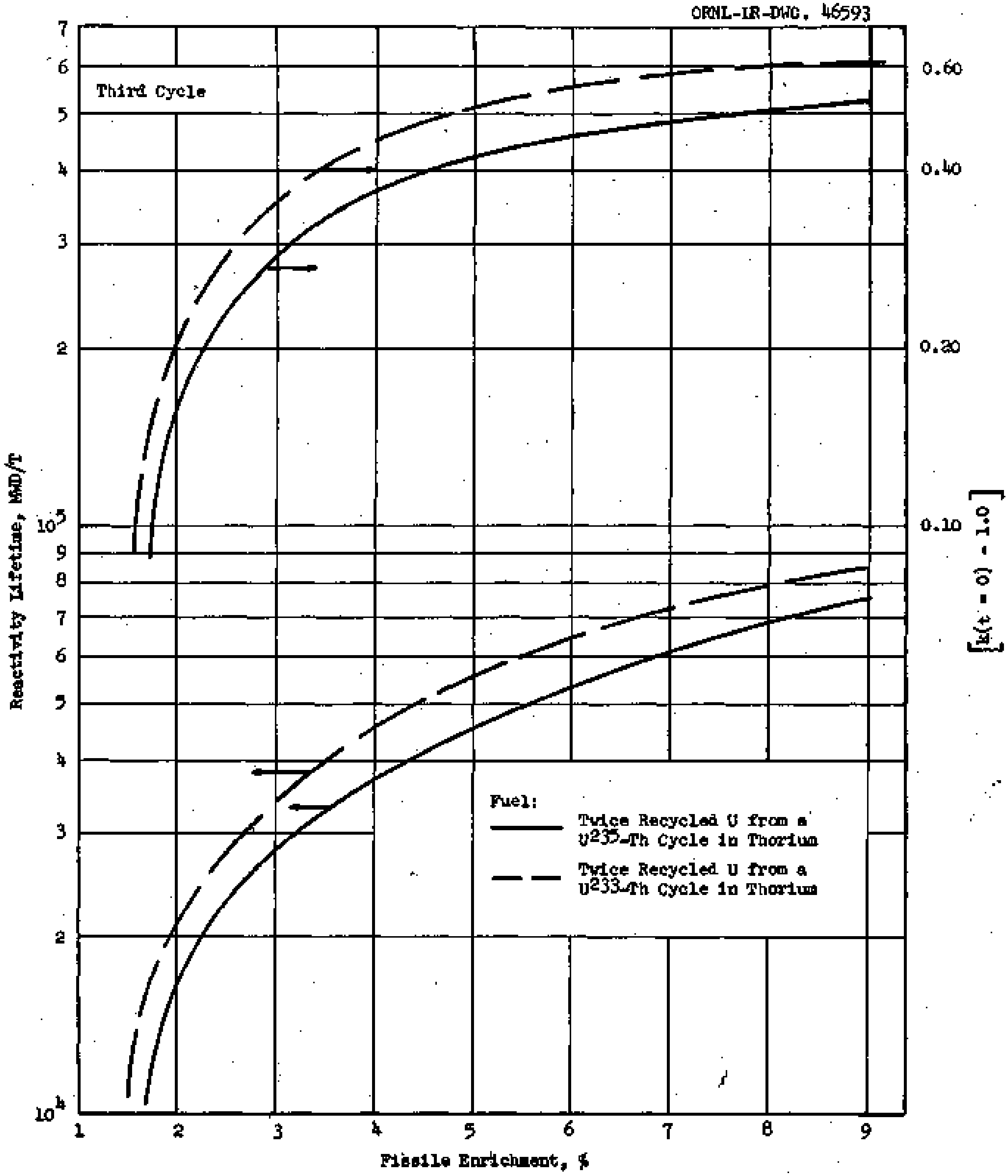

Fig. 12E. Reactivity Lifetime and Initial Reactivity Vs. Fissile Enrichment for GCR-II.

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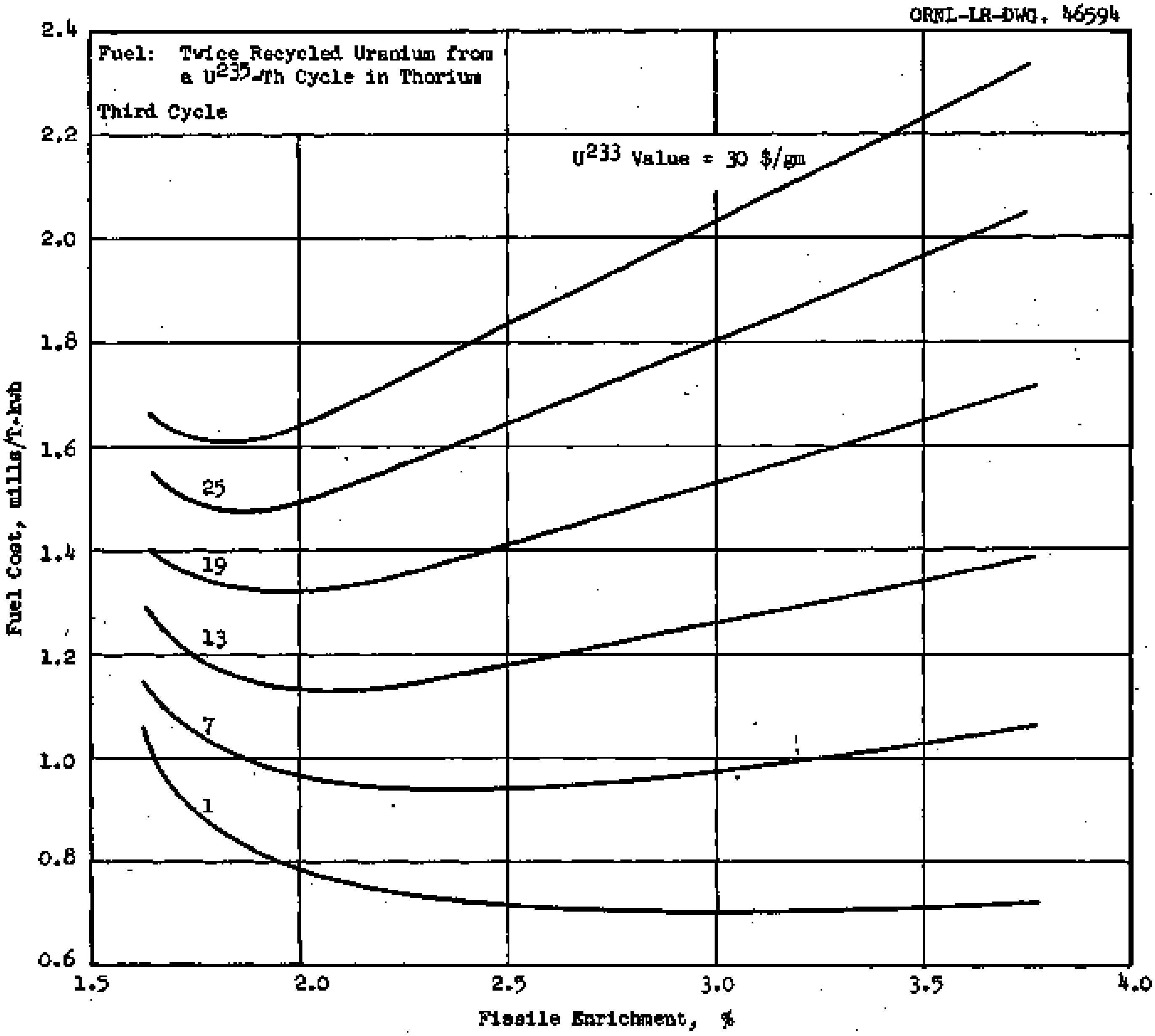

Fig. 13E. Fuel Cost Vs. Fissile Enrichment for GCR-II.

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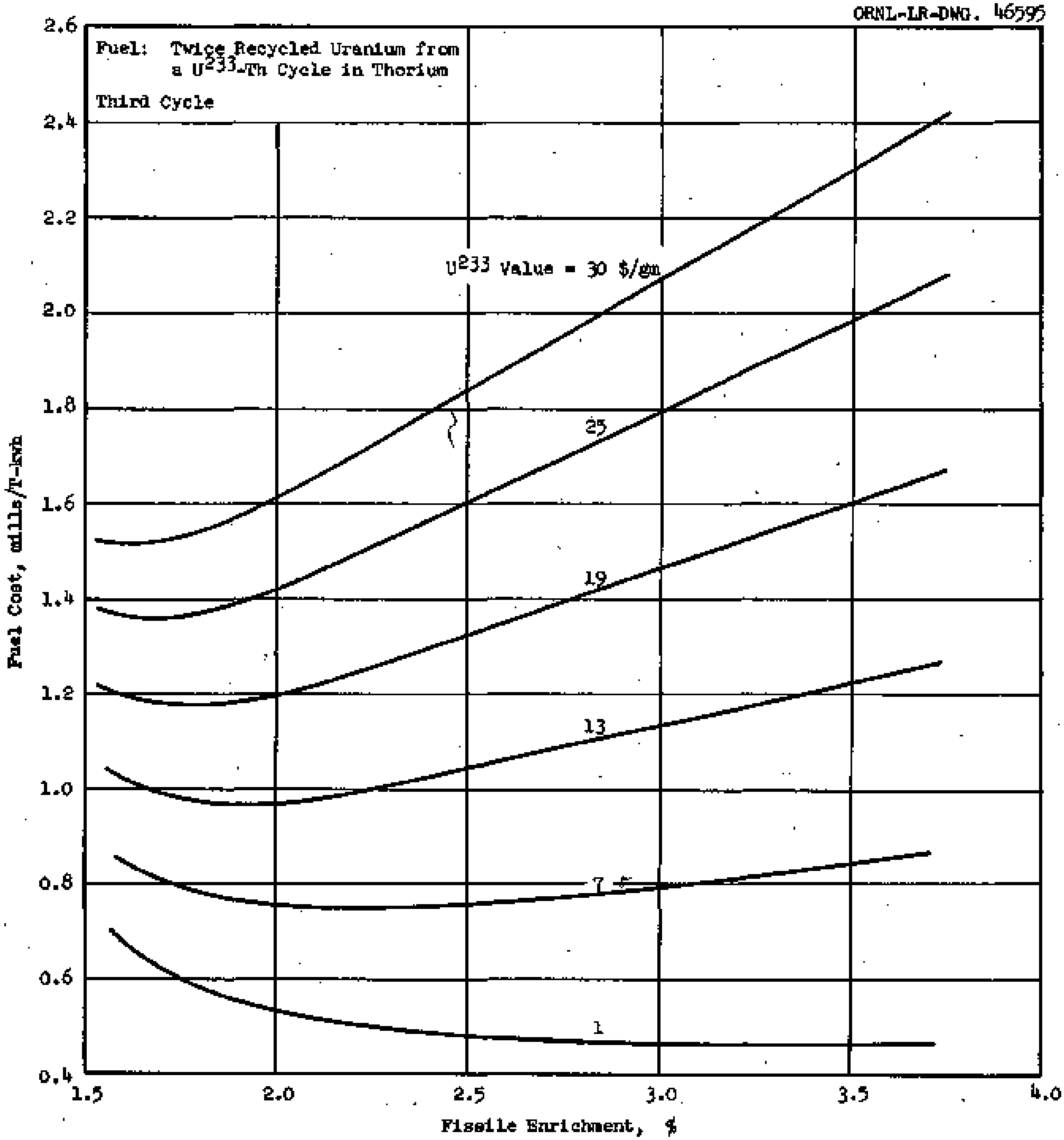

Fig. 14E. Fuel Cost Vs. Fissile Enrichment for GCR-II.

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ORNL-LR-DWG. 46596

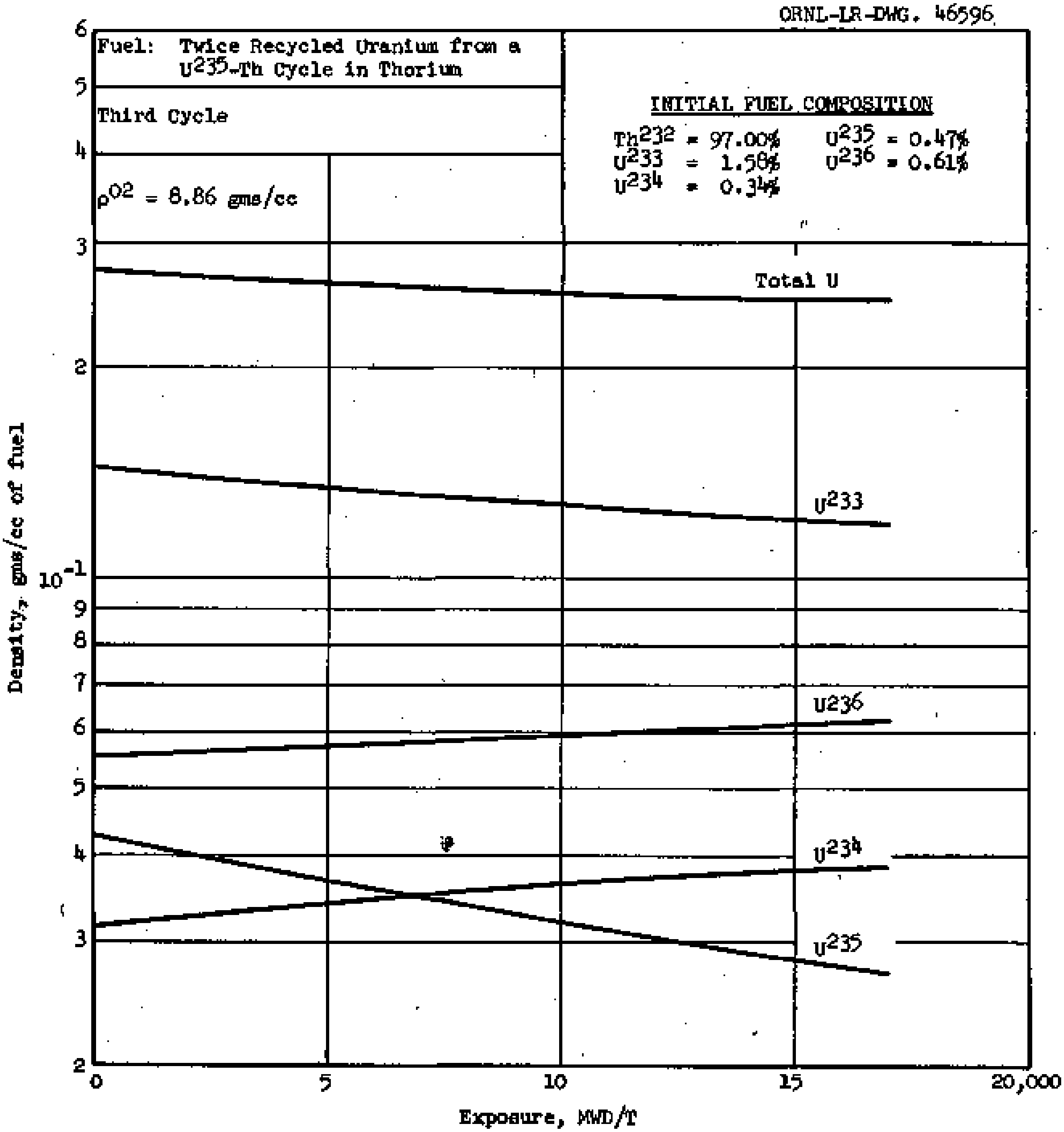

Fig. 15E. Fuel Isotopic Densities Vs. Exposure for GCR-II.

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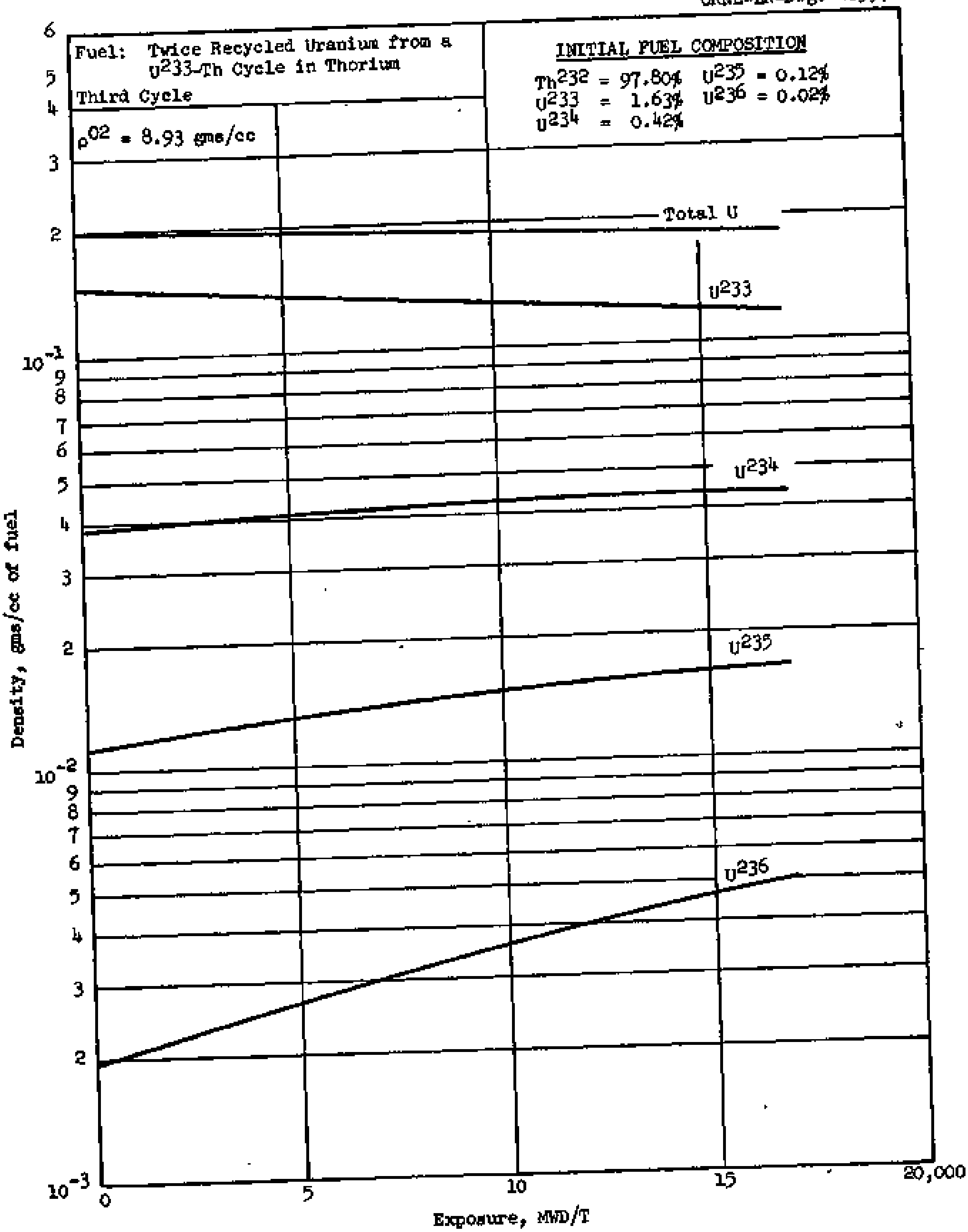

Fig. 162. Fuel Isotopic Densities Vs. Exposure for GCR-II.

Distribution

1. L. G. Alexander
2. S. E. Beall
3. M. Benedict (MIT)
4-8. L. L. Bennett
9. E. P. Blizard
10. E. G. Bohlmann
11. R. B. Briggs
12. F. R. Bruce
13. W. D. Burch
14. A. D. Callihan
15. C. E. Center
16. R. A. Charpie
17. R. D. Cheverton
18. H. C. Claiborne
19. E. L. Compere
20. F. L. Culler
21. L. G. Epel
22. W. K. Ergen
23. D. E. Ferguson
24. T. B. Fowler
25. W. R. Gall
26. E. H. Gift (AEC, Washington)
27. J. C. Griess
28. E. Guth
29. C. E. Guthrie
30. P. N. Haubenreich
31. J. P. Hammond
32. H. W. Hoffman
33-37. S. Jaye
38. G. H. Jenks
39. W. H. Jordan
40. P. R. Kasten
41. J. F. Kaufmann (AEC, Washington)
42. J. A. Lane
43. S. Levin (K-25)
44. M. P. Lietzke
45. L. E. Link (ANL)
46. R. N. Lyon
47. H. G. MacPherson
48. H. F. McDuffie
49. L. H. McEwen (HAPO)
50. R. L. Moore
51. C. W. Nestor
52. F. S. Patton (Y-12)
53. A. M. Perry
54. B. E. Prince
55. M. W. Rosenthal
56. H. C. Savage
57. M. J. Skinner
58. I. Spiewak
59. R. Stoughton
60. J. A. Swartout
61. D. G. Thomas
62. M. L. Tobias
63. J. R. Triplett (HAPO)
64-68. J. M. Vallance (AEC, Wash.)
69. D. R. Vondy
70. C. E. Winters
71. A. M. Weinberg
72. J. Ulhmann
73. REED Library
74-75. Central Research Library
76-77. Document Reference Library
78-92. Laboratory Records
93. ORNL-RC
94-108. TISE