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WILEM J. OOSTERKAMP

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INSTITUTO DE ENERGIA ATÔMICA
Caixa Postal 11049 (Pinheiros)
CIDADE UNIVERSITARIA "ARMANDO DE SALLES OLIVEIRA"
SAO PAULO — BRASIL

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Willem J Oosterkamp

Coordenadoria de Engenharia Nuclear
Instituto de Energia Atômica
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I INTRODUCTION

Brazil has a natural interest in the thorium fuel cycle for nuclear reactors as it has large proven reserves of thorium and only small uranium deposits. In the thorium cycle, fissile U 233 is formed from Th 232. Thorium has been used in the cores of several power reactors in the mid sixties (Indian Point[1,2], 250 MWe, ELK River 58 MWTh[3], Borax IV). The experimental high temperature reactors Peach Bottom (40 MWe)[4,5], AVR (15 MWe)[6] and Dragon (70 MWe)[7,8,9] are thorium reactors and also the 300 MWe prototype HTGR's of Fort St. Vrain and Schmehausen[10,11] will use the thorium cycle. A number of commercial size 1200 MWe thorium HTGR's have been ordered from General Atomic[12].

Most work on the use of thorium in light and heavy water reactors has been discontinued because the low prices for uranium ore and separative work a number of years ago did not give any incentive to develop the thorium cycle further. Due to the ever increasing prices of uranium the situation has changed now internationally and a renewed interest in the utilization of thorium can be observed.

Work on the utilization of thorium in high temperature reactors has been carried to the commercial stage. This is due to the fact that uranium is not competetive in homogeneous reactors like the HTGR. The uranium resonances in a homogeneus reactor are poorly shielded, leading to a low resonance escape probability. This means that a high enrichement is required to achieve criticality. The resonances of thorium are not so pronounced and the requirements of fissile material are thus less.

Water cooled reactors have much lower effective resonance integrals caused by the selfshielding of the heterogeneous fuel. The resonance integrals of thorium and uranium are for this reactor type about the same. Thorium has a disadvantage as its thermal capture cross section is about three times the value for uranium leading to a significant lower thermal utilization and thus requiring a higher fissele loading.

Thus far fuel cycles have been mainly compared by the fuel cycle costs. The cost of all steps of the fuel cycle mining, enrichment, fabrication and reprocessing were mainly those at the time the studies were made and the optimizations were accordingly [13]. Few consider the longterm trends in the costs and only the work on fast breeders has given attention to the availability of resources [14].

The incentive to use thorium is its potential to conserve the recources. Uranium 233 that is bred from U Thorium is potentially a better fuel in thermal reactors than Pu 239 that is bred from U 238. U 233 does not occur naturally and has to be converted in thermal or fast reactors. Uranium has to be used to start up and maintain non breeding reactors as U 235 is the only naturally occuring fissile material. It is thus not obvious if thorium utilization will indeed reduce the demand for uranium.

The requirements of uranium are mainly given by the conversion ratio of the reactors in the power system and depend on the layout of the reactor. In this paper we will show that with more emphasis on the conversion ratio, a substantial reduction of the ore requirements can be obtained and we will outline under what conditions thorium utilization will reduce the uranium consumption.

2 REACTOR TYPES

2.1 High Temperature Reactors

Thorium utilization in high temperature gas cooled reactors has reached a commercial stage and has been well documented. A comparison of the fuel cycle with uranium and thorium has been made by GA for prismatic fuel elements[15] and for pebbels (Shulten elements)[16] by Jülich. From the work of Teuchert we have taken Table I. This shows that the use of thorium gives only a limited reduction on the uranium consuption.

Table I

Characteristics of the fuel cycle

$1000 MW_{th}$, $8 MW/m^3$, 250 1060 °C

Fuel cycle		Low. enr.	Thorium	Th recycle	Hi conv
N_C/N_{HM} in feed batches		355	259	259	110
Av. fuel residence time	days	848	1094	1113	630
Average burn up	MWd/t	115 000	114 000	115 000	28 000
Conversion ratio		0.54	0.56	0.60	0.90
Power peaking		2.8	2.6	2.5	1.3
Control Rods Withdrawal	$\Delta k/k$	0.020	0.018	0.018	-0.006
Xe-Override 100 - 40%	$\Delta k/k$	0.016	-0.019	-0.018	-0.007
Fissile inventory	kg	345	361	360	620
supply	gr/d	916	783	729	1082
U-nat. requirement	kg/d	217	190	135	-
Separative work	kg SWU/d	160	169	120	-
Fuel cycle costs	mills/KWh_e	2.12	1.92	1.84	2.91
Fabrication only	mills/KWh_e	0.49	0.41	0.41	1.20

2.2 - Light Water Reactors

There exist a relative large amount of information on the use of thorium in light water reactors from the prototypes in the early sixties. This information is however not too pertinent now as the cladding of the fuel elements used in these reactors consisted of stainless steel. Stainless steel is not now used as it has a high absorption cross section. The favorite material now is Zircaloy. A zirconium alloy with an extreme low capture cross section. The more recent work of Zorzoli[17,18,19] focusses on the use of Th metals as a replacement for uranium oxide and stresses fuel cycle costs. A low fuel cycle cost is obtained and the uranium demand is significantly reduced. Lin and Zolotar[20] have done some zero dimensional burnup calculations comparing UO_2, ThO_2 and Th metal using the code LEOPARD[21]. Their results are of a preliminary nature and are given in Table II.

Table II

P W R Fuel Cycle Characteristics

	UO_2 PuO_2	ThO_2 UO_2	Th U
Initial uniform loading MT U^{235}	2.740	3.681	4.583
Nat U (MT)*	6.028×10^2	7.189×10^2	8.951×10^2
Sepertive work (Kg)*	4.083×10^5	9.324×10^5	11.161×10^5
Conversion ratio of first cycle	0.61	0.76	0.81
Make up requirement per year - Mt U^{235}	0.449	0.315	0.176
Nat. U (MT)*	0.824×10^2	0.615×10^2	0.344×10^2
Separative work (Kg)*	1.018×10^{5}**	0.798×10^5	0.446×10^5
Coversion ratio of second cycle	0.67	0.79	0.84

* 0.2 w/o U-235 in diffusion plant tails.

** Includes enrichment of recycled uranium.

The light water breeder reactor program is intended to develop a thermal breeder reactor[22,23] on the basis of the existing light water reactor technology. A conversion ratio of nearly one is obtained which implies that except for the initial loading, practically no new fuel is needed. But the complexity of the seed and blanket concept and specifically the movable seed reactivity control make it very doubtfull if a high availability can be obtained.

2.3 - Heavy water Reactors

Some work has been performed on heavy water reactors to obtain breeding using the thorium cycle. For the suspension power reactor[24] a homogeneous fueled heavy water reactor a conversion ratio of .99 is pressurized heavy water reactor - a concept similar to the standard PWR but moderated and cooled with heavy water and larger distances between fuel pins - conversion ratios close to 1.05 for thorium loadings have been obtained[25]. Work on a similar reactor type has been performed by Siemens in Germany[26]. The large pressure vessels for these reactors can possibly be made from prestressed concerte[27]. The natural uranium cycle for these reactors is not attractive as the burnup reach only 4 MWd/kg.

Thorium utilization in heavy water moderated organic cooled reactors of the pressure tube type CANDU ORGEL have been extensively studied[29 30 31 32 33], and offers a high conversion ration with low fuel cycle costs One can start CANDU type reactors with natural uranium reprocess the fuel and use the plutonium in thorium elements so as to start a U 233 Th cycle But this way though promising, takes about 30 years to build the necessary inventories[28]

2 4 - Molten Salt Breeder Reactor

An advanced and interesting thermal converter is the molten salt breeder reactor[35 36] It combines a low inventory with an high conversion ratio It is likely that with this system thermal breeding will be possible The MSBR consists of a graphite matrix in which a mixture of lithium uranium and thorium fluorides are passed through The high conversion ratio is obtained by online reprocessing of the fuel mixture, thus removing virtually all fission products The reactor has no structural material end the moderator does not absorb neutrons These factors explain the high conversion ratio Some basic problems, it seems, require a lot of development work

One is a corrosion resistent alloy for the reactor vessel and piping as the fission products in the fluoride solution can be aggressive

A large amount of tritium is formed by the reaction $Li^{6}(n,\alpha)T^{3}$ about 2 4 KCi/d, and unless suitable measures are taken an excessive amount of the tritium could reach the atmosphere by diffusion through the heat exchangers into the steam system

Solutions to these problems do exist, but they require extensive testing on an engineering scale In the opinion of this author the development of the MSBR is lagging behind the liquid metal fast breeder reactor by about a decade and will probably not be in commercial operation before the next century

3 PHYSICS CONSIDERATIONS

As an example of the effects that are involved in the transition from the uranium cycle to the thorium cycle we will have a more detailed look at the light water reactors First approximations are used to demonstrate the effects that are involved The results, though basically correct should be treated with some care as second order effects can significantly modify them This is particularity true for conversion ratios close to unity Small changes in this number lead to large changes in the fuel consumption

3 1 - Conversion Ratio

The basic quantity governing the fuel consumption is the conversion ratio In comparing the conversion ratio of thorium and uranium reactors one should be careful to separate the effects of U 233 and Pu 239 from other effects like change in enrichment, burnup, cladding absorption, absorption in moderator and control requirements

The number of neutrons that are available for conversion per absorption in a fissionable atom are given by η 1 of that isotope We have listed the η together with the fission cross section and the ratio of absorption to fission for the most important isotopes in table III

Table III

Thermal Properties of Some Fissile Isotopes

	σ_f	η	α
U 233	276	2 3	1
U 235	277	2 0	2
Pu 239	786	1 8	4
Pu 241	766	2 2	2

Figures 1 to 4 give graphs of some of these quantities

In the standard light water reactor, plutonium is built up during the irradiation and contributes about 30% to the fissions The average η is thus $\eta_{LWR} = 2$ The fast fissions in uranium increase the number of neutrons available to breeding to $\epsilon\eta - 1 = 1\ 1$ This number is reduced to 6 by capture in cladding, coolant, fission products and control absorber In replacing uranium 238 with Th 232, we will have several compensating effects First of all the fast fission bonus is practically lost because Th 232 has a lower fast fission cross section, secondly because the η of U 233 is so much higher than that of Pu 239 we obtain for $\epsilon\eta$ $1 = 1\ 1$ The reducton due to capture in the intermediate isotope Pa 233 is not very significant We can thus conclude that the conversion ratio of a light water reactor without recycling is not affected by the substitution of U 238 by Th 232 for the same enrichment, burnup etc

3 2 Critical Mass

What one would do in an existing light water reactor is to substitute the UO_2 in the fuel pins with a mixture of ThO_2 and highly enriched UO_2 as was done in the early light water reactors ThO_2 behaves very similar to UO_2 so that this would not present significant problems

The absorption of thorium in standard LWR's is about 20% higher than that of U-238 which is caused by thermal absorption cross section that is three times higher The effect of the thermal absorption is somewhat compensated by an effective resonance integral that is only 75% of that of U-238

The increase in absorption together with the loss of fast fissions means that the fissile mass has to be increaded by 20% in order for the system to remain critical as the density of ThO_2 is only 90% of UO_2 Th metal has a 20% higher density and, if that is used, the enrichment should be increased by 60%

This increase in enrichment necessary for Th metal results in a conversion ratio of 75 a value close to that obtained by Zorzoli[28] when his values are extrapolated to burnups of 30 MWd/kg The same conversion ratio can be obtained for a uranium system by reducing the fuel to moderator ratio because the increase in conversion ratio is a result of a change in enrichment

3 3 Recycling

We will now consider the effect of recycling the fuel We will consider two types of reactors. one type we call a convertor that not only produces electricity but converts fertile isotopes to fissile e g U 238 to Pu 239 The other type we call a burner that burns converted fissile material both of itself and of true converters

The net production of bred fuel in a converter is

$$P_{net} = \left\{ \left[(1 + \alpha 5) \; (1 \quad f) + (1 + \alpha b) \, f \right] CR_c \quad (1 + \alpha b) \, f \right\} / X \qquad (1)$$

where

- 5 indicates U 235
- b indicates bred material, e g , Pu 239 or U 233
- f is the fraction of the power generated in the bred fuel
- X is the power per kg of fissioned material
- CR_c is the conversion ratio

The first term is the total production and the second term is the loss of bred material by fission and absorption in the converter itself

The net consuption of a burner, assuming that the bred material is recycled, is given by

$$C_{net} = (CR_b \quad 1) \, (1 + \alpha_b)/X \qquad (2)$$

where

CR_b is the conversion ratio of the burner

From these equations we can now calculate the relation between the number of converters and the number of burners

In Table IV we have given the values for the thorium and uranium cycle The standard case is a thorium converter with the same enrichment as the standard PWR The high conversion case is a thorium metal fed standard PWR with an adjusted enrichement and the equivalent uranium reactor As a variant on the U Th metal reactor we have included a Pu-Th metal reactor.

The different conversion ratios of the burner reflect the distinct properties of U-235, U 233 and Pu 239 The large consuption of plutonium in the burner in the uranium cycle, is a strileing fact This is due to the low conversion ration and to the high α of plutonium. If we have a power system with converters and burners in the relation as given in Table IV we can calculate the average fuel consumption per reactor as given in Table V

Table IV

Production and Consumption of Reactor Fuel

	Standard	Standard		High Conversion	
	U cycle	Th cycle	U cycle	Th cycle	Py Th cycle
CR_c	6	6	75	75	65
CR_b	.45	75	60	.90	90
P_{net}(kg/y)	160	240	300	360	480
C_{net}(kg/y)	800	220	520	90	90
Ratio of converter					
Burner	5 1	1 1	3 2	1 4	1 5

Table V

Average Fuel Consumption per Reactor. *Pu consumption **$30/kg U_3O_8 and $47/SWU

	Standard	Standard		High Conversion	
	U cycle	U cycle	U cycle	Th cycle	Pu Th cycle
U 236	500	320	400	130	670*
U_3O_8(10^3kg/y)	100	64	80	25	
Enrichment (SWU)	66	100	50	40	
Costs**($10^6$$/y)	6.	5 8	4 8	2 4	

It can beobserved that the reduction in uranium consumption is substantial, for the thorium cycle. This is offset by the encreased enrichment costs as it is twice expensive to obtain 93% enriched material than 3% enriched.

For the high conversion system a factor of four reduction is achived in ore consumption and nearly a factor of two in separative work requirements

It is possible to start the thorium cycle with plutonium as a fuel and a nice relationship between Pu thorium and U 233 thorium reactors is obtained. It takes however, 1500 kg or ten/discharges of present day light water reactors for the loading of a Pu thorium converter, and eight dischargers of this convertor are needed to load a U-233-thorium burner.

It is thus evident that long time periods are involved in building up U-233-thorium burners using plutonium as an intermediate fuel.

3 4 The use of 20% enriched uranium

Thus far we have assumed that 93% enriched uranium would be available This might not be the case and the enrichment could be limited to 20% There are two possibilities to build up the U 233 thorium cycle under this conditions

One is to use plutonium as an intermediate step To produce the 870 kg/y fissile plutonium that are needed for a Pu Th metal reactor the output of five conventional light water reactors is needed In equilibrium conditions one standard light water reactor produces enough fissile material to sustain one U 233 Th metal burner intermediate Pu converter. If highly enriched material is available, one LWR uranium converter could sustain four burners This is a loss of a factor of four in ore consuption and a factor of two in seperative work

The other possibility is to use the uranium at the maximum permissible enrichement. Then, plutonium is produced together with U 233 The overall enrichment for a Th-metal reactor has to be of the order of 6% Thus 30% of the heavy metal is U 238 The capture cross section of U 238 increases by a factor of two due to the dilution and consequent reduction in self shielding of the resonances Thus about 50% of the production of fissile material will be in the form of plutonium

To obtain an idea of the mass balances involved we assume that the bred U-233 can be kept separate from the U 238 by a separation of fissile material Then, we assume that we construct a system of ten light water reactors as converters, twenty thorium burners supplied with the U 233 fuel from the converters, one plutonium converter supplied with the plutonium of the ten uranium converter and five thorium burners fueled from the plutonium converter. Thus one light water reactor can sustain 3 5 thorium burners

It is obvious that heavy penalties are involved should the uranium enrichment be limited to 20% It probably does mean that the thorium cycle can not economically be developped.

4 REPROCESSING AND REFABRICATION

It has been observed[37] that the lack of a large scale facility for thorium reprocessing has been a principal barrier to the development of the thorium cycle

Reprocessing of thorium based fuels can be done at existing facilities optimized for uranium and plutonium recovery but the cost is much higher A plant optimized for thorium recovery can be made competitive to those of uranium plutonium[38] Work is in progress in the United States and Germany to come to large scale reprocessing of HTGR fuel The German Jupiter plant will use, after a head end that removes the bulk of the graphite, a Thorex solvent (13 M HNO_3, 1M $Al(NO_3)_3$ 0 5 M HF) and extracts uranium, thorium and plutonium isotopes from this solvent with TBP[39] (Fig 5) This is a modified form of the well known pyrex process In the U S a similar scheme will be used[40] These process can be adapted for water reactor fuel by a different head end to remove the bulk of the cladding

A problem for the fabrication of fuel elements containing recycle fuel is the radioactivity. In the uranium cycle this is due to the α activity of the plutonium isotopes and glove box handling is considered to be sufficient

For the thorium cycle there are some added problems due to the buildup of U 232 (Fig. 6) The decay chain (Fig 7) involves the production of γ rays with energies over one MeV that require heavy shielding (Table VI) Feed U 232 decays to Th 228 with a halflife of 2 y Its daughters have short half lives (< 1 d) Thus low radiation levels can be chemicaly obtained by removing Th 228 from the uranium feed before reprocessing is done Th 228 cannot be separated from the thorium itself so that one has to wait a decade till the Th 228 has decayed before the thorium can be reused Under these conditions glove box handling is sufficient and no refabrication penalty is incurred with respect to plutonium

Experience has been obtained on a pilot plant scale by the Babcock and Wilcox Company on the fabrication of U 233 for water cooled reactors[41] as seen in Fig 8

The radioactive nature of the uranium 233 and the recycle thorium made it seem worthwhile to consider a close coupling between reprocessing and refabrication in which the used fuel is only partially decontaminated and the fabrication is done remotedly

Two such facilities have been constructed, the thorium uranium recycle facility (TURF) at Oak Ridge[3] and "programma ciclo uranium torio (PCUT)" in Italy TURF has been designed mainly for HTGR elements whereas PCUT[42] was designed for light and heavy water fuel elements.

Essentially, in these facilities it is used the Sol-Gel process, is used for the oxide production which is then vibratory compacted in the fuel elements for water reactors These steps are very much suited to remote handling (Fig 9)

5 PROPERTIES OF THORIUM METAL AND THORIA

The properties of thorium, its alloys and compurids have been reported by Peterson et al[43] Thoria behaves very much the same as uranium dioxide and does not pose particular problems (Table VII) Metallic thorium (Table VIII) is very atractive because it has a higher density than UO_2 and also has a high thermal conductivity Its irradiation behavious is considered to be excelent and burnups of 30 MWd/kg should be obtained provided the maximum temperature is not much greater than 650°C[44] The large swelling above 650°C (Figs 10 e 11) is probably caused by the agglomeration of fission products in pores and it is not clear whether the swelling levels of 8% $\Delta V/V$ per % burnup will be exceeded at temperature above 1000°C

6 CONCLUSIONS

The thorium cycle offers substantial savings in uranium consumption and separative work for reactor with a high conversion ratio The reactor that can be used are of a standard type and will need only slight modifications A very intereting type is the Th metal pressurized water reactor into which existing pressurized water reactors can be converted

Fuel fabrication facilities to be set up in Brasil should be able to handle slightly radioactive fuel and provide for removal of Th 228 from uranium

Reprocessing plants should be optimized for a large through put of thorium even if initially the uranium cycle will be used

A limit on the enrichment of feed uranium will at least double the uranium consumption

Table VI

Important Properties of Thorium and Uranium Dioxides

Property	Value for ThO_2	reference	Value for UO_2 (24)
Crystal structure	Face-centred cubic (CaF_2 type)		Face-centred cubic (CaF_2 type)
Space group	$O_h^5 Fm3m$		$O_h^5 Fm3m$
Lattice parameter (Å)	5.5974 at 26°C	(32)	5.4704 at 20°C
	5.6448 at 942°C		5.5246 at 946°C
Theoretical density (g/cm^3)	10.00		10.96
Interatomic distances (Å)			
M-M	3.958		3.868
O-O	2.799		2.735
M-O	2.424		2.368
Termal properties			
Melting point (°C)	3300 ± 100	(30)	2760 ± 30
Spectral emissivity ($\lambda = 0.65\ \mu m$)	0.53 at 300°C to 0.21 at 800°C	(33)	0.418 ± 0.026 (near m.p.)
	0.2 to 0.65 at 1300°C depending on sample history	(34)	0.850 at 727°C
			0.370 at 1947°C
Thermal conductivity (W/cm deg C)	0.103 at 100°C 0.034 at 800°C		0.106 at 100°C
	0.086 at 200°C 0.031 at 1000°C		0.0915 at 200°C
	0.080 at 400°C 0.025 at 1200°C	(35)	0.0590 at 400°C
	0.044 at 600°C		0.0462 at 600°C
			0.0376 at 800°C
			0.0351 at 1000°C
Heat capacity (cal/mole deg C)	$17.080 + 18.06^{-4})T - 2.5166(10^5)/T^2$	(26)	$18.45 - 2.431(10^{-3})T \quad 2.272(10^5)/T^2$
(298 to 1200°C)			870°K
Debye temperature (°K)	200		< 600°K
			(300-600°K)

Table VI (cont.)

Property	Value for ThO_2	Ref	Value for UO_2 24
Coefficient of linear expansion ($^{\circ}C^{-1}$)	8216 (10) + 3.541 (10^{-9}) T - 0.1125/T^2	36	10.8 × 10^{-6} (20-926 °C)
			9.9 × 10^{-6} (25-800 °C)
			10.0 × 10^{-6} (400-800 °C)
			10.82 × 10^{-6} (26-1000 °C)
Vapour pressure (atm)	7.64 3.3440(10^4)/T(2200-2900 °K)	37	log P = 33115/T - 4.026 log T + 23.111
	9.02-3.78 (10^4)/T(2170-2400 °K)	38	
Thermodynamic properties			
Heat of formation, Δ_{298} (kcal/mole)	293.2 ± 0.4	29	259.2 ± 0.6
Free energy of formation, $-\Delta F_{298}$			
(kcal/mole)	279.2 ± 0.65		246.6 ± 0.6
Entropy, 298 °K, (cal/mole deg C)	15.593 ± 0.02	25	18.6 ± 0.1
Heat of sublimation (kcal/mole)	158.7 ± 2.5 in range 2000-3000 °K	37	137.1 ± 1.7 at 1800 °K
Entropy of sublimation (cal/mole deg C)	35.3 ± in range 2000-3000 °K	37	38.4 at 1800 °K
Mechanical properties			
Elastic properties			
Young's modulus (kilobars, lb/in^2)	1370, 19.8 (10^6)	23	1930,28.0(10^6) at room temperature
			1827,26.5(10^6) at room temperature
			1656,24.0(10^6) at 800 °C
Shear modulus (kilobars, lb/in^2)	990,14.3(10^6) at 30 °C		746,10.8(10^6) at room temperature
	390,5.6(10^6) at 1300 °C	39	
Poisson's ratio	0.17		0.302 at room temperature
Modulus of rupture (kilobars, lb/in^2)	0.83, 12 000	40	0.965-1.10, 14 000 - 15 000
Compressive strength (kilobars, lb/in^2)	15, 214 000	23	4.14-9.65, 60 000 - 140 000
Fracture strength (kilobars, lb/in^2)	1, 14 000	23	0.16 - 0.37, 2300-5400
Hardness, Knoop	640 (500-g load)	41	666 ± 14
			626
Electrical, magnetic, and optical			
properties			
Electrical resistivity (ohm cm)	1 to >10^4 at 1600 °C depending on sample and treatment	23	3. × 10^{-4} - 10^{-6} at room temperature
			about 10^{-1} at 600 °C
			about 10^{1} at 1000 °C
Index of refraction	2.09		2.35
			1.2 - 2.7

Table VII

Physical and Mechanical Properties of Thorium Metal

Lattice parameter, A	
Face-centered cubic structure up to	
1400°C(2550°F)	a_0(25°C, 77°F) = 5.086 ± 0.001
Body-centered cubic structure 1400°C	
(2550°F) to melting point	a_0(1450°C, 2640°F) = 4.11 ± 0.01
Density, g/cm^3	
Theoretical	11.72
Calcium reduced (as cast)	11.5 11.6
Arc melted iodide	11.66
Melting point, °C(°F)	1690-1750 (3075-3180)
Boiling point, °C(°F)	3300-4500 (5975-8130)
Heat of vaporization, Kcal/mole	130-177
Heat of fusion, Kcal/mole	< 4.6
Elastic constants (25°C, 77°F)	
Modulus of elasticity, psi	10.3 x 10^6
Shear modulus, psi	4.1 x 10^6
Poison's ratio	0.27
Compressibility, cm^2/dyne	16.4 x 10^{-13}
Thermal conductivity, 100-650°C	
(212-1200°F) cal/sec/cm^2/°C/cm	0.090-0.108
Coefficient of linear expansion (av.), °C^{-1}	
25-200°C(77-390°F)	11.0 x 10^{-6}
25-1000°C(77-1830°F)	12.5 x 10^{-6}
Electrical resistivity, μohm-cm	
Calcium reduced metal	18
Estimated for pure thorium	13-14
Self-diffusion coefficients, cm^2/sec	
1100-1400°C(2010-2550°F)	2 x 10^{-10}-2 x 10^{-8}
1450-1550° (2640-2825°F)	2 x 10^{-8}-1 x 10^{-7}

Table VIII

RADIATION ENERGIES OF THORIUM DECAY PRODUCTS[1]

Alpha decay			Beta decay		
Isotope	Mev	Mev	Isotope	Mev	Mev
U - 232	5 3	0 06, 0 129			
Th-232	4 0, 4 2		Ra-228(Ms Th_1)	0 002	
Th-228(RdTh)	5 4	0 09	Ac-228(Ms Th_2)	1 55	0 97
					0 91
Ra-224(ThX)	5 7, 5 4	0 25			0 46
					0 33
Rn-220(Tn)	5 3				0 06
Po-216(Th A)	6 8				
Bi-212(Th C)	6 1	0 29, 0 14	Pb-212(Th B)	0 33(88%)	0 24(90%)
				0 57(12%)	0 30(5%)
Po-212(Th C')	8 8				0 12(2%)
					0 18(1%)
			Bi-212(Th C)	2 25	0 72(18%)
					0 83(16%)
					1 03(6%)
					1 35(6%)
					1 61(12%)
					1 80(10%)
			Tl-208(Th C'')	1 79	2 62(40%)
					0 58(40%)
					0 51(20%)

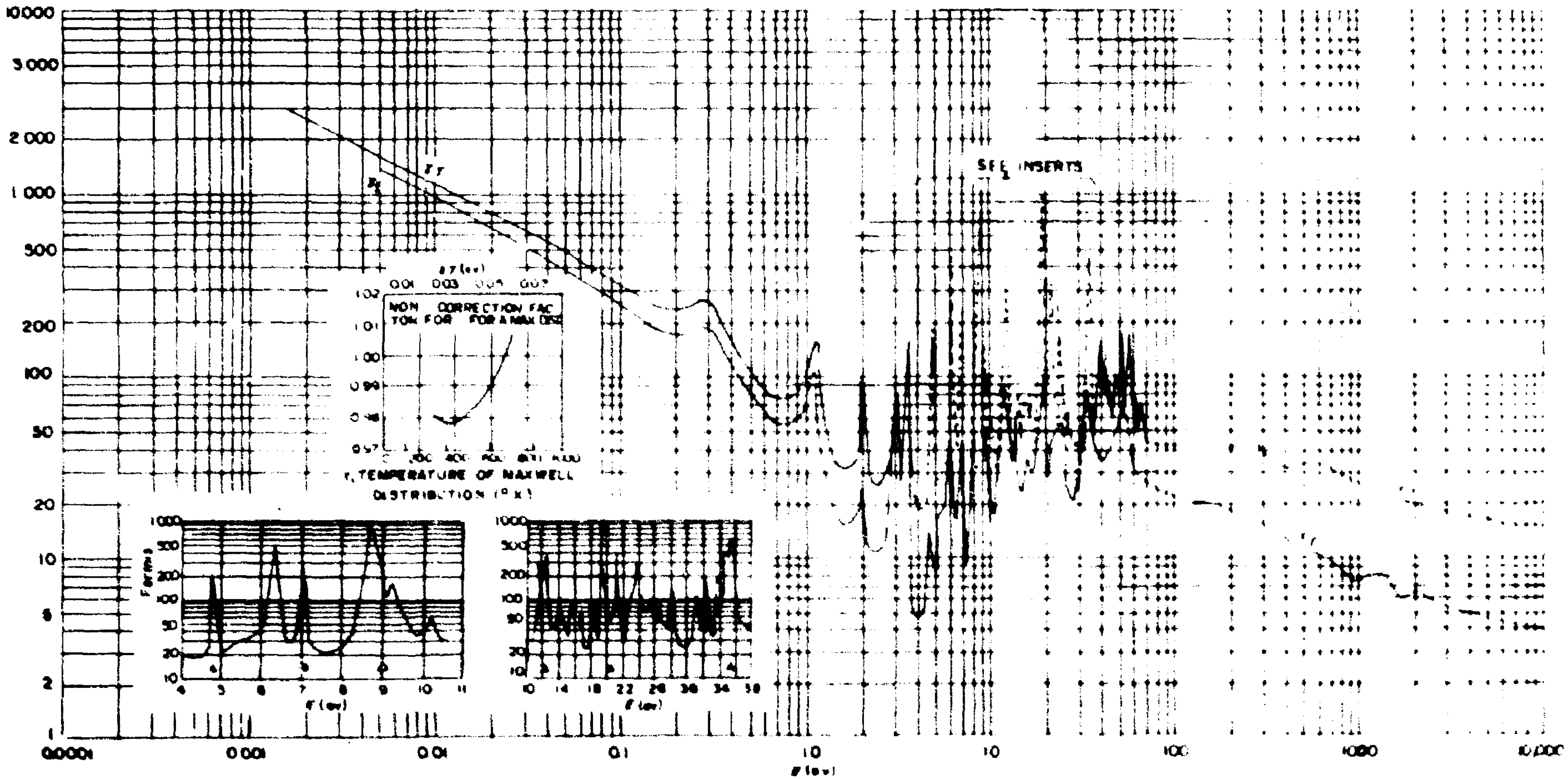


Fig. 1 - Total (σ_T) and fission (σ_F) cross-section of U^{233} in the low resonance and thermal regions. The triangles in this and the next three figures give the resolution width

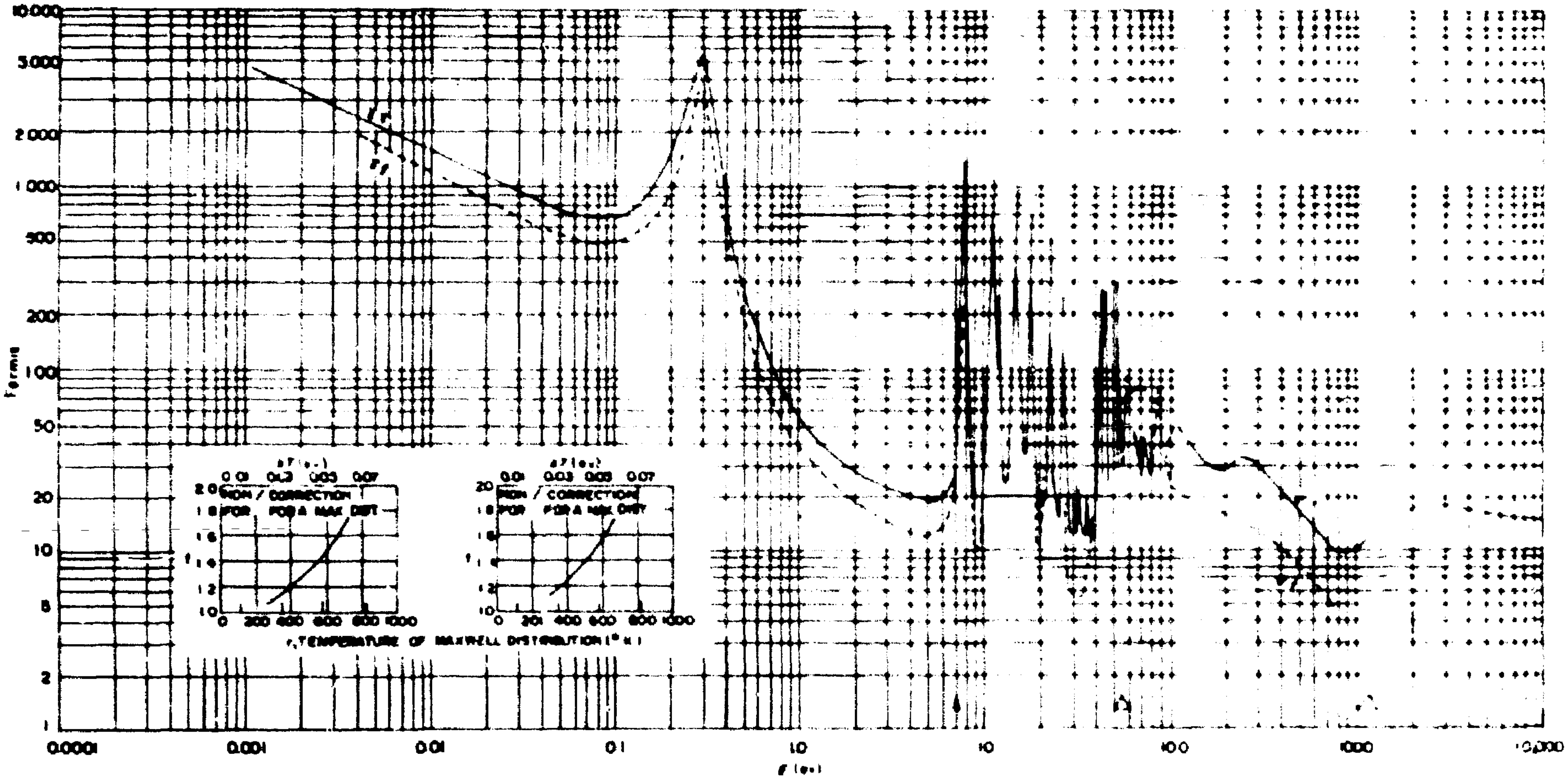


Fig 2 —Total (σ_T) and fission (σ_f) cross-sections of Pu^{239} in the low resonance and thermal regions

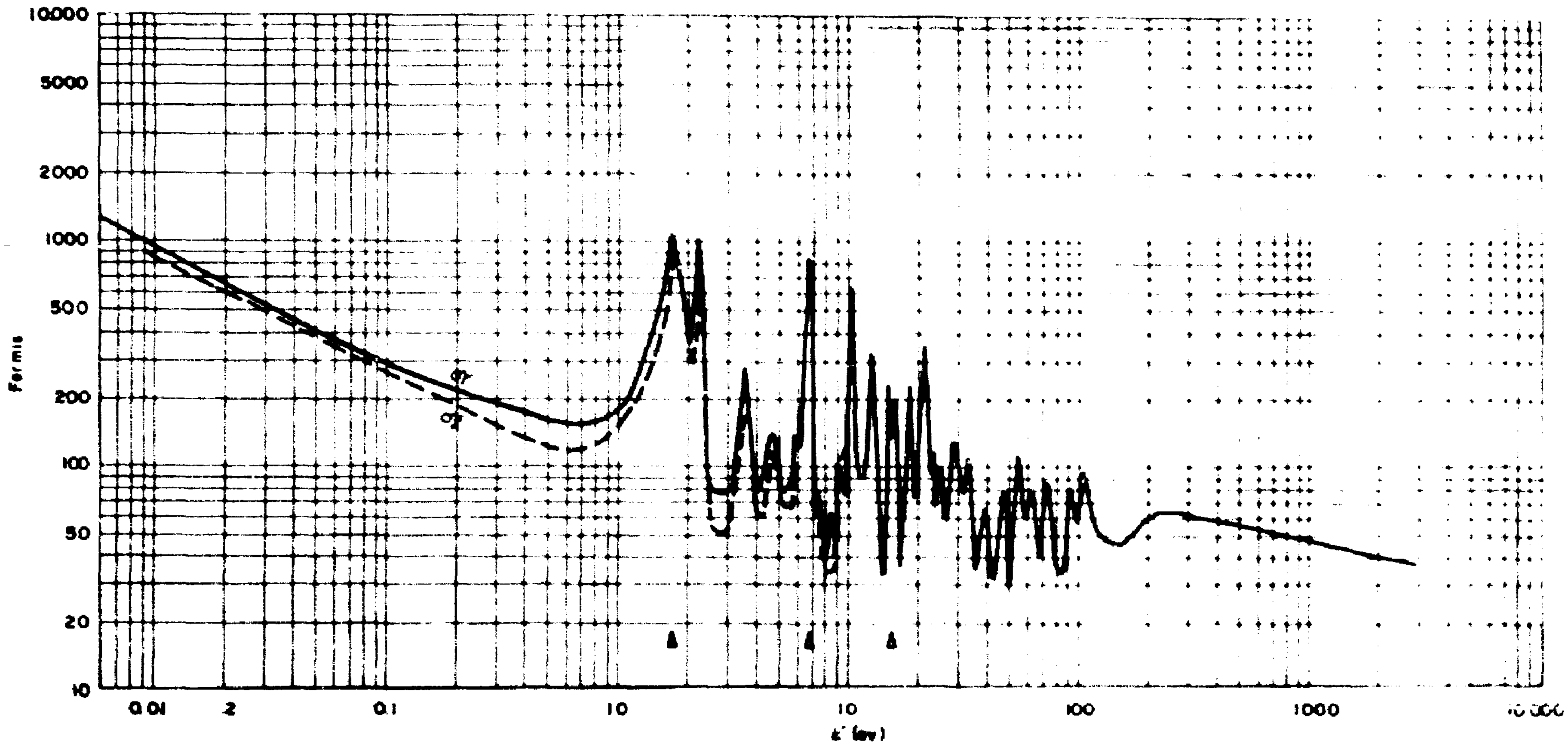


Fig. 3 – Total (σ_T) and fission (σ_f) cross-section of U^{233} in the low resonance and thermal regions

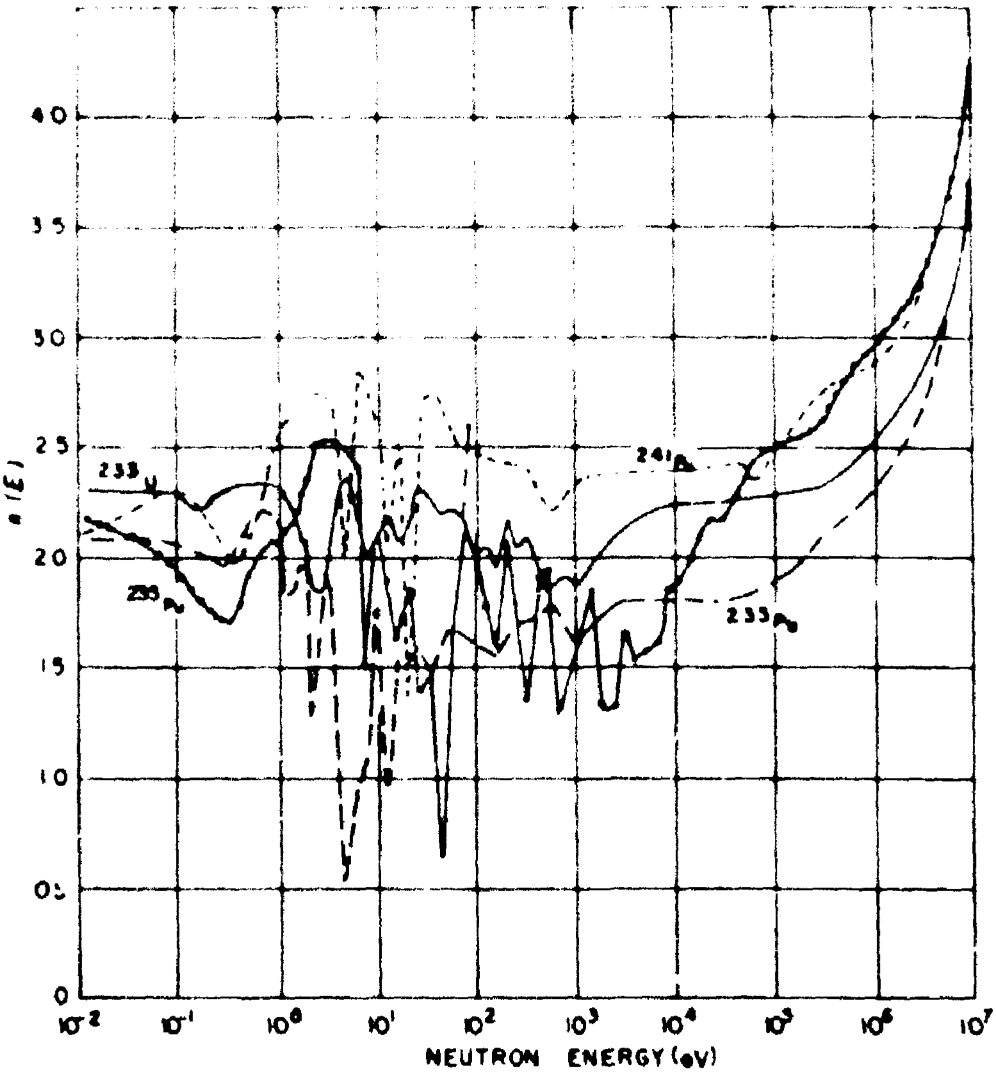


Figure 4 Energy dependence of eta for the principal fissile nuclides (4).

REPROCESSING OF THTR FULL ELEMENTS

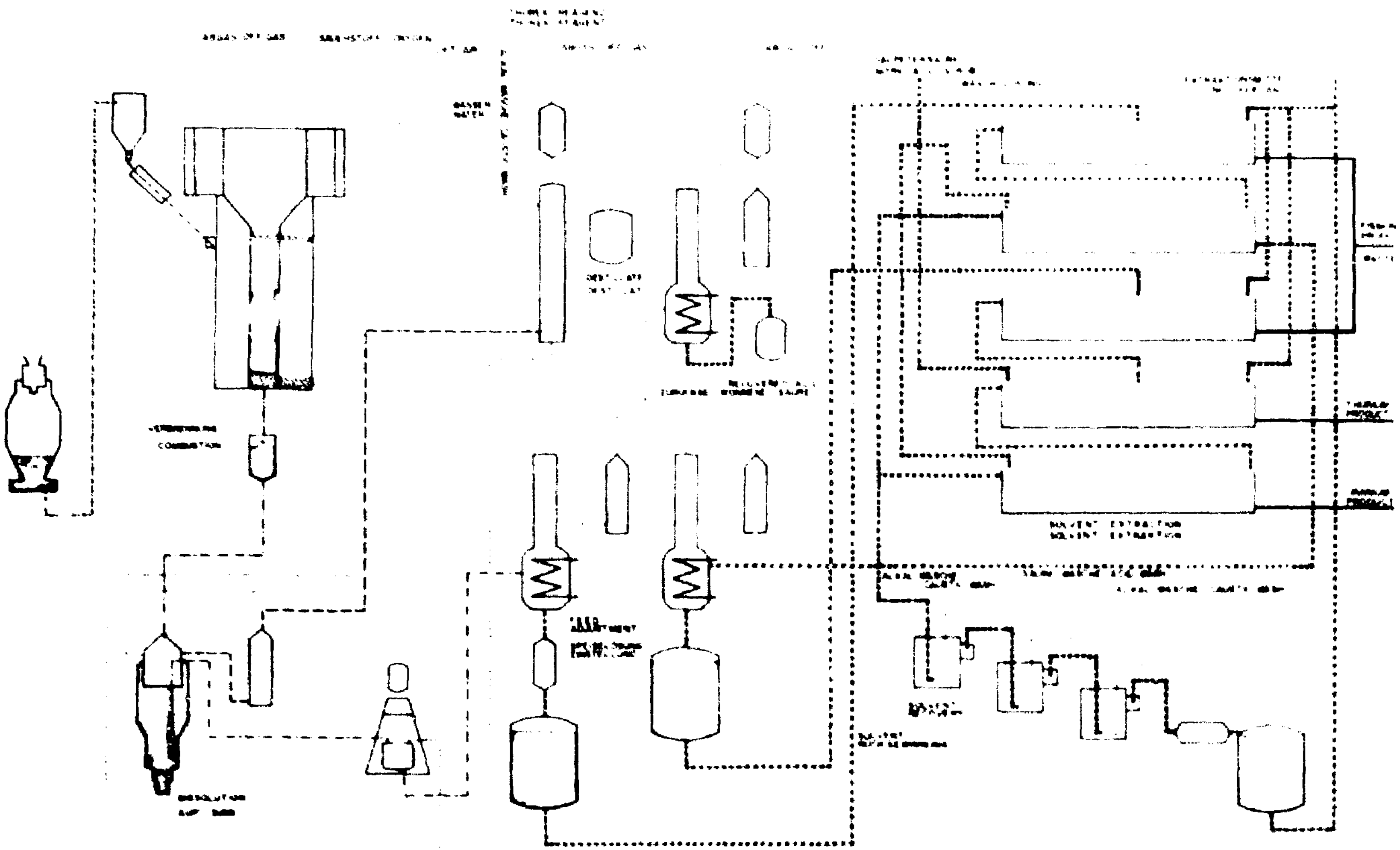
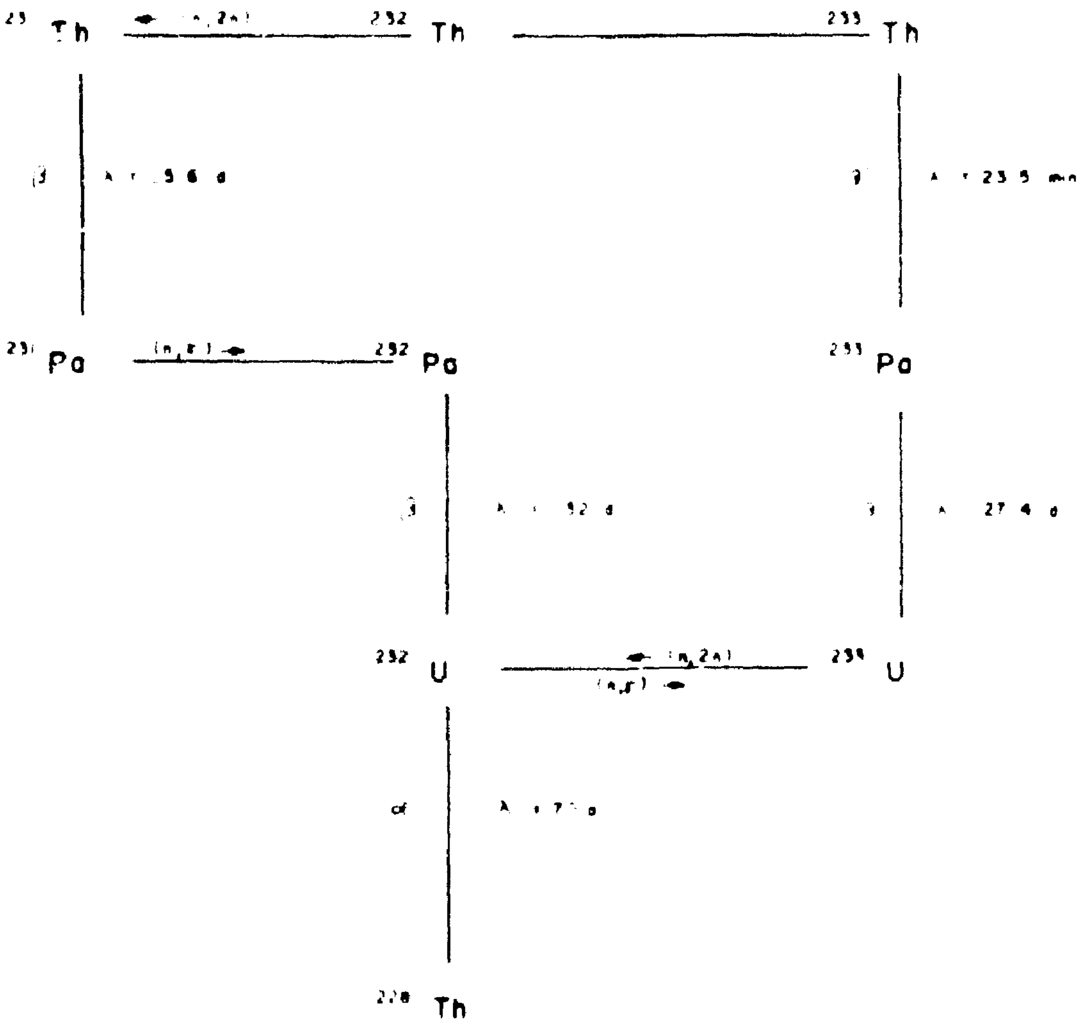


Fig 5 Generalized equipment flowsheet of JUPITER

FIG 6 PRODUCTION OF U-232 and U-233



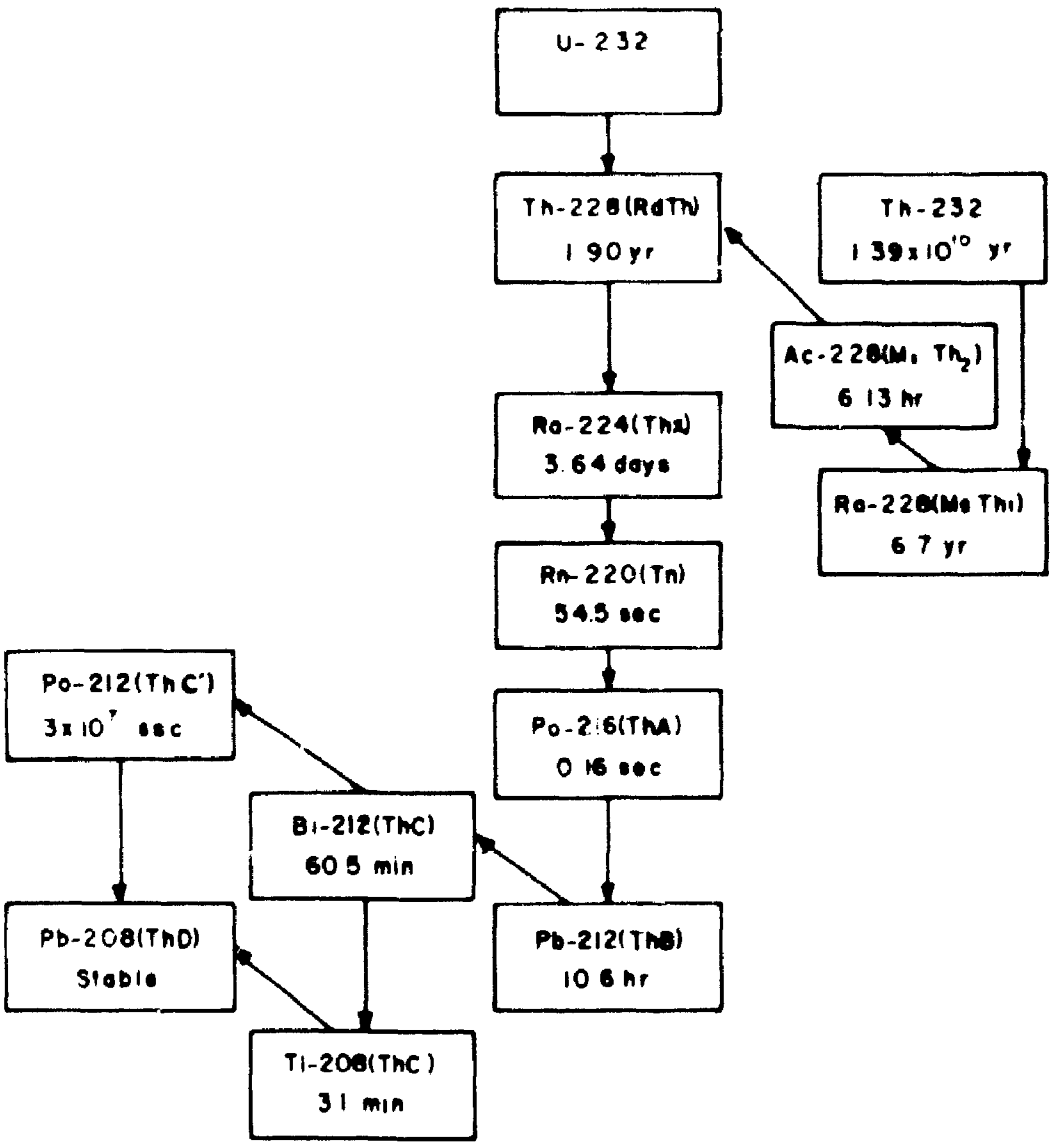


Fig 7. Decay scheme for thorium en U-232

Fabrication of Thorium Fuel Elements Ans

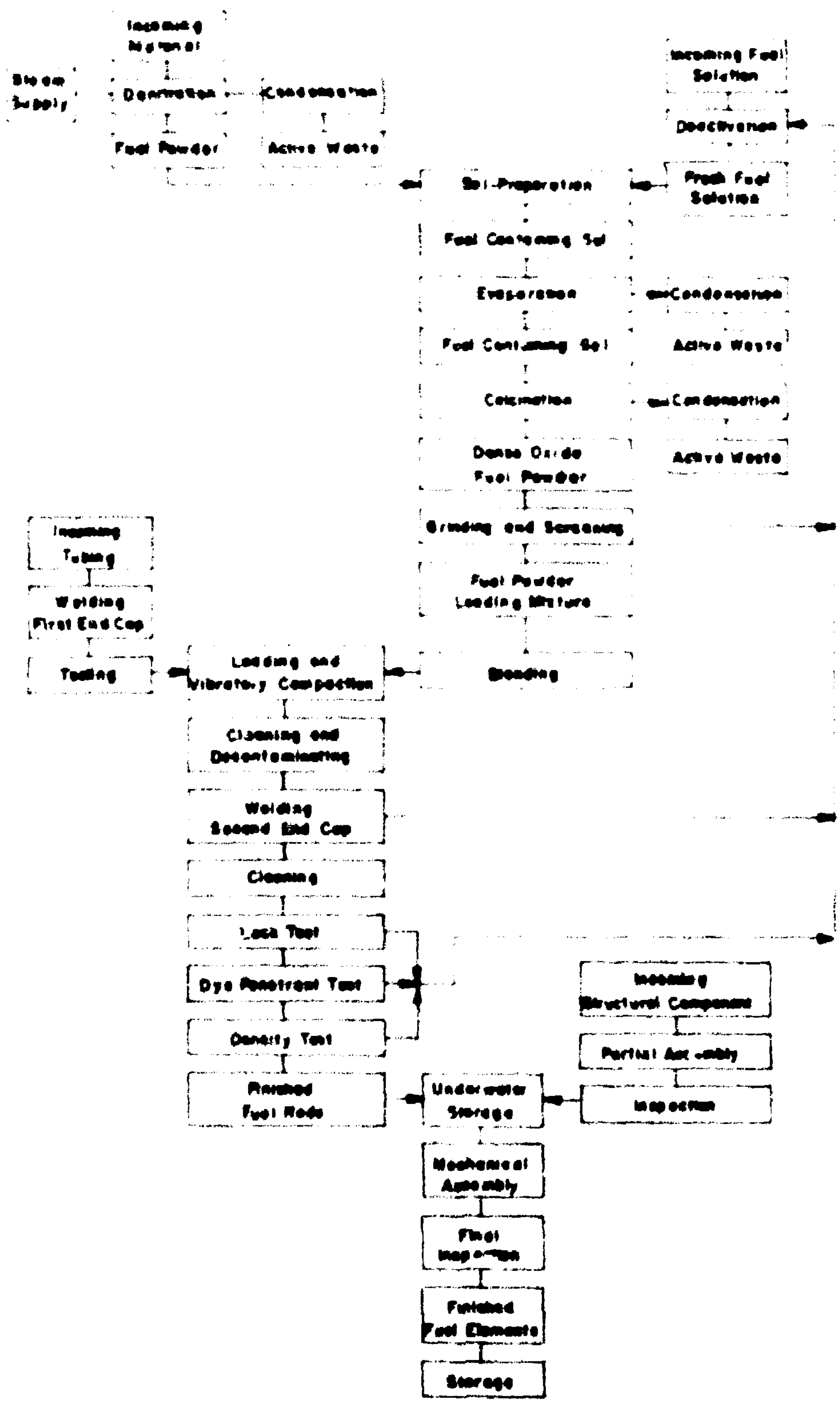


Fig. 8 Fuel fabrication flow sheet.

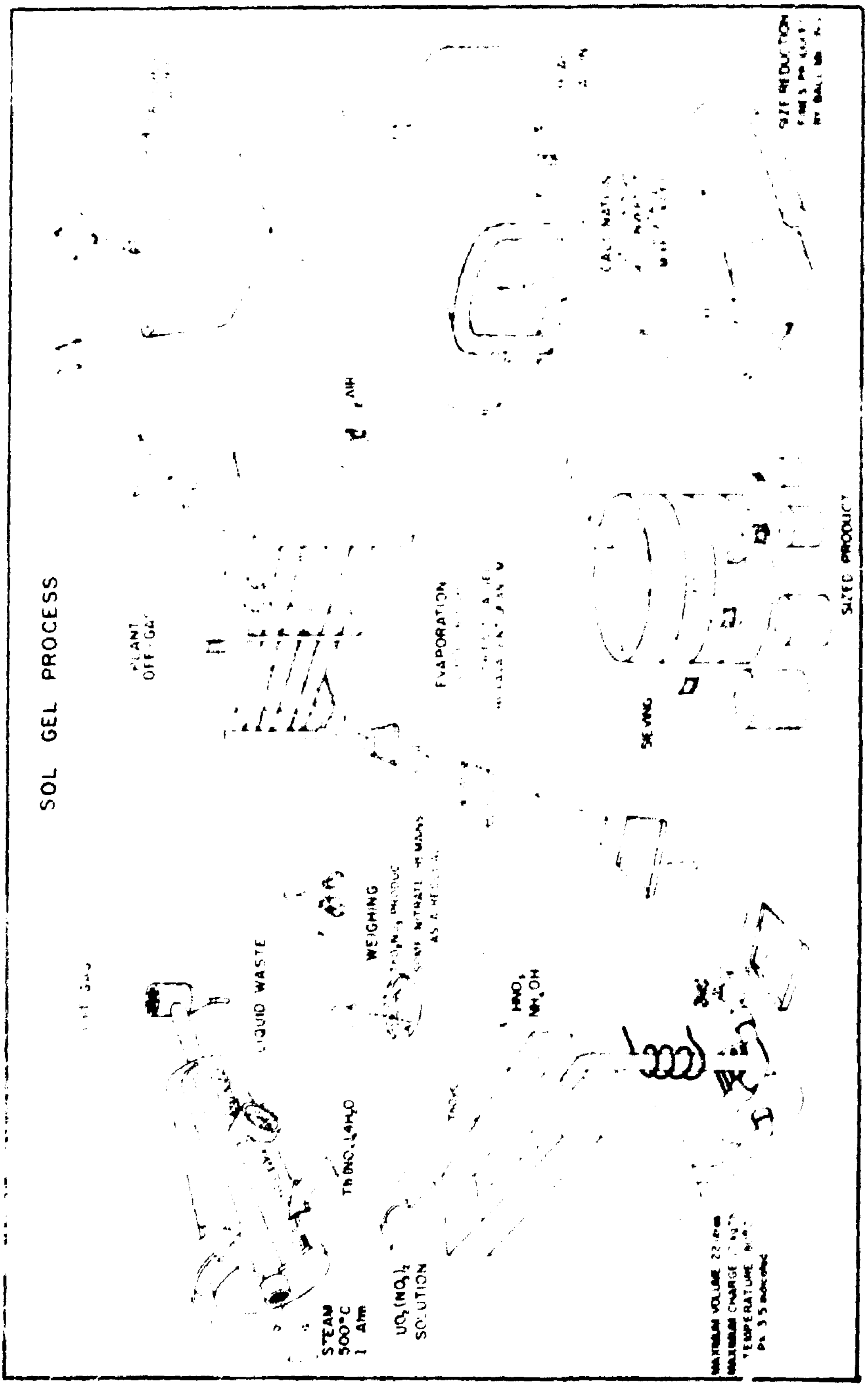


FIG 9—SOL GEL PROCESS FLOW SHEET

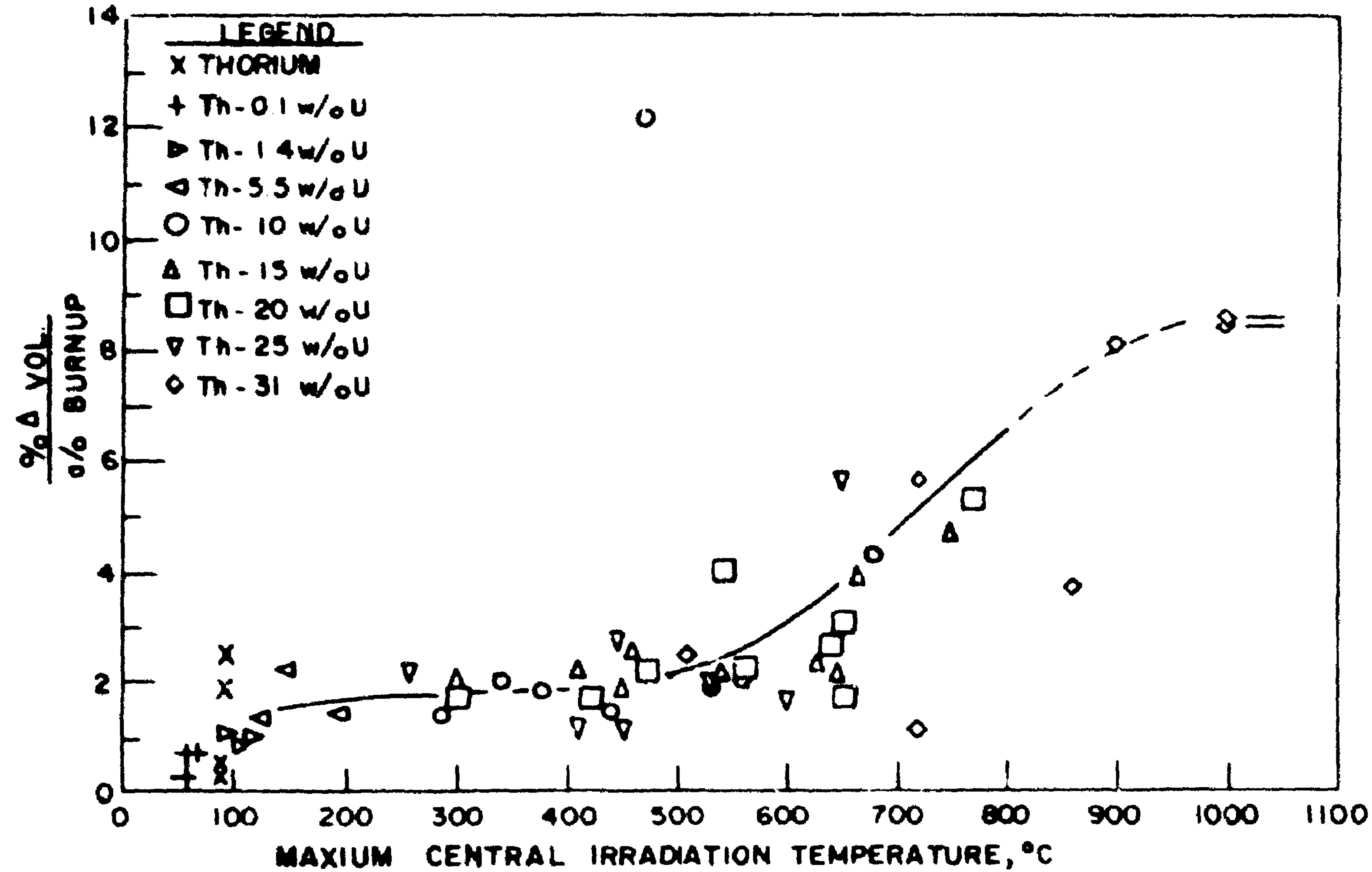


FIG. 10. Effect of irradiation temperature on the swelling rate of thorium and thorium-uranium alloys
Ref: KITTEL, J. H. et al., Effects of irradiation on thorium and thorium alloys. USAEC Rep. ANL 5
(1 April 1963)

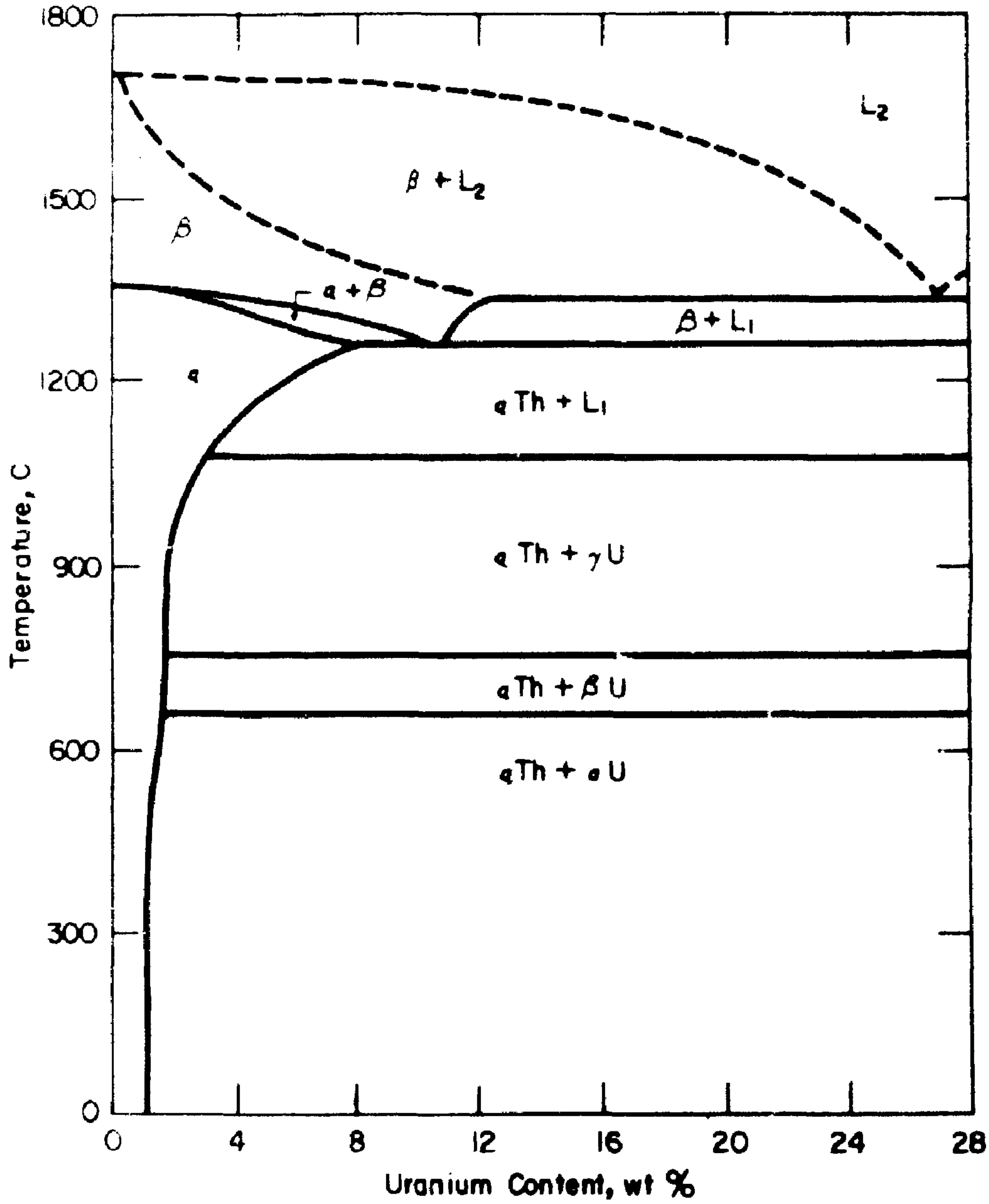


Fig. 11. Thorium–uranium equilibrium phase diagram for the range of interest of nuclear fuels.

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