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FUEL CYCLES FOR AN 800 Mw(t) PEBBLE-BED REACTOR

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ABSTRACT

Reactivity lifetime calculations have been made for an 800 Mw(t) pebble-bed reactor on the basis of a batch-fueling cycle, a once-through equilibrium cycle, and a graded-exposure equilibrium cycle. The maximum lifetime, obtained with the graded-exposure equilibrium cycle, was 1.41 fissions per initial fissionable atom. In this case the conversion ratio was 0.62 and the neutron leakage from the core was 0.078. The same fuel composition gave 1.29 fissions per initial fissionable atom on a once-through equilibrium cycle and 0.92 fissions per initial fissionable atom on a batch cycle.

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Introduction

An ORNL design for a pebble-bed reactor power plant was issued in December 1960.[1] At that time it had not been possible to study reactivity lifetimes for the reactor. Hence, there was considerable uncertainty regarding fuel composition, conversion ratio, reactivity lifetime, and fuel management. Further calculations have now been done to provide some of this information.

The characteristics of the reactor which affect the present study are as follows. The core is 12.4 ft high by 20.7 ft in diameter. A 3-ft-thick reflector surrounds the core on all sides. It is assumed that the core has a uniform void fraction of 0.39, the radial reflector a void fraction of 0.10, and the axial reflector a void fraction of 0.20. At 100% density it is assumed that the graphite has a density of 1.65 g/cm^3 (0.0828 x 10^{24} atoms/cm^3). The fission power is 800 Mw, giving a power density of 6.77 w/cm^3 of core.

The criticality calculations were all made with one-dimensional, 27-group diffusion theory. The axial dimension was represented explicity, while the radial dimension was accounted for by a buckling term. The burnup equations for the fuel were solved explicitly in each case, starting from a feed material containing various proportions of graphite, U^{235}, and Th^{232}. Concentrations of the heavy isotopes from Th^{232} through Np^{237} were computed, and the fission-product poisoning was allowed for as recommended by Nephew.[2] For the equilibrium cycles an iteration was performed between the criticality calculation and the burnup calculation to obtain a consistent simultaneous solution.

Three different fuel management schemes were considered. The first, the once-through equilibrium cycle, requires that the fuel be fed continuously at the top of the core and discharged at the bottom with no

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[1] A. P. Fraas et al., Design Study of a Pebble-Bed Reactor Power Plant, ORNL CF-60-12-5, Revised (May 11, 1961).

[2] E. A. Nephew, Thermal and Resonance Absorption Cross Sections of the U^{233}, U^{235}, and Pu^{239} Fission Products, ORNL-2869 (Jan. 18, 1960).

mixing. Fuel removed from the bottom of the core is not used again as feed. The feed rate is determined by criticality considerations, i.e., for a given feed composition there is only one feed rate which will always maintain the reactor critical without the use of control poisons. It was assumed in these calculations that the nuclide compositions are not a function of radial position. Since the radial power distribution is quite flat, and the ball flow may be partially controllable, this should not be a bad assumption. For calculational purposes the core was divided axially into twelve regions. In the burnup calculation the flux was held constant within a region, while in the criticality calculation the nuclide concentrations were held constant within a region at their average values.

In the second fuel management scheme, the graded-exposure equilibrium cycle, the fuel within the core is continuously mixed and is withdrawn at the terminal exposure determined by criticality. This condition is approximated in a pebble-bed reactor by withdrawing fuel from the bottom of the core and re-introducing it at the top several times before the terminal exposure is reached.

In the batch cycle the reactor is fueled entirely with fresh fuel, and the excess reactivity is offset by control poison. The control poison is reduced as required, and the fuel replaced when the reactor becomes subcritical without control poison. The calculations assumed a uniformly distributed 1/v control poison.

No recycle of reprocessed fuel was considered.

Results

The fuel residence times are shown in Figs. 1-3 for various fuel compositions. Figure 2 also gives a comparison of the three fuel management schemes. The graded-exposure equilibrium cycle always gives the greatest reactivity lifetime for a given fuel composition. The slight decrease in lifetime obtained with a once-through equilibrium cycle is associated with a greater net leakage of neutrons from the core. This leakage, in turn, comes from the uneven fission distribution, which is concentrated at the top of the core. In the batch cycle the

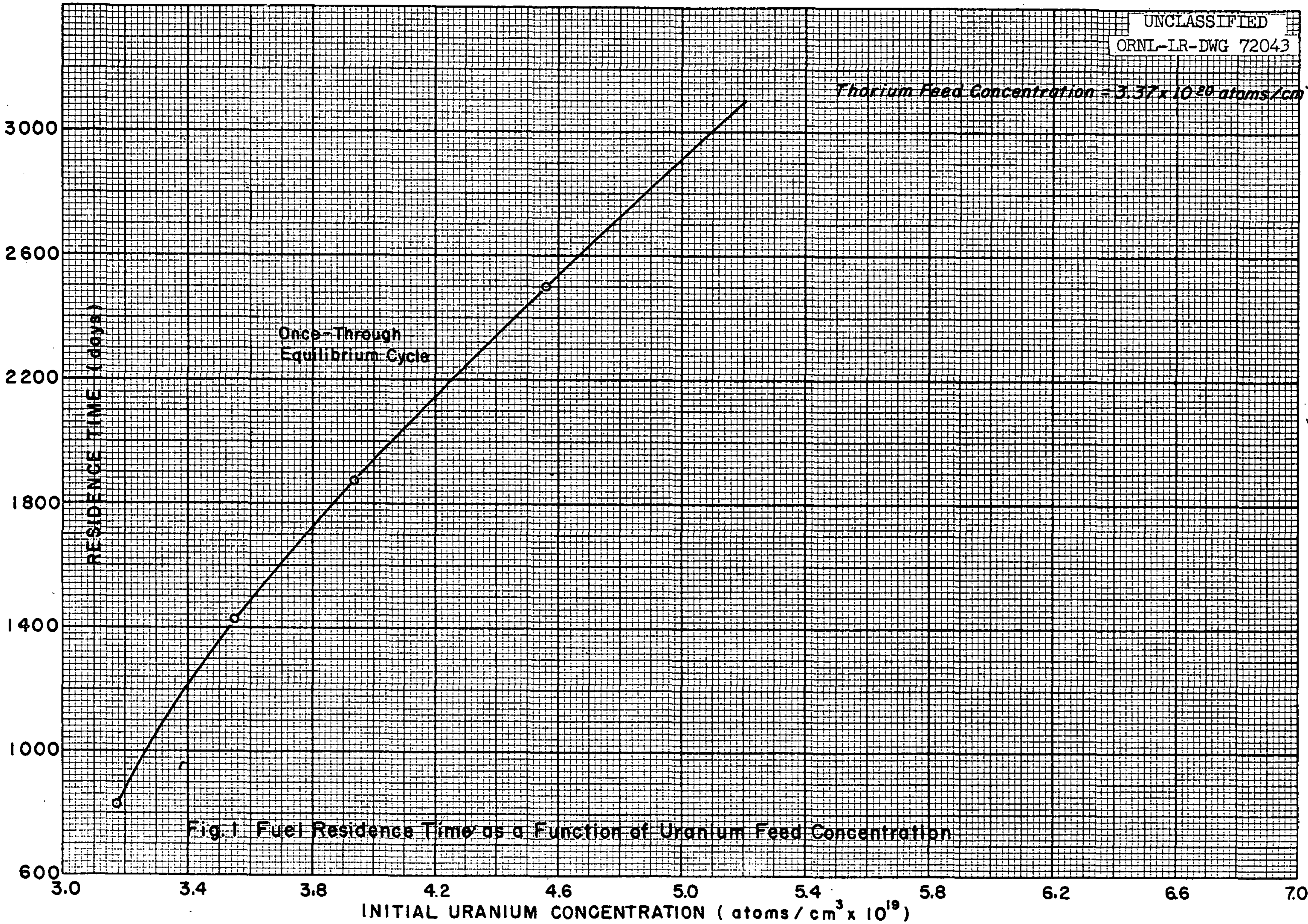

Fig. 1 Fuel Residence Time as a Function of Uranium Feed Concentration

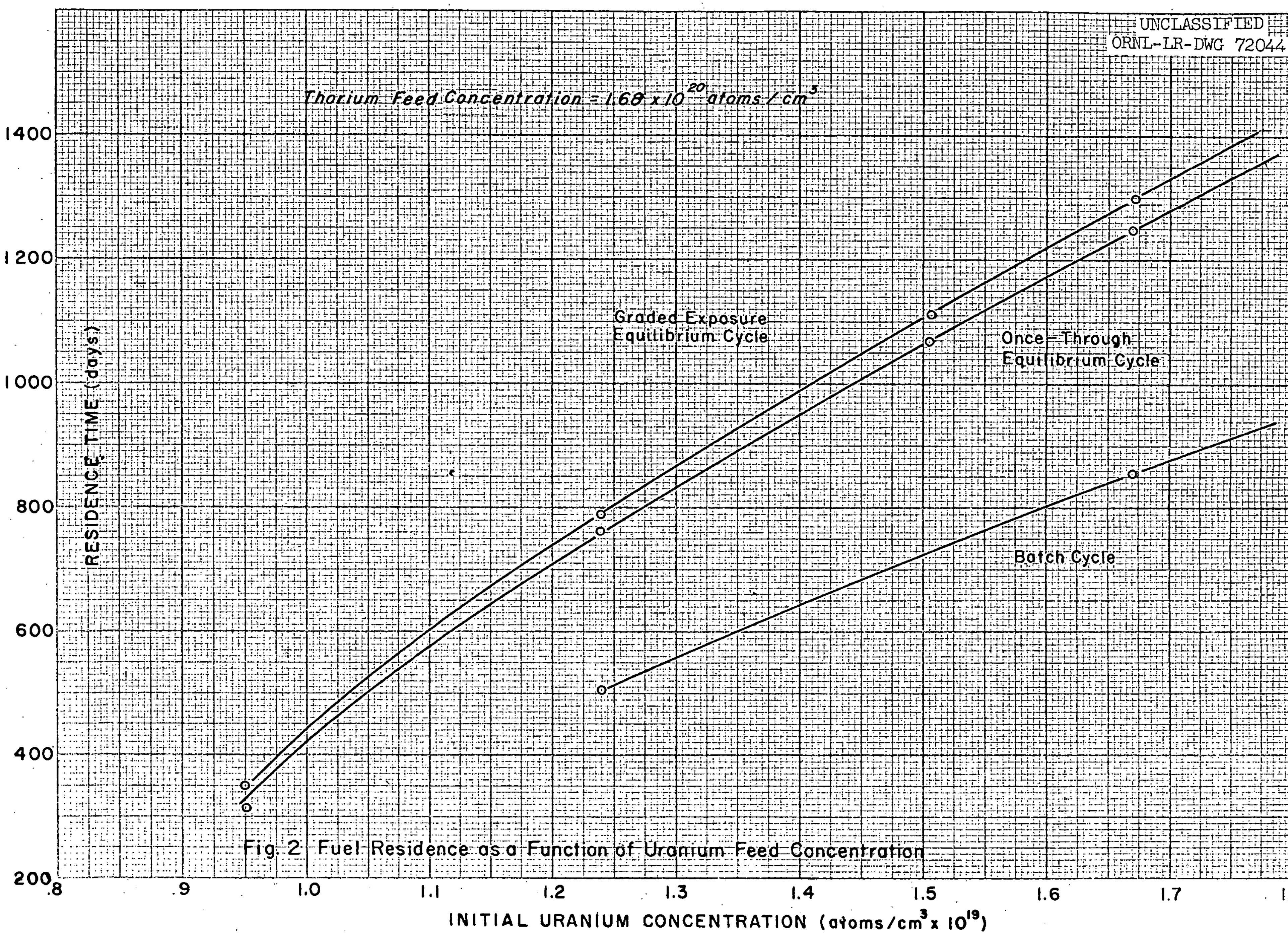

Fig. 2 Fuel Residence as a Function of Uranium Feed Concentration

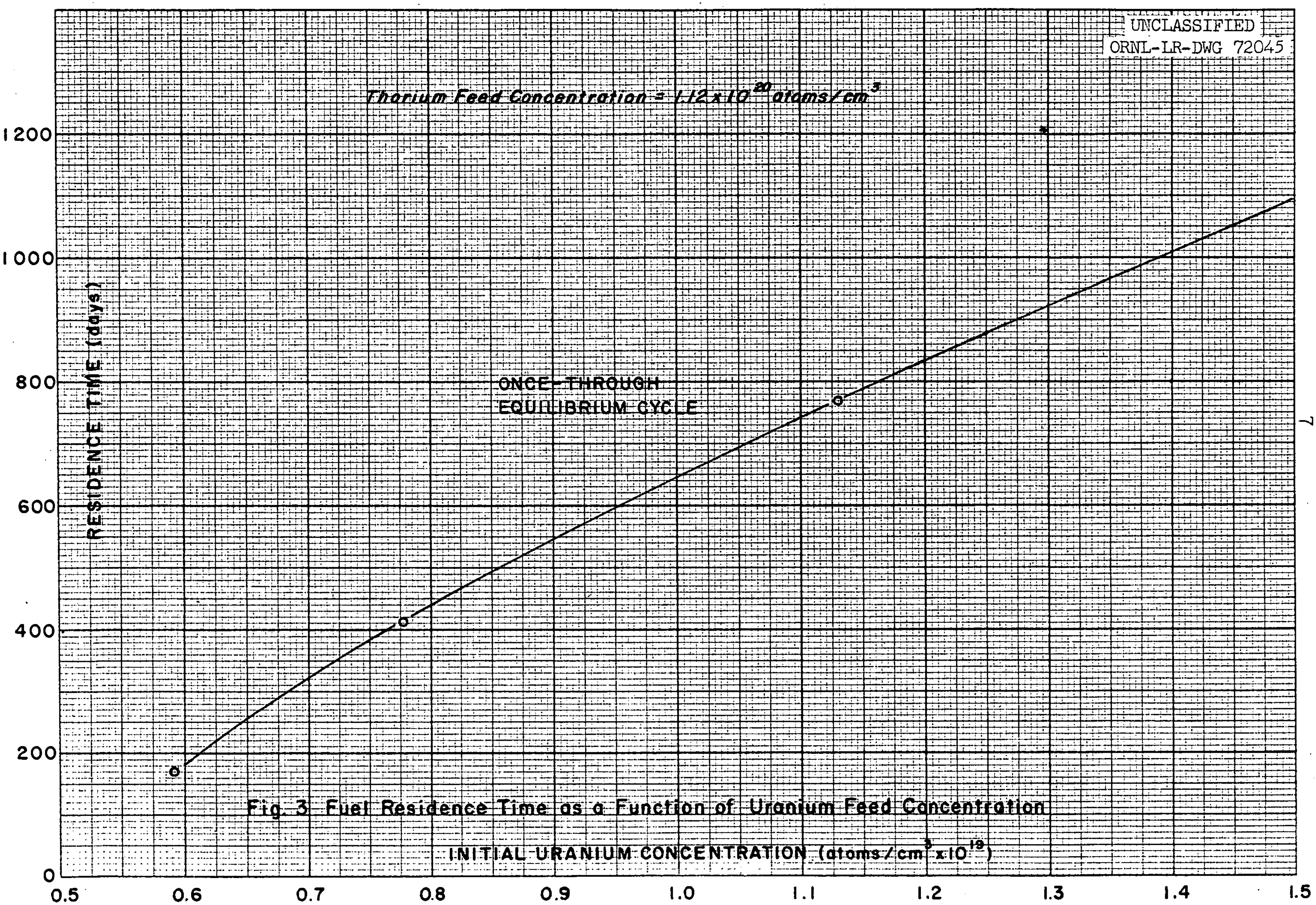

Fig. 3 Fuel Residence Time as a Function of Uranium Feed Concentration

large reduction in lifetime is attributable principally to the loss of neutrons to control poisons which does not occur in the equilibrium cycles.

The lifetimes for the once-through equilibrium cycle are replotted in Fig. 4 in units of fissions per initial fissionable atom. The highest calculated value is 1.36 fissions per initial fissionable atom with a fuel which has an initial carbon-to-uranium ratio of 3024 and an initial thorium-to-uranium ratio of 10.1. This fuel composition gives a conversion ratio of 0.60 and a core neutron leakage of 0.089. It appears that a lifetime as high as 1.45 fissions per initial fissionable atom would be obtained with a fuel having the same thorium concentration and a slightly higher uranium concentration.

For a given value of the thorium feed concentration, an increase in uranium concentration (over the range of interest) produces an increase in lifetime and a decrease in conversion ratio. Thus, in the once-through equilibrium cycle, the compositions with high uranium concentrations have a much higher fission cross section at the top of the core than at the bottom. This situation is reflected in the axial power distributions shown in Figs. 5-7. The peak-to-average power ratio corresponding to the case with greatest lifetime is 3.45.

Axial power distributions for the graded-exposure cycle are shown in Fig. 8. Since the fuel is kept mixed in this cycle, there is no power gradient from the top of the core to the bottom. However, there is at any one axial position in the core, a mixture of fuel of all ages from fresh to nearly spent. There is a corresponding local peak-to-average power ratio which is superimposed on the spatial peak-to-average power ratio. Both factors are included in the curves of Fig. 8. In comparing the curves of Fig. 8 to those of Fig. 6 (where the same fuel compositions were used) one sees that the peak-to-average power ratio is always worse in the once-through equilibrium cycle than in the graded-exposure equilibrium cycle.

Little can be done to improve the spatial distributions of the power for the graded-exposure equilibrium cycle since they are already quite flat. In the once-through equilibrium cycle, however, the

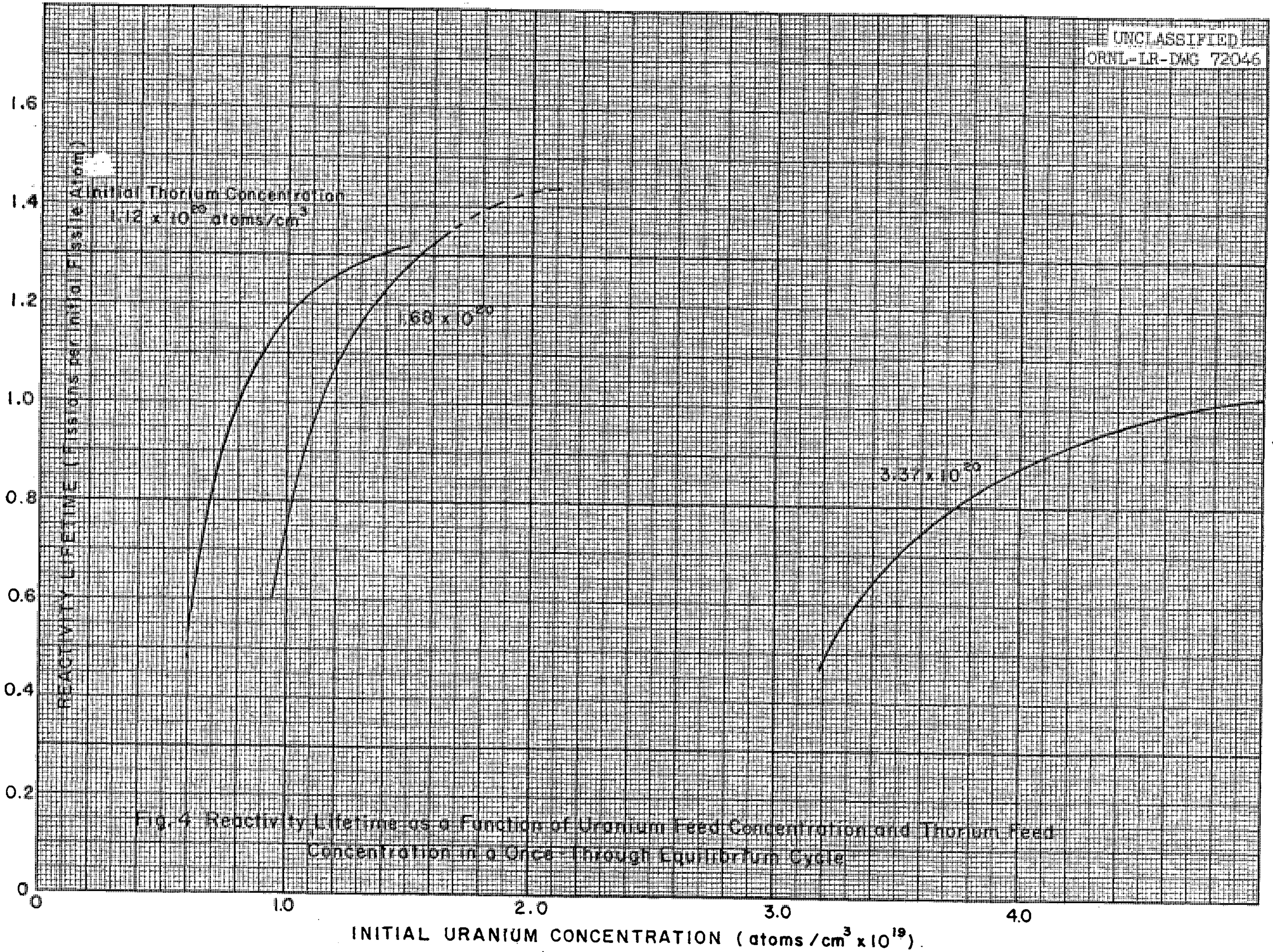

Fig. 4 Reactivity Lifetime as a Function of Uranium Feed Concentration and Thorium Feed Concentration in a Once-Through Equilibrium Cycle

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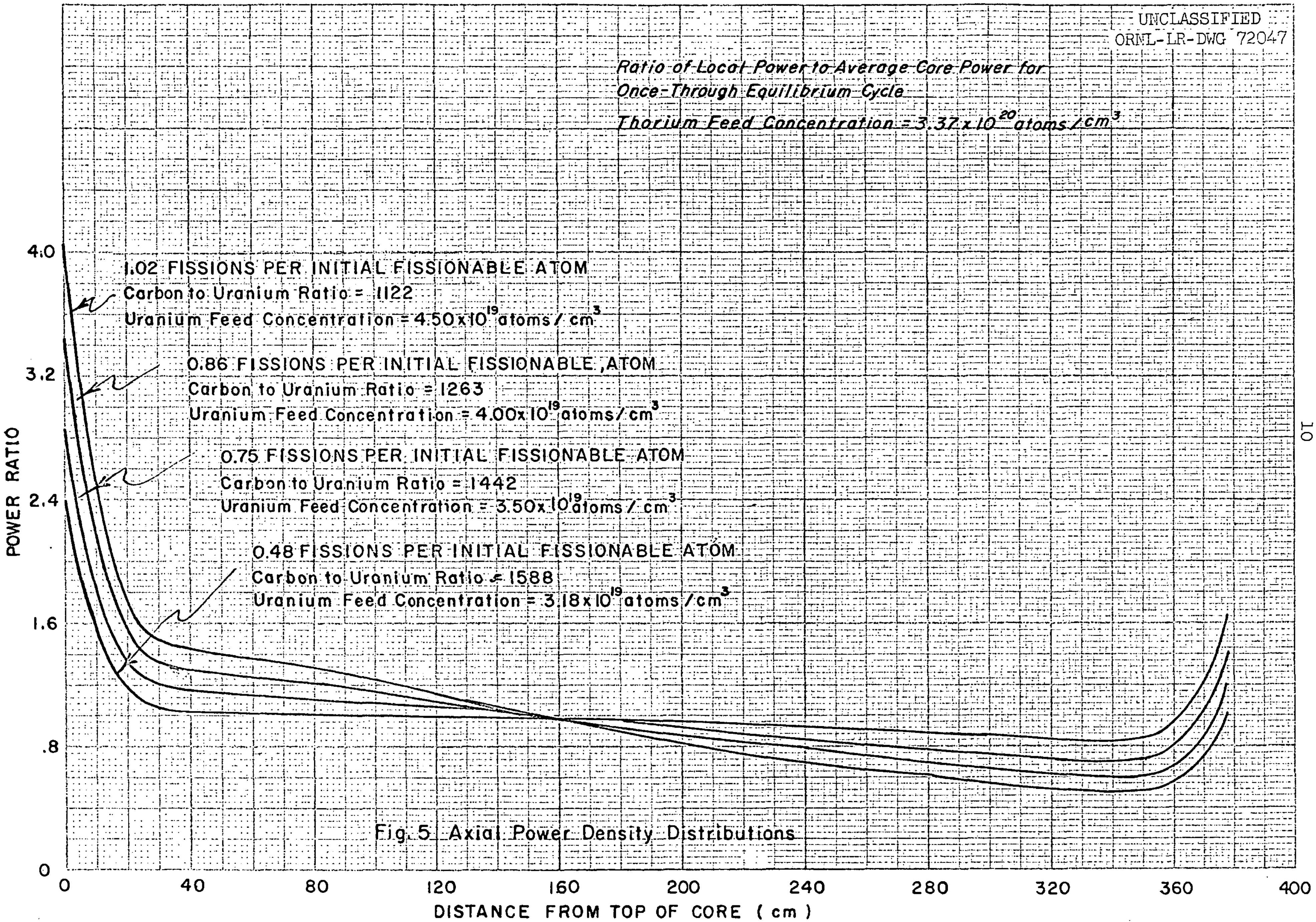

Fig. 5 Axial Power Density Distributions

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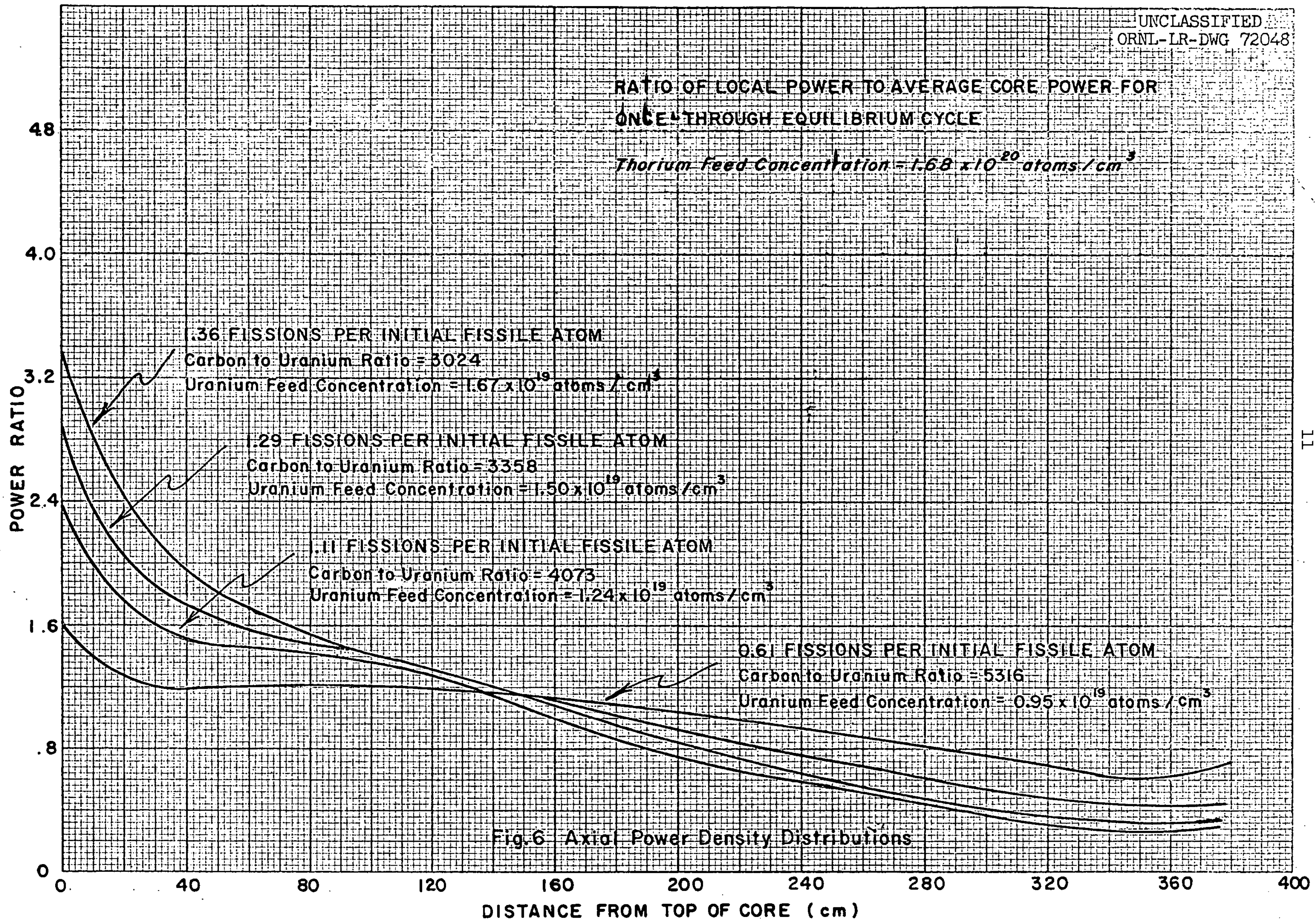

Fig. 6 Axial Power Density Distributions

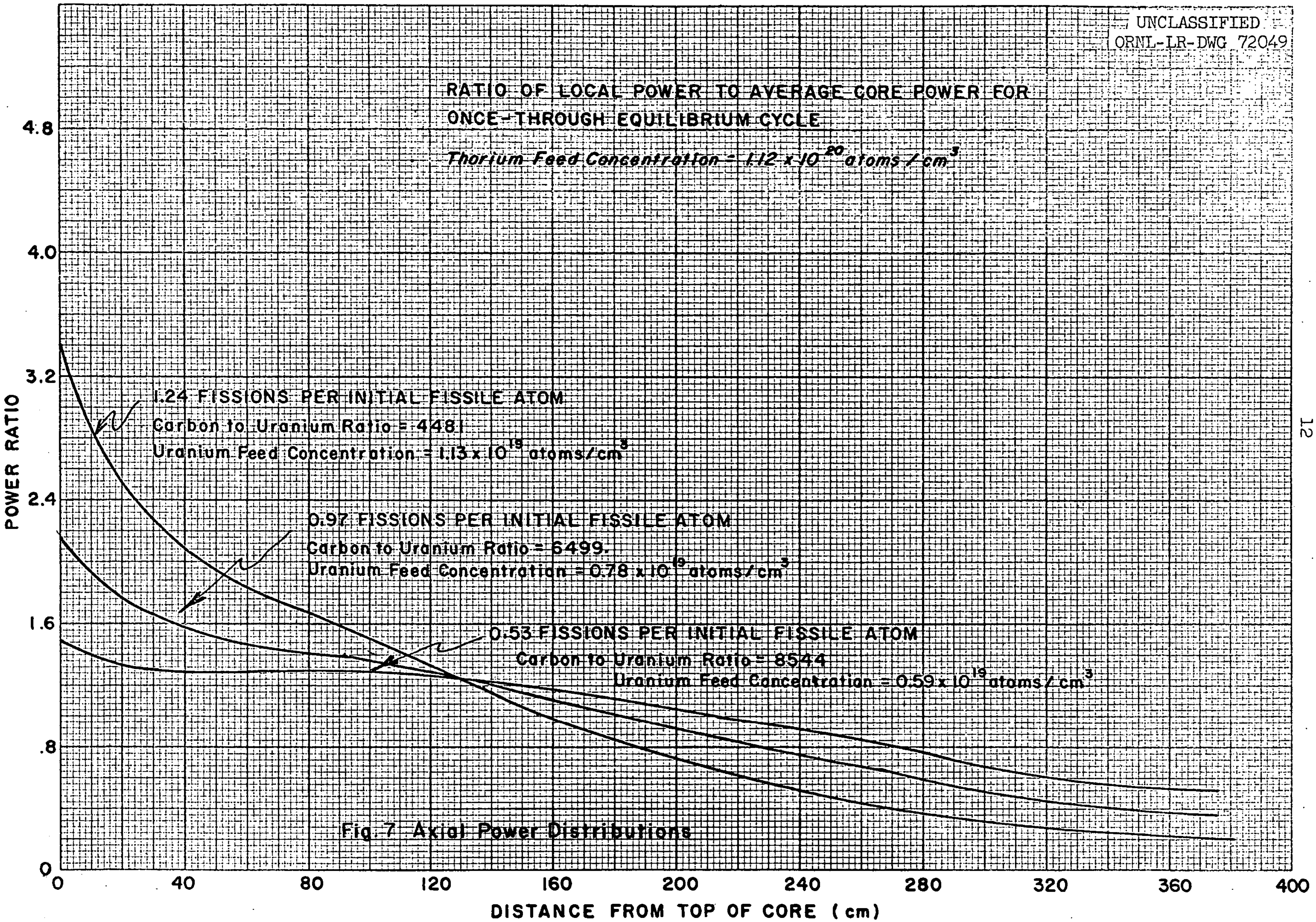

Fig. 7 Axial Power Distributions

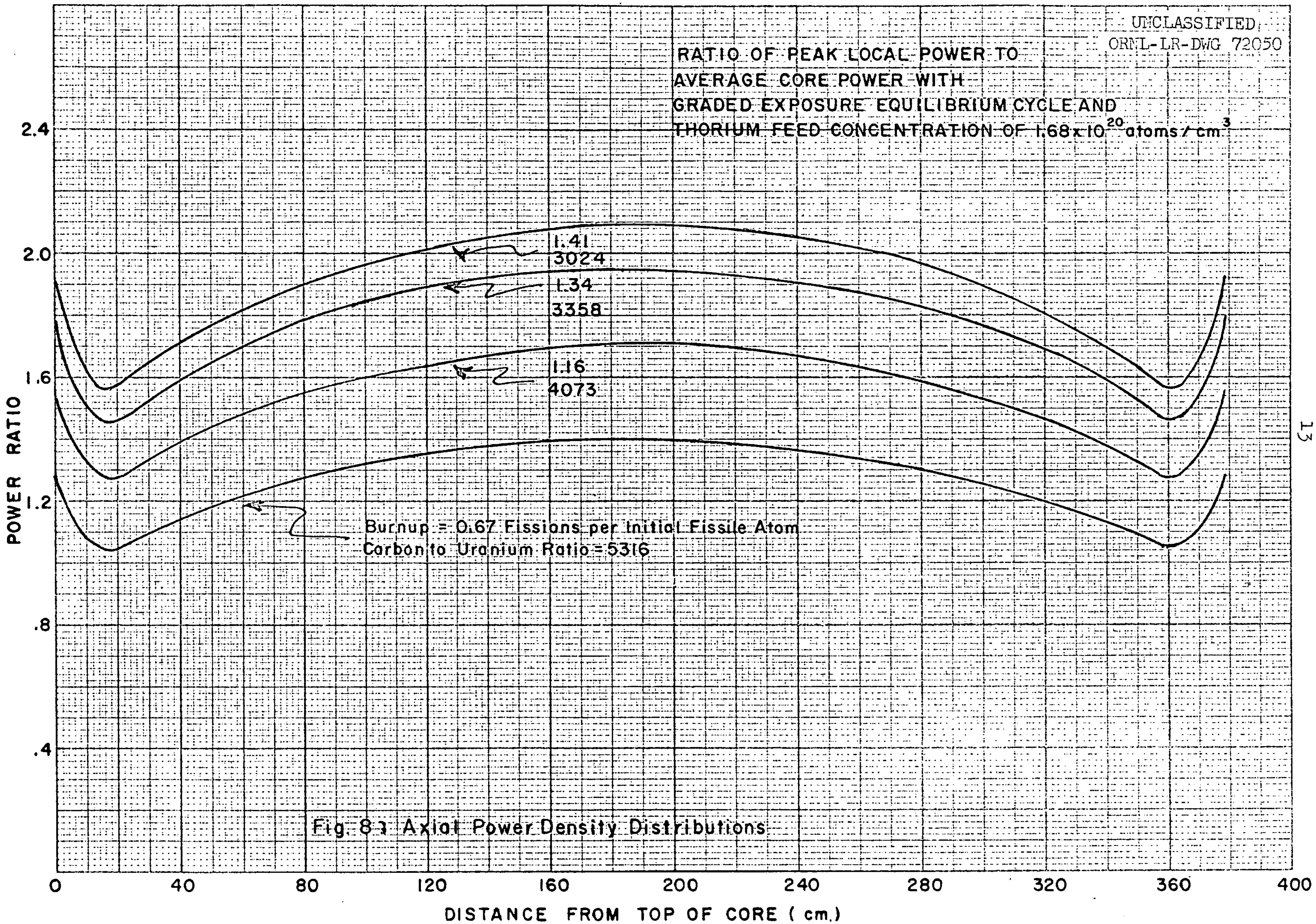

Fig. 8.3 Axial Power Density Distributions

pronounced peaking at the top of the core can be reduced by introducing a small amount of poisoning in this region. Calculations were made in which the top reflector was uniformly poisoned with a 1/v absorber in order to investigate the amount of power flattening that could be obtained. The reduction in the power peak is shown in Fig. 9 as a function of the associated reduction in reactivity lifetime. The actual power distributions with two different poison concentrations are shown in Fig. 10. It can be seen that it is possible to reduce the peak-to-average power ratio to the value of 2.10 obtained with the same fuel in a graded-exposure cycle. The reactivity lifetime is correspondingly reduced to 1.29 fissions per initial fissionable atom.

The reactivity lifetimes for the batch cycle are much lower than for the equilibrium cycle. The highest value computed was 0.92 fissions per initial fissionable atom. However, the power distributions are inherently better for a batch-loaded cycle since all of the fuel in the core at any one time has had the same residence time and nearly the same flux-exposure time. The power distributions are shown in Fig. 11 for the beginning and end of life of the batch cycle which gave 0.92 fissions per initial fissionable atom. The maximum peak-to-average power occurs at the start of life and is 1.39.

Fuel-cycle costs were obtained on the following basis:

1. Fuel fabrication costs $0.175/g of uranium plus thorium plus $1.10/ball (2-1/2-in.-diam balls were used).

2. Thorex reprocessing costs $34,000/day for 600 kg of thorium per day or 44 kg of uranium per day whichever is smaller. Head-end costs, if any, were neglected.

3. U^{235} costs $12.01/g. Recovered fuel is credited for $12.01/g of contained U^{233}, U^{235}, plus Pa^{233}.

4. Thorium costs $0.017/g.

5. Use charge on U^{235}, U^{233}, and Pa^{233} is 4.75%/year.

6. Working capital charges on other materials are 12.5%/year.

7. The thermal efficiency is 40%, and the plant factor is 80%.

The minimum cost obtained was 1.2 mills/kwhr(e). This cost occurred with the graded-exposure equilibrium cycle for the case with the highest

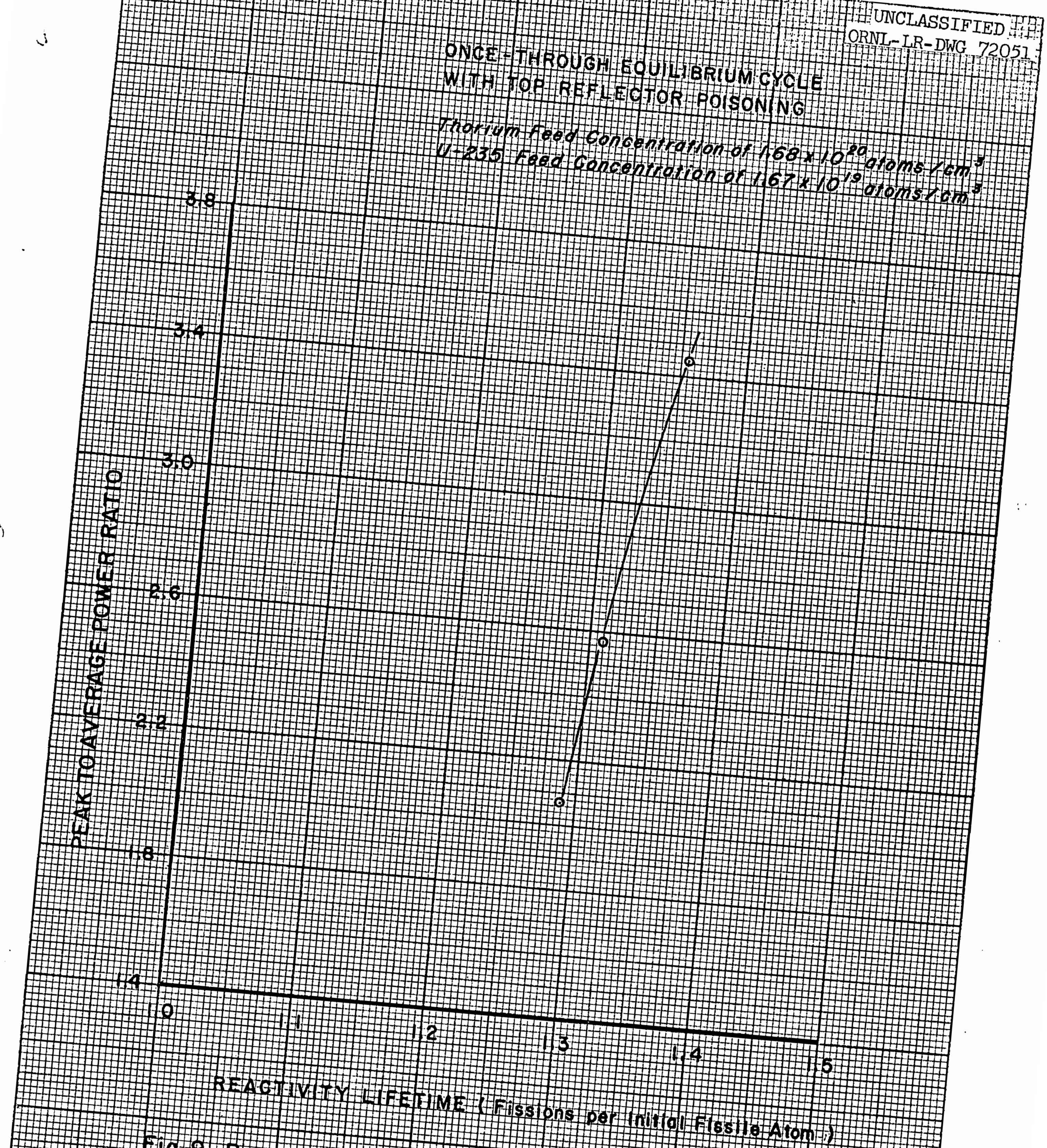

Fig. 9 Reactivity Lifetime and Power Peaking

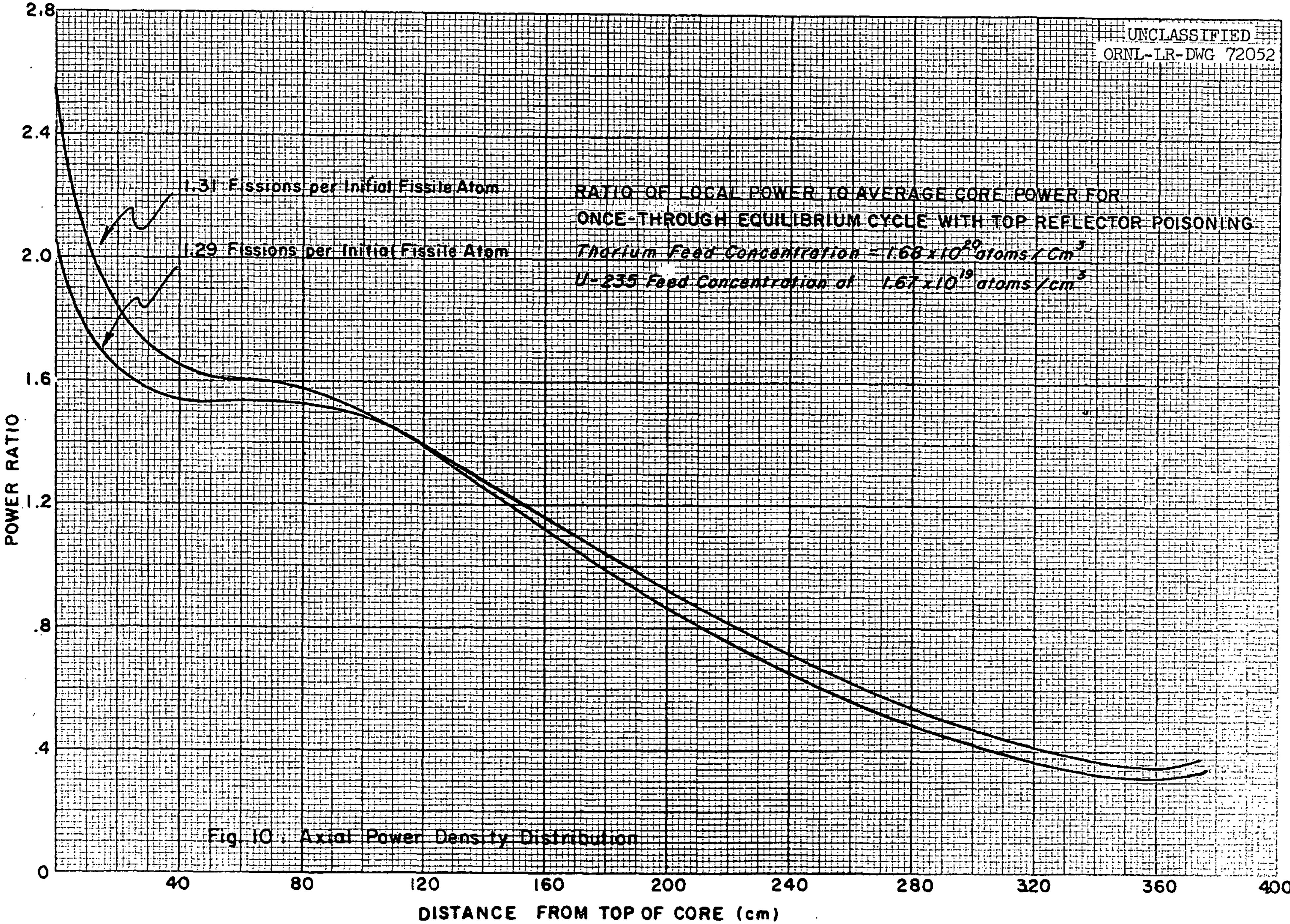

Fig. 10. Axial Power Density Distribution

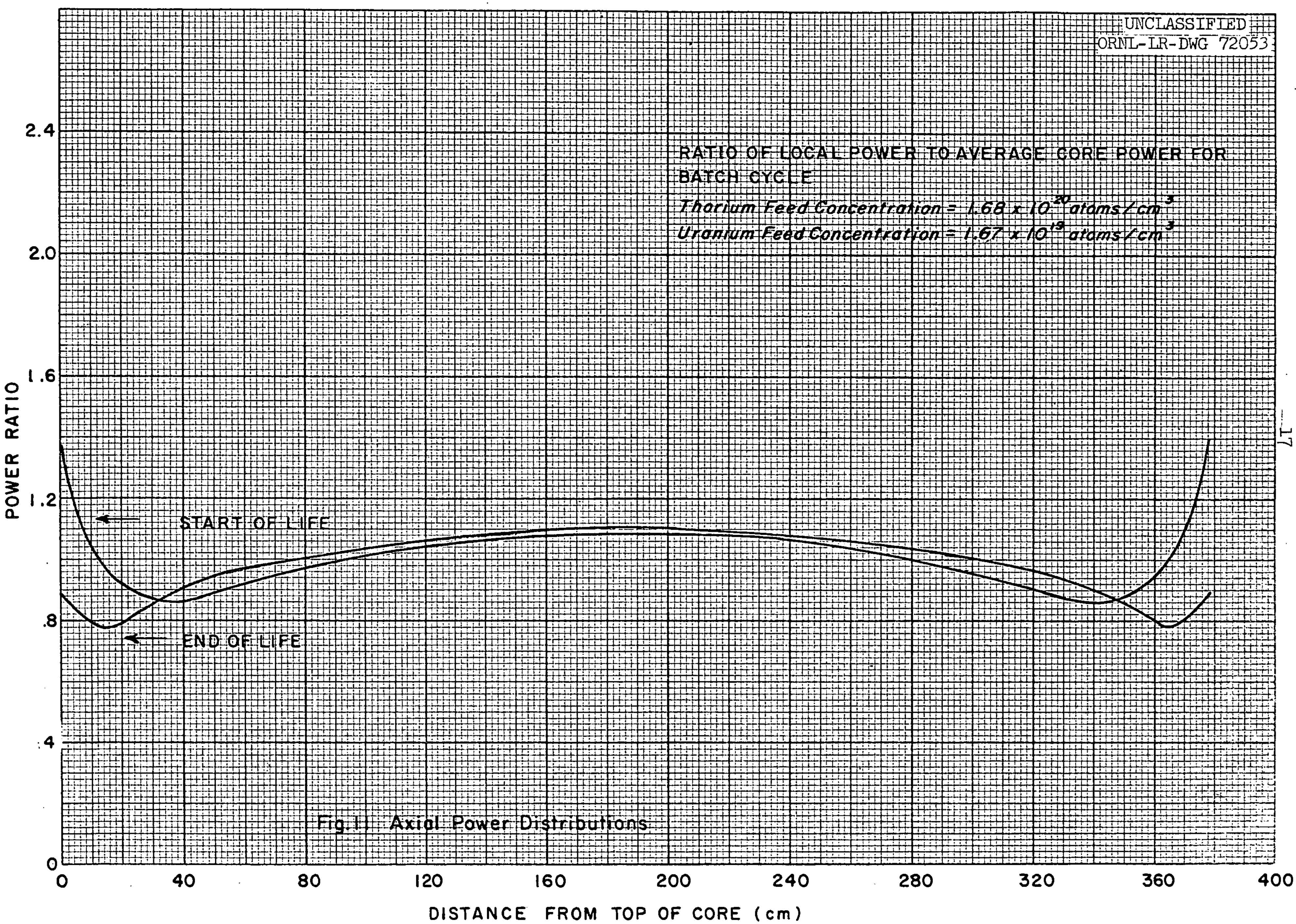

Fig. 11 Axial Power Distributions

burnup. The results of the fuel-cycle cost calculations are summarized in Table 1 along with the other pertinent data for the three fuel cycles.

Conclusions

1. The reactivity lifetime in a once-through equilibrium cycle is always less than in a graded-exposure equilibrium cycle.

2. The power distribution in a once-through equilibrium cycle is always worse than in a graded-exposure equilibrium cycle unless the upper end of the reactor is poisoned to hold down the flux peak.

3. When the upper end of the reactor is poisoned sufficiently for the once-through cycle to have the same peak-to-average power as the graded-exposure cycle, the following comparisons may be made for a fuel composition which produces near-maximum lifetime:

a) once-through cycle produces 0.12 less fissions per initial fissile atom,
b) once-through cycle produces 0.06 smaller conversion ratio,
c) once-through cycle produces 0.079 mills/kwhr(e) higher fuel-cycle cost ($177,000/year for this reactor).

4. The batch cycle produces much shorter reactivity lifetime, and a fuel-cycle cost in the order of 0.33 mills/kwhr(e) higher than the graded-exposure equilibrium cycle. However, the peak-to-average power density ratio is much better, and the fuel handling equipment would presumably be simpler. Hence, it would be necessary to consider the capital costs before discarding the batch cycle completely.

5. The neutron leakage from the core of this reactor represents a serious loss to the neutron balance. The neutron balance in Sec. 5 of ORNL CF-60-12-5 indicates that the core leakage from this reactor was about 5% with an average carbon-to-uranium ratio of 4000. A re-examination of the calculations on which that report was based indicates that 7.2% leakage should have been reported. Even with concentrated fuels (initial carbon-to-uranium ratios from 1500 to 2000) the leakage will be around 6% on a graded-exposure cycle. A 6% loss of neutrons implies about 12% loss in conversion ratio for a given fuel composition. As the leakage is increased, however, the thorium concentration must be decreased to maintain the same reactivity lifetime so that the effect

Table 1. Summary of Fuel Cycle Results

Fuel Composition		Operating Conditions: Average $N^C/(N^{25} + N^{23})$			Lifetime (fissions per initial fissile atom)			Leakage (neutrons per source neutron)			Conversion Ratio			Peak-to-Average Power Ratio			Fuel-Cycle Cost [mills/kwhr(e)]		
Initial N^C/N^{25}	Initial N^{02}/N^{25}	Equilibrium Cycle: Once Through	Equilibrium Cycle: Graded Exposure	Batch Cycle	Equilibrium Cycle: Once Through	Equilibrium Cycle: Graded Exposure	Batch Cycle	Equilibrium Cycle: Once Through	Equilibrium Cycle: Graded Exposure	Batch Cycle	Equilibrium Cycle: Once Through	Equilibrium Cycle: Graded Exposure	Batch Cycle	Equilibrium Cycle: Once Through	Equilibrium Cycle: Graded Exposure	Batch Cycle	Equilibrium Cycle: Once Through	Equilibrium Cycle: Graded Exposure	Batch Cycle
1588	10.6	1811			0.48			0.065			0.68			2.41			1.912		
1442	9.6	1793			0.75			0.065			0.68			2.86			1.543		
1263	8.4	1688			0.86			0.065			0.65			3.43			1.482		
1122	7.5	1635			1.02			0.066			0.65			4.07			1.409		
5316	17.7	6773	6815		0.61	0.67		0.085	0.082		0.64	0.65		1.62	1.40		1.926	1.798	
4073	13.6	6710	6514	5185	1.11	1.16	0.73	0.086	0.080	0.076	0.63	0.64	0.59	2.40	1.70	1.23	1.263	1.223	1.588
3358	11.2	6525	6187		1.29	1.34		0.088	0.079		0.60	0.63		3.02	1.95		1.159	1.117	
3024	10.1	6474	6020	4272	1.36	1.41	0.92	0.089	0.078	0.072	0.60	0.62	0.56	3.45	2.10	1.39	1.125	1.085	1.411
3024[a]	10.1[a]	6068[a]			1.31[a]			0.092[a]			0.59[a]			2.58[a]			1.152[a]		
3024[a]	10.1[a]	5823[a]			1.29[a]			0.092[a]			0.59[a]			2.07[a]			1.164[a]		
8544	19.0	11 257			0.53			0.103			0.57			1.48			2.377		
6499	14.4	11 152			0.97			0.105			0.56			2.15			1.483		
4481	10.0	10 933			1.24			0.109			0.53			3.42			1.237		

[a]Cases in which the upper reflector was poisoned to reduce power peaking.

on conversion ratio is still greater.

Acknowledgement

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