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THE THORIUM FUEL CYCLE IN WATER-MODERATED REACTOR SYSTEMS

by

E. CRITOPH

Paper IAEA-CN-36/177 presented at the IAEA International Conference on Nuclear Power and its Fuel Cycle, Salzburg, Austria, 2-13 May 1977

Chalk River Nuclear Laboratories
Chalk River, Ontario
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Le cycle de combustible au thorium dans les réacteurs modérés par eau lourde ou légère*

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Résumé

L'intérêt actuellement porté au cycle de thorium, comme solution de rechange au cycle d'uranium pour les réacteurs modérés par eau, est fondé sur deux aspects avantageux de son emploi - la prolongation des approvisionnements d'uranium et le fait que le coût de l'énergie produite serait moins affecté par le prix de l'uranium. Bien que la plupart des bases scientifiques requises soient déjà disponibles, quelques démonstrations ayant trait à l'ingéniérie sont nécessaires pour que l'on puisse avoir de meilleures données économiques qui permettront de prendre des décisions rationnelles. On compare le cycle de thorium au cycle d'uranium en ce qui concerne les caractéristiques des réacteurs et leur technologie, la technologie des cycles de combustible, les paramètres économiques, le coût des cycles de combustible et les caractéristiques des systèmes. L'emploi du thorium ne semble donner lieu à aucun grave problème de faisabilité, bien que des développements soient requis pour la mise à l'essai et la gestion du combustible. Les cycles de thorium rendent nécessaire le recyclage du combustible. Les principales incertitudes concernent le coût de cette opération. De l'expérience doit être acquise dans la conception et le fonctionnement des installations de retraitement du combustible et de fabrication active pour pouvoir estimer les coûts avec une précision suffisante pour définir adéquatement l'éventail des conditions économiquement favorables aux cycles de thorium. Dans les réacteurs à eau lourde (HWR) des cycles de thorium ayant, à l'équilibre, des besoins en uranium, allant de zéro au quart de ceux du cycle d'uranium naturel à passe unique, semblent faisables. Une charge en oeuvre d'uranium se situant entre 1 et 2 Mg/MWe est nécessaire pour la transition vers l'équilibre. Les cycles ayant les plus faibles besoins en uranium ne peuvent concurrencer les autres que si l'uranium coûte cher. Dans les réacteurs à eau légère, les besoins en uranium des cycles de thorium peuvent être réduits par un facteur allant de deux à trois par rapport au cycle d'uranium à passe unique. Le réacteur surrégénérateur à eau légère qui promet, à l'équilibre, un besoin nul en uranium est en voie de développement. Ce type de réacteur, cependant, nécessite une plus grande charge en oeuvre d'uranium que les réacteurs HWR. Une vingtaine d'années s'écouleront entre le moment où l'on décidera d'employer le thorium et le jour où un impact significatif se produira sur l'utilisation de l'uranium (comparé au cycle de l'uranium, recyclage du plutonium).

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*Rapport IAEA-CN-36/177 présenté à la Conférence Internationale de l'AIEA sur l'Energie Nucléaire et son Cycle de Combustible, à Salzbourg, Autriche, les 2-13 mai 1977.

Imprimé par
l'Energie Atomique du Canada, Limitée
Laboratoires Nucléaires de Chalk River
Chalk River, Ontario
mai 1977

AECL-5705

THE THORIUM FUEL CYCLE IN WATER-MODERATED REACTOR SYSTEMS*

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ABSTRACT

Current interest in the thorium cycle, as an alternative to the uranium cycle, for water-moderated reactors is based on two attractive aspects of its use - the extension of uranium resources, and the related lower sensitivity of energy costs to uranium price. While most of the scientific basis required is already available, some engineering demonstrations are needed to provide better economic data for rational decisions. Thorium and uranium cycles are compared with regard to reactor characteristics and technology, fuel-cycle technology, economic parameters, fuel-cycle costs, and system characteristics. There appear to be no major feasibility problems associated with the use of thorium, although development is required in the areas of fuel testing and fuel management. The use of thorium cycles implies recycling the fuel, and the major uncertainties are in the associated costs. Experience in the design and operation of fuel reprocessing and active-fabrication facilities is required to estimate costs to the accuracy needed for adequately defining the range of conditions economically favourable to thorium cycles. In heavy-water reactors (HWRs) thorium cycles having uranium requirements at equilibrium ranging from zero to a quarter of those for the natural-uranium once-through cycle appear feasible. An "inventory" of uranium of between 1 and 2 Mg/MW(e) is required for the transition to equilibrium. The cycles with the lowest uranium requirements compete with the others only at high uranium prices. Using thorium in light-water reactors, uranium requirements can be reduced by a factor of between two and three from the once-through uranium cycle. The light-water breeder reactor, promising zero uranium requirements at equilibrium, is being developed. Larger uranium inventories are required than for the HWRs. The lead time, from a decision to use thorium to significant impact on uranium utilization (compared to uranium cycle, recycling plutonium) is some two decades.

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*Paper IAEA-CN-36/177 presented at the IAEA International Conference on Nuclear Power and its Fuel Cycle, Salzburg, Austria, 2-13 May 1977.

Printed by
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Chalk River Nuclear Laboratories
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1. INTRODUCTION

The adequacy of fissile uranium resources to meet the needs of large nuclear power programs based on present commercial reactor designs using uranium fuel cycles, is being questioned. Furthermore, the trend toward higher uranium prices provides an increasing incentive to utilize fissile uranium more efficiently.

Several current concepts are directly relevant. Aside from schemes that are independent of fission, these include the fast breeder reactor, electrical production of neutrons (and fissile material), and the use of advanced fuel cycles in thermal reactors.

Most industrialized countries have fast breeder reactor programs designed to exploit the capability of fast breeders to produce more fissile material than they consume. The concept of the production of fissile material from fertile, using neutrons from the fusion or spallation processes, is being pursued in several places. In principle, all these routes would permit almost total utilization of the fertile isotopes. It will be some time before commercial feasibility is proven for any of them, and technical feasibility has yet to be demonstrated for the use of fusion and spallation processes to produce fissile material.

While new thermal reactor types specifically designed for using thorium cycles may have advantages, the quickest and easiest step to take in the direction of improved uranium utilization is the use of thorium cycles, as an alternative to uranium cycles, in existing commercial reactor designs, i.e., in water-moderated reactors. It makes sense to evaluate what is involved, at least to provide a basis for judging other alternatives, and interest has

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revived in this topic over the last few years. It is the purpose of this paper to summarize the status of our understanding of thorium cycles applied to water-moderated reactors.

2. REACTOR TECHNOLOGY AND CHARACTERISTICS (PROVEN DESIGNS)

Thorium cycles could be used in both light- and heavy-water moderated reactors with only minor modifications in reactor design. This avoidance of new reactor development is a great potential advantage. We will first discuss these applications and later briefly mention modifications which have been proposed to take better advantage of thorium cycle characteristics.

2.1 Light-Water Moderated Reactors

There are two types of commercial light-water moderated reactors [1] - the Pressurized Water Reactor (PWR) and the Boiling Water Reactor (BWR). Many reactors of both types are in operation throughout the world.

Studies of the use of thorium cycles in these reactor types have been done [2,3,4,5,6], with the emphasis on the PWR. It is generally accepted that thorium cycles can be employed in them with no basic change in reactor design, and that existing reactors could be converted to the thorium cycle relatively easily.

Table I summarizes important characteristics of "standard" PWR designs converted to thorium fuel cycles, as well as reference once-through uranium cycles, and uranium cycles with plutonium and uranium recycling. The characteristics quoted in Table I have been put on a common basis with respect to reactor capacity (1 GWe), load factor (80%), enrichment tails (0.2%), and out-reactor delay for cooling, reprocessing, fabrication and hold-up (1 year). In some cases, where the characteristics quoted could not be derived from the available information, they were estimated on a consistent basis, and are shown in parentheses in the table. There are still relatively minor differences in reactor design parameters (notably specific power) which account for some of the differences in characteristics. On the whole the agreement among the various sets of results is quite good.

All the cases in the table use U-235 for external fissile-feed requirements. Some of the studies included other cases in which fissile plutonium as well as recycled uranium was added to the thorium. These will be mentioned later in connection with system studies.

Some aspects of Table I require explanation.

(a) In the "standard" burnup cases the fuel is substituted in a "standard" design and has the same average in-reactor dwell time as the "standard" fuel. Differences in burnup and specific power arise from differences in heavy-element densities.

(b) The "equivalent natural uranium" is the uranium which must be mined to satisfy the needs of the particular reactor. In most cases the uranium is enriched before being used in the reactor. The enrichment plant is assumed to operate with 0.2% U-235 in the tailings.

(c) "Inventory" has a very specific meaning as used here. It is defined as the difference between actual requirements over a fairly long period of time and the requirements determined from the equilibrium net feed rates applied from the in-service date. This concept permits an approxi-

TABLE 1

CHARACTERISTICS OF "STANDARD" PWR FUEL CYCLES

(assuming 0.2% enrichment tails and 1 year out-reactor delay for cooling, reprocessing, fabrication and hold-up).

CHARACTERISTIC	STANDARD BURNUP								VARYING BURNUP		
	UO_2 Once-Through		UO_2 : Pu + U Recycling		ThO_2 : U Recycling		Th Metal : U Recycling		Th Metal : U Recycling		
Reference	[6] (Lane)	[5] (Hellens et al.)	[6] (Lane)	[5] (Hellens et al.)	[6] (Lane)	[5] (Hellens et al.)	[6] (Lane)	[2] (Zorzoli)	[2] (Zorzoli)		
Burnup (MWd/kg HE)[a]	33.0	(32.4)	33.0	(32.4)	34.5	(35.6)	25.8	25.0	20.0	15.0	15.0
Equilibrium Feed Fuel[a]	3.2%	(3.26%)	Enriched UO_2 + Recycled Pu & U		ThO_2 + U-235 + Recycled U		Th Metal + U-235 + Recycled U				
	Enriched UO_2										
Net Station Efficiency	0.325	0.342	0.325	0.342	0.325	0.342	0.325	0.325	0.325	0.325	0.325
Specific Power (MW/Mg HE)	36.0	37.0	36.0	37.0	37.7	40.6	28.0	26.0	26.0	26.0	26.0
Equilibrium Net Feed Rates for 1 GWe at 80% Load Factor											
Equivalent Natural U (Mg U/a)	160	158	100	96	74	72	63	49	40	33	27
Thorium (Mg Th/a)	-	-	-	-	25	23	34	35	44	59	89
Separative Work (kg SWU x 10^3 /a)	130	129	96	84	96	93	82	64	52	43	35
HE to Reprocessing (Mg/a)	-	-	27	26	26	24	35	36	45	60	90
Net Production Rates for 1 GWe at 80% Load Factor											
Fissile Pu (Mg/a)	0.194	0.163	-	-	-	-	-	-	-	-	-
"Inventories" for 1 GWe at 80% Load Factor											
Equivalent Natural U (Mg U)[a]	(363)	(334)	(430)	(433)	(625)	(575)	(746)	(769)	(767)	(810)	(938)
Thorium (Mg Th)[a]	-	-	-	-	(84)	(72)	(114)	(124)	(124)	(131)	(146)
Separative Work (kg SWU x 10^3)[a]	(253)	(230)	(300)	(342)	(817)	(752)	(975)	(1005)	(1002)	(1059)	(1226)

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[a] Figures in parentheses are author's estimate

mate characterization of the fuel cycle uranium requirements by only two parameters - the equilibrium net feed rate and the "inventory". The bulk of the "inventory" requirements occur very early in the cycles - within the first few years of the in-service date. For the once-through cycles an allowance is made for fabrication and hold-up amounting to half of the annual equilibrium feed rate.

The equilibrium equivalent natural-uranium net feed rates for these cases are plotted in Figure 1 as a function of burnup, and the natural uranium "inventories" in Figure 2. (The solid lines connecting some points indicate a common source.) It is expected that BWR reactors would have similar uranium net feed rates but somewhat higher "inventories".

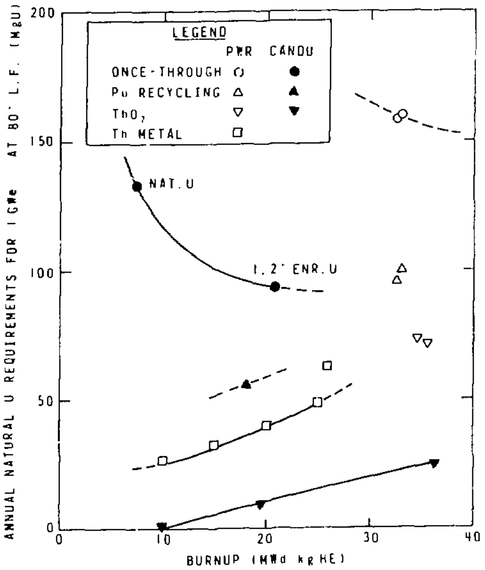

Fig.1. Annual Natural Uranium Requirements at Equilibrium for Various PWR and CANDU-PHW Cycles

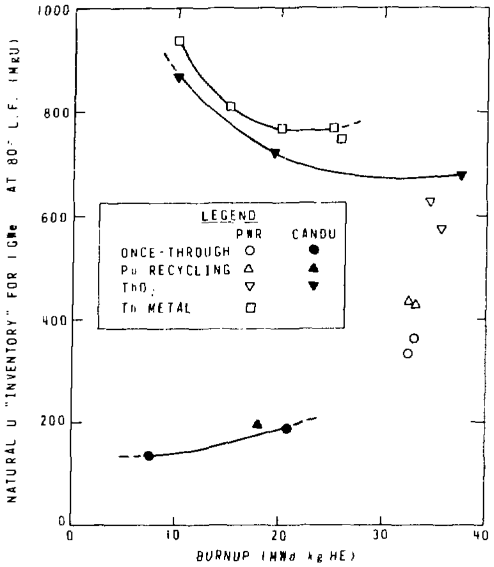

Fig.2. Natural Uranium "Inventories" for Various PWR and CANDU-PHW Cycles

2.2 Heavy-Water Moderated Reactors

Canada has developed a natural-uranium heavy-water reactor design, designated as the CANDU-PHW[1], to the commercial stage. Four 500 MWe units at the Pickering Nuclear Generating Station [7] have given more than 18 reactor-years of operating experience, and have performed well [8]. Another nuclear generating station (Bruce) with four 750 MWe units is well on the way to completion, with the first unit currently undergoing low-power commissioning (Fall 1976).

Atomic Energy of Canada Limited (AECL) has studied thorium cycles in CANDU-PHW reactors extensively over the last few years [9,10,11,12,13].

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[1] Canada Deuterium Uranium-Pressurized Heavy Water

The reactor designs used are almost identical to those for reactors using the uranium cycle, and so there are no new feasibility problems in design. The reference fuel material is ThO_2 (plus fissile isotopes) and fuel development and testing will be required to establish adequate fuel performance. Control is expected to be similar to that in natural uranium reactors of equivalent size, and no new feasibility questions in safety have arisen to date. Some extension of present methods and analysis will be required in the areas of reactor physics and fuel management.

TABLE II

CHARACTERISTICS OF CANDU-PHW FUEL CYCLES

(assuming 0.2% enrichment tails and 1 year out-reactor delay for cooling, reprocessing, etc.)

	UO_2 Once-Through		UO_2	ThO_2 : U Recycling and U-235 Topping		
Characteristic	Natural U Feed	1.2% Enr. U Feed	With Pu Recycling	High Burnup	Intermediate	Self Sufficient
Burnup (MWd/kg HE)	7.5	20.8	18.0	37.4	19.5	10.0
Equilibrium Feed Fuel	Natural Uranium	1.2% Enr. Uranium	Nat. U + Recycled Pu	ThO_2 + Recycled U + U-235		
Net Station Efficiency	0.291	0.291	0.291	0.291	0.291	0.291
Specific Power (MW/Mg HE)	23.4	23.4	23.4	26.3	26.3	26.3
Equilibrium Net Feed Rates for 1 GWe at 80% Load Factor						
Equivalent Natural U (Mg U/a)	133	94	56	26	10	0
Thorium (Mg Th/a)	-	-	-	26	51	99
Separative Work (kg SWU x 10^3 /a)	-	34	-	34	13	0
HE to Reprocessing (Mg/a)	-	-	56	27	52	100
Net Production Rates for 1 GWe at 80% Load Factor						
Fissile Pu (Mg/a)	0.360	0.158	-	-	-	-
"Inventories" for 1 GWe at 80% Load Factor						
Equivalent Natural U (Mg U)	140	190	194	680	719	871
Thorium (Mg Th)	-	-	-	79	91	115
Separative Work (kg SWU x 10^3)	-	68	-	882	932	1130

Table II summarizes the important characteristics of a basically common design operating on a number of different fuel cycles. Natural uranium and slightly enriched uranium once-through cycles and a uranium cycle with plutonium recycling are included in addition to three thorium cycles to provide a basis for comparison. The three thorium cycles cover the range of interest; from the "high burnup" case, which requires relatively large additions of external fissile material to recycled fuel, to the "self-sufficient" case in which, at equilibrium, no external fissile material is added to the recycled fuel.

The equilibrium natural-uranium net feed rates and natural-uranium "inventories" are also plotted in Figures 1 and 2. The thorium cycles here use U-235 for external fissile requirements but fissile plutonium may also be used, as will be discussed under "system studies".

2.3 Discussion

An examination of Figures 1 and 2 brings out the following two general points:

(a) Equilibrium annual uranium requirements in both light- and heavy-water reactors can be reduced progressively by going from once-through to plutonium recycling to thorium fuel cycles. The heavy-water moderated reactors have smaller annual requirements for each type of fuel cycle than light-water reactors, with a self-sufficient thorium cycle (at equilibrium) being possible for heavy-water moderated reactors.

(b) Natural-uranium "inventories" for both light- and heavy-water reactors increase progressively in going from once-through to plutonium recycling to thorium fuel cycles. For the once-through and plutonium recycling cases, heavy-water reactors have smaller natural-uranium "inventories" than light-water ones, but for thorium cycles the situation is reversed (due mainly to the lower specific power in the heavy-water cases).

3. URANIUM RESOURCE UTILIZATION

3.1 Lifetime Uranium Requirements

A single parameter which is often used to show the combined effects of "inventory" and feed rate is the lifetime uranium requirement. These are listed in Table III for the cases in Tables I and II using a 30-year lifetime at 80% load factor.

TABLE III

LIFETIME URANIUM REQUIREMENTS

(assuming 30 year lifetime at 80% load factor)

	PWR			CANDU-PHW	
Cycle	Lifetime Uranium Requirements (MgU)			Lifetime Uranium Requirements (MgU)	
Once Through	"Standard" burnup	[Ref.6]	5083	Natural Uranium	4130
	"	[Ref.5]	4995	1.2% enriched U	3010
Pu Recycling (+ U recycling for PWRs)	"	[Ref.6]	3380	(Natural U feed)	1874
	"	[Ref.5]	3265		
ThO_2 (U-235 external feed) with U recycling	"	[Ref.6]	2808	High burnup	1460
	"	[Ref.5]	2699	Intermediate	1019
				Self-sufficient	871
Th-metal (U-235 external feed) with U recycling	"	[Ref.6]	2604		
	"	[Ref.2]	2214		
	Varying burnup				
	20 MWd/kg Th	[Ref.2]	1947		
	15 "	[Ref.2]	1784		
	10 "	[Ref.2]	1735		

The lifetime uranium requirements are not particularly useful in considerations of resource conservation since, on the one hand, the "inventories" can be used to start replacement reactors whereas, on the other hand, the "inventory" requirements occur near the beginning of life and consequently have a disproportionate effect on total uranium requirements in an expanding system at any given time.

3.2 System Studies

To make realistic estimates of the impact of various fuel cycles on uranium requirements, system studies must be done. There are two main reasons:

(a) If advanced cycles are introduced, nuclear power systems will usually consist of a varying mix of reactors using different fuel cycles. These may be interdependent, in which case energy costs, as well as uranium requirements, can only be properly determined for the system as a whole.

(b) The relative importance of "inventory" and equilibrium feed requirements depends on the growth rate of the system.

There is also a third reason for doing system studies. This is to estimate the total requirements and appropriate unit sizes for ancillary facilities such as enrichment, D_2O production, fabrication, reprocessing and waste disposal plants as a function of time. These considerations can affect both feasibility and economics.

3.2.1 Use of Plutonium with Thorium

Plutonium produced by either light- or heavy-water reactors operating on a once-through uranium cycle can be used, instead of highly enriched U-235, to supply the external fissile requirments for thorium fuelled reactors. For light-water reactors it has been found [5] that the recycling of plutonium into thorium will produce about 22% more energy per unit quantity of plutonium consumed than will the recycling of plutonium into uranium. This would then be an advantageous way of utilizing existing stockpiles of plutonium. However, in the longer term, if only plutonium were used as the topping material in the thorium fuelled PWRs, 70% of the reactors would have to be operated on the uranium once-through cycle to provide plutonium for 30% of the reactors operating on the thorium-plutonium cycle (with uranium recycling). This dilutes the benefits and this system requires 3% less uranium and 2% more separative work than the uranium cycle with plutonium recycling.

The situation is more favourable for heavy-water reactors. A number of studies have been done [10,11,12,13] which assume systems composed of CANDU-PHW reactors operating on a once-through uranium cycle, feeding plutonium to other reactors operating on a plutonium-thorium cycle (with uranium recycling). Table IV gives characteristics of these latter reactors for cycles corresponding closely to those in Table II. Table V shows the proportion of the reactors in the system of each type, and the equilibrium system uranium requirements. Stockpiles of plutonium would have to be used for the inventory requirements of the plutonium-thorium reactors.

TABLE IV

CHARACTERISTICS OF CANDU-PHW PLUTONIUM-THORIUM CYCLES

(assuming 1 year out-reactor delay for cooling, reprocessing, fabrication and hold-up)

	ThO_2: U Recycling and Plutonium Topping		
Characteristic	High Burnup	Intermediate	Self-Sufficient
Burnup (MWd/kg HE)	37.2	18.7	10.0
Equilibrium Feed Fuel		(Th + Recycled U + Pu)	
Net Station Efficiency	0.291	0.291	0.291
Specific Power (MW/Mg HE)	26.3	26.3	26.3
Equilibrium Net Feed Rates for 1 GWe at 80% Load Factor:			
Fissile Pu (Mg/a)	0.1345	0.0535	0
Thorium (Mg Th/a)	26.9	53.5	100.1
"Inventories" for 1 GWe at 80% Load Factor:			
Fissile Pu (Mg)	3.74	4.02	4.93
Thorium (Mg Th/a)	78.6	91.9	115.2

TABLE V

ANNUAL EQUILIBRIUM SYSTEM URANIUM REQUIREMENTS

(natural uranium CANDU-PHWs feeding plutonium-thorium CANDU-PHWs)

System	Fraction of System in Plutonium-Thorium Reactors	Annual Uranium Requirements for 1 GWe at 80% Load Factor	
		(Mg U/a)	
Natural uranium CANDU-PHWs + ThO_2 (high burnup) CANDU-PHWs	0.73	36	(26)[a]
Natural uranium CANDU-PHWs + ThO_2 (intermediate) CANDU-PHWs	0.87	17	(10)[a]
Natural uranium CANDU-PHWs + ThO_2 (self-sufficient) CANDU-PHWs	1.00	0	(0)[a]

[a] values in parentheses are for corresponding systems consisting of U-235-thorium CANDU-PHWs only.

3.2.2 Expanding Systems

To get a feel for the effect of growth rate, assume that the power production capacity from a reactor type operating on a particular fuel cycle is growing at a fixed exponential rate, i.e., $P(t) = P_o e^{\alpha t}$. Then it can easily be shown that the annual uranium requirement per GWe operating at 80% load factor, A, is given by:

$$A = \alpha I + R \quad \text{(MgU/a for 1 GWe at 80\% load factor)}$$

where I is the "inventory" in Mg for 1 GWe at 80% load factor, and R is the annual feed rate in MgU/a for 1 GWe at 80% load factor.

Table VI gives the annual uranium requirements for the cycles which have been discussed in both PWRs and CANDU-PHWs for various growth rates. Note that the annual uranium requirements are proportional to the lifetime uranium requirements (30-year lifetime) for a growth rate of 3.3% per annum.

TABLE VI

ANNUAL URANIUM REQUIREMENTS FOR VARIOUS GROWTH RATES

(assuming 80% load factor, 0.2 enrichment tails, and 1 year out-reactor delay)

		Annual Uranium Requirements (MgU/a) for 1 GWe				
		Value of α				
		$0\ a^{-1}$	$0.0333\ a^{-1}$	$0.06\ a^{-1}$	$0.10\ a^{-1}$	$0.15\ a^{-1}$
PWR						
Once-through	[ref.6]	160	172	182	196	214
	[ref.5]	158	169	178	191	208
Pu recycling	[ref.6]	100	114	126	143	165
	[ref.5]	96	110	122	139	161
ThO_2 (U-235 topping)	[ref.6]	74	95	112	137	168
	[ref.5]	72	91	107	130	158
Th-metal (U-235 topping)						
Standard burnup	[ref.6]	63	88	108	138	173
	[ref.2]	49	75	95	126	164
20 MWd/kg HE	[ref.2]	40	66	86	117	155
15 "	[ref.2]	33	60	82	114	155
10 "	[ref.2]	27	58	83	121	168
CANDU-PHW						
Once-through, natural U		133	138	141	147	154
Pu recycling		56	62	68	75	85
ThO_2 (U-235 topping)						
high burnup		26	49	67	94	128
intermediate		10	34	53	87	118
self-sufficient		0	29	52	87	131
ThO_2 (Pu Topping)[a]						
high burnup		36	58	70	86	101
intermediate		17	47	63	82	99
self-sufficient		0	43	64	85	104

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[a] in systems with required fraction of natural uranium reactors for plutonium production

Computer codes such as FISS [14] and NEEDS [15] have been developed to simulate expanding nuclear power systems with more complicated growth scenarios. These provide more accurate estimates of fissile and fertile mass flows, resource requirements, ancillary facility capacity requirements, etc. Little or no work has been reported for light-water reactors employing thorium cycles. Results have been reported [10,12,16] for a number of studies on heavy-water reactors using thorium cycles.

The following general observations are based on Table VI and these other studies:

(a) In each reactor type (i.e., light- and heavy-water moderated) plutonium recycling (plutonium + U recycling in the case of PWRs) gives a substantial reduction in uranium requirements from those of the corresponding once-through cycle. For PWRs this saving varies from about 40% of the once-through consumption at low growth rates ($\alpha = 0$ to $0.03\ a^{-1}$) to about 30% at high growth rates ($\alpha = 0.06$ to $0.10\ a^{-1}$). The corresponding CANDU-PHW savings relative to its once-through cycle consumption are about 60% and 50%.

(b) In both cases, further reductions in uranium consumption can be realized, for all except high growth rates, by employing thorium cycles. For the CANDU-PHW at low growth rates, savings as high as 100% are envisaged.

(c) If uranium supply were suddenly exhausted or the price became prohibitive the CANDU-PHW self-sufficient thorium cycles could operate indefinitely at constant capacity, being limited eventually by thorium supply. The other CANDU-PHW and -PWR thorium cycles could operate with negative growth rates adjusted to give zero annual uranium consumption, i.e., the "inventories" of decommissioned reactors could provide feed for the remainder. Under these circumstances, although there are limits on capacity, the total energy derived from a given uranium supply is approximately inversely proportional to the equilibrium feed rate (except in the unlikely event that thorium supply is limiting).

4. FUEL CYCLE TECHNOLOGY

Since once-through thorium cycles are not attractive from the point of view of both economics and resource conservation, the use of thorium cycles implies the recycling of fissile material. This, in turn, means reprocessing discharged fuel, active fabrication of fuel containing recycled material, and disposal of separated radioactive wastes. No feasibility problems are foreseen but there are large uncertainties in cost.

Canada is planning a research, development and demonstration program in these areas. This program involves the building of pilot and demonstration plants for reprocessing, active fuel fabrication and waste disposal. It is expected that 20 years will be required to accumulate sufficient data and expertise to, first, make a decision on advanced cycles, and then, if indicated, to commence their implementation.

5. ECONOMIC CONSIDERATIONS

The main uncertainties in the economic evaluation of thorium cycles are in the reprocessing costs, penalties associated with active fabrication, and uranium price. The procedure adopted here is to calculate the break-even value of reprocessing cost plus active-fabrication penalty, at various uranium prices, for each of the thorium cycles relative to the appropriate once-through and plutonium recycling fuel cycles. The following assumptions are made (where values are constant in 1976 dollars):

(a) Fabrication cost for standard UO_2 fuel (including conversion to the oxides but excluding heavy element cost)

PWR fuel : \$100/kg HE
CANDU-PHW fuel : \$40/kg HE

Thorium metal and ThO_2 fuels were assumed to have the same basic cost per fuel assembly, i.e., the basic cost per kilogram was assumed to be inversely proportional to density. The active-fabrication penalty was then assumed to be added to the basic cost.

(b) Conversion of U_3O_8 to UF_6 : \$4/kgU,

(c) Separative work : \$75/kg SWU,

(d) Thorium price : \$15/kg Th,

(e) Discount rate : 4%/a,

(f) Radioactive waste disposal costs were assumed to be the same for all cycles (differences can be assumed to be part of the reprocessing plus active-fabrication penalty cost).

(g) The reprocessing plus active-fabrication penalty cost for plutonium recycled fuels was assumed to be 81% of that for thorium recycled fuels, and 68% of this was assumed to be associated with reprocessing for CANDU-PHW plutonium recycled fuel.

The results are shown for PWRs in Figure 3 and CANDU-PHWs in Figure 4 (note change in vertical scale). The most economic cycles are shown as a function of uranium price and thorium reprocessing plus active-fabrication penalty cost.

Current estimates for thorium reprocessing plus active-fabrication penalty costs are about \$150/kg HE for CANDU-PHW fuel and \$400/kg HE for PWR fuel. These estimates are not necessarily consistent, although there are factors leading to lower values for CANDU-PHW fuels than PWR fuels. The major factor is that public financing has been assumed for CANDU fuel reprocessing and active-fuel fabrication plants as opposed to private financing for PWR fuels. The simpler fuel geometry, which makes the basic fabrication cost lower for CANDU fuel than PWR fuel, should also tend to reduce active-fabrication penaltie. and, to some extent, reprocessing costs. Other minor factors include differences in burnup level and allowances for waste and plutonium storage facilities.

Of interest also are the penalties one would pay for using thorium cycles in the region where use of the uranium cycle with plutonium recycling is favoured. A few values of the penalties are indicated in the figures, with the most favourable thorium cycle being assumed.

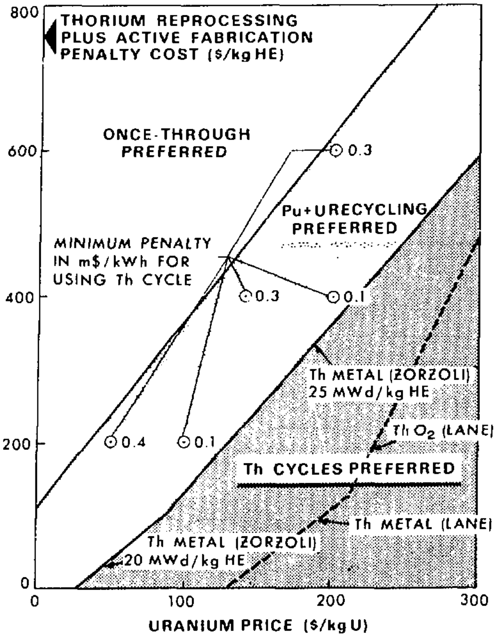

Fig.3. Preferred Cycles in PWRs from Economic Considerations

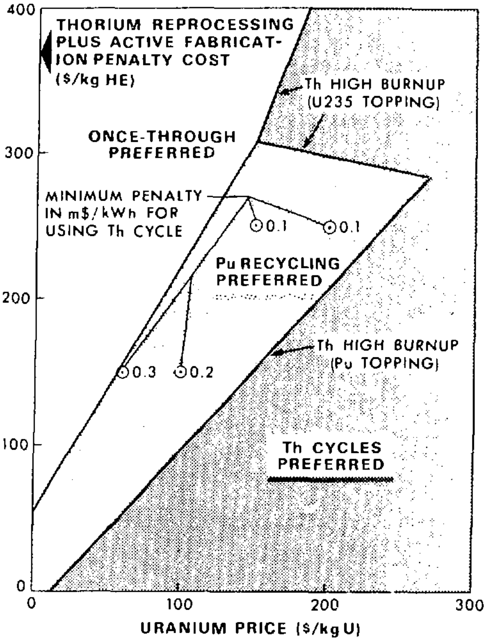

Fig.4. Preferred Cycles in CANDU-PHWs from Economic Considerations

6. UNPROVEN REACTOR DESIGNS

While the proven water-moderated reactor designs are basically suitable for adaptation to thorium cycles, it would be a remarkable coincidence if they were the optimum. Other designs using the same basic technology would still have an advantage over new reactor types using a new technology, and, therefore, are worth considering.

Studies have been done of variations in design parameters of standard heavy-water reactors [10,12,17,18], including changes in fuel design, lattice pitch, specific power and coolant (boiling light water, organic liquid and pressurized light water). The relative performance of thorium cycles to uranium cycles over a wide range of reactor designs is surprisingly similar. Certain aspects of the use of thorium cycles can be improved (e.g., lower inventories and capital costs) but no single design is clearly preferred on all counts. The choice of reactor design for large scale implementation of thorium cycles will depend on the particular conditions expected at the time the choice is made.

More drastic revisions to the proven light-water reactor design are involved in the development of the Light Water Breeder Reactor (LWBR) [19]. This seed-blanket concept is expected to attain at least "break-even" breeding from cores which could be installed in present light-water cooled nuclear plants, with some modifications. The improved performance with respect to uranium utilization is achieved primarily through two aspects of the concept:

(a) the separation into seed and blanket regions makes it possible to tailor the neutron spectrum in each region to best advantage, and

(b) it employs a unique system of reactivity control which involves changing the relative absorption in fissile and fertile material by moving the seed relative to the blanket, thereby reducing the loss of neutrons to parasitic control absorbers.

A demonstration of this concept is scheduled to start operating at Shippingport in 1977. Since the LWBR needs a U-233/thorium core from the start, pre-breeders are required to produce the relatively large U-233 "inventories". The economics of this concept are very uncertain and it is too early to predict where it will stand relative to the more conventional schemes.

Radkowsky et al. [20] have patented a variation of the LWBR - the close-packed heavy-water seed-blanket breeder. This concept has the potential advantage, compared to the LWBR, of increased breeding ratio and lower "inventories", but is at a much earlier stage in terms of technical feasibility.

Finally, it has been suggested [5] that incorporating the spectrum shift control concept in PWRs would reduce both uranium "inventories" and equilibrium feed rates. Using this concept, neutron capture would be reduced in both control poisons and coolant by introducing a variable amount of heavy water into the light-water coolant to control the excess reactivity of the fuel.

7. CONCLUSIONS

(a) Proven designs of light- and heavy-water reactors can be adapted to the thorium cycle with little or no modification.

(b) The energy derivable from a given uranium resource is considerably larger for thorium cycles than uranium cycles. Uranium resource utilization is particularly favourable in heavy-water reactors.

(c) The economic competitiveness of thorium cycles compared to uranium cycles depends on costs associated with reprocessing plus active fabrication and uranium price. It seems likely that, within a couple of decades, these will be such as to make thorium cycles economically preferred or at only a slight economic disadvantage.

(d) The main developments required for the implementation of thorium cycles are in the out-reactor parts of the fuel cycle.

(e) High priority should be given to development of the out-reactor fuel cycle to permit, in the first instance, more rational decisions on the use of thorium cycles and, in the second, their rapid implementation when the need arises.

(f) Unproven water reactor designs, with characteristics favourable to the thorium cycle, should be further assessed.

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The International Standard Serial Number

ISSN 0067–0367

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