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ATOMIC ENERGY
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L'ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

INTRODUCING
ADVANCED NUCLEAR FUEL CYCLES IN CANADA

by

M.F. DURET

Chalk River Nuclear Laboratories

Chalk River, Ontario

May 1978

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Vers l'adoption de cycles de combustible avancés au Canada

par

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Résumé

On a étudié dans quelle mesure différents cycles de combustible avancés pourraient fournir de l'énergie en fonction de divers scénarios de croissance de la demande pour quelques situations présentant un intérêt particulier au Canada. Le plutonium, produit dans les centrales CANDU-PHW (version de la filière Canada Deutérium Uranium où le caloporteur est de l'eau lourde sous pression) qui sont alimentées par de l'uranium naturel, va être employé pour commencer la réalisation de cycles de combustible avancés en l'an 2000. Voici les quatre cycles de combustible ayant été comparés:

1. Uranium naturel dans les centrales CANDU-PHW.
2. Cycle au thorium à haut taux de combustion dans les centrales CANDU-PHW.
3. Cycle au thorium auto-entretenu dans les centrales CANDU-PHW.
4. Cycle au plutonium et à l'uranium dans un réacteur surrégénérateur.

Les caractéristiques générales des résultats sont tout à fait claires. Bien que le plutonium produit avant la mise en service d'un cycle avancé reste disponible, les besoins des systèmes en matière d'uranium naturel seront les mêmes pour tous les cycles possibles et ils dépendront du temps qu'il faudra pour mettre hors service les centrales dont le fonctionnement est assuré par de l'uranium naturel. Lorsque le stock de plutonium accumulé aura été complètement épuisé, il faudra de nouveau se servir d'uranium naturel pour alimenter les réacteurs fonctionnant avec un cycle de combustible avancé. La période de temps au cours de laquelle on n'aura pas besoin d'uranium pourra varier de 25 à 40 ans pour les deux cycles au thorium et elle dépendra essentiellement du taux de croissance de la demande en énergie. Etant donné qu'un réacteur surrégénérateur n'aurait pas besoin de tout le stock de plutonium produit, il permettrait de recycler moins de combustible provenant des réacteurs PHW.

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ABSTRACT

The ability of several different advanced fuel cycles to provide energy for a range of energy growth scenarios has been examined for a few special situations of interest in Canada. Plutonium generated from the CANDU-PHW (Canada Deuterium Uranium-Pressurized Heavy Water) operating on natural uranium is used to initiate advanced fuel cycles in the year 2000. The four fuel cycles compared are:

1. Natural uranium in the CANDU-PHW
2. High burnup thorium cycle in the CANDU-PHW
3. Self-sufficient thorium cycle in the CANDU-PHW
4. Plutonium-uranium cycle in a fast breeder reactor

The general features of the results are quite clear. While any plutonium generated prior to the introduction of the advanced fuel cycle remains, system requirements for natural uranium for each of the advanced fuel cycles are the same and are governed by the rate at which plants operating on natural uranium can be retired. When the accumulated plutonium inventory has been entirely used, natural uranium is again required to provide inventory for the advanced fuel cycle reactors. The time interval during which no uranium is required varies only from about 25 to 40 years for both thorium cycles, depending primarily on the energy growth rate. The breeder does not require the entire plutonium inventory produced and so would call for less processing of fuel from the PHW reactors.

Chalk River Nuclear Laboratories

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INTRODUCTION

Recent world energy studies(1,2) have pointed out how precarious the world energy supply position has become. This, in part, is due to resource depletion, but also depends on limits to the rates at which these resources can or will be exploited. Traditionally the world has depended upon wood, coal, oil and water power for its energy. The contribution from wood is declining but two new sources, gas and nuclear energy have recently entered the picture. Approximate estimates of available world primary energy sources are given in the table below.

TABLE I

World Primary Energy Sources

(World Energy Consumption 1972 = 267 exajoules)

Fuel	Amount	Energy Content Exajoules (10^{18} joules)	Remarks
Coal	650×10^9 tonnes	20,000	About 6% of the geological resources are considered to be technically and economically recoverable.
Conventional Oil	250×10^9 tonnes ($\sim 1800 \times 10^9$ bbls)	11,000	Does not include tar sands heavy oils, deep offshore or polar regions. Recovery rate of 40% assumed. This is the median of many estimates.
Gas	N.A.	10,000	Including estimates of undiscovered resources.
Hydro		29/annum	This is a rate.
Nuclear	3×10^6 tonnes U	1,500	With present converter reactor technology.

The price of oil will undoubtedly rise as world production levels off and gradually declines. When this will happen is not known precisely but most experts expect it before the turn of the century. Since oil now provides more than 40% of the world's energy supply, it is not expected that any single energy source (or conservation) can be expanded rapidly enough to compensate for the decline in oil production. All sources will be needed.

Heavy oils, tar sands and oil shales have not contributed significantly in the past because of their cost compared to conventional oil. Other unconventional sources such as solar and geothermal energy may become more important in the future. However, it appears that the most abundant fuel which can be exploited with known technology is coal. When more advanced nuclear fuel cycles capable of extracting a greater fraction of the potential energy content of uranium and thorium are developed, nuclear power can also make a large contribution to world energy supplies.

The uranium mining industry is in its infancy and much more uranium will undoubtedly be discovered. However, so far there have been no discoveries comparable in size with, for example, western U.S. coal fields or the Middle East oil reservoirs. It takes time to discover and develop uranium resources. This development rate could represent, in the future, a real limitation on the rate at which nuclear power can be introduced, if only converter reactors are available. For this reason many countries are involved in the research and development necessary to use more advanced nuclear fuel cycles.

Of the five major primary fuels, the three fossil fuels are fundamentally different from the other two, nuclear and hydro, in that they can be used in small amounts - for example, they can be used with reasonable efficiency to heat units as small as a single household. On the other hand, nuclear and hydro units tend to be large and the most convenient way of distributing the energy produced is by means of electricity. With future development it may be possible to use nuclear power directly as a heat source, but in the meantime one must accept the loss in efficiency which occurs with thermally generated electricity.

Energy use in Canada has increased rapidly in this century. Initially energy production was largely from coal and wood. However, the fraction of the market supplied from these sources has declined dramatically, so that the major primary energy sources in Canada today are oil, hydro and natural gas. This transition is illustrated in Fig. 1.

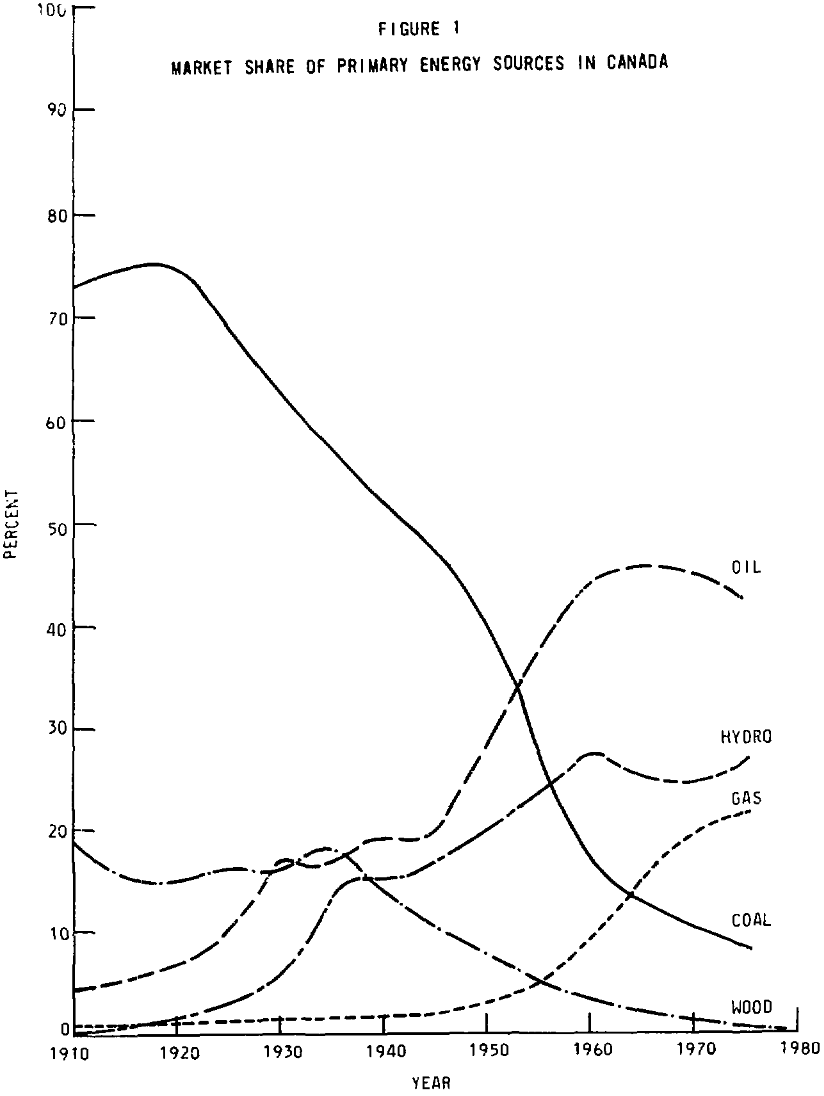


FIGURE 1

MARKET SHARE OF PRIMARY ENERGY SOURCES IN CANADA

The use of electricity has also increased significantly. A fit to the statistical data in Fig. 2 indicates that total primary energy use has been increasing at about 3-4% per year (except for the period 1960-1973 when the increase was exceptionally rapid). The fraction of this primary energy which is eventually used in the form of electricity has also been increasing and corresponds to a rate of penetration of electricity into total energy use of about 3% per year.

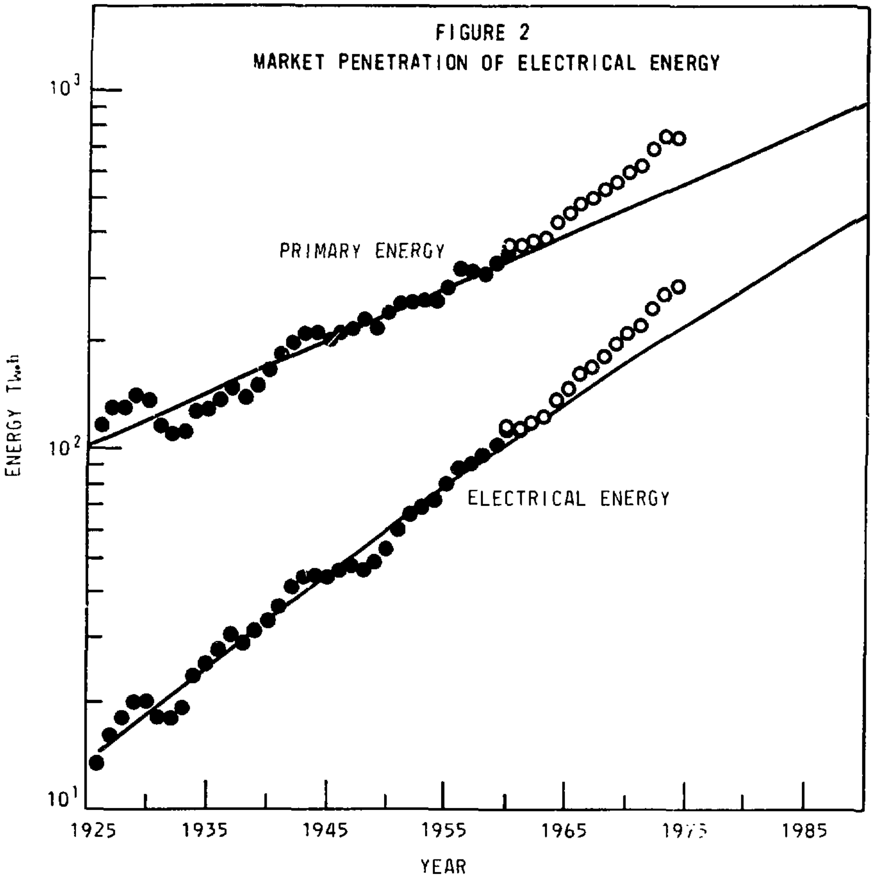


FIGURE 2
MARKET PENETRATION OF ELECTRICAL ENERGY

During the period 1910 to 1975 the population has increased from 7 million to 22.9 million corresponding to an average rate of increase of 1.8% per year. It is apparent that per capita use of energy in Canada has been increasing. During the same period the gross national product has increased at the same rate as total energy use, the ratio varying over a small range from 4¢ to 5¢ per kilowatt hour during the period.

The production of nuclear energy is a new technology and must compete with other established technologies of energy production. Cost is not the only criterion on which to judge competitiveness but it is certainly one of the most important. The cost of uranium is still a small component in the cost of nuclear power. I expect capital costs of nuclear plants to decrease, in real terms, in the future, merely because it is a new technology.

This report examines some aspects of introducing advanced nuclear fuel cycles in Canada on the assumption that normal economic forces will generate the incentive to provide energy from all sources available (including conservation).

ADVANCED FUEL CYCLES

A great variety of advanced nuclear fuel cycles are possible and only a few are considered here. The pertinent characteristics of these fuel cycles are listed in the table below. Most are appropriate for 1 GW(e) CANDU-PHW (Canada Deuterium Urandium-Pressurized Heavy Water) units but a breeder with a doubling time of 24 years has been included for comparison. The breeder performance specified in the table lies beyond that characteristic of the present prototypes but improvements can be foreseen which would allow such performance in a commercial reactor which could probably be available about the turn of the century.

TABLE II

Reactor Fuel Cycle Characteristics

1 GW(e) at 80% Capacity Factor

Time delay = 1.5 years

	CANDU-PHW				BREEDER
Fuel Cycle	Natural Uranium	Thorium Cycle With Plutonium		Thorium Cycle with U^{235}	Uranium Plutonium Doubling Time ∿ 24 years
Burnup MW.d/kgH.E.*	7.5	37.2	10	10	37.4
Equilibrium net feed rates					
Fissile Pu - Mg/a	0	.1345	0	0	0
Natural U - Mg/a	133.4	0	0	0	0
Equilibrium net production rates					
Fissile Pu - Mg/a	.360	0	0	0	.152
Inventories					
Fissile Pu Mg	0	4.07	5.98	0	4.05
Natural U Mg	173	0	0	0	0
U-235 Mg				5.43	

* Heavy element

FUTURE ENERGY DEMANDS

Most long-term projections of future energy demand start from estimates of GNP and, using various assumptions concerning price elasticities and relative state of industrial development etc., estimate from past correlations what the future demand for energy is likely to be, if the economic development proceeds as assumed.

I have preferred to separate as much as possible energy considerations from economic assumptions. The result is probably no less controversial than conventional methods and I admit that the main reason for adopting this approach is simplicity.

A variety of considerations concerning future energy demand are developed in the following five scenarios.

Scenario 1:

A consideration basic to any estimate of future energy demand is the inevitable levelling off in conventional oil and gas supplies and their subsequent production decline. The most likely course of events according to the World Energy Conference studies on oil and gas is that oil production will peak around 1990 and decline thereafter according to the depletion rate in different areas. The lowest depletion rate considered was 5%. A similar situation will occur with natural gas but peak production will probably not occur until somewhat later, perhaps by 2010. This is the situation concerning world supplies of oil and gas. In particular regions, shortages may occur sooner or later. If it is assumed that Canada will have access to these world supplies then the diminishing supply picture emerging in 1990 for oil and 2010 for gas is equivalent to a positive demand for replacement developing from these dates. The gap must be filled. To some extent it can be filled by electricity.

In the past, most of the electricity in Canada has been generated from hydraulic sources. However, the relative proportion supplied by hydro is falling rapidly and future thermally generated electricity will involve some loss in overall fuel efficiency. If we assume that electrical penetration into the energy supply market continues at the historical rate with an assumed asymptotic limit of 60%, the useful energy output falls by about 20% for a given primary input during this transition. This assumes that electricity has a 50% greater end-use efficiency, on average, than the primary fuel. If this 20% loss is spread uniformly over 80 years (1970-2050) it amounts to about 1/4% per year as an extra demand for primary fuel to satisfy the same end use requirements.

None of these demands results in the production of more end-use energy than that produced in 1970. They merely are estimates of the new primary sources required to maintain the status quo, and as such must be considered to represent a very minimum "growth" scenario.

The "growth" picture for this scenario assuming a conservative depletion rate of 5% for both oil and gas, is shown in Fig. 3. Not included in this assessment are other inefficiencies which will undoubtedly evolve as resources become more difficult to exploit (for example, exploiting the heavy oils, tar sands or oil shales, the gasification or liquifaction of coal, etc.).

Scenario 2:

Scenario 1 provides no increase in energy for end-use consumption. This means a decreasing use of energy per capita with the concomitant implications of a declining productivity and a declining standard of living.

Over the first part of this century the Canadian population grew at about 1.8% per annum. During the latter part of this period the growth rate was slowing down, however, and future population growth is expected to be somewhat lower. Using United Nations statistics for median growth to the year 2000 (31.6×10^6 by 2000) and assuming a growth of 1% thereafter (52×10^6 by 2050) results in Scenario 2, in which the incremental primary fuel requirements to maintain per capita energy consumption at the 1970 value have been added to the requirements of Scenario 1.

Scenario 3:

The trend in per capita energy use in Canada has been upward in the first part of the century although the variation has not been smooth. In particular in the period from 1920 to 1935 per capita energy use remained roughly constant. The trend from 1960 to 1973 saw a rather large increase. Neglecting this later period the trend is about 1.4% per annum.

The increase in primary energy required to allow for a continuation of this trend can be seen by comparing scenarios 2 and 3 in Fig. 3.

Scenario 4:

Many claim that we have come to use energy wastefully and that we could do much to alleviate the coming energy shortage by conservation. Because of the broad spectrum of energy conserving methods possible it is difficult to assess just how much energy can be saved and how quickly.

Scenario 4 was derived from scenario 3 simply by assuming that all energy consuming devices were replaced by others having an efficiency 75% greater than those in use in 1970 over a time span of about 30 years starting in 1970.

None of these growth scenarios approach the historic energy growth rate of 3½-4%, primarily because of the assumed lower growth in population.

Scenario 5:

To examine the effect of higher growth rates a continuation of the historic trend (3.7%) is assumed. This is below some projections of the recent past but well above the target value of about 2%.

In deriving these scenarios no assumptions have been made concerning the growth rate in GNP. In the past the GNP in Canada has been very highly correlated with energy production, including fairly short-term fluctuations. Unfortunately this correlation does not give any information concerning cause and effect. Does energy production decline because the economy declines or does the economy decline because of decreased energy production? Probably both effects are involved in a complex way - which may not be particularly important as long as the system is in equilibrium but which probably does become important when this equilibrium is disturbed, as it has been recently with the large increase in the price of oil.

Thus to predict future economic development from these energy scenarios would be presumptuous. However, in view of the real inefficiences which will be encountered in energy production in the future, it seems preferable to me to aim for high rather than low growth in future energy production.

RESULTS

General:

To estimate the contribution that advanced nuclear fuel cycles could make to our energy supply, a simple substitution model, suggested by Fisher and Pry to describe industrial change, was used. Fisher and Pry found that in many situations a new product will displace an existing product at a fractional rate proportional to the amount of original product remaining to be displaced. In this report this prescription has been applied successively to the penetration of electrical energy into total energy, the penetration of nuclear energy into electrical energy and the penetration of advanced nuclear fuel cycles into the production of nuclear energy, where account is also taken of other limitations such as old plant retirement rates or limitations on plutonium availability. Processing losses and time delays have not been taken into account explicitly, but are allowed for approximately in the fuel cycle characteristics given in Table 2.

The total annual demand for primary energy for Scenarios 1 to 5 is shown in Fig. 3. It is given in units of exajoules (10^{18} joules). Total energy use in Canada in 1970 amounted to about 6.7 exajoules. Typical demands for electrical energy are shown in Fig. 4, which in 1970 amounted to an electrical output of about 0.8 exajoules. In this figure it is assumed that electrical energy continues to penetrate total energy at the historic rate shown in Fig. 2 with an asymptotic limit corresponding to the use of 60% of our primary resources for electricity production. This asymptotic limit is not reached in this figure, the value in 2050 amounting to about 55%.

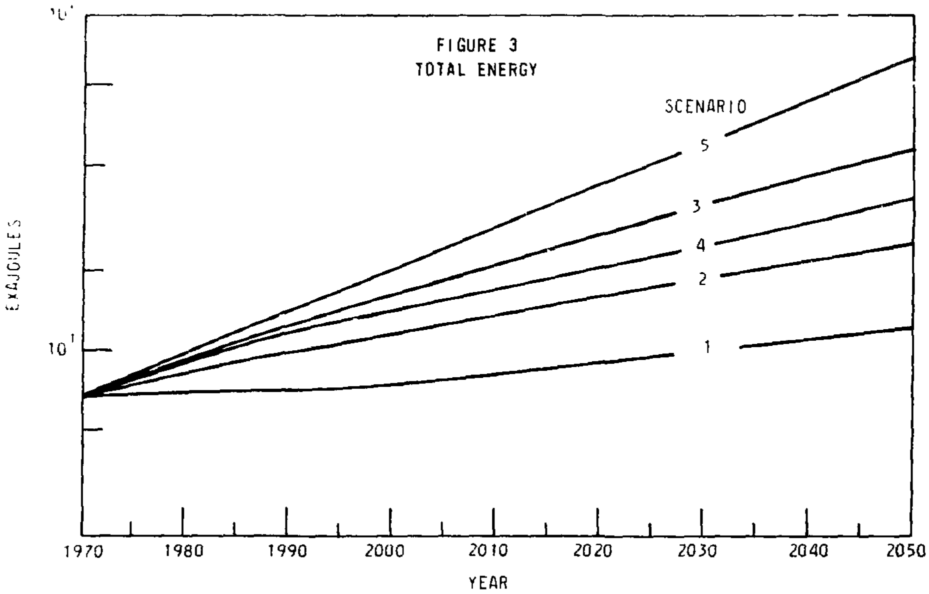


FIGURE 3
TOTAL ENERGY

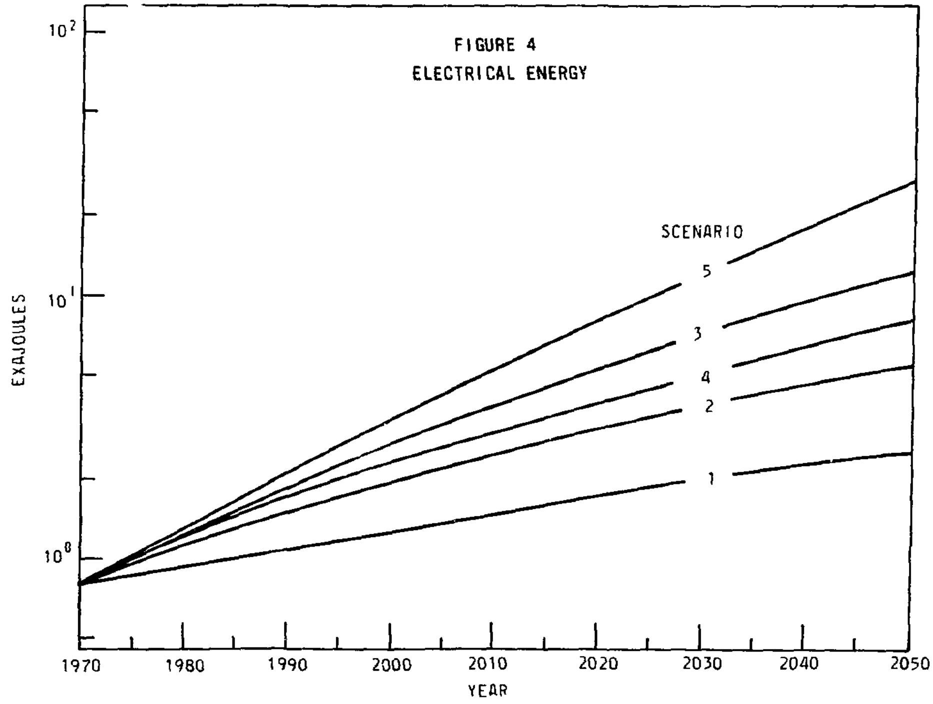
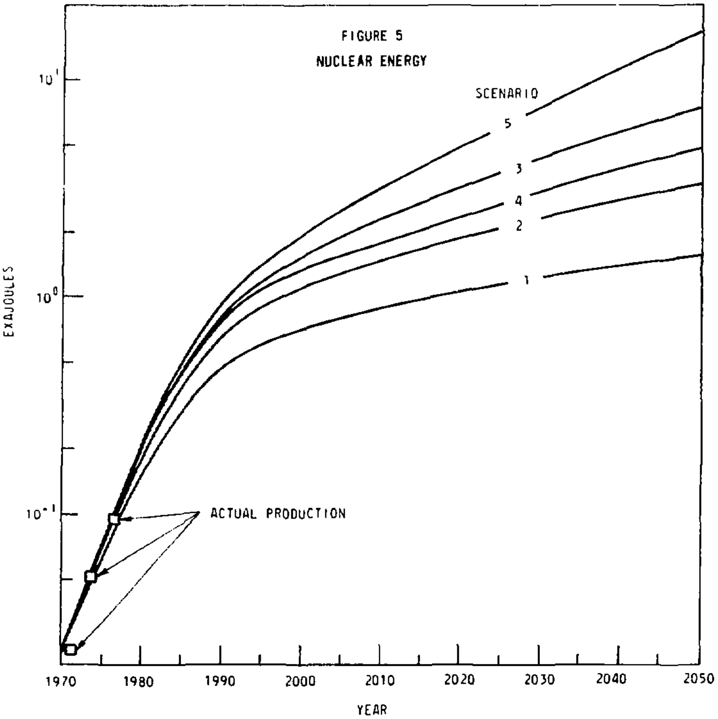


FIGURE 4
ELECTRICAL ENERGY

Nuclear energy penetrates electrical energy much more rapidly, as shown in Fig. 5. The penetration rate assumed here was 20% which soon brings the fraction of electrical energy supplied by nuclear power to an assumed asymptotic limit of 60%. Beyond about 2020 the nuclear curves and electrical curves are parallel. Some production figures for nuclear energy are shown in Fig. 5 but there are too few data to firmly establish a penetration rate.



At 80% load factor 1 exajoule/annum corresponds to about 40 GW(e) so that the 5 scenarios indicate a range of 28 to 80 GW(e) of nuclear power installed in the year 2000. If the load factor were only 60% the installed power would have to be ∿33% higher.

Contributions of possible primary energy sources to end-use energy are shown in Fig. 6 and 7 for scenarios 4 and 3. It is assumed that end-use efficiency of electricity is 1½ times that of the primary fuels. Scenario 4, the conservation scenario, suggests that by 2050 our end-use requirements could be met in approximately equal proportions from conservation, electricity and other sources such as conventional fossil fuels, heavy oils, synthetic fuels, etc. Such a large effect due to conservation may be difficult to realize and a larger contribution from nuclear power may be required. The relative contribution from nuclear power in scenario 4 increases only slowly after 2010 and reaches about 18% by 2020.

FIGURE 6
FRACTIONAL CONTRIBUTION TO END USE ENERGY
SCENARIO 4

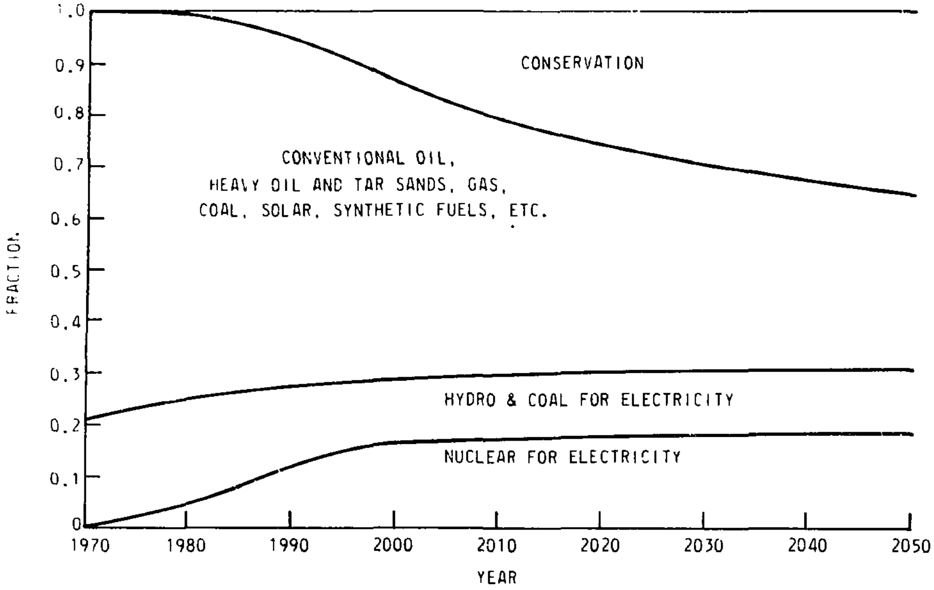
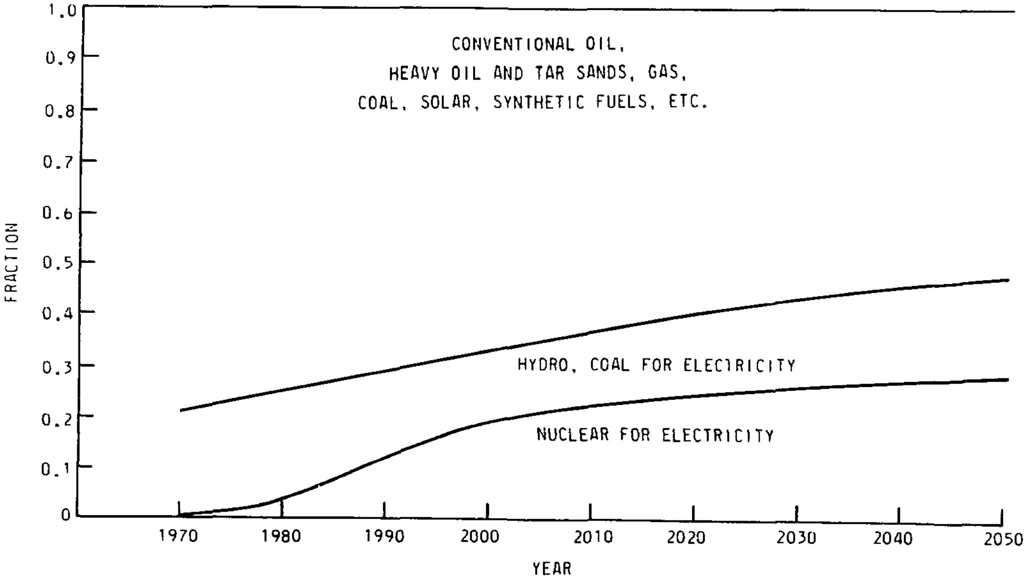


FIGURE 7
FRACTIONAL CONTRIBUTION TO END USE ENERGY
SCENARIO 3



In scenario 3 (Fig. 7) nuclear power continues to increase its relative contribution after the year 2000 reaching about 28% by 2050. This seems a reasonable target and to reduce the amount of data presented, most results are presented only for scenario 3.

Fuel cycles using plutonium:

Advanced nuclear fuel cycles using thorium fuel and the plutonium produced from the CANDU-PHW power program could be initiated in Canada in about 20 years. Probably it would take somewhat longer to initiate a power program based on fast breeders. However, for comparitive purposes it has been assumed that they could be introduced at the same time and rate, if the fast breeders were purchased. By the year 2000 nuclear technology will have advanced, and it is assumed that advanced fuel cycles could be introduced with a penetration rate of 25%.

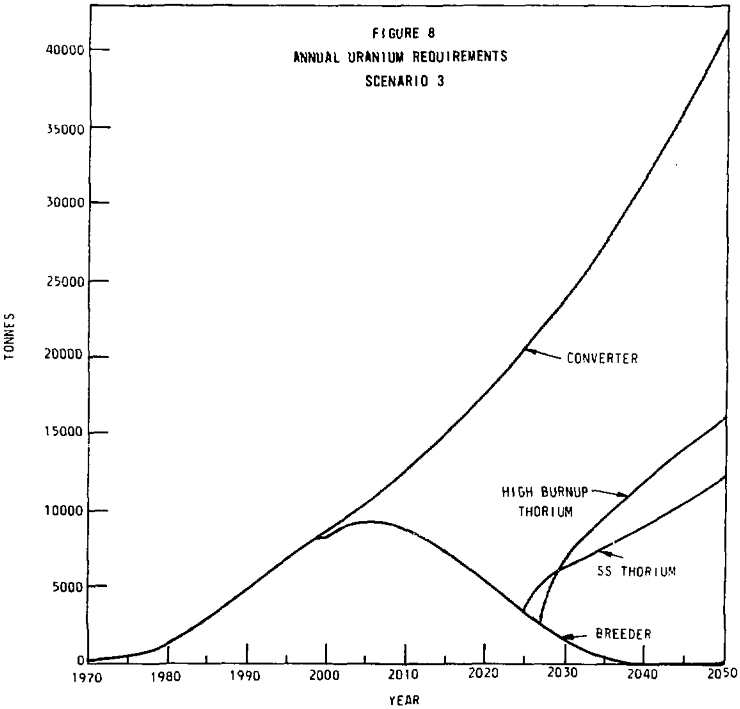


FIGURE 8
ANNUAL URANIUM REQUIREMENTS
SCENARIO 3

Annual uranium requirements for scenario 3 are shown in Fig. 8. The same general features occur for all scenarios. With only PHW converter reactors, annual uranium demand rises continually to 2050, reaching more than 40,000 Mg/a. Shortly after advanced fuel cycles are introduced, annual requirements reach a peak, the magnitude of which depends on the maximum installed converter power at that time and varies from 3900 Mg/a for scenario 1 to 13,000 Mg/a for scenario 5. From this point onward, demands for uranium fall off according to the rate at which converters are decomissioned and replaced by advanced cycle reactors. While any of the plutonium inventory remains, annual requirements are the same for any of the advanced cycles. The time taken to completely deplete the accumulated plutonium inventory varies with the growth scenario and the fuel cycle considered. The breeder does not run out of plutonium for the scenarios considered here and hence its good neutron economy is not being used to the fullest extent possible. The two thorium cycles considered differ very little and both run out of plutonium in about 25-40 years depending on the scenario. At this point it will become necessary to install more converter reactors and annual requirements rise again.

If advanced fuel cycles are introduced in the year 2000 the maximum annual demand reaches 13,000 Mg/a for scenario 5. Since the present uranium production rate in Canada is about 6,100 Mg/a there is little doubt that total Canadian production could expand to cope with this maximum rate. However, because of international commitments it is not clear that such a production rate could be reached for domestic use only, especially in view of the following 25-35 year reduction in requirements and the possibility that similar reductions will be occurring in other foreign nuclear programs because of the introduction of advanced fuel cycles. Clearly the timing and rate of introduction of advanced fuel cycles will depend on prospects for uranium supply and will need more detailed study.

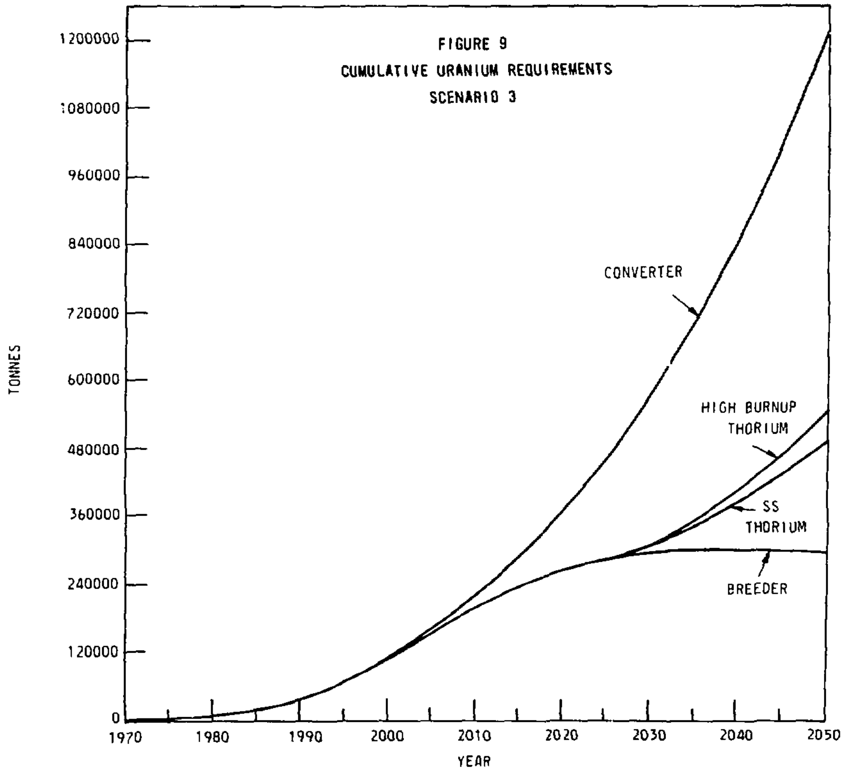


FIGURE 9
CUMULATIVE URANIUM REQUIREMENTS
SCENARIO 3

Cumulative (from 1970) requirements for scenario 3 are given in Fig. 9. This gives the total amount of uranium required to operate the system up to time t. Probably of more practical interest to electrical utilities are uranium commitments which include, in addition to the cumulative requirements, the uranium required to operate any existing converter reactors for the remainder of their 30 year life. These are given in Figures 10-14 for scenarios 1 to 5. Again all scenarios show common features. Shortly after the advanced cycles have been introduced, uranium commitments reach a plateau varying from 130,000 Mg for scenario 1 to 420,000 Mg for scenario 5. For the two thorium cycles this plateau lasts until all plutonium stocks have been used, which varies from about 2023 for scenario 5 to about 2040 for the zero growth scenario 1. The breeder does not use all the plutonium accumulated in any of the scenarios and this plateau represents the total uranium required. For the natural uranium cycle, commitments increase continuously reaching requirements ranging from 500,000 Mg for scenario 1 to 3.6 million Mg for scenario 5 by the year 2050. For the two thorium cycles, commitments begin to rise again for all scenarios, but at a much slower rate than that required for the natural uranium cycle, which implies a more efficient use of the primary uranium fuel.

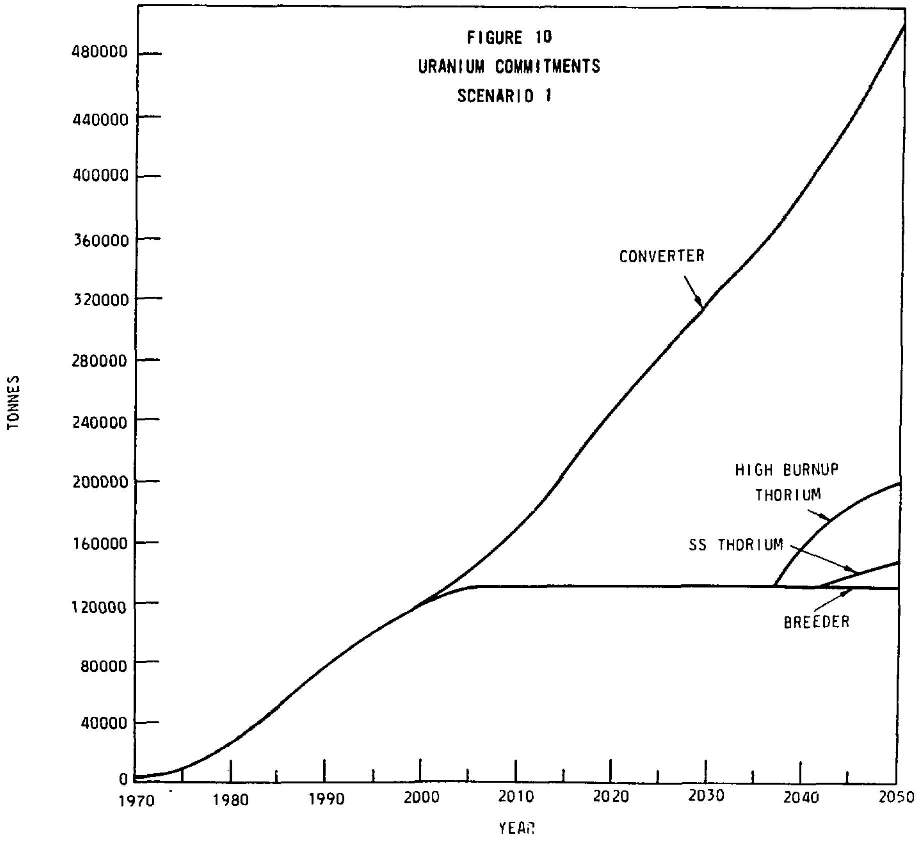


FIGURE 10
URANIUM COMMITMENTS
SCENARIO 1

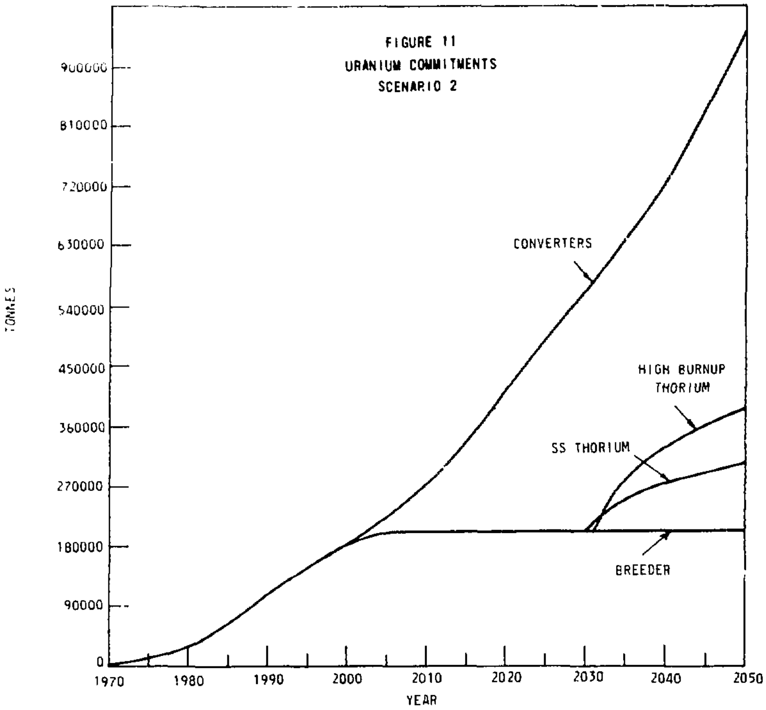


FIGURE 11
URANIUM COMMITMENTS
SCENARIO 2

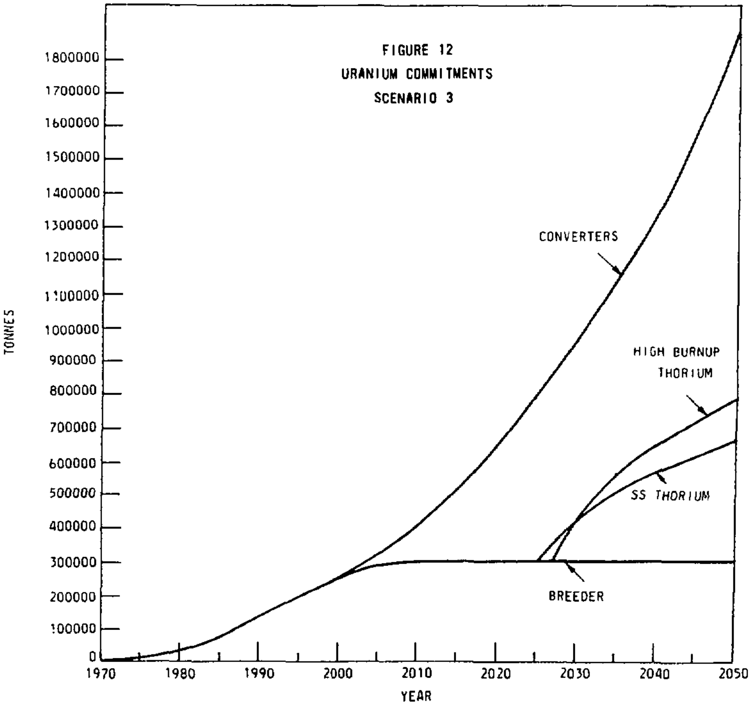


FIGURE 12
URANIUM COMMITMENTS
SCENARIO 3

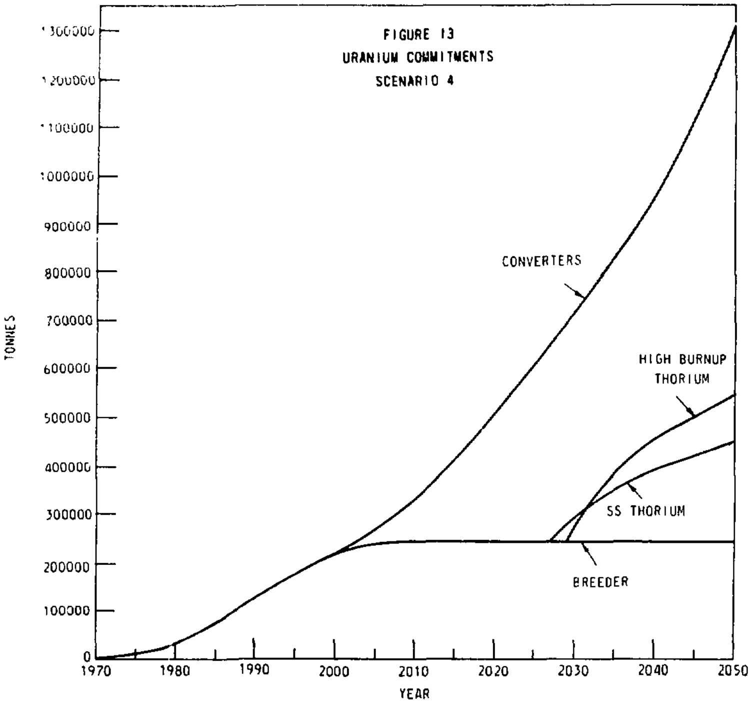


FIGURE 13
URANIUM COMMITMENTS
SCENARIO 4

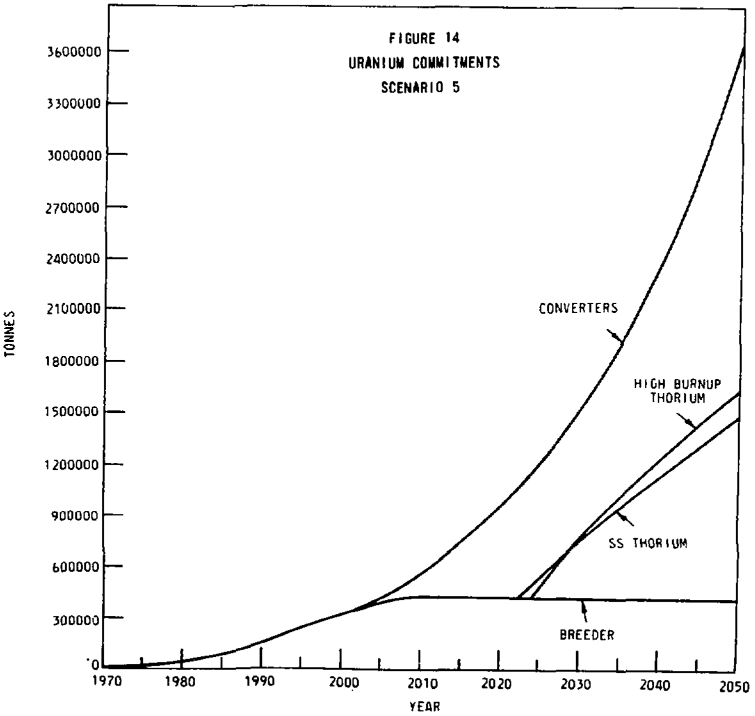
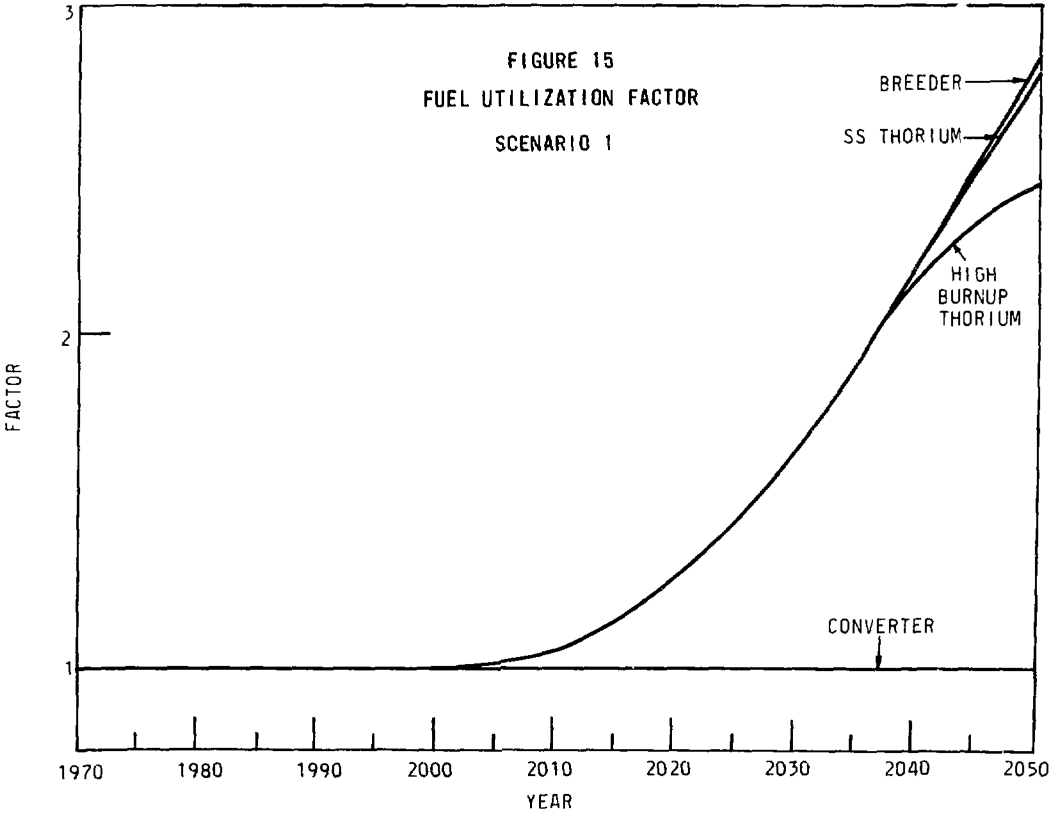


FIGURE 14
URANIUM COMMITMENTS
SCENARIO 5

This is indeed the case, as shown in Figures 15 to 19, which show, as a measure of nuclear system efficiency, a ratio called average fuel utilization which is defined as

$$\text{average fuel utilization} = \frac{\text{total energy produced up to time "t"}}{\text{total natural uranium used (excluding inventory)}}$$

For the natural uranium cycle this fuel utilization is 1 corresponding to 7.5 MW·d/kg. For other cycles it varies with time in each scenario and for different fuel cycles, but the same order is maintained in all scenarios, the utilization being best with the breeder, lower with the self-sufficient thorium cycle, and still lower with the high burnup thorium cycle. In scenario 3 in 2050, fuel utilization for the breeder has reached 4.0 (implying an effective system burnup of ∿30 MW·d/kgU) and is still rising, while the two thorium cycles have reached factors of 2.47 (18.5 MW·d/kgU) and 2.24 (16.8 MW·d/kgU) and both show signs of saturation. For the scenarios considered the average fuel utilization using the breeder improves as the growth rate increases.



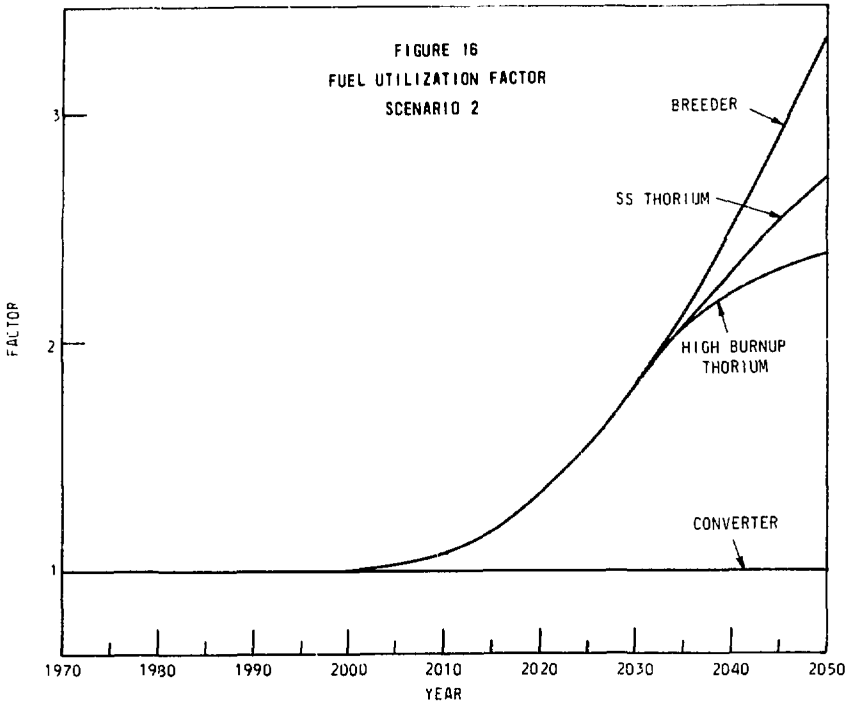


FIGURE 16
FUEL UTILIZATION FACTOR
SCENARIO 2

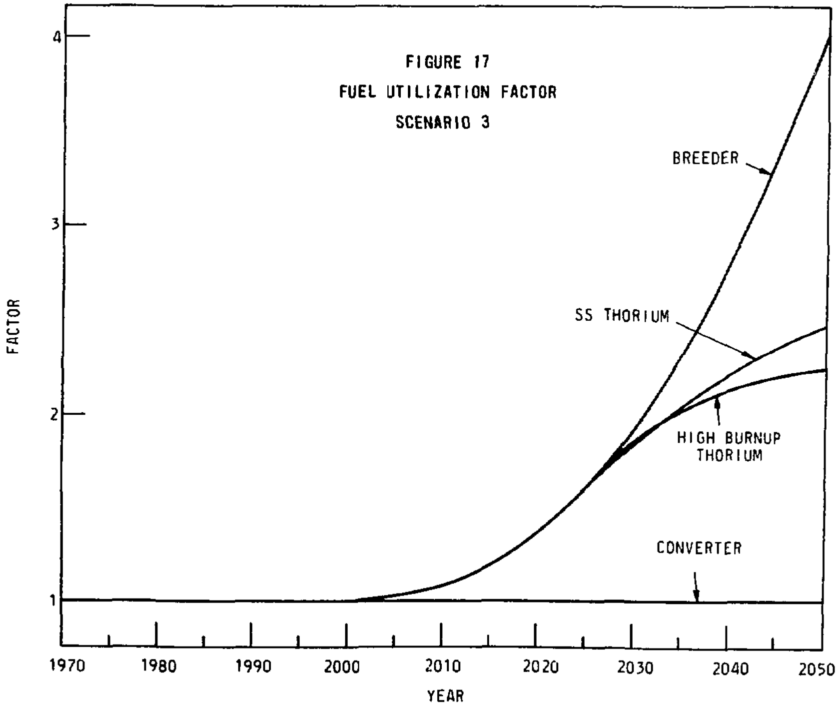


FIGURE 17
FUEL UTILIZATION FACTOR
SCENARIO 3

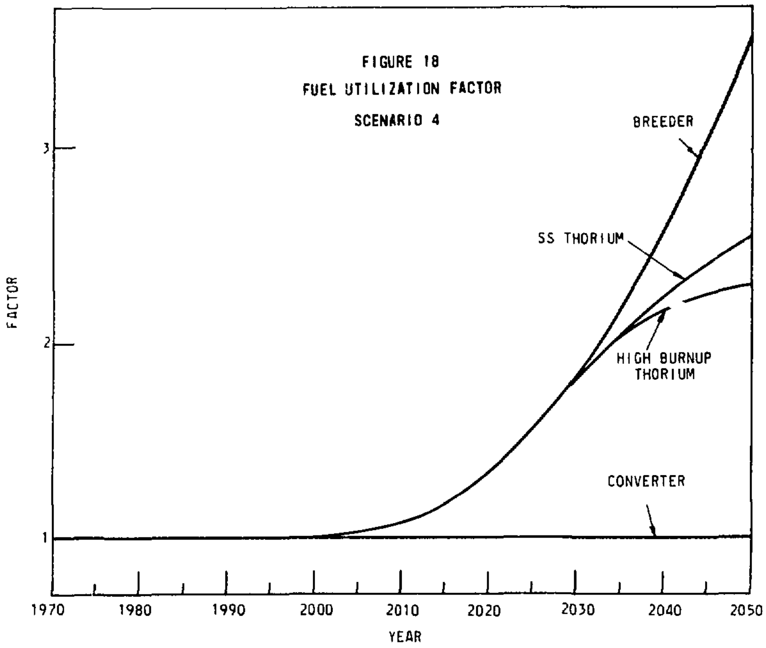


FIGURE 18
FUEL UTILIZATION FACTOR
SCENARIO 4

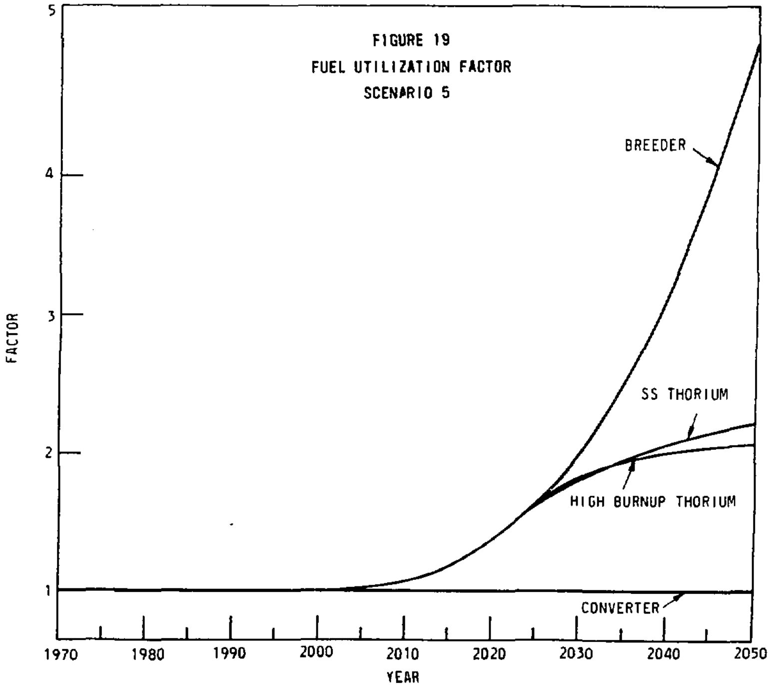


FIGURE 19
FUEL UTILIZATION FACTOR
SCENARIO 5

Improvement in the average fuel utilization begins to appear immediately the advanced fuel cycles are introduced and is the same for all fuel cycles initially. Differences between the fuel cycles appear only some 20 to 30 years later depending on the scenario - that is, in about 50 years. Other differences between the fuel cycles become apparent much earlier.

To initiate these advanced fuel cycles, plutonium from the CANDU-PHW's operating on natural uranium is required. Thus in scenario 3 about 300,000 Mg of uranium (commitment plateau in Fig. 12) must be processed between 2000 and 2025 if thorium cycle reactors are to be installed as rapidly as has been assumed. This corresponds to an average rate of about 12,000 Mg/a. If new plants continue to use plutonium as the initial fissile material there will be a continuing requirement for processing natural uranium fuel. These processing requirements are in addition to those required for continued operation of the advanced cycle itself. Even with the breeder in scenario 3 about 150,000 Mg of natural uranium would probably have to be processed in about 35 years. Scenarios with lower growth would require processing less urgently and it thus appears likely that satisfying the processing requirements for advanced fuel cycles will prove to be the bottleneck rather than the reactor technology itself - at least for the thorium cycle. One way to avoid (or delay) the necessity for processing natural uranium fuel would be to initiate the thorium cycle using highly enriched uranium.

Enriched Uranium Fuel Cycles:

Annual uranium requirements for a system using enriched uranium to introduce the self-sufficient thorium cycle in the year 2000 are shown in Fig. 20. As expected, requirements are higher than those using plutonium to introduce the advanced cycle, the initial peak in uranium requirements ranging from about 5,000 Mg/a for scenario 1 to about 25,000 Mg/a for scenario 5 compared to the range 4,000-13,000 Mg/a for the same system using plutonium. Cumulative requirements are shown in Fig. 21 for the self-sufficient thorium cycle introduced using enriched uranium and plutonium. Cumulative requirements are significantly higher when enriched uranium is used to introduce the cycle but much lower than requirements would be using only the natural uranium cycle.

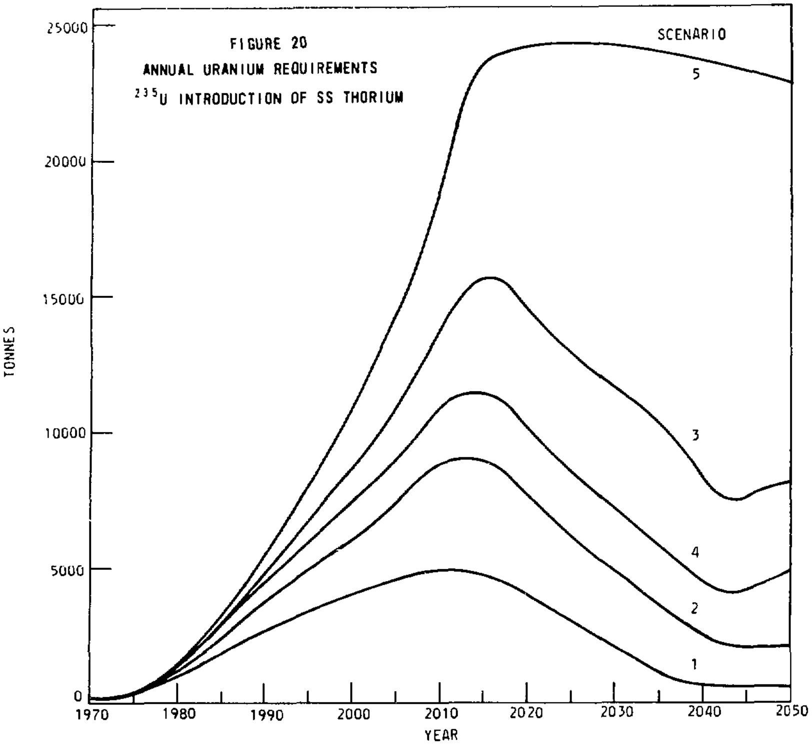
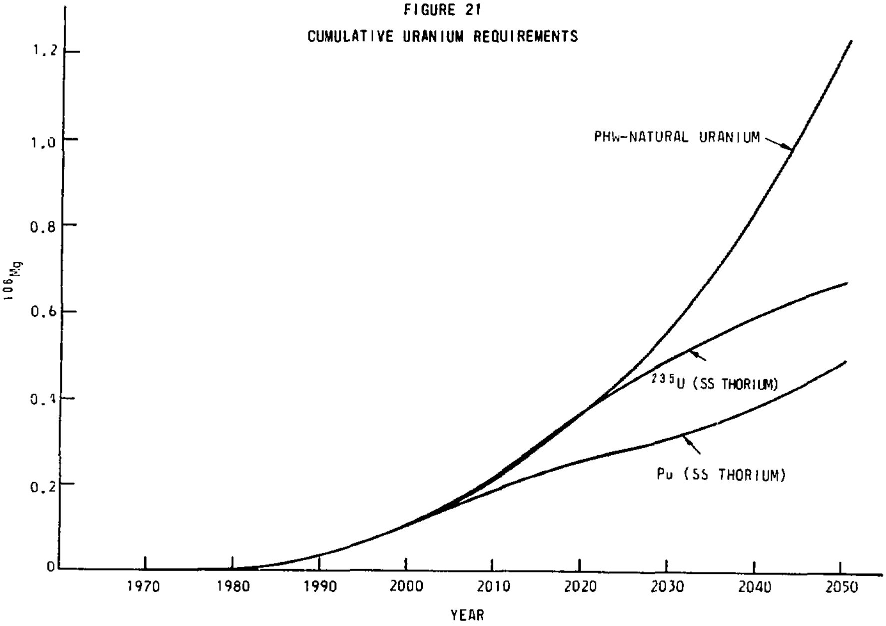


FIGURE 20
ANNUAL URANIUM REQUIREMENTS
^{235}U INTRODUCTION OF SS THORIUM

FIGURE 21
CUMULATIVE URANIUM REQUIREMENTS



Discussion:

Present uranium production in Canada is based on mines which were discovered some time ago and production from these mines is expected to fall off within the next few decades. Estimates of future uranium production rates made for the World Energy Conference study are shown in the table below and in Fig. 22.

TABLE III

Estimated Maximum Annual Uranium Production and Demand$^{(3)}$

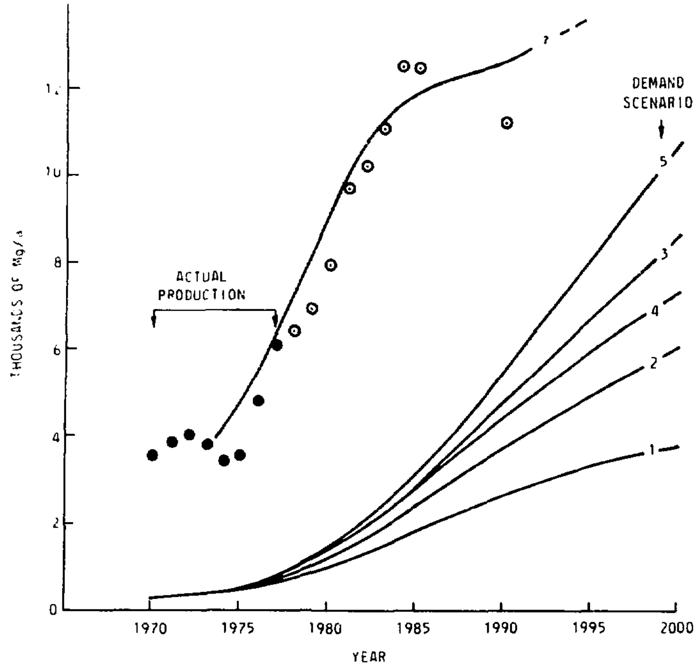
(Mg/ a)

	1975	1977	1980	1981	1982	1983	1984	1985	1990
Production (estimated after 1977)	3510	6100	7950	9750	10200	11150	12500	12500	11250
Demand (Scenario 3)	480	737	1315	1577	1866	2182	2523	2885	4837
Ratio	.14	.12	.17	.16	.18	.120	.20	.23	.43
Foreign commitments		8750	4910	5330	4740	5330	4500	4350	3650

FIGURE 22

ANNUAL URANIUM REQUIREMENTS

ESTIMATED MAXIMUM PRODUCTION RATES



It is probable that an increasing fraction of future production will be devoted to domestic use over the next few decades. How rapidly production from new discoveries can increase after 1990 is not clear but since only a small fraction of Canada's estimated resources have been produced to date, it is likely that production can continue to expand for a while, at least from the resource point of view. However, technical difficulties and other restrictions may lead periodically to restraints in development and short-term shortages are likely to occur. Even if it were possible to continue to expand production, the uranium supply is unlikely to expand at the same rate as our domestic nuclear power system requirements based only on the natural uranium cycle, so that the trend of requiring a larger fraction of domestic production for domestic consumption is likely to continue, unless more energy can be extracted economically from the fuel.

Thus our interest in improving the efficiency of using uranium resources by introducing advanced fuel cycles has both a long- and short-term goal. The long-term goal would ensure that nuclear power could satisfy a significant fraction of Canada's long term energy needs; in the interim, improvements in efficiency would lead to a greater export capability and a more assured domestic supply. Both aspects are apparent in Fig. 12, which shows commitments for scenario 3. By introducing advanced fuel cycles rapidly (perhaps more rapidly than could be achieved in practice) commitments have been reduced from more than 800,000 Mg (PHW-natural uranium) to about 300,000 Mg (advanced fuel cycles) in 2025. This reduction must be associated with short-term goals and, in fact, is merely a way of selling (in the form of natural uranium) the plutonium generated in the natural uranium cycle. If the commitment curves for the natural uranium cycle and advanced cycle were parallel from this point onwards, no further savings would be possible and we would not have progressed towards our long-term goal. However, the slopes of the curves for the advanced cycles are less than those for the natural uranium cycle so that to this extent progress towards the long-term goal is achieved.

Factors affecting the introduction of advanced fuel cycles include uranium resources, fuel processing capability, regulatory and proliferation considerations as well as economics. Only a few fuel cycles have been considered here and more work is in progress to determine the best fuel cycle to adopt. The urgency of introducing new fuel cycles depends on how rapidly uranium production rates are expected to increase about the turn of the century and how much of this production can be allocated to domestic consumption. On the other hand, the rate at which advanced fuel cycles can be introduced depends on developments in fuel processing. With reasonable progress in these areas, satisfying the demands of scenario 3 appears reasonable, at least for the nuclear contribution.

ACKNOWLEDGEMENTS

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