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ATOMIC ENERGY
OF CANADA LIMITED

L'ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

CANDU ADVANCED FUEL CYCLES
A LONG-TERM ENERGY SOURCE

Cycles de combustible avancés CANDU
une source d'énergie à long terme

J.B. SLATER

Chalk River Nuclear Laboratories
Laboratoires nucléaires de Chalk River

Chalk River, Ontario

March 1986 mars

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by

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Reactor Development
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Résumé

Ce rapport est basé sur des conférences officieuses et sur des présentations au sujet des cycles de combustibles avancés CANDU, données au cours de cette dernière année, et discute du rôle futur du CANDU à l'intérieur de l'environnement changeant pour l'industrie nucléaire énergétique Canadienne et internationale.

Les perspectives changeantes des dix dernières années ont mené à la conclusion qu'un marché futur, significatif, existera pour un réacteur thermique avancé CANDU, et ceci pour plusieurs périodes de dix ans. Un réacteur de ce genre pourra fonctionné dans une stratégie d'un système indépendant ou pourra être intégré dans stratégie mixte de CANDU à eau légère ou de CANDU du type rapide-surgénérateur.

L'emphase consistant du dessein CANDU d'une utilisation des ressources, avec une efficacité rehaussée, combinée avec une technologie simple pour parvenir à des objectifs économiques, donnera une flexibilité suffisante pour maintenir CANDU comme producteur énergétique viable pour un futur à moyen et à long terme.

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ABSTRACT

This report is based on informal lectures and presentations made on CANDU Advanced Fuel Cycles over the past year or so, and discusses the future role of CANDU in the changing environment for the Canadian and international nuclear power industry.

The changing perspectives of the past decade lead to the conclusion that a significant future market for a CANDU advanced thermal reactor will exist for many decades. Such a reactor could operate in a stand-alone strategy or integrate with a mixed CANDU-LWR or CANDU-FBR strategy.

The consistent design focus of CANDU on enhanced efficiency of resource utilization combined with a simple technology to achieve economic targets, will provide sufficient flexibility to maintain CANDU as a viable power producer for both the medium- and long-term future.

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1. INTRODUCTION

This report is based on informal lectures and presentations made on CANDU* Advanced Fuel Cycles over the past year or so, and discusses the future role of CANDU in the changing environment for the Canadian and international nuclear power industry.

The security and cost of long-term energy supplies continue to be a matter of deep concern to most nations. Recent history, particularly that of the past ten years, has revealed the fragility of the world energy supply mechanism for conventional fuels and has emphasized the need for greater efficiency in the utilization of natural energy resources. Many international studies indicate that nuclear power will play an increasingly important role in the world's energy supply during the 21st century. The bulk of the world's existing and planned nuclear generating capacity, however, operates on the uranium once-through cycle, in which only 1-2% of the uranium is consumed in energy production, the remainder being discharged in spent fuel. Increasing world use of such a fuelling system must result inevitably in a long term situation where world uranium supplies and resources are unable to meet demand. Consequently, many nations are examining advanced fuel cycles with a view to expanding and assuring the nuclear fuel resource base. In Canada, Atomic Energy of Canada Limited (AECL) is conducting a research and development program on advanced fuel cycles with the objective of the long-term assurance of economic supplies of nuclear fuel for the CANDU reactor.

Beginning in the early 1950's, AECL developed the CANDU reactor and, in collaboration with Ontario Hydro and many segments of Canadian industry, brought it to commercial realization. A parallel program developed the technology for large-scale heavy water production. Successful commissioning and operation of the 4 x 500 MWe Pickering Nuclear Generating Station in the early 1970's signalled the achievement of commercial viability. At that time, AECL decided to increase the resources committed to research and development on fuel cycles which made economical and efficient use of all potential fuels - uranium, plutonium and thorium. In addition the funding of activities to develop and demonstrate all aspects of nuclear waste immobilization and long-term disposal, was increased. This latter aspect of the program was further highlighted in the late 1970's with the signing of an agreement between the governments of Canada and the Province of Ontario. The objective of this program is to provide, in the early 1990's, convincing evidence for the proof-of-concept for disposal of these high-level nuclear fuel wastes in deep geological repositories in the Canadian Shield (Reference 9). In parallel, research and development on all other components of CANDU advanced fuel cycles has continued.

The pace and focus of this CANDU advanced fuel cycle program, however, is influenced by a number of considerations including the current status and future prospects for the nuclear fuel supply industry, both in Canada and the rest of the world.

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*CANDU is an acronym for CANada Deuterium-Uranium. CANDU is a registered trademark of Atomic Energy of Canada Limited

2. BACKGROUND

The past decade has seen large changes in the prospects for the world nuclear fuel supply industry. The oil shocks of the 1970's led many nations to introduce policies which promoted the replacement of oil by fission energy and resulted in projections of high growth rates for installation of nuclear power stations. In parallel, the extent of natural uranium resources and supply appeared inadequate to fuel this rapidly expanding system and significant demand/supply imbalances were anticipated in the early decades of the next century. Consequently, many nations accelerated their Research, Development and Demonstration (RDD) activities on programs for spent fuel recycling and on Fast Breeder Reactors (FBR) in order to enhance the security of their future nuclear fuel supplies.

The actual growth in installed nuclear power has fallen far short of the projections of a decade ago and current projections of future growth are the lowest of the past decade. Concurrently, increased uranium exploration activity has defined large new deposits, for example, in Australia and Canada and world supplies appear adequate for many decades. In addition, these supplies will be enhanced in the 1990's by increasing amounts of recovered uranium and plutonium from reprocessing plants, which are either planned or under construction in France, United Kingdom, Federal Republic of Germany and Japan. As a consequence, there is a growing appreciation that the need for the commercialization and large-scale deployment of FBR's has receded by a number of decades into the future. The economics of FBR's also appear less favourable than originally hoped. Both capital costs and initial fissile inventory charges appear significantly higher than those for the current generation of thermal reactors, and FBR's will not be economically attractive until natural uranium is several more times more expensive than current levels, perhaps in excess of $500 US/kg U.

Finally, mention must be made of increasing competition from coal-fired generation. The past decade has seen a rapid increase in the capital cost of nuclear plants in many countries. This increase has been far greater than inflation and also greater than the increase in the capital cost of fossil-fuelled plants. The result has been a narrowing of the economic advantage previously enjoyed by nuclear power, and increasing competition from coal in many areas.

Consequently, while the need for long-term assurance of nuclear fuel supplies still remains, the pace of transition from the current once-through cycle will be slower than originally projected and will be effected more by economic competitiveness and national strategic concerns, than by constraints on uranium supply. The period over which thermal reactors will continue to be the major nuclear energy source installed by utilities will also be many decades longer than previously envisioned because of the lack of economic challenge posed by the current generation of FBR's.

3. REQUIREMENTS AND POTENTIAL

The previous discussion indicates there will be a significant future market for an advanced thermal reactor. The period of installation and operation for these reactors will cover a time-scale from the current situation of ample, cheap uranium supplies through increasing demand and rising uranium prices until introduction of FBR's is economically justified. Even then, FBR's may not supplant the thermal reactors but may operate in a mixed strategy. In this case, the FBR plays the role of a "fissile" factory rather than a primary power producer. The basis for the mixed strategy is that the advanced thermal reactor will be the lower cost, long-term power producer while the FBR would be optimized for maximum fissile material production and would constitute part of the fuel supply industry. Deployment of the FBR would then be governed by fuel supply needs rather than directly by power needs and would avoid the conflict inherent in attempting to design for both minimum power costs and maximum fissile material supply. Obviously the advanced thermal reactor could also operate with other methods of fissile supply, e.g., accelerator breeders or fusion breeders.

To execute this future role the advanced thermal reactor would need the following four desirable characteristics.

(1) Its associated capital costs should be no higher, and if possible less, than the costs of the current generation of reactors.

(2) The reactor should be capable of changing from operation with once-through uranium fuelling to recycle fuelling during its life-time.

(3) Net fissile consumption of the associated advanced fuel cycles should be significantly less than that for uranium, once-through fuelling.

(4) Initial fissile inventory requirements should be similar to or lower than the needs of current once-through fuelling.

The current CANDU reactor is well poised as an ideal candidate for this advanced thermal reactor role.

(1) It is already developed to the stage of commercial viability. Capital costs of future reactors will be lower as the benefits of previous construction and commissioning experience are utilized and design improvements are made. No change to the existing design is required to accommodate advanced fuels, as discussed below.

(2) Current designs of CANDU reactor use natural uranium oxide as fuel. Recent in-depth engineering studies have been conducted on the feasibility of using both Low-Enriched Uranium (LEU) and plutonium-uranium Mixed Oxide (MOX)* fuels in the present design of

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*The enrichments assumed for the study were LEU-1.2% U-235 and MOX fuel composed of 1 wt% fissile plutonium plus 0.2% enriched uranium, i.e., enrichment plant "tails" uranium. These studies are now being extended to higher enrichment fuel.

CANDU-600 reactor. The conclusions of this study are that the reactor can burn these fuels without any change to the reactor design. Key factors underlying this fuelling flexibility are the fuel design and the on-power refuelling capability. The fuel bundles are short (0.5 m) and of simple design (Figure 1) and 12 bundles are loaded into each fuel channel. On-power refuelling allows flexibility as to when each channel is refuelled and the number of bundles replaced at each visit. Adjacent channels can be refuelled with differing numbers of bundles and a "checkerboard" fuel management scheme (Reference 1) was designed for the enriched fuel which maintains reactivity balances together with control of both axial and radial power shapes within design limits.

In consequence, the current design of CANDU reactor satisfies the first two of the four criteria defined earlier, i.e., stable or reducing capital costs and the flexibility to burn a variety of fuels, within the same reactor during its lifetime.

4. FUEL CYCLE CHARACTERISTICS

From the earliest days, a major driving force underlying the CANDU development program, has been the concept of "neutron economy", i.e., reducing neutron absorption in materials, other than the fuel, to a minimum. This results in the highest possible rate of neutron capture in the fertile material and, in consequence, high rates of replacement of the original fissile material as it is destroyed by fission. The concept of neutron economy permits the use of natural uranium oxide as fuel but is also the ideal criterion for more advanced uranium-conserving cycles.

CANDU advanced fuel cycles have been reported in detail, particularly at the International Nuclear Fuel Cycle Evaluation (INFCE) during 1977-1980 (Reference 2,3,4,5,6). Information on the range of possible advanced cycles was presented and typical figures are given in Table 1 to illustrate the potential reductions in annual equilibrium requirements for natural uranium which are possible, relative to the current natural uranium cycle. With the implementation of once-through LEU, an immediate reduction of greater than 30% is possible. Introduction of fuel recycle permits a greater than 50% reduction by recycling plutonium with uranium. There is, however, the potential of almost complete elimination of uranium requirements by the introduction of thorium cycles, with the end-point of the "near-breeder" or "self-sufficient equilibrium thorium" cycle, which requires no uranium when equilibrium fuelling conditions are established (References 13,14).

Comparisons of the resource needs of various reactor types were also made at INFCE, such as Figure 2, and show the advantage of the CANDU fuel cycle, whether the fuel be uranium, plutonium/uranium or thorium (it should be noted that the range for CANDU thorium cycles has been added to the original figure).

The equilibrium annual fissile requirements, however, are only one component of fuel cycle characteristics. The other major component is the initial fissile inventory required to initiate a new reactor installation. For

TABLE 1

EQUILIBRIUM NATURAL URANIUM REQUIREMENTS FOR CANDU

1000 MWe CANDU Operating at 80% Capacity Factor(5)

	Equilibrium Fuelling Rate(1) (Mg Nat U/annum)	
ONCE-THROUGH		
Natural Uranium	138	(100%)(4)
LEU	95	(69%)
RECYCLE		
Natural Uranium + 0.5 wt.% Puf(2)	62	(45%)
Depleted Uranium(3) + 1.0 wt.% Puf	57	(41%)
Thorium/U-233 - High burnup (U-235 make-up)	28	(20%)
Thorium/U-233 - Near breeder	0	(0%)

NOTES

(1) Assuming 1000 MWe net output, thermal efficiency = 29.2%; tails enrichment = 0.2 wt.% U-235, fabrication loss = 1%.
(2) Puf = Fissile plutonium
(3) Enrichment for depleted uranium assumed 0.25 wt.% U-235.
(4) Percentage in brackets is equilibrium fuelling rate as percentage of equilibrium fuelling rate for once-through natural uranium cycle.
(5) Data taken from references 3, 4, 5 and 6.

once-through cycles, the inventory is generally the initial core inventory. For recycle fuelling, however, the inventory also includes the extra fissile material required during the early years of operation before recycling can commence. Again typical data for various reactor types (e.g. from References 11,12) is given in Table 2 for plutonium-depleted uranium recycle. For this cycle, the parameter is the inventory of fissile plutonium required for the initial core plus a number of years of operation. Information is given for both 2 years and 5 years of operation. The plutonium recycle time (reactor-out to reactor-in) during the early years of implementation of such a system will likely be of the order of 5 years. This may shorten to 2 years with system growth and improvements, provided facilities can be located near to power plants. It can be seen that the inventory requirements and the annual net needs do not correlate and the two systems with the lowest net requirements have the highest inventories.

In a growing nuclear system, the overall fissile requirements are a function of both fissile inventory and net requirements. Obviously, this poses a problem if the desirable objective of low equilibrium fissile requirements can only be approached through large investments of fissile material. This problem is further compounded by the fact that the growth rate of the advanced systems (i.e., reactors and/or fuel cycles) is generally higher than the overall power system growth rate. The new system is not only supplying the new capacity but is also replacing old capacity as it reaches the end of its assumed lifetime.

The interaction of fissile inventory, net requirements and system growth can be studied using a simple approximation. If the system is assumed to be growing exponentially with exponent "a", then the fissile requirement per installed GWe per year is given by (R + a.I), where R is the net fissile requirement for reactors which have already reached the equilibrium fuelling stage, and I is the initial fissile investment required by new reactors. This initial investment consists of the initial core plus initial fuel supply needs while recycling is established, i.e., it is assumed that there will be a delay between spent fuel discharge and the recovered material re-entering the core.

The variation of the fissile requirements is plotted on Figure 3 as a function of growth rate, covering the range from 0 to 10% annual growth, for CANDU and LMFBR, and assuming a 2-year recycling delay. The increasing requirements are due to the inventory needs and show that the fast breeder system can be a net consumer of fissile material when growth exceeds the 2-4% range, and the needs of both systems start to converge in the 7-10% growth range. The data illustrate why more complex scenario studies (e.g., References 2,15) show similar behaviour when either LMFBR or CANDU advanced cycles are introduced into growing systems. The graph also illustrates that a strategy of delaying the introduction of breeder reactors until needed (i.e., when fissile supply is becoming constrained) creates an inventory problem. In scenario studies these are usually resolved by extensive "mining" of accumulated spent fuel stockpiles with assumed rapid growth in the reprocessing industry, which - again - creates problems of a different nature. On the other hand early introduction in anticipation of fissile supply constraints poses the potential problem of premature commercialization and excessive costs.

TABLE 2

Fissile Plutonium Requirements for Pu/U Recycling

MG FISSILE PLUTONIUM FOR 1 GWe REACTOR

ASSUMING PLUTONIUM + DEPLETED URANIUM (0.2%)

	Reactor Type	Inventory (Core + 2 a Operation)	Inventory (Core + 5 a Operation)	Annual Net
1	ATR(2)	4.3	6.4	0.50
2	PWR	5.2	8.8	0.42
3	CANDU	2.2	3.5	0.26
4	HCPWR(1)	8.4	13.8	0.13
5	LMFBR(3)	5.6	9.1	-0.18

NOTES:

1. High Conversion PWR
2. Advanced Thermal Reactor (Japan)
3. Liquid Metal Fast Breeder Reactor

The data for ATR and PWR have been extrapolated from existing information but it should be noted that it may not be possible to fully load either reactor with the above type of fuel because of design constraints. The data presented in the table have been obtained from that given in References 11, 12, 16, 17, 18, 19, 20 plus some internal data generated using the WIMS-CRNL lattice code (Reference 21).

A more fruitful approach is to consider ways in which the initial fissile investment can be reduced. Three approaches can be identified for CANDU.

1. One approach is to reduce the delay time between spent fuel discharge and recovered material re-entering the core, which would reduce the requirements for initial fuelling. The major technical problem is shipping and reprocessing spent fuel with a shorter cooling time. While this appears feasible, it also results in higher costs. The actual feasibility may also be determined by geographical and transportation systems which may limit the areas in which such an approach could be implemented.

2. The second approach relies on the fact that the CANDU design will be virtually unchanged from the current version, and consequently can be initially fuelled by natural uranium. This results in the lowest possible fissile investment in the initial core inventory. Transition to a fuel cycle with low net fissile requirements (i.e., plutonium-uranium recycling) during the early years of operation is feasible and results in lower fissile requirements and costs.

3. A third approach to the inventory problem is to avoid it by making advanced fuel cycles economically attractive under to-day's economic conditions. Introduction of more uranium efficient advanced cycles could be implemented, based on resource availability and strategic considerations, without economic penalty. Current estimates indicate that this is possible with CANDU if use is made of the material recovered from reprocessing of spent LWR fuel (see below).

The above considerations lead to the evolution of CANDU advanced fuel cycles illustrated in Figure 4. The cycles have been arranged in order of increasing efficiency in resource utilization and in probable order of implementation in the future, to respond to increasing prices for natural uranium supplies.

The initial step is likely to be the adoption of LEU as fuel, with an approximate 30% reduction in natural uranium requirements. Recent fierce competition in the international uranium enrichment services market and the expectation of future reductions in the price of enrichment have reinforced the expected economic benefits to be realized from this change. Further need for improved efficiency in fuel utilization would then be available by the adoption of fuel recycle, in particular the recycle of plutonium with either natural or depleted uranium (e.g., enrichment plant tails).

Adoption of these cycles opens the possibility of LWR-CANDU mixed strategies. The neutron economy of CANDU is such that LWR spent fuel could be irradiated in the reactor, without removal of fission products, and produce additional energy in the range 11 000 - 16 000 MWd/MgHE. Obviously there are significant practical problems to be overcome in reconfiguring or refabricating the fuel before such a cycle becomes possible. However, these strategies could be implemented by burning the fuel materials recovered by reprocessing LWR spent fuel. Either the recovered uranium alone (Reference 7) or the uranium-plutonium mixture could be used in an economic cycle without the need for uranium re-enrichment or adjustment of the plutonium-uranium ratio. The subsequent irradiation in CANDU reduces the uranium-235 content below the level of enrichment plant tails. Consequently there is no economic inventive for further recycling and this removes uranium-236 and uranium-232 from the fuel system. Considerable quantities of both recovered uranium and plutonium will become available as large reprocessing plants become operational, and the use of this fuel in CANDU is the most efficient and economical method of obtaining additional energy.

In the longer-term, the flexibility of CANDU to utilize a broad range of fuels will maintain a broad range of options.

1. Thorium cycles - the establishment of plutonium-uranium recycling leads naturally into the adoption of thorium as a fertile material and further improvements in uranium utilization. The end-point is the potential of the CANDU "near-breeder" with large blocks of power being supported by thorium supplies and no further need for uranium resources.

2. CANDU-LMFBR - optimization of LMFBR as a fissile supplier would lead to the construction of "power supply blocks". These consist of one LMFBR supplying fissile material to a number of CANDU's operating on a high efficiency fuel cycle. The basis for the strategy is the expectation that the CANDU will have significantly lower capital and fuelling costs. The costs of the "power supply block" will be significantly lower than an "all-LMFBR" system.

3. Accelerator Breeder (AB) - instead of LMFBR, the needed fissile material could be supplied by accelerator breeders (Reference 8). The major difference, and advantage, in a time of severe constraints on fissile material supply is that the AB does not require an initial fissile inventory to start operation. Future developments will establish whether this is a cheaper method of producing fissile material than LMFBR.

In summary, the inherent "neutron economical" characteristics of CANDU allows a broad range of fuel cycle options to provide a flexible response to changing conditions. Compared to perceived alternatives, there is the advantage of low net fissile material requirements combined with low inventory requirements, which makes CANDU an optimum technology for implementation during a period of power system expansion and steadily tightening fissile supply constraints.

5. ECONOMIC POTENTIAL

The economic potential of advanced fuel cycles is obviously an important consideration in assessing their future value and usefulness. As indicated earlier, the major uncertainties lie in the fuel cycle costs, since capital and operating costs for CANDU are already firmly established for the current design.

In general, it is expected that CANDU reactors will maintain their advantage over alternative systems in having lower fuelling costs. The advantages arise from four different aspects of the fuel cycle.

1. Lower fissile requirements - as indicated in Table 2 and from other sources, CANDU requires low net amounts of fissile material for equilibrium operation and/or requires a smaller inventory for startup and initial operation. As fissile costs increase, this difference becomes increasingly important.
2. Lower enrichment service requirements - in fuel cycles needing enrichment services, the requirements for CANDU are generally only one-third to one-half of those needed for alternative systems.
3. Lower fabrication costs - the CANDU fuel bundle is a small unit of simple design (Figure 1), which is also more adaptable to remote, automation fabrication processes needed for advanced fuels. Current fabrication costs for natural uranium fuel are approximately $60(Cdn)/kg which is very significantly lower than the cost for alternative reactor system. A similar cost ratio situation is expected for MOX fuels.
4. Similar or lower backend costs - with advanced cycles CANDU fuel burnup will be greater than 22 000 MWd/Mg. Again the small size of fuel bundle allows lower costs for both spent fuel transportation and storage. Reprocessing costs will be no higher than those for LWR fuel, if done in plants designed for LWR fuel, and will be lower if done in plants designed to take advantage of CANDU spent fuel characteristics. Consequently, the overall cost per unit energy output will be either similar to or lower than those for alternative systems.

The above considerations lead to the conclusion that CANDU fuel cycle costs will remain significantly lower than those for alternative systems, particularly in a period of escalating fissile material cost.

6. SUMMARY

The changing perspectives of the past decade lead to the conclusion that a significant future market for a CANDU advanced thermal reactor will exist for many decades. Such a reactor could operate in a stand-alone strategy or integrate with a mixed CANDU-LWR or CANDU-FBR strategy.

The existing characteristics of CANDU fuel cycles are those of low fissile inventory and high conversion ratio. No major design change to the reactor will be required to allow the use of a wide range of advanced fuels. Consequently, the research and development program can be focussed on fuel cycle topics, including fuel performance characteristics (Reference 10), future improvements in neutron economy and the technology required to permit economic recycle fuelling.

The consistent design focus of CANDU on enhanced efficiency of resource utilization combined with simple technology to achieve economic targets, will provide sufficient flexibility to maintain CANDU as a viable power producer for both the medium- and long-term future.

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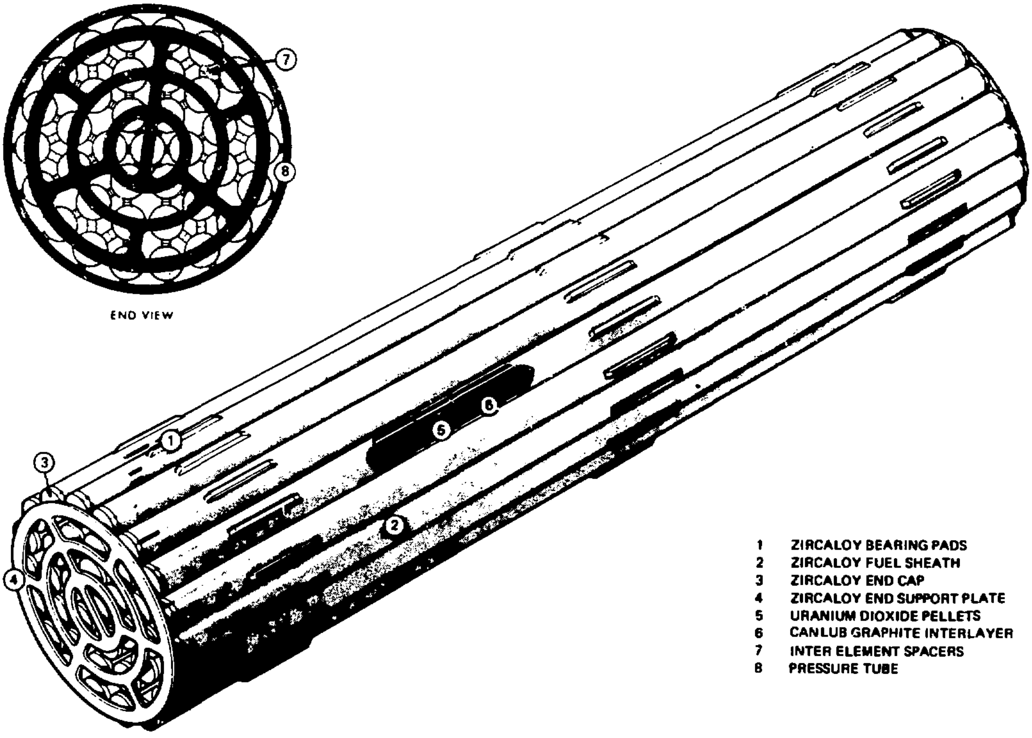

37 ELEMENT FUEL BUNDLE

FIGURE 1

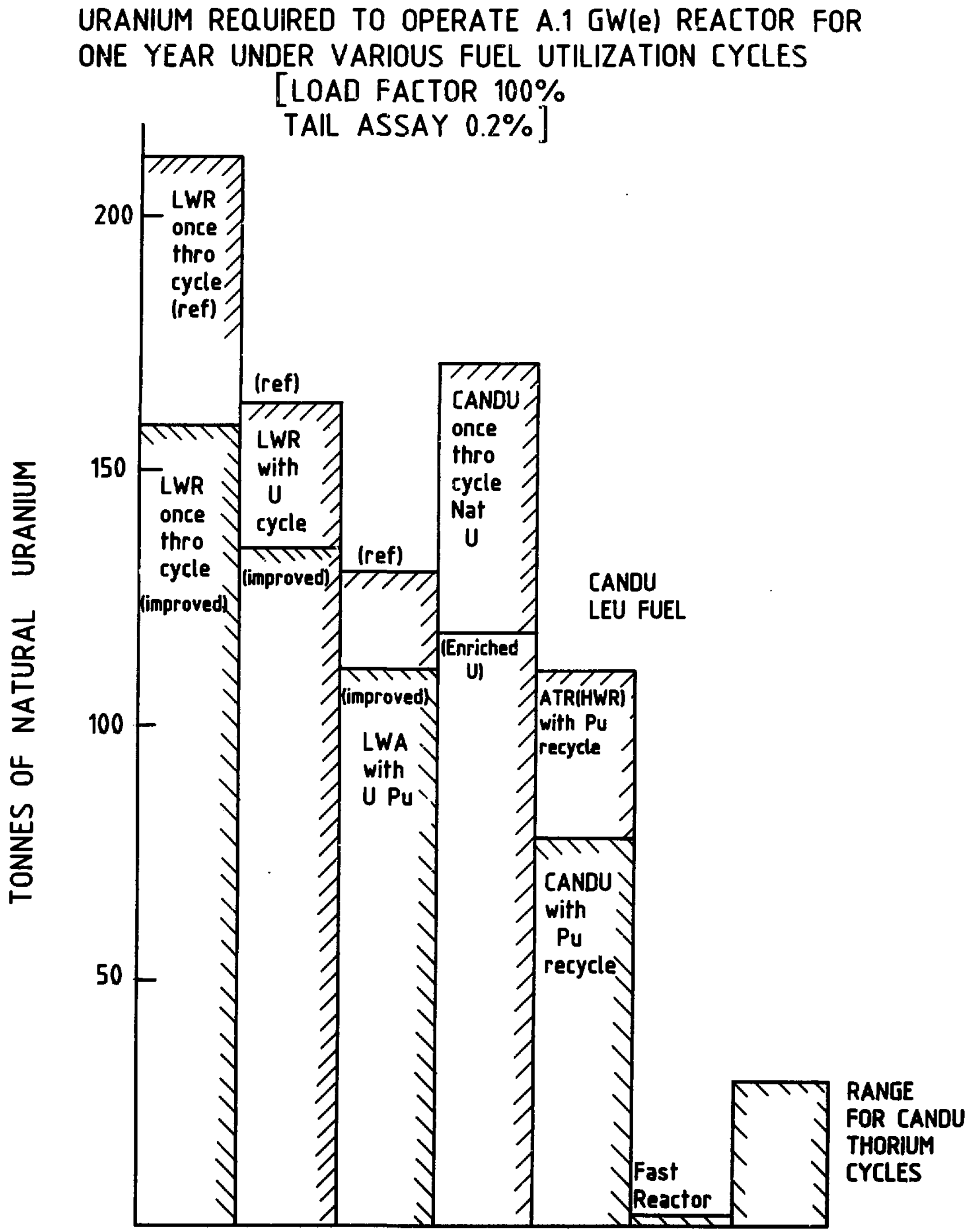
URANIUM REQUIRED TO OPERATE A.1 GW(e) REACTOR FOR ONE YEAR UNDER VARIOUS FUEL UTILIZATION CYCLES
[LOAD FACTOR 100%
TAIL ASSAY 0.2%]
TONNES OF NATURAL URANIUM
200
150
100
50
LWR once thro cycle (ref)
LWR once thro cycle (improved)
(ref)
LWR with U cycle
(improved)
(ref)
(improved)
LWA with U Pu
CANDU once thro cycle Nat U
(Enriched U)
CANDU LEU FUEL
ATR(HWR) with Pu recycle
CANDU with Pu recycle
Fast Reactor
RANGE FOR CANDU THORIUM CYCLES

FIGURE 2

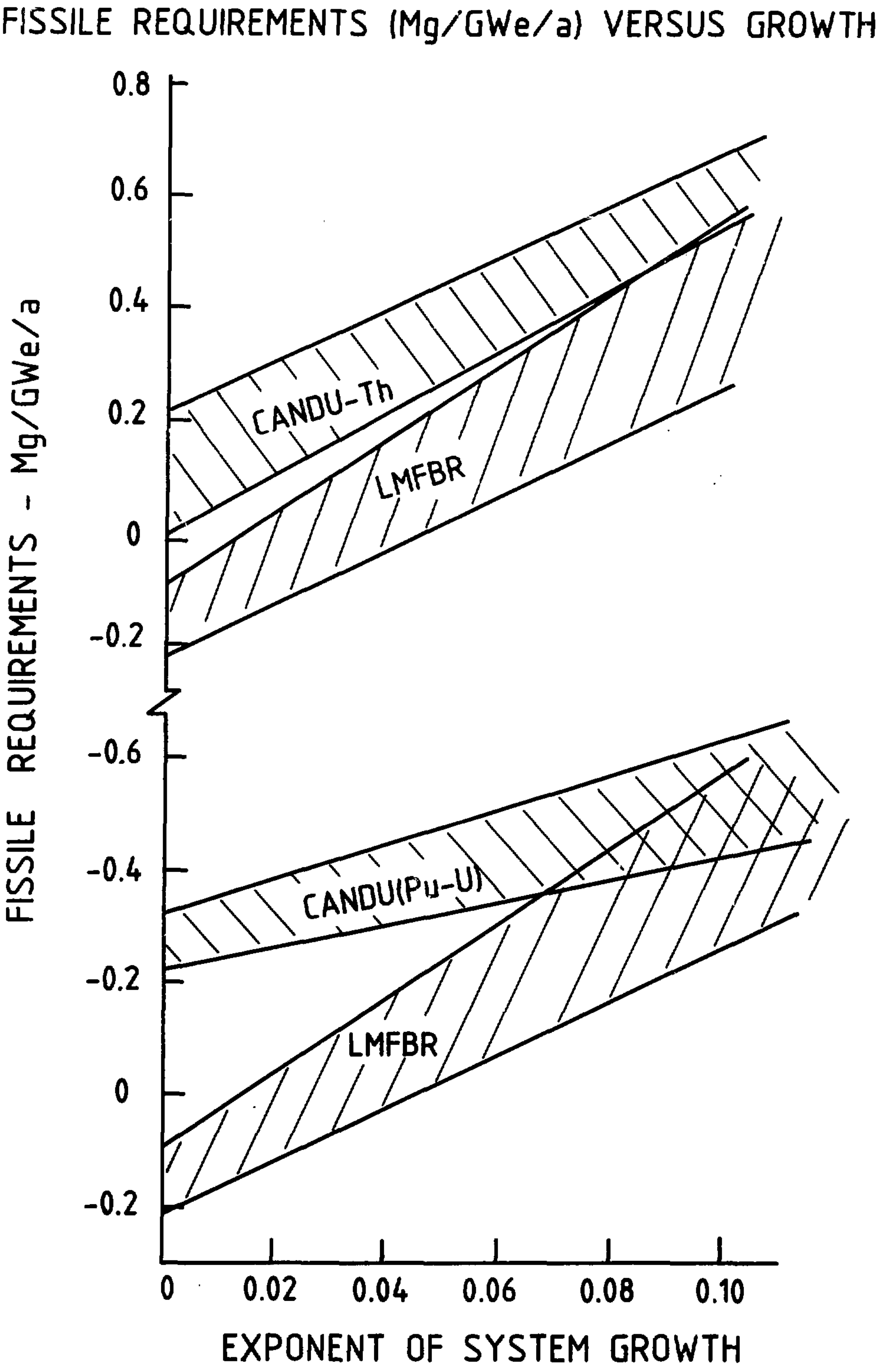
FISSILE REQUIREMENTS (Mg/GWe/a) VERSUS GROWTH
FISSILE REQUIREMENTS - Mg/GWe/a
0.8
0.6
0.4
0.2
0
-0.2
-0.6
-0.4
-0.2
0
-0.2
CANDU-Th
LMFBR
CANDU(Pu-U)
LMFBR
0
0.02
0.04
0.06
0.08
0.10
EXPONENT OF SYSTEM GROWTH

FIGURE 3

THE CANDU STRATEGY

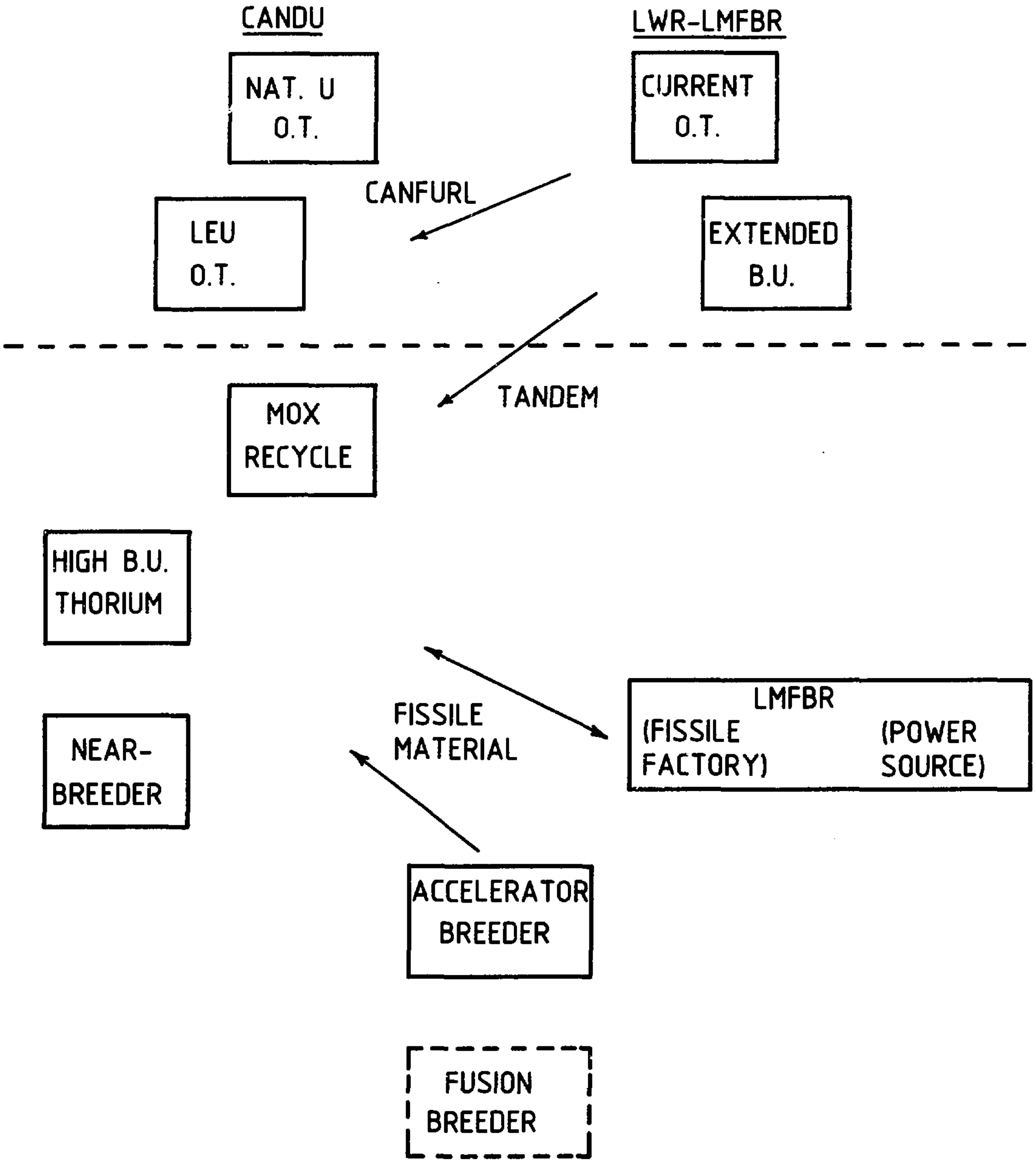

FIGURE 4

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