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SUBJECT: Nuclear and Economic Characteristics of Several Two-Region Homogeneous Reactors

TO: Distribution

FROM: M. W. Rosenthal

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ABSTRACT

The nuclear characteristics and fuel costs of a number of aqueous homogeneous reactors have been estimated. Most of the reactors studied were cylindrical, two-region power-breeders variously having between 0 and 300 g/l of thorium in the core and between 500 and 1000 g/l of thorium in the blanket. The results of the calculations, including breeding ratios, fuel inventories, doubling times, and net fuel costs, are summarized in this report.

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NUCLEAR AND ECONOMIC CHARACTERISTICS OF SEVERAL TWO-REGION HOMOGENEOUS REACTORS

In January, 1959, a committee, termed the Fluid Fuel Reactors Task Force, was assembled in Washington by the AEC to review its program for the development of fluid fuel reactors. While the Task Force was in session, a variety of nuclear and economic computations were performed by members of the REED Research and Analysis Section to provide information regarding aqueous homogeneous reactors. The results of those calculations are summarized in this memorandum. A notebook containing a set of the results from the nuclear computations, including neutron balances, is available in the HRP Director's Office.

Nuclear Computations

Several two-region reactor systems were analyzed to determine their breeding ratios and doubling times under a number of design conditions. The sizes and operating conditions of the reactors, all of which were cylindrical, are given in the following table.

Table 1. REACTORS ANALYZED

Core I.D. and Length, ft.	Blanket Thickness, ft.	Core Th Conc. g/l	Blanket Th Conc., g/l	Power (heat), Mw
4 x 12	2	0 - 300	500,750,1000	200
6 x 25	1-1/2,2	0 - 300	500,750,1000	1000
7 x 18	1-1/2,2	0 - 300	500,750,1000	1000

Both the nuclear and economic computations were performed with equilibrium concentrations of isotopes and reactor poisons, using modifications of the ORACLE routine "Thorobred-I". In this program the nuclear computations are based on a two-group treatment of spherical reactors. The program is described in detail in ORNL-2313.

The major modification in the routine was the use of a spherical reactor having the same core critical concentration to represent a cylindrical core (but with the actual cylinder volume being employed in the isotope calculations). Another change was in the treatment of reactor poisons, viz: an allowance was made for corrosion products by doubling the yield of group-3 poisons (this is equivalent to a corrosion rate of about 1/2 mpy for 347-type stainless steel); the poison fraction attributable to xenon was 2.5% for slurries. The poison fraction for the other high cross section isotopes was 0.8%. In all calculations the effective thermal cross section of Pa^{233} was 146b. The remaining conditions associated with the nuclear calculations are those given in ORNL-2313.

The breeding ratios, fuel inventories and doubling times of the two-region reactors are given in Tables 2, 3, and 4. The breeding ratios are plotted in Fig. 1. They were obtained using an effective value for η^{23} of 2.25. This value is lower than the thermal value, and allows for the adverse effect of resonance fuel absorptions (which were neglected in the two-group program) on the average eta.

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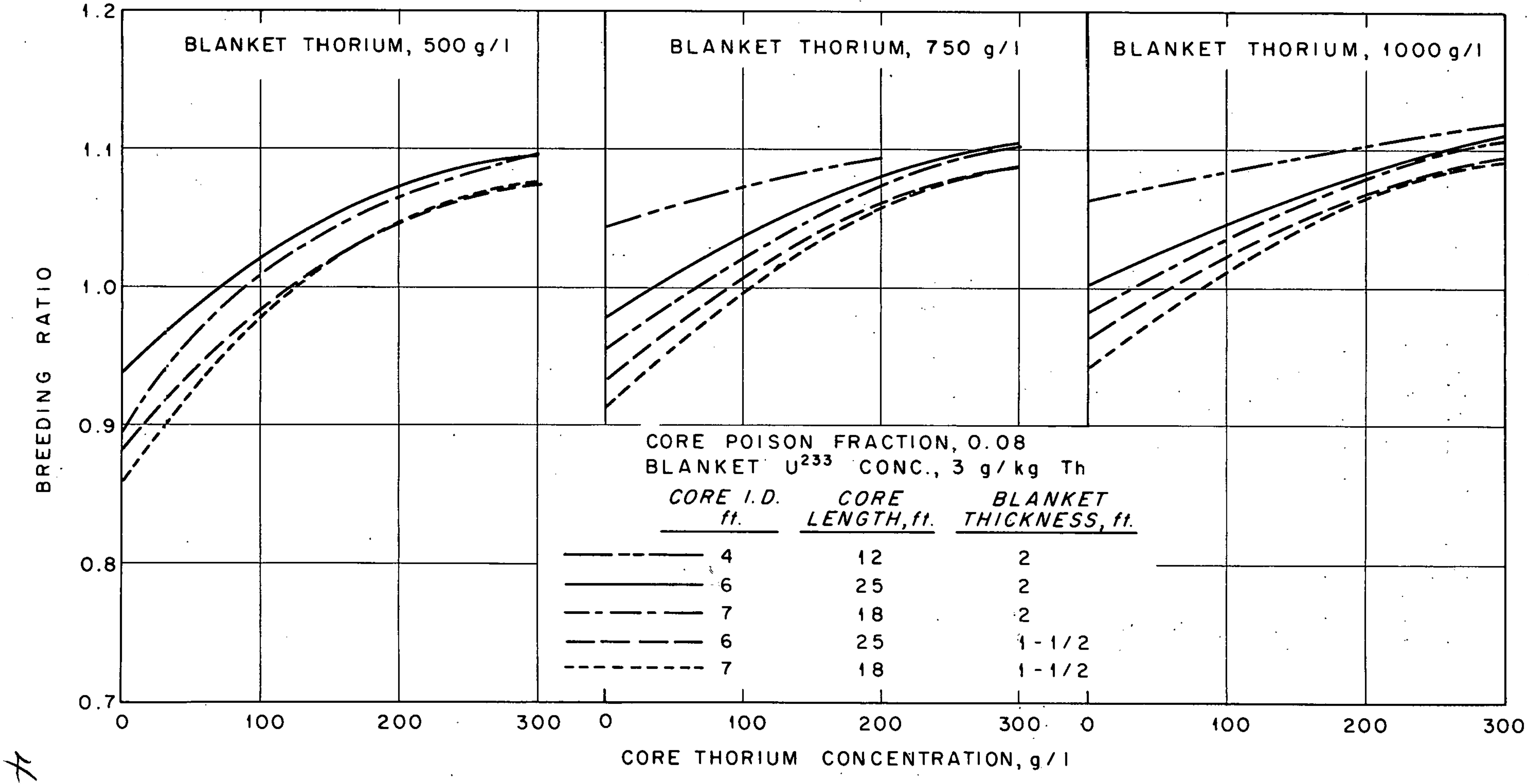

Fig. 1. Effect of Core and Blanket Dimensions and Thorium Concentrations on Breeding Ratio of Cylindrical Reactors.

Table 2. RESULTS FOR 4 x 12 FT CYLINDRICAL CORE*

Core Thorium g/l	Blanket Thorium g/l	Net Breeding Ratio	Total U^{233} $+U^{235}$ Inventory kg	Doubling Time yrs
0	750	1.046	89.1	26.2
	1000	1.066	105	21.7
100	750	1.073	155	28.7
	1000	1.084	171	27.6
200	750	1.098	235	32.7
	1000	1.106	253	32.3
300	750			
	1000	1.121	390	43.9

*Blanket thickness, 2 ft; power (heat), 200 Mw; core poison fraction, 0.08; blanket U^{233} concentration, 3 g/kg Th.

Table 3. RESULTS FOR 6 x 25 FT CYLINDRICAL CORE*

Core Thorium	Blanket Thorium	Blanket U^{233}	Blanket thickness, 1 1/2ft Net Breeding Ratio	Blanket thickness, 1 1/2ft Total U^{233} $+U^{235}$ Inventory	Blanket thickness, 1 1/2ft Doubling Time	Blanket thickness, 2 ft Net Breeding Ratio	Blanket thickness, 2 ft Total U^{233} $+U^{235}$ Inventory	Blanket thickness, 2 ft Doubling Time
g/l	g/l	g/kg Th		kg	yrs		kg	yrs
0	500	3	0.881	180	---	0.938	200	---
		5	0.877	215	---	0.940	246	---
	750	3	0.934	212	---	0.980	237	---
		5	0.932	272	---	0.984	316	---
	1000	3	0.964	240	---	1.004	274	174
		5	0.962	327	---	1.011	386	97.3
100	500	3	0.985	443	---	1.020	450	59.6
		5	0.980	463	---	1.018	480	73.2
	750	3	1.010	462	123	1.037	478	35.1
		5	1.003	502	397	1.036	532	40.0
	1000	3	1.023	481	55.4	1.045	508	30.6
		5	1.020	536	72.5	1.045	585	35.0
200	500	3	1.047	691	39.9	1.071	696	26.6
		5	1.042	708	46.3	1.067	722	26.6
	750	3	1.062	711	31.1	1.082	728	24.0
		5	1.058	744	35.0	1.080	775	26.3
	1000	3	1.070	732	28.4	1.088	759	23.4
		5	1.067	781	31.8	1.086	826	25.8
300	500	3	1.076	1069	38.0	1.098	1068	29.4
		5	1.071	1081	41.3	1.095	1088	31.1
	750	3	1.089	1092	33.3	1.108	1104	27.8
		5	1.085	1119	35.7	1.105	1144	29.4
	1000	3	1.096	1115	31.5	1.112	1137	27.4
		5	1.093	1157	33.9	1.111	1198	29.3

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*Power, 1000 Mw (heat); core poison fraction, 0.08.

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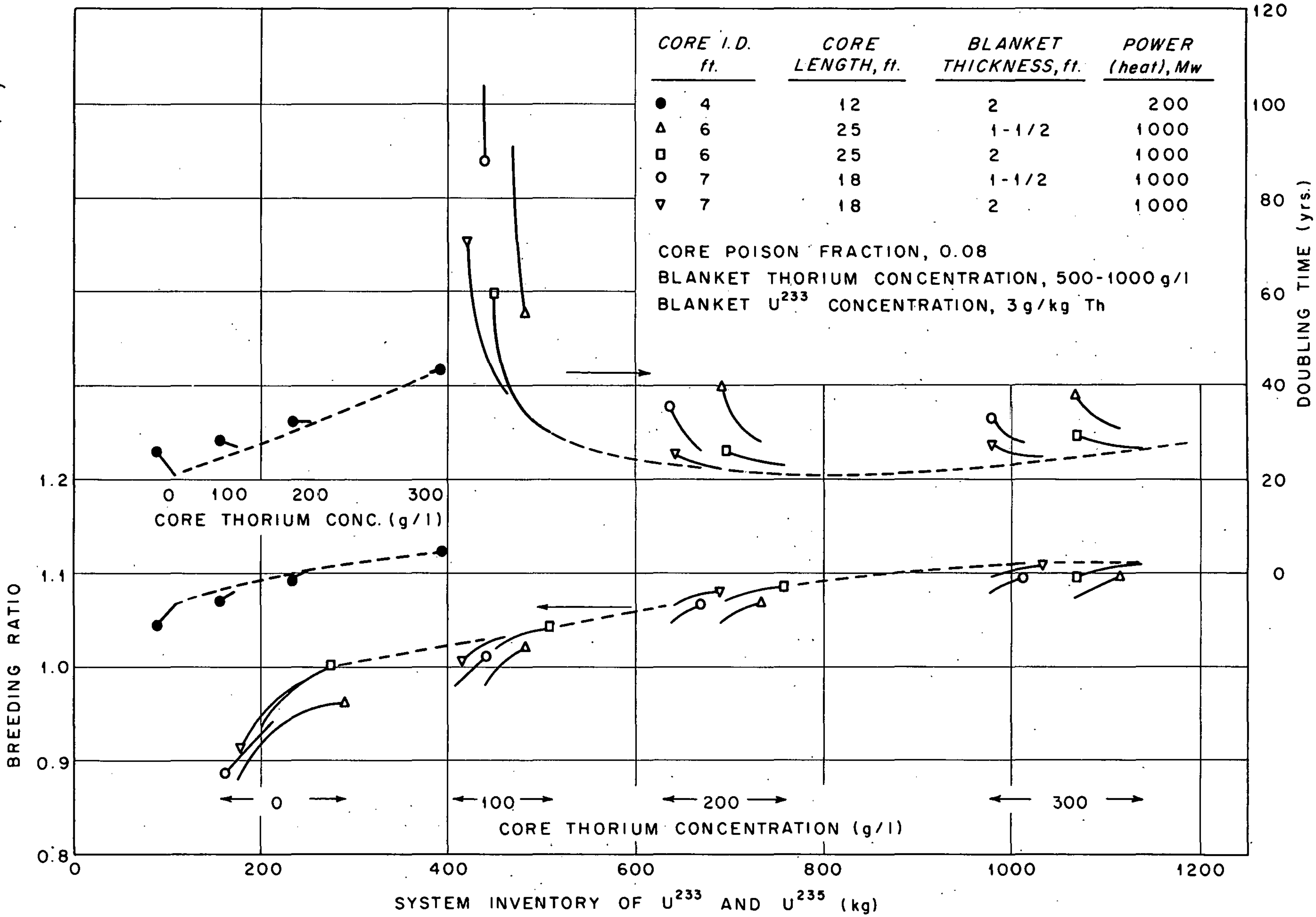

Fig. 2. Breeding Ratio and Doubling Time of Various Cylindrical Reactors vs. Fuel Inventory

Table 4. RESULTS FOR 7 x 18 FT CYLINDRICAL CORE*

Core Thorium	Blanket Thorium	Blanket U^{233}	Blanket thickness, 1 1/2 ft: Net Breeding Ratio	Blanket thickness, 1 1/2 ft: Total U^{233} $+U^{235}$ Inventory	Blanket thickness, 1 1/2 ft: Doubling Time	Blanket thickness, 2 ft: Net Breeding Ratio	Blanket thickness, 2 ft: Total U^{233} $+U^{235}$ Inventory	Blanket thickness, 2 ft: Doubling Time
g/l	g/l	g/kg Th		kg	yrs		kg	yrs
0	500	3	0.860	160	---	0.914	176	---
		5	0.859	191	---	0.919	217	---
	750	3	0.914	187	---	0.957	208	---
		5	0.914	242	---	0.964	276	---
	1000	3	0.944	212	---	0.982	240	---
		5	0.945	290	---	0.988	337	---
100	500	3	0.981	408	---	1.009	416	123
		5	0.977	425	---	1.007	442	178
	750	3	0.998	428	---	1.025	438	47.3
		5	0.995	458	---	1.025	483	52.2
	1000	3	1.013	440	88.2	1.033	462	38.4
		5	1.011	487	124	1.033	525	42.4
200	500	3	1.048	636	35.9	1.068	642	25.8
		5	1.043	651	40.6	1.065	663	27.7
	750	3	1.061	652	29.1	1.077	666	23.5
		5	1.057	680	32.2	1.076	705	25.3
	1000	3	1.068	669	26.9	1.082	690	22.9
		5	1.065	709	29.6	1.081	746	25.0
300	500	3	1.080	978	33.2	1.098	979	27.2
		5	1.075	988	35.5	1.095	996	28.4
	750	3	1.091	996	29.8	1.106	1006	25.9
		5	1.087	1018	31.6	1.104	1040	27.2
	1000	3	1.096	1013	28.5	1.110	1032	25.5
		5	1.094	1048	30.9	1.108	1083	27.0

*Power, 1000 Mw (heat); core poison fraction, 0.08.

(Although the actual resonance eta of U^{233} is somewhat uncertain, the available data indicated that it is lower than the thermal value.) The estimated average value of 2.25 is probably too low for solution-core reactors, but may not be too low for slurry-core systems with core thorium concentrations in the range of 200 to 300 g/l.

In Fig. 2 both the breeding ratio and the doubling time are plotted as functions of the system inventory of U^{233} and U^{235}. As defined here, the doubling time is the time required to produce an excess of fissionable uranium equal to the complete inventory of the reactor system at equilibrium. The inventory includes the uranium in the core and blanket. However, it does not consider Pa inventory in the reactor. A plant factor of 80% was used in computing the production rate, i.e., the average power level of the nominal 1000 Mw reactors was taken as 800 Mw.

The breeding ratio curves of Fig. 2 illustrate how one pays for higher breeding ratio in increased inventory; the improved neutron economy that results from the addition of thorium to core or blanket is obtained at the expense of a greater fuel investment. Consequently, as shown in the upper curves, the doubling time of the reactor may increase as the breeding ratio increases.

Addition of thorium to the core, while always improving the breeding ratio, did not always decrease the doubling time. When the neutron economy was already good, the improvement in breeding ratio was not sufficient to overcome the increased inventory. This was markedly true for the smaller reactor, in which the critical concentration for the solution core was sufficiently high to give good neutron economy without the thorium. Higher blanket thorium concentration (within the range of 500 to 1000 g/l studied) did always result in reduced doubling times, however. This is seen in the changes in variables along the short curves in Fig. 2, which, going from left to right, correspond to increases in blanket thorium.

The uncertainties in the estimates of the breeding ratio should be kept in mind when considering the results obtained in this study. The major questions are associated with the effective value of η^{23}, which was discussed earlier, and the poison fraction allowed for xenon absorptions. The HRT experience with xenon and iodine removal from solution fuels is favorable, and the 1% poison xenon fractions used for solutions in the calculations appears reasonable. The behavior of slurry systems, however, is quite uncertain, and the 2.5% allowed for xenon in the thorium-loaded cores may be either high or low.

A small error in the breeding ratio can cause a large error in the estimated doubling time, since the doubling time is proportional to the breeding gain (BR - 1.0) rather than the breeding ratio itself. A change in either η^{23} or the core poison fraction is numerically equal to about the same change in breeding ratio. For example, if the effective value of η^{23} is 2.28 rather than 2.25, the breeding ratio would be higher than estimated by about 0.03. Should this change the breeding ratio from, say, 1.06 to 1.09, the doubling time would be shortened by one-third, and if the change were from 1.03 to 1.06, the doubling time would be halved.

Fuel Cost Calculations

A series of fuel-cost calculations were performed for the 7 x 18 ft. core described in Table 1, with the blanket thickness always being 2 ft. Fuel cost, as defined here, is the sum of the charges for uranium, heavy water, and thorium inventories; fuel preparation and reprocessing; fuel purchase or sale (credit), thorium purchase, and heavy water makeup.

The program "Thorobred-I" was used to compute the costs, but the fixed charge on heavy water and the basis for estimating processing charges were changed from those given in ORNL-2313. The fixed charge on heavy water was 20.5%, which includes a 5% allowance for heavy water makeup. The processing charge was based on $28 per kilogram of thorium, independent of the amount of uranium and heavy water associated with it (this includes shipping costs equivalent to $8/kg thorium). This "variable" charge represents the entire processing cost, and there is no fixed component of the processing cost, as in previous calculations. As before the fixed charge on urnaium was 4%, the value of uranium was $16 per gram of U^{233} and U^{235}, the value of heavy water was $28/lb, and the plant factor was 80%. The nuclear computations were the same as those described in the preceding section, except that the core poison fraction attributed to xenon was 3.2%.

The effect of core poison fraction on the breeding ratio, doubling time, and fuel cost is shown in Fig. 3 for several core thorium concentrations. The poison fraction used is the sum of a variable poison from corrosion products and group-3 fission products, plus the 3.2% mentioned above for the noble gases and 0.8% for the other high cross-section isotopes. The curves in Fig. 3 show that with the cost bases used, the lowest fuel cost is not associated with the shortest doubling time. At low poison fractions, the higher processing costs which result from the more rapid processing offset the value of the higher uranium yield and the slightly lower fuel inventory. The lowest fuel cost was that for 200 g Th/l in the core. With regard to the optimum core thorium concentration, there is some correspondence between fuel cost and doubling time, but the relation depends on the fixed charges on uranium inventory.

The curves of Fig. 4 show the effect of different blanket thorium and uranium concentrations on breeding ratio, doubling time, and fuel cost. The lowest fuel cost was obtained with the highest blanket uranium concentration, mainly because of the lower processing cost. At 6 g U^{233}/kg Th, the processing rate, and hence the blanket processing cost, is about one-third that at 2 g U^{233}/kg Th.

One study was done in which the reactor power was increased from 1000 to 1200 Mw. The change in power had little effect on either the doubling time or fuel cost, because the external reactor volume and the processing plant hold-up, which between them contain a large fraction of the uranium inventory, are proportional to the power. The inventory increases as the uranium production rate does, and the doubling time---the ratio of inventory to production rate---remains nearly constant.

The results of economic analyses, such as this one, depend strongly on the cost bases used. This is true not only of the absolute values of the fuel cost, but also of the costs of one design or condition relative to another. For example, the optimum core thorium concentration for the reactor studied here was about 200 g Th/l.

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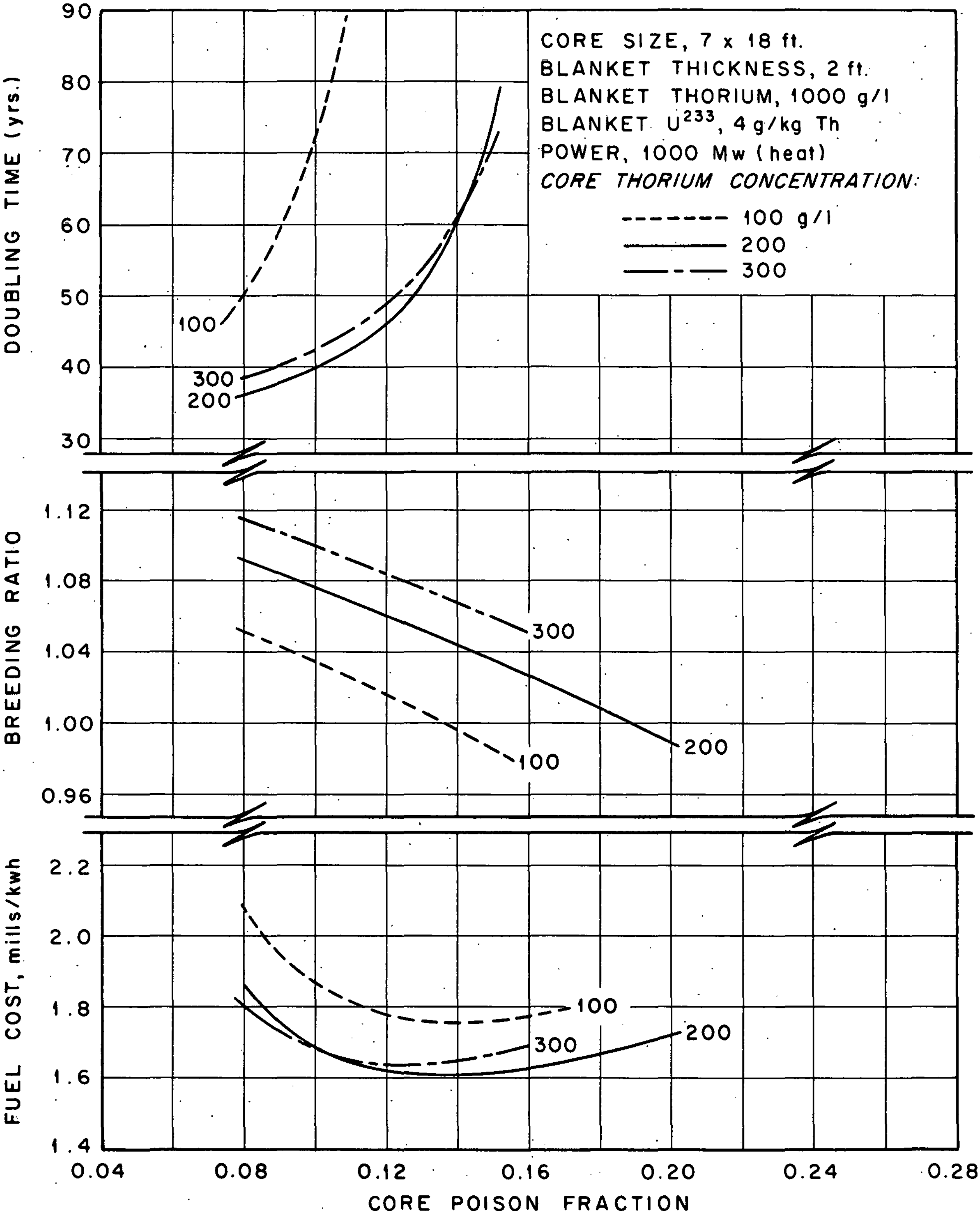

Fig. 3. Doubling Time, Breeding Ratio, and Fuel Cost as Functions of Core Poison Fraction for a Two-Region Cylindrical Reactor.

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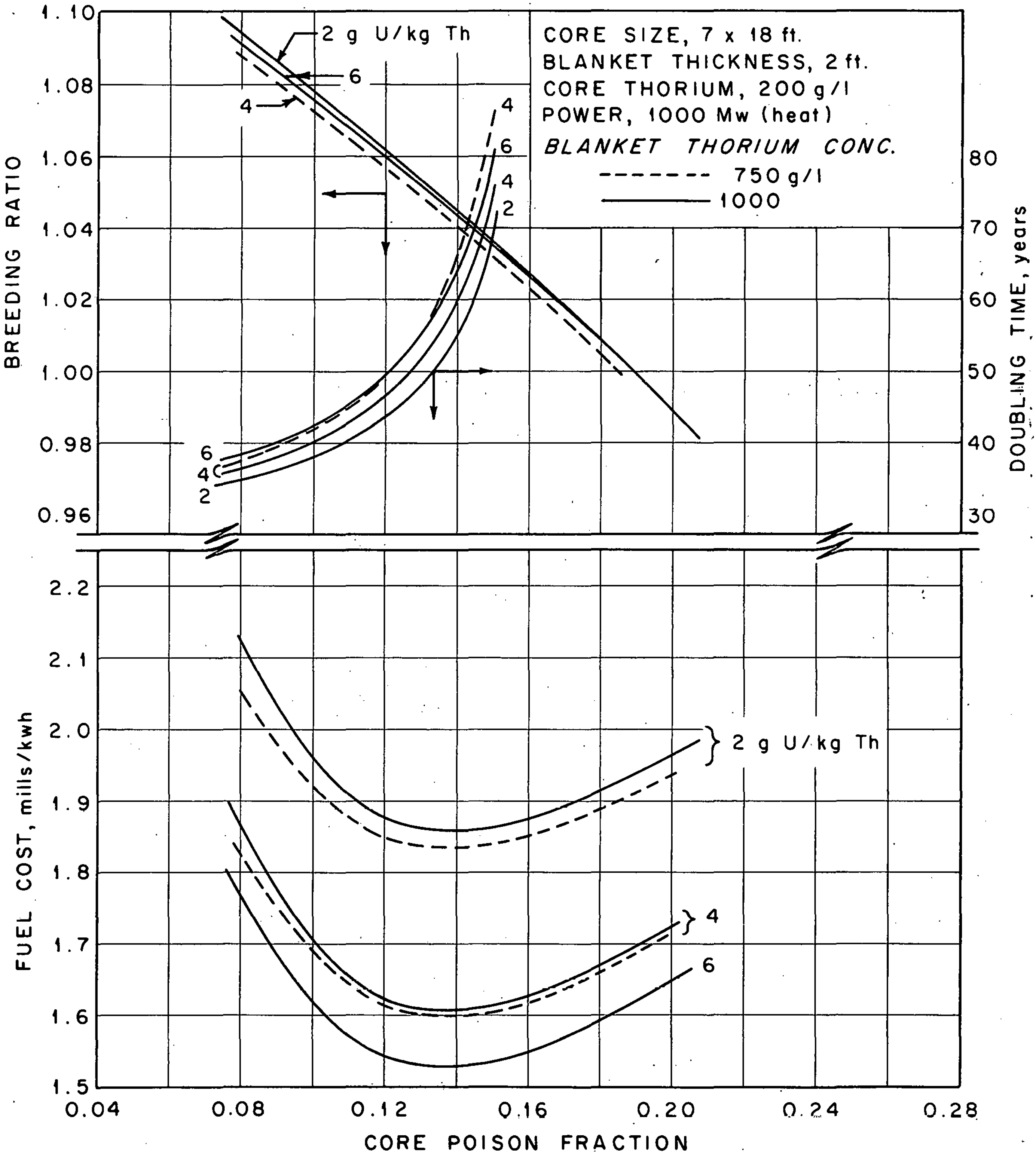

Fig. 4. Effect of Blanket Thorium and Uranium Concentrations or Doubling Time, Breeding Ratio and Fuel Cost.

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If the inventory charge on uranium was taken as 12% a year, rather than 4%, the increased importance of uranium inventory would make a lower core thorium concentration desirable. Similar effects would result from changes in other cost items.

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