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LONG-TERM NUCLEAR R&D
POLICY OPTIONS
A MOSST POSITION PAPER

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LONG-TERM NUCLEAR R&D
POLICY OPTIONS
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EXECUTIVE SUMMARY

This paper considers whether, and in what manner, Canada should pursue R&D on advanced fuel cycles for the CANDU system, and R&D on nuclear fusion.

CANDU ADVANCED FUEL CYCLES

The CANDU nuclear reactor is an important Canadian energy technology. Designed, developed and manufactured in Canada, it is a leading Canadian high technology product that contributes towards our goal of energy self-sufficiency. It provides an increasing share of our electricity needs, and is capable of meeting far more of these needs as they grow in the future. It represents an economic source of electricity in Ontario today, and will likely become more economically attractive in the future and in certain other areas of Canada. In terms of reliability and performance, CANDU consistently surpasses its foreign counterparts, and it requires significantly less uranium fuel than these other reactors. It has also long been recognized that CANDU, with only a modest modification of its basic reactor design, has the potential to use advanced fuel cycles that would result in up to an 80% savings in the amount of uranium fuel required. This potential for adaptation is not shared by the existing light water reactors. In a world and at a time concerned with energy supply constraints, this CANDU potential for uranium conservation is not an unimportant consideration.

The need for such CANDU advanced fuel cycles, however, is not indicated at the present time. World uranium resources will be able to meet world demand until well into the next century. Further, Canada's uranium resources should be more than adequate to meet our long-term domestic needs, and to maintain our position as a leading uranium exporter. Moreover, CANDU advanced fuel cycles are now estimated to be 20-40% more costly than the existing system, and will only become economically competitive if real uranium prices increased 4 or 5 fold -- a situation that is unlikely to develop for at least another 4 or 5 decades. This suggests that there now exists no reason -- based on resources or on economics -- for Canada to undertake the long and costly R,D&D program required to develop CANDU advanced full cycles.

This assessment, however, could change at a future point. There are enormous uncertainties involved in looking beyond the next few decades, and changing events and shifting factors could render any present assessment irrelevant and obsolete. The energy scene, in particular, seems to be replete with such uncertainties, and remains highly sensitive to such developments. The nuclear power situation is obviously no exception.

The need for Canada to proceed with CANDU advanced fuel cycles may develop at some future time if certain conditions that now seem unlikely actually come about: nuclear power growth seriously accelerates; uranium resource discoveries and additions prove meagre; shrinking uranium supplies fall far short of rising world demands and uranium price increases become dramatic. Under such conditions, it would be desirable for Canada to be in a position to proceed with advanced fuel cycles. Canada should, therefore, seek to keep open its policy options for such future decisions on demonstrating and deploying advanced fuel cycles. This requires a small continuing R&D effort in this area.

AECL has had a modest R&D program on advanced fuel cycles for some years now, with current funding totalling about $4-5 million annually. Funding sufficient to keep the policy option open could be provided by a maximum of $10 million per year for about ten years. These funds should be obtained from within the existing budgetary allocation of AECL but should not be at the expense of other essential nuclear R&D efforts, such as waste disposal, reactor safety, and the decommissioning of nuclear facilities. A full review of the R&D program should be made at the end of five years.

In addition, the R&D program should be national in scope, involving participants from the relevant sectors - the nuclear electric utilities, the nuclear manufacturing industry and the university sector. Further, it would be highly advantageous if the program were undertaken as an international co-operative venture between Canada and one or more foreign research partners. Every effort should be made to gain this national flavour and to seek international co-operation. An interdepartmental task force should immediately be formed to investigate and to assess the potential for international collaboration in this R&D area.

NUCLEAR FUSION

Nuclear fusion is a potentially inexhaustible energy source -- an attractive solution to our long-term energy supply needs. It also promises to have substantial advantages over nuclear fission in terms of environmental and safety concerns, and risks of nuclear weapons proliferation. It might well become economically competitive in the future.

For these reasons, fusion power development is now being actively pursued by industrialized countries throughout the world. This effort will be long and costly. Although the scientific feasibility of the fusion reaction will almost certainly be demonstrated within a few years, a commercial fusion reactor will likely not be available for introduction before the year 2030.

Canada cannot afford to sit on the sidelines of this world effort in fusion developments. While it would not be practical for Canada to mount a full-scale fusion development program of its own -- the costs involved would be prohibitive -- the contrary is not desirable either. A total dependency by Canada on importing foreign fusion technology in the future would render the goal of sustained energy self-sufficiency impossible, and make it difficult for Canadian industry to participate in the development and manufacture of components and materials for fusion systems. Canada should, therefore, seek to keep open the fusion energy option for the future by establishing the necessary scientific expertise and technological capacity to develop fusion power when and if such an option becomes technically available and economically attractive.

This effort must be centred on the keystone of significant international collaboration. Access to the scientific knowledge and technical know-how of foreign fusion programs will enable a Canadian industrial capability to be developed in fusion power systems. To gain such access, however, we must have in place a domestic R&D program capable of making a significant contribution of real value to the world fusion effort. This contribution can only come from Canada concentrating or specializing in narrowly focussed technical areas in fusion R&D - areas that are of real international interest and that are based on some indigenous advantage or existing expertise. This R&D should also be done as a national effort involving all the relevant sectors, and should provide substantial interim industrial benefits.

The two recently established projects in the Canadian Fusion Program - the Tokamak de Varennes with Hydro-Québec and tritium management with Ontario Hydro - are worthwhile specializations in fusion R&D and offer good prospects for success. They deserve to be fully supported on a continuing basis, including the currently planned funding over the next 5 fiscal years (up to and including 1987-88) of approximately $50 million and $30 million, respectively (of which half would be the federal government's share). A full review of these projects should be undertaken at the end of this five year period.

On the other hand, an adequate case has not been made for Canada undertaking the proposed R&D project on gas laser fusion technology, and this project should not be approved at this time.

In summary, then, this paper proposes that the existing CANDU advanced fuel cycles program be kept within a ceiling that is not much above the present level of effort; and that the two established fusion projects be fully supported over time, as now intended. It may become appropriate to change this level of support in the future. At present, however, these R&D programs will suffice to keep Canada's long-term nuclear options open -- which is a legitimate course of action for Canada to take in addressing its long-term energy needs. If one or the other of the options is not pursued, this would narrow considerably our future energy possibilities.

INTRODUCTION

This paper examines the principal long-term nuclear R&D options open to Canada. The purpose of the paper is to consider whether, and in what manner, Canada should pursue R&D on advanced fuel cycles for the CANDU system, and R&D on nuclear fusion. The positions adopted by the paper -- highlighted by the recommendations -- are based on a detailed examination of the various resource, technical, economic, environmental and social aspects involved.

Advanced fuel cycles and nuclear fusion represent quite different R&D areas. They both, however, demand long development times at substantial costs, involve energy technologies with the potential to provide essentially inexhaustible supplies of energy for a very long time into the future, and are the subject of either recent or upcoming policy and funding decisions by the federal government.

Since these nuclear R&D areas are technically complex, a number of "monographs" are presented throughout the study to serve as brief simplified summaries of important technical aspects. The pages containing these monographs, as well as those presenting the tables and figures involved, are not numbered. The actual text of the paper, therefore, is the only part that is consecutively numbered.

This study was undertaken through an extensive consultative process involving many individuals from different organizations. The following list indicates the consultations that took place, and includes as well the relevant professional conferences that were attended over the course of the study.

CONSULTATIONS

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CONFERENCES

November 29 - December 2, 1981: Annual Conference of the American Atomic Industrial Forum, San Francisco, California.

April 26 - 30, 1982: International Conference on New Directions in Nuclear Energy with Emphasis on Fuel Cycles, Brussels, sponsored by the Belgian Nuclear Society, the European Nuclear Society and the America Nuclear Society.

June 6 - 9, 1982: Annual Conference of the Canadian Nuclear Association, Toronto.

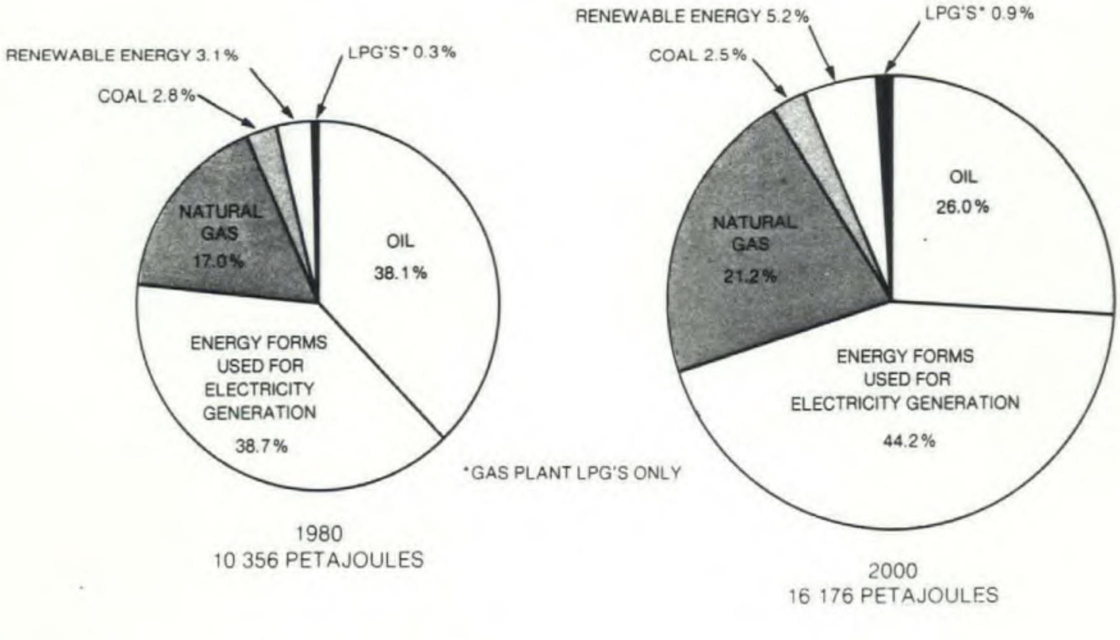
Table 1. 1980-2000 Electrical Demand By Province

Province	Electricity Demand (TWh)		
	1980	1981	2000
Newfoundland	8.4	8.6	19.3
Prince Edward Island	.5	.5	1.2
Nova Scotia	6.8	6.8	13.4
New Brunswick	8.8	8.8	17.0
Quebec	118.2	120.5	205.0
Ontario	106.3	106.7	188.9
Manitoba	14.0	13.5	22.6
Saskatchewan	9.8	9.9	17.4
Alberta	23.1	24.4	63.2
British Columbia	42.7	43.2	85.7
Yukon/North West Territories	.8	.9	2.1
Total Domestic Demand	339.4	343.8	635.8
Net U.S. Exports	27.3	33.9	25.6
Grand Total Demand	366.6	377.6	661.4

Source: EMR, Electricity in Canada-Update 1981, spring 1982, Table 7

NEB, June, 1981, p. 391-394

Figure 1. 1980-2000 Electrical Demand and Primary Energy Demand



Source: NEB, June 1981, p.28.

A. ELECTRICITY IN CANADA 1980-2000

This section assesses the likely place of nuclear power as a future electricity source in Canada. This is done within the basic context of the electricity situation in Canada, now and in the year 200, with respect to demand, supply and capacity; and in terms of the current outlook for each of the alternative means for generating electricity.

1. DEMAND AND SUPPLY

Demand

In 1981 total electricity consumption in Canada was 344 terawatt hours (TWh) or some 39% of total primary energy demand (Table 1 and Figure 1). This demand was two-thirds more than in 1970 and three times as much as in 1960. The two provinces of Quebec and Ontario accounted for two-thirds of this 1981 demand (35% and 30%, respectively). Approximately half of this total demand was in the industrial sector and one-quarter in each of the residential and commercial sectors (Table 2).

The 1981 electricity demand represented an increase of 1.3% over 1980 -- well below the 5.2% increase in 1980, the 4.5% average annual growth rate since 1973 and the average 6 or 7% rate in the 25 years before 1973. Based on the National Energy Board's recent middle demand forecast (see 'Future Electrical Demand'), electrical demand in Canada will be 636 TWh in the year 2000 -- an 85% increase over the current demand (Table 1). The distribution of this electrical demand among the major sectors is not expected to change: two-thirds of the increase in electrical demand will be in the commercial and industrial sectors. Electricity's share of the total demand for secondary energy in the combined residential, commercial and industrial sectors will rise from the

Table 2. 1980-2000 Electrical Demand By Sector

Sector	Electricity's Market Share (%) of Secondary Energy Demand 1980	Electricity's Market Share (%) of Secondary Energy Demand 2000	% Sector Share of Total Electricity 1980	% Sector Share of Total Electricity 2000
Residential	26	39	26	25
Commercial	33	45	24	27
Industrial	21	23	40	39
Energy Supply Industry	25	33	10	9
Transportation	--	--	--	--
Other (1)	--	--	--	--
Total	16	21	100	100

Source: NEB, June 1981, p. 31-67.

(1) Other includes the petrochemical sectors and various non-energy uses of petroleum products.

FUTURE ELECTRICAL DEMAND

The historically high and stable rate of change in the demand for electricity in Canada before 1973 shifted to a lower, fluctuating rate of change after 1973 - mainly because of reduced economic activity, rising electricity prices and the impact of conservation measures. This shift was the reason why the major electrical demand forecasts made in the 1970's, which were based on the high historical growth rates, rapidly became outdated. More recent forecasts of electrical demand have therefore tended to be steadily and even drastically lower.

The existing unsettled and changing conditions in the economy and in the energy market make it very difficult to forecast long-range electrical demand with any degree of confidence. Such forecasts are necessarily based on specific assumptions related to the major factors that will, in large measure, determine the future level of electricity demand: demographic elements, such as population growth rates; the pace of economic activity in terms of real GNP growth; the extent and impact of conservation measures; the future price of electricity and its relation to other future energy prices; the market penetration of electricity, especially in displacing other energy sources in end-use applications; the energy policies and programs of governments; and even consumer life-styles and societal structures. Since these factors, especially over the long-term, may be quite variable, assumptions made about them inherently contain a substantial degree of uncertainty, risk and value judgement.

Given this situation, recent major forecasts have nevertheless reflected the general view that future growth in electrical demand will likely continue to remain appreciably below the historical trend of 6 or 7%. A reasonable range for electrical demand growth in the next few decades seems to be between 2% and 5% per year on average, with the most plausible or realistic growth rate being around 3.5% or so. (A growth rate of more than 5% or less than 2% may be credible but appears to many at this point to assume too much or too little conservation, oil and gas availability, electricity substitution, economic growth, etc.)

For the limited purposes of this paper and as a basic reference forecast only, the National Energy Board's recent middle demand base case will be used: an average annual growth rate in electricity demand from 1980 to 2000 of 3.2%. (The assumptions made included average annual growth rates from 1980-2000 of 3.2% in real GNP and of 2.3% in primary energy demand, and electricity prices remaining constant in real terms after 1984, thus becoming more and more attractive relative to the rising oil and gas prices.) The NEB's low demand and high demand cases resulted in electricity demands in 2000 that were 9% lower and 30% higher respectively than this middle demand level.

See National Energy Board, Canadian Energy Supply and Demand 1980-2000, June 1981.

Table 3. 1981 Electricity Generation By Fuel Source and By Province

Province	Electricity Generation (TWh): Hydro	Coal	Nuclear	Oil	Gas	Total	% Total
Nfld.	44.2	--	---	.5	-	44.7	12
P.E.I.	--	--	---	--	-	--	--
N.S.	1.2	2.7	---	2.7	-	6.6	2
N.B.	3.8	1.1	---	4.0	-	8.9	2
Que.	102.7	--	---	.2	-	102.9	27
Ont.	37.3	33.4	37.8	.3	1.2	110.0	29
Man.	17.9	.4	---	.1	-	18.4	5
Sask.	3.1	5.9	---	.1	6	9.7	3
Alb.	2.0	18.2	---	--	4.3	24.5	7
B.C.	49.4	--	---	.9	.7	51.0	14
Yukon/NWT	.6	--	---	.3	-	.9	--
Total	262.3	61.7	37.8	9.1	6.7	377.6	100
% Total	70	16	10	2	2	100	

Source: EMR, Electricity Update, spring 1982, Table 3.

Table 4. 1981 Installed Electrical Generating Capacity by Fuel Source and By Province

Province	Installed Capacity (GW): Hydro	Coal	Nuclear	Oil	Gas	Other	Total	% Total
Nfld.	6.2	--	--	.8	--	--	7.0	8
P.E.I.	--	--	--	.1	--	--	.1	--
N.S.	.4	.6	--	1.0	--	--	2.0	2
N.B.	.9	.3	--	1.6	--	--	2.8	3
Que.	20.8	--	--	1.2	--	--	22.0	26
Ont.	7.2	8.9	5.6	2.8	1.4	.1	26.0	31
Man.	3.6	.4	--	--	--	--	4.1	5
Sask.	.6	1.5	--	--	.3	--	2.3	3
Alb.	.7	3.7	--	--	1.6	.1	6.2	7
B.C.	8.8	--	--	.5	1.1	.2	10.5	13
Yukon/NWT	.1	--	--	.2	--	--	.3	--
Total	49.2	15.4	5.6	8.2	4.5	.4	83.3	100
% Total	59	19	7	10	5		100	

Source: EMR, Electricity in Canada-Update 1981, spring 1982, Tables 2 and 4

(1) Includes steam, gas turbine and internal combustion.
(2) Mainly wood wastes and black liquor.

current 25% to 31% in the year 2000 or from 16% to 21% for all sectors (Table 2).

This means that electricity demand will clearly replace oil demand as the major component in our total primary energy demand by the year 2000: electricity's share will increase from its present 38% to 44% while oil's share will decrease from its present 39% to 26% (Figure 1). Canada will, in short, become an increasingly electrical society in its energy demand pattern.

As well, this trend may become even more pronounced if, for instance, our economic growth performance improves; if oil and gas shocks in terms of rising prices and supply difficulties take place; if electricity prices become more and more attractive and competitive; if greater electricity substitution and penetration take hold; etc. As a highly flexible and convenient energy carrier, electricity also has the future potential to meet a wide range of end uses and to contribute to a greater extent to our energy needs (e.g. electric powered vehicles, railway electrification, electric hybrid space heating, the production of hydrogen through electrolysis, etc.). As we get further into the next century, the role of electricity in our overall energy demand picture will probably become more and more important.

Supply

In 1981 total electricity production in Canada was 378 TWh, an increase of 2.8% over 1980 (Table 3). More than half of this electricity generation came from Ontario and Quebec (29% and 27% respectively) with B.C. and Newfoundland combined contributing about one-quarter of the total. Hydro provided 70% of this total electricity, with smaller shares coming from coal (16%) and nuclear (10%) and only very minor contributions from oil (2%) and gas (2%). This electricity generation in 1981 was supplied from a total installed electrical capacity of 83.3 GW (Table 4), a 2.8%

THE PATTERN OF ELECTRICITY SUPPLY IN CANADA - 1981 AND 2000

1981

The pattern of electricity generation in Canada in 1981 is basically characterized by a high degree of concentration -- in terms of geography and of each individual fuel source. Four provinces (Newfoundland, Quebec, Manitoba and B.C.) rely virtually totally (95% or more) on hydro. Almost half of the electricity generated in the Maritime provinces is oil-fired. Electricity generation in Alberta and Saskatchewan is based heavily on coal -- 75% and 60% respectively. Ontario is the sole exception here with a relatively varied generation mix: hydro 34%, nuclear 34% and coal 30%.

There is also a concentration pattern in the use of particular fuel sources. Some 40% of the total hydroelectricity generated originates in Quebec (and some 50% is generated in B.C., Newfoundland and Ontario - about an equal amount in each of these three provinces). Over 50% of the coal-fired electricity is generated in Ontario (and almost 30% in Alberta). Almost 3/4's of the oil-fired electricity is from the Maritimes and almost 2/3's of the gas-fired electricity is from Alberta. And Ontario alone produces all of the nuclear generated electricity in Canada.

The pattern of installed electrical generation capacity across Canada in 1981 naturally followed quite closely this basic generation pattern: almost 60% of the total capacity was hydro. The 1981 installed capacity was 75% peak load capacity, with the remainder equally divided between planned reserve and surplus capacities.

2000

Although hydro generation will grow at an average annual rate of 2.8% and increase by over 50% in absolute terms, its share of the total electricity supply will fall from the present 68% to 56% in 2000. Similarly, hydro capacity will increase by 55%, but, as a proportion of total capacity, will go down from 59% to 54% in 2000. This hydro supply will remain highly concentrated, with almost half from Quebec and 40% from the three province of Newfoundland, B.C. and Ontario.

The generation of coal-fired electricity will, at an average annual growth rate of 4%, almost triple in absolute terms by 2000, with capacity more than doubling. Coal's share of both total generation and total capacity will rise to 23% in 2000 (from the present 15% and 18% respectively).

Over two-thirds of this coal-fired electricity will be generated in the two provinces of Ontario and Alberta, on a roughly equal basis.

Nuclear electricity generation will increase at an average 2.8% per year to more than triple its 1980 level. The nuclear contribution to the total electricity supply will increase from its present 10% to 17% in 2000. Nuclear capacity in 2000 will be 18 MW (three times its 1980 level) and will constitute 13% of the total capacity (double its 1980 share). About 90% of this nuclear generation will come from Ontario, with minor contributions from New Brunswick (8%) and Quebec (2%).

Since oil and gas generation will basically remain at the same absolute level in 2000, its share of the total electricity supply will be halved to only 3%. Similarly, because it will stay at the same absolute level of about 13 GW, oil and gas capacity will go down as a part of total capacity from 16% to 10%. Almost 60% of this electricity will be generated in Ontario and Alberta, with only 13% in the Maritimes.

Certain changes in the electricity makeup of some provinces in 2000 will also be evident, while the situation in some other provinces will basically remain the same. Newfoundland, Manitoba, Quebec and B.C. will remain extensively hydro dominated (although Quebec will have a very minor nuclear presence and B.C. will significantly expand its coal generation). Nova Scotia and New Brunswick will greatly reduce their current heavy reliance on oil-fired generation through a greater use of coal and nuclear. Saskatchewan and Alberta will expand and continue to rely predominantly on coal-fired electricity, with some minor hydro development. Ontario will maintain its current hydro generation, almost double its coal generation and almost triple its nuclear generation, making nuclear the predominant fuel source, accounting for over half of Ontario's electricity in the year 2000.

Table 5. 1980-2000 Electricity Generation By Fuel Source and By Province

Electricity Generated (TWh): (1)

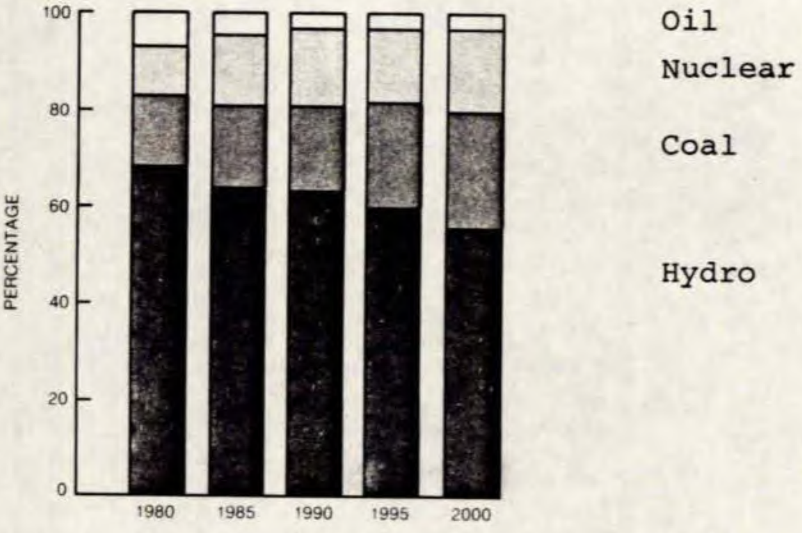
Province	Hydro		Coal		Nuclear		Oil	Gas	Oil & Gas	Total (2)	
	1980	2000	1980	2000	1980	2000	1980	1980	2000	1980	2000
Nfld.	44.9	56.8	--	--	--	--	1.4	--	.2	46.3	56.9
P.E.I.	--	--	--	.6	--	--	.1	--	.1	.1	.8
N.S.	.9	1.1	1.5	11.4	--	--	4.5	--	.9	6.9	13.4
N.B.	2.7	2.8	.5	1.3	--	8.8	6.2	--	1.6	9.3	14.6
Que.	97.6	174.6	--	--	--	3.0	.2	--	.5	97.8	178.0
Ont.	40.2	40.0	28.9	51.8	35.9	103.3	1.2	4.0	5.9	110.1	200.9
Man.	19.1	25.2	.1	--	--	--	.3	--	.1	19.5	25.2
Sask.	2.6	5.4	5.8	11.5	--	--	.1	.8	.6	9.2	17.5
Alb.	1.7	6.0	16.9	55.6	--	--	---	4.8	3.9	23.4	65.4
B.C.	40.9	59.3	--	20.0	--	--	.9	1.5	5.4	43.3	86.7
Yukon/NWT	.6	1.5	--	--	--	--	.2	--	.5	.8	2.0
Total	251.0	372.7	53.7	152.2	35.9	115.1	15.1	11.1	19.7	366.7	661.4
% Total	68	56	15	23	10	17	4	3	3	100	100

Source: NEB, June 1981, p. 391-394.

(1) Other primary fuel sources contributed less than 1%. In 2000 this amounts to 2 TWh (almost all from BC) and is included in the total.

(2) Includes net U.S. electricity exports of 27.3 TWh in 1980 and 25.6 TWh in 2000.

Figure 2. 1980-2000 Electricity Generation By Fuel Source



Source: NEB, June 1981, p. 190

increase over 1980 and almost double the 1970 capacity. The overall pattern of electricity generation and capacity in Canada in 1981 was basically one of a high degree of concentration -- in terms of geography and of each individual full source.

The NEB forecast for the year 2000 (using 1980 as the base year) projects electricity generation increasing by 80% to 663 TWh (Table 5 and Figure 2) and installed capacity by two-thirds to 137 GW (Table 6 and Figure 3). The existing pattern of electrical supply being highly concentrated in terms of geography and of each individual fuel source will continue, as each province will rely on its particular strength by expanding its existing base of fuel sources, be it hydro, coal or nuclear. (See 'The Pattern of Electricity Supply in Canada - 1981 and 2000'.) The general electricity situation by 2000, however, will be characterized, relatively speaking, by less of a reliance on hydro and oil and gas and by more of a reliance on coal and nuclear.

2. FUEL SOURCES FOR THE FUTURE: POTENTIALS AND PROBLEMS

In order to better understand this electricity picture in the year 2000 and what may possibly unfold in the post-2000 era, it is necessary to consider each alternative fuel source for electricity in terms of its basic potentials and possible constraints.

Hydro

Hydro power has long been the ruling mainstay of Canada's electricity generation and has steadily produced increasing amounts of electricity. The ready accessibility, long life-times, low operating costs, continued reliability and "inflation-proofing" aspects of hydro units have offset the high first capital costs and made hydro generation attractive and desirable.

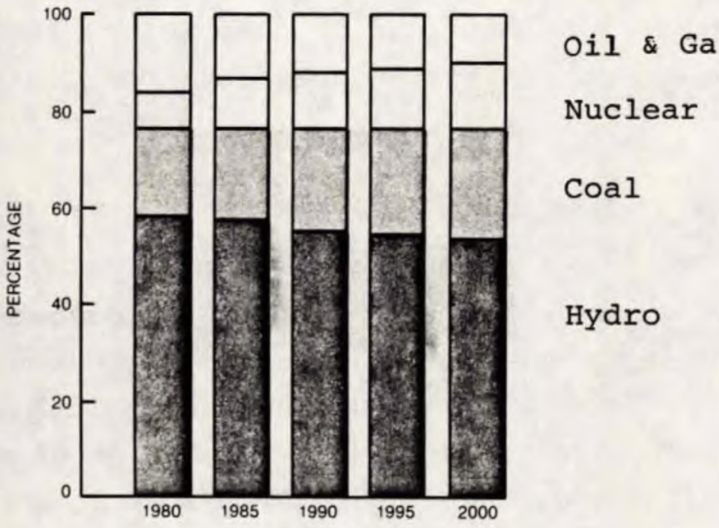
Table 6. 1980-2000 Installed Electrical Generating Capacity By Fuel Source and By Load Shape

	1980		2000	
	GW	%	GW	%
Installed Capacity: (1)				
Hydro	47.9	59	74.0	54
Coal	14.6	18	31.5	23
Nuclear	5.9	7	17.8	13
Oil	8.3	10	9.6	7
Gas	4.5	6	4.1	3
Total	81.6	100	137.0	100
Installed Capacity:				
Peak Load (2)	61.5	75	114.5	84
Planned Reserves	9.7	12	17.7	13
Surplus	10.4	13	4.8	4
Total	81.6	100	137.0	100

Source: NEB, June 1981, p. 191.

(1) Other primary Fuel sources are estimated to contribute less than 1%.
(2) 'Peak load' capacity consists of baseload, intermediate and peaking plant capacities.

Figure 3. 1980-2000 Installed Electrical Generating Capacity By Fuel Source



Source: NEB, June 1981, p. 192.

Table 7. Canada's Hydroelectric Power Potential in 1980

	(GW)	Undeveloped Power Potential:		
Province	Actual Operation and under Construction	Remaining Theoretical Hydro Potential	Remaining Technically Developable Potential	Economically & Technically Developable Potential
NFld.	6.5	7.0	6.3	4.8
P.E.I.	-	-	-	-
N.S.	.4	.2	.1	.1
N.B.	.9	.6	.6	.5
Que.	25.8	42.2	30.8	18.8
Ont.	7.1	7.8	6.2	2.1
Man.	4.8	7.0	4.9	4.9
Sask.	.6	2.4	1.7	1.2
Alb.	.7	18.8	11.4	4.4
B.C.	12.1	29.4	25.8	17.6
Yukon/NWT	1.2	15.9	16.4	9.2
Total	59.0	141.2	104.2	63.4

Source: Energy Alternatives, Report of the Special Committee on Alternative Energy and Oil Substitution (the Lefebvre Report), March, 1981, p.35.

HYDROELECTRICITY: POTENTIAL AND PROBLEMS

Canada has been blessed with abundant hydro resources and the future potential of hydro power remains impressive (Table 7). There is now almost 60 GW of hydro capacity in actual operation or under construction in Canada. In 1980, it was estimated that the remaining theoretical hydro potential to be tapped was 140 GW, although only about 100 GW of this potential was considered to be technically feasible to develop. Of this amount, perhaps some two-thirds or 63 GW was also economically developable. Although this was equivalent to the 1980 hydro capacity in actual operation and under construction, almost 60% of it resided in the provinces of Quebec and B.C. Given this uneven distribution across Canada, most provinces will have very little if any hydro potential left to develop in the next century. (An extensive intergrid connection across regions to realize interprovincial electricity trade may develop in the West or between Ontario and Quebec, but this would involve certain problems, not the least of which is an undesired dependency of one province on another for its electrical supply. The difficulties encountered in establishing a Western electrical grid highlight the problems involved here.)

By the year 2000, most of the major, readily accessible hydro sites will have been developed with principal additions located in the James Bay and St. Lawrence north shore areas of Quebec; the Gull Island, Lower Churchill River and Muskrat Falls regions of Labrador; the Nelson and Churchill Rivers of Manitoba; the Peace River district in Alberta and B.C.; and some sites in the NWT. If there is 74 GW of installed hydro capacity in 2000 as forecast, then less than 50 GW in hydro potential will be left to be harnessed - about as much as is now currently installed. While further additions from this remainder can be expected in the first few decades of the new century, they will likely be further away from the major urban demand centres, and more difficult and costly to develop than many past hydro developments. Land-use issues and other environmental and ecological concerns, such as the flooding of agricultural lands and the impact on inland fisheries, will act as major constraints to put a limit or ceiling on the amount of hydro electricity that will actually be supplied from what is technically and economically available.

Although most of the viable hydro potential will eventually be harnessed in conventional, large-scale plants, there does exist numerous opportunities for low-head, small-scale, mini and macro hydro projects, particularly in remote areas not served by an electrical grid and where an appropriate hydro site could be used to replace diesel-electrical generation. The rate at which such hydro is tapped will likely remain a function of the particular site-specific economics involved.

Further hydro expansions in Canada to the year 2000 will be substantial -- some 26 GW (Table 6). On the other hand, the proportion of total generating capacity represented by hydro has dropped steadily from a high of over 70% in the 1940's and 1950's to a low of almost 60% in 1980, and this trend will continue in the future with hydro capacity accounting for just over half of the total installed capacity in the year 2000. Similarly, the share of hydro generation will drop from almost 70% of the total current generation to 56% in 2000 (Table 5).

Although hydroelectricity does, in a sense, constitute a renewable resource and its ultimate resource potential remains sizeable (Table 7), its future contribution to our electricity needs over time will be limited. (See 'Hydroelectricity: Potentials and Problems'.) The majority of the readily available and economically attractive hydro potential will be harnassed by the year 2000 and most of the rest largely exploited within the first few decades of the next century. Canada as a whole will obviously continue to develop its hydro resources but, equally obviously, hydroelectricity will be able to satisfy only a part of our future demand needs and, increasingly over time, a smaller and smaller part.

Coal

Although coal supplied over half of Canada's primary energy requirements as recently as 1950, it now supplies only about 10%. Of the 37 million tonnes of coal now consumed in Canada, about 3/4's is for the generation of electricity. In 1981 coal-fired thermal units provided 16% of the total electricity supply and constituted almost 20% of the total installed electrical capacity (Tables 3 and 4). By the year 2000 this coal role will be substantially greater, with coal-fired generation almost tripling in absolute terms to provide almost 1/4 of the total electricity supply and with coal-fired units more than doubling to account for almost 1/4 of the total electrical capacity (Tables 5 and 6). In

COAL: POTENTIALS AND PROBLEMS

Coal constitutes the most abundant fossil fuel in Canada and, indeed, in the world. The Canadian coal resource base can only be described as extremely massive and the reserve base as enormous (Table 8). There are estimated to be literally billions of tonnes of measured coal resources (3.6 for lignite, 30 for sub-bituminous and 16.8 for bituminous). Thus, Canadian coal resources are extremely large in relation to current coal requirements and certainly more than sufficient to meet any future demand for centuries. For example, at the level of current consumption (37 million tonnes), our measured resources would last more than 1,400 years and, even at an annual consumption five times the current level, these resources would last close to 3 centuries! This Canadian situation is basically mirrored on the world scene where there is little doubt that worldwide coal resources will be more than adequate to support increased coal use for at least the next century.

Coal has a number of other advantages as well. The coal supply industry in Canada is a well-established one with a historically long operating experience. The technology of coal-fired electrical units is a well-known and familiar one, with coal as an energy commodity generally accepted by the public through long use and familiarity.

The future development of coal does, however, face some substantial constraints or obstacles. Since coal is not distributed evenly across Canada, the high costs of transporting large amounts of coal for use in places a fair distance from where the coal is mined is a serious disincentive. Coal will be confronted with increasing competition from other electricity alternatives, especially nuclear, which, at least in Ontario, now has substantial cost advantages over coal and is expected to become even more economically attractive in the future. Moreover, the use of coal for generating electricity will likely face increasing competition from other new uses of coal, such as the production of synthetic natural gas and liquid fuels.

There may also be an import-export constraint with respect to coal. Although half of Canadian coal production is now exported, about half of our coal consumption is imported -- a result of the large distances between Ontario, the main consumer, and the West, the main producer, and of the availability to Ontario of large quantities of comparatively economic American coal. The increased use of coal for generating electricity in Ontario may mean increased coal imports. This may have a negative impact on our balance of payments situation and on our overall thrust towards energy self-sufficiency. In this way the use of coal may suffer since, unlike the other major fuel sources for electricity, it lacks a totally indigenous character.

Coal is also troubled with a number of serious environmental problems. The single most worrisome environmental feature of coal combustion in the long term may be the so-called greenhouse effect -- an increasing buildup of atmospheric carbon dioxide levels and the possible irreparable effects that this could have on the world climate. The more immediate and prominent environmental concern lies, of course, in the combustion products of coal, principally nitrogen oxides and sulfur dioxide, which form acid rain.

This environmental constraint may, however, be considerably overcome as more stringent regulations and remedial technologies are implemented. Various 'scrubbers' can remove most of the sulfur dioxide from flue gases - although at considerable cost. Alternate control techniques may be adopted, such as the use of coal-in-oil mixtures, coal cleansing, switching to low-sulfur coal and limestone injection systems. Fluidized-bed combustion systems hold the promise of being clean-burning and environmentally acceptable since they could eliminate up to 90% of sulphur dioxide emissions and substantially reduce emissions of nitrogen oxides.

Table 8. 1978 Canadian Coal Resources and Reserves

(billion tonnes)	Rank:		
Resources	Lignite	Sub-bituminous	Bituminous
Immediate Interest:			
Measured	3.6	30.0	16.8
Indicated	2.8	-	10.4
Inferred	10.9	102.0	71.5
Future Interest:			
Measured	.2	-	-
Indicated	3.9	-	.1
Inferred	23.5	198.0	.1
Reserves			
Mineable	3.2	7.3	5.6
Recoverable	2.1	2.2	1.6

Source: EMR, Discussion Paper on Coal 1980, p.8 and 10.

Terms:

Resources - Level of Confidence

Measured - resources computed from specific measurements

Indicated - resources computed partly from specific measurements and partly from reasonable geological projections

Inferred - resources based largely on broad knowledge of geological character and on few measurements

Feasibility of Exploitation

Immediate Interest
- resources of immediate interest for exploration or exploitation

Future Interest
- resources not of immediate interest but may become of interest in the foreseeable future.

Reserves

Mineable - those measured and indicated resources of immediate interest that can be considered for mining using current technology and applying a broad economic judgment only to the mining method.

Recoverable -that mineable coal that could be recovered as a run-of-mine coal with current technology and at current market prices.

Rank - coal classifications determined by the degree of alteration of the original organic material. A decreasing order of rank (bituminous, subbituminous and lignite) is characterized by lower carbon content, lower heat value and increasing softness.

the year 2000 coal generated electricity will be much more important in those areas with or near coal deposits, most notably the West and especially Alberta, and in those areas such as the Maritimes that are moving to convert existing oil-fired units to coal.

Coal-fired electricity will therefore likely play an increasingly important role in providing our future electricity supply needs. Given its massive resource/reserve size (Table 8), coal can be considered as an electricity fuel source with a really long-term and truly large-scale potential contribution to make in our electricity future. But greater coal utilization in the future may be seriously hampered by intractable or unacceptable environmental problems and by considerable transportation and cost constraints. (See 'Coal: Potentials and Problems'.)

Oil and Gas

Oil-fired electricity will definitely be playing a diminishing role in our overall energy future. It will supply only about 1% of our electrical supply in 2000 as compared to the current 4% and will represent 7% of our installed capacity in 2000 as compared to the current 10% (Tables 5 and 6). Despite temporary ups and downs in supply and price, oil remains a rapidly diminishing fossil fuel resource that will likely become increasingly expensive. Rather than being burnt to generate electricity, oil will be reserved for more important and necessary uses, such as for transportation. Responding to the active encouragement of the National Energy Program, the Maritime provinces are planning to convert existing oil units to coal. Other existing oil units will be used only as reserve capacity or in emergency situations. No utility expansions of oil-fired capacities are anticipated, although Hydro Quebec does appear to be planning to add some oil-based capacity to meet its peaking problem and for use as a spinning reserve for possible export opportunities.

Table 9. Possible Electricity Contribution of Unconventional Renewable Energies in the Year 2000

Renewable Energy	Possible Annual Electricity Supply By 2000 (GW)
Solar	0.8 - 4.4
Photovoltaic	.01
Wind	0.1 - 10.0
Biomass	2.0
Tidal	1.0
Wave	0
Small Hydro	1.2
Geothermal	max. 1.0
Total	6.1 - 19.6

Source: CREB, EMR, "Unconventional Electricity Sources and Conservation," in EMR, Nuclear Policy Review Background Papers, 1980, p. 65.

The situation for gas-fired electricity is basically analogous to the oil one. Its share of electrical supply is expected to drop from the current 3% to 2% in 2000 and its share of electricity capacity from 6% to 3% in 2000 (Tables 5 and 6). Although our natural gas resources now appear to be quite sufficient to our needs for some time to come, natural gas will likely remain much too valuable a primary fuel to burn for electricity generation. Other uses such as direct heating and as a transportation fuel, as well as gas exports, will be much more attractive than the use of gas as a source of electricity. Existing plants will be used only for peaking of emergency operations, and utilities are not planning to develop any new gas-fired units in the future.

It is clear, therefore, that electricity generated from oil and gas will be diminishing in importance over the next few decades and will have only a very minor role in our energy future.

Renewables

Unconventional renewable energies for electricity generation are usually considered to include solar energy (solar power towers, photovoltaic solar cells, solar satellites), biomass (forest, agricultural and municipal wastes and peat), windpower, geothermal energy, tidal energy, wave energy, small hydro, and ocean thermal differences. They all appear to have a number of attractive features: they are not finite, depleting resources such as fossil fuels but practically inexhaustible or unlimited; they are not now extensively used; they are regarded as relatively environmentally benign sources; and they are looked on as the needed basis for a more self-sustaining energy economy in the future, as the inevitable transition is made away from oil dependency. On the other hand, these renewable energy sources also appear to share certain limitations or disadvantages. All of them remain in various stages of early development and will require considerable amounts of time and effort to develop and to deploy. Some are highly localized in nature with only limited applicability. Most have a certain reliability problem in that they are largely dependent on such variables as the amount of sunshine, velocity of the wind, and time of the tides. All face the necessity of considerable cost reductions to become economically attractive. As well, considerably more experience in actual use must be gained to achieve a good working sense of the difficulties and problems actually to be faced in practice.

The actual potential of these renewable energies is generally estimated to be about 6-20 GW of possible electricity supply by the year 2000 (Table 9). Given the existing limitations or constraints, however, it is realistically expected that their actual electrical contribution in 2000 will be only about 1 or 2 GW - less than 1% of the total electricity supply at that time. Their potential contribution in the next century could, of course, be quite considerable.

Although electricity generation from unconventional renewable energy sources is almost negligible at the present time, such sources will, given their practically inexhaustible or unlimited nature and other attractive features, be developed over the next few decades. In light of the expected limitations or problems with such development, however, their potential energy contribution will not be fully realized by the turn of the century when they are realistically expected to make only a relatively minor contribution. The real promise of renewables, however, lies sometime in the next century when their role in our electricity picture could be substantially greater.

Nuclear

Elecricity generated form nuclear fission reactors will clearly be playing a more important role in our electricity future for the rest of this century. Nuclear electricity is expected to triple in absolute terms by the year 2000, when it will provide

17% of our total electricity generation as compared to the current 10% (Table 5). Nuclear capacity will more than triple to about 17.8 GW in 2000, when it will account for 13% of our total installed electricity capacity, double its current share (Table 6). (This nuclear forecast can be presented with reasonable confidence since there will be 15.1 GW of installed nuclear capacity by the year 1991: 5.2 GW from the nine existing reactors operating now, and 9.9 GW from the 14 other reactors now under construction, and which will come in-service from 1982 to 1990.)

Although Canada's existing uranium resource base and uranium production capability will be analyzed extensively in Part B of this paper, it can be indicated here that they are certainly far more than adequate to meet the fuel needs of this forecast domestic nuclear capacity in the year 2000 and even to meet a much greater nuclear capacity in Canada far into the next century. What makes nuclear fission so attractive as an energy source is the enormous energy that is available from a relatively small amount of uranium. The fissioning of one U235 atom releases 50 million times more energy in the form of heat than the combustion of a single carbon atom; a single uranium fuel bundle which weighs 50 lbs. can produce as much heat as burning 400 tons of coal or 1,700 barrels of oil. Moreover, as will be discussed in depth later in this paper, there exists the possibility of considerably improved uranium utilization through advanced fuel cycles and reactors.

This means that nuclear energy offers the promise of being a truly long-term electricity source that could potentially meet much more of our electricity needs far into the future.

Whether or not this nuclear potential is realized in the future, however, will depend on a variety of factors and determinants. The Canadian nuclear industry is well-established, with proven high technology capabilities, but it is now facing a serious dissipation due to the current lack of domestic reactor

Table 10. 1980 Ontario Hydro Cost Comparison for Coal-fired and Nuclear Generated Electricity

Unit Energy Costs in mills per kilowatt-hour	Nuclear (Pickering A)(1)	Coal (Lambton)(2)
Capital Cost (3)	6.1	1.8
Operation and Maintenance Cost	4.0	1.8
Fuel Cost	2.3	17.5
Heavy Water Upkeep	0.4	n.a.
Total Unit Energy Cost	12.8	21.2

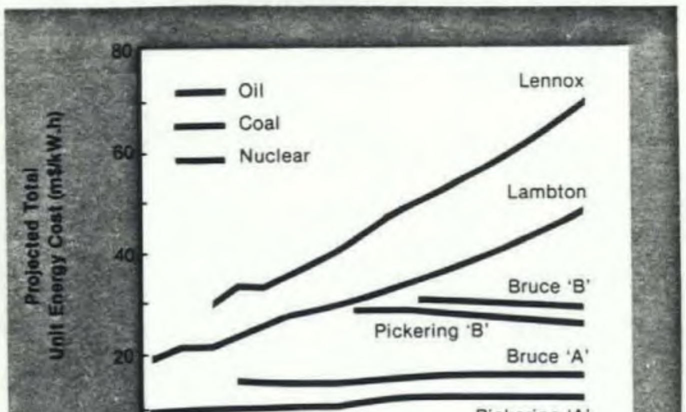
(1) The Pickering A Nuclear Station is composed of four 540 MW units

(2) The Lambton Station is composed of four 532 MW units. It is assumed that Lambton operated at base load with a 82.6% capacity factor like Pickering A.

(3) Interest and depreciation, including amortization, of heavy water inventory.

Source: Ontario Hydro, Ontario Hydro's CANDU Projects, June 1982, p. 24.

Figure 4. Ontario Hydro's Projected Cost of Electricity From Oil, Coal and Nuclear Fuels



Oil - Lennox

Coal - Lambton

Nuclear - Bruce & Pickeri

Source: J.A.L. Robertson, Nuclear Energy in Canada: The CANDU System, AECL, March 1981, p.8.

orders. This has been brought on by the economic slow-down and declining electrical demand growth and by the extremely competitive and dwindling reactor export market. The immediate and future status of this industry is in serious jeopardy, with the eventual outcome depending on the extent of economic recovery, success in the reactor export market and the possible pre-building of domestic nuclear reactors to export electricity to the U.S. The short-term fate of this industry in the 1980's could be an important factor in determining the eventual role of nuclear power in Canada. Such a domestic industry might be reassembled at a later date if needed but this might prove to be difficult and risky. Canada could also import foreign nuclear reactors from abroad if future nuclear capacity is needed but this would certainly entail considerable costs including a move away from energy self-sufficiency.

The CANDU nuclear technology certainly looks attractive from a number of important viewpoints. Ontario Hydro's extensive operating experience indicates that the total unit energy cost in mills per kilowatt-hour of nuclear generated electricity is almost 50% less than the cost of coal-fired electricity (Table 10). Although a nuclear unit has a higher capital cost component, it enjoys much lower fuel costs. (Unlike coal, nuclear fuel costs tend to be independent of the distance between the source and its point of use because the volume, and hence the transportation cost, is very small. To generate the same amount of electricity with bituminous coal requires 20,000 times the weight of the equivalent natural uranium fuel bundle.) Moreover, this nuclear cost advantage is expected to substantially widen in the next few decades (Figure 4).

On the other hand, this nuclear cost advantage does not now obtain in other provinces where there are readily available and less expensive electricity alternatives such as hydro in Quebec and coal in Alberta. Indeed, although Ontario is fully committed to a more nuclear future and nuclear electricity is expected to make some additional contributions in New Brunswick and Quebec by the turn of the century, it will be more difficult and take longer for nuclear power to be introduced and to make an inroad into other provinces which have no nuclear expertise or experience.

Ontario Hydro's CANDU plants have been an outstanding technical success in their lifetime performance records, making nuclear power in Canada a reliable commercial generator of electricity. Indeed, with the Pickering and Bruce plants leading world reactors in average annual load factors of 93-99%, the CANDU reactor surpasses every other reactor in its lifetime gross capacity factor. In 1981, for example, 7 out of Ontario Hydro's 8 units at Pickering and Bruce were in the top 8 positions in gross capacity factor out of the total 115 nuclear units in the western world with over a 500 MW capacity. In addition, in contrast to some other electricity alternatives, nuclear power can be operated continuously and therefore represents an ideal source for meeting base load requirements in electrical demand.

Despite this astonishing performance and reliability, the excellent CANDU reactor safety record, and the defence-in-depth safety features of CANDU, there remains a great deal of serious concern and apprehension, especially since the Three Mile Island accident, over the reactor safety issue and the possibilities and consequences of reactor accidents. Similarly, reservations and objections to the environmental aspects of nuclear power remain a dominant issue, even though a comprehensive nuclear waste R&D program is well in progress and will likely demonstrate and establish a safe and reliable waste disposal regime by the end of the century and even though programs are in place to handle other environmental problems, such as the management of low-level wastes and uranium mine/mill tailings and the decommissioning of reactor units. In addition, even though Canada has one of the most stringent non-proliferation safeguards policies in the world, there is a widespread concern over the possible spread of nuclear weapons through nuclear reactor exports and nuclear materials.

In short, the most important constraint to the further use of nuclear power in Canada (and elsewhere) remains the question of public acceptability. Because of adverse public attitudes and reactions and their influence on political decisions, nuclear development may be halted if, for instance, a Canadian Three Mile Island accident occurs, or if the nuclear waste disposal program is not successful, or if Argentina opts for nuclear weapons. This public response to nuclear power has yet to crystallize firmly and will only emerge over time as the result of a continuing national debate -- one which will be highly politicized and which will involve many complicated aspects related to competing philosophies and lifestyles, centralization and big government, technological disenchantment and available alternatives. The end result is certainly not clear at this time.

In summary, nuclear power certainly has the potential capability of providing electricity on an indefinitely large scale for the long-term future. Exploiting nuclear electricity, however, is one of the controversial political and public issues of today. The extent to which Canada utilizes this source and realizes this potential in a major way in the next century is a question still to be resolved, and will only be done so over time through the political process.

3. CONCLUSIONS

Based on the preceding overview of the Canadian electricity situation, the following conclusions may be presented:

(1) Future growth rates in electricity demand in Canada will likely be considerably less than the historically high growth rates. Nevertheless, electricity demand will become the clearly dominant part of our total primary energy demand by the year 2000 and will likely increase in importance into the next century.

(2) The current pattern of electricity generation and capacity will, on the whole, remain highly concentrated in terms of geography and of each individual fuel source. The general electricity situation by the turn of the century will, however, be characterized, relatively speaking, by less of a reliance on hydro and oil and gas and by more of a reliance on coal and nuclear.

(3) Hydroelectricity in Canada will be significantly expanded in the next few decades but will continue to have a declining share of the total electricity generation and capacity. Although the remaining hydroelectric potential is impressive, the most readily available and accessible potential will be basically harnassed by the early part of the next century. Hydroelectricity will therefore be able to satisfy only a part of our future demand needs and, increasingly over time, a smaller and smaller part.

(4) Coal-fired electricity will likely play an increasingly important role in meeting our future electrical supply needs. Given its massive resource/reserve size, coal can be considered as an electrical fuel source with a really long-term and truly large-scale potential contribution to make in our electricity future. But greater coal utilization may be seriously constrained by considerable transportation and cost factors, and by difficult environmental problems.

(5) Electricity generation from oil and gas in Canada will likely play only a very minor role in the future.

(6) Given their practically inexhaustible or unlimited nature and other attractive features, electricity generation from unconventional sources of renewable energies in Canada will likely be seriously pursued for development over the next few decades. In light of the expected limitations or problems

with the development of such sources, however, they are not expected to make more than a relatively minor contribution to our electrical supply by the turn of the century. The real promise of renewables lies well into the next century when their role in our electricity picture could be substantially greater.

(7) Nuclear electricity will clearly play a role of growing importance in our electricity future by the end of the century. Given the substantial uranium resource base that now exists in Canada and the massive energy potential inherent in uranium, nuclear fission energy offers the promise of being a truly long-term and large-scale electricity source -- one that has the potential to meet much of our future need for electricity. It is uncertain at this time, however, to what extent this nuclear potential will be developed, given the controversial and unresolved political and public issues associated with nuclear energy, particularly in terms of public acceptability.

Table 11 Estimated World Nuclear Power Capacity 1990-2025

(Low-High) Net GWe

	1980	1990	2000	2025
OECD	122	330-370	500- 680	920-1,910
Developing WOCA	3	30	90- 120	400- 880
Total WOCA(1)	125	360-400	590- 800	1,300-2,800
CPEA(2)	17	60- 85	150- 260	350- 780
Total World	142	420-485	740-1,060	1,650-7,580

Source: OECD/NEA, Nuclear Energy and Its Fuel Cycle - Prospects to 2025, 1982, p,17-18, 216.

(1) WOCA = World Outside Centrally Planned Economies Area, i.e., non-Communist countries. Unless otherwise stated, 'world' in this paper means WOCA.

(2) CPEA = Centrally Planned Economies Area, i.e. Communist countries.

Table 12 1974-1982 Forecasts of World Nuclear Capacity to 2025

(Low-High) Net GWe

Year of Forecast-Forecaster	Forecast World Nuclear Capacity In: 2000	2020	2025
1974 NEA/OECD	2,010-2,480	-	-
1977 NEA/OECD	1,000-1,890	1,980-5,630	2,160-6,650
1977 WEC(1)	1,000-1,320	2,490-3,770	-
1977 WAES(2)	910-1,770	-	-
1978 INFCE(3) Survey	1,080-1,900	-	-
1980 INFCE Report	830-1,200	1,650-3,350	1,800-3,900
1981 IIASA(4)	-	-	2,000-3,000(5)
1981 Uranium Institute			
1982 NEA/OECD	590- 800	1,180-2,370	1,300-2,800
1982 World Utility-Based	550	-	-
1982 Nuclear Assurance Corp.	428	-	-

Source: mainly OECD/NEA, 1982, p.22, 58.
(1) WEC - World Energy Conference
(2) WAES - Workshop on Alternate Energy Strategies
(3) INFCE - International Nuclear Fuel Cycle Evaluation
(4) IIASA - International Institute for Applied Systems Analysis
(5) In 2030

B. NUCLEAR POWER AND URANIUM IN THE WORLD AND CANADA - 1980-2025

In this part of the report, a general overview is presented of the currently expected future growth in nuclear fission power capacity and the extent of existing uranium resources to fuel this capacity. A determination is sought as to whether or not the existing and likely future uranium resources and production capabilities can be considered adequate to meet this forecast future nuclear power development. This future outlook is first done on a worldwide basis and then on a Canadian basis.

1. WORLD

Nuclear power is generally expected to make an increasing contribution to the world's electricity and energy supply needs over the next half century, although significantly less of a contribution than was just as generally anticipated only a few years ago. (Unless otherwise stated, 'world' in this report means WOCA-World Outside Centrally Planned Economies' i.e. the non-Communist countries.) In 1981 the world's almost 300 nuclear power stations at a total installed capacity of 125 GWe provided about 4% of the total energy needs and about 11% of the total electricity supply. In the spring of 1982, the Nuclear Energy Agency (NEA) of the OECD projected this nuclear capacity to grow by some 400-600% to 600-800 GWe by the end of the century and by some 1,000-2,100% to 1,300-2,800 GWe by the year 2025, when it will contribute an estimated 20-30% of the total energy supply (Table 11).

Although this nuclear growth is indeed substantial, it is also substantially less than recent forecasts: about one-third less than those of only two years ago; about one-half less than those of four years ago; and about 70% less than those of eight years ago (Table 12). This general and steady downturn in recent

Table 13 World Natural Uranium Resources

(thousands of tonnes U)(1)

Resource Category and Cost Recovery(2)

	Reasonably Assured Resources (RAR):			Estimated Additional Resources (EAR):			Speculative Resources:
	<$80/kgU reserves	$80-130/kgU	Total at <$130/kgU	<$80/kgU reserves	$80-130/kgU	Total at <$130/kgU	<$130/kgU
Australia	294	23	317	264	21	285	
Canada	230	28	258	358	402	750	
Namibia	119	16	135	30	23	53	
Niger	160	0	160	53	0	53	
South Africa	247	109	356	84	91	175	
U.S.A.	362	243	605	681	416	1,097	
Others	335	127	462	135	162	297	
Total(3)	1,747	546	2,293	1,605	1,115	2,720	6,600-14,800

Source: OECD/NEA and IAEA, Uranium - Resources, Production and Demand, 1982, p.18-19

(1) 1 tonne (metric ton) of uranium = 1.2999 short tons U_3O_8.

(2) 'Reasonably Assured Resources' (RAR) - uranium that occurs in known mineable deposits that could be recovered with currently proven mining and processing technology; a high assurance of existence. 'Estimated Additional Resources' (EAR) - uranium in addition to RAR that is expected to occur, mostly on the basis of direct geological evidence, in extensions of well-explored deposits, little-explored deposits, and undiscovered deposits believed to exist along a well-defined geological trend with known deposits; less reliance than RAR. 'Speculative Resources' - uranium in addition to EAR that is thought to exist mostly on the basis of indirect indications and geological extrapolations in deposits discoverable with existing exploration techniques; highly speculative. 'Reserves' - RAR and EAR at a cost recovery of up to $80/kgU.

Cost categories:
$1/lb U_3O_8 = $2.6/kgU
$30/lb U_3O_8 = $80/kgU
$50/lb U_3O_8 = $130/kgU

(3) Does not include CPEA:
RAR + EAR at <$80/kgU - 1,950-2,000
Speculative - 3,300-7,300

nuclear forecasts has resulted from the great uncertainties and many complexities still surrounding such forecasts. Many factors have contributed to this state: the economic slowdown of the last decade,the less than expected growth in energy and electricity demand, the impact of conservation measures, the repercussions from the Three Mile Island accident, continuing public concerns, doubts and opposition to a range of nuclear issues such as reactor safety, waste disposal and non-proliferation, etc. In the rapidly evolving energy situation of today, it is important to emphasize the high degree of uncertainty involved in any nuclear forecast, especially when such a forecast spans half a century into the future.

Given this forecast rollback, the existing uncertainties and the continuing cutback of planned and committed nuclear programs, however, it would perhaps be reasonable to view the NEA's low growth nuclear power projection, at least for the year 2000, as the more realistic one. (Indeed, two more recent forecasts-one by the world's utilities and one by the European Nuclear Assurance Corporation - are now estimating nuclear capacity in the year 2000 to be 550 GWe and 428 GWe respectively[1].) This NEA forecast still, however, entails a very substantial world-wide growth in nuclear power.

The spiralling downturn in nuclear power forecasts over the last decade has been accompanied by an upward trend in world uranium resource assessments. In 1982 the NEA estimated that, at a recovery cost of up to $130/kgU, there were 2.3 million tonnes U of Reasonably Assured Resources (RAR) and another 2.7 million tonnes U of Estimated Additional Resources (EAR) (Table 13). Although the 1980 world uranium production of 44,000 tonnes U was more than double that of 1974, it still amounted to less than 1%

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[1] I.J.J. Stobbs and A.M. Taormina, 'The Current Status and Long-Term Perspectives of Fissile Material Availability in the World', a paper presented at the Brussels Nuclear Energy Conference, April, 1982.

Table 14. 1974-1982 World Uranium Resource Assessments

	Thousands of Tonnes U:		
Resource Category	1974 $78/kg U	1977 $130/kg U	1982 $130/kg U
RAR	1,810	2,190	2,290
EAR	1,680	2,180	2,720
	3,490	4,470	5,010

Source: 1974-1982 NEA/OECD and IAEA Assessments

Table 15. Pre-1977 -1981 Uranium Exploration Expenditures

		($ million 1980)				
	Pre-1977	1977	1978	1979	1980	1981 (planned)
Australia	99	23	34	35	n.a.	n.a.
Canada	92	83	90	121	107	n.a.
France	140	23	32	67	90	73
South Africa	---	16	29	34	29	26
USA	730	373	438	420	333	227
Others	292	97	104	91	69	62
Total	1,353	615	727	768	632	388

Source: NEA/OECD & IAEA, Uranium, 1982, p.44.

of these total RAR-EAR resources. In other words this uranium production level could be maintained by these existing resources alone (leaving aside any additional discoveries) for over 100 years before they would be fully depleted.

In addition, since 1974, and as a result of exploration efforts (Table 15), these uranium resources have increased (including the total cumulative production of 190,000 tonnes U since 1974) by almost 1.7 million tonnes - an increase of 50% since 1974 (Table 14). This means that in 1982 the world had about one and a half tonnes U in its resources for every tonne U it had in 1974. The cumulative uranium production from 1974 to 1980 accounted for only 1 out of every 8 tonnes U that was added over that period. Those resource additions since 1974 are sufficient to last by themselves, at the 1980 production level, for some 35 years - well into the next century - before the 1974 resource level is returned to once more (assuming no further discoveries).

There are also sources of supply in addition to these uranium resources. It is estimated that there exists, also at a recovery cost of up to $130/kgU, some 6.6-14.8 million tonnes U in 'speculative' resources - about 130%-300% of the total RAR/EAR resources (Table 13). Continuing exploration efforts will, over time, move some of these speculative resources into more precise categories with higher levels of confidence. Other supply sources, of course, include unconventional and by-product sources that are generally lower grade and higher cost (more than $130/kgU). Although no grand total for such resources has been made, it is estimated, for instance, that the U.S. contains about 700,000 tonnes of low-grade U that could be recovered at a cost between $130 and $260 kg/U - or 40% of its current RAR/EAR resources at a $130 kg/U cost recovery.[2] As another example, the world's oceans may contain some 4 billion tonnes U but at a

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[2] NEA/OECD and IAEA, <u>Uranium</u>,1982, p.35.

Table 16. World Uranium Requirements 1980-2025

(thousands of tonnes U)

	1980	1990	2000	2025
Cumulative U Requirements				
Fuel Cycle Strategy:				
Light Water Reactor once through	30-33	466-527	1,133-1,435	4,355-7,645
Mixed Reactors	30-33	466-527	1,126-1,478	2,946-6,647
Liquid Metal Fast Breeder	30-33	466-518	1,179-1,498	2,557-3,963
All Strategies	30-33	466-527	1,126-1,498	2,557-7,645
Annual U Requirements				
Fuel Cycle Strategy:				
Light Water Reactor once through	30-33	53-65	81-123	169-374
Mixed Reactors	30-33	53-65	81-126	76-304
Liquid Metal Fast Breeder	30-33	53-64	89-129	41-100
All Strategies	30-33	53-65	81-129	41-374

Note: A large variety of reactor strategies could be imagined to meet the low and high projections of world nuclear power growth. The world uranium requirements in the future would depend on which particular reactor strategy was employed. Generally speaking, Table 16 assumes that all reactor strategies in the pre-2000 period follow the same course, i.e., the reactor and fuel cycle mix currently being planned or indicated by the nuclear countries of the world. This means that they have almost exactly the same uranium requirements by the year 2000 (expressed in a low-high range based on the low-high nuclear power forecasts). It is only in the post-2000 period that the reactor strategies start to diverge in terms of uranium requirements.

The reactor strategies are illustrative ones to indicate the possible range of future uranium requirements:

Light Water Reactor Once-Through. This strategy is based on a 15% improved LWR operated on a once-through fuel cycle. After the year 2000, all nuclear capacity additions and replacements installed are exclusively 15% improved LWR's.

Mixed Reactors. This strategy represents the low and high extremes of four different illustrative mixed reactor strategies, each of which involves different reactors being introduced after the year 2000 at different rates in different places of the world.

Liquid Metal Fast Breeder. This strategy is based on a U-Pu fast breeder reactor. After the year 2000 only current once-through LWR's are introduced until the year 2010 when all nuclear capacity additions and replacements installed are exclusively fast breeder reactors.

All Strategies. This strategy represents the low and high uranium requirements of all of the above strategies. It thus indicates the minimum uranium requirements (those under the low nuclear power forecast in the most uranium conserving strategy) and the maximum uranium requirements (those under the high nuclear power forecast in the least uranium conserving strategy).

What all of this indicates, therefore, is the possible range of future world uranium requirements for both low and high nuclear power forecasts under possible reactor strategies.

Source: NEA/OECD + IAEA, Uranium, 1982, p. 32.

possible recovery cost of $500-$1,000/kg U and with many technical and engineering problems (350,000 tonnes of water must be treated to produce one kg U.).[3] One can assume, however, that, if uranium prices increase and if exploration activities also increase correspondingly, there is certainly the potential for significant additions to the existing currently estimated uranium resource base.

The actual amount or magnitude of ultimately recoverable uranium resources is of course debatable. But the real interest should be in the total uranium resources that could be discovered over the long term. In this light, the existing uranium resource base is only a part of the picture, rather than the whole picture. Realizing this, the International Institute for Applied Systems Analysis (IIASA) has suggested, based on a simple extrapolation of the current U.S. uranium resource base to a global level, that ultimate recoverable world resources are about 18 million tonnes U - or over 3 times the current world assessment.[4] Although it may be argued that this is actually too much or too little, it can serve as a useful indication that considerably more uranium actually exists in the earth than is suggested by the current estimate of existing resources and that, with higher uranium prices and greater exploration efforts, the existing uranium resource base could be significantly increased in the future.

For illustrative purposes, however, but not disregarding the points made above, it is instructive to determine whether or not the existing uranium resource base <u>alone,</u> assuming no further additions to this base in the future, will be able to meet the fuel needs of the forecast future nuclear power. In evaluating the demand for and supply of uranium in the future, the resulting projections are, like the nuclear growth forecasts, by their nature uncertain and subject to many varying factors. Future

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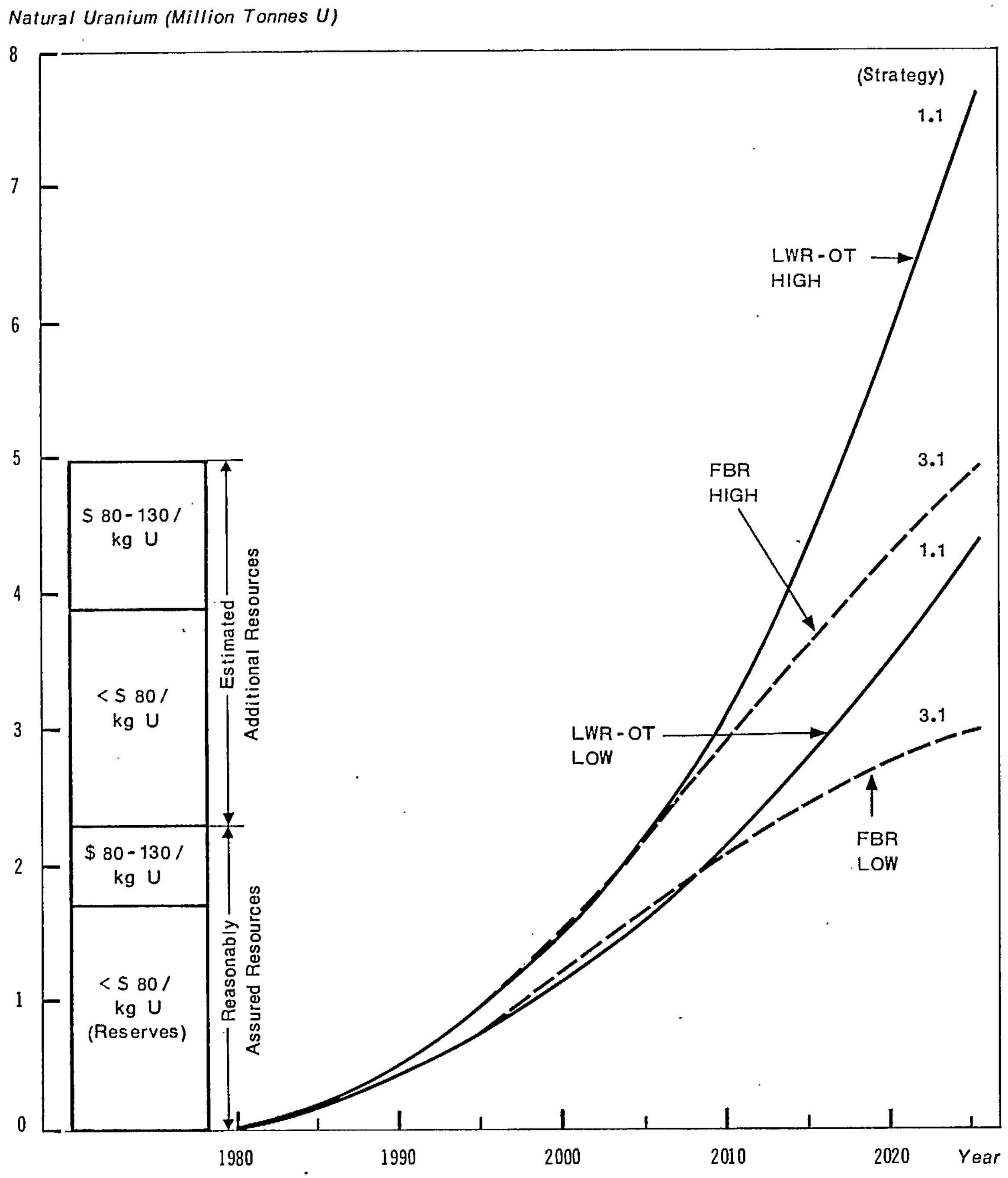
[3] <u>Ibid</u>., p. 38.

[4] IIASA, <u>Energy in a Finite World</u>, 1981, p.48-49.

Figure 5. World Cumulative Natural Uranium Requirements



Source: NEA/OECD, Nuclear Energy and Its Fuel Cycle-Prospects to 2025, 1982, p. 116

Note: LWR-OT = Light Water Reactor Once Through Strategy
FBR = Fast Breeder Reactor Strategy
The LWR-OT and the FBR Strategies represent the upper and lower limits, respectively, of uranium requirements. Mixed Reactor Strategies fall between these limits.
LOW = low nuclear growth forecast
HIGH = high nuclear growth forecast
See Table 16 Note.

uranium demand will be dependent upon the actual nuclear power growth realized and the particular nuclear reactor mix employed (since different reactors operating on different fuel cycles have different uranium needs). Future uranium supply will be dependent upon the developing resource and reserve base, the existing production capability and the maximum possible production capability. Both supply and demand will be highly dependent upon the actual price of uranium and, not the least important element, upon the market perceptions of both producers and consumers. Certain basic assumptions must therefore be made.

For the limited purposes of this illustrative exercise, then, it will be assumed that the future nuclear power capacity in the world will be within the low and high forecasts recently presented by the NEA (Table 11) and that the existing uranium resources estimated by the NEA (table 14) constitute the total ultimate resource base possible. In other words, this means that future nuclear capacity will not be below the low growth forecast and that no uranium resource additions in the future will be realized. As previously pointed out, such assumptions may not be realistic, given the persistently declining nuclear forecasts of the past, and the resource additions that have been realized over the last decade and that,it can be safely predicted, will be continued.

Based on these specific assumptions, however, Table 16 and Figure 5 indicate that the cumulative world uranium requirements by the year 2000, under both the low and high nuclear forecasts and for all reactor strategies, will total 1.1-1.5 million tonnes. These requirements could be easily met by the 5 million tonnes of existing uranium resources (RAR and EAR). (Indeed, these requirements by 2000 could be adequately covered by only the 1.7 million tonnes of existing low-cost (up to $80/kg U) RAR reserves.)

Table 16 and Figure 5 also indicate that the existing 5 million tonnes resource base is, under the low nuclear growth

Table 17. World Uranium Production and Planned Production Capacity
(thousands of tonnes U)

	Australia	Canada	France	Namibia	Niger	South Africa	USA	Others	Total
Actual U Production:									
Pre-1977	8.2	112.1	23.1	.6	6.1	75.3	209.8	37.0	472.2
1977	.4	5.8	2.1	2.3	1.6	3.4	11.5	1.3	28.3
1978	.5	6.8	2.2	2.7	2.1	4.0	14.2	1.5	33.9
1979	.7	6.8	2.4	3.8	3.6	4.8	14.4	1.6	38.1
1980	1.6	7.2	2.6	4.0	4.1	6.1	16.8	1.5	44.0
1981 (planned)	2.6	8.4	2.8	3.9	4.5	6.7	13.5	1.5	44.0
Planned U Production Capability									
1981	2.6	8.4	3.7	3.9	4.5	6.7	17.1		48.8
1982	4.5	9.5	3.9	3.9	4.5	7.2	16.9		53.7
1983	4.5	10.8	3.9	3.9	5.8	7.8	19.5		60.1
1984	4.5	14.8	3.9	3.9	8.0	8.2	20.5		67.7
1985	3.8	14.7	3.9	3.9	10.5	8.0	23.0		72.6
1986	6.0	14.0	4.1	4.2	12.0	7.9	24.7		77.8
1987	6.0	12.9	4.1	4.2	12.0	7.8	23.5		75.7
1988	5.2	12.3	4.1	4.2	12.0	7.8	23.0		73.7
1989	4.7	11.5	4.1	4.2	12.0	7.7	22.3		71.7
1990	4.7	10.5	4.1	4.2	12.0	7.6	21.8		70.2

Source: NEA/OECD + IAEA, Uranium, 1982, p.20 and 22.

forecast, large enough to meet the 2.6-4.4 million tonnes of cumulative uranium requirements to 2025 for all reactor strategies. Except for the sole case of a fast breeder reactor strategy, however, the cumulative uranium requirements by the year 2025 under the high nuclear forecast would exceed the existing resource base by about 1.6-2.6 million tonnes.

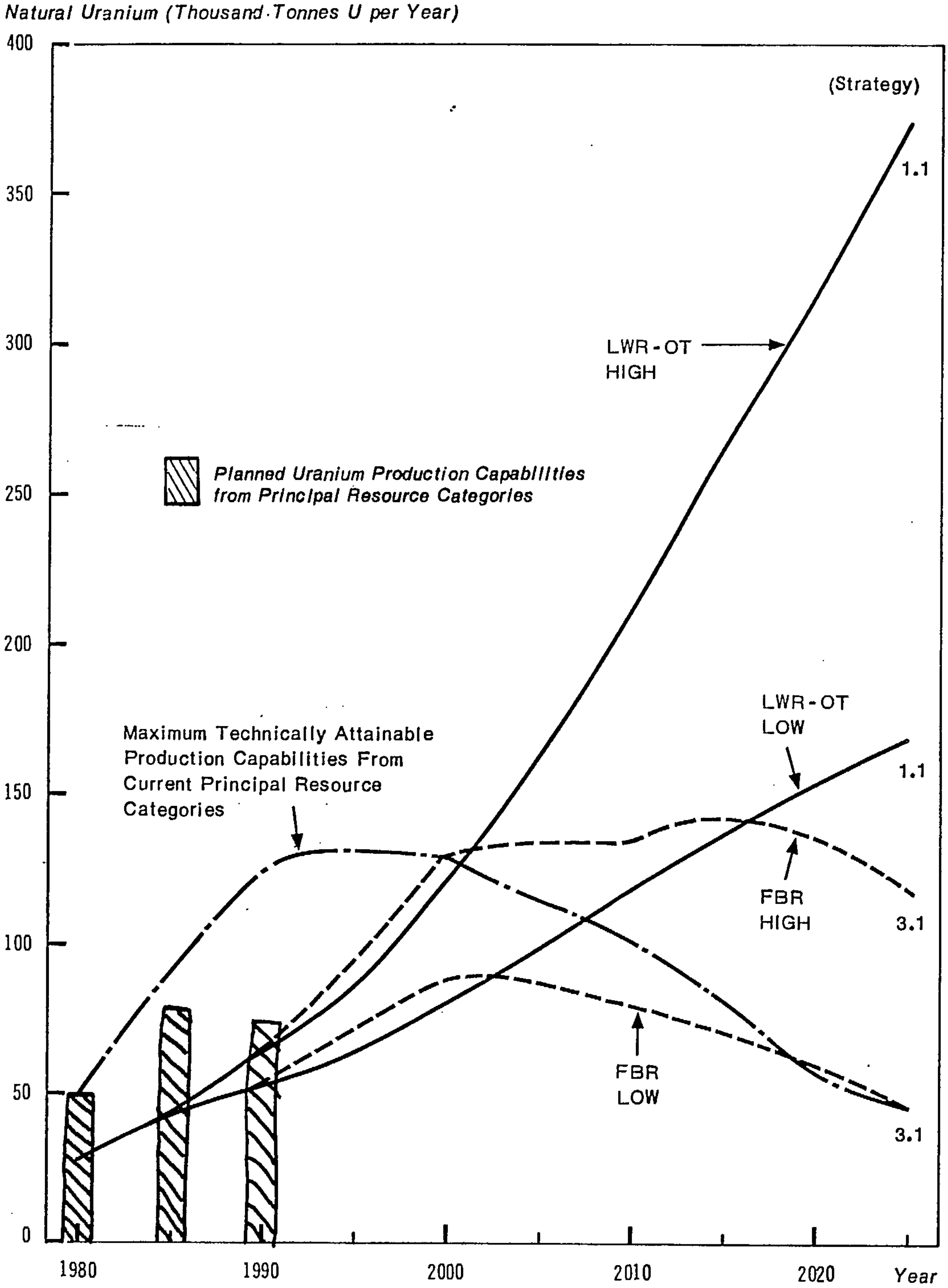
It appears, therefore, that the existing resource base is sufficiently large enough by itself, with no future additions, to meet the cumulative uranium demand to 2000 for the low and high nuclear forecasts under all reactor strategies and to 2025 for the low nuclear growth forecast under all reactor strategies. It is only in the high nuclear growth forecast that by 2025 that this resource base would be inadequate and would need a fast breeder reactor strategy to avoid a supply-demand imbalance.

It should be remembered, however, that, if the IIASA forecast of 18 million tonnes U of ultimate recoverable world uranium resources are used, then the resource base would be enough to meet the cumulative uranium requirements out to 2050 for the high nuclear growth forecast and all reactor strategies.

One must, however, go beyond this simple uranium resources - cumulative demand matching to determine whether or not the planned or potential production capability can meet the anticipated annual uranium demand expected. The potential of the resource base must, after all, be adequately and timely converted into actual production of available uranium if real supply/demand imbalances are not to develop.

Currently planned uranium production capability is expected to increase from 49,000 tonnes per year in 1981 to a high of 78,000 tonnes by 1986 and then decrease slightly to 70,000 tonnes by 1990 (Table 17). (Many of the planned facilities would not operate at full capacity in the absence of increased market demand.) If required and given adequate incentives, it is estimated that a

Figure 6. World Annual Natural Uranium Requirements



Source: NEA/OECD, Nuclear Energy and Its Fuel Cycle-Prospects to 2025, 1982, p. 114

Note: See Figure 5 Note and Table 16 Note.

uranium production capability of around 130,000 tonnes per year by the mid 1990's, supported by existing resources, could be achieved. (If future additions are made to the existing resource base, however, the production capability would, of course, be greater.) This level could not, however, be maintained from existing resources for very much longer after the turn of the century and would, in fact, steadily decrease to 2025 when it would reach the 1981 level of 49,000 tonnes. This projection is essentially an estimate of the maximum rate of production technically attainable from existing uranium resources under optimum conditions.

Table 16 and Figure 6 indicate that this maximum production level would be able to meet the annual uranium demand in 2000 of 81,000-129,000 tonnes U for both the low and high nuclear forecasts and under all reactor scenarios. After 2000, however, this production capability would be declining and would be unable to meet the annual uranium demand of the low nuclear forecast under all reactor strategies, except the fast breeder one, within less than two decades; and of the high nuclear forecast under all reactor strategies, including the fast breeder one, within about a decade.

This situation has been widely interpreted by many to suggest a possibly serious world demand-supply crunch in uranium coming about shortly after the turn of the century. To avoid this situation it is therefore argued that it is necessary to ease the future uranium demand situation by developing and using more uranium fuel-efficient reactor strategies, particularly the fast breeder reactor one.

As previously indicated, however, this uranium demand-supply imbalance will only occur if, on the demand side, the future nuclear capacity forecasts are actually realized and if, on the supply side, no further uranium resource additions are made in the future to increase the possible production capability. Both of these aspects, however, are subject to serious question.

On the demand side, the current nuclear growth forecasts, including the low growth forecast, may, as their recent predecessors have before them, turn out to be actually too high. Certainly, given the continuing worldwide slowdown in the nuclear industry and the persistent uncertainty concerning the future development of nuclear power, it is not at all assured that even the low growth forecast will be forthcoming. If, however, the low growth nuclear forecast is viewed as more realistic than the high growth one, then the possible uranium demand-supply imbalance expected in the first few decades of the next century is certainly much less pronounced.

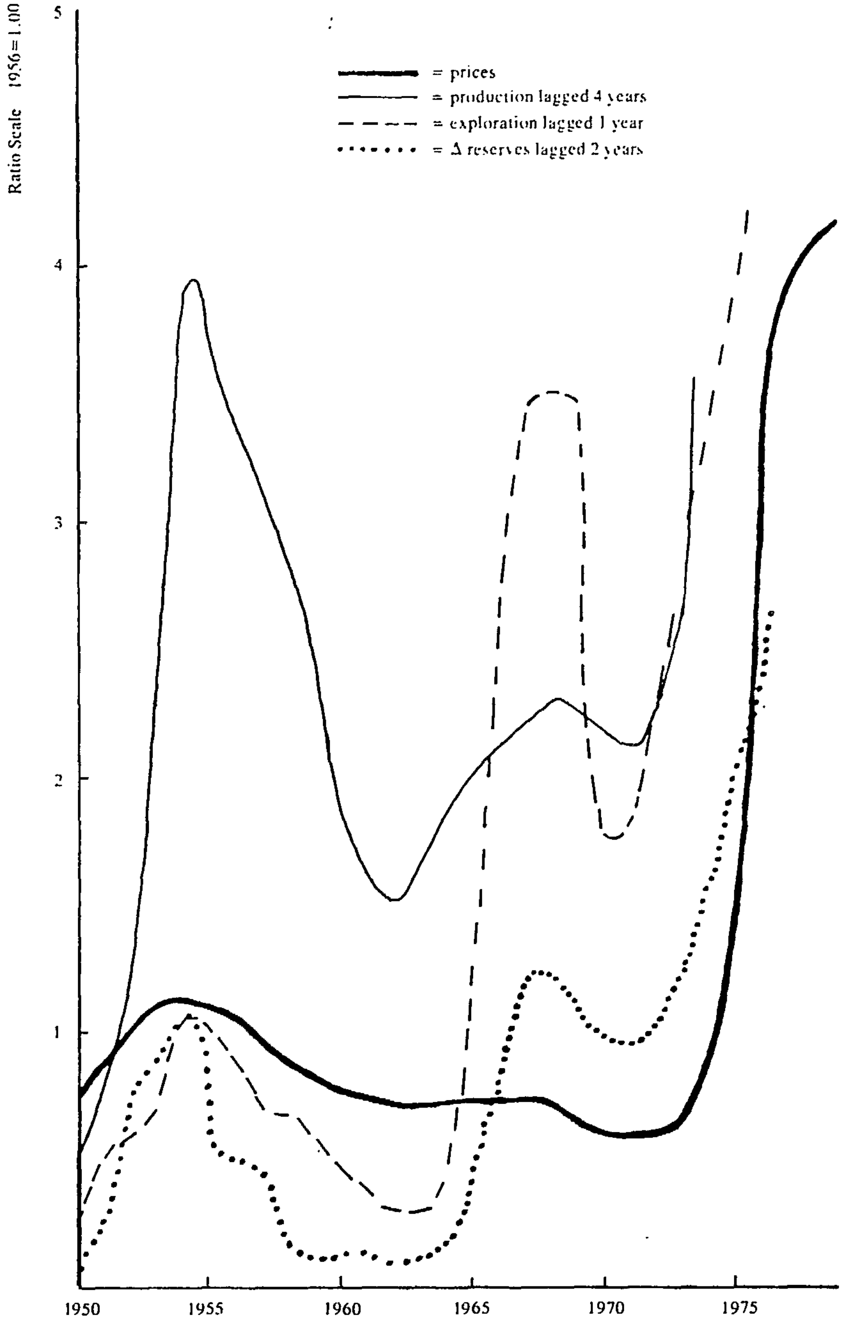
In addition, on the supply side, there is little reason to expect that, in the face of a uranium supply-demand imbalance becoming a real possibility or an actual reality, the existing uranium resource base will not grow. Given the significant resource additions over the last decade and the apparent potential for the existing resource base to at least triple in size, it is reasonable to expect that further resource additions will be made in the future through continuing or increased uranium exploration efforts. Although some possible short-term annual uranium shortages might develop, the production capacity could, if so needed, be increased to meet the required demand because the resource base upon which this capacity depends will become larger over time.

Although the current world uranium situation is marked by low demand, oversupply, low prices, and cutbacks in production and exploration efforts, this would be expected to change if a uranium shortfall starts to develop and the uranium price increases as a result. Indeed, the history of the world uranium industry has been a consistent one of periodic ups and downs in terms of demand, supply, prices and production. Historically, however, as Figure 7 indicates, there has existed this relationship between price and production-exploration-resource additions: changes in exploration activity and additions to reserves followed changes in price by one and two years respectively, while changes in production lagged behind price changes by about four years. If a uranium supply problem becomes apparent after the turn of the century, it is reasonable to expect that this would induce higher uranium prices which would stimulate greater exploration efforts and produce new resource additions to make possible an increased production capability. The chain reaction of the marketplace in terms of this demand- price-supply-resource relationship would be in force.

The full force of this market reaction may, however, be blunted by several factors. The actual market signals and responses may be inappropriate or perceived inaccurately, especially given the long lead-times involved of about a dozen years now between resource discovery and actual uranium production. Escalating cost requirements for mining and producing may be real disincentives. Non-economic influences may, as they have in the past, come into play, e.g. increased regulatory requirements in terms of the environment and non-proliferation considerations, public opposition to uranium activities and other political factors. Moreover, individual countries relying on foreign sources for their uranium requirements may experience at some times certain supply difficulties or disruptions. Although such influences could seriously affect the future uranium situation, it can be reasonably stated that the actual uranium resource base, as such, need not be inadequate to meet the expected future uranium demand needs, and that there is enough uranium supply to meet world demand.

In conclusion, it is misleading to assume that the existing uranium resource base constitutes the ultimate amount of uranium that will be recoverable and made available in the next four or five decades. In fact, it would appear quite unlikely that any enduring uranium supply problems will arise in the world over the

Figure 7. 1950-1975 Impact of Uranium Prices on Production, Exploration and Changes in Reserves



Source: Donald J. Lecraw, 'Uranium Supply and Demand: Implications for Policy,' in G. Bruce Doern and Robert W. Morrison, ed., *Canadian Nuclear Policies*, IRPP, 1980, p. 124.

next four or five decades. From a purely world uranium resource point of view, therefore, it does not seem essential to deploy a more uranium conserving cycle or reactor for at least the next century and if, as they must at some time under such a situation, uranium resources become unable to meet the uranium fuel requirements involved. In the far long term - in about a hundred years or so -, therefore, the world uranium base may prove to be inadequate but this will likely not be the case in the next fifty years.

2. CANADA

As previously indicated in this paper, nuclear power is expected to play a role of growing importance in Canada's electricity future. Based on the latest National Energy Board forecast as a basic reference point, the generation of nuclear electricity will grow at an average rate of 2.8% per year to 2000 to more than triple its 1980 level (Table 5). The nuclear share of the total electricity supply will rise from its current 10% to 17% in the year 2000. Nuclear capacity is projected to more than triple to 17.8 GWe in 2000 when it will constitute 13% of the total electrical capacity or double its present share.

It has also been previously indicated that this nuclear forecast should turn out to be quite close to the actual mark. There are already 5.2 GW of nuclear capacity in existing and operating reactors and an additional 9.9 GW under construction to come on-stream over the period 1982 to 1990 (Table 18). By 1991, therefore, the installed nuclear capacity will be 15.1 GW. For the NEB forecast of 17.8 GW in 2000 to be reached, only 2.9 GW would have to be added in the 1990's - a not unrealistic expectation.

This NEB forecast is also the end result of a steady downturn in the nuclear forecasts for 2000 made during the last decade

Table 18. 1991 Installed Nuclear Capacity in Canada

	Owner	In-Service	Generating Capacity (MWe Net) Unit	Station
Operating Reactors: (1)				
Douglas Point	AECL	1967	200	206
Pickering A 1 to 4	OH	1971-73	515	2,060
Bruce A 1 to 4	OH	1977-79	740	2,960
Total Operating Reactors - 9				5,226
Reactors Under Construction:				
Gentilly 2	HQ	1982	638	638
Point Lepreau	NBEPC	1982	635	635
Pickering B 5 to 8	OH	1983-85	516	2,064
Bruce B 5 to 8	OH	1983-87	756	3,024
Darlington A 1 to 4	OH	1988-90	881	3,524
Total Reactors Under Construction - 14				9,885
Grand Total By 1991-23				15,111

Source: EMR, *Uranium in Canada - 1980 Assessment of Supply and Requirements,* September 1981, p. 14 and June 1982 update

(1) Not included: the 22 MWe NPD reactor at Rolphton which is basically an experimental and training facility; and the 250 MWe Gentilly 1 reactor in Quebec which is a boiling light water prototype not now operating.

Table 19. Recent Forecasts of Nuclear Power in Canada

Year of Forecast and Forecaster	Forecast Nuclear Capacity 2000 (GWe)
1973 EMR *Energy Policy Phase I*	100
1974 AECL	131
ITC Nuclear Industry Study	130
1977 CNA	83
AECL	80
1978 EMR *LEAP* Report	70
EMR	52-67
AECL	60
CNA-Leonard & Partners Study	45
1979 AECL/EMR	45
MOSST Nuclear Study	30
1981 SECOR study	20-25
1982 AECL	20-35
NEA/OECD	25-35
EMR	21-28
NEB	17.8

Table 20. 1980 Estimates of Canada's Uranium Resources

Resource Category(4)	Mineable at uranium prices (1) Up to $135/kgU (2)	Between $135 + $200/kgU	Up to $200/kgU
	(thousands of tonnes U contained in mineable ore)(3)		
Measured	67	6	73
Indicated	163	22	185
Inferred	214	101	315
Prognosticated	144	301	445
Speculative			1,200 - 1,400

Source: EMR, Uranium in Canada - 1980 Assessment of Supply and Requirements, September 1981, p.4, 17 and 20.

(1) The dollar figures refer to the market price of a quantity of uranium concentrate containing 1 kg of elemental uranium.
(2) $C 135/kgU was the average weighted price in 1980.
(3) Uranium recoverable from mineable ore will be about 7% less than the uranium contained in the ore because of milling losses. One metric ton (tonne) of elemental uranium (U) is equivalent to 1.2999 short tons of uranium oxide (U_3O_8).
(4) These resource classifications are listed in a decreasing level of confidence and a decreasing feasibility of exploitation. The first three categories are considered to be reserves.
Measured: resources specifically measured and well established.
Indicated: resources partly measured and partly projected.
Inferred: resources based largely on broad geological knowledge with few if any measurements
Prognosticated: resources undiscovered but assumed by extrapolation to be associated with identified deposits
Speculative: resources undiscovered but though to exist in areas not associated with identified deposits.

Table 21 1974-1980 Canadian Uranium Resource Assessments

Resource Category	Thousands of Tonnes U Mineable at U Prices (up to $/kg U) 1974 ($78)	1975 ($104)	1976 ($156)	1977 ($160)	1978 ($175)	1979 ($200)	1980 ($200)	Resource Additions Since 1974
Measured	62	74	83	82	80	77	73	11
Indicated	95	99	99	107	155	182	185	90
Inferred	247	259	307	318	302	328	315	68
Prognosticated	--	346	349	388	426	442	445	99
Speculative	--	--	--	700-800	1,000-1,200		1,200-1,400	500-600

Source: EMR, Uranium Resource Appraisal Group, Assessment of Canada's Uranium Supply and Demand, 1974-1980.

(Table 19). Indeed, the 17.8 GW forecast is about 7 times less than those of the early 1970's and about 3 times less than those of only four years ago. As we have also seen, this Canadian situation has been mirrored on the world nuclear scene and is a result of the same basic reasons.

Beyond 2000, it is still the expectation of AECL that nuclear power in Canada will grow to about 100 GW by the year 2025. This may be an overly optimistic forecast since the EMR LEAP report of 1978 also forecast a 100 GW nuclear capacity by 2025 but forecast 70 GW by 2000 - a figure that, as we have seen, is now far too high and outdated. For comparison, the NEA/OECD now projects that Canadian nuclear capacity in 2025 will be in the range of 40-110 GW, depending on whether a low or high nuclear growth scenario materializes.

One may therefore conclude that nuclear power will likely be growing to about 15-20 GW by the turn of the century and can realistically be expected to double this level by the year 2025. Nuclear power in Canada will clearly be coming more and more important in our energy future but, just as clearly, will not be as important as was widely expected only a few years ago.

This future nuclear power will, of course, need to be fuelled from our natural uranium resource base. In 1980 uranium resources in Canada - in the measured, indicated, inferred and prognosticated categories and mineable at uranium prices of up to $200/kg U - were assessed at over one million tonnes U (Table 20). Although the 1980 uranium production level of 7,145 tonnes U was double that of 1974 (Table 23), it still amounted to only 0.7% of these existing resources. In other words, the 1980 production level could in theory be maintained by these <u>existing</u> resources (assuming no further resource additions are discovered - an unlikely assumption) for almost 150 years before they would be eventually depleted. Put in another way, and excluding the 62,000 tonnes U required for the lifetime fuel needs of the 15 GW of

Table 22. 1971-1980 Canadian Uranium Production and Exploration

Year	Uranium Production (tonnes U)	Uranium Exploration: Drilling (thousands of metres)	Uranium Exploration: Expenditures (1) (millions of $)
Pre-1974	99,210	--	--
1971-1974	----	n.a.	24.8
1974	3,420	--	--
1975	4,600	n.a.	23.9
1976	4,850	155	43.5
1977	5,794	304	71.7
1978	6,803	334	90.0
1979	6,817	483	129.5
1980	7,145	503	128.0
1981(est.)	8,400		

(1) Does not include 1975-78 expenditures of $17 million under the Uranium Reconnaissance Program.

Source: EMR, URAG, Uranium Assessments, 1974-1980.
NEA/OECD + IAEA, Uranium, 1982, p. 77,81

Table 23. 1980 Canadian Uranium Exploration by Province

Province	Exploration Drilling and Surface Development Drilling Activity (thousands of metres) 1980	Exploration Expenditures (millions of dollars) 1980
Sask.	368.6	77.2
NWT	55.1	29.1
Que.	24.1	6.4
N.S.	16.4	4.5
Nfld.	8.1	3.7
Ont.	11.1	1.7
N.B.	9.1	1.4
Yukon	1.0	1.3
Man.	2.9	1.1
Alb.	1.7	1.0
BC	0	0.6
Unspecified	5.3	0.3
Total	503.3	128.0

Source: EMR, 1980 Uranium, p. 22-23.

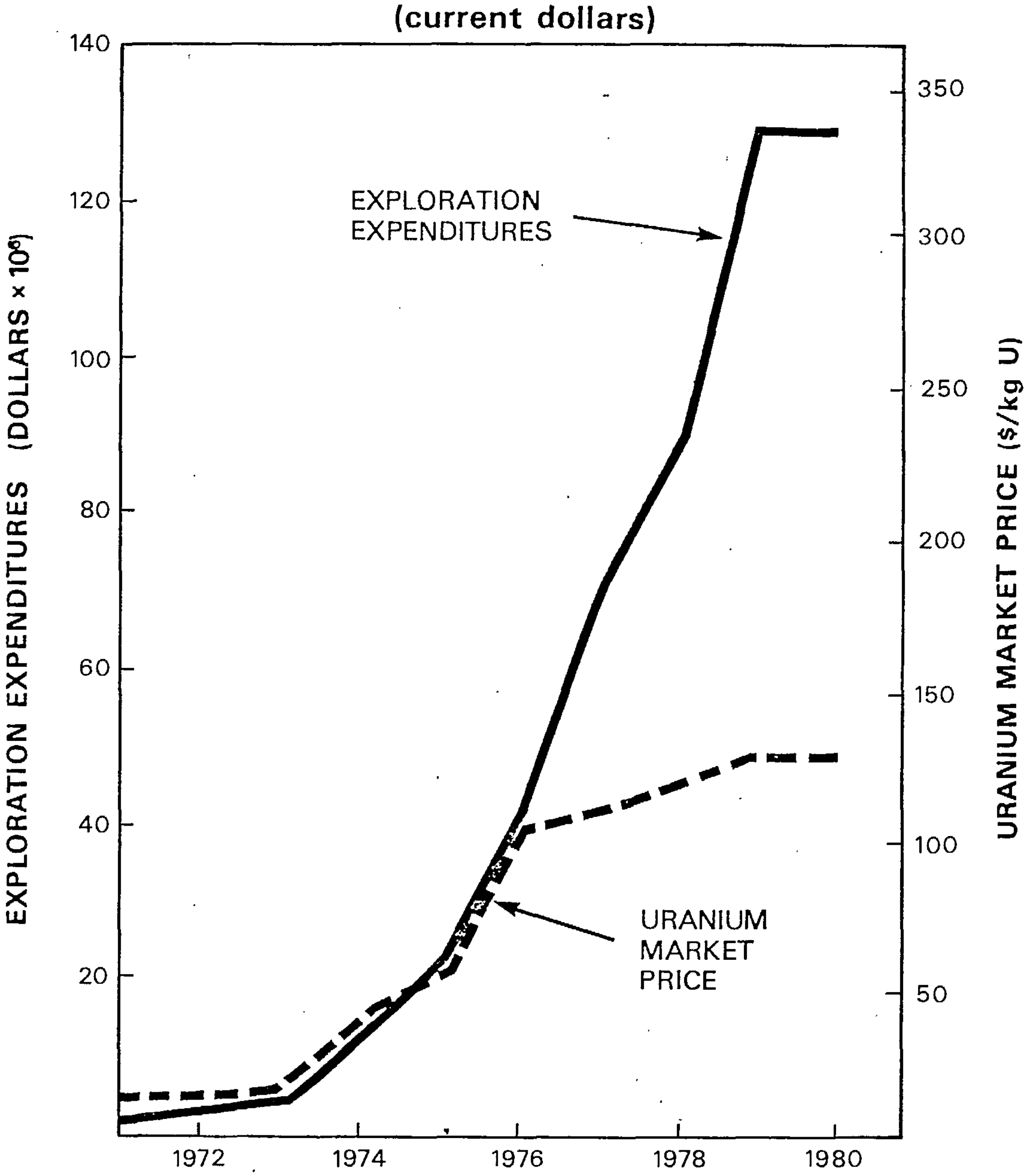
nuclear capacity expected in 1991, these existing resources would be sufficient to sustain the 1980 uranium export level of 5,400 tonnes U for about 180 years. Alternatively, and excluding the 48,500 tonnes U committed in remaining export contracts (Table 25), these resources would be able to meet the lifetime fuel needs of almost 250 GW of CANDU nuclear capacity - 14 times the 17.8 GW expected to be in operation in Canada at the turn of the century.

These resources are indeed massive and, furthermore, have been growing substantially over the last decade. Since 1974, the resources have increased by 268,000 tonnes U or actually (if the total cumulative production of 36,000 tonnes U since 1974 is included) by some 300,000 tonnes U - an increase of 40% over 1974 (Table 21). This means that about 7 tonnes U were resources in 1980 for every 5 tonnes U that were known in 1974. The cumulative uranium production from 1974 to 1980 amounted to only about 1 out of every 8 tonnes U of these resource additions. In fact, these resource additions are sufficient to last by themselves and at the 1980 production level for almost 40 years before the original 1974 resource level is reached (assuming no further resource additions in the interim).

These resource additions resulted from exploration efforts that totalled some $500 million since 1974 (Tables 22 and 23). This increased exploration effort directly resulted from the rising uranium market price level since 1974 (Figure 8). On the average over this period, every million dollars in exploration expenditures resulted in the addition of some 600 tonnes U to the existing current resource base. Since 1979, however, as a result of the downturn in the world nuclear power program and in uranium demand, a uranium oversupply situation developed which flattened out and then dropped the uranium market price. One of the effects of this has been a dramatic cutback in exploration expenditures and efforts.

Under favourable conditions, however, -- a rising uranium

Figure 8. 1971-1980 Uranium Exploration Expenditures in Canada and Uranium Market Price



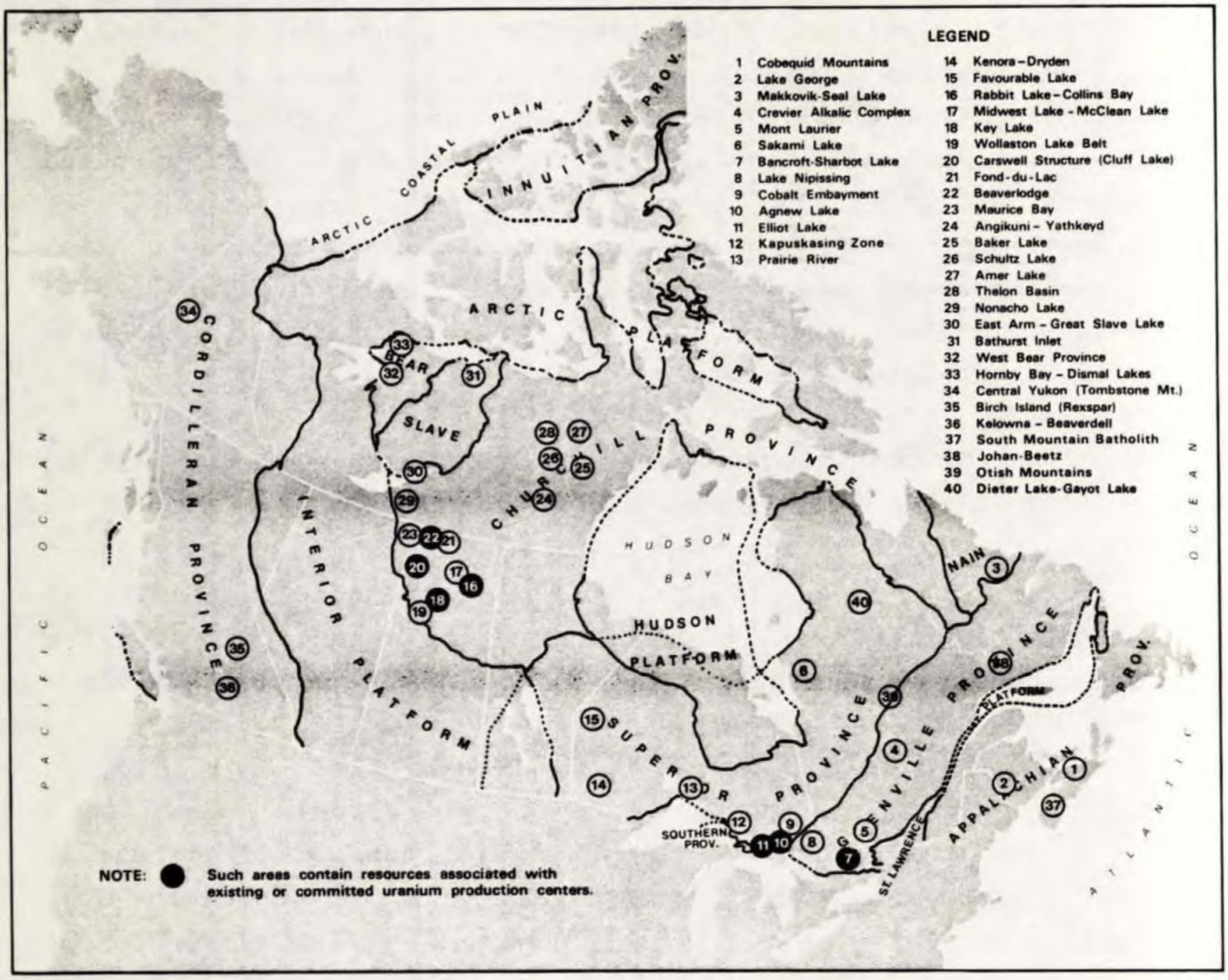
Source: EMR, 1980 Uranium Assessment, p. 24

price to encompass possible resources mineable at more than $200 kg/U and with the continued and increased exploration efforts that would result -- significant further resource additions could be realistically expected. Right now, for instance, it is estimated that there exists a further 1.2-1.4 million tonnes U of as yet undiscovered (speculative) resources in Canada. (This category by itself has increased some 70-75% since 1977.) Much of these resources are spread out across Canada in areas that have yet received only relatively minor attention in terms of exploration efforts (Figures 9 and 10 and Table 23). The realization of even part of this considerable potential would significantly augment the existing resource base.

A number of conclusions can be reached about Canada's existing uranium resources. They are massive in size - large enough to continue the current production level to the year 2130 and to meet the lifetime fuel needs of Canada's expected nuclear capacity in 2000 some 17 times over. Additions to these resources over the last decade have been substantial and further potential additions in the future to these resources could double or triple them.

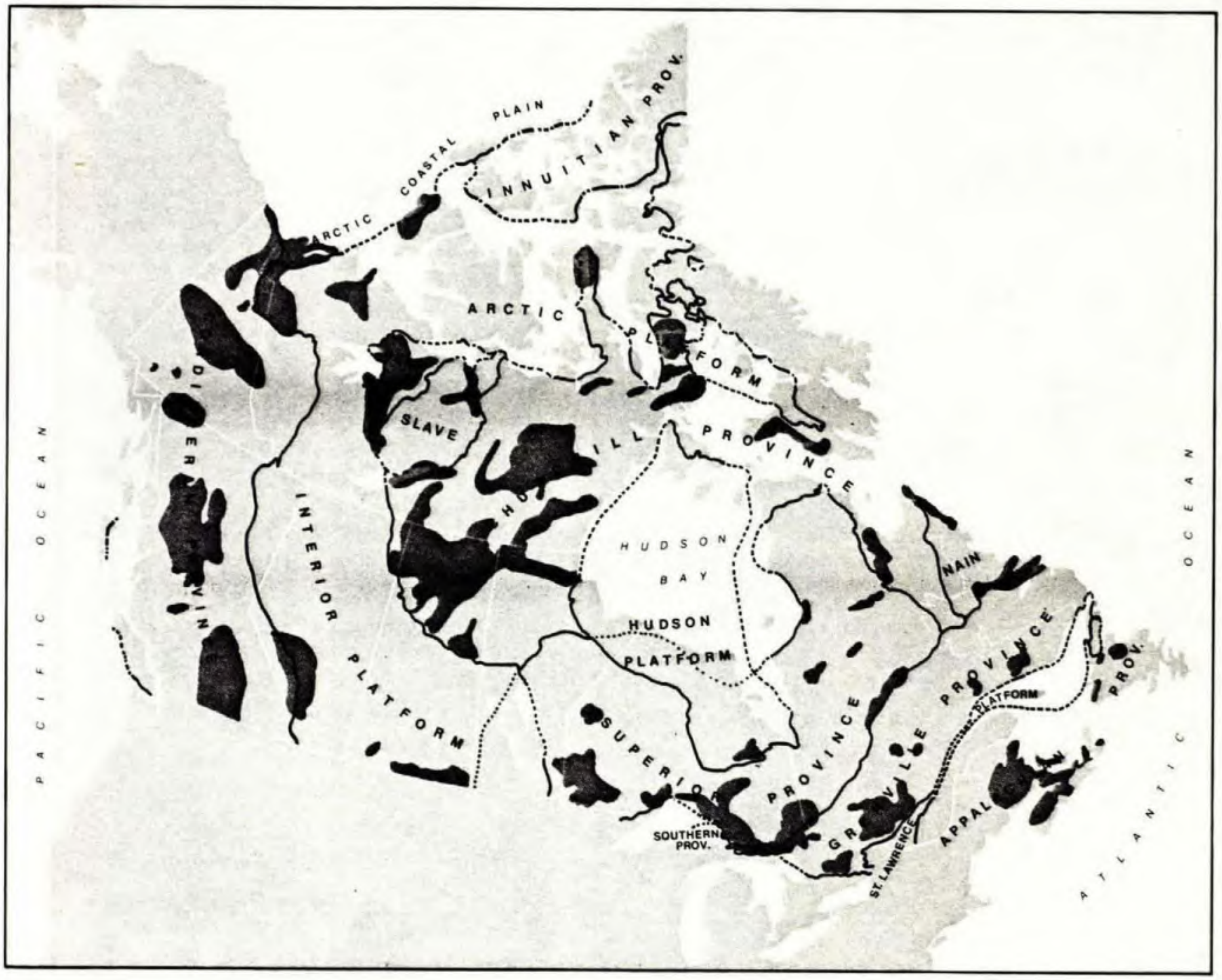
These Canadian uranium resources should also be viewed in a world perspective. They constitute 20% of the world's resources (11% of RAR and 28% of EAR), ranking Canada second behind the U.S. in total resources (Table 24). The Canadian uranium production of 7,145 tonnes U in 1980 was 16% of the total world production, second again behind the U.S. Uranium exports in 1980 accounted for some 85% of the 6,368 tonnes U in Canadian shipments which were valued at $638 million. From 1974 to 1981, uranium export contracts totalled 59,000 tonnes U, with 48,500 tonnes U in forward export commitments still remaining for delivery over the period 1981 to 1993 (Table 25). Thus, Canadian uranium resources and production are a very important part of the global uranium situation; and, given the relatively minor domestic requirements, the export market plays a predominate role in Canadian uranium production.

Figure 9. Areas in Canada with Uranium Resources Associated with Identified Deposits



Source: EMR, 1980 Uranium Assessment, p.3

Figure 10. Areas in Canada with Speculative Uranium Resources or Areas Favourable to the Occurrence of Uranium Deposits



Source: EMR, 1980 Uranium Assessment, p. 19

Table 24. Canadian and World Uranium Resources

Resource Category (1)	Uranium Resources (thousands of tonnes U): Canada	World
Measured	73	1,717
Indicated	185	546
RAR	285	2,293
Inferred	315	1,605
Prognosticated	445	1,115
EAR	760	2,720
Speculative	1,200-1,400	6,600-14,800

(1) For purposes of international comparison, Canada's low and high price categories are considered equivalent to the NEA/IAEA's low and high 'cost' categories, respectively. Therefore, Canada's 'measured' and 'indicated' equal the NEA/IAEA's 'RAR'; and Canada's 'inferred' and 'prognosticated' equal the NEA/IAEA's 'EAR'. See Tables 13 and 20 of this paper for more details.

Source: NEA/OECD + IAEA, Uranium, 1982, p. 18-19 and 77.

Table 25. Canadian Uranium Under Export Contracts (Since September, 1974 and as of December, 1980)

Country	Tonnes U
Japan	19,507
United States	12,032
United Kingdom	7,693
West Germany	6,384
Spain	4,808
South Korea	1,910
Finland	1,769
France	1,538
Italy	1,385
Belgium	938
Sweden	906
Switzerland	154
	59,024

Source: EMR, 1980 Uranium, p. 16.

Table 26. 1980 Canadian Uranium Ore Processing Plants

Plant	Location	Annual Production (tonnes U)
Operating		Actual
Agnew Lake Mines Ltd.	Agnew Lake, Ont.	195
Cluff Mining (Amok/SMDC)	Cluff Lake, Sask.	11
Denison Mines Ltd.	Elliot Lake, Ont.	1,712
Eldorado Nuclear Ltd. (1)	Eldorado, Sask.	423
Gulf Minerals Canada Ltd.	Rabbit Lake, Sask.	1,960
Madawaska Mines Ltd. (1)	Bancroft, Ont.	235
Rio Algom Ltd.	Elliot Lake, Ont.	2,609
		7,145
Committed		Planned
Key Lake Mining Corp.	Key Lake, Sask.	3,100-4,600
Rio Algom Ltd.	Elliot Lake, Ont.	--
Planned and Possible		
Brinco Ltd.	Makkovik, Nfld.	--
Canada Wide Mines Ltd.	Midwest Lake, Sask.	--
Consolidated Rexspar	Birch Island, B.C.	--
Norcen Energy Resources	Beaverdell, B.C.	--
Rio Algom Ltd.	Elliot Lake, Ont.	--

Source: EMR, Uranium in Canada - 1980 Assessment of Supply and Requirements, p. 10.

(1) Decisions were recently made to close these production centres in 1982.

Table 27. 1981-1990 Planned Uranium Production Capability in Canada and Domestic Canadian Uranium Requirements

(thousands of tonnes U)

Year	Planned Annual Production Capability (1)	Annual Domestic Uranium Requirements
1981	8.4	1.1
1982	9.5	1.2
1983	10.8	1.3
1984	14.8	1.4
1985	14.7	1.5
1986	14.0	1.6
1987	12.9	1.7
1988	12.3	1.8
1989	11.5	1.9
1990	10.5	2.0
	119.4	15.5

(1) Projection based on, operating and committed production centres only (see Table 28) and on existing uranium resources currently mineable at a uranium price of $135/kg U or less.

Source: NEA/OECD and IAEA, Uranium, 1982, p. 83.

This can be seen more clearly when one looks at future production capabilities and future domestic requirements for uranium in Canada. As noted above, Canadian uranium production totalled 7,145 tonnes U in 1980, about double the 1974 level. This production came from seven existing operators in Ontario and Saskatchewan employing over 6,000 people. In addition to this existing production capability, however, there are a number of production centres that are either committed or planned and possible but not yet committed (Table 26). These may become sources of uranium within ten years, depending on the market developments with respect to the demand and price for uranium.

The planned production capability (i.e., based on operating and committed centres only and on only those existing measured, indicated and inferred resources mineable at a uranium price of $135/kg U or less) is expected to double by the mid-1980's to almost 15,000 tonnes U and then to decline to about 10,000 tonnes U by 1991 (Table 27). The total uranium production from 1981 to 1990 would be 120,000 tonnes U - about half of the existing measured and indicated resources at less than $135/kg U.

On the other hand, the maximum technically attainable production capability (i.e., based on operating, committed and planned and possible but uncommitted centres and on all existing measured, indicated and inferred resources mineable at a uranium price of $200/kg U or less) would reach a peak of 18,500 tonnes U in the early 1990's and then decline to some 8,500 tonnes U by 2005 and still further to 1,500 tonnes U by 2025 (Table 28). Under this maximum scenario, the total output from 1981 to 2025 would be 440,000 tonnes U - about 3/4's of the existing measured, indicated and inferred resources. If existing prognosticated resources were also included, then even under this maximum scenario, almost 60% of the total existing resources would not be touched, not to say anything of any possible resource additions that may be realised over this time, especially if a uranium price

Table 28. 1981-2025 Maximum Technically Attainable Uranium Production Capabilities

Year	Annual Capability (1) (thousands of tonnes U)	Source of Production (thousands of tonnes U) Measured & Indicated	Inferred
1981	8.4	8.4	-
1982	9.5	9.5	-
1983	10.8	10.8	-
1984	14.8	14.8	-
1985	14.9	14.9	-
1986	15.9	15.5	.4
1987	16.8	16.3	.5
1988	16.5	14.8	1.7
1989	16.5	14.6	1.9
1990	17.0	15.0	2.0
1995	17.6	3.5	14.1
2000	14.8	2.6	12.2
2005	8.5	-	8.5
2010	4.7	-	4.7
2015	4.7	-	4.7
2020	1.5	-	1.5
2025	1.5	-	1.5

(1) Projection based on operating, committed, planned and possible but uncommitted production centres (see Table 28). Output is based on existing resources currently mineable at a uranium price of $200/kg U or less.

Source: NEA/OECD & IAEA. Uranium, 1982, p. 84.

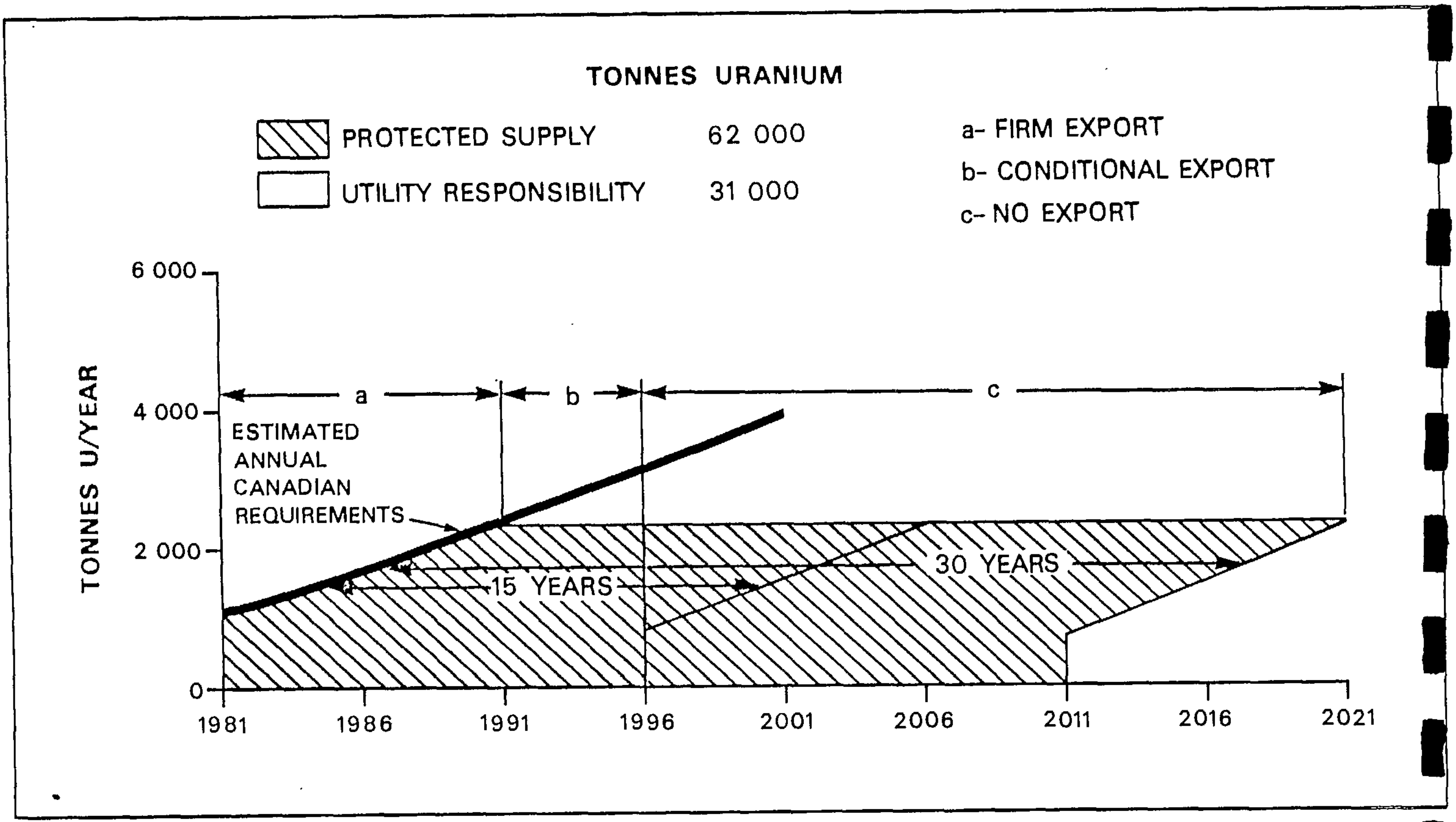
of more than $200/kg U is realized.

Canada's future domestic uranium requirements can now be looked at in light of these two production capability scenarios. Canadian uranium policy requires that sufficient uranium be reserved for domestic use to enable each nuclear power reactor currently on-stream, or planned to come on-stream within the next ten years, to operate at an average annual capacity factor of 80% for 30 years after 1981, or from the in-service date of the nuclear unit, whichever is later. For the 15,111 MWe of nuclear capacity projected to be in operation by 1991, this "protected supply" amounts to some 62,000 tonnes U - almost 85% of the existing low-price measured resources but only 6% of the total existing resource base. Canadian uranium policy also requires domestic utilities to demonstrate that they are maintaining a 15 year forward supply of uranium on a firm contract basis for both operating and committed reactors. This utility responsibility now amounts to 31,000 tonnes U. Since the bulk of Canada's domestic needs are those required by the Ontario nuclear program, Ontario Hydro's two principal uranium supply contracts approved in 1978 - one with Denison Mines Ltd. for 48,465 tonnes U from 1980 to 2011 and the other with Rio Algom Ltd. for an additional 27,695 tonnes U from 1984 to 2020 - satisfy most of these needs to the early part of the next century (Figure 11).

Annual domestic uranium requirements are expected to more than double over the decade from some 1,100 tonnes U in 1981 to 2,100-2,400 tonnes U in 1991 (Table 27). The planned production capability scenario would be far in excess of these domestic requirements: annual production would be ten times annual domestic requirements in 1985 and five times them in 1990. The maximum production capability scenario would, of course, be even more dramatically in excess of domestic uranium requirements (Figure 12).

Domestic requirements in the longer-term will, of course,

Figure 11. 1981 Uranium Supply for Domestic Requirements



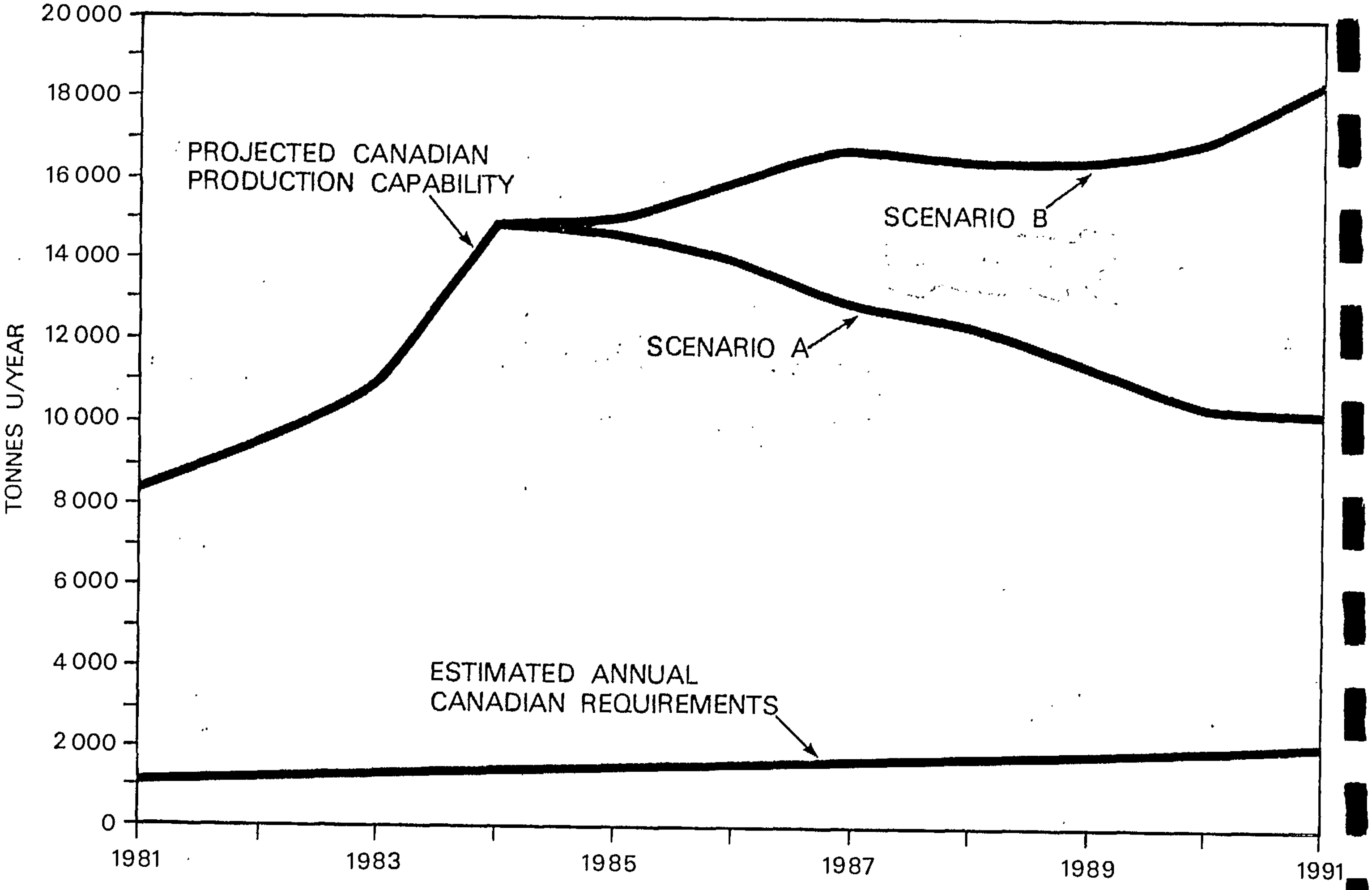
Source: EMR, *1980 Uranium Assessment*, p. 15

depend on the actual growth in nuclear power capacity. If, for instance, total installed nuclear capacity in the year 2000 is 21-28 GW (EMR's recent forecast but one that is considerably more than the NEB's 17.8 GW), then the domestic requirement would be 2,900-3,900 tonnes U per year. Even at this high nuclear power level, these domestic uranium requirements would be only 20-25% of the maximum production capability in 2000.

There is a possibility, however, that in the much longer term - by 2050 and beyond - a conflict may develop between Canada's domestic uranium requirements and foreign uranium exports. As nuclear power in Canada grows, the 30 years 'protected supply' for domestic needs will also grow in size and, of course, not be available for export. Depending on the world market at that time and the actual resource holdings of Canadian uranium suppliers, there might be considerable pressure, especially from these suppliers, to export such protected uranium for immediate export benefits. At that point, the benefits of having a 30 year uranium supply in the ground for future domestic needs would have to be weighed against the benefits of increased uranium exports. This possible situation, however, is so far in the future and involves so many variables and uncertainties that one can not at this point consider it as a determining factor in Canada's foreseeable uranium future.

In summary, then, nuclear power will be playing a more important role in canada's energy future, although not as large as recently expected. The Canadian uranium resource base is massive, has been growing significantly in recent years, and has the potential of growing considerably more. Even if no resource additions were realized, however, existing resources and the planned production capability are far in excess of the domestic uranium requirements needed for any realistic projection of future nuclear power in Canada. Canada should be able to maintain its important world position as a leading supplier of uranium in the export market well into the next century, and could even improve

Figure 12. Projected Canadian Uranium Production Capabilities and Estimated Domestic Uranium Requirements



Source: EMR, 1980 Uranium Assessment, p. 13
Scenario A - Planned Production Capability
Scenario B - Maximum Technically Attainable Production Capability

on this position considerably.

3. CONCLUSIONS

Based on the preceding outlook for future nuclear power capacity and uranium resources in the world and in Canada, the following conclusions may be presented:

(1) Nuclear power will make a significantly greater contribution to the world's electricity needs over the next half century, although significantly less than was expected only a few years ago. Given the continuing cutbacks in nuclear programs and the persistent uncertainties concerning future development, a low nuclear growth forecast may now be more realistic than a high growth one. Moreover, it is not entirely certain at this time that even a low growth forecast will be actually realized.

(2) The world's existing uranium resource base is large and has been growing significantly over the last decade. In addition, this resource base has the potential and the probability of becoming considerably larger in the future.

(3) Only when one assumes that no further additions will be made to the existing uranium resource base does the possibility of a world uranium shortage arise in the first few decades or so of the next century. Within a reasonable view of total resource availability and with the likely resource additions to be made in the future, however, such a world shortage is highly unlikely. In the much longer term future - beyond the middle of the next century or so -, if nuclear power continues to grow, then the world uranium resource base may at some time prove to be inadequate to meet the uranium fuel requirements involved.

(4) Nuclear power will play a role of growing importance in

Canada's electricity future, but not as large as was recently expected. Nuclear power capacity in Canada should grow to about 15-20 GW in 2000 and can realistically be expected to be double this level by the year 2025.

(5) Canada's existing uranium resource base is extremely large and has been growing significantly over the last decade. In addition, this resource base has the potential and the probability of becoming considerably larger in the future.

(6) Even if no uranium resource additions were realized in the future (an unrealistic assumption) the existing resources and planned production capability in Canada are far in excess of the domestic uranium requirements needed for any realistic nuclear power growth in Canada. Canada should be able to maintain its important world position as a leading supplier of uranium in the export market, and could, if called upon by the world marketplace, even improve on this position considerably. From a strictly uranium resource point of view, therefore, it is not clearly apparent that a more uranium conserving fuel cycle or reactor for Canada is needed to meet either its own or the world's future requirements for uranium.

C. CANDU ADVANCED FUEL CYCLES

A general account is provided of the likely benefits and possible drawbacks of adopting advanced fuel cycles in the CANDU nuclear reactor. The key elements assessed involve the potential uranium utilization and savings; the expected economics involved; the necessary technology development program including the likely implications for reactor safety, the environment and nuclear non-proliferation; the impact on the nuclear export market; and public acceptability.

In order to assess advanced fuel cycles, however, one must have a basic grasp of the technical fundamentals involved. ForD this reason, several brief, reference monographs are provided on the following few pages. These are outline sketches, in general language, of the nature of the nuclear fission process; the operation of the CANDU nuclear reactor; the existing natural uranium once-through fuel cycle now used in the CANDU reactor; the essentials of a range of possible advanced fuel cycles: the low enriched uranium cycle, the plutonium-uranium cycle and a variety of thorium fuel cycles; an account of thorium resources; electronuclear breeding concepts; and, lastly, a description of the fast breeder reactor.

1. Uranium Utilization and Savings

The Canadian CANDU nuclear reactor now operates on a natural uranium once-through fuel cycle. Since a heavy water moderator is used and a good neutron economy is realized, the fuel is natural uranium (0.7% U235 and 99.3% U238). In contrast, the Light Water Reactor (LWR), the other major available nuclear reactor and the dominant one in the world, now uses an ordinary water moderator and an enriched uranium fuel (3.2% U235) in its existing once-through cycle. The result is that the CANDU cycle uses

THE BASICS OF NUCLEAR FISSION

fundamental laws of the conservation of energy and mass
hol mass and energy are basically equivalent: energy may
be :ed into matter and matter may be converted into energy.
Thi:ionship is expressed in Einstein's famous law, based on
the of relativity, $E = mc^2$, in which E is the energy
eqv:e of a mass m and c is the velocity of light. The con-
ver even a microscopic quantity of matter produces a very
lar nt of energy because c^2 is a very large number.

of nature is composed of less than a hundred different
ch elements. The smallest unit of each element that still
re he characteristic properties of that element is an atom.
An as a core or nucleus that is made up of positively-charged
pa: called protons and uncharged particles called neutrons.
Or the nucleus are negatively-charged particles called
el. The protons and neutrons are held together in the
nu y a nuclear binding force which overcomes the natural
re of the like-charged protons. Nonetheless, some atoms
ca lit or fissioned if the binding force can be overcome.

:nium consists of three types of atoms -- U238, U235 and
U2 he figures are simply the total number of protons and
ne in the nucleus. These atoms have the same number of
pr ut a different number of neutrons and are called isotopes).
Ir uranium contains 99.3% U238, 0.7% U235 and a tiny trace
oi The U235 nucleus can be fissioned easily because it is
mc able and is called 'fissionable'; but the
U leus, with a greater nuclear binding force, is very
d t to fission and is called 'non-fissionable'.

en an atom of U235 is hit by a neutron, the collision
m e nucleus so unstable that it splits up almost instantly
i ction known as nuclear fission into two lighter nuclei.
T sioning produces very large amounts of heat ($E=mc^2$) and
r ivity and releases 2 or 3 fast neutrons. If one of these
n hits another U235 atom, another fission occurs that
e re neutrons, causing the process to be repeated time and
a a chain reaction. The heat produced by this continuous
f ng is used in a nuclear reactor station to convert water
i am which spins a turbine-generator to make electricity.

: one of the emitted neutrons hits a U238 atom, however,
i likely to cause fission. Instead, the two will probably
c and become Pu239, an isotope of another element called
u m. Although U238 is not fissile, Pu239 is, so U238 is
: be fertile. (Similarly, if thorium 232 nuclei capture
o n, U233 is produced and is fissionable.)

However, when naturally occurring uranium or natural uranium is confined in a limited space, there are not enough fissile atoms present to sustain a chain reaction. The few neutrons produced by the occasional spontaneous fissioning in the uranium are travelling too fast, up to 42,000 km a second, to split other atoms readily. They are therefore either captured by or pass through the much more abundant U238 atoms and so are unavailable to cause further fissions.

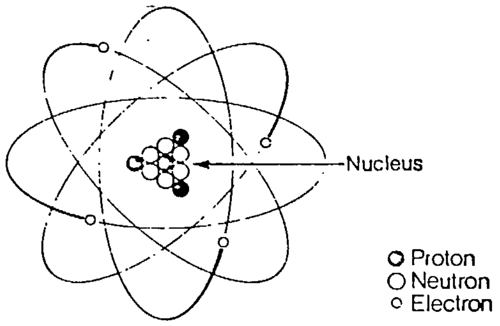
One solution to this problem is to increase the proportion of fissile atoms artifically by enriching the uranium to a level of about 3-4% U235. Another way to get a chain reaction is to slow down the neutrons to about 3km a second so that they will be more likely to strike and split the U235 nuclei in the uranium. Slow neutrons are much more likely to cause fission in U235 than fast neutrons. Such a neutron 'braker' is called a moderator.

Elements with light atoms are generally good moderators. Ordinary water, a compound of hydrogen and oxygen, is good but not good enough to sustain a chain reaction with natural uranium. Very pure graphite (carbon) is better, but the most efficient is heavy water, a compound of deuterium and oxygen. Deuterium is present in natural, ordinary water in 1 part in 10,000. Heavy water or deuterium oxide (D_2O) is produced by greatly enriching the deuterium content of natural water through the Girdler-Sulphide process.

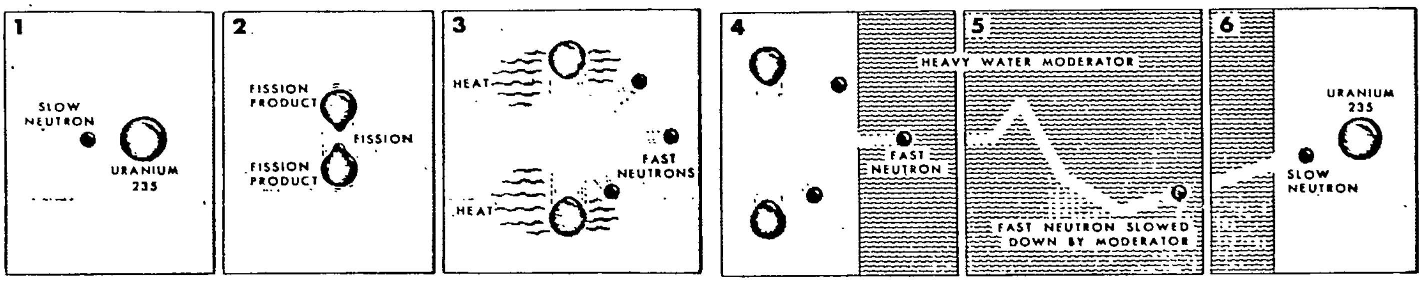
The basic ingredients of a chain reaction with natural uranium, then, are the collection of enough uranium in the right configuration so that the number of fissions increase to the desired level for a given heat output, and enough heavy water to slow down the neutrons efficiently so that they are more likely to collide with U235 nuclei and cause fission.

FIGURE: THE BASICS OF NUCLEAR FISSION

A TYPICAL ATOM



THE FISSION PROCESS



Source: AECL

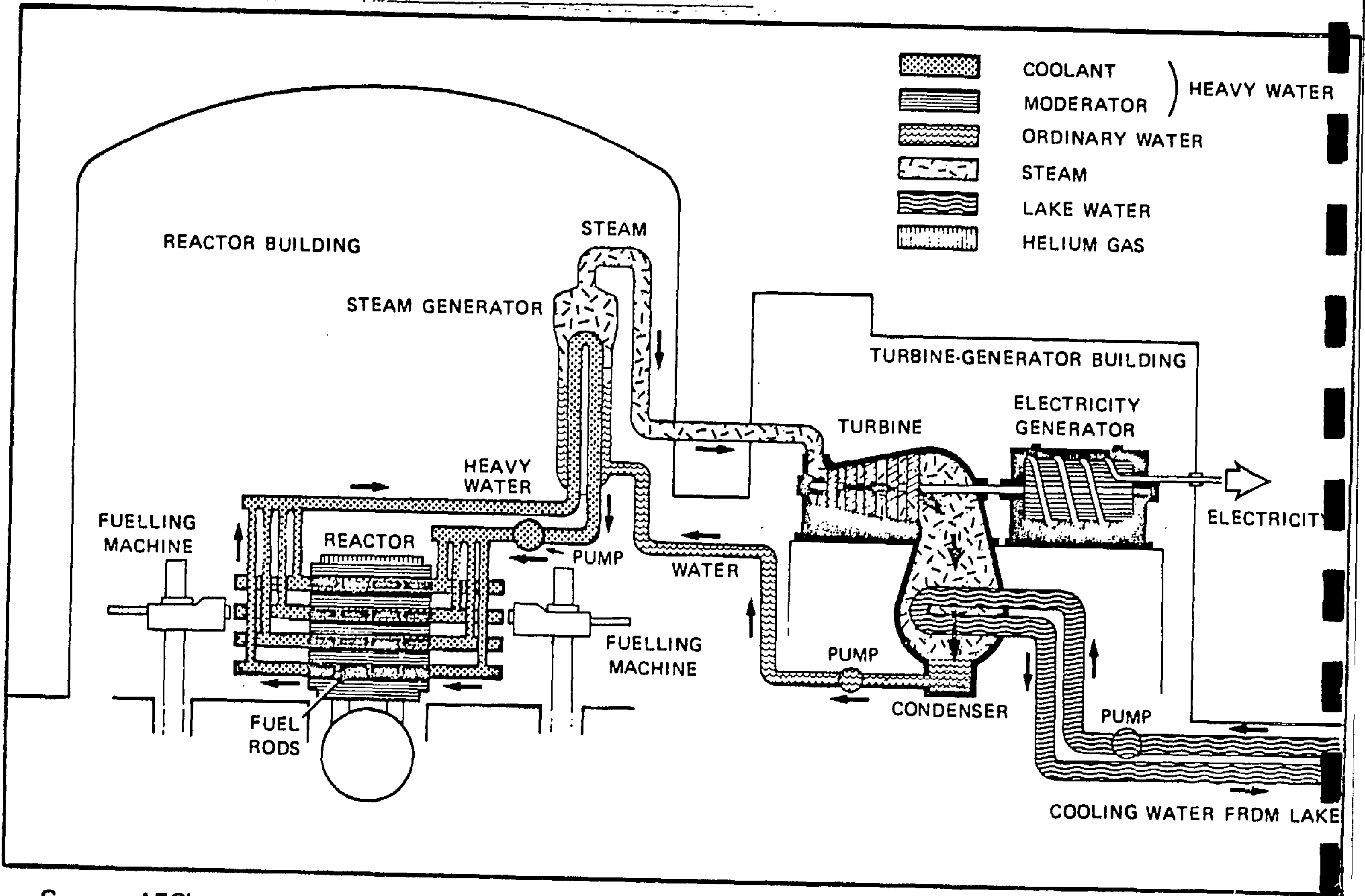
THE CANDU REACTOR

CANDU stands for Canada Deuterium Uranium. It is a uniquely Canadian designed nuclear reactor that uses natural uranium as the fuel and deuterium or heavy water as the moderator and coolant.

The CANDU reactor itself consists of a large cylindrical steel tank vessel called a calandria filled with the heavy water moderator. This is the 'core' of the reactor. Natural uranium oxide (UO_2) fuel bundles are placed end-to-end in pressure tubes which are then inserted into about 400 horizontal fuel channels of the calandria. A heavy water coolant is pumped through the pressure tubes and around the fuel bundles to pick up the heat generated during the fission process. The heated heavy water travels to heat exchangers (boilers) containing ordinary water, which is boiled to produce steam. The cooled heavy water is recycled. The steam is piped to spin the blades of conventional turbines which are connected to drive generators which in turn produce electricity. Lake or river water cools and condenses the steam back to water which is recycled.

This pressurized heavy water (PHW) reactor is the main CANDU reactor concept. There are, however, two variant concepts of this basic CANDU reactor design: Gentilly 1, a 250 MW prototype reactor in Quebec that uses light or ordinary water as a coolant instead of heavy water; and the CANDU OCR test reactor near Pinawa, Manitoba that uses an organic liquid - light oil - as a coolant instead of heavy water. Only the CANDU-PHW reactor, however, has been commercially used and proven to date.

FIGURE CANDU REACTOR FLOW DIAGRAM

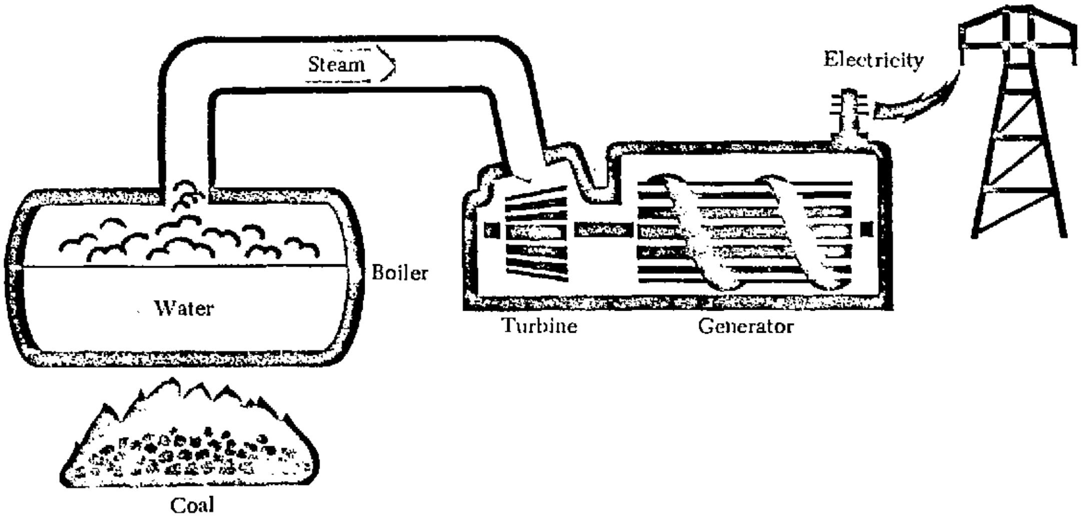


Source: AECL

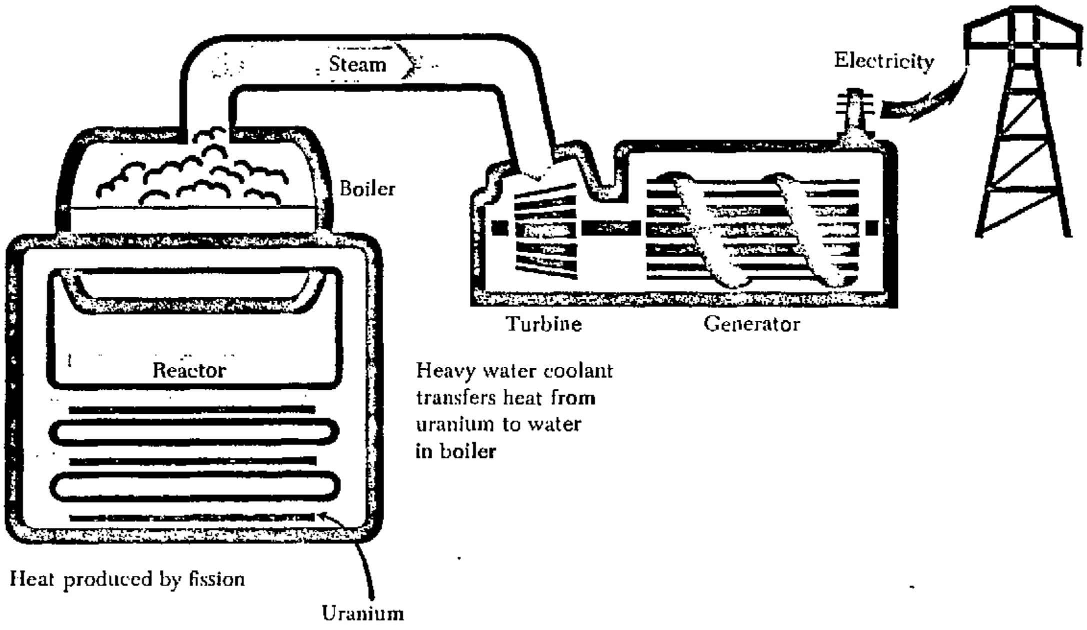
FIGURE

OPERATION OF FOSSIL-FUELLED AND CANDU POWER PLANTS

Fossil Fuelled



CANDU



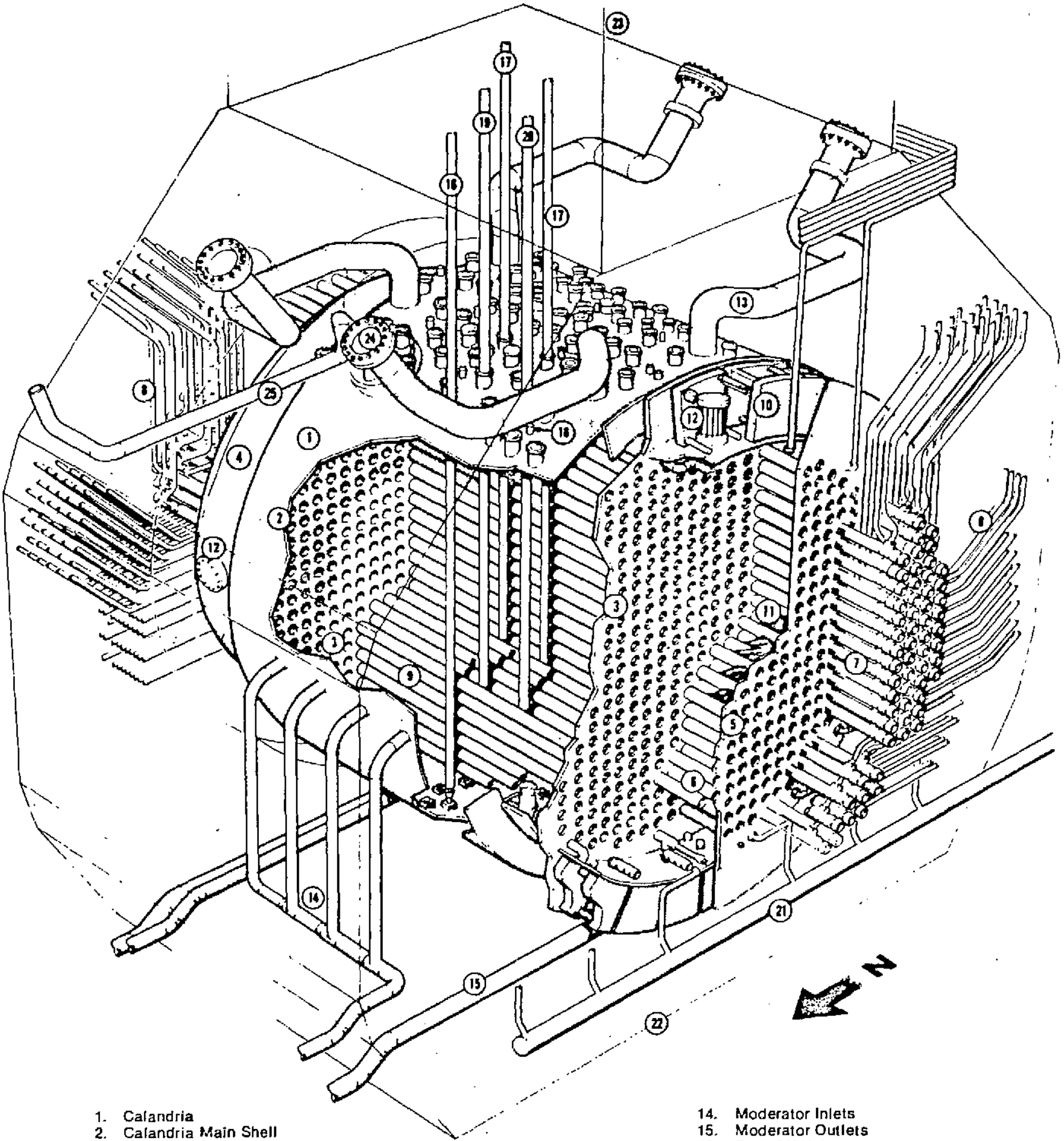
Heavy water coolant transfers heat from uranium to water in boiler

Heat produced by fission

Source: AECL

FIGURE

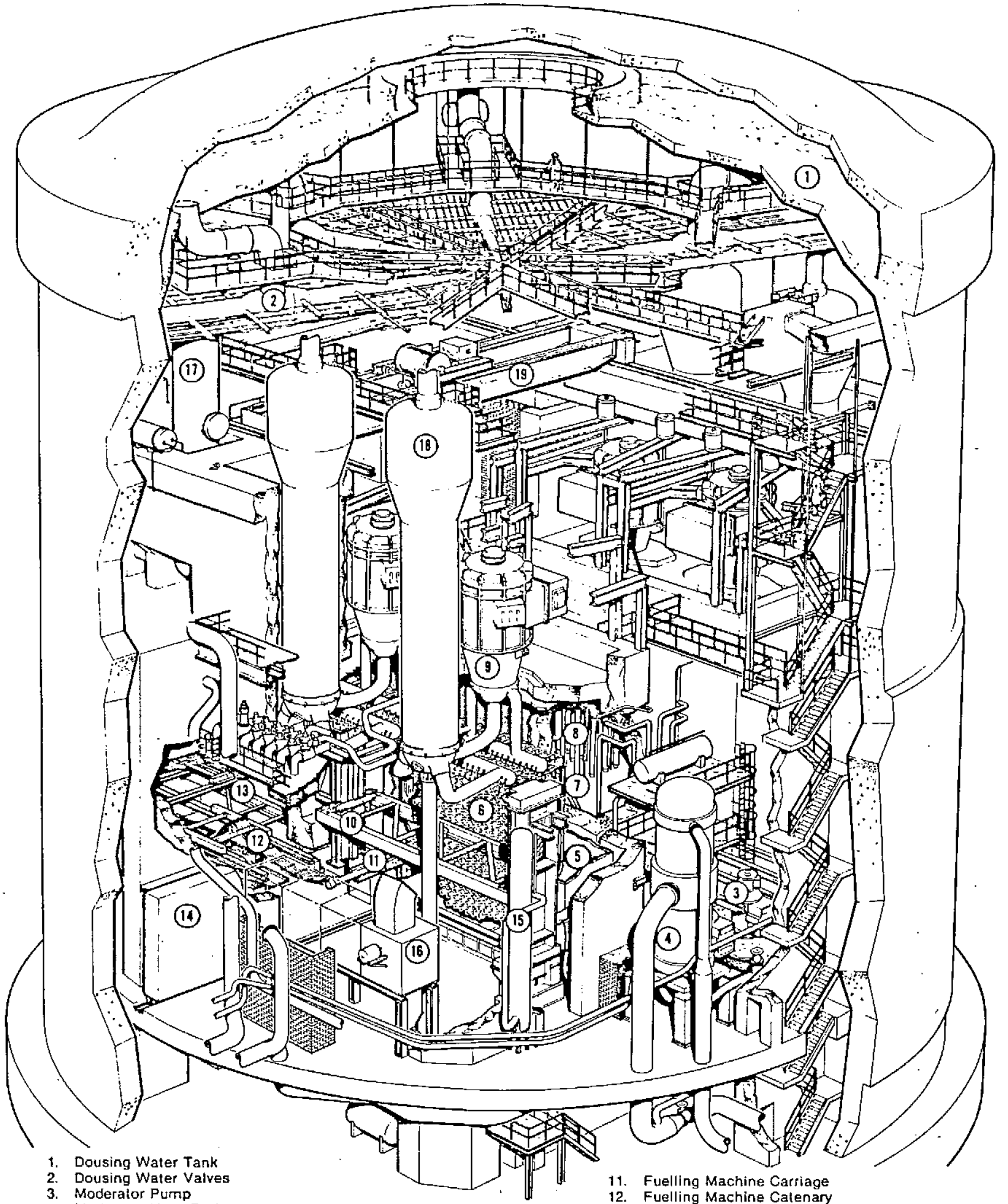
THE REACTOR ASSEMBLY CORE OF A CANDU



1. Calandria
2. Calandria Main Shell
3. Calandria-Side Tubesheet
4. Calandria Sub-Shell
5. Fuelling Machine-Side Tubesheet
6. Lattice Tubes
7. End Fittings
8. Feeders
9. Calandria Tubes
10. Shield Tank Solid Shielding
11. Steel Ball Shielding (end shield)
12. Manhole
13. Emergency Discharge Pipes
14. Moderator Inlets
15. Moderator Outlets
16. Shut-Off Unit
17. Adjuster Unit
18. Vertical Flux Detector
19. Control Absorber
20. Liquid Zone Control Unit
21. End Shield Cooling Piping
22. Shield Tank
23. Shield Tank Extension
24. Rupture Disc Assembly
25. Moderator Overflow

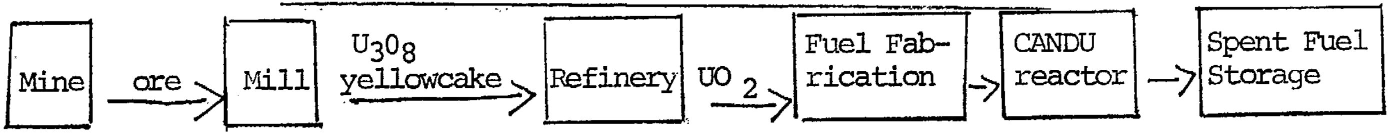
FIGURE

THE CANDU REACTOR BUILDING



1. Dousing Water Tank
2. Dousing Water Valves
3. Moderator Pump
4. Moderator Heat Exchanger
5. Feeder Cabinets
6. Reactor Face
7. Reactor
8. Reactivity Mechanism
9. Primary Heat Transport System Pump
10. Fuelling Machine Bridge
11. Fuelling Machine Carriage
12. Fuelling Machine Catenary
13. Fuelling Machine Maintenance Lock
14. Fuelling Machine Maintenance Lock Door
15. End Shield Cooling Water Delay Tank
16. Vault Cooler
17. Pressurizer
18. Steam Generator
19. Steam Generator Room Crane

NATURAL URANIUM ONCE-THROUGH FUEL CYCLE



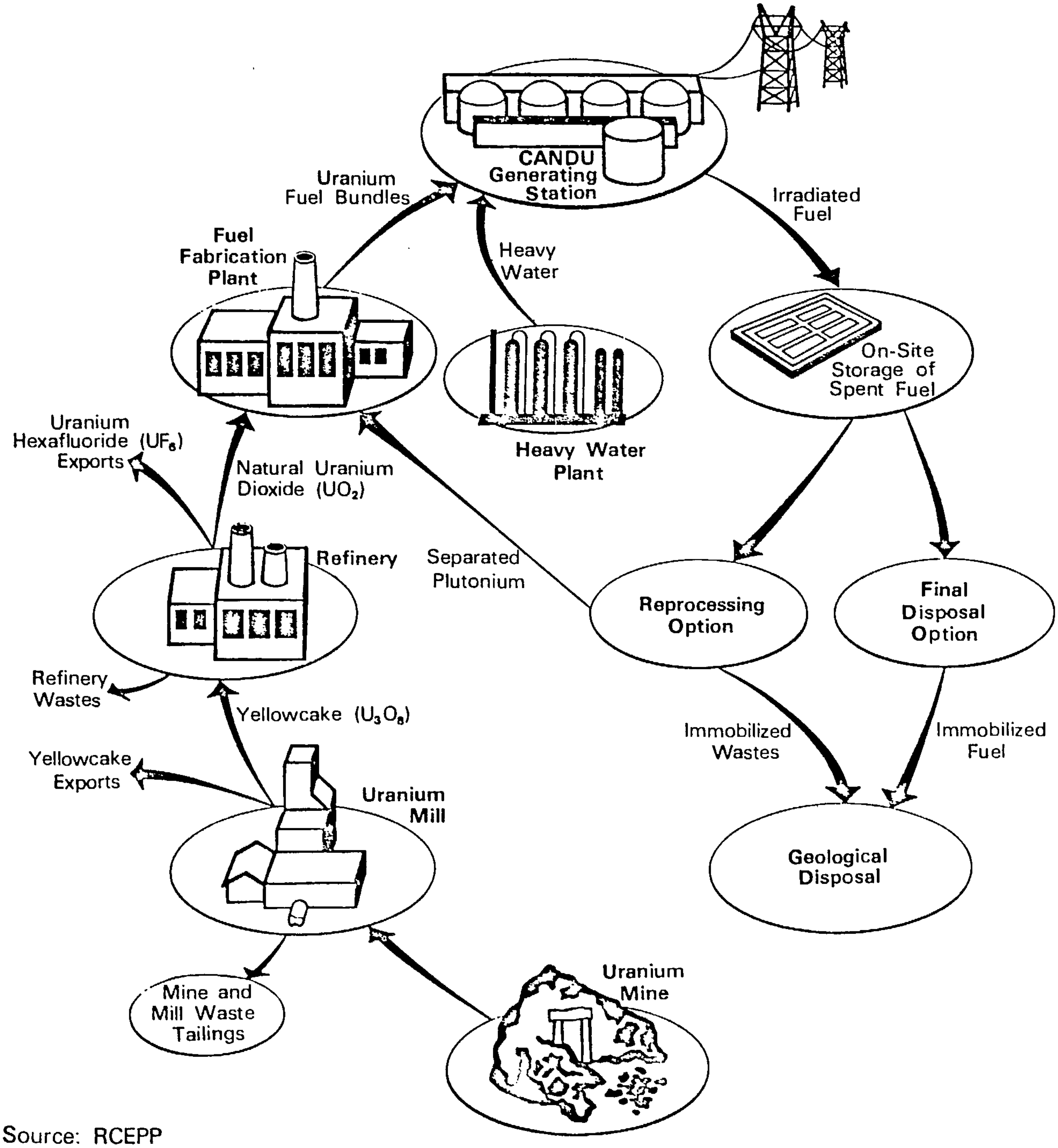
In most uranium mines, one tonne of ore must be mined to obtain about one or two kilograms of uranium concentrate. A mill at or near the mine crushes and grinds the ore to a fine sand and then, by chemical treatment and separation, extracts the uranium oxide, U_3O_8. This resulting uranium concentrate, called 'yellowcake', contains 60-70% uranium by weight. It is then shipped to a uranium refinery where it is chemically converted into a uranium compound called uranium dioxide (UO_2). This is then shipped to a fuel fabrication centre where the uranium oxide powder is pressed, sintered and ground to form hard, ceramic fuel pellets. These are sealed into metal tubes which are assembled into zirconium-sheathed fuel bundles for insertion into a CANDU reactor. A 600 MW CANDU contains about 4,600 fuel bundles and consumes about 90 tonnes of UO2 fuel each year.

The moderator and coolant for the CANDU reactor is heavy water, a rare but natural form of water. Ordinary water is a combining of one oxygen and two hydrogen atoms (H_2O). Heavy water is virtually identical except that each of its hydrogen atoms has an extra neutron. This hydrogen isotope is called deuterium. One part of deuterium occurs in every 6,700 parts of hydrogen in ordinary water. Since heavy water (D_2O) is bulkier, it slows the neutrons in the reactor without significantly absorbing them and is, therefore, a most effective moderator. Heavy water is extracted from natural water in a series of tall towers by a chemical exchange and distillation process which enriches the heavy water concentration in natural water to 99.75% before shipment to a CANDU reactor. A 600 MW CANDU reactor requires an initial loading of about 450 tonnes of heavy water, with replacement requirements of about 4.5 tonnes over its lifetime.

A fresh fuel bundle for the CANDU reactor contains pure natural uranium (99.3% U238 and 0.7% U235 in the form of UO_2. The bundle remains in the reactor for about one and a half years at which time about 70% of the U235 has been consumed and the accumulated fission products -- radioactive elements resulting from the fission process -- act as poisons to dampen the reaction by absorbing vital neutrons which would otherwise contribute to the splitting of the U235 atoms. A used or spent fuel bundle is unchanged in appearance but consists of 98.6% U238 (about 0.7% of the original U238 atoms have captured neutrons and changed into plutonium, Pu239 about half of which fissions in the reactor to contribute more than one-third of all the heat produced in the reactor by the fuel bundle); 0.2% U235; 0.3% Pu; and 0.9% other radioactive isotopes (actinides and other fission products). A 600 MW CANDU reactor produces about 100 tonnes of spent fuel bundles per year.

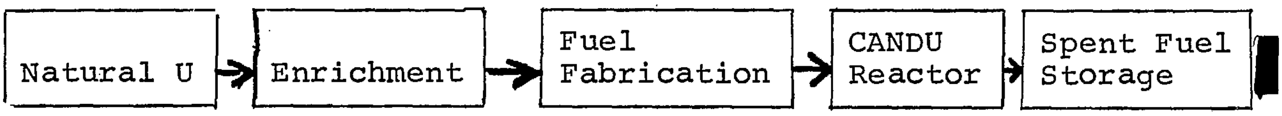
These spent fuel bundles are removed from the reactor by remotely controlled machines and transferred to storage bays at the reactor site. The bays are filled with water which cools and shields the bundles. This storage is safe and secure for decades.

Figure . Once-Through CANDU Fuel Cycle



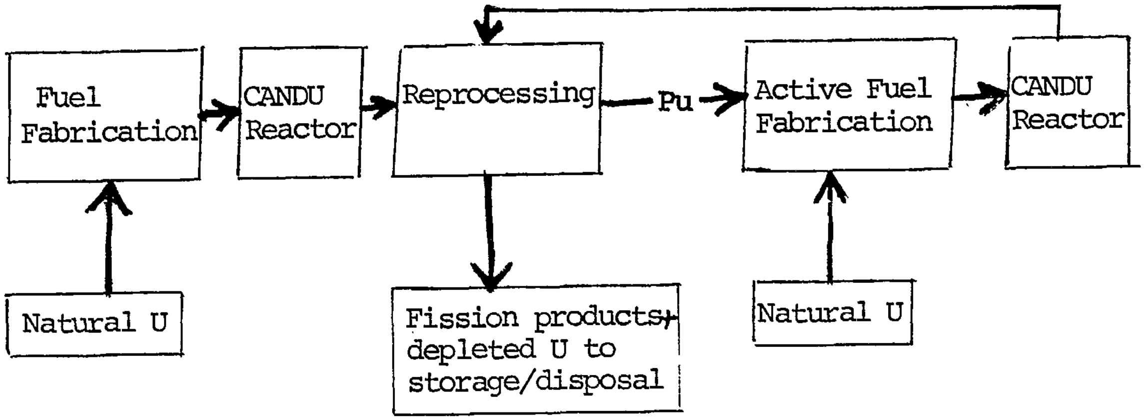
Source: RCEPP

LOW ENRICHED URANIUM FUEL CYCLE



A low enriched uranium (LEU) fuel cycle in the CANDU reactor would simply use about 1.2% enriched U235 as the fuel instead of the 0.7% natural U235 in the existing natural uranium cycle. A LEU cycle would therefore require an enriched uranium supply but this would be a relatively small demand compared to the U.S. LWR enriched uranium cycle which uses about three times as much. By using slightly enriched uranium, the reactivity-limited burn-up life of the fuel is increased to almost three times as much as that of a natural U fuel. Although a greater amount of natural fuel is required to produce the fuel, the increase in burn-up is such that the energy yield per unit mass of natural U is increased considerably. This means that the life-time uranium requirements of a LEU cycle are about 70% those of the existing natural uranium once-through cycle.

PLUTONIUM-URANIUM FUEL RECYCLE

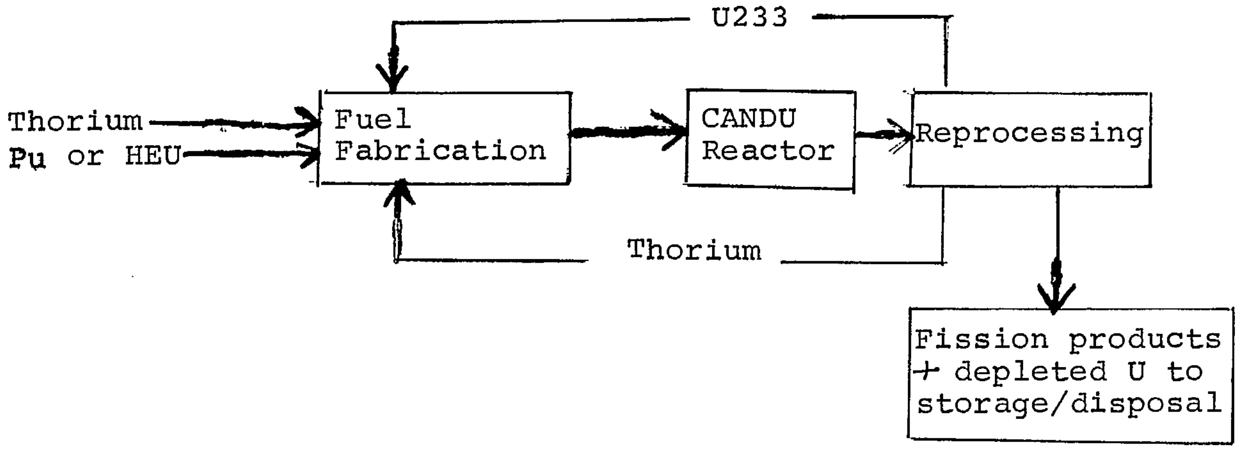


In the Plutonium-Uranium (Pu-U) Fuel Recycle, Pu is extracted from the CANDU spent fuel in a reprocessing plant, blended with natural U to produce a mixture containing about 0.5% Pu, and then fabricated into new fuel. During the utilization of this recycled fuel in a CANDU reactor, most of the U235 is consumed along with much of the Pu, but fresh P_u is produced from the U238. This spent fuel is then reprocessed for recovery of the Pu which is returned to the cycle.

Such a recycle uses the significant amounts of fissile Pu now contained in the accumulating stockpiles of spent CANDU fuel. (There are now some 5,000 tonnes of spent fuel stored on site at nuclear power plants in Canada, with 800 tonnes being added each year.) Since the lifetime Pu requirements of a 1GWe reactor operating for 30 years on this recycle would be 2.7 tonnes, it is estimated that more than four such reactors could be fuelled from the 11.2 tonnes of Pu produced in 30 years by a 1 GWe CANDU reactor operating on the natural uranium once-through cycle. Since this Pu-U recycle gets about twice as much of an energy yield from the uranium, its overall uranium requirements are less than half -- about 45% -- those of a natural uranium once-through cycle. (In comparison, a U.S. LWR operating on a Pu-U recycle would have the same uranium requirements as a natural uranium once-through cycle in a CANDU reactor, because the LWR's use of Pu is only 80% effective relative to U235 due to the higher enrichment level involved.

A variation of this Pu-U recycle would be to use the depleted uranium recovered from the spent CANDU fuel rather than natural uranium. Because such depleted U has about three times less of a U235 level than does natural U, this recycle would require about twice as high a Pu content in the fuel mixture and about four times the lifetime Pu requirements as the Pu-natural U recycle.

THORIUM FUEL CYCLES



Although thorium does not have a naturally-occurring fissile isotope, the predominant Th232 is a fertile material that, by neutron capture, leads to the formation through radioactive decay of U233, a fissile atom. This is a particularly effective fissile material in the CANDU reactor since one neutron absorption leads to the release of about 2.25 fissile neutrons (compared to 2.0 for U235 and 1.9 for Pu 239). This means that the destruction of fissile material is compensated for by an almost equivalent conversion of fertile into fissile material.

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Since the effective absorption cross-section of Th232 is roughly twice that of U238, the fissile enrichment level must be roughly double that for the uranium supply. On the other hand, since U233, as indicated, has the highest fission neutron yield per absorption, it can support the highest conversion ratio. Consequently, a recycle using Th and U233 would need the highest initial fissile inventory but would require the smallest net fissile supply during reactor operation. Conversely, U235 and Pu239 would imply smaller initial fissile inventories but higher operation requirements.

There are several thorium cycle possibilities but the main variants are the following:

Thorium-Enriched Uranium (Th-U) Once-Through

Th could be used in a once-through CANDU cycle in two ways: a homogenous fuel mixture of Th and highly-enriched or medium-enriched uranium; or a heterogeneous fuelling in which Th oxide fuel bundles are loaded in one out of every five fuel channels with the other channels filled with low-enriched uranium (1.8% U235) oxide fuel bundles. Both approaches indicate an improved uranium utilization over the natural U cycle, with the two-fuel concept showing the greatest improvement by having about 70% of the uranium requirements of a natural U cycle. This gain is the same as that of a LEU cycle but would require a very high burn-up fuel and a more complex fuel management system. The main interest in this cycle lies in its potential value as an introductory cycle to the more efficient and complicated Th recycles.

Thorium-Plutonium Initiated (Th-Pu) Recycle

Since Th is a fertile not a fissile material, a fissile material such as Pu or U235 must be used to produce a reactor fuel to initiate a Th recycle. If Pu is used for such initiation, then the Pu in spent CANDU fuel is extracted and blended with Th to produce a mixture containing about 2.5% Pu, which is then fabricated into fuel. Some of this Pu is consumed during use in the reactor and U233 is produced from the Th. The irradiated fuel is then reprocessed to recover this fissile U233 and the residual Pu which are recycled to the fabrication plant to produce new fuel for use in the reactor.

In a Th recycle, therefore, the composition of the fresh fuel varies from the initial start-up of the reactor through to equilibrium fuelling conditions. Since the fissile U233 in the irradiated fuel is recycled, successive generations of fuel after the initial charge require smaller amounts of external fissile material until equilibrium is reached. Overall, however, the Th-Pu recycle has lifetime requirements of 530 tonnes Th and 9.5 tonnes Pu (i.e., less than the 11.2 tonnes of Pu produced in 30 years by a 1GWe CANDU reactor operating on the natural uranium once-through cycle). At a lower burn-up and a lower Pu level in the fuel, of course, less Pu and more Th would be required. This Th-Pu recycle would require a little more than half of the uranium requirements of the natural uranium once-through cycle.

Thorium-Enriched Uranium Initiated (Th-U) Recycle

Instead of Pu, the Th recycle could be initiated with highly-enriched uranium (93% U235) as the necessary fissile material for initial start-up. Thereafter, the Th recycle would be similar to the Th-Pu recycle by utilizing the fissile U233 produced. The actual natural uranium requirements would depend on the exact composition of the initial core inventory and on whether the out-reactor delay time was one or two years. Overall, however, this Th-U recycle would need about one-third of the uranium requirements of the natural U once-through cycle.

Instead of using highly-enriched uranium (93% U235), the Th recycle could start off by using medium-enriched uranium (20% U235). This is called the 'denatured' Th recycle and has been suggested as a possible non-proliferation measure. The idea is that nowhere in the reprocessing and fuel stages would uranium appear as a weapons usable isotope. This is done by diluting the U235 and U233 with non-fissile U238. Although Pu production is not eliminated, it is significantly reduced by an order of magnitude. The fissile enriched uranium in the fresh fuel is kept below 20% and the Pu produced by neutron capture in U238 is not recycled. Such a denatured Th cycle would need about 40% of the uranium requirements of the natural uranium once-through cycle.

Self-Sufficient Equilibrium Thorium (SSET Cycle)

A variant of the basic Th recycle is called 'the self-sufficient equilibrium thorium'(SSET) cycle. In this cycle the only external fissile requirement is in the initial first fuel charge. After that, under equilibrium fuelling conditions, no external fissile material is required at all since only the U233 produced within the discharge fuel burn-up of around 10 MWd/kg HE.(MW per day per kilogram of heavy elements -- uranium, plutonium or thorium). Sinc as much fissile fuel is created as is consumed (i.e., the conversion ratio is 1), this thorium cycle becomes 'self-sufficient' and is considered to be a 'near-breeder' cycle. The SSET cycle does, however, require additional fissile material for each new reactor unit added to the system. In contrast, a fast breeder, with a conversion ratio of greater than 1, produces Pu in excess of its needs and would supply enough Pu in about 20 or 25 years of operation to fuel another breeder reactor).

The fissile material required to initiate a SSET cycle could, once again, be either highly-enriched uranium (93% U235) or Pu,and a significant starting fuel inventory is needed. A 1 GWe CANDU reactor operating on a SSET cycle with one year out-reactor delay time would require either 4.5 tonnes of U235 (which could be obtained from 870 tonnes of natural U) or 4.9 tonnes of Pu (which could be obtained from less than half of the spent fuel produced in 30 years from a 1 GWe CANDU reactor on the natural uranium once-through cycle). For the HEU and Pu SSET cycles, therefore, the natural uranium requirements would be about 20% and 40%, respectively, of those of a natural U once-through cycle.

THORIUM RESOURCES

Current knowledge of the world's thorium resources is significantly less than that of the world's uranium resources. Exploration efforts in this field have been relatively small given the limited commercial market for thorium, which is mainly in minor industrial applications. The possibilities of making new discoveries and of increasing the resources contained in discovered deposits are therefore excellent. It is reasonable to expect that a large part of the world's thorium resources have not yet been identified or discovered.

The largest known reserves of thorium are occurrences of the heavy mineral monazite in beach sands. Other thorium deposits occur in vein deposits of thorium minerals, in quartz-pebble conglomerates associated with uranium, and in igneous alkaline intrusions and similar host rocks. Monazite, from which thorium can be extracted, is produced by several countries and used largely as a source of rare earth elements. World production, however, is in the order of several thousand tonnes containing several hundred tonnes of Th. Actual production of thorium as metal oxide or a salt is only a fraction of that amount contained in the monazite produced.

World thorium resources recoverable at less than $80/kg Th are currently estimated to total some 3 million tonnes: 0.7 in Reasonably Assured Resources and 2.3 in Estimated Additional Resources. The production possibilities based on these resource estimates are likely to be more than the cumulative thorium requirements to 2025, even if thorium fuelled nuclear reactors or fuel cycles were adopted extensively in the past 2000 period and demand for thorium expanded greatly.

Thorium commonly occurs in Canada mineralogically associated with uranium in several types of environments and in both soluble and insoluble forms. Large thorium resources associated with uranium occur in quartz-pebble conglomerates in the Elliot Lake-Agnew Lake area of Ontario. The soluble thorium to uranium ratios are quite variable, generally ranging from 3.5 to 1 to approximately 0.5 to 1 in producing uranium mines. Thorium also occurs in granite or synthetic rocks in many areas across Canada.

There has been no exploration solely for thorium in Canada; known thorium resources have been identified only as a result of the exploration of uranium. It was estimated in 1980 that 186,000 tonnes of soluble thorium are associated with Canada's measured, indicated and inferred uranium resources, mineable at prices of $200/kg U or less. These thorium resources are classed as inferred. In addition, 114,000 tonnes of thorium are associated with Canada's prognosticated uranium resources in the same price category. This total of 300,000 tonnes thorium could likely be recoverable at costs less than $80/kg Th ($30/lb ThO_2).

Should a demand for thorium recovery occur, some 1,500-1,700 tonnes Th/year might be made available, based on current uranium production rates in Ontario. Based on Canada's projected peak levels of uranium production capability, a rate of 1,700-1,900 tonnes Th/year might be attainable over the next decade. An increase to 4,000 tonnes Th/year would be possible in the near future. This latter rate of production should sustain the introduction of some 10-20 GWe CANDU per year on the thorium fuel cycle.

Source: NEA/OECD and IAEA, Uranium, February, 1982, p.199-204.

THE FAST BREEDER REACTOR

A fast breeder reactor is a totally different type of nuclear reactor from the existing, commercial CANDU and Light Water Reactors which are both 'thermal' reactors (i.e., slow, thermal neutrons produce fission) and 'burner' reactors (i.e., they consume more fissile material than they create with a fissile-fertile conversion ratio of less than one). All of the major breeder programs around the world are concentrating on the development of the Liquid Metal Fast Breeder which uses a mixed Pu-U oxide fuel and a liquid sodium coolant.

The breeder fuel cycle requires an initial supply of Pu which is reprocessed from the spent fuel of conventional reactors. Subsequent fuelling requires periodic reprocessing of the fuel from the breeder reactor itself and a recycling of both Pu and U. In the reactor a core of highly concentrated fissile material is arranged to sustain a controlled chain reaction in which the fast-travelling neutrons of one fission not only collide with other fissile atoms (to produce more neutrons) but also produce more fissile material (Pu) than is consumed in the chain reaction by combining with fertile material. Because its conversion ratio is greater than one, the breeder can generate more Pu from the U238 blanket material than it consumes - about 1½ times as much - and is expected to be able to double the Pu initially fed into it in about 20 or 25 years of operation. This Pu could then be used to fuel another breeder reactor, making it totally independent of any external Pu or spent fuel. Thus, the fast breeder reactor breeds fissile fuel using fast, high energy newtrons.

Thus, once provided with an initial amount of Pu, the breeder would from then on produce all its Pu requirements and more itself, although U238 would have to be provided on a continuous basis. The breeder's ability to make use of the energy 'content' of U is tremendous. The existing commercial nuclear reactors of today utilize only 1 to 3% of the energy 'content' in a unit of uranium and could approximately double this energy yield by recycling the Pu produced. A breeder reactor, however, is expected to utilize some 60 or 70%, thereby increasing the lifetime of fuel supplies many fold.

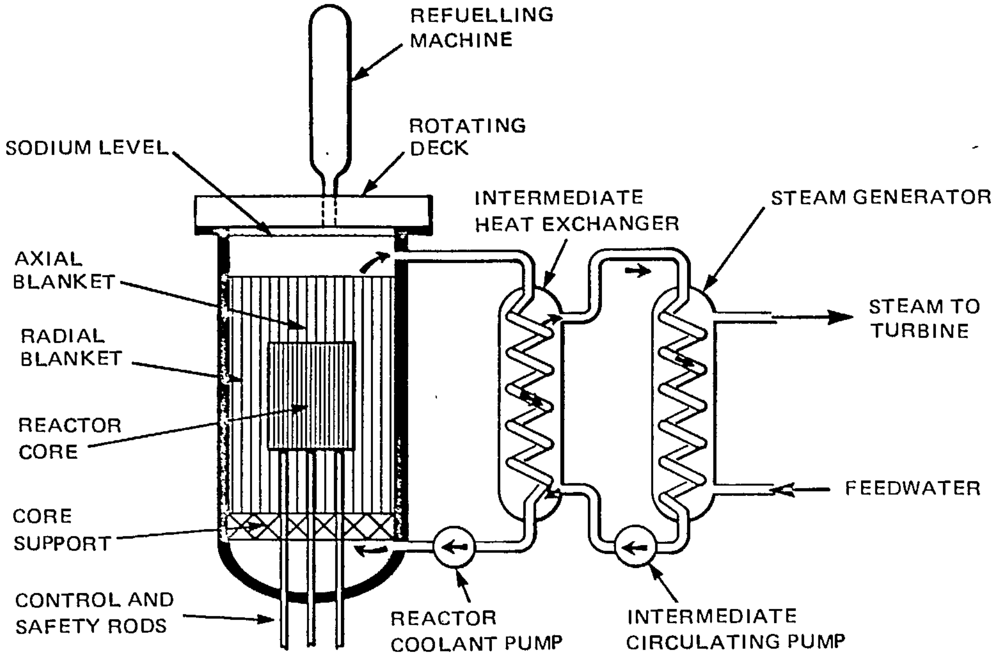
It is interesting to note that, given the high Pu production rate in the CANDU natural uranium once-through cycle - twice that of the existing LWR cycle -, the natural uranium requirements for a breeder reactor would be only about 40% if Pu from the CANDU rather than Pu fr the LWR were used. It is for this reason that it has often been pointed out that there could be a fruitful symbiotic relationship from the combination of CANDU and fast breeder technologies. The lifetime Pu production of a 1GW CANDU is sufficient to launch more than 2 GW of breeder reactors. The excess fissile material produced by the breeder reactor is, in turn, sufficient to support more than 2 GW of CANDU operating on a Pu-depleted U recycle. In other words, the spent fuel from 1 GW CANDU operating on the natural uranium once-through cycle can launch more than 4 GW of fast breeder - CANDU reactors requiring only depleted U as feed.

The development of the fast breeder reactor is being pursued vigorously by major industrialized countries of the world, especially Japan and in Europe. These countries have based their nuclear programs on the predominant Light Water Reactor line. The breeder reactor is seen as a way to achieve a nuclear fuel self-sufficiency and to guard against future uranium supply difficulties and price increases. The successful development and introduction of the breeder will ensure these countries an independent and reliable supply of nuclear energy fuel in the future and, therefore, would provide a long-term, virtually permanent, solution to the nuclear fuel resource problem.

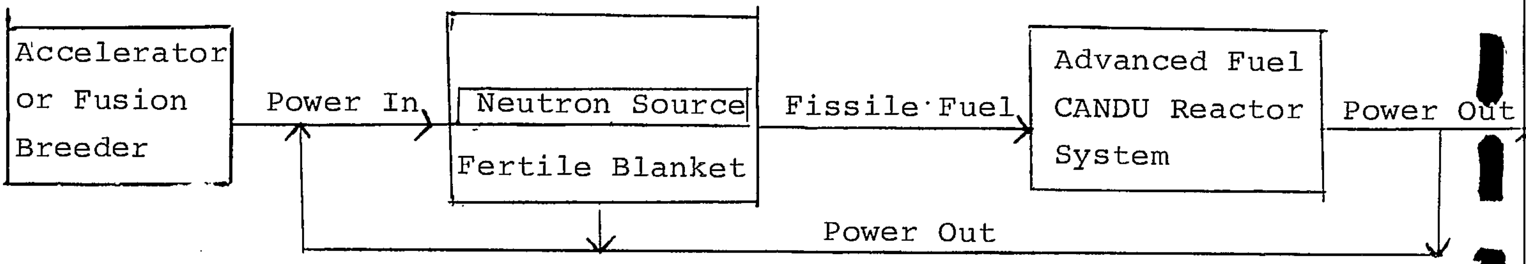
Breeder programs actually started more than thirty years ago with the American Experimental Breeder Reactor No. 1 in Idaho in 1951. Over the next two decades, 9 more experimental breeders were built around the world. Three demonstration plants became operational in 1973-74: the BN-350 in the USSR, the PFR in Great Britain and the 250 MW Phénix in France. These paved the way for the large-sized power plants needed to confirm a commercial breeder reactor. The most powerful commercial-size breeder in the world is the BN-600 MW reactor in the USSR which has been operating since 1980. The Superphénix, a 1200 MW reactor, is now undergoing completion at Creys-Malville in France for an early 1984 startup date. In the United States, the Clinch River Fast Breeder, a 350 MW demonstration reactor in Oak Ridge, Tennessee, has been recently resurrected under the Reagan Administration for a 1990 operational date. Breeder reactor development programs, including the associated reprocessing and fuel fabricating elements, are proceeding apace around the world, in spite of the current troubles and slowdowns plaguing the nuclear industry. These breeder efforts totalled some $7 billion prior to 1977 and now amount to approximately $2 billion a year.

Given the considerable progress made to date and the likely developments, it is expected with a high degree of confidence that the fast breeder reactor may be technically available around the turn of the century and could be a commercially viable and economically attractive proposition around the year 2025. At present, and based on the Phénix exprience, a breeder reactor has a very high capital cost compared to the light water reactor, making its total electrical production cost about twice as much. If the capital cost could be significantly reduced and if very high world uranium prices come about, the fast breeder reactor would become economically attractive.

Figure Schematic Diagram of a Fast Breeder Reactor



ELECTRONUCLEAR BREEDING



Electronuclear breeding is the electrically driven process to generate a source of neutrons (other than from nuclear reactors) that can be used to convert fertile material (U238 and Th232) to fissile material (Pu239 and U233). Such fissile material is therefore created away from a nuclear reactor but is then used in an advanced fuel reactor as nuclear fuel. As an option to ensure and extend the fissile fuel supply, electronulcear breeding could be a future alternative fissile fuel supply to the fast breeder reactor, and to a fusion reactor -- both of which would create more fissile material than they would use. In this way electronuclear breeding could play a possible role as a long-term, fissile production support option for the CANDU advanced fuel cycle.

There are two basic electronuclear breeding concepts or approaches: accelerator breeding involving the spallation reaction and fusion breeding involving a fusion device and fusion reactions.

In accelerator breeding, an accelerator (for example, a proton linear accelerator) delivers a high current beam of high energy protons to a thick heavy element target (such as lead or bismuth) surrounded by a suitable blanket assembly. The beam bombardment interacts with the target to produce heat and an intense source of cascading neutrons by the spallation process. (One proton at 1 GeV or a billion electronvolts on a bismuth thick target produces about 3 GeV heat and 30 neutrons). The neutrons are then multiplied and absorbed in the surrounding blanket of fertile material (U238 or Th232) to produce fissile material (Pu239 or U233). The energy generated and released in the target/blanket could be removed to drive the accelerator.

Accelerator breeding could be employed in conjunction with a CANDU reactor operating on a thorium fuel cycle - one that typically involves ThO_2 feed with U233 recycle and U235, Pu or U233 topping. A one tonne per year fissile output from an accelerator breeder would be sufficient to provide the U233 inventory for about .25 GW per year of installed reactor capacity or, alternatively, topping enrichment for about 10 GW of reactors with a conversion efficiency ratio of 0.93. One accelerator breeder could thus supply fissile fuel for a very substantial nuclear power growth rate. It has been estimated that, at a capital cost of $1.5 billion (1981 $), a 1 GeV accelerator breeder would result in fissile production costs per gram equivalent to some 2 mills/kW.h in the cost of electricity.

Based on the long-term goal of keeping open electronuclear breeding as a means of extending the fissile fuel supply, accelerator breeding work is being carried out by AECL, primarily in its main test facilities (the High Current Test Facility, the Fast Intense Neutron Source, the Injector Test Experiment and the Electron Test Accelerator) and in experiments with the TRIUMPH accelerator in Vancouver on target neutron production and fertile-to-fissile conversion efficiency. AECL has established a long-term development program including the Canutron under development and a series of planned facilities (the ZEBRA, the Electronuclear Materials Test Facility and the CANAB).

The other basic electronuclear breeding concept or approach is fusion breeding involving a fusion device and fusion reactions. Nuclear fusion itself will be treated in detail in Parts E and F of this paper but in fusion breeding the fusion device provides neutrons to a blanket of fertile material in order to breed fissile material as well as tritium. It is the current judgment that, as compared to the fusion breeder, the accelerator breeder rests on a firmer technological foundation and that it could be demonstrated at an earlier time. Given the intense world fusion effort, however, the relative fusion breeder position could improve considerably. AECL's current work on fusion breeding involves paper studies, a watching brief on the state of the art, personnel visits to foreign fusion laboratories and some theoretical in-house work relating to fusion plasma physics and to fusion breeding blankets.

Sources: AECL, 'Electronulcear Breeder Concepts For Canada', November 1980;
AECL, 'A Review of the Prospects for Fusion Breeding of Fissile Material', October 1981;
AECL, 'A Review of Prospects for an Accelerator Breeder', December 1981.

Table 29. Existing Once-Through Fuel Cycles in CANDU and Light Water Reactors (LWR)

	CANDU	LWR
Once-Through Fuel Cycle	natural U	enriched U
Fresh Fuel	0.7% U235	3.2% U235
	99.3% U238	96.8% U238
Spent Fuel	0.2% U235	.8% U235
	98.4% U238	95.7% U238
Lifetime Characteristics (1):		
Natural U requirements (Mg/GWe)	4,230	4,930
Enrichment requirements (Mg SWU/GWe)	--	3,875
Fissile Pu in spent fuel (Mg)	11.2	5.4

(1) 1GWe reactor, 80% capacity load factor, 30 years operation, 0.2% enrichment plant tailings.

Source: J.B. Slater, 'Advanced future fuel cycles for CANDU reactors', AECL, September, 1981, p.2.

significantly less uranium - about 20% less - than does the current LWR cycle (Table 29).

The existing LWR, however, can be improved through new fuel cycles involving reprocessing, recycling, and the use of plutonium (Pu), U235, thorium (TH), and U233. With such changes, the best reduction in uranium requirements that could be possibly achieved with the same basic reactor design would be about 60% that of the existing enriched U once-through cycle or about two-thirds that of the existing natural uranium once-through cycle in the CANDU (Table 30).

The CANDU reactor could also use advanced fuel cycles which would result in equivalent and, in most cases, much lower uranium requirements, than any possible improved LWR cycle. Table 30 indicates, in terms of the lifetime natural uranium requirements for a 1 GW CANDU reactor operating at an 80% capacity factor for 30 years, the potential uranium requirements of a range of advanced fuel cycles and the associated uranium savings over the natural uranium once-through cycle. If the lifetime natural uranium requirements of a natural uranium once-through cycle were 100%, then it is expected that a low enriched uranium (LEU) cycle would be about 70%; a plutonium- uranium (Pu-Nat U) re-cycle about 45%; and the various thorium fuel cycles 20% to 70% depending on the particular thorium cycle involved.

Thus, advanced fuel cycles in the CANDU would require significantly less natural uranium than the existing natural uranium once-through cycle. The best advanced fuel cycle from a uranium requirements and savings point of view would be the self-sufficient equilibrium thorium (SSET) cycle initiated by highly-enriched uranium - a "near-breeder" cycle that would require only about one-fifth of the natural uranium required in a natural uranium once-through cycle. Moreover, every advanced fuel cycle in the CANDU reactor (with the exceptions of the two once-through cycles involving low enriched uranium and thorium-

Table 30. Lifetime Natural Uranium Requirements of Different Reactors and Fuel Cycle

(1 GWe, 80% capacity Factor, 30 years operating life, 0.2% enrichment tails assay

Reactor	Fuel Cycle	Lifetime Natural U Requirements (tonnes)	% CANDU Natural U Once Through
CANDU	Existing-Natural U Once-Through	4,230	100
	LEU Once-Through	3,005	71
	Pu-Natural U Recycle	1,910	45
	Thorium Cycles:		
	Th-Enriched U Once-Through	3,000	71
	Th-Pu Recycle	2,375	56
	Th-HEU Recycle	1,545	37
	Th-Denatured Recycle	1,750	41
	SSET Recycle:		
	Pu Initiated	1,830	43
	HEU Initiated	870	21
LWR	Existing-Enriched U Once-Through	4,930	117
	U Recycle	4,490	106
	Pu-U Recycle	3,300	78
	Th-U Recycle	2,800	66
LMFB	Pu from LWR	4,210	100
	Pu from CANDU-Nat. U	1,750	41

Sources: NEA/OECD, Nuclear Energy and Its Fuel Cycle-Prospects to 2025, 1982, p. 156-157.

J. Veeder and J.V. Donnelly, 'CANDU-The Versatile Option', AECL, April 1982.

J.B. Slater, 'Advanced future fuel cycles for CANDU reactors', AECL, September 1981.

enriched uranium) would require less uranium than any possible advanced fuel cycle in the existing LWR.

Besides achieving these uranium savings, however, advanced fuel cycles would also make possible for use as a nuclear reactor fuel two potential sources that are not now being exploited - the plutonium contained in spent fuel bundles and our thorium resources. Besides conserving uranium, therefore, advanced fuel cycles would expand the existing nuclear fuel base to include these nuclear fuels.

The actual extent of these potential uranium savings can only be placed in proper perspective by relating them to the future Canadian nuclear power program and to the existing natural uranium resource base. As previously indicated in Part B, the recent NEA/OECD forecast estimated that Canada's installed nuclear power capacity by 2030 would be 40-110 GW, depending upon whether a low nuclear growth or a high nuclear growth is realized. Although AECL is currently estimating a 100 GW nuclear capacity in 2030, it would seem, given the recent downturn in future nuclear forecasts and the continuing uncertainties related to future nuclear development, that a lower forecast of some 50 GW in 2030 is probably a more realistic projection at this time - and even this forecast may turn out to be an optimistic one. For illustrative purposes in this paper, however, and to cover the possible range involved, it will be assumed that the Canadian nuclear capacity in 2030 will be either 50 GW or 100 GW.

If there is 50 GW nuclear in 2030, all of which is fuelled by an advanced fuel cycle rather than by the natural uranium once-through cycle, then the lifetime uranium savings would range from a minimum of 62,000 tonnes U in the LEU once-through cycle to a maximum of 168,000 tonnes U in the SSET-HEU initiated re-cycle (Table 31). If there is 100 GW nuclear in 2030, then the lifetime uranium savings would range from a minimum of 122,000 tonnes U to a maximum of 336,000 tonnes U. Thus, the maximum uranium savings

Table 31. Lifetime Natural Uranium Savings of Advanced Fuel Cycles Over the Natural Uranium Once-Through Cycle Under Different Nuclear Power Futures

(thousands of tonnes U)

	Lifetime Natural U Requirements		Lifetime Natural U Savings over Natural U-Once-Through	
	Installed Nuclear Capacity in 2030 of:			
CANDU Fuel Cycle	50 GW	100GW	50GW	100GW
Natural U Once-Through	212	423	-	-
LEU Once-Through	150	301	62	12[illegible]
Pu-Natural U Recycle	96	191	116	232
Thorium Cycles:				
Th-Enriched U Once-Through	150	300	62	123
Th-Pu Recycle	119	238	93	18[illegible]
Th-HEU Recycle	77	155	135	268
Th-Denatured Recycle	88	175	124	24[illegible]
SSET Recycle:				
Pu Initiated	92	183	120	240
HEU Initiated	44	87	168	33[illegible]

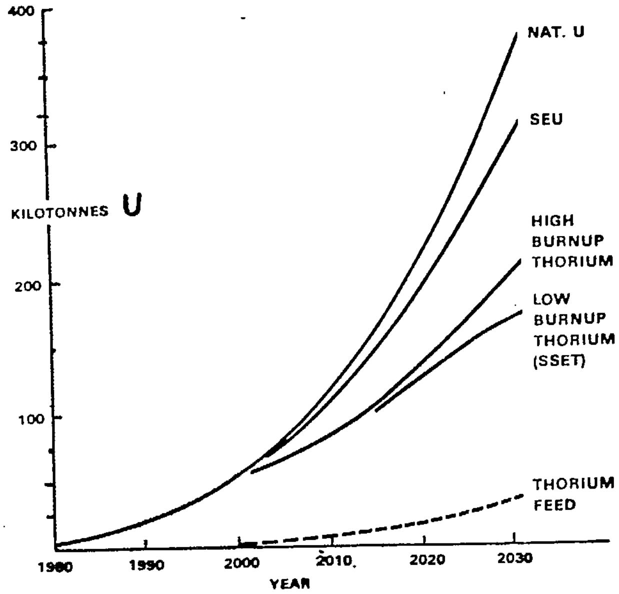
Source: Calculated from Table 30.

- under what could only be considered to be a high nuclear growth forecast and in the best possible uranium conserving advanced fuel cycle - would be 336,000 tonnes U. This amount is equivalent to about one-third of Canada's existing uranium resource base of one million tonnes U (or, to put it in another light, almost equivalent to the net resource additions of 300,000 tonnes U that were added to Canada's resource base over the period 1974 to 1980).

This is, however, only one way - and a rather simple way at that - to measure the uranium conserving nature of advanced fuel cycles. A more accurate measurement - one that is dynamic rather than static - is obtained from looking at the cumulative uranium requirements and the actual uranium savings of each advanced fuel cycle to the year 2030. This takes into account such important factors as initial inventory, the dependence of one cycle on another for a supply of fissile material, the time-delay at various stages of the cycle, the point in time when a particular cycle is introduced, the gradual growth over time of the nuclear power capacity, and so on.

Figure 13 reflects a recent AECL assessment of the possible cumulative uranium requirements by the year 2030 for the high growth nuclear forecast of 100 GW under the least uranium conserving advanced fuel cycle (the LEU) and under the most uranium conserving advanced fuel cycle (the low-burnup SSET-HEU initiated re-cycle). The cumulative uranium savings over the natural uranium once-through cycle by 2030 range from a minimum of 50,000 tonnes U - a 13% uranium savings - to a maximum of 200,000 tonnes U - a 33% uranium savings. This maximum 200,000 tonnes U savings by the year 2030, however, is the equivalent of only one-fifth of Canada's currently known uranium resource base of one million tonnes U (or about two-thirds of the net resource additions of 300,000 tonnes U that were added to Canada's resource base over the period 1974 to 1980).

Figure 13. Cumulative Uranium Requirements of Selected Advanced Fuel Cycles to 2030 - AECL



This assessment is based on the following assumptions:

CANDU reactors: 80% load factors; 1 year recycle delay; 0.2% tails enrichment

Installed Nuclear Capacity GW(e):

1980 -	5.4
1990 -	15.6
2000 -	30
2030 -	100

Advanced Fuel Cycle Introduction Dates - shortly after 2000

Thorium cycle: based on Pu from spent natural U fuel and then switched over to HEU

SEU (slightly enriched uranium cycle) ≃ LEU

Cumulative uranium requirements and savings of the Pu-U recycle (not shown here) are intermediate between the SEU and the high-burnup thorium cycle

Source: J. Veeder and J.V. Donnelly, AECL, 'CANDU - The Versatile Option', a paper presented at the Brussels Nuclear Fuel Cycles Conference, April, 1982.

Another assessment of the possible cumulative uranium savings associated with advanced fuel is cycles is available from the series of detailed studies carried out by Ontario Hydro in the 1978-1980 period.5 The most recent and updated exposition of these study results is displayed in Figure 14 and provides some added insights into the potential uranium savings of various advanced fuel cycles over the long-term.

Based on the stated assumptions, including a nuclear growth forecast with installed nuclear capacities in Canada of 160 GW in 2050 and 175 GW in 2075, the cumulative uranium savings over the natural uranium once-through cycle range, by 2050, from a minimum 100,000 tonnes U (a 17% uranium savings) to a maximum 300,000 tonnes U (a 46% uranium savings); and, by 2075, from a minimum 350,000 tonnes U (a 30% uranium savings) to a maximum 650,000 tonnes U (a 57% uranium savings). This maximum 650,000 tonnes U savings by the year 2075 is the equivalent of about two-thirds of Canada's currently known uranium resources of one million tonnes U (or more than double the net resource additions of 300,000 tonnes U that were added to Canada's resource base over the period 1974 to 1980).

It should be noted, of course, that this nuclear forecast by Ontario Hydro will more than likely turn out to be an optimistic

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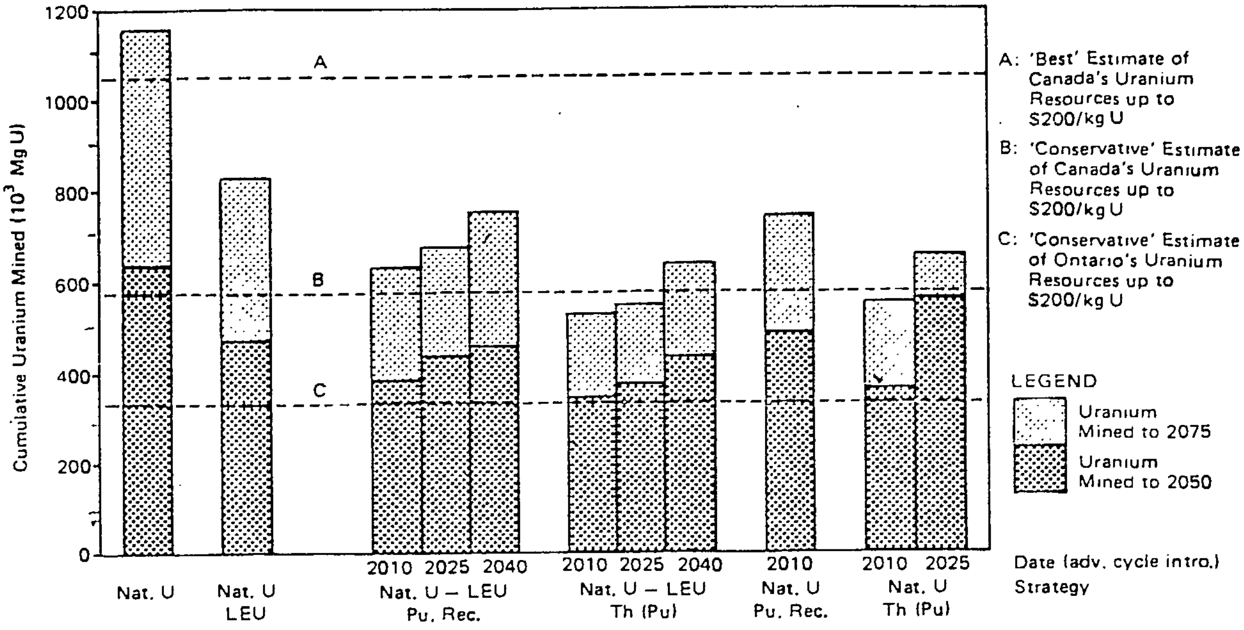
5 Lau, Penn, James and Blahnik, 'The Influence of Uranium Availability on Nuclear Strategy for Ontario', Ontario Hydro, June, 1978;
James and Penn, 'Advanced Fuel Cycles: What is Their Economic Potential?', Ontario Hydro, June, 1978;
Archinoff and Penn, 'The Low Enriched Uranium Fuel Cycle in Ontario: A Resource Utilization Study', Ontario Hydro, February, 1979;
Penn and Meneley, 'Alternative Fuel Cycles: Which Options to Develop?', Ontario Hydro, May, 1979;
Archinoff, James, and Brown, 'Future Fuel Cycles: A Resource Utilization and Economic Assessment', Ontario Hydro, January, 1980;
James and Brown, 'Advanced Fuel Cycles: A Rationale and Strategy for Adopting the Low-Enriched Uranium Fuel Cycle', January, 1980.

Figure 14. Cumulative Uranium Requirements of Various Advanced Fuel Cycles and Strategies to 2050 and to 2075 - Ontario Hydro



This assessment is based on the following assumptions:

'Base Growth' Installed Nuclear Capacity GW(e):
2000 - 31
2025 - 85
2050 - 160
2075 - 175

Advanced Fuel Cycle Introduction Dates - as indicated in Figure and LEU introduced in 1994.

Gradual introduction of new fuel cycles according to the Fisher-Pry model (only new reactors operate on the new cycle; old reactors maintain the same cycle until decommissioned)

Uranium Resource Estimates:
'Best' includes Measured, Indicated, Inferred and Prognosticated
'Conservative' includes Measured, Indicated and Inferred but excludes Prognosticated

Ontario Hydro did not include the SSET cycle in this assessment because, although it is recognized as the most uranium conserving cycle, its low fuel burnup results in the requirement to frequently reprocess and fabricate thorium fuels and makes this cycle considerably less economically attractive than an intermediate - burnup thorium cycle, which still has good resource utilization.

Source: G.H. Archinoff, Ontario Hydro, 'A Resource Utilization and Economic Assessment of Alternative Fuel Cycles for CANDU - PHW Reactors', a paper presented at the Brussels Nuclear Fuel Cycles Conference, April, 1982.

one and, if so, then the maximum uranium savings potential of advanced fuel cycles over time would be correspondingly reduced. Although this was Ontario Hydro's 'base growth' forecast, Ontario Hydro itself has now acknowledged - in the spring of 1982 - that 'at the present time, it appears that the total installed nuclear capacity in Canada will be somewhat less than the base growth estimate'.[6] Moreover, if Ontario Hydro's 'low growth' estimate is used as the more realistic forecast rather than the 'base growth' one - a not unreasonable judgement to make at this time - then the cumulative uranium requirements by the year 2075 of a natural uranium fuelled CANDU system would be 675,000 tonnes less than it otherwise would be (Table 32). Thus, if a more realistic forecast of long-term nuclear growth is used, the uranium 'saved' in this way would be equivalent to the maximum cumulative uranium savings potential of advanced fuel cycles.

Figure 14 also indicates that, if only the LEU cycle were developed, the cumulative uranium savings would be 350,000 tonnes U by 2075 - about one-half of the maximum possible savings that could be achieved under the PU or Th re-cycles. Moreover, if the LEU cycle were developed first and then the PU or Th re-cycles were added on to it later, then the minimum cumulative uranium savings would be 450,000 tonnes by 2075 - about two-thirds of the maximum savings of the PU or Th re-cycles. Foregoing the LEU cycle completely by going directly to PU or Th re-cycles would not result in any significant long-term uranium savings. In short, the LEU cycle has a real value as a possible interim cycle to the longer-term and more uranium conserving PU or Th re-cycles.

Figure 14 also shows that varying the introduction date of PU or Th re-cycles from 2010 to 2040 would result in a relatively small impact on the long-term cumulative uranium savings - a

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[6] G.H. Archinoff, Ontario Hydro, 'A Resource Utilization and Economic Assessment of Alternative Fuel Cycles for CANDU - PHW Reactors', a paper presented to the Brussels Nuclear Fuel Cycles Conference, April, 1982.

Table 32. Cumulative Uranium Requirements of Natural Uranium Fuelled CANDU's Under Varying Nuclear Power Forecasts - Ontario Hydro

	Total Nuclear Installed Capacity (GW)			Cumulative Natural Uranium Requirements for Natural Uranium Once-Through Cycle (thousands of tonnes U)		
Year	High	Base	Low	High	Base	Low
2000	33	31	25	70	70	50
2025	140	85	60	325	250	200
2050	340	160	90	800	650	325
2075	610	175	50	1,750	1,150	475

Source: G.H. Archinoff, Ontario Hydro, 'A Resource Utilization and Economic Assessment of Alternative Fuel Cycles for CANDU - PHW Reactors', a paper presented to the Brussels Nuclear Fuel Cycles Conference, April, 1982.

Archinoff, James and Brown, 'Future Fuel Cycles: A Resource Utilization and Economic Assessment', Ontario Hydro, January, 1980, p. 14, 46 and 54.

maximum difference of about 100,000 tonnes U by 2075. Since the exact introduction date is not that critical to these savings, these re-cycles could easily be introduced closer to the middle rather than to the beginning of the next century without incurring significant sacrifices in uranium savings. From this point of view, the introduction of such re-cycles at the earliest possible time is not warranted.

These maximum cumulative uranium savings from advanced fuel cycles must, however, be viewed in full relation to Canada's uranium resources. As indicated previously in Part B, the currently known uranium resource base is now very large and has been growing significantly over the last decade. In addition, this resource base has the potential and the probability, with continued or increased exploration efforts, of becoming considerably larger in the future.

As suggested above, advanced fuel cycles could possibly result in a maximum cumulative uranium savings of 650,000 tonnes U by the year 2075. This would be equivalent to about two-thirds of Canada's currently known uranium resources of about one million tonnes. Uranium resource additions from now to the year 2075 would have to be only twice those realized over the period 1974 to 1980 to equal these maximum savings. From this point of view, uranium savings from advanced fuel cycles may well be not as significant as the likely future uranium discoveries.

Furthermore, if there were 175 GW of installed nuclear capacity in the year 2075, all of which was based on a natural uranium once-through cycle, then the cumulative uranium requirements would be about 1,150,000 tonnes U (Figure 14). This is just a little more than the million tonnes U of currently known resources. This means that even if no uranium additions at all were realized by 2075, the existing uranium base would still be sufficient to meet almost all of the domestic uranium requirements to 2075 even if no advanced fuel cycles were developed and deployed

It must, therefore, be concluded that Canada's existing and future uranium resources will be more than adequate to serve its domestic nuclear needs for over a century without the need for advanced fuel cycles.

This conclusion, however, should be viewed in light of certain considerations. Even if Canada's existing uranium base is adequate in itself to meet domestic requirements to the year 2075, the current policy of establishing a thirty year protected reserve means that, in the absence of significant additional resource discoveries in the future, Canada's nuclear power program would be severely constrained and perhaps made impossible by about the year 2045. No utility would want to or even be able to decide on new nuclear capacity at that time since all of the uranium resource base would have been accounted for already. In addition, Canada's uranium supply over the next century will not be used solely to meet domestic needs. As previously indicated, exports are a large part of the Canadian uranium situation and will likely continue to be so in the future. The uranium exported from Canada's resource base will not be available for use in the domestic nuclear power program. Therefore, not all of Canada's existing uranium resources can be counted on for domestic use in the future. If necessary, such exports could be curtailed at some point in the future but only at considerable costs and after a considerable part of the uranium base has been exported.

Conclusions

From the above analysis of uranium utilization and savings, the following conclusions can be drawn:

(1) The CANDU natural uranium once-through fuel cycle now uses considerably less uranium than the enriched uranium Light Water Reactor. Moreover, the lifetime natural uranium

requirements of advanced fuel cycles would be far less in the CANDU reactor than in the Light Water Reactor.

(2) Advanced fuel cycles in the CANDU reactor have the potential to achieve lifetime natural uranium requirements that are 20% to 70% those of the existing natural uranium once-through cycle, with the most uranium conserving cycles involving thorium.

(3) Under a high nuclear growth forecast, the maximum cumulative uranium savings of advanced fuel cycles over the natural uranium once-through cycle would total 650,000 tonnes U by 2075 - a 57% uranium savings. Since such uranium savings are very sensitive to the actual long-term installed nuclear capacity, a lower and, at the present time, a more realistic estimate of this capacity in 2075 would result in just as much uranium 'saved' as this maximum savings potential of advanced fuel cycles.

(4) The low-enriched fuel cycle by itself could achieve one-half of these maximum cumulative uranium savings by 2075. No significant long-term uranium savings benefit would accrue from foregoing the earlier introduction of the low-enriched fuel cycle or by introducing the plutonium or thorium re-cycles at the earliest time possible.

(5) The maximum cumulative uranium savings of 650,000 tonnes U by 2075 would be equivalent to about two-thirds of Canada's currently known uranium resources of about one million tonnes U. This existing resource base, however, can be expected to increase considerably over the next century as the result of further resource additions. Such resource additions would have to be only twice those realized over the period 1974 to 1980 to equal the maximum cumulative uranium savings from advanced fuel cycles over the next century.

Table 33. 1981 Total Unit Energy Cost Comparison for Pickering A Nuclear Station and Lambton Coal Station (net Capacity Factor: 88.1%)

	Mills per kilowatt-hour (m$/kW.h) (1)	
	Pickering A	Lambton
Interest and Depreciation (2)	6.4	1.9
Operation, Maintenance and Administration	4.5	1.7
Heavy Water Upkeep	0.7	-
Fuelling	2.2	19.5
Total Unit Energy Cost (TUEC)	13.8 (3)	23.1

Source: Ontario Hydro, CANDU Operating Experience, March, 1982, p. 46

(1) 1 mill = $0.001

(2) includes amortization of heavy water inventory

(3) The TUEC of the more recent Bruce A Nuclear Station is higher - 17.0 m$/kW.h - due to capaital cost inflation, with the fuelling costs of 2.7 m$/kW.h. The TUEC can actually vary considerably depending on a number of factors: the size of the reactor, the capacity factor, the discounted rate of return on capaital investment, the interest rate and inflation, the status of the reactor (well-established, starting-up, planned, a first reactor), etc.

(6) The currently known uranium resource base in Canada would still be sufficient, if no uranium were exported, to meet almost all of the domestic uranium requirements of a natural uranium fuelled CANDU system by 2075, even under a high nuclear growth forecast. Since future uranium resource additions will be realized and since the high nuclear forecast will more than likely not be achieved, Canada's uranium resources will be more than adequate to serve its domestic nuclear needs based on the existing fuel cycle for the next a century.

(7) Although advanced fuel cycles for the CANDU reactor are an attractive proposition from the uranium conserving point of view, they are not a required necessity for Canada from the more important standpoints of uranium resources and domestic nuclear requirements over even the very long-term. The introduction of advanced fuel cycles is therefore neither required nor warranted by the uranium resource situation alone.

2. Economics

This section examines the economic aspects of the CANDU nuclear reactor operating on the natural uranium once-through cycle and on advanced fuel cycles, with particular attention given to the relative importance of future uranium prices. A determination is sought of the likely future conditions under which advanced fuel cycles would become economically attractive compared to the natural uranium once-through cycles.

The Total Unit Energy Cost (TUEC) for electrical power production (the total annual cost divided by the total annual energy produced) is well defined for a CANDU reactor operating on the natural uranium once-through cycle. There are four main cost components involved: capital recovery (interest and depreciation on the capital cost); operation, maintenance and administration;

Table 34. Impact of U_3O_8 Cost Increases on Total Unit Energy Costs of a CANDU Natural Uranium Once-Through Fuel Cycle

	U_3O_8 Cost (\$/kgU) (1)			
	\$ 99	\$132	\$176	\$220
Total Discounted Fuel Cost (m\$/kW.h)	3.8	4.7	5.8	7.0
Average Production Cost (m\$/kW.h)	14.0	14.9	16.1	17.2

Source: AECL, Data Base for a CANDU-PHW Operating on a Once-Through Natural Uranium Cycle, July, 1979, p.145.

(1) \$1/lb U_3O_8 = \$2.6/kgU.

Table 35. Total Unit Energy Cost Comparison of CANDU Advanced Fuel Cycles

CANDU Fuel Cycle	Total Unit Energy Cost (mills\$/kW.h) At Given Uranium Prices (1)	
	\$104/kgU	\$260/kgU
Natural U Once-Through	19	22.50
LEU Once- Through	19.17	21.68
P_u-Natural U Recycle	22.06	22.85
Th-Denatured U	21-26	23.27
Th-Denatured U-P_u	24.15	19.75

Source: Secor Inc., A Strategy for the Development and Strengthening of the Canadian Nuclear Industry, March, 1981, p.85.

(1) \$1/lbU_3O_8 = \$2.6/kgU.

heavy water upkeep; and fuelling cost.

It is generally considered that the fuelling cost amounts to only approximately 15% of the TUEC or about one-third the size of the capital cost component (Table 33). This fuelling cost is currently about $150 kg U, of which about two-thirds represents the U308 cost and one-third the fuel fabrication cost.[7]

Naturally, everything else being equal, an increase in the cost of U3O8 would increase the fuellirg cost and, consequently, the final TUEC. If, for example, the U308 cost component were to rise by 150% from $104/kg U to $260/kg U, then the TUEC would increase by about 20% (Table 34). This would, however, represent a four-fold increase over the current uranium price of about $65/kg U.[8] It has been estimated that such a uranium price, under the scenarios of a U308 price in 1985 of $117/kg U and a 2-3% real increase per year beyond 1985 (possibly higher than might be realistically expected), would not be reached before 2015-2025.[9] Therefore, even a four-fold increase in the current U308 price, which is not likely for at least another 40 years or so, would only result in a 20% increase in the TUEC of a CANDU reactor operating on a natural uranium once-through cycle.[10] Moreover, as Table 33 indicates, this 20% higher CANDU TUEC around the year

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[7] AECL, Data Base for a CANDU-PHW Operating on a Once-Through Natural Uranium Cycle, July, 1979, p.138.

[8] Uranium market prices have fluctuated widely over the last decade from $12/kg U in 1972 to a record high of $125/kg U in 1979 to about $60/kg U in early 1982.

[9] R.A. James and W.J. Penn, 'Advanced Fuel Cycles: What is Their Economic Potential?', Ontario Hydro, June, 1978, p.5-6 and Figures 4 and 5.

[10] Since all electricity generated from whatever fuel source is fed into a common grid from which the consumer draws, this increase in CANDU TUEC would actually result in a smaller increase in the TUEC for the electrical system as a whole. If, for instance, the electricity generating system in the year 2025 were half-nuclear and half-non-nuclear and all of the nuclear part recorded a 20% TUEC increase, then the increase in the electricity price to the consumer would be only 10%.

2020 would still be considerably more economic than even the current coal TUEC.

To put this into perspective, it should be noted that capital cost remains the dominant component in the CANDU TUEC: as Table 33 indicates, capital cost was almost 50% of Pickering A's TUEC of 13.8 mills $/kWh. Capital cost is, of course, very sensitive to inflationary and high interest rate pressures, as evidenced by the fact that the TUEC of the more recent Bruce A Nuclear Station is, largely due to capital cost inflation, 17.0 mills $/kWh - a 23% increase over the Pickering A TUEC. Moreover, current cost estimates of future CANDU reactors are even higher, reflecting the worsening inflation and interest rate situation, as evidenced in Hydro-Quebec's 1980 estimate that the capital cost of CANDU would now constitute about two-thirds of the TUEC.[11] A lowering of interest rates would clearly reverse this trend. This suggests that changes in capital costs are far more important in terms of increasing the CANDU TUEC than are changes in fuelling costs: capital cost inflation in the last few years have raised the TUEC of a CANDU reactor by more than would a four-fold increase in the current U308 price over the next three to four decades!

This is, moreover, exactly the opposite situation from that of the TUEC of a coal-fired electricity unit (Table 33). Fuelling costs account for about 85% of the coal TUEC but for only 15% of the CANDU TUEC. Since nuclear is much less fuel cost intensive, its TUEC is that much less sensitive to increased fuel costs than that of coal. Capital costs account for less than 10% of the coal TUEC but for almost 50% of the CANDU TUEC, so the latter is that much more sensitive to increased capital costs than that of

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[11] Secor, Inc., 'A Strategy for the Development and Strengthening of the Canadian Nuclear Industry', March 1981, p.33.

[12] See EMR, 'A Comparison of the Economics of Nuclear Energy and Coal in Generating Electricity', in EMR, Nuclear Policy Review Background Papers, 1981, p.33-47.

coal.12

The above outline of the TUEC of a CANDU reactor operating on a natural uranium once-through cycle, and the relative importance of the fuelling cost component, especially in terms of future uranium price increases, provides the necessary perspective from which to view the possible economic attractiveness of a CANDU operating on an advanced fuel cycle.

The TUEC for such an advanced fuel cycle CANDU reactor would, of course, have the same four basic cost components. The use of the same reactor technology - the basic, currently commissioned CANDU design - would mean that virtually the same costs for capital, operating and maintenance and heavy water upkeep would be involved.13 If this is so, then the only factor that would make advanced fuel cycles economically competitive and attractive to the natural uranium once-through cycle would be a favourable reduction in fuelling costs.

The impact on costs of changing from natural uranium to LEU once-through fuelling can be reasonably indicated in that the required services are now commercially available (although the

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[13] Costs for capital recovery may in fact be slightly higher (perhaps .5 mill $/kWh higher) to compensate for modified fuel handling facilities and fuel management operations. Although only minor reactor design changes are expected, it is possible that the actual changes involved might prove to be more substantial and therefore more costly than now anticipated. On the other hand, advanced fuel cycles do offer the potential of modifying the current commercial CANDU design to obtain capital cost reductions. Major benefits, for example, might accrue from changing the coolant from heavy water to either boiling water (as in the 250 MW Gentilly I CANDU) or an organic fluid (as in the 60 MW WR-1 CANDU). Detailed design estimates indicate that the potential of reducing capital costs would be 15-25%, although such reductions would be counterbalanced to some extent by increases in fuelling costs due to the less neutron economical nature of the designs. See J.B. Slater, 'Advanced Future Fuel Cycles for CANDU Reactors', AECL, September, 1981, p.6.

Figure 15. The Economics of Natural Uranium vs Low Enriched Uranium Once-Through Fuel Cycles: Impact of Enrichment and Uranium Costs - AECL

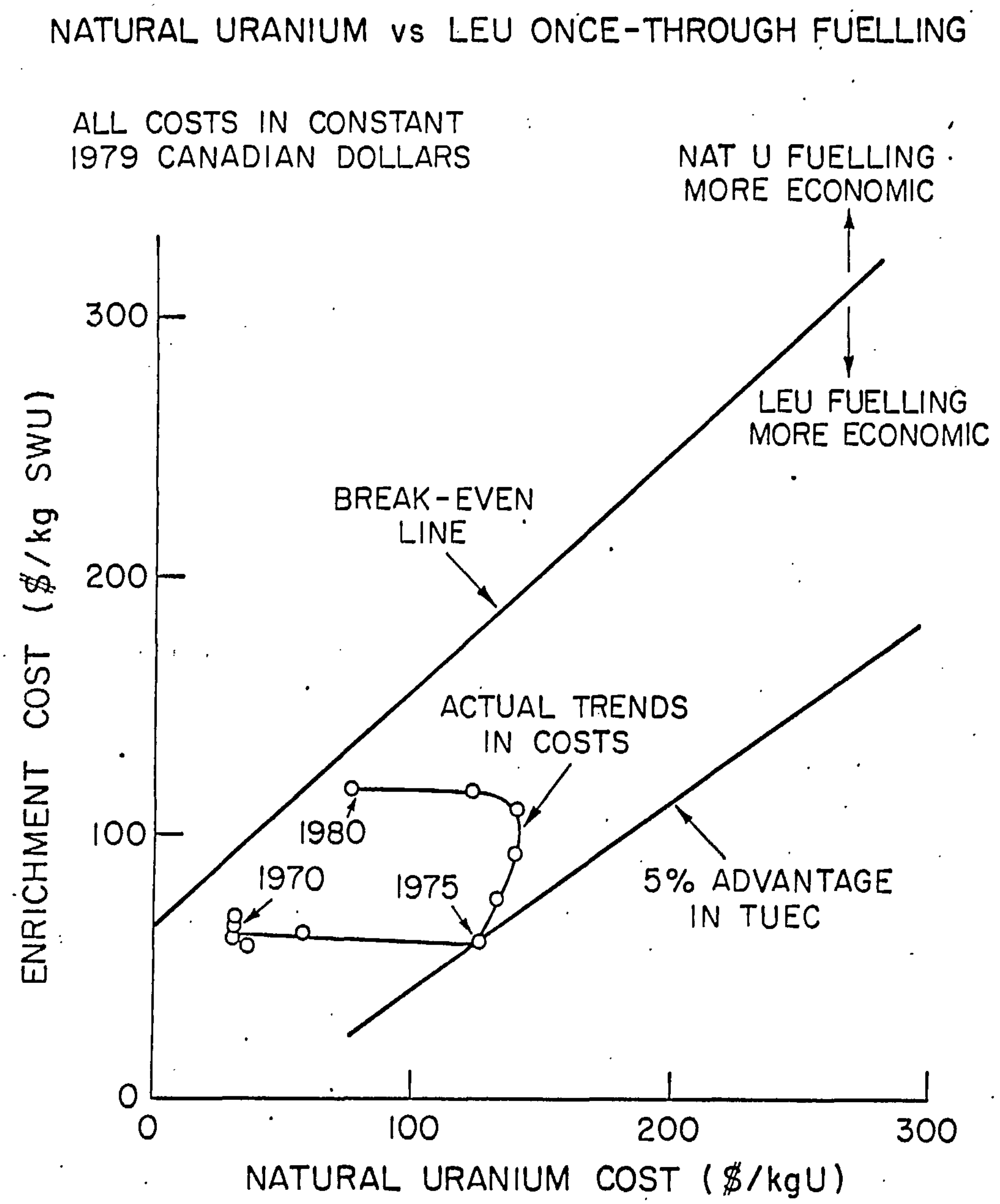

Figure 15 illustrates the impact on TUEC (Total Unit Energy Costs) of changing from natural uranium to LEU once-through fuelling. The break-even line relates the two parameters - a reduced requirement for uranium and a new requirement for enrichment services. Abov the line (higher SWU-Separated Work Units - costs), natural uranium fuelling is more economic; below the line, LEU fuelling is advantageous. Also plotted is a line showing the cost combination which would produce a 5% reduction in TUEC if LEU fuelling were used instead of natural uranium. The trend of world market costs from 1970 to 1980 of natural uranium and enrichment services is also shown (in constant 1979 Canadian dollars).

Source: John B. Slater, 'Potential of Advanced Fuel Cycles in CANDU Reactors', AECL, nd.

future costs of such services must, of course, still be assumed). Basically, as Figure 15 shows, the cost change is a simple trade-off between a reduced requirement for uranium and a new requirement for enrichment services. If uranium costs increase more rapidly than enrichment costs, then the LEU cycle becomes more economically attractive. It appears that the economic incentive to change to LEU fuelling has varied considerably over the past decade and that, in the current situation, an LEU cycle may be competitive with the natural uranium once-through cycle. There is, however, currently little incentive to change and only a sustained long-term increase in uranium prices combined with stable enrichment costs will provide the necessary market conditions. The last few years, however, have seen contrary moves - a significant fall in uranium price and continual increases in the cost of enrichment services - which have reinforced the attractiveness of the natural uranium cycle.[14]

The detailed LEU studies carried out by Ontario Hydro, based on a number of assumptions related to uranium prices, enrichment prices and fuel fabrication costs, indicated that, if LEU were introduced in 1994 and came to comprise all of the nuclear system by the year 2030, then, compared with the natural uranium once-through cycle, there would be expected reductions of 25% in cumulative uranium requirements, 30% in fuelling costs and about 15% in the cost of nuclear generated electricity. Cumulative financial savings to the year 2030, in constant 1982 Canadian dollars, would then be $2.6 billion (under 'base case' assumptions including 85 GW of installed nuclear capacity in 2030) or $1 billion (under 'worst case' assumptions - lower uranium prices and higher enrichment/fuel fabricaiton prices - and a 60 GW nuclear capacity in 2030).[15] These studies therefore concluded that the

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[14] Ibid., p.3.

[15] G.H. Archinoff, Ontario Hydro, 'A Resource Utilization and Economic Assessment of Alternative Fuel Cycles for CANDU-PHW Reactors', a paper presented at the Brussels Nuclear Fuel Cycle Conference, April, 1982.

Figure 16, The Economics of Advanced Fuel Cyles: Impact of Uranium Costs on Total Unit Energy Costs - AECL

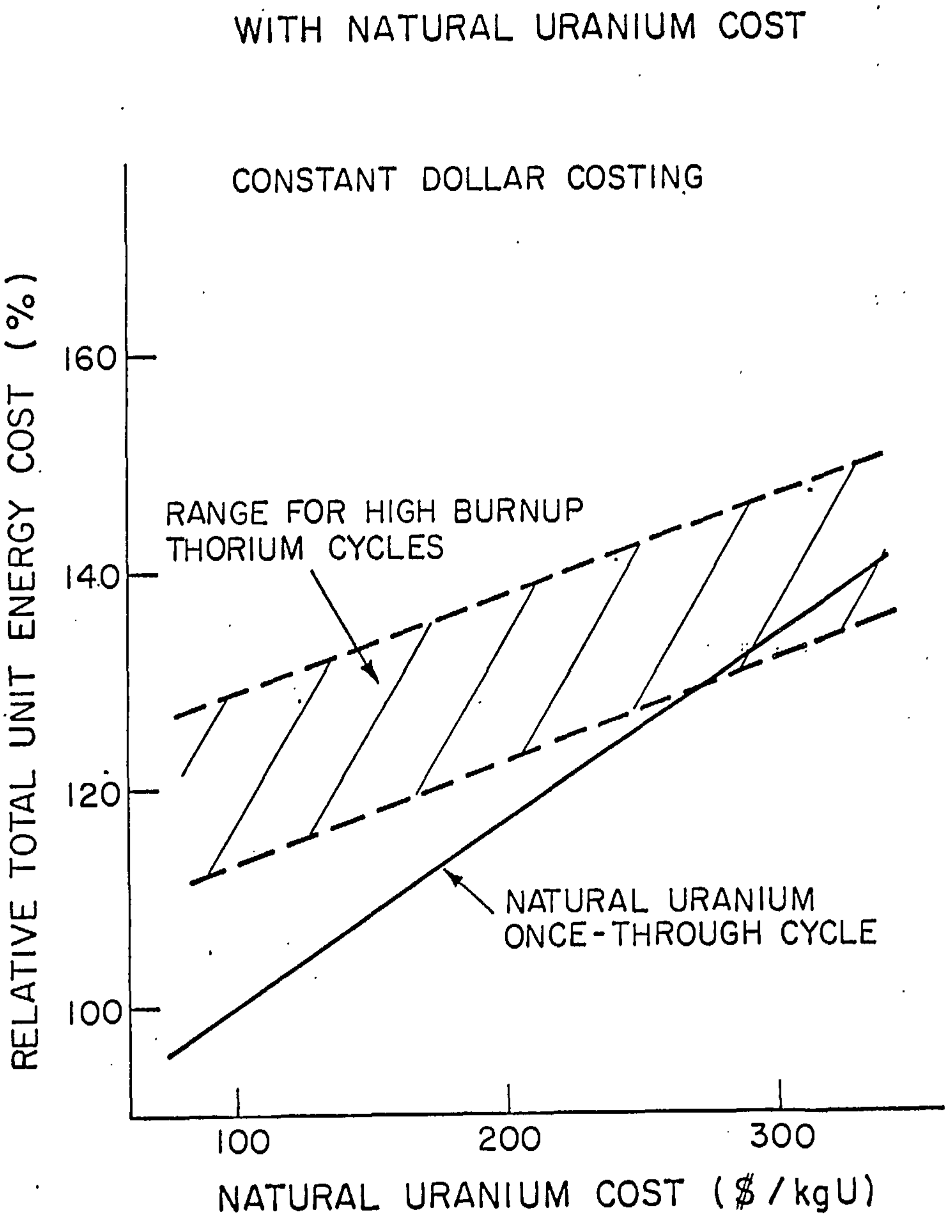

Figure 16 illustrates the impact on TUEC of changing to recycle fuelling, using "best estimate" data. This shows TUEC (Total Unit Energy Cost) as a function of natural uranium cost with the TUEC for the natural uranium once-through cycle normalized to 100% at a natural uranium cost of $100/kgU. For recycle fuelling, the range of costs for the combined reprocessing and refabrication operations has been put in the range $500-100/kg Heavy Element (1979 Canada dollars). This is lower than current commercial prices but is judged reasonable for a large-scale, nature recycle industry dedicated to CANDU technology and taking advantage of future technological innovation and characteristics (e.g., simple CANDU fuel fabrication, co-located facilities). The limits of the range are dictated by costs for thorium recycle initiated by enriched uranium. The costs for plutonium recycle (where plutonium is extracted from spent CANDU fuel) also fall within this band, provided the combined reprocessing-refabrication cost is at the lower limit of its range.

Source: John B. Slater, 'Potential of Advanced Fuel Cycles in CANDU Reactors,' AECL, n.d..

LEU fuel cycle is economically attractive, compared to the natural uranium once-through cycle, and would result in considerable economic savings over time under a wide range of future conditions.

The actual economic impact of changing from a natural uranium once-through fuel cycle to non-LEU advanced fuel cycles involving highly enriched uranium, plutonium, thorium or U233 is, however, more uncertain and tentative. The general cost change here involves a basic trade-off between a reduced requirement for uranium and new requirements for the asociated fuel activities of enrichment, reprocessing, thorium supply and fuel fabrication. To be economically competitive with the natural uranium once-through cycle, then, such advanced fuel cycles would need to achieve a net cost savings from this trade-off, with the trend being for higher uranium prices and lower costs for the associated activities working towards this economic competitiveness.

The necessary operations for enriching, reprocessing and fabricating fuel for such advanced fuel cycles, however, are complex and costly. World experience in building and operating such facilities on a commercial industrial scale is limited and detailed cost experiences are neither extensive nor readily available. Given this situation, estimates of future costs from such large-scale facilities dedicated to CANDU advanced fuels are difficult to make and may differ by a factor of at least 2 or 3.[16]

As Figure 16 indicates, however, the 'best estimate' data available suggests that the TUEC for the CANDU reactor operating on advanced fuel cycles is now about 20-40% greater than that for the natural uranium once-through cycle. With an increasing uranium price, of course, this difference narrows. In the uranium cost range of about $250-300/kg U (4-5 times the current price),

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[16] J.B. Slater, 'Advanced Future Fuel Cycles for CANDU Reactors', AECL, September, 1981, p.6.

the difference disappears and, at higher uranium prices, the advanced fuel cycle becomes cheaper.[17] As previously indicated, however, this uranium price situation is not expected to occur until about at least the year 2020 or 2030, if then. And, moreover, if it does, then the estimated TUEC savings would be relatively small - in the neighborhood of a maximum 12% over the TUEC of a natural uranium once-through (Table 35). Of course, this possible economic attractiveness of advanced fuel cycles would not materialize if future uranium prices were lower and/or if future costs for associated activities were higher (as they may well turn out to be).

It is true, as often stated, that advanced fuel cycles, once established, would show a greater resistance to further increases in uranium prices - i.e., they would reduce the sensitivity of long-term nuclear power costs to further increases in uranium prices. This would only be the case, however, well into the next century - in the post 2030 era - and at the expense of becoming dependent or vulnerable to the costs of the associated fuel activities. Given this situation, it would be exaggerated to claim that these advanced fuel cycles 'will provide stability in long-term (nuclear) costs ... an upper limit to nuclear energy costs' or 'offer the potential of long-term power costs at current constant dollar levels'.[18] What would be basically achieved, however, would be a long-term decoupling of energy prices from resource costs - certainly an attractive feature in an energy technology.

From an economic point of view, it would appear that the plutonium natural uranium re-cycle and the intermediate or high burnup thorium-highly enriched uranium re-cycle may be the optimum advanced fuel cycles. Although SSET cycles have the greatest

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[17] <u>Ibid.,</u> p.6.
[18] <u>Ibid.,</u> p.1, 5 and 6.

potential for reducint uranium requirements they would be decidely more expensive simply because the low fuel burnup involved would require more frequent reprocessing and fuel fabricating and therefore greater costs.[19]

The Ontario Hydro studies previously mentioned have also indicated that, under the 'base case' scenario, advanced fuel cycles such as the Pu-Natural U and the Th-Pu ones may become economically attractive compared to the natural uranium once-through cycle after the year 2020 (Figure 17). However, such cycles would not likely become economically attractive compared to the LEU cycle until at least the year 2040 and, moreover, by the year 2050 would at best only achieve a TUEC savings over the LEU of about 2 mills $/kWh or some 10% .

This situation, however, is naturally quite sensitive to the nuclear growth rate and the assumptions concerning the prices of uranium, enrichment, reprocessing and fuel fabrication. For a low nuclear growth of 60 GW(e) of nuclear capacity in 2030, for instance, there is no economic incentive to develop a more advanced fuel cycle than the LEU. Uranium prices must be greater than those assumed for a low nuclear growth case to warrant the superceding of the LEU cycle by a more highly uranium conserving advanced fuel cycle. Thus, the need for a thorium or plutonium re-cycle to replace the LEU cycle would occur only under specific conditons, namely, high nuclear growth and high uranium prices. Even under such favourable circumstances, however, higher reprocessing, enrichment or fabrication costs could eliminate this economic incentive for introducing such fuel cycles after the LEU. Thus, the optimum path for economic savings over the long-term begins with the introduction of the LEU cycle - if this proves advisable - and, perhaps sometime after 2040 under very favourable conditions, a transition to the more advanced fuel cycles involving plutonium or thorium.

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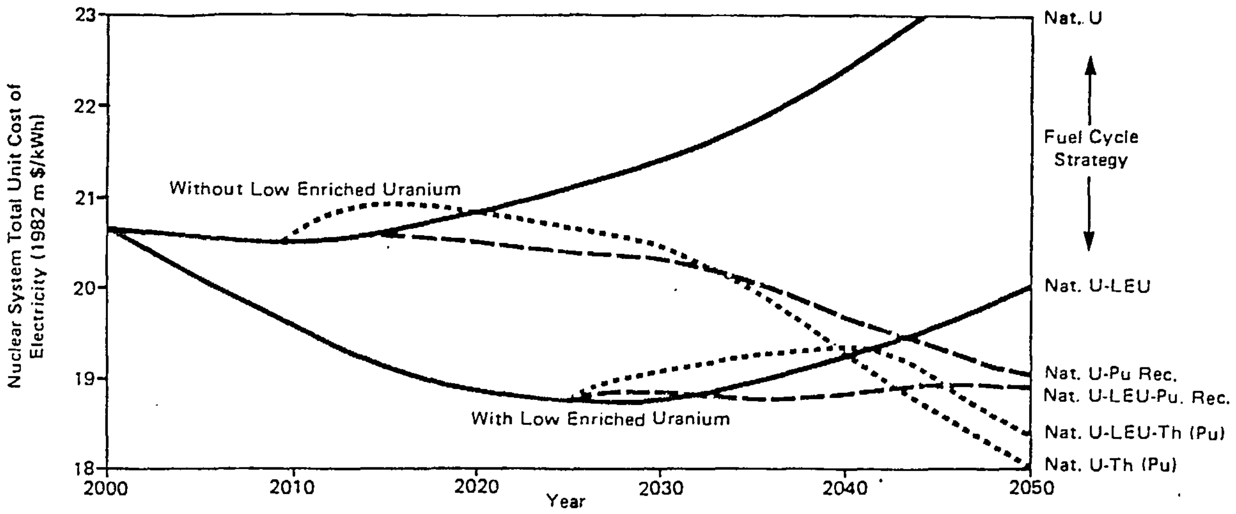
[19] Ibid., p.5.

Figure 17. Economic Assessment of Advanced Fuel Cycles - Ontario Hydro



Source: G.H. Archinoff, Ontario Hydro, 'A Resource Utilization and Economic Assessment of Alternative Fuel Cycles for CANDU-PHW Reactors', a paper presented at the Brussels Nuclear Fuel Cycle Conference, April, 1982.

Note: This economic assessment of advanced fuel cycles represents Ontario Hydro's 'base' nuclear power growth case and the following base assumptions (constant 1982 dollars):

Installed Nuclear Capapcity GW(e): 31 in 2000; 85 in 2025; 160 in 2050.

Fuel Cycle Introduction Dates: 1994 for LEU and as shown in Figure for others.

Uranium Prices ($/kgU): $132 in 1985; $295 in 2020; $345 in 2030; and $405 in 2040.

Uranium Enrichment Prices ($/SWU: $156 in 1985; $165 in 2000; $140 in 2020; and $110 in 2040+.

Fuel Fabrication Prices ($/kgHE depending on plant size):

Nat. U	-	$ 49- 80
LEU	-	$ 68-105
Pu-Recycle	-	$135-185
Th(U), Th(Pu)	-	$295-455

Fuel Reprocessing Costs ($/kgHE depending on plant size):

$(U,Pu)O_2$	-	$ 92-221
$(Th,U,Pu)O_2$	-	$110-264

Conclusions

From the above economic analysis, the following conclusions can be drawn:

(1) Since fuelling costs now represent only a relatively small part of the Total Unit Energy Cost (TUEC) of a natural uranium fuelled CANDU reactor, a four-fold constant dollar increase in the current uranium price (not likely until at least the year 2020 or even well beyond) would by itself only result in a 20% increase in the CANDU TUEC. This increase would still make the CANDU TUEC more economic than the current coal TUEC.

(2) Since capital costs now amount to a much greater proportion of the TUEC of a natural uranium fuelled CANDU than do fuelling costs (the opposite situation from that of the coal TUEC), increases in capital costs are more important than increases in fuelling costs in determining the future level of CANDU TUEC. Capital cost increases in only the last few years have increased the CANDU TUEC more than would a four-fold increase in current uranium prices over the next four decades.

(3) To become eocnomically attractive compared to the natural uranium cycle, advanced fuel cycles must achieve sufficient reductions in the fuelling cost component of the CANDU TUEC. This would result from a favourable cost trade-off between the reduced uranium requirements and the additional associated fuel activities of reprocessing, enrichment and fuel fabrication.

(4) A LEU fuel cycle may now be almost economically attractive compared with the natural uranium cycle. A LEU cycle could result in a 15% cost savings in nuclear generated electricity

and could (under a wide range of future conditions including unfavourable ones such as low nuclear power growth, low uranium price increases and high enrichment/fuel fabrication costs) result in economic savings which Ontario Hydro has estimated to be $1 to $2.6 billion by the year 2030.

(5) The TUEC for thorium or plutonium advanced fuel cycles are now about 20-40% greater than that for the natural uranium cycle and will only become economically competitive if the uranium price increases to 4 or 5 times the current price level in constant dollar terms - a situation that will likely not develop until at least the year 2020 or so. Higher costs for the associated activities of reprocessing enrichment and fuel fabrication involved in such advanced fuel cycles would undermine this possible economic competitiveness, as would also a lower nuclear growth and lower uranium price increases.

(6) Advanced fuel cycles based on thorium or plutonium will likely not become economically attractive compared to the LEU cycle until at least the year 2040 and then only under specific conditions of high nuclear growth, high uranium prices and stable or modest cost increases in the associated fuel activities.

(7) From a strictly economic point of view, therefore, there seems no compelling reason to introduce any advanced fuel cycles based on thorium or plutonium for at least the next three or four decades and, if the LEU cycle is already present at that time, for at least another quarter of a century after that.

3. Technical Status and R,D&D Requirements

The technical feasibility of using advanced fuel cycles in the CANDU reactor is considered to be at a high level of confidence.

The technical availability of such fuel cycles for actual commercial implementation, however, will require an extensive developmental program of R,D&D. This is described briefly below in the major areas involved.[20]

Reactor Design

The expectation is that the basic CANDU reactor design and operating procedures for the natural uranium once-through cycle will be almost identical to that needed for advanced fuel cycles. Since such cycles could apparently be used directly in the existing CANDU reactor concept with only limited modifications, no major changes and no large reactor development program would be needed. This would be in sharp contrast to other countries which have based their nuclear programs on the light water reactor and which must develop the fast breeder reactor, a completely different reactor concept, to achieve significant uranium fuel savings.

Nevertheless, some modifications requiring developmental work will be necessary in a number of areas: fresh fuel handling and storage, spent fuel management, channel power peaking and bundle shifts, control and safety mechanisms, and instrumentation systems. Such changes, however, are expected to be relatively straightforward and basically an extension of existing technology and past experiences.

The operational character of a CANDU reactor fuelled by a LEU

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[20] For more details, see, in particular:
AECL, 'Data Base for a CANDU-PHW Operating on a Once-Through, Slightly Enriched Uranium Cycle', July, 1979;
AECL, 'Data Base for a CANDU-PHW Operating on the Thorium Cycle', July, 1979;
J.B. Slater, 'Advanced Future Fuel Cycles for CANDU Reactors', AECL, September, 1981;
Penn and Meneley, 'Alternative Fuel Cycles: Which Options to Develop?', Ontario Hydro, May, 1979.

cycle can be predicted with confidence and, with only slightly less assurance, so can the Pu re-cycle. For thorium fuels, however, reactor physics codes have not been thoroughly validated and there is less confidence in the achievable burnup, probably more serious power-peaking problems and possibly greater reactor control problems.

Fuel Design

Initial studies and accumulated experience have indicated that no major fuel design changes will be required. The same short, multi-element bundle is considered adequate even for high burnup performance. An extensive fuel irradiation testing program, however, will be needed to verify the actual fuel performances, including irradiations at different fuel burnups and measurements of fuel behaviour. In particular, existing uncertainties related to the physics of thorium will require attention and experimentation.

Enrichment

Certain advanced fuel cycles would involve the use of enriched uranium - either low, medium or highly enriched U235. Uranium enrichment is commercially established with four major world suppliers (the USA, France, Britain and the USSR). Such enrichment facilities are large, expensive and complex establishments. Since Canada has no enrichment experience or expertise, a large R,D&D program would be required to provide a domestic enrichment facility - even if the necessary technology could be purchased abroad. The LEU cycle with only 1% U235 would require relatively small SWU (separative work units) requirements compared to the thorium cycles with about 92% U235.

Reprocessing

All Pu and Th re-cycles would require the commercial development of reprocessing technology to recover the Pu, Th and U233 from spent fuel bundles. There are now no commercial facilities available for reprocessing CANDU fuel and very few around the world which can reprocess the Pu from other reactor fuels. A substantial development program would be required before a CANDU reprocessing capability could be commercially achieved. Of course, no commercial thorium fuel reprocessing plants exist anywhere in the world and Canadian experience is limited to the laboratory scale with a small facility - the Thorium Fuel Reprocessing Experiment - at AECL's Whiteshell Nuclear Research Establishment. Although much of the technology required for Th fuel reprocessing is very similar to that already established for uranium fuels (the PUREX process), there are significant differences in the chemistry of the solvent extraction process. Attention has been focussed on developing the THOREX process (originally developed for U-Th fuels) into the MODIFIED THOREX process which is capable of separating the components of irradiated U-Pu-Th fuels. A substantial R&D program would be required in this field, followed by pilot and demonstration plants. A LEU cycle, of course, would require no reprocessing at all.

Fuel Fabrication

Given the associated alpha and gamma activity of Pu and Th fuels, active fuel fabrication would be necessary. There is now only a glove-box laboratory facility - the Recycle Fuel Fabrication Laboratory - at AECL's Chalk River research establishment for fabricating Pu bearing CANDU fuel. Since the existence of toxic Pu requires total containment in the fabrication process, major differences from the existing natural uranium fabrication would be required to produce Pu fuels. Since U232 involves highly energetic gamma activity, the fuel fabrication process for thorium fuels would need to be not only contained but also heavily shielded with provision for remote robotic operation and maintenance of equipment mandatory. Conceptual design studies of such a plant have concluded that its design and operation using currently available technology was both feasible and economical.

Although the reference route is considered to be the sintered pellet fuel produced from mixed heavy element oxides, other processes may be adopted to remote fabrication - impregnation of thoria pellets with uranyl nitrate before sintering, extrusion and spherepac processes. Such alternative possibilities would have to be investigated further.

In contrast to the Pu-Th cycles, however, the fuel fabrication lines presently being used in Canada to produce natural uranium fuel are capable of processing the LEU cycle's uranium fuel enriched to 1% U235.

Electronuclear Breeding

Electronuclear breeding is the electrically driven process to generate a source of neutrons other than from nuclear reactors that can be used to convert fertile material (U238, Th232) to fissile material (Pu239, U233). In other words, fissile material is created away from a nuclear reactor but is used as a fuel in a nuclear reactor operating on an advanced fuel cycle. As an option to ensure and extend the fissile fuel supply required by advanced fuel cycles, electronuclear breeding, either in the form of accelerator breeding involving the spallation process or fusion breeding, could be a future alternative fissile source. Electronuclear breeding could thus play an important future role as a long-term, fissile production support option for advanced fuel cycles.

Such a capability may be warranted or become necessary sometime in the next century if shortages of fissile uranium or reprocessed plutonium develop and if the fast breeder and stand-alone fusion reactors are not forthcoming. Advanced fuel cycles could then rely on electronuclear breeding.

AECL is currently conducting a relatively minor R&D program in electronuclear breeding, primarily in accelerator breeding which appears at this point to have a distinct edge over fusion breeding in terms of scientific feaibility, closeness to engineering practicality and economic attractiveness. Plans have been formulated to expand this program over the long-term to encompass larger and costly facilities and research.

Thus, in assessing advanced fuel cycles, one must include the possible R,D&D requirements of an electronuclear breeding program to develop an alternative supply source of fissile material. Such a program would not, however, be necessary or warranted under the LEU cycle.

Safety

In terms of reactor safety, an advanced fuel cycle is expected to be quite similar to the existing natural uranium once-through cycle. An advanced fuel cycle could likely be introduced into the basic CANDU reactor without seriously compromising or undermining the safety standards, controls features and practices that already exist and are in place. No significant new feasibility questions or difficulties related to reactor safety have arisen to date and none are foreseen. Advanced fuel cycles involving Pu and Th will, however, necessitate remote fueling, active fuel fabrication, transportation and storage - all activities with real safety concerns that will need to be appropriately controlled and regulated by AECB. Certainly these and other safety related matters will have to be thoroughly investigated in any R&D program in order to ensure that the use of advanced fuel cycles will pose no real safety problems compared to the natural uranium once-through cycle.

Environment

Advanced fuel cycles will likely not, general speaking, be greatly different from the natural uranium once-through cycle in terms of its environmental impacts and waste problems. The International Nuclear Fuel Cycle Evaluation Report, for instance, concluded that the radioactive wastes of the advanced fuel cycles it studied could, like the current fuel cycles, be managed and disposed of with a high degree of safety and without undue risk to man or the environment. This was not considered to be a decisive factor in choosing among the fuel cycle possibilities.

Nonetheless, advanced fuel cycles using Pu or Th would entail certain additional environmental considerations. Although reprocessing would not add to the total burden of radioactive wastes on the environment, it does create waste by-products which are highly radioactive and which must therefore be carefully managed and immobilized prior to disposal. Certainly one important aspect of any R&D program to develop advanced fuel cycles would be to pay proper attention to the environmental aspects involved; and the current waste disposal R&D program would need to be able to accommodate the particular wastes resulting from such cycles. The actual operation of an advanced fuel cycle and its associated reprocessing and fuel fabrication technologies would, of course, need to meet the appropriate standards and procedures as established by the AECB.

In one sense, though, an advanced fuel cycle may be an environmental plus since, if obtaining more power per kg of uranium means less uranium needs to be mined, the production of low-level mine-mill wastes could be correspondingly reduced. A LEU cycle, of course, would not involve any additional environmental strains that a Pu or Th cycle might incur.

In summary, then, although the technical feasibility of advanced fuel cycles is considered to be quite high, they would require an extensive, long-term development program of R,D&D in many areas before they could become technically available for actual commercial introduction and use. It has been estimated that, given the past experiences and current efforts by AECL in this area, such a fuel development program would take about 20-25 years at a total cost of approximately $1.5-2 billion.[21]

Conclusions

Based on the above analysis of the technical status and R,D&D requirements involved in advanced fuel cycles, the following conclusions may be reached:

(1) From experiences to date and current assessments, the technical feasibility of using advanced fuel cycles in the CANDU nuclear reactor is considered to be high.

(2) It is anticipated that the basic, existing CANDU reactor design concept would be suitable, with only certain modifications, to using advanced fuel cycles. Since the changes would not be major, there would be no need for a large reactor development program, as is the case for the fast breeder.

(3) On the other hand, the use of advanced fuel cycles would require a substantial development program of R,D&D in the new associated areas such as enrichment, reprocessing and active fuel fabrication (and possibly electronuclear breeding).

(4) Because of the presence and use of Pu and U233, advanced fuel cycles may involve possible additional problems related to safety, the environment and non-proliferation. Such problems are not, however, expected to pose insurmountable difficulties but will need to be properly identified,

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[21] For more details and an illustrative work plan with time frames and funding levels, see Science Council of Canada, Roads to energy Self-Reliance: The Necessary National Demonstrations, Report No. 30, June 1979, p.140-143.

evaluated and remedied in an R,D&D developmental program.

(5) It has been estimated that a full developmental program for Pu and Th advanced fuel cycles - to demonstrate their technical feasibility at a high enough level of assurance for commercial introduction - would take about 20-25 years at a total cost of approximately $1.5-2 billion.

(6) It is therefore anticipated that such advanced fuel cycles would not be technically available for actual commercial introduction or implementation until at least the first few decades of the next century.

(7) The LEU fuel cycle has certain definite advantages over the Pu and Th fuel cycles. It is technically simpler, being a much more straightforward extension of the natural uranium once-through cycle. It uses only slightly enriched uranium - not highly enriched uranium, plutonium or thorium. It does not require the associated activities of reprocessing or remote fuel fabrication (or, in the future, possibly electronuclear breeding). Due to the absence of Pu and Th and their associated activities, it would be environmentally less complicated and hazardous; pose fewer safety difficulties; and contain certain non-proliferation advantages. It would not require a costly and long-term R,D&D developmental program but could, following a modest and short R&D effort, be introduced into a CANDU reactor within a decade. Its technical development and implementation could act as a valuable technological bridge to the longer-term, more complicated advanced fuel cycles involving Pu and Th. On the other hand, the LEU would need a low enriched uranium supply (either from abroad or within Canada).

4. Non-Proliferation

All commercial nuclear power reactor systems generate varying quantities and qualities of plutonium and the conventional reprocessing of irradiated fuel from such systems can lead to the separation of pure plutonium appropriate for use as a nuclear weapons material. The possibility of using uranium enrichment facilities to produce highly enriched U235 as a weapons material rather than as a reactor fuel has also been acknowledged. The CANDU nuclear reactor operates under a strict safeguards and regulatory system that minimizes the risks of nuclear weapons proliferation.

The International Nuclear Fuel Cycle Evaluation Report[22] studied the proliferation aspects of advanced fuel cycles and reached a number of conclusions: there is no totally proliferation proof fuel cycle; no magic technical fix exists to eliminate completely all proliferation risks; proliferation is basically more of a political than a technical problem; and non-proliferation will depend more upon international agreements and arrangements than upon the particular technological fuel cycle employed.

The INFCE Report did indicate, however, that a number of specific improvements might be instituted to lessen the proliferation risks involved. Besides improved safeguards systems and institutional arrangements, such possible improvements could include technical measures such as the co-location of reprocessing and fuel fabricating facilities to minimize the transfer of fissile material; co-processing such that in reprocessing what is recovered is a fissile-fertile mixture, i.e., fissile Pu or U233 is left associated with non-fissile material such as Th rather than as separated substances, thereby making further chemical

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[22] International Nuclear Fuel Cycle Evaluation (INFCE) - Summary Volume, IAEA, March, 1980.

separation to produce weapons-grade material necessary; isotope dilution; radioactive protection; and physical barriers.

It will certainly be necessary in an advanced fuel cycles development program to identify and assess those critical points that are sensitive from the proliferation point of view: uranium enriching, reprocessing and fuel fabricating, the fuel use in the reactor, fuel storage and disposal, and fuel transportation. Any necessary measures to minimize the proliferation risks or dangers involved would be required, along with the proper regulatory standards and controls. Given this focus, it is anticipated that an advanced fuel cycle should not or at least need not be any more proliferation conducive than the existing natural uranium once-through cycle.

A denatured uranium-thorium cycle may be the most proliferation resistant cycle. Although plutonium production is not eliminated totally, it is reduced by orders of magnitude and does not appear in the active processes involved. In addition, the uranium used would be in an isotopic composition that is not directly weapons-usable material since the U235 and U233 are diluted with non-fissile U238. An isotopic separation would then be necessary to obtain weapons-usable material.

A LEU cycle would use fresh fuel that is 1.2% enriched U235 and hence not directly usable for nuclear weapons. Although plutonium is still present in the LEU spent fuel, the amount is relatively small (6g/kg Heavy Element), the isotopic composition is not ideal (35% Pu 240), and the fuel is initially highly radioactive with a relatively slow decay. All these factors would make the separation of plutonium for weapons use relatively unattractive, thereby giving the spent fuel a low vulnerability to theft or seizure. Thus, the LEU fuel cycle would appear to have certain advantages in the non-proliferation area compared to Pu and Th cycles or even the natural uranium once-through cycle.

5. Nuclear Exports

Advanced fuel cycles in the CANDU reactor may have certain impacts on Canada's nuclear exports of uranium and CANDU reactors. A brief asessment of these likely impacts is provided below.

Uranium

It has been asserted that the use of advanced fuel cycles in the CANDU reactor would improve the Canadian uranium export situation. Through better uranium utilization, advanced fuel cycles would achieve uranium savings over the natural uranium once-through cycle. Because less uranium for the domestic requirements of the Canadian nuclear power program would be necessary, the uranium so saved could be made available for export to countries around the world to fuel their nuclear programs. This will be particularly important if a worldwide uranium supply/demand inbalance were to develop shortly after the turn of the century. In such a situation of supply falling short of demand, Canada, with its major uranium resources, will be called upon to meet this world demand. Thus, advanced fuel cycles would enable Canada to better play its role as a prime uranium exporting country.

This uranium export argument is not a strong or convincing one for a number of resons. Given the relatively minor nuclear power program in Canada now and for the foreseeable future, and also given the relatively small domestic uranium requirements that such a program would entail, it is reasonable to expect that Canadian uranium production will remain overwhelmingly geared to serving foreign markets. Based on its large uranium resource base and the likely additions to this base that are possible over time, Canada should be able to maintain and, if called upon by the world marketplace, to improve its position as a uranium exporter.

It is true that the maximum cumulative uranium savings associated with advanced fuel cycles over time are impressive: 200,000 tonnes U by 2030, 300,000 tonnes U by 2050 and 650,000 tonnes U by 2075. This is especially so when viewed in light of the 5,400 tonnes U exported by Canada in 1980! It should, however, be noted that these are the maximum savings possible under the best uranium conserving advanced fuel cycle and based on a high nuclear growth rate that is less than likely. Even so, the maximum savings by 2050 -- almost 80 years from now -- would only be equivalent to the net uranium resource additions made in the 6 year period from 1974 to 1980. It is not at all clear that, if such savings from Canada over time are in fact necessary to meet future world demand, advanced fuel cycles are the optimum route over simple resource additions from exploration efforts. In this case "adding more" might be easier, quicker and cheaper than "using less".

Moreover, it is far from certain that a worldwide uranium supply/demand imbalance will necessarily develop early in the next century, resulting in a greater demand for Canada's uranium resources and the need for such uranium savings. The current nuclear growth forecast may still be quite optimistic, as they have been in the past, and a significantly lower nuclear growth may well be realized. This would result in an easing of the future uranium demand pressures. In addition, it would certainly be unrealistic to expect that only the currently known uranium resource base will be available to meet whatever long-term uranium needs develop. If a uranium supply problem becomes apparent or imminent, this would result in greater exploration efforts.

Thus, the actual uranium savings resulting from the use of advanced fuel cycles in the CANDU reactor will likely not be as much as expected; could probably be obtained through an expanding uranium resource base in the future; are not essential for Canada to maintain and even to improve its position as a uranium exporter; and may not be needed to alleviate a world supply shortage shortly after the turn of the century, since such a shortage may well not actually develop. In short, the argument of supposed benefits from advanced fuel cycles on Canada's uranium export situation in the future should be seriously questioned if not considered to be doubtful at best.

CANDU Reactors

It has also been argued that the use of advanced fuel cycles in the CANDU rector would improve the prospects of selling the CANDU reactor on the world market. An advanced fuelled CANDU reactor, with its greater uranium utilization and its closure of the now open fuel cycle, would be appealing to potential reactor customers around the world who are concerned about the future security of their uranium supply and who would therefore prefer adopting a reactor with lower uranium requirements. An advanced fuel cycle would therefore enhance Canada's reactor sales opportunity around the world.

To date the CANDU has been unable to make a significant penetration into the world nuclear reactor market since its main competitor, the light water reactor, has accounted for about 95% of all world reactor exports and remains the dominant reactor technology in the world. Although several CANDU prospects do exist, the reactor market is shrinking with the nuclear downturn and the competition for these limited sales possible is becoming extremely fierce. The recent Mexican experience amply supports this view.

Within this context, it would appear that technically improving the CANDU reactor by using an advanced fuel cycle would only at best marginally enhance its sales attractiveness. It has of course been repeatedly stressed that the CANDU is a better reactor technically than the light water alternative -- in terms of less uranium requirements as well as no need for enrichment, better performance and reliability records, on-power fuelling, etc. A recent study has indicated, however, that when a country is

Table 36. Canadian Export Sales of the CANDU Reactor

Reactor	Country	Power MWe net	In-Service Date
CIRUS	India	20	1967
RAPP	India	2 x 200	1972
NRX type	Taiwan	20	1971
KANUPP	Pakistan	125	1971
CORDOBA	Argentina	600	1983
WOLSUNG	Korea	600	1982
CERNAVODA	Romania	2 x 600	1987-88

Source: AECL

deciding between available competing nuclear reactor technologies, such technical considerations are generally not the decisive criterion and are in fact significantly less important than the key factors of the credibility of the supplier, intergovernmental relations and marketing strategy.[23] Indeed, another recent study reached a similar conclusion in assessing the importance of CANDU's better uranium utilization feature in the export market: 'The argument that natural uranium use is a major CANDU selling point due to greater self-sufficiency, while certainly valid in some cases, is not very strong. The 'technological' market for CANDU is small ... CANDU's use of natural uranium is advantageous in few markets'.[24]

A CANDU reactor operating an advanced fuel cycles would not be available for export until at least the year 2020 or 2030. By that time, there may be little if any real market for the CANDU to realize and, if there was, then an advanced fuelled CANDU would probably be competing with a fast breeder reactor and/or a fusion reactor -- alternatives that would be enormously more attractive in terms of uranium utilization.

It is true that current and potential customers for nuclear reactors are concerned about the uranium supply situation and are interested in new reactor technologies that promise to achieve significant uranium savings and fuel independence. However, given the predominant position of the light water reactor technology in the world, the future development that is being looked to in this regard by virtually every nuclear country is the fast breede reactor. The actual commitment and confidence in the fast breeder as the future nuclear technology to develop dwarfs any possible interest that might be expressed from time to time in considering the advanced fuelled CANDU alternative.

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[23] Woods Gordon, The Canadian Nuclear Industry's Marketing Performance, EMR, November 1980, p.1-2.

[24] Secor, A Strategy for the Development and Strengthening of the Canadian Nuclear Industry, March, 1981, p.23, 29.

On the other hand, there may be some marketing benefits to be gained in the near future if a Canadian development program on advanced fuel cycles were well in place. Evidence of such work would demonstrate a confidence on the part of Canada in the long-term future of CANDU; an indication that the CANDU is being developed into a better, more attractive reactor sales package; and an alternative long-term possibility for the world to the fast breeder/fusion reactors should they fail to become technical or economic realities.[25] The existence of such a development program, however, would realistically be able to have only a very modest contribution to make to enhancing the prospects for CANDU export sales.

Conclusions

From the above analysis, the following conclusions may be reached:

(1) It is very doubtful that advanced fuel cycles in the CANDU reactor would achieve significant benefits for Canada's uranium and reactor exports. The real benefits that might accrue would likely be relatively small, at least over the next few decades.

(2) In terms of uranium exports, Canada should be able to maintain and to improve its position as a leading world uranium suppier in the future without advanced fuel cycles. The likely cumulative uranium savings from advanced fuel cycles could probably be obtained through an expanding uranium resource base in the future. The size of the future export market is far from certain since it is not inevitable by any means that a world supply shortage will in fact

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[25] Woods Gordon: p.7, 31 and 47; Secor: p.44

materialize shortly after the turn of the century.

(3) In terms of reactor exports, Canadian sales opportunities will remain limited in the current and foreseeable world market of few orders and fierce competition. Technically improving the CANDU reactor through advanced fuel cycles would be far less important in enhancing Canada's export position than would a number of other factors. Almost all countries concerned with the future uranium supply situation and interested in new technology improvements are looking to the future development of the fast breeder reactor rather than to the advanced fuelled CANDU reactor. The existence of a development program on advanced fuel cycles in Canada would provide some confidence and hope for the future possibility of the CANDU reactor but this would make only a very modest contribution to strengthening Canada's reactor export prospects.

6. Public Acceptability

By the time that advanced fuel cycles could become technically available -- 2020 or 2030 -- the nuclear power situation as a whole will have been become considerably clearer. By that time, depending on the energy situation and the available energy alternatives, nuclear power will have been either widely accepted as a necessary or desirable energy technology or rejected as an unnecessary or undesirable one. In the former case, the possible introduction of advanced fuel cycles will be publicly more acceptable; in the latter situation, of course, any such introduction would not occur. As previously pointed out, the future development of nuclear power will be determined by a variety of factors but will largely depend upon the evolution of public attitudes, and the eventual determination as to the need, risks and economics of nuclear power in relation to other available and competing energy technologies.

It is clear, however, that for advanced fuel cycles to ever become publicly acceptable, the many aspcts of their use relating to the environment, waste disposal, safety and non-proliferation will have to be fully demonstrated and proven to entail no significant hazards or risks to society. Advanced fuel cycles will also have to be shown to be economically competitive and attractive compared to the natural uranium once-through CANDU cycle, to the available non-nuclear energy technology alternatives, and to the foreign nuclear alternatives such as the fast breeder and fusion reactors which may be available in the first half of the next century. Moreover, the domestic electrical utilities in Canada, who will, after all, be the actual customers or users of such advanced fuel cycles, must also accept them.

Although in the current nuclear debate around the world there has been strong opposition from anti-nuclear groups and other participants to the development of a 'plutonium economy' involving reprocessing, or of a fast breeder reactor, in Canada the advanced fuel cycles issue has received relatively little public attention. There have been a number of reasons for this: only a rather minor, laboratory scale research effort has been undertaken to date; other nuclear issues such as reactor safety, waste disposal, export sales and non-proliferation have predominated; and the current slowdown in the nuclear industry and in nuclear growth has had a dampening effect. This situation could, however, change considerably if a substantial advanced fuel cycles program were undertaken. Serious questions and criticisms could expect to be raised in a number of ways. This could take many forms but would likely focus on the need for such a costly effort at a time of economic troubles and fiscal restraints; for such a long-term endeavour when other energy R&D pursuits might provide shorter-term payoffs in meeting more immediate energy problems; for such uranium savings when Canada is so amply endowed with an abundance of uranium resources, far in excess of its future domestic requirements; and for such a program at a time when the very future of the nuclear industry and nuclear power development in Canada is in serious jeopardy. It will no doubt be pointed out that even Ontario Hydro, the major future user of any advanced fuel cycle, may in principle support such a development program but does not intend to support it in practice through significant contributions of its own money and time.

It should be noted here that the LEU fuel cycle would appear to have quite favourable benefits in terms of public acceptability as compared to the Pu or Th advanced fuel cycles. It is the simplest and most straightforward extension of the existing natural uranium once-through cycle; would not therefore require the highly enriched uranium, Pu or U233 and their associated reprocessing and active fuel fabrication processes; and would entail less difficulties in terms of environmental, safety and non-proliferation hazards. Moreover, a LEU development would not require a long-term and expensive R,D&D program. Indeed, studies done by Ontario Hydro have indicated that, if it did decide to favour an advanced fuel cycle, Ontario Hydro would first prefer the LEU cycle over any other one.

In short, a development program in advanced fuel cycles could become a source of controversy in the Canadian nuclear debate, with public acceptability of such a program uncertain at best. Developing the LEU fuel cycle, however, would probably be subject to less public criticism, more public acceptability and greater utility interest than would developing other advanced fuel cycles.

7. Conclusions

From the preceding assessment of CANDU advanced fuel cycles, the following conclusions can be reached:

(1) Advanced fuel cycles in the CANDU reactor have the potential to achieve lifetime natural uranium requirements that are 20% to 70% those of the existing natural uranium once-through cycle, with the most uranium conserving cycles involving

thorium. The maximum uranium savings of advanced fuel cycles over the natural uranium once-through cycle by 2075 would be about 57% -- the equivalent of about two-thirds of the currently known uranium resource base or about twice the total net additions to this base from 1974 to 1980. The low-enriched uranium (LEU) fuel cycle by itself, however, could achieve one-half of these maximum cumulative uranium savings by 2075. Furthermore, no significant long-term uranium savings benefit would accrue from either foregoing the earlier introduction of the low-enriched fuel cycle or introducing the plutonium or thorium recycles at the earliest time possible.

(2) Even under a high nuclear growth forecast, with no advanced fuel cycles development, and with no further uranium resource additions at all by 2075, the currently known uranium resource base in Canada would still be sufficient to meet almost all of the domestic cumulative uranium requirements of a natural uranium fuelled CANDU system by 2075. Since it is more than likely that a lower nuclear growth and future uranium resource additions will be realized, Canada's uranium resources will be more than adequate to serve its domestic nuclear needs based on the existing fuel cycle for over a century, and to meet, as well, significant export demand.

(3) Although advanced fuel cycles for the CANDU reactor represent an attractive proposition from the uranium conserving point of view, they are not an urgent or compelling necessity for Canada from the more important standpoints of uranium resources and domestic nuclear requirements over even the very long-term. The introduction of advanced fuel cycles is therefore neither demanded nor warranted by the uranium resource situation alone.

(4) Since the CANDU's Total Unit Energy Cost is much more capital cost intensive than it is fuel cost intensive, it is more

sensitive to small increases in capital costs than to large increases in uranium prices. To become economically attractive compared to the natural uranium cycle, advanced fuel cycles must achieve a substantial reduction in the fuelling cost component.

(5) A LEU fuel cycle may now be economically competitive compared to the natural uranium cycle and could result in time in a 15% nuclear electricity cost savings. The thorium or plutonium fuel cycles are now about 20-40% more expensive than the natural uranium cycle and will only become economically competitive if the uranium price rises to four or five times its current level -- a situation that will likely not develop until at least the year 2020 or so. Such advanced fuel cycles will likely not become economically attractive compared to the low enriched fuel cycle until at least the year 2040. Moreover, this would occur only under specific conditions of high nuclear growth, high uranium prices and stable or modest cost increases in the associated fuel activities of reprocessing, enrichment and active fuel fabrication.

(6) From a strictly economic point of view, therefore, there will likely be no reasonable incentive to introduce a thorium or plutonium advanced fuel cycle for at least four decades from now and, if the low-enriched cycle were already present at that time,for at least another quarter of a century after that.

(7) Although the technical feasibility of advanced fuel cycles is considered to be high, and although the basic, existing CANDU reactor design concept would, with certain modifications, be suitable for using advanced fuel cycles, a substantial development program of R,D&D would be required in the new associated areas of enrichment, reprocessing and active fuel fabrication (and possibly electronuclear breeding), and in

such important areas as safety, the environment and non-proliferation. It is estimated that such a development program would take about 20-25 years at a total cost of approximately $1.5 - 2 billion.

(8) The LEU cycle has several technical advantages over the plutonium and thorium cycles. Since it is technically simpler and uses only slightly enriched uranium, it does not require highly enriched uranium, plutonium or thorium. It would therefore neither require the associated activities of reprocessing and active fuel fabrication (and, in the future, possibly electronuclear breeding) nor entail the kind of possible difficulties related to the environment, safety and non-proliferation. It would not require a costly and long-term R,D&D development program but could, following a modest and R&D effort, be introduced into a CANDU reactor within a decade. A LEU cycle would, however, require a supply of enriched uranium (either from abroad or within Canada); would require an electric utility decision to develop it, and would not result in as great a uranium savings as other advanced fuel cycles.

(9) It is very doubtful that CANDU advanced fuel cycles would achieve significant benefits for Canada's uranium and nuclear reactor export situation. Canada should be able to maintain and to improve its position as a leading world uranium supplier in the future without advanced fuel cycles, even if a possible, but by no means inevitable, world supply shortage should develop early in the next century.

(10) Advanced fuel cycles or the existence of a program to develop them would now provide a relatively modest contribution of only secondary importance to improving Canada's reactor export prospects.

(11) A development program in advanced fuel cycles would likely

become a major source of controversy in the Canadian nuclear debate, with public acceptability of such a program uncertain at best. Developing the LEU cycle, however, would probably be subject to less public criticism, more public acceptability and greater utility interest than would developing other advanced fuel cycles.

D. A CANADIAN DEVELOPMENT PROGRAM IN CANDU ADVANCED FUEL CYCLES

Based on the preceding analyses of nuclear power and advanced fuel cycles in Canada, this section provides an assessment of whether or not Canada should undertake a long-term development program in CANDU advanced fuel cycles and, if so, then an indication of the general contours or guidelines that should be involved in such a program.

1. Rationale

An assessment of whether or not Canada should develop advanced fuel cycles in the CANDU reactor will, in the final analysis, be a matter of choice of perspective. Given the possible interpretations on a range of complex issues and factors, there is no simple, irrefutable, 'correct' position to take in such an area -- only differing assessments and evaluations based on the personal judgements one makes. It is for this reason that the critical judgements used must be clearly delineated and fully understood if the final assessment is to be useful. What follows is a statement of the basic views adopted in this paper.

One such view involves the future role perceived for nuclear generated electricity in Canada and around the world. If nuclear power is considered to be a passing technological aberration that will eventually be rejected and eliminated by society for whatever reason (public opposition, unacceptable risks, available and attractive alternative energy technologies, etc.), then such nuclear development work as pursuing advanced fuel cycles will not be viewed favourably. If, on the other hand, nuclear power is to play an increasingly important role in our electricity and energy future, becoming an energy choice that will be relied upon to a much greater extent over time, then such advanced fuel cycles work would obtain a more favourable reception.

The first sections of this paper suggest that the latter view of these two stark alternatives is the more realistic and likely one. Despite the substantial difficulties it is currently encountering and the thorny path it must travel in the near future, nuclear power will likely assume a greater role of importance in meeting our growing electricity needs in the future.

Moreover, the ultimate promise or potential of nuclear power as an energy source in the future is virtually unlimited. Because of the tremendous energy potential locked by nature within the nucleus of an atom and capable of being unleashed by the fission process, nuclear power offers the promise of ultimately becoming a truly large-scale and long-term energy source -- one that could possibly provide almost all of our energy needs for a very long time to come. Indeed, at this time, only nuclear fission, nuclear fusion and possibly solar energy have such a vast potential to become a permanent and lasting solution to our future energy supply needs. A move towards realizing this vast potential of nuclear energy over the long-term, however, will require considerable development efforts in areas such as advanced fuel cycles and fast breeder reactors.

In addition, this future promise of nuclear energy has a special applicability to Canada which has established a unique capability, expertise and opportunity in nuclear energy. The unique capability lies in the CANDU nuclear reactor -- a leading Canadian success story in R&D and in high technology that has proven itself on a commercial scale to be safe, reliable and economic. The unique expertise is vested in the team of AECL nuclear scientists which is internationally recognized and respected as world-class in quality. The unique opportunity rests in the versatility and flexibility of the CANDU reactor to use advanced fuel cycles -- a use that would achieve considerable nuclear fuel benefits by reducint uranium requirements and by extending the fuel base to include plutonium and thorium.

Pursuing advanced fuel cycles would take advantage of this unique Canadian capability, expertise and opportunity in nuclear energy. If this Canadian advantage is not pursued at all, then the CANDU advanced fuel cycle opportunity will be left stagnant since the rest of the nuclear world is concentrating on the fast breeder reactor approach. This would mean the loss of a possible future advanced nuclear alternative to the world, should the fast breeder and nuclear fusion turn out to be technically or economically unavailable for use. In this sense, because of its unique position in the CANDU advanced fuel cycles area, Canada has a special role to play in moving towards realizing the full potential of nuclear energy.

Developing CANDU advanced fuel cycles would also be a positive reflection of several basic principles concerning the proper role of science and technology in society. As well as creating new areas of technological expertise, Canada should also develop its present strengths and advantages in existing technological areas such as the nuclear one. High technology industries, such as the nuclear reactor industry, are essential for Canada's future economic development and growth and should be actively encouraged. There is a constant need to improve high technology products, such as the CANDU reactor, through R,D&D efforts if such products are not to become outdated and obsolete in the future marketplace. Established scientific expertise such as the nuclear one in AECL, will eventually wither away without new and exciting research challenges to maintain its scientific credentials and to remain an attractive field of work for the next generation of scientists. Long-term R&D endeavours such as developing advanced fuel cycles represent an important investment in the future by society -- one that should not be neglected or postponed due to purely short-term perspectives and the pressures of more immediate concerns. Although such science and technology principles do not mean that every possible R&D proposal must be accepted, a failure to pursue advanced fuel cycles in particular -- given the nature of the industry, the technology and the scientific establishment involved in nuclear energy in Canada -- would be a strong signal that such principles are not being acted upon in practice.

In moving from these important general considerations to the more specific aspects of advanced fuel cycles themselves, the assessments previously made in this paper indicated that such cycles are, at the present time, not absolutely necessary from a uranium resource point of view; not economically attractive or competitive over the existing natural uranium once-through fuel cycle; and not technically available at this time. Canada's uranium resources should be more than adequate to meet the domestic fuel requirements of the developing Canadian nuclear power program for a long time into the future, and to maintain and even improve upon Canada's position as a leading uranium exporter to the world. Advanced fuel cycles will become economically attractive compared to the existing fuel cycle, if at all, only after the first few decades of the next century and then only under rather extreme conditions of high nuclear growth, high uranium prices and modest associated fuel costs. Because an extensive development program of research, development and demonstration (R,D&D) over the next 2 or 3 decades would be necessary, advanced fuel cycles will not become technically available for actual adoption until about the year 2020 or so. (The exception to this is the LEU cycle, which could be technically available in a decade.)

This means that a decision at this time to introduce or implement CANDU advanced fuel cycles is not demanded by the current uranium resource situation; not warranted by economic considerations; and not presently possible because of their technical unavailability. Such a deployment decision may, however, be necessary in the future if assessments other than the one presented here turn out to be more accurate, or if circumstances in the future change to make this assessment invalid. It is not inconceivable that such might actually be the case, given the extremely long period of time involved, the large uncertainties that unavoidably exist, the many key factors at play, and the vulnerability of the energy situation to dramatic shocks.

For this reason, it would be advisable for Canada to position itself so that it could be able to make an intelligent and informed decision on whether or not to implement advanced fuel cycles. Such a future deployment decision will only be possible if advanced fuel cycles are technically available at that time and if an adequate development program has been undertaken on them to establish the necessary information base.

It should be noted, of course, that a development decision at this time to keep the advanced fuel cycles option open need not in any way presuppose or predetermine what that future deployment policy decision will actually be. Although certain development programs in the past might have been undertaken and have gained such a technological momentum and accumulated investment that the actual deployment decision became inevitable or irreversible, this need not be the case here. This deployment decision could turn out to be a positive or negative one, depending upon a range of factors to be assessed at the time of the decision: the actual results of the development program, especially in terms of safety, the environment and non-proliferation; the uranium resource and production situations; the expected economics involved; the status of nuclear energy and the state of the nuclear industry; public attitudes; etc. In this way, a decision now to work forwards the development of advanced fuel cycles will assist - not preempt - a decision later on deployment. The policy option to adopt or not to adopt advanced fuel cycles is being kept open, rather than being foreclosed.

Moreover, a development program to keep the advanced fuel cycles option open would be particularly relevant to the nuclear waste disposal question. It is currently expected that the existing R,D&D waste disposal program will result in a full-scale demonstration facility being in place and operational by the end of the century. At that time there will likely be considerable pressure to actually dispose of nuclear material and, therefore, to make a decision on whether such material should be the entire spent fuel bundle or the reprocessed wastes after the plutonium content has been extracted. Although the waste disposal program is being conducted so that either decision could be accommodated, a decision on disposing of reprocessed wastes only will not be possible in the absence of a prior development program that will have examined the possible aspects of using plutonium in an advanced fuel cycle. With such an examination, the decision to dispose of the entire spent fuel bundle may then be made with greater confidence. In this way, a development program to keep the advanced fuel cycle open would also contribute to the waste disposal decision that must be made in the future.

Thus, a development program would keep the advanced fuel cycles policy option open, and would enable Canada to be in the desirable position, if required at a future date under the then prevailing circumstances to make a decision as to whether or not to actually adopt such fuel cycles. Keeping an option open for a future decision is a worthwhile goal for R&D and a useful policy aide: 'The role of research in the policy process shows that it is often supported because decision-makers genuinely lack knowledge about a given problem or need some knowledge to keep their options open. Work on advanced fuel cycles can certainly be justified on this basis.'[26]

This raises the question of the appropriate extent or scope of such a development program. Based on the assessment of advanced fuel cycles presented in this paper, there should not be at this time a full-scale, all out effort over the complete range of research, development and demonstration. The demonstration stage

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[26] G. Bruce Doern, Government Intervention in the Canadian Nuclear Industry, IRPP, 1980, p.197.

involves large-scale and costly pilot plants and demonstrations. It should be entered into only after a more definite and assured assessment of the eventual costs/benefits of advanced fuel cycles has been obtained. It would also need a better than existing likelihood that a favourable deployment decision will be made on advanced fuel cycles. Since it would represent a significant commitment towards advanced fuel cycles and be a source of public controversy, a full public scrutiny and understanding of this important step would be necessary. Of course, a decision now to undertake the necessary R&D work does not presuppose or predetermine what a future demonstration decision will actually be.

It is therefore recommended that Canada should undertake an adequate R&D effort on CANDU advanced fuel cycles in order to keep open the policy options for future decisions on demonstrating and deploying these cycles. This is, in fact, the specific recommendation that was proposed in the Report of the Ontario Royal Commission on Electric Power Planning (the Porter Commission): 'Although it is important to keep open the thorium fuel cycle option by enegaging in an R&D programme, a firm decision to go ahead with a major demonstration and/or commercial programme should be delayed at least until 1990, and then made only if it is acceptable to the public after appropriate dialogue and study concerning the full implications and impacts of such a projct. Indeed, only after the future of Canada's nuclear industry has been clarified can the thorium fuel cycle proposal be put into an adequate perspective.'[27]

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[27] The Report of the Ontario Royal Commission on Electric Power Planning, Volume 1 - Concepts, Conclusions and Recommendations, February, 1980, p.75.

2. Program

It would be presumptuous and ill-advised for this paper to attempt to delineate in detail the exact technical components of an optimum advanced fuel cycle development program for Canada. Such detailed work is best left to the scientific experts who possess the necessary knowledge and capability to make such suggestions. What can be legitimately indicated, however, are certain overall general guidelines or approaches that should be undertaken in such a program.

R&D

As indicated in the rationale, an advanced fuel cycle development program should at this time consist of an adequate R&D effort only and not the expensive demonstration stage. Although this strict separation between R&D and demonstration may not be totally applicable in certain areas due to a blurring of lines and unavoidable overlapping, this basic distinction should be maintained. Demonstration efforts in selected areas could, however, be proposed and decided upon at the appropriate times, taking into consideration the prevailing circumstances then in force.

The exact funding levels and duration times required for an adequate R&D program will obviously depend upon the exact R&D work to be undertaken. Based on some past, rough indications made by the Science Council and AECL and subject to revision from a more detailed update, an R&D program in the order of about $10 million a year for about ten years would seem to be in order.

The best and easiest source for such funding would be the existing expenditure budget allocated to AECL. This would involve the current funds now being spent on advanced fuel cycles work (approximately $5 million a year, depending on what is considered to be advanced fuel cycles work), funds made possible from a reordering of research priorities within AECL, and funds made available from AECL's current efforts to place some of its activities and services on a commercial contract basis. Given the existing expenditure restraint effort within government in these economic times, this funding approach would be the most suitable and promising arrangement. If totally new funds are sought for this R&D program, of course, then this would have to be decided upon in direct relation to other competing proposals for R&D and non-R&D efforts and in light of the existing priorities of the government at that time.

A commitment in principle from the government to a long-term R&D program of about ten years funded from existing resources would provide some long-term stability and make possible some long-term planning for the R&D work. Naturally, the necessary expenditure controls and periodic program evaluations and assessments would be required.

Low-Enriched Uranium Cycle

The R&D program should explore the range of advanced fuel cycle possibilities. To date, however, the research emphasis has been on the plutonium and thorium cycles, since they are the most uranium conserving ones and the most technically complex and challenging ones. As pointed out in this paper, however, the low-enriched uranium (LEU) fuel cycle has a number of distinct advantages over these more advanced fuel cycles. Moreover, Ontario Hydro studies have indicated that only a modest research effort for only a few years is required to make the LEU cycle one that would actually be technically available for introduction into the CANDU reactor. It would seem reasonable, therefore, that one short-term goal of an advanced fuel cycle R&D program would be to complete the necessary research work required for a LEU cycle. It should be recognized, however, that the most important step now in making the LEU cycle available is actually demonstrating it within a CANDU reactor and not undertaking a large research effort. An

Ontario Hydro decision to proceed with the LEU cycle would, therefore, appear to be a prerequisite. Who should appropriately incur the costs of undertaking the remaining R&D work necessary is also a matter that would need to be resolved.

Sensitive Work Areas

An essential component of the R&D program will be an appropriate emphasis on the sensitive areas of advanced fuel cycles -- environmental impacts, waste disposal, safety concerns and non-proliferation implications. Although a considerable amount of information has already been accumulated in these areas on a world basis, a comprehensive knowledge base in Canada must be acquired to determine with assurance the likely consequences involved in such fuel cycles and their associated activities. This will likely be a leading source of public concern and a critical factor in decisions concerning any further demonstration and possible deployment.

Public Awareness

As previously indicated, future decisions on the possible demonstration and deployment of advanced fuel cycles will likely be marked by controversy, with the public acceptability factor being a prime consideration. For this reason, it will be important that there is developed over time a solid public understanding about the nature of the R&D program and the results it achieves, and about the likely implications of advanced fuel cycles (especially in the sensitive areas of the environment, waste disposal, safety and non-proliferation). An adequate public awareness effort should therefore be undertaken, including, as in the case of the current waste disposal R&D program, periodic reviews, available to the public, of the research progress achieved.

The Energy R&D Context

It will be necessary to place an advanced fuel cycles program within the overall energy R&D context. It should clearly not be undertaken at the expense of other necessary efforts in nuclear R&D such as waste disposal, the handling of uranium tailings, reactor safety and for decommissioning facilities. These priority areas within nuclear R&D must not in any way be neglected or undermined because of an overriding preoccupation on advanced fuel cycles work. Fortunately, such a conflict is neither necessary nor likely since these nuclear R&D efforts should be complementary in nature and mutually supportive. In the same manner, of course, an advanced fuel cycles R&D program need not by itself preclude other possible nuclear research efforts that might prove to be worthwhile endeavours in the future.

The R&D program should also be placed within the context of other federal non-nuclear energy R&D programs. It could be pointed out in this regard that the lion's share of increased funding in energy since 1977 and especially since the National Energy Program of 1980 has been allocated to non-nuclear areas such as conservation, renewables and new liquid fuels. Although significant programs have been mounted in the areas of waste disposal and nuclear fusion, the relative predominance of the nuclear area in the overall energy R&D funding by the federal government has been decreasing. The adoption of the suggested development program on advanced fuel cycles would not change this trend, since additional funds for the program would be obtained from within AECL's existing budget allocation.

The R&D program in advanced fuel cycles should also be placed within the NEP's overall R&D policy framework. This is possible since, although it specifically identified the three energy R&D priorities of new liquid fuels, conservation and new energy sources for an increased effort, the NEP also acknowledged the need for a large nuclear R&D commitment: 'This commitment will continue. Indeed, the effort will increase in some areas'.[28] This commitment to support nuclear power research was reiterated in the NEP Update 1982. The NEP also recognized that 'research and development provides a technological basis for long-term energy options beyond 1990'[29] -- a point of particular relevance to advanced fuel cycles work.

A National Program

Although historically AECL has been the major nuclear R&D funder and performer, and currently accounts for the bulk of scientific expertise in nuclear energy, it would be desirable for an advanced fuel cycles R&D program to be as national in scope as possible and to involve as many participants from different sectors as possible. This would share the financial burdens and risks involved in such a program and would take advantage of all of the nuclear expertise that is available in the country.

There is no doubt, however, that AECL would need to be the leading actor in the R&D proram; but other actors should be involved as well. Although the nuclear manufacturing industry is a fragmented assortment of companies with relatively minor R&D activities or capabilities, some consulting relationship or personnel secondments might be possible. Nuclear expertise in the university sector could be tapped through joint efforts and some contracting out.

The most important potential partners, however, are the electric utilities and, more specifically, the three that have a nuclear component to them -- Ontario Hydro, Hydro Quebec and the New Brunswick Electric Power Commission. Ontario Hydro, of course, is the dominant nuclear utility in Canada and will remain so in the future. It will likely also be the first possible

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[28] EMR, The National Energy Program 1980, p.74-75.
[29] Ibid., p.75.

customer if and when advanced fuel cycles in the CANDU reactor are actually deployed. Because its planning time frame is less than that associated with the development of advanced fuel cycles, and given its long-term uranium contracts that provide an assurance of nuclear fuel supply into the next century, Ontario Hydro is not greatly interested at present in a long-term pursuit of advanced fuel cycles. Indeed, Ontario Hydro decided a few years ago not to proceed with developing even the LEU fuel cycle -- the one it would be most interested in seeing developed.

Nevertheless, if an advanced fuel cycle R&D program is to be undertaken, every effort should be made to interest and to include the relevant utilities in such a program. One possible way to do so might be to stress that the program would be addressing the full reseach needs of the LEU cycle in order to make it a technically available reality as soon as possible. Another way might be to link it in some manner to the existing joint AECL-Ontario Hydro waste disposal development program. Every such possible avenue should be fully explored to obtain a national flavour to the advanced fuel cycles R&D program.

International Cooperation

Historically, Canada has pursued its own nuclear R&D path in developing the CANDU reactor. Although this turned out to be a Canadian R&D success story, it does mean that Canada is now outside of the nuclear mainstream -- which involves the use of light water reactors. It also means that the overwhelming attention of the rest of the nuclear world is focussed on developing the fast breeder reactor from the light water reactor line, since the latter is not suitable to easy adaptation to advanced fuel cycles and not on the possibility of CANDU advanced fuel cycles.

Canada, however, can ill afford to have its CANDU reactor remain an isolated Canadian phenomenon. The existing nuclear manufacturing industry may have difficulty surviving if its market is largely restricted to Canada. However, the problems involved in the CANDU penetration of the world marketplace are many and difficult.

One possible way for CANDU to become more accepted in the future, however, is for the Canadian R&D program on advanced fuel cycles to be undertaken as an international cooperative venture with one or more foreign research partners. This would result in significant benefits, especially in terms of sharing the expenses involved (especially in the more costly advanced phases) and of creating a common pool of nuclear knowledge being built up on such areas as reprocessing, enrichment and fuel fabrication. It would indicate that there is a real interest in the world in realizing the CANDU potential. A research partner might also be able to open its nuclear reactor market to CANDU. Moreover, Canada might well benefit from linking itself with a country with proven marketing skills.

A foreign research partner in a cooperative R&D program on advanced fuel cycles should ideally meet the following specifications:

i) The partner should have a potential dometic market of significance for the advanced fuel cycle CANDU nuclear reactor;

ii) The partner should possess proven international marketing skills and experience that would enhance the future prospects of a possible joint marketing effort in ultimately selling the advanced fuel cycle CANDU reactor to other countries;

iii) The partner should have an existing expertise and capability in associated technologies or processes that would be directly relevant to the development of CANDU advanced fuel cycles, e.g., enrichment, reprocessing, fuel fabrication;

iv) The partner should have an established base of nuclear R&D scientists capable of working within the CANDU advanced fuel cycles research area; and

v) The partner should have a real interest in undertaking such a joint R&D effort with Canada -- to the extent that it would be willing and able to share the costs involved in an appropriate manner.

Although, as indicated, the current world interest lies in developing the fast breeder reactor as the future route to conserve uranium, there do seem to exist a number of possible ways to involve foreign actors in the Canadian advanced fuel cycles R&D effort. For example, a cooperative arrangement might be realized with the United States which, in addition to the Clinch River fast breeder program, is also undertaking R&D work on plutonium and thorium cycles in an advanced light water reactor; might be interested in developing a possible CANDU-fast breeder symbiotic relationship; and might be receptive to the development of a greater nuclear compact involving uranium, R&D and prebuilding CANDU reactors in Canada dedicated to electricity exports. Developing countries such as Mexico, which are contemplating or planning a nuclear reactor program, might be interested in realizing their nuclear expertise through a joint R&D program with Canada. Industrialized countries such as Japan, which is committed to a large nuclear future and which has shown some interest in the CANDU reactor, might view with favour the possibility of a common development program.

Clearly, international cooperation could take many forms, depending on the special interests and abilities of the possible countries involved. The principle that should be adhered to, though, is that an intensive investigation of such international cooperative possibilities should be part and parcel of the

Canadian advanced fuel cycles R&D program.

Such an investigation should be undertaken as soon as possible to indicate what real possibilities do in fact exist for such international collaboration. If required and appropriate, this effort could obtain funding assistance from the recently established catalytic seed fund for international collaboration in S&T.

3. Conclusions

Based on the above material, this paper presents the following conclusions on a Canadian development program in CANDU advanced fuel cycles:

(1) Nuclear power will play a role of increasing importance in meeting our future electricity and energy needs.

(2) Nuclear energy has a vast potential to become a large-scale solution to our future energy supply needs in the long-term.

(3) Canada possesses a unique nuclear capability in the CANDU reactor, a world-class scientific expertise in nuclear energy, and a special opportunity in the advanced fuel cycles area. Pursuing advanced fuel cycles would take advantage of this nuclear situation.

(4) Developing such cycles would also be a positive reflection of several basic principles concerning the proper role of science and technology in society: the need to develop present strengths and advantages in existing technological areas; the importance of high technology industries for future economic development and growth; the constant need to improve high technology products; the concern for maintaining established scientific expertise; the role of long-term R&D as an important

investment in the future.

(5) At the present time advanced fuel cycles are not absolutely necessary from a uranium resource point of view; not economically attractive or competitive over the existing natural uranium fuel cycle; and not technically available at this time. This situation will not change until after the first few decades of the next century, if then.

(6) A deployment decision on advanced fuel cycles may become necessary, however, at a future time - if dictated by evolving circumstances. To make such a decision will require an adequate development program to have been undertaken beforehand. Such a development program need not presuppose or predetermine what that deployment policy decision will actually be. It would also contribute to an eventual waste disposal decision in the future.

(7) Therefore, based on the above viewpoints, a Canadian development program in CANDU advanced fuel cycles should be undertaken in order to keep open this policy option for future decisions.

(8) Based on the assessment presented of the prospects for advanced fuel cycles, however, this development program should consist of an adequate R&D effort and not the demonstration phase.

(9) Certain general guidelines or approaches should be involved in making the development decision and in undertaking the R&D program:

- The program should be an R&D effort, perhaps at about a $10 million annual funding level for ten years, with funds obtained from within AECL's existing expenditure budget.

- A short-term goal of the program should be to complete the necessary research work required for the low-enriched uranium (LEU) fuel cycle to become technically available. This may depend, however, on an actual electric utility decision to proceed with the LEU and a resolution of who should incur the costs involved in such R&D.

- The program should provide an appropriate emphasis on the sensitive aspects concerning the environment, waste disposal, safety and non-proliferation.

- A public awareness effort should be undertaken concerning the nature of the R&D program and the results intended, and about the likely implications of advanced fuel cycles.

- The program should be properly placed within the overall context of other nuclear R&D areas, non-nuclear energy R&D programs and funds, and the National Energy Program's R&D policy framework.

- The program should, if possible be, a national effort involving AECL and other sectors such as the nuclear manufacturing industry, university expertise, and electric utilities with nuclear programs. Every effort should be made to obtain such a national flavour to the program.

- The program should, if possible, be undertaken as an international cooperative venture between Canada and one or more foreign countries. This would result in a sharing of costs and a common pool of nuclear knowledge. It might provide a special foreign reactor market for CANDU and an opportunity for Canada to cooperate with a foreign country with proven marketing skills. The feasibility of such a cooperative venture should be thoroughly investigated as soon as possible.

E. AN ASSESSMENT OF NUCLEAR FUSION

A general assessment of nuclear fusion is presented in terms of its promise or potential, as indicated by its likely advantages and disadvantages in a number of important contexts, and in terms of its current status, including its expected future path of development. In order to assess nuclear fusion, however, a basic grasp of the technical fundamentals involved is needed. For this reason, the following few pages provide a number of brief, reference monographs or outline sketches, in general language, of the nature of the fusion process and fusion reactions; the conditions necessary for a fusion reaction; the different approaches of magnetic and inertial confinements; and the expected operation of a typical fusion reactor.

1. The Promise of Fusion

This section provides an overall evaluation of the basic promise or potential of nuclear fusion in terms of its likely advantages and disadvantages in a number of critical contexts: energy supply and fuel sources; possible applications; environmental impacts and safety aspects; risk of nuclear weapons proliferation; and public acceptability.

Energy Supply and Fuel Sources

Energy is a crucial ingredient in the future of industrial society and modern civilization. The world's current energy production, however, is based mainly on the fossil fuels of oil, natural gas and coal. This fossil fuel era is of recent vintage, and limited future duration. Due to their limited supply, these fossil fuels will not be able to provide the growing needs of the world indefinitely. At some point -- not perhaps in the next decade or two but certainly in the next century or two -- these

BASICS OF THE FUSION PROCESS

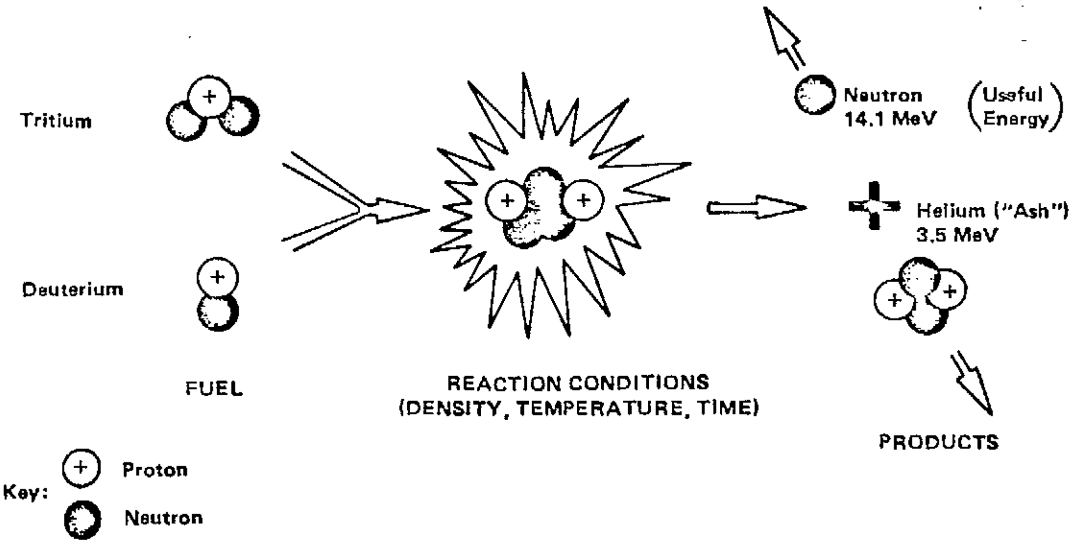
Atomic nuclei are made up of positively-charged protons and uncharged neutrons. These protons and neutrons are held together by a certain force of 'binding energy'- a sort of nuclear glue. The rearrangement of the protons and neutrons of certain nuclei into other groupings can lead to a release of surplus binding energy. If, for instance, two nuclei combine together to form a third nucleus whose protons and neutrons need less energy to stay together than did the two original nuclei, then some of the total binding energy is not needed and is therefore released.

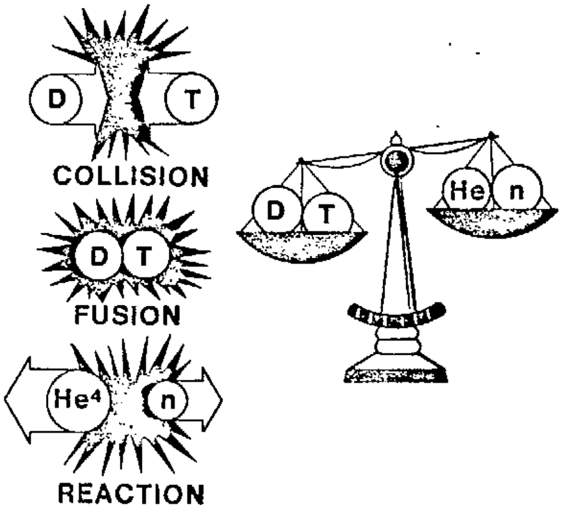
Fusion, the process that powers the sun and other stars, involves the joining together, or fusing, of the nuclei of light elements such as hydrogen. The resulting product is a larger nucleus but one with a lighter total mass. Based on the equivalence of energy and mass in Einstein's famous formula, $E= mc^2$, this difference in mass is converted into released energy - the kinetic energy of the products in the form of heat. Conversely, the fission process involves the splitting apart, or fissioning, of a heavy nucleus, such as uranium, into lighter nuclei, with the loss in total mass also resulting in an energy release in the form of heat. Thus, although fusion and fission are opposite processes, they both result in a reduction in total mass and a release of binding energy.

There are, in principle, several possible fusion reactions, but the deuterium-tritium one is the easiest to realize or imitate, and therefore the one that is of the greatest interest for study. The most common form of the hydrogen atom consists of a single electron revolving around a much heavier nucleus made up of one proton. The rarer forms, or isotopes, of hydrogen are deuterium (D), with a nucleus of 1 proton and 1 neutron, and tritium (T), with a nucleus of 1 proton and 2 neutrons. In a D-T fusion reaction in which the nuclei of these two hydrogen isotopes come together, the highly excited nuclei form a helium (He) nucleus (2 protons and 2 neutrons) with a kinetic energy of 3.5 MeV (million electron volts); and yield a neutron that is ejected almost simultaneously with a kinetic energy release of 14.1 MeV. (This neutron could be used in a subsequent reaction with lithium to produce tritium and helium, thereby breeding the tritium fuel for further fusion reactions).

This deuterium-tritium reaction imposes reasonably achievable conditions for fusing and gives the highest energy yield at the lowest temperatures. It will therefore be used to fuel the first fusion reactors. There are, however, other possible fusion reactions that are more difficult to bring about but that may offer certain advantages in the future. A deuterium-deuterium reaction, yielding either helium, a neutron and 3.2 MeV, or tritium, a proton and 4.0 MeV, would not require a tritium fuel and would therefore pose less of a radioactive hazard. A deuterium-helium reaction, yielding helium, a proton and 18.5 MeV, would involve no redioactivity but only positively charged particles that might be used to produce electricity at up to 90% efficiency. Other possible reactions involve tritium-tritium, lithium-deuterium and boron-hydrogen.

Deuterium-Tritium (D-T) Fusion Reaction





CONDITIONS FOR A FUSION REACTION

For a fusion reaction to occur and to be sustained, certain specific, very extreme conditions of temperature, density and confinement time must be attained. The positively-charged nuclei must fi-st come in contact with each other but, since similar electrical charges tend to repel one another, there is a natural force of electrical repulsion between such nuclei. The energies of approach in these nuclei must be sufficiently great to overcome this repulsion. This energy must be provided externally, and the minimum required to produce fusion is 10,000 electron volts. This energy is sufficient to raise the "temperature" of the atoms being fused to about 100 million°C-roughly 6 times the temperature of the sun's interior. At such an extremely high temperature, the atoms are stripped of their electrons (ionized). The resulting ionized gas is called a plasma and, within this plasma, the fusion process takes place. The temperature at which fusion commences is called the ignition point since the reaction will now proceed without any further energy input.

In a fusion (hydrogen) bomb, of course, the explosion of fission bomb acts as the detonator to produce the high temperature required to initiate the fusion reaction. For a controlled fusion reaction, however, another source of energy to achieve the necessary high temperature must be used. Plasma heating can be accomplished in several ways. Ohmic or resistance heating involves passing an electric current through the plasma -- similar to the heating in a light bulb. Such heating, however, depends on the electrical resistance of the plasma: as the temperature increases, such resistance decreases and eventually becomes too low for ohmic heating to be effective. Another technique involves a neutral beam injection into the plasma: the neutral beam consists of uncharged, highly energetic atoms, which, when injected, collide with the plasma particles, and transfer their kinetic energy to the plasma, thereby raising its temperature. Because neutral beam heating is more dependent upon mechanical resistance, i.e. collisions, than upon the electrical resistance of the plasma, it can be used as an effective supplementary technique to raise the plasma temperature to higher values than those achieved by ohmic heating alone. Other methods being investigated involve laser, electron and ion beams; microwave and radio frequency radiation; and magnetic or adiabatic compression.

For a sustained reaction to occur however, the plasma must be maintained at above the ignition temperature for a significant period of time, so that as much energy is generated as is required to reach the ignition point. (The ratio of the energy input to the energy output from a fusion reaction is called the energy gain, with the energy breakeven point occuring at 1.0). This requires that the plasma must have a density (the number of ions per unit volume of plasma) sufficiently high to ensure that the ions are close enough for a sustained reaction. Because the energy output is proportional to the reaction rate times the confinement time, and because the energy input is proportional to the density, the density-confinement conditions for the D-T reaction must exceed a threshold value of 10^{14} sec/cm^3

(ions-second per cubic centimeter). This minimum product of density and confinement time to achieve the fusion condition is called the Lawson Product after its formulator, the British physicist, J.D. Lawson.

This Lawson Product is, however, extremely difficult to attain. High temperature plasma has a natural tendency to expand unless restrained, since the individual particles are moving at very high speeds - a few million kilometres per hour. The fusion plasma in the sun is held together by large gravitational forces. Since such forces do not exist on earth and cannot be practically simulated, other confinement approaches must be used. The plasma must be confined in a non-material container since no known material can withstand the high temperature involved without vaporizing and colling the plasma by contact. This, in turn, must be contained within some material container such as a high vacuum vessel so that the composition of the plasma can be controlled. Confining the plasma has been compared to trying to hold jelly together with rubber bands. The two major confinement approaches being pursued are magnetic confinement and inertial confinement - each of which is briefly described in the following few pages.

MAGNETIC CONFINEMENT

The magnetic confinement approach takes advantage of the fact that the plasma, while ionized, is, as a whole, electrically neutral. This makes it a very good conductor of electricity and subject to magnetic forces. The positively-charged protons of the plasma can be made to follow helical paths around inside a magnetic field line, thereby isolating the plasma from material container walls by enclosing it in a magnetic cage. The plasma is therefore controlled or confined in much the same way as iron filings can be moved by a bar magnet.

Although there exist a wide variety of possible 'magnetic bottles' and many different magnetic confinement configurations, two major techniques have received the greatest investigation - the mirror or open confinement, and the torus or closed configuration.

The Mirror - Open Confinement

The simplest method is to trap the plasma in a magnetic field shaped like a straight, open-ended cylinder. Although it involves straightforward physics and geometrical simplicity, such an 'open' system results in plasma particles tending to shoot out of the ends. Some kind of 'mirror' is therefore required to reflect back those nuclei that try to escape. An increased density of magnetic field lines at the ends produces a force that slows and reverses the motion of the escaping particles by converting the particles' parallel energy into perpendicular rotational energy. Such a simple magnetic mirror traps the plasma between two end coils, but still suffers a high leakage rate.

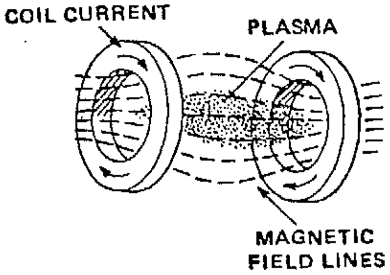
There are, however, more advanced or novel techniques for mirror confinement. The minimum B or Yin-Yang concept involves a 'baseball seam' magnet that creates a magnetic 'well' in the centre to help to localize and stabilize the plasma. The tandem mirror is a solenoidal, coiled magnetic field terminated by standard minimum B mirror devices that act as end plugs to inhibit the loss of plasma from the solenoidal region. The field-reversed mirror is based on the idea that a strong electrical current induced within a mirror-confined plasma generates its own magnetic field around the plasma and therefore reduces end losses. The bumpy torus is a toroidally linked set of simple mirrors, that does not have any ends, and is, in fact, a closed configuration.

The Torus - Closed Confinement

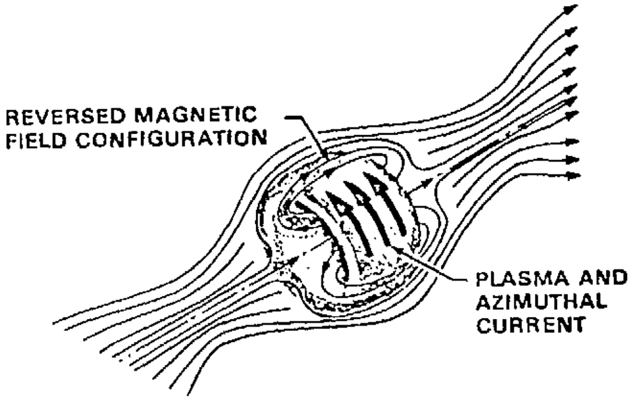
To eliminate plasma end losses a closed confinement configuration bends the magnetic field lines to close on themselves in the shape of a toroid or doughnut. The charged particles follow these lines around in a continuous circle. Such a magnetic confinement device is called a torus.

MAGNETIC MIRROR SYSTEMS

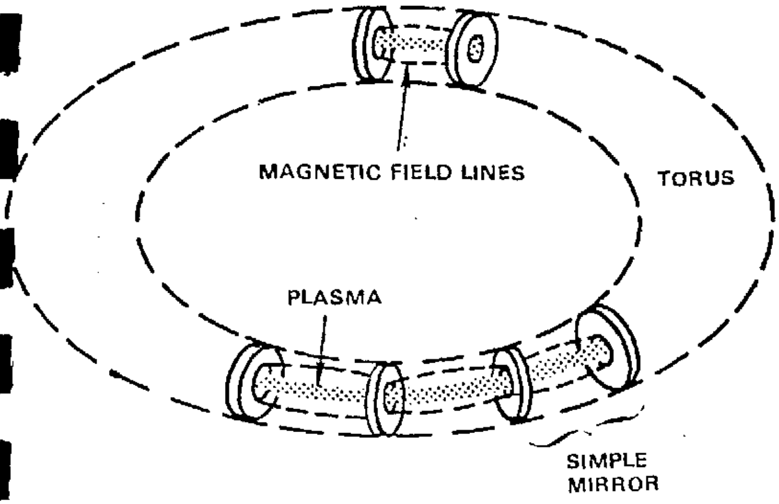
Simple Magnetic Mirror



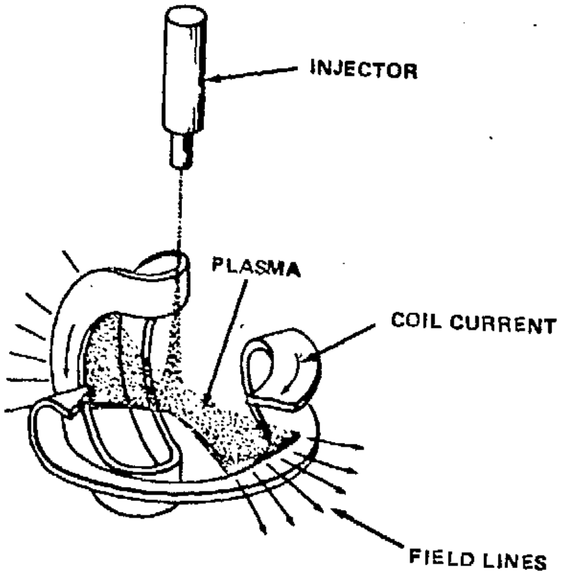
Field Reversed Concept



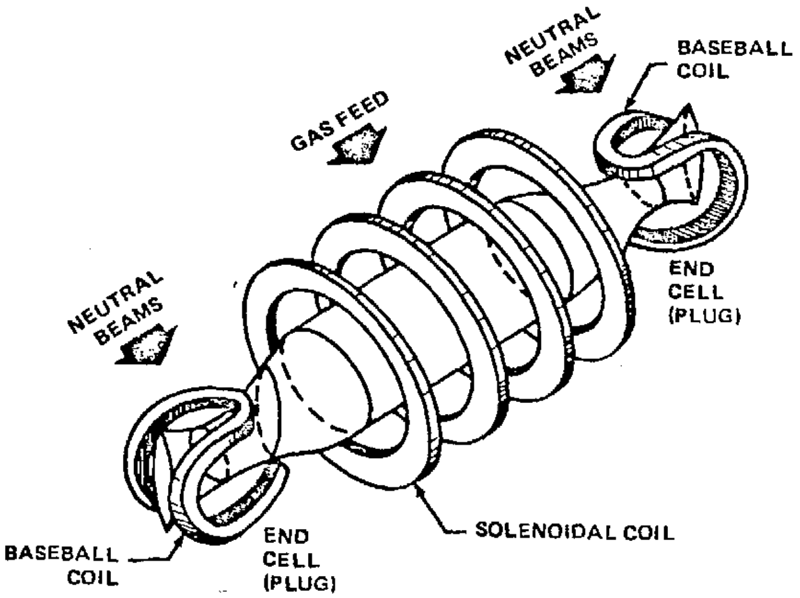
Bumpy Torus Concept



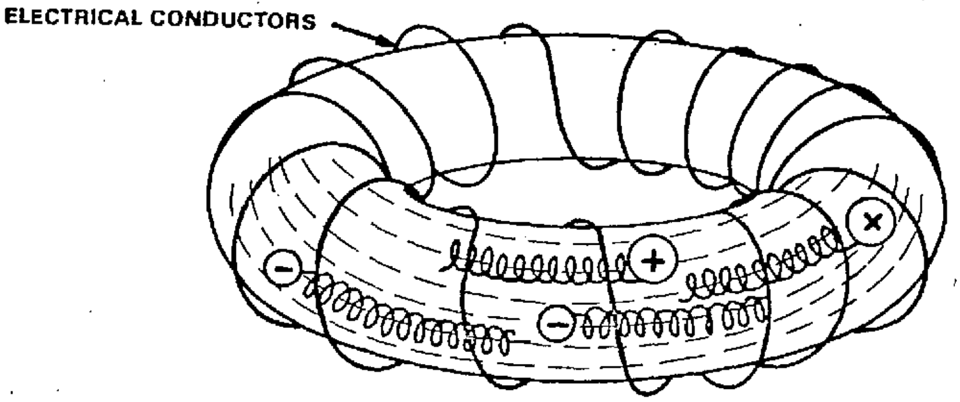
Minimum—B Mirror



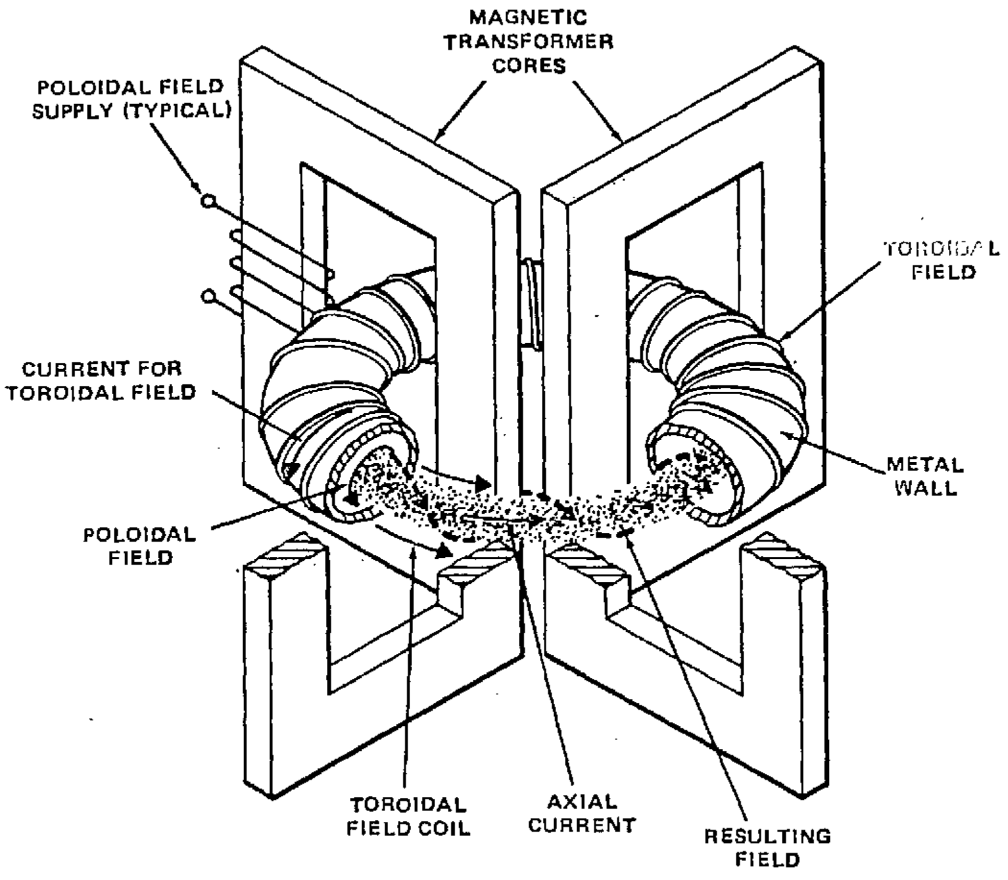
Tandem Mirror Concept



Toroidal Magnetic Confinement



Schematic Diagram of a Tokamak Device



Because the magnetic fields are curved, however, the plasma ions tend to drift sideways into the wall of the vacuum container. This can be overcome in a torus device called a tokamak - a concept first introduced by the Soviet Union in the late 1960's, and the main area of effort in the world fusion program since then. The tokamak concept involves the magnetic confinement of a stable high temperature plasma in a torus-shaped vacuum chamber. This confinement is accomplished by three magnetic fields. The toroidal field is the basic one directed inside the torus from coils of wire wrapped around the body of the torus. To overcome the drift of the plasma sideways into the torus wall, magnetic transformer coils are used to induce a high electrical current to pass through the plasma itself. Besides heating the plasma in the same way that electricity heats wire, this plasma current, in turn, generates its own magnetic field - a poloidal field that flows inside the toroidal ring producing a twisting, pressuring effect that forces the plasma towards the middle of the toroidal ring. This helps to contain the ions and to reduce the likelihood of their crossing the field lines. These toroidal and poloidal fields combine to produce the total magnetic confinement effect desired. In addition, a third set of magnetic fields generated by smaller coils that run around the outside periphery of the torus are used to maintain plasma equilibrium and stability.

Although the tokamak concept is the dominant magnetic confinement approach, other torus designs do exist. The stellarator design produces the extra poloidal field through external coils wound around the outside of the torus. Pinch devices have different ratios of the two magnetic fields.

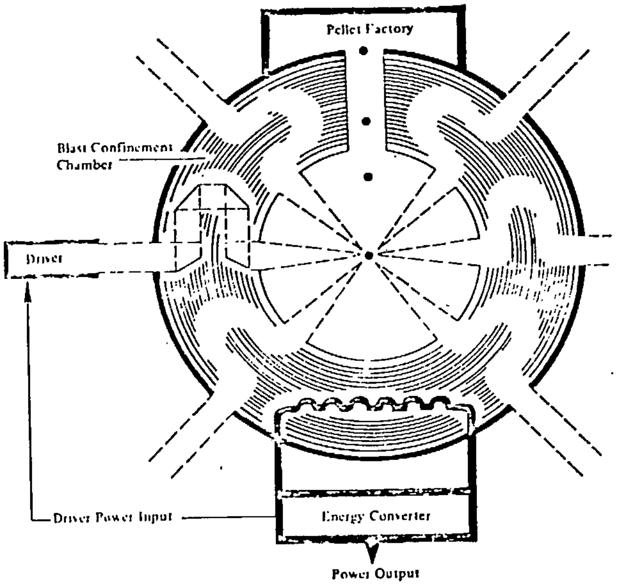
INERTIAL CONFINEMENT

Apart from magnetic confinement, the other basic approach to contain a high temperature plasma is by means of inertial confinement. This process mimics the hydrogen bomb technique and, due to its close connection with potential military applications, much of it is still shrouded in secrecy.

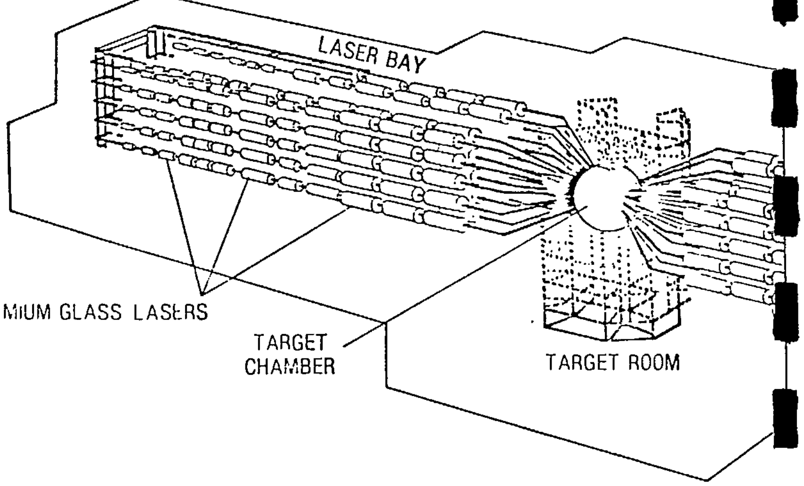
The basic concept, however, is clear. Brief, intense, extremely powerful pulses of either colossal laser radiation or highly energetic electron or ion beams are symmetrically focussed on a miniscule pellet of fusion fuel positioned in a target chamber. These energy pulses cause the outer surface layers of the pellet to evaporate, producing a hot, expanding gas. This gas heats and compresses - literally crushes - the inside of the pellet to the extent that the necessary fusion conditions of temperature and density are met instantly. The confinement time is determined by the time it takes a rarefaction wave to travel from the surface to the centre of the imploded pellet. Thus, the Lawson confinement criteria can be expressed as the density-radius product of the pellet, which must exceed about one gram per square centimeter. The pellet then collapses, or implodes, in many miniature fusion explosions. The net result is that, before the pellet totally disperses or disintegrates, there is a release of fusion energy in the form of 14 MeV neutrons, alpha particle kinetic energy, pellet debris kinetic energy and x-rays.

The inertial confinement approach, therefore, is a precision process that travels almost instaneously from the monumental to the miniscule -- the accurate delivery in less than a billionth of a second of huge pulses of energy to a tiny target less than the width of a human hair.

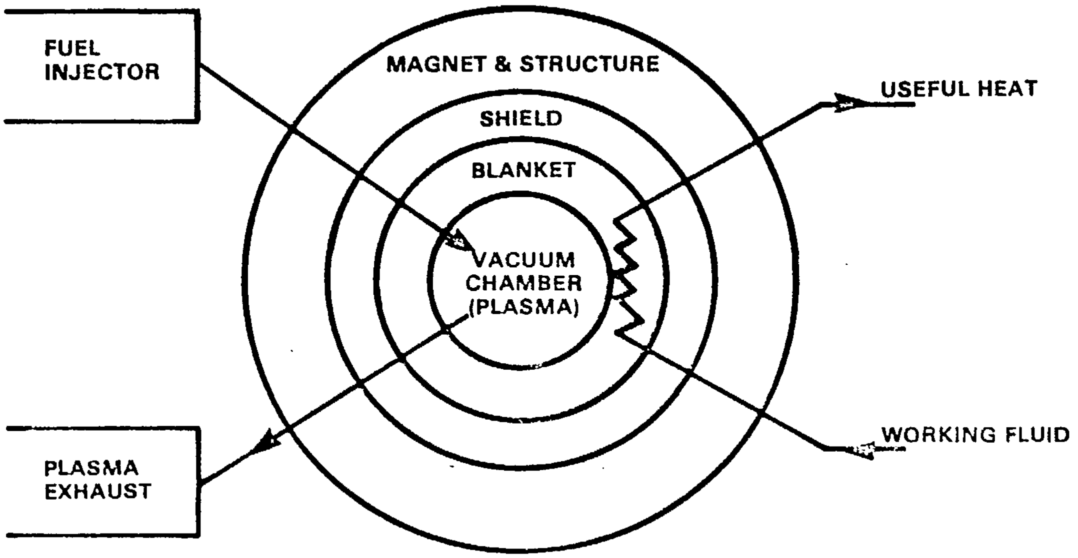
An Inertial Confinement Scheme



A Laser Fusion Machine



A FUSION REACTOR



Understanding plasma physics is a necessary but not sufficient condition to developing fusion as a practical energy source. The engineering aspects of a fusion reactor must also be developed. This involves a host of advanced materials, techniques and devices: high-intensity, large-volume electromagnets to create the magnetic fields; high-intensity, high-energy neutral beam particle injectors and radio frequency heating systems to heat the plasma; materials that can withstand intense neutron bombardment, especially in the first wall of the vacuum chamber and in the surrounding blanket; and extremely low pressure vacuum systems to contain the plasma. All of these technological requirements special to fusion energy extend beyond the frontiers of basic knowledge in each field. Moreover, they must exist in a fusion reactor in a highly integrated manner.

In a typical fusion reactor concept the centre is the vacuum chamber where the deuterium-tritium plasma is confined by strong magnetic fields and the fusion reactions take place. A blanket, or energy conversion device, containing lithium surrounds the vacuum chamber. Neutrons released from the fusion reactions perform two functions in the blanket: they react with lithium to breed tritium which can be extracted and used as fuel; and they heat the blanket - which heat can be extracted and used to drive steam turbines to produce electricity. Because the bombardment of high energy neutrons produces radioactivity in the blanket and the vacuum chamber walls, these parts are surrounded by local shields for personnel safety, prevention of physical damage to the reactor components and protection of the environment. The large magnets and the physical support structure surround the shield. Additional biological shields will further protect personnel and the environment from strong magnetic fields and escaping radiation. The spent plasma is periodically removed from the vacuum chamber and the tritium still present is recovered. Fresh fuel is injected into the vacuum chamber, either discretely for pulsed systems, or continously for steady-state systems.

Source: Office of Energy Research, U.S. Department of Energy, Magnetic Fusion Energy-Program Summary Document FY 1981, January 1980, p. II-10-12.

conventional energy sources will become physically unavailable or economically and socially unacceptable. New sources of energy will then be required and must be tapped to meet this future world demand. Opinions vary considerably as to what these future energy supplies should be but, at the present time, there are only three virtually inexhaustible possibilities with the potential to release the world from fuel constraints and to sustain human society for centuries to come: solar energy in all of its renewable forms; nuclear fission via advanced fuel cycle reactors; and nuclear fusion.

Fusion energy, the energy source of the sun, is, perhaps, the ultimate energy source. It offers virtually limitless energy from almost inexhaustible fuel sources. A typical deuterium-tritium fusion reaction can only convert 0.4% of its original fuel mass to energy but this results in an enormous release of energy - the equivalent of 400 MWh per gram or as much energy as contained in 45 barrels of oil.[30] The net energy so released would be in the order of 2,000 times the initial energy needed to initiate the fusion reaction in the first place. Fusion could, in principle, transform a glass of ordinary water into the energy equivalent of 600,000 litres of gasoline; one single drop of water would correspond to 125 litres of gasoline![31] Fusion could, in fact, potentially produce more energy per gram of fuel than any other source of power imaginable: deuterium, if burned to completion in a fusion reaction, could provide about four times the amount of energy per gram as is released in the fission of uranium.[32] It has been estimated that 1 GW of electrical production could be supplied by fusion using only about 125 grams of deuterium and 400 grams of lithium per day - compared to 5,000 tons of oil or 9,000

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[30] T.S. Brown, 'Canadian Fusion Program', a presentation to the Canadian Nuclear Association, June, 1982, p.2.

[31] Allan Bailey, 'Fusion Power - Getting it together', Ascent, Spring, 1980, p.3.

[32] Richard Post, Lawrence Livermore National Laboratories, testimony to the Lefebvre Committee, Wednesday, December 10, 1980, Minutes No. 35, p.14.

tons of coal.33

Moreover, the basic fusion fuel sources - deuterium, tritium and lithium - are readily available. The supply of deuterium, a heavy hydrogen isotope, is essentially limitless. It is most easily obtained from ordinary water where it is present to a small extent in every drop; approximately 1 in 6,000 hydrogen atoms is the deuterium isotope. Extracting this deuterium is a known, not technically difficult process that can be done at a relatively minor cost - a present cost per unit of energy 1/10,000 that of coal. Once the deuterium is obtained, the water can be returned to its source to all intents and purposes unchanged. The reserves in the oceans, for example, are so large and the amounts required for fusion so small in comparison, that deuterium may be considered to be virtually inexhaustible on any time scale of human relevance.

The other main fusion fuel is tritium - a heavier hydrogen isotope. Although not a naturally occurring element, tritium can be readily manufactured, either as an unavoidable byproduct in a deuterium-moderated fission reactor or as a desired product in a lithium-blanketed fusion reactor. Only very small quantities of tritium would be required to initiate the fusion reaction. After that, the tritium could be 'bred' within the surrounding lithium blanket that captures neutrons resulting from the fusion reaction and yields tritium and helium. In this way, a fusion reactor would actually be a 'breeder' since it generates its own tritium fuel and becomes totally fuel self-sufficient. Of course, if the more advanced deuterium-deuterium fusion reaction is realized and used in the future, then tritium will not be needed at all as a fusion fuel. (See 'Basics of the Fusion Process'.)

Lithium, the lightest of all the metals, is widely distributed

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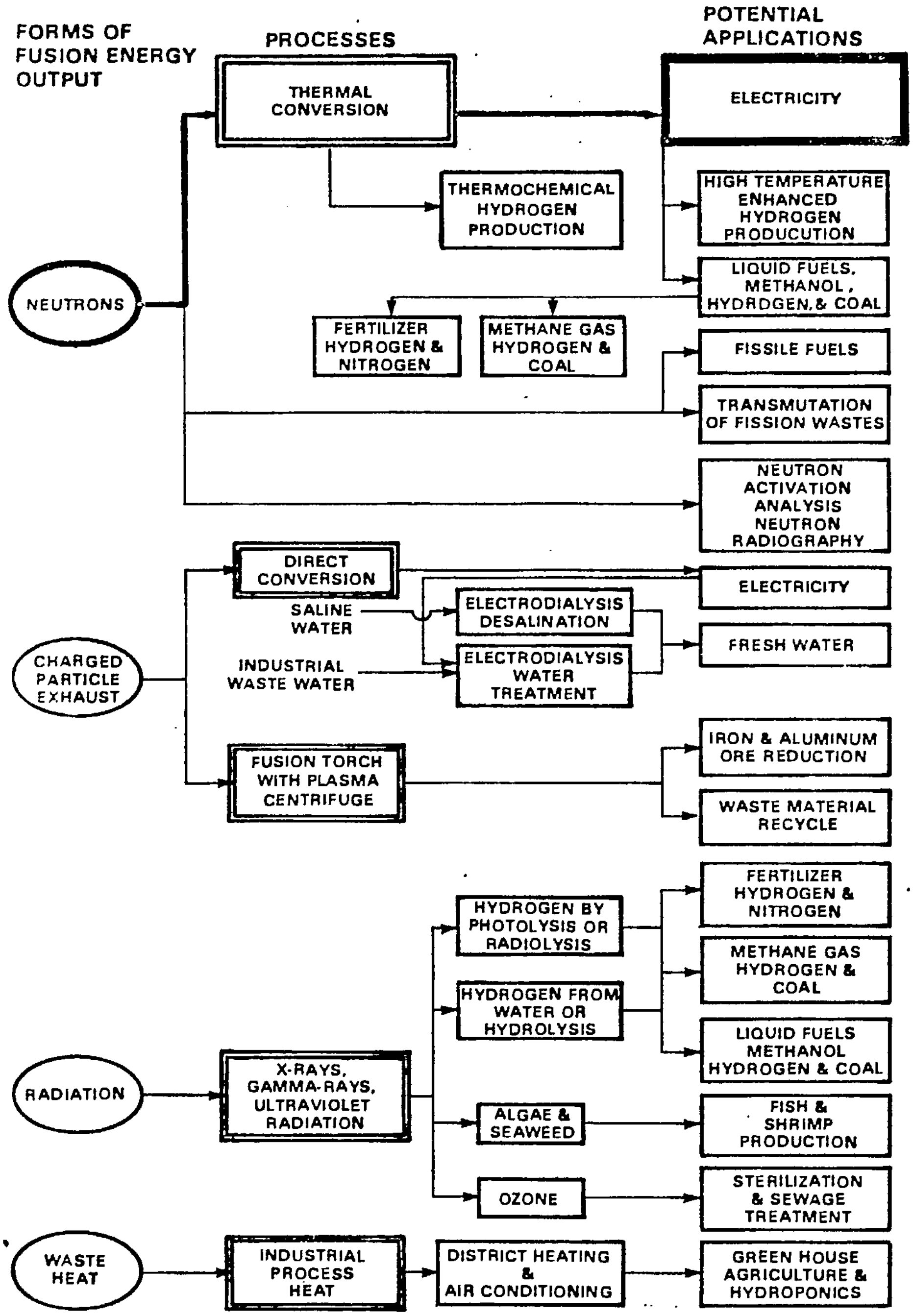
[33] Commission of Europen Communities, Towards Fusion Energy: The European Programme, January, 1976, p. 5.

Figure 18. Potential Applications of Fusion Energy



Source: Office of Energy Research, U.S. Department of Energy, *Magnetic Fusion Energy - Program Summary Document FY 1981*, January 1980, p. II-14 and available in great supply in the rocks of the world. Reasonably assured terrestrial reserves have been conservatively estimated at ten million tonnes - with an energy equivalent of the existing world coal resources. Lithium is also present in seawater in about two parts per million - some one hundred billion tonnes (although some uncertainty exists as to extraction costs and methods). Considering the relatively small amounts required in a fusion reactor, this lithium supply can be regarded as practically inexhaustible.

Given its enormous energy supply potential from this abundant fuel base, fusion is one of the very few possible energy sources vast enough to serve society's energy needs over the really long-term. The real promise of fusion lies in the possibility it offers of being a lasting, permanent solution to the world's future energy needs. Such a potent and ubiquitous energy source is naturally appealing to a world concerned with future energy supplies and resource dependencies.

Potential Energy Applications

Moreover, fusion power has the flexibility or scope to be used in a wide variety of potential energy applications. (See Figure 18.) Historically, fusion energy has been developed as a means of generating electric power: the energetic fusion products generate heat upon absorption and this thermal energy is then used to produce steam and drive conventional turbogenerators. (See 'A Fusion Reactor'.) In an advanced fusion fuel cycle - the deuterium-deuterium reaction - energy is created entirely in the form of electrically charged particles with the potential of direct conversion to electricity with efficiencies in the order of 90%. Direct process heat could be produced from a fusion reactor for chemical processing and district heating purposes. Fusion could also be used by electrochemical or thermochemical processes for the direct production of hydrogen, which could then be used directly as a gaseous fuel or indirectly as a feedstock in the production of various forms of synthetic fuels. In a fission-fusion hybrid system, a fusion reactor could be used as a neutron source to convert fertile materials such as U238 and Th232 into the fissile reactor fuels of Pu239 and U233. There is also a possibility that fission waste products could be burned up in a fusion reactor and made innocuous. In these and other ways, nuclear fusion could potentially contribute to the full range of society's energy needs.

Environmental and Safety Aspects

Nuclear fusion promises to be, relative to nuclear fission, a comparatively better, rather than an absolutely benign, energy technology in terms of its environmental impacts and safety aspects.[34] A fusion reactor would likely involve far less radioactive material than any fission reactor. Since both deuterium and lithium are non-radioactive substances, the only fuel element of any real concern here is tritium. The tritium radiosotope is quite difficult to contain due to its ability to permeat heated material. A safe and secure tritium handling system must therefore be in place in a fusion reactor.

But tritium, one of the least dangerous radionuclides, is vastly less hazardous than fission material by a factor of thousands. Tritium has low activity; when it decays the electron emitted is a low-energy electron that can not even penetrate skin. Tritium's half-life is relatively short - 12 years - and its decay products have little penetrating power. Although external exposure to tritium is not harmful to man, tritium can be harmful if taken internally. Even if it enters the body, however, it becomes associated with the water phase which changes rapidly, giving tritium a residence time of about 12 days - in contast to

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[34] See especially Kerry O'Banion, 'Long-term nuclear options', Environmental Science and Technology, October 1981, p.1130-1136.

certain fission isotopes which tend to deposit themselves in bones and other tissues. Although tritium will be present in the fusion reactor, only a minimal amount - perhaps a few kilograms - would be required in the reaction chamber, and plant inventories would be only 1-10 kilograms. If a major rupture of the reactor vessel occurred, only a very small amount of tritium would be released to the atmosphere. This would escape mostly in gaseous form and then exchange to form tritiated water, which, with the same chemical properties as normal water, would dilute rapidly to very low concentrations in lakes, rivers and oceans. Such tritium releases, therefore, would likely be quickly dispersed with little noticeable effects. Since tritium would be both consumed and produced in a closed cycle within a fusion reactor, only a small external amount would be needed to initiate a reaction and then no further outside transportation or presence would be required. A future deuterium-deuterium fusion reaction, of course, would eliminate the need for any tritium at all. Thus, tritium represents a relatively low hazard, with no continuing threat to biological and environmental systems.

Unlike a fission system, a fusion reactor would leave behind no radioactive residue from the fuel used. The only real 'waste' or end product of the fusion fuel is helium, a non-radioactive gas that is chemically inert and biologically harmless.

The only source of radioactive waste in a fusion reactor would be the activated reactor materials or structural components that become radioactive through neutron bombardment. While most of the energetic neutrons would react with the lithium blanket to produce tritium, some would unavoidably react instead with the structural materials near the core. Because of the strain imposed by the intense neutron flux and the extreme temperatures, some components would have to be replaced periodically and properly stored in isolation. These wastes, however, would all be in solid form and therefore less difficult to contain than liquid wastes. It has also been estimated that the cumulative biological hazard potential of such radioisotopes over their lifetime would be ten times less than those from a fast breeder. Moreover, since a variety of materials and shielding configurations are possible in an eventual fusion reactor, the quanitity and radioactivity of these activation products could be significantly reduced by the use of materials such as vanadium and titanium, which are less prone to neutron activation. Indeed, fusion offers a unique opportunity for biomedical and environmental investigation to suggest ways to reduce the production of radioactive materials.

A fusion reactor that generated electricity would do so at the same power conversion rate of about 30-40% as a fission reactor. The resulting thermal waste or waste heat - the balance of thermal energy produced in the reactor - would be rejected to the cooling water flowing through the condenser. A possible future deuterium-deuterium fusion reactor may, however, appreciably reduce such thermal pollution (and also result in far less radioactivity), if the energy charged particles are converted directly into electricity.

Other potential risks or hazards may exist in a fusion reactor. The biological implications and health hazards of high magnetic fields and powerful electrical field strengths are not as yet fully determined. Magnetic or pressurization failures could lead to the release of tritium under certain circumstances. The large-scale use of lithium poses some hazards. It is a toxic material which, if inhaled or ingested, can produce toxic effects in lung tissues, the nervous system and kidneys. Liquid lithium is chemically very active in the presence of air or water and the consequences of a lithium fire could be quite serious. For this reason, a number of nonreactive forms of lithium and other coolant concepts are being investigated. Another toxic material is beryllium, which might be used in a fusion reactor as a neutron multiplier. In addition, environmental difficulties may arise with the development and use of new alloys and materials whose exact nature and impact can not be foreseen in detail or assessed properly at this time. Although there is no a priori reason that they would have to be environmentally dangerous, they could be highly 'unnatural' in their characteristics with the potential at least for some environmental risks.

A fusion reactor, however, would tend to be inherently safe. Since it is so difficult and demanding to initiate and to sustain a fusion reaction, any slight deviation or imaginable mishap would result in a plasma failure that douses the reaction and stops the reactor almost immediately. Because fusion is thus self-limiting or self-quenching, and given the small amounts of fuel involved, there would be no prospect of a dangerous runaway reaction or a nuclear 'meltdown' situation. Even if all the plasma fuel could somehow react at once, the energy release would merely be absorbed by the surrounding blanket with a minor rise in temperature. There would be no Three Mile Islands and no China Syndromes in nuclear fusion. No elaborate safety systems such as the emergency core cooling system would be necessary. Any fusion accident situation would result in only very limited energy releases, with routine radiation emissions expected to be quite tractable.

Thus, although a fusion reactor would entail certain potential hazards or dangers - the presence of radioactive tritium, the activated structural materials, the use of toxic lithium -, the risks are expected to be relatively small and should be readily manageable or controllable. For these reasons, the potential environmental and safety advantages of fusion, especially over any fission system, are likely to be impressive and attractive. A definitive assessment, however, will only be possible once a particular fusion reactor technology has been fully developed and actually operated. Meanwhile, close attention will need to be paid throughout the fusion development process to environmental impacts and safety aspects.

Nuclear Non-Proliferation

Another important feature of fusion power will be its likely impact on the risks of nuclear weapons proliferation. The hydrogen bomb, of course, derives its power from the fusion process. But fusion bombs are far harder to design and build than fission bombs and their proliferation has been limited, not by a lack of fuels, but rather by a lack of knowledge. This is exactly the reverse of fission bombs. Any group or country sophisticated enough to make a fusion bomb would almost certainly be sophisticated enough to produce the fuel for it without access to a fusion reactor. (The fusion-fission hybrid reactor system would, however, entail proliferation risks since it would produce the fissile materials of U233 and Pu239.)

In stark contrast to a fission system, though, the byproducts generated in a fusion reactor would not lend themselves to the production of nuclear weapons. A fusion reactor would have nothing of interest to a weapons maker. Tritium alone is not a weapons hazard and is certainly not a material with nuclear blackmail potential. Although tritium is used in a hydrogen bomb, an atomic fission bomb is needed to create the high temperatures and conditions necessary to set it off. The knowledge entailed in a magnetic confinement fusion reactor is not relevant to a bomb design, as evidenced by the fact that all such research work has been declassified by international agreement since the 1950s. Inertial confinement work, however, does have relevance to weapons design and, for this reason, still remains largely classified.

Thus, fusion energy promises to have great advantages over a fission system in terms of the risks of nuclear weapons proliferation.

Public Acceptability

The future public acceptability of fusion power will likely be determined by the prevailing energy conditions at the particular time. Certainly, a future society in real, even desperate, need of fusion as an energy source will tend to accept its presence far more than a society that has other available alternatives from which to choose - ones that may be more familiar and comfortable than fusion. The exact public reaction to fusion in the future is, of course, very difficult to detail with any great confidence at this point in time.

It is clear, however, that general public knowledge or understanding of fusion power is currently scanty and meagre at best. Whatever fusion awareness that does exist is probably not marked by any real distinction between nuclear 'fusion' and nuclear 'fission'. Although these two processes are quite different and have very contrasting features as energy sources, there is a real danger that the public may nevertheless transfer whatever apprehension or opposition it now has over 'nuclear power' from one process to the other. This possibility of a mental and emotional spillover from fission will probably represent a serious drawback to eventual public acceptability of fusion.

Another major hindrance lies in the unfortunate clash between excessive expectations and sobering realities. Eager proponents of fusion could easily trap themselves by raising public hopes too high and too fast. Categoric and unequivocal statements on the merits of fusion, especially at this early stage in its development, when not even the actual technology is in hand, do not serve the cause of fusion. Such a situation developed in the mid-1950s when premature optimism about fusion was widespread, based on a grievous underestimation of the hard scientific difficulties involved. A more recent example was in 1978, when experiments with the Princeton Large Torus device managed to exceed the previous high temperature mark of 26 million °C by realizing a 75 million °C temperature - one that is fairly close to the 100 million °C level theorized as sufficient for a functioning, self-sufficient fusion reactor. This was indeed a significant accomplishment, but, unfortunately, became grossly overblown in the media, leaving the impression that nuclear fusion, as a viable process, was just around the corner.

This overselling or premature trumpeting of fusion power is simply counterproductive to gaining eventual public acceptance. It is, however, all too understandable, given that the very demanding requirements for fusion development - large-scale expenditures over long lead times at high risks of failure - are not easily met in a political system that tends to emphasize fast paybacks and the quick solution to most of its problems. The attempt to win public approval and support of fusion development must not be at the expense of warping reality.

Nevertheless, fusion power certainly does hold the long-term promise of greatly easing world energy problems and doing so in a advantageous way with respect to fuel dependency, environmental and safety aspects and non-proliferation risks. To the extent that this promise can be realized, fusion offers itself as an energy source that could be publicly accepted. Such acceptance will only materialize, however, as the result of a lengthy process of generating public awareness - a process that must proceed in tandem with the development of fusion.

2. The Status of Fusion Development

This section indicates the worldwide efforts being made in fusion development, the progress achieved to date and the remaining work and time involved in establishing fusion as a future energy source.

Fusion power is probably the most actively and intensively pursued new energy option in the world. The worldwide fusion R&D expenditures have risen from $100 million in 1969 to about $1 billion in 1977, to $2.5 billion in 1980 and to over $3 billion this year. (See Table 37.) This international effort will likely at least double by the end of the century. The principal actors with major fusion programs are the highly industrialized and technologically developed nations: the Soviet Union, the United States, the Euratom countries (France, United Kingdom, West Germany, Italy, Holland, Belgium, Denmark, Sweden and Switzerland), and Japan. Other nations involved in fusion on a smaller scale include Australia, South Africa, Spain, Brazil and Argentina.

Not only is the pursuit of fusion power very expensive, the development time-scale involved is probably longer than for any other energy source. Indeed, such development may well constitute the most time consuming R&D effort in recorded history - literally spanning generations. Almost thirty years have already been spent in fusion R&D, with advances coming slowly and difficultly but with steady progress being made, especially over the last decade.

To indicate the progress to date and the remaining path to travel, the three major successive crossroads or thresholds that must be reached in order to establish fusion power as a practical energy source will be described: scientific feasibility, technical and engineering feasibility, and commercial (economic) feasibility.

Scientific feasibility is proof that under laboratory conditions a reacting fusion plasma can actually be confined for a sufficiently long time that a positive energy balance can be obtained. (See 'Conditions for a Fusion Reaction'.) To achieve this scientific breakeven - the point at which as much energy or more is released by a fusion reaction as is put into the plasma to heat it - the Lawson Product of temperature, density and confinement time must be simultaneously achieved. This

Table 37. Estimated World Fusion R&D Expenditures

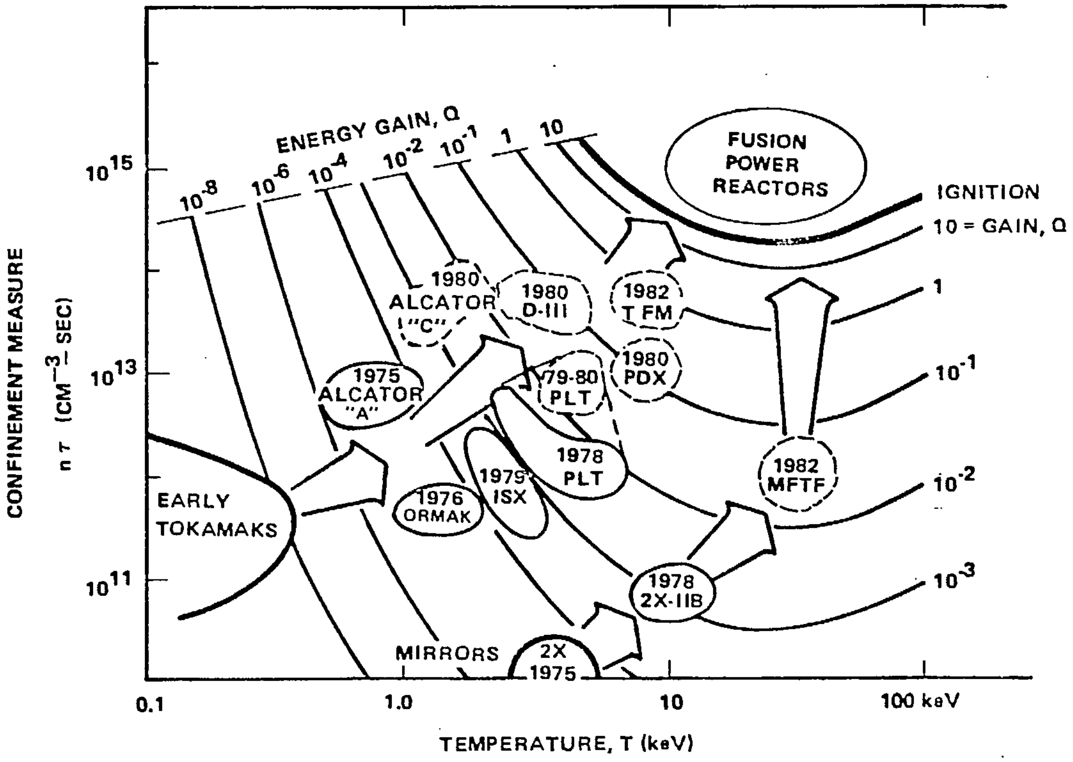
	millions of $		
	1977(1)	1980(2)	1982(3)
United States	415	600	750
Soviet Union	625	1,000	1,100
European Community	115	500	700
Japan	45	400	700
Total	1,200	2,500	3,250

(1) Geoffrey Newell, 'Canada's Fusion Future', Canadian Research, November, 1978, p. 14.

(2) Energy Alternatives, the Lefebvre Committee Report, March 1981, p. 167

(3) T.S. Brown, 'Canadian Fusion Program', presentation to the Canadian Nuclear Association, June, 1982, p. 6-7.

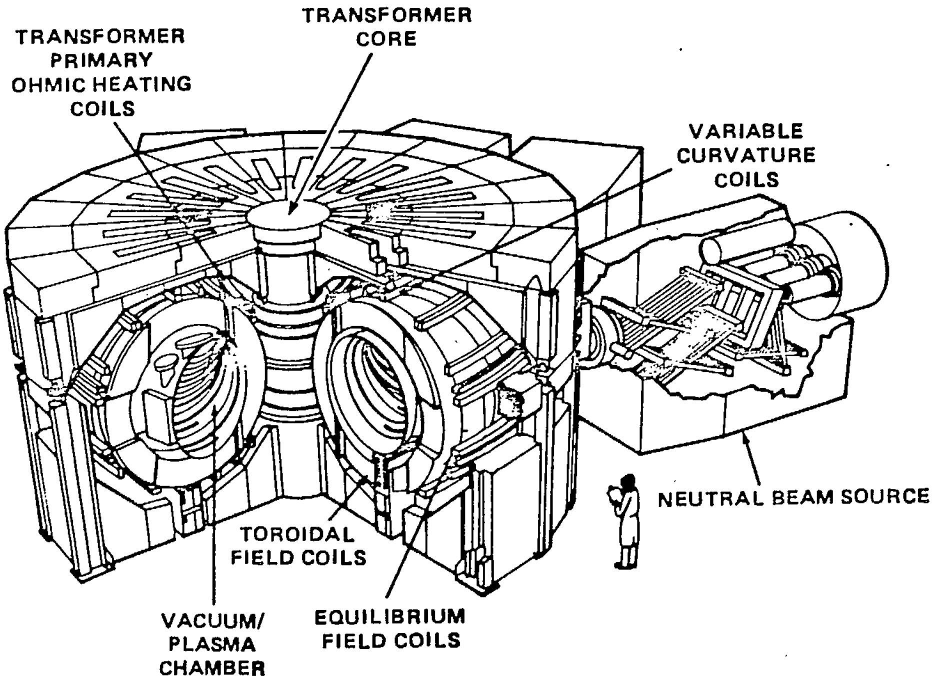
Figure 19. U.S. Progress Towards Scientific Feasibility in Magnetic Confinement



This figure identifies the plasma operating regime for each magnetic confinement concept with respect to the two critical plasma characteristics: the confinement measure (density X time) in centimetres per second and the temperature in thousands of electron volts. A self-sustaining fusion reaction requires a confinement measure of 10^{14} sec. cm^{-3} and about 10 KeV or 100 million °C (see 'Conditions for a Fusion Reaction'). Each contour line represents a value of energy gain, with Q=1 being energy breakeven where the energy output from the reaction equals the energy input to the reaction. Ignition is the condition when a burning plasma becomes self-sustaining in energy by fusion reactions alone.

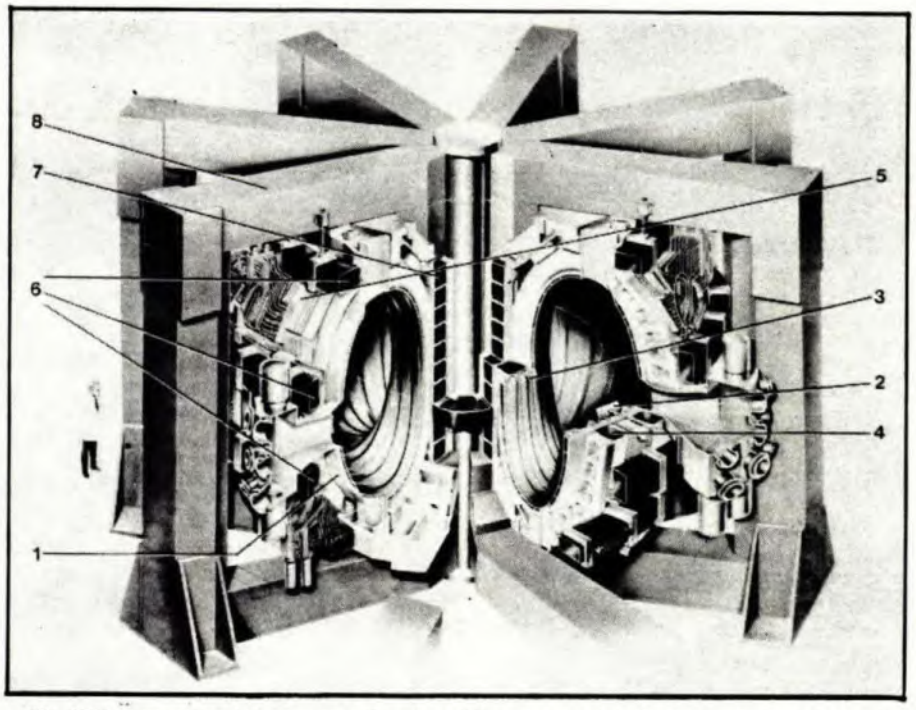
Source: Office of Energy Research, U.S. Department of Energy, Magnetic Fusion Energy - Program Summary Document, January, 1980, p. II-17.

TOKAMAK FUSION TEST REACTOR (TFTR)



TFTR, located at the Princeton Plasma Physics Laboratory in New Jersey, is scheduled to be operational by the end of 1982. Over $300 million will have been spent on constructing it, and roughly the same amount will be spent on operating it throughout the decade. Although it is the world's largest tokamak device, TFTR is not actually a reactor; it represents a unique opportunity to create and experiment with a fusion plasma. It is expected to reach or exceed a density - confinement time value of 10^{14} cm $^{-3}$sec - enough to ensure that the total fusion power output is comparable to the neutral-beam power input, or energy breakeven. It would therefore be the first fusion device in the world to demonstrate proof of scientific feasibility. Since it will have a tritium plasma with deuterium being injected into the plasma, actual fusion fuel will be burned for the first time, permitting physics and engineering studies to be conducted under real fusion reactor conditions. TFTR will also involve remote maintenance methods, significant alpha particle heating, an extensive diagnostic and monitoring system, and tritium fuel handling systems.

JOINT EUROPEAN TORUS (JET)



The JET apparatus: (1) vacuum chamber; (2) water-cooled limiter, which defines the outer surface of the plasma; (3) protection plates covering the bellows units; (4) toroidal field coil; (5) mechanical structure; (6) outer poloidal field coils; (7) inner poloidal field coils; (8) transformer magnetic circuit

JET will be Western Europe's largest fusion tokamak device. Located at the Culham Laboratories near Oxford, England, it was formally established in 1978 as a joint undertaking of the European Economic Community (United Kingdom, France, West Germany, Italy, Belgium, Netherlands, Denmark, Sweden and Swtizerland). It is scheduled to start operations next year at a total construction cost of $500 million. A twelve year experimental program will then be undertaken, the principle objectives of which will be the study of plasma physics under conditions approaching those required in a fusion reactor; the study of methods of heating plasma to temperatures at which, in a practical reactor, the energy produced by fusion will be enough to sustain the reaction (i.e. ignition point is reached); and the study of impurity problems with the plasma and in the torus walls. JET will therefore involve plasma in conditions and with dimensions that approach those needed for a fusion reactor, and is expected to demonstrate that such plasma can be made to fuse to release a net energy balance. This will constitute a proof of the scientific feasibility of a fusion reaction.

Source: Commission of the European Communities, Towards Fusion Energy: The European Programme, January, 1976.

Commission of the European Communities, The JET Project - Design Proposal, 1976.

Commission of the European Communities, The JET Project, 1975.

achievement has been the immediate goal of all fusion R&D efforts to date. As Figure 19 indicates, experimental programs have been such that it is now widely and confidently expected within the fusion community that this scientific feasibility will in all probability be suitably demonstrated by the mid 1980's. Based on a decade of experience in successively larger experimental devices, a number of scientific proof-of-principle test reactors involving the Tokamak concept are being constructed around the world and are scheduled to come on line shortly: the Tokamak Fusion Test Reactor (TFTR) at Princeton in the United States; the Joint European Torus (JET) of the European Community near Culham, England; the T-15 in the Soviet Union; and the JT-60 in Japan. (See 'TFTR' and 'JET'.) Magnetic confinement mirror devices are also being constructed (the Shiva Nova at the Lawrence Livermore Laboratories and the Elmo Bumpy Torus - Proof of Principle at the Oak Ridge National Laboratory) and in the inertial confinement approach (the Mirror Fusion Test Facility also at Livermore). The demonstration of scientific feasibility is considerably further off for these non-Tokamak devices than for the Tokamak approach.

The demonstration of scientific feasibility will, however, be only the end of the beginning. The next step will be to achieve technical feasibility including engineering practicality - proof that the basic technical problems of a fusion reactor can be solved, making such a reactor a technical and engineering reality. A host of formidable problems - some of which may not even be apparent as yet - in the actual design and materials of such a reactor will have to be successfully and confidently mastered. Such problems will include large-scale tritium handling, materials behaviour under extreme irradiating activity, remote handling of very complex machines, and the conversion of kinetic fusion energy into a useful secondary energy form. (See 'A Fusion Reactor'.)

Given the confidence with which the attainment of scientific feasibility is viewed for the Tokamak approach, the fusion emphasis is already shifting to this engineering phase with serious consideration and planning being devoted to the next generation of very large experimental devices: the Fusion Engineering Device (FED) in the United States; the Next European Torus (NET) in Euratom; the Fusion Experimental Reactor (FER) in Japan; the T-20 in the Soviet Union; and INTOR (The International Tokamak Reactor) under International Atomic Energy Agency auspices. (See 'FED' and 'INTOR'.) It is hoped that at least one of these engineering test devices will start construction by the middle of this decade, begin operating in the early part of the next decade, and achieve technical feasibility by the end of the century. Current program plans in the United States also call (perhaps optimisticaly) for the start of designing a full-scale demonstration fusion power reactor in the early 1990s and for initial operation by the year 2000.

To realize its potential, of course, fusion power must be commercially feasible. Besides demanding an effective and reliable resolution of all the technical and engineering problems associated with its practical application, fusion power will require that the economics of its technology must be such that it offers an attractive alternative to other existing energy technologies. Having a technicaly proven fusion technology in place and available will not necessarily mean that it will also be economically worthwhile on a commercial scale at prices competitive with other energy sources.

A 1 GWe fusion reactor could cost as little as $2 billion.[35] It might also cost $10 billion but it might just as well cost half as much or twice as much.[36] Given the present position of fusion development, it is simply too early to make a definitive and reliable economic assessment. Such an assessment will likely not be possible until a better indication of the probable technology

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[35] Pat Ohlendorf, 'Fusing the future', <u>Maclean's</u>, June 23, 1982, p.48.

[36] 'Fusion hots up', <u>The Economist</u>, July 24, 1982, p.79.

INTOR

INTOR, the acronym for International Tokamak Reactor is the name for a proposed international project to construct a 'next generation' fusion reactor in magnetic confinement. A joint study group composed of the leading contributors to the world fusion effort -- the United States, the Soviet Union, the European Economic Community and Japan -- was formed in the late 1970's under the auspices of the International Fusion Research Council of the International Atomic Energy Agency in Vienna. This group conducted technical workshops on the preliminary design and basic parameters for such a reactor.

INTOR was expected to entail capital expenditures of $1 billion and would probably have at least a twenty year operational lifetime, beginning in 1990, at the level of perhaps $50-100 million per year. It was expected to identify and resolve certain engineering problems which must be overcome in order to develop a practical fusion reactor. This would have involved a number of activities: burning a deuteurium-tritium plasma, reaching the ignition point, breeding tritium in a blanket, generating net power and demonstrating the long-term reliability of component materials. Since fusion devices capable of demonstrating scientific feasibility were under construction for operations starting in the early 1980's, the concern was to initiate an engineering test-bed program to demonstrate technical feasibility. A possible international cooperative venture was suggested, given the extremely large expenses involved and the advantages of having one such test reactor rather than a number of different national ones.

The international situation that developed, however, cast serious doubt as to whether the project would be pursued. The deteriorating American-Russian relationship and the apparent end to détente, stalled progress. Meanwhile, the U.S. appears to have opted for developing its own domestic device -- the Fusion Engineering Device (FED). There remains a great uncertainty as to whether the INTOR project will be pursued to realization.

At one point in the late 1970's, the possibility of Canada hosting the INTOR facility was raised. Canada might have become a compromise site if agreement on the first selections of the major participants were not approved by all. An interdepartmental study committee chaired by MOSST studied this possibility and, after considering the likely merits and benefits involved, recommended in the fall of 1979 that Canada should express a serious interest in hosting INTOR. With the subsequent Soviet invasion of Afghanistan and the resulting world political situation, the possibility of INTOR became seriously undermined and the siting question became irrelevant. Since then, Canada has maintained a watching brief in this area.

Source: MOSST, Report of the Interdepartmental Ad Hoc Committee on INTOR in Canada, September 20, 1979.

THE FUSION ENGINEERING DEVICE (FED)

In 1978 a U.S. Department of Energy review of the fusion program, headed by John Foster, recommended a major increase in emphasis on engineering problems related to fusion in order to provide the basis for choosing a demonstration reactor type. In 1980, a Congressional Fusion Advisory Panel concluded that the very significant recent progress in fusion research warranted an engineering thrust centering on an engineering test facility. Also in 1980, a Fusion Review Panel chaired by Solomon Buchsbaum for the Department of Energy made the major recommendation that a broad program of fusion engineering experimentation should be undertaken. The result was that in September of 1980 the Congress enacted and President Carter signed the Magnetic Fusion Engineering Act of 1980. This Act called for an accelerated development of fusion R,D&D: the creation of a Centre for Fusion Engineering (CFE); the construction within ten years and at a cost of $1 billion of a Fusion Engineering Device (FED), which would focus on developing and testing reactor-relevant technologies and components in order to prove engineering feasibility; and the production of a commercial demonstration fusion reactor by the end of the century. This 20 year effort would cost about $20 billion.

Given the Reagan Administration's budgetary constraint exercise over the last few years, however, the appropriate scale-up of fusion funding as called for in the 1980 Act has not been forthcoming. Although the principle of fusion development is still endorsed and although other energy R&D areas such as conservation and solar have been decimated, the fusion program has remained basically static in its budget. Cutbacks have, however, been made on plans for the Centre for Fusion Engineering, the Fusion Engineering Device, the Elmo Bumpy Torus - Proof of Principle project, the Mirror Fusion Test Facility and the Fusion Materials Irradiation Test Facility. These cutbacks in fusion research programs and policies led to the protest resignation in December of 1981 of Edwin Kintner as director of the Department of Energy's Office of Fusion Energy. It appears that, in spirit and in practice, the Apollo-like acceleration in fusion development called for in the 1980 Act has been derailed. Whether or not it will be be able to get back on the fast track remains an open question.

Source: Edwin Kintner, 'Casting Fusion Adrift', Technology Review, May-June, 1982, p. 64-73.
'DOE budget cuts fusion and boosts basic research', Physics Today, April, 1982, p. 55-57.

involved is available. This will not occur until after a fusion reactor has been technically demonstrated - perhaps sometime after the turn of the century. This kind of time span is so much beyond the usual planning horizon that a conventional cost/benefit analysis can not be made accurately or confidently at this point in time.[37] An attempt to project exactly when fusion power would be an economically viable energy alternative would entail aiming at a moving target and must be highly speculative in nature: 'Actual commercial introduction will depend on many factors ... none of these factors can be predicted with great confidence'.[38] It is clear, however, that the route to commercial fusion power will be a long and costly one involving the solution of extremely difficult technological problems. In view of the many steps that have to be taken, it appears unlikely that a commercial fusion power reactor will be in use within the next fifty years.

Energy and economic considerations at that particular future time will govern whether or not the developed fusion reactor is economically competitive and commercially deployed. A proven fusion technology may not be commercially justified if alternative energy technologies, such as the fast breeder reactor, are available at an economic advantage. A fusion reactor may be too large and too expensive to be of any real commercial interest. The particular fusion reactor actually developed may be the best fusion technology but may not be the best one economically. In short, there is no certainty that fusion will turn out to be an economic proposition - ever.

On the other hand, there is a real possibility that fusion could become a relatively low-cost energy source in the next century and quite competitive with its likely major alternative, the fast breeder reactor. Current studies and data, preliminary

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[37] Energy Alternatives, Report of the Special Committee on Alternative Energy and Oil Substitution (the Lefebvre Committee), March, 1981, p.166.

[38] T.S. Brown, 'Canadian Fusion Program', June, 1982, p.6

and tentative as they must be, involve a wide range of cost estimates but indicate that the cost of a fusion reactor, although higher, could well compare acceptably with that of the fast breeder and would not differ in order of magnitude from that of a conventional fission reactor. One estimate indicated that the capital costs of a fusion reactor might be 50% more than that of a fast breeder reactor. (See Table 38.)

Electricity from a fusion reactor would indeed be extremely capital cost intensive - at least 90% - with almost all of the remaining costs involved with operating and maintenance. A fusion reactor would be very materials intensive, requiring appreciable quantities of what might become scarce and costly materials - beryllium, niobium, vanadium, molybdenum and titanium. Such component materials could in the future not be readily available or only at expensive costs. Since the exact material requirements will, of course, only be determined by the actual reactor technology deployed, other less expensive materials could conceivably be designed or used to reduce the materials requirements and the capital costs involved.

On the other hand, given the abundant and very cheap fusion fuels involved, it has been estimated that the fuel cost of a fusion reactor would be negligible - less than 1 mill per kWh.[39] The cost of deuterium, for instance, could be the equivalent of buying gasoline at about 1¢ per hundred gallons.[40] Since costs would, therefore, be relatively insensitive to any rise in the prices of scarce fuels, a fusion reactor could be expected to eventually develop a stronger economic advantage over those other energy systems that do not share this unique feature. However, a fusion reactor operating as a neutron source for the production of fissile material in a fission-fusion symbiosis would tend to

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[39] Paul Redhead, National Research Council, July 2, 1980, Lefebvre Committee Minutes No. 2, p.36.

[40] Richard Post, December 10, 1980, Lefebvre Committee Minutes No. 35, p.14.

Table 38. An Estimate of Possible Costs of Electricity from a Fusion Reac[illegible]o and a Fission Breeder Reactor

	Fusion	Fission Breeder
Power Level (MWe)	900	900
Capital Cost ($/KW)	1250	800
Operating Cost (Mills/kW-h)	24-28	17-27
Fuel Cost (Mills/kW-h)	Negligible	5-9
Plant Lifetime (Years)	30-35	30-35

Source: Geoffrey Newell, 'Canada's fusion future', Canadian Research, November, 1978, p.23.

become economic at an earlier point in time than would a stand-alone fusion reactor for energy production.

3. Conclusions

Based on the preceding assessment of nuclear fusion, the following conclusions can be reached:

(1) Fusion energy represents one of the few possibly inexhaustible energy sources with the potential to sustain society's energy needs indefinitely. It offers virtually limitless energy from a virtually limitless fuel base.

(2) Although not absolutely clean and safe, fusion does promise to have substantial environmental and safety advantages over other energy technologies, especially fisson reactors. A fusion reactor would not entail any real risk of enabling nuclear weapons proliferation. Future public acceptability of fusion power is an open question, but may be favourable if the fusion-fission distinction is appreciated, if fusion is not oversold and if a solid public awareness of fusion is developed over time.

(3) Fusion power development is now being actively pursued by industrialized countries throughout the world. This effort will continue and increase in the next few decades. The fusion research progress to date has been such that a number of major fusion devices, now coming into operation around the world, will almost certainly demonstrate the scientific feasibility of the fusion reaction within the next few years. The engineering phase of developing the fusion reactor technology is now being entered into, with major engineering test-bed devices close to being committed and constructed. A full-scale demonstration of a fusion reactor could be in place not too long after the turn of the century. A commercial fusion reactor will likely not be available for introduction before the year 2030.

(4) A definitive and reliable economic assessment of the commercial feasibility of a future fusion reactor is simply impossible at this time, and will not be possible until the actual reactor technology has been developed and demonstrated. Indications are, however, that the cost of a fusion reactor, although higher, could well compare acceptably with that of the fast breeder reactor, and would not differ in order of magnitude from that of a conventional fission reactor. Although a fusion reactor would be extemely capital cost intensive, it would have negligible fuel costs, and this would be insensitive to fuel price increases in the future.

(5) The promise of fusion energy is great and the effort needed to realize this promise in practical fusion power is also great. The development of fusion power will probably be the most time-consuming, costly and technologically challenging venture ever embarked upon. It may also turn out to be the most important pursuit for the long-term energy future of society.

F. A CANADIAN FUSION R&D POLICY AND PROGRAM

This section concerns fusion R&D in Canada and is in three main parts. The first part provides an account of the development of fusion R&D policy over the last decade. The second part involves a statement of governing policy principles: the basic rationale for a Canadian fusion R&D effort, the appropriate objectives and goals involved, and the necessary guidelines or conditions. The last part applies these principles to examine the current and future fusion R&D program elements in Canada.

1. Policy Development

What follows is a summary account of the development of fusion R&D policy in Canada since the early 1970's, based on the key studies, concepts and events. This development was the basic embryo from which evolved the current policy position.

The November 1974 report to MOSST of the Project Fusion Canada (Study Project for a Canadian Programme on Controlled Thermonuclear Fusion)[41] made a number of important recommendations that formed the conceptual basis for much of the subsequent policy thinking in fusion R&D matters. In essence, it was suggested that Canada should develop and maintain a small but sophisticated technical effort in fusion research, so that it would have access to and benefit from the development in other countries. A coordinated fusion R&D program in Canada was proposed, with the immediate goal of developing a scientific know-how and an engineering/technological awareness capability. It was recommended that the initial program should consist of viable applied R&D activities in magnetic confinement with a small Tokamak machine, in inertial confinement by high power carbon

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[41] Project FC-Study Project for a Canadian Programme on Controlled Thermonuclear, Recommendations for a Canadian Programme on Controlled Fusion - Volume 1, November, 1974.

dioxide lasers, in fusion reactor materials with an intense neutron source, and in systems engineering with the design and engineering and economic evaluation of conceptual fusion reactors. The annual budget for capital costs and operations should increase from $4 million in the first year to $18 million in the sixth year. An agency of the federal government should be appointed to take full responsibility for the program, and this lead agency should set up an advisory board. A single, central fusion laboratory should be created as the focus for fusion activities in Canada. Canadian industry should be strongly encouraged to participate through contracts in the research, design, development and construction of the program. Research contracts should also be let to appropriate universities. All possible mechanisms of international cooperation should be explored in order to assure Canada of the maximum benefit in fusion research.

The Project Fusion Canada study laid the basis in principle and in rationale for a Canadian fusion R&D program. The only direct tangible results from the study, however, were the appointment of the National Research Council of Canada as the lead agency responsible for fusion R&D, and the formation by NRC in 1977 of an Advisory Committee on Fusion Related Reserach to advise NRC on matters related to the planning, context and implementation of a proposed Canadian fusion R&D program.

In March of 1975 the Science Council of Canada's energy study, entitled Canada's Energy Opportunities, considered fusion R&D in the broader energy context and arrived at a number of interesting conclusions. Canada can neither wait for fusion to solve its energy problems nor afford the many billions of dollars that will be required to prove and develop the technology. In this situation Canada should buy its way into future fusion advances by cooperating with interested foreign groups and undertaking one particular aspect of the total program. This would be a very profitable investment if it gained Canada access to the total technology. The risk of losses could be offset considerably by concentrating on an area of fusion technology that would have extensive spin-off benefits for Canadian industry, e.g., materials technology. This could accredit Canada in the context of world fusion programs, and add significantly to its technological capacity. Thus, the most attractive alternative for Canada would be a program of international collaboration with domestic specialization - two elements that were to become integral components of the eventual fusion R&D program developed. In addition, the Science Council report suggested that initial work should concentrate on fusion as a neutron source for use in breeding fissile material rather than on fusion as a net energy generator. In this way, involvement in fusion technology could become a natural long term adjunct to the nuclear fission power program. Finally, it was envisaged that Canada's contribution to fusion technology would cost in the range of $10 to $20 million annually, averaged over the next 20-25 years.

In July of 1978 NRC announced the establishment of a National Fusion Program, with the objective of the program being to establish and maintain in Canada the necessary expertise as a foundation from which the capability of providing fusion reactors could ultimately be developed, if and when engineering and economic feasibility have been demonstrated. The roles of the various sectors of the scientific community were identified - the universities, the federal government, the provincial governments and industry.

At the Federal-Provincial energy meeting in November of 1978, the Provincial Energy Ministers presented a statement to the federal Minister of EMR on the Canadian Fusion R&D program.[42] The statement it recognized that fusion energy appears to be one of the most promising long term alternative energy sources, and recommended that Canada should accelerate its fusion R&D program

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[42] Geoffrey Newell, "Canada's fusion future', <u>Canadian Research</u>, November, 1978, p.15.

to avoid becoming total dependent on foreign technologies in the future. It further asserted that significantly increased funding must be granted by the federal government, that the R&D program must be worked out in close collaboration with the provinces to avoid duplication and to ensure the maximum utilization of the existing expertise in Canada, and that the program must put emphasis on those areas where Canada has already developed some technical comparative advantages (materials, magnetic confinement and laser confinement). The Inter-Provincial Advisory Committee on Energy (IPACE) established a Fusion Committee to provide it with information and advice on progress being made. The provinces reiterated their fusion recommendations at the Council of Provincial Energy Ministers in October of 1979. In addition, individual provincial governments wrote to federal Ministers asking that their interests be respected in inertial confinement fusion (B.C. and Alberta), in materials/engineering (Ontario) and in Tokamak magnetic confinement (Quebec).

In the summer of 1979, an interdepartmental committee on INTOR, chaired by MOSST, was established to evaluate the merits of Canada hosting the joint international Tokamak project. The resulting committee report[43] in September of 1979 recommended that Canada should make a strong statement of interest in hosting the INTOR project. However, with the Soviet invasion of Afghanistan, and the deteriorating world political climate in East-West relations, the INTOR project was not pursued and the possibility of a Canadian site, very small to begin with, became irrelevant.

The National Fusion Program began with a modest initial budget of about $0.3 million in 1978-79 - a budget level that remained modest at that same level for the next three years. The best that could be accomplished was the support of several studies and the temporary posting of a couple of engineers at foreign fusion

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[43] MOSST, Report of the Interdepartmental Ad Hoc Committee on INTOR in Canada, September 20, 1979.

laboratories. Meanwhile, fusion related activities in Canada plodded along in a variety of diverse directions, with no major facilities or focus and with the loss of key personnel to the expanding U.S. program. During this period, support was provided by the Natural Sciences and Engineering Research Council through its strategic grants competition in the order of $750,000 annually. This support presently involves over $1 million per year.

As an attempt to stimulate movement in the National Fusion Program, NRC'S Advisory Committee made a direct representation in a brief submitted to the MOSST Minister in March of 1980.[44] This brief stressed that Canada was the only important industrialized nation that did not have a serious fusion program. With the rapid fusion advances being made in the world, it is important, the brief noted, that Canada develop a technological base from which well informed decisions regarding the role of fusion for Canadian needs can be made. Furthermore, it is essential that Canadian industry be put in a position to supply at least some of Canada's requirement for fusion hardware in the future and, if possible, to compete for the supply of some specialized sub-systems and auxiliary equipment on a world wide basis. It was recognized that this is a long term process that will take time. The brief indicated that while immediate opportunities for international collaboration exist today, once scientific feasibility has been demonstrated in the mid-1980s, a nation that does not have a credible fusion program will likely be excluded.

The Advisory Committee brief stated that the immediate goal for Canada must be to establish a national program of technological and scientific capability and industrial preparedness which would permit Canada to gain access to, and be in a position to use, the vastly increasing pool of knowledge and

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[44] NRC Advisory Committee on Fusion-Related Research, 'A National Fusion Program for Canada', March 1980.

technology on fusion energy. Achievement of this goal will require: the federal government to take the lead in funding and initiating the program; a coordinated effort by federal and provincial governments, the utilities and Canadian industry; concentration on a few selected areas in order to achieve and maintain international credibility by contributing to the world pool of knowledge; intensive international collaboration; and a strategy to ensure adequate and properly trained manpower.

Recommendations for a minimal National Fusion Program for Canada to achieve these goals included three actions. First, the development of a National Capability consisting of concentrated centres for inertial confinement (a national laser fusion facility with emphasis on CO2 lasers established around the NRC laser capability), for magnetic confinement (a Tokamak technology fusion facility at IREQ-Hydro-Québec in Varennes, operated as a national facility), and for selected technologies (specialization in one or two selected engineering technologies associated with fusion power systems). Secondly, the implementation of an intensive program of international collaboration through a planned exchange of experts between Canadian and foreign facilities, through formal bilateral agreements between major Canadian centres and appropriate foreign centres, and through an involvement in the next major international or U.S. fusion facility (INTOR or FED). And lastly, the approval of a minimal federal budget for the National Fusion Program (constant 1979 dollars): $3 million in 1980/81 increasing to a steady level of $12 million annually by 1983/84; and cumulative funding totals of $30 million over the four year period from 1980/81 to 1983/84, and of $81 million over the eight year period from 1980/81 to 1987/88.

In June of 1980 the NRC submitted to the federal government a detailed plan for A National Program of Fusion R&D.[45] (The

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[45] NRC Program Plan, 'A National Program of Fusion R&D', June 25, 1980.

program described in NRC's document was supported by the Interdepartmental Panel on Energy Research and Development on June 26, 1979.) The document recommends that the preferred program alternative is one of 'international collaboration and industrial preparedness'. The program objective is to establish and maintain in Canada the necessary expertise as a foundation from which the capability of providing fusion power systems can be developed, when the scientific and economic feasibility have been demonstrated. The short-term goal is to gain, within five years, access to international knowledge and know-how in fusion technology. The intermediate-term goal is to gain, within ten years, a capability to exploit some areas of fusion technology. The long-term goal is to gain, within twenty years, a technological capability sufficient to allow Canadian industry to participate in the manufacture of fusion power systems. In order to attain the program's short-term goal, a technology base for international collaboration is required in each of the three general areas of fusion technology: inertial confinement technology, magnetic confinement technology and materials/engineering technology. Also in order to attain the program's short-term goal, Canada must begin to make a significant contribution to the international fusion effort in the very near future. Given the complexity of fusion technology, this requires concentrating the effort on a minimum number of focal technologies and building the expertise in these focal technologies on the strongest capabilities that currently exist. The participation of industry and the utilities from the beginning was recognized as important so as to maximize their opportunity in the near-term to exploit applications of the focal technologies. The concentration on a few focal technologies was considered important, since it would lead to earlier exploitation. The minimum cost to establish a narrow fusion technology base just sufficient to gain access to international know-how through collaboration was estimated to be $10-20 million per year. The total cost of the eight-year program from 1980/81 to 1987/88, in 1979 dollars, was estimated at $147 million, of which $88 million would be the federal government share and $60 million the provincial governments contribution.

This NRC commitment to fusion R&D was strongly reiterated in its long range plan of October 1980.[46] In this plan, the NRC first pointed out that the problem of exploiting Canada's vast energy sources will continue to be an urgent national priority for the foreseeable future. Canada's need to achieve energy flexibility will require substantial investment in R&D in order to exploit options for alternative energy sources as the conventional oil and gas reserves dwindle. A particular concern was expressed for the longer-term energy options because the energy strategy for national self-reliance must not be pegged to a single date in the future, nor to a single energy commodity. Because of its mandate, NRC has a special responsibility to evaluate long-term options for energy and to foster these options if they are found to offer a future opportunity for exploitation.

These considerations led NRC to sponsor a national fusion program for Canada and to submit a proposal to Cabinet for fusion R&D. NRC offered to vigorously pursue its special role within the national energy R&D program by carrying out expanded activities in fusion. Research in support of nuclear energy should be increased, NRC noted, so that more resources could be channelled towards establishing a nuclear fusion program. NRC proposed that the fusion program would require resources from 1980-81 to 1985-86 of $54 million (constant 1980 dollars) and 38 person-years.

The last study to be mentioned here in this history of Canadian fusion R&D policy development is the Report of the Special Committee on Alternative Energy and Oil Substitution in March of 1981.[47] After describing the nature and status of fusion

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[46] NRC, The Urgent Investment - A Long Range Plan for the NRC of Canada, October, 1980, p.17, 46-50.

[47] 'Fusion Energy', Energy Alternatives, Report of the Special Committee on Alternative Energy and Oil Substitution, March, 1981, p.161-169.

energy, evaluating the advantages and difficulties in using fusion energy and noting the international and Canadian fusion development efforts, the report comes to a number of conclusions. For example, it concludes that evidence strongly suggests that fusion will be harnessed in commercial power systems early in the next century. Although a time can not be identified at which the Canadian energy system would require the input of fusion energy, the report nonetheless anticipated that substantial benefits would flow from participation in the international program to commercialize fusion energy. Those benefits will not accrue to Canada at its current level of support of fusion R&D. The report therefore recommends that the program of expenditures proposed by the NRC Advisory Committee be adopted by the federal government, i.e., approximately $54 million (in constant 1979 dollars) for the five year period from 1980/81 to 1984/85. An independent review should be carried out in the third year of the program, and after five years, to determine its effectiveness.

This history of fusion R&D policy development in Canada over the last decade indicates the road travelled to reach the current Canadian Fusion Program. What follows is a statement of the policy principles that should govern Canadian fusion R&D: the basic rationale, the appropriate objectives and goals involved, and the necessary guidelines or conditions.

2. Policy Principles

Energy is a vitally critical element in the present and future development of Canada as a modern, industrial society. With the potential to achieve energy self-sufficiency within the decade, Canada has establishd an array of policies and programs to realize this potential. In the long term, however, Canada, like the rest of the world, will need to make the inevitable transition away from an energy economy based largely on dwindling fossil fuels to one that is reliant on renewable and/or virtually inexhaustible energy sources. Canada's long-term energy needs must be considered now, if there is to be any hope of meeting them, and of sustaining an energy self-sufficiency position. There are good reasons for suggesting that Canada will need to develop additional, inexhaustible energy sources that depend on a widely available and abundant fuel base.

In order to have such future energy sources available at the time and to the extent that they will be needed, Canada must work to keep open its options in these areas. This will require a continuing energy R&D effort to develop a competence in the science and technology of these inexhaustible energy alternatives. The real importance in keeping open these long-range energy options through the use of R&D was appropriately acknowledged in the National Energy Program of 1980: 'The transition from our current heavy reliance on fossil fuels is inevitable. It will be difficult and costly. R&D provides a technology basis for long-term energy options beyond 1990 ... and for the choice of transitions.'[48] This principle was recently reiterated in the National Energy Program Update of 1982, which acknowledged 'the central role of R&D in increasing Canada's long-term energy options'.[49] It is therefore prudent and far-sighted to make an R&D investment now in order to keep open future energy supply options in the areas of potential, inexhaustible energy sources.

As previously indicated, the inexhaustible energy sources that are potentially available to Canada and the world in the future consist of renewable energy sources, advanced cycle nuclear fission and controlled thermonuclear fusion. Fusion is, therefore, one of the very few possible energy alternatives with the potential promise to offer virtually limitless energy from a fuel base that is practically inexhaustible. Such a potent and ubiquitous energy source could provide a lasting, permanent

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[48] EMR, National Energy Program 1980, November, 1980, p.75.

[49] EMR, National Energy Program - Update 1982, June, 1982, p.30.

solution to Canada's long-term future energy needs. Fusion might also offer as well considerably attractive advantages over other energy technologies in terms of its environmental impacts, safety aspects and the risk of nuclear weapons proliferation. Although it is too early to make a reliable and confident assessment, fusion might well become an economically competitive energy alternative in the future.

Given this promise of fusion, all of the major industrialized nations are undertaking substantial fusion development programs as a possible way of meeting their long term energy needs. Canada should keep open this fusion energy option for the future. This would enable Canada to be in the flexible position to make a decision at an appropriate future time on whether or not to actually adopt a fusion power system. If this flexibility is not kept, Canada is unlikely to be in a position to choose what may turn out to be an extremely important and perhaps critically necessary energy technology in the future. Therefore, in order to meet long range energy needs and to sustain energy self-sufficiency in the long-term, a strategic objective of Canada's energy policy should be to keep open the fusion power option by establishing the necessary scientific expertise and technological capacity to develop fusion power when and if such development becomes desirable or necessary in the future.

Of course, there is always the option of purchasing and importing fusion technology from abroad on a licensed or branch-plant or turn-key basis. This would eliminate the need for a lengthy S&T development in Canada on fusion, and free the resources so saved into other areas. The costs of this action, however, would be prohibitive and unacceptable. A total reliance in the future on fusion technology from abroad would leave Canada entirely subservient to foreign technology, and would undermine the desired posture of sustained energy self-sufficiency. It would also entail considerable balance of payments costs. Further, there would be no real S&T expertise in Canada to ensure that the best available fusion system is imported. Nor would there be a capability in Canadian high technology industry to allow any effective participation in designing and/or constructing such a fusion system. There would also be another very disturbing effect. All the major industrialized nations are actively funding significant fusion programs, not only as a possible way of meeting their long term energy needs, but also because fusion power is internationally recognized as being on the cutting edge of the technological frontier - with the potential of having a profound impact on society in the next century. A decision by Canada not to participate in this key advanced technology, in what is undoubtedly a great technological challenge, would likely undermine Canada's scientific and technical reputation, and thereby weaken Canada's independent international influence in S&T matters. A nation that so excludes itself from one of the most important of high technologies in the mainstream of world development would be in danger of abrogating its status as a first-rate technological nation.

The other extreme to a no fusion R&D approach is for Canada to undertake on its own a totally independent and full-scale effort to develop a complete fusion power system - one that Canada would have the capability to manufacture and export as its very own, much as is the case with the CANDU reactor. However, as a relatively small country with comparatively minor resources, and as a late comer to the fusion effort, Canada could not possibly undertake this task, since it would require a minimum cost of $100-200 million a year for at least 30 years. Indeed, because even the major fusion actors such as the Soviet Union, the United States, Euratom and Japan are finding it increasingly difficult to undertake their programs alone, especially given the great costs involved in the next generation of engineering and demonstration fusion reactors, there is an active seeking of joint, common efforts to minimize costs and to optimize results.

Because a totally foreign dependency on fusion technology is undesirable and because a totally independent and full-scale indigenous program on fusion development is impractical, a Canadian fusion R&D program must be based on the cornerstone of international collaboration. It must be undertaken in a close relationship with and as an integral part of the accelerating world fusion effort. Only in this way will Canada be able to gain access to the scientific knowledge and technical know-how now being developed abroad, and to benefit from that access by developing a Canadian industrial capability to manufacture components and materials for both Canadian and foreign markets.

However, Canada must be able to contribute something of its own that is worthwhile, meaningful and of interest to the world fusion community if collaboration is to be a realistic possibility. The price of gaining access to the world pool of fusion knowledge is providing a significant contribution of value to that pool in return. Such a contribution requires that Canada have in place an established domestic R&D program of its own that is sufficiently scientifically sophisticated to make an original input of real value. Such a program therefore needs to be more than merely a 'watching brief' or a minimal awareness effort; it must be an active and innovative activity at a level and of a calibre that breaks new scientific ground of importance and interest.

Moreover, such a program must be firmly established and making its contribution within this decade. With the demonstration of scientific feasibility of the fusion process confidently expected by the mid-1980s, and with plans to establish a demonstration fusion reactor by the end of the century, the engineering phase of fusion development - seeking to prove technical feasibility - is now being embarked upon, and industry is beginning to play a major role. As expected in this shift of emphasis, technical and engineering information is becoming commercially confidential and access to such information more resricted. For instance, the last, large open laboratory - the Princeton Plasma Physics

Laboratory - imposed controls on its technical and engineering documents in 1979. There is therefore good reason to doubt that information will be as readily accessible and that cooperative arrangements under favourable conditions will be as easily available by 1990 as they are now. If Canada has not established and proven itself as a contributing fusion actor of some importance by that time, it will likely be excluded from particpating in the future exploitation of fusion technology.

This suggests that the primary objective of a Canadian fusion R&D policy for the 1980's should be to establish and maintain a domestic scientific and technical capability as the basis for achieving international collaboration with foreign fusion programs. This collaboration will enable Canada to make a significant scientific contribution of value and interest to the world fusion effort, and, thereby, to gain effective access to the world's developing fusion knowledge and know-how. The collaboration will also allow Canadian industry to develop a capability in the area, and to participate in the future manufacture of fusion power systems for domestic and foreign markets.

It is evident, however, that, if its fusion R&D program is to make a signficant contribution of real interest and value to the much larger and more developed international fusion effort, Canada must concentrate or specialize in narrowly focussed technical areas within one or more of the three broad fields of fusion development - magnetic confinement technology, inertial confinement technology and non-confinement materials and engineering technology. These specialized elements should be selected and undertaken in accordance with the following set of guidelines or criteria:

International Interest - As already indicated, the real interest to foreign fusion programs must be sufficiently high to make international collaboration and exchanges attractive and likely, to indicate that a valuable Canadian contribution is forthcoming and to ensure that a Canadian access to world fusion knowledge is a probable outcome. Such international interest will, of course, decrease the risk associated with a narrow Canadian specialization.

Canadian Advantage - It is only realistic for Canada's fusion R&D effort to specialize in areas where there are already some existing advantages or expertise due to indigenous capabilities or skills. Such an existing base would enhance the potential for Canada to make a valuable fusion contribution and develop a leadership role in the certain specialty areas.

National Cooperation - The fusion R&D effort should, to the greatest extent possible, be one of national cooperation involving the participation and involvement of the relevant sectors within Canada - the federal government, provincial governments, electric utilities, universities and industries. Such a national flavour or scope would tend to take full advantage of all the indigenous expertise and capability in the area; to involve all the interested and concerned fusion actors now and in the future; to result in a sharing of the cost burdens involved; and to provide for benefits to more than one region of Canada.

Interim Industrial Benefits - The long-term aim is to ensure that Canadian industry will be capable of providing major parts of a fusion power system at home or abroad in the future. Although the primary importance of fusion R&D lies far in the future, there are, in the interim, potential commercial applications and industrial opportunities. It is, therefore, highly desirable that the Canadian fusion effort should maximize such interim industrial benefits as much and as soon as possible. This would tend to interest and involve Canadian industry in the developing fusion R&D area; to initiate the development of a Canadian industrial capability for the future; and to provide concrete benefits of value from the fusion R&D commitment whether or not fusion ever becomes a viable economic option. For these reasons, a Canadian fusion R&D speciality should have a high probability of interim industrial benefits to be realized.

To sum up, the Canadian fusion R&D program should be highly specialized in nature, and such specializations should meet the four basic selection criteria outlined above.

These domestic specializations should form the basis of the fusion program. The other essential requirement for the program is international collaboration. This would entail, of course, the relationships established with foreign fusion programs as a direct result of the domestic specializations undertaken. It would also involve Canadian participation in fusion-related international organizations and the secondment of Canadian scientists to foreign projects and foreign scientists to Canadian projects. As previously indicated, such international collaboration is an absolute necessity to optimize the domestic R&D program, and to maximize the program objectives and goals.

The actual Canadian fusion R&D program should be soundly based on these policy principles. What follows is an assessment of the current program elements in place and some future possibilities in light of the stated policy principles.

3. Program Elements

The selected specializations - the Tokamak de Varennes Project in magnetic confinement, the Fusion Fuel Technology Project in materials/engineering, and the proposed Laser Fusion Project in inertial confinement - represent the three major components of the Canadian fusion R&D program. Also of concern are the international collaboration component, and the current and planned program funding levels.

Magnetic Confinement: The Tokamak de Varennes Project

Within the broad area of magnetic confinement, the Canadian Fusion Program is concentrating on the Tokamak approach. The most important reason for this choice is that the Tokamak is currently the leading contender among the various alternative approaches - the one on which most of the world funding is being spent and the one that is considered to be the most likely avenue to develop a practical fusion power reactor. Moreover, the type of expertise developed from constructing and operating a Tokamak machine can generally be applied to other types of magnetic confinement schemes (mirror machines, stellarators and toroidal pinches). It was judged that a significant and valuable scientific contribution could reasonably be expected from a focussed research program employing a small Tokamak device.

On January 16, 1981 the Minister of MOSST, John Roberts, and the President of NRC, Larkin Kerwin, announced a plan to establish a national fusion research facility - the Canadian Centre for Magnetic Fusion - at Varennes, Quebec. This was to represent a major element in the National Fusion Program for Canada. The decision resulted directly from a report in October of 1980 which recommended the construction of a small, experimental Tokamak fusion device, called the Tokamak de Varennes. The report was the product of a year long $1 million conceptual design study that was cost-shared on an equal basis by the Quebec Government/Institut de recherche d'Hydro-Québec (IREQ) and by NRC/NSERC. The study was carried out by scientists and engineers from five participating institutions: IREQ, Institut national de la recherche scientifique (INRS-Energie), a branch of the Université du Québec involved in physics research; the physics department of the Université de Montréal; Canatom Inc., an engineering firm that specializes in nuclear power plants; and MPB Technologies Inc., a high technology company that, among other things, manufactures lasers.

The total construction and commissioning costs of the Tokamak

TOKAMAK DE VARENNES

SCIENTIFIC AND TECHNICAL GOALS

High duty cycle
Fast plasma current reversal
Impurities control using magnetic field divertors
Plasma control under high duty factor conditions
Investigation of hot liners, thermal effects and wall materials
Electro-technical problems with components and magnets under high duty factor operations
Directly driven from electrical grid connection and system-grid interactions
Magnetic energy recovery
Development of advanced and sophisticated diagnostics instrumentation and techniques, particularly far infrared laser (scattering, interferometry, polarimetry) and laser fluorescence (hydrogen and impurities)

KEY FEATURES

Quasi-continuous operation of plasma current
Rapid plasma current rampdown capability
Large ohmic heating flux swing
Poloidal divertor
Internal liner, replaceable, heated
Long toroidal field pulse length
Generous diagnostic access
Advanced diagnostic systems
Quasi-continuous systems
Elaborate power conditioning systems
Powerful and flexible instrumentation and control

BASIC PARAMETERS

MACHINE

Major radius	0.83 m.
Minor radius	0.25 m.
Toroidal magnetic field	1.5 tesla
Pulse length, toroidal field	30 s.
Pulse length, ohmic heating	100 ms.
Duration of pulse train length	30 sec.
Time between pulses	5 min.

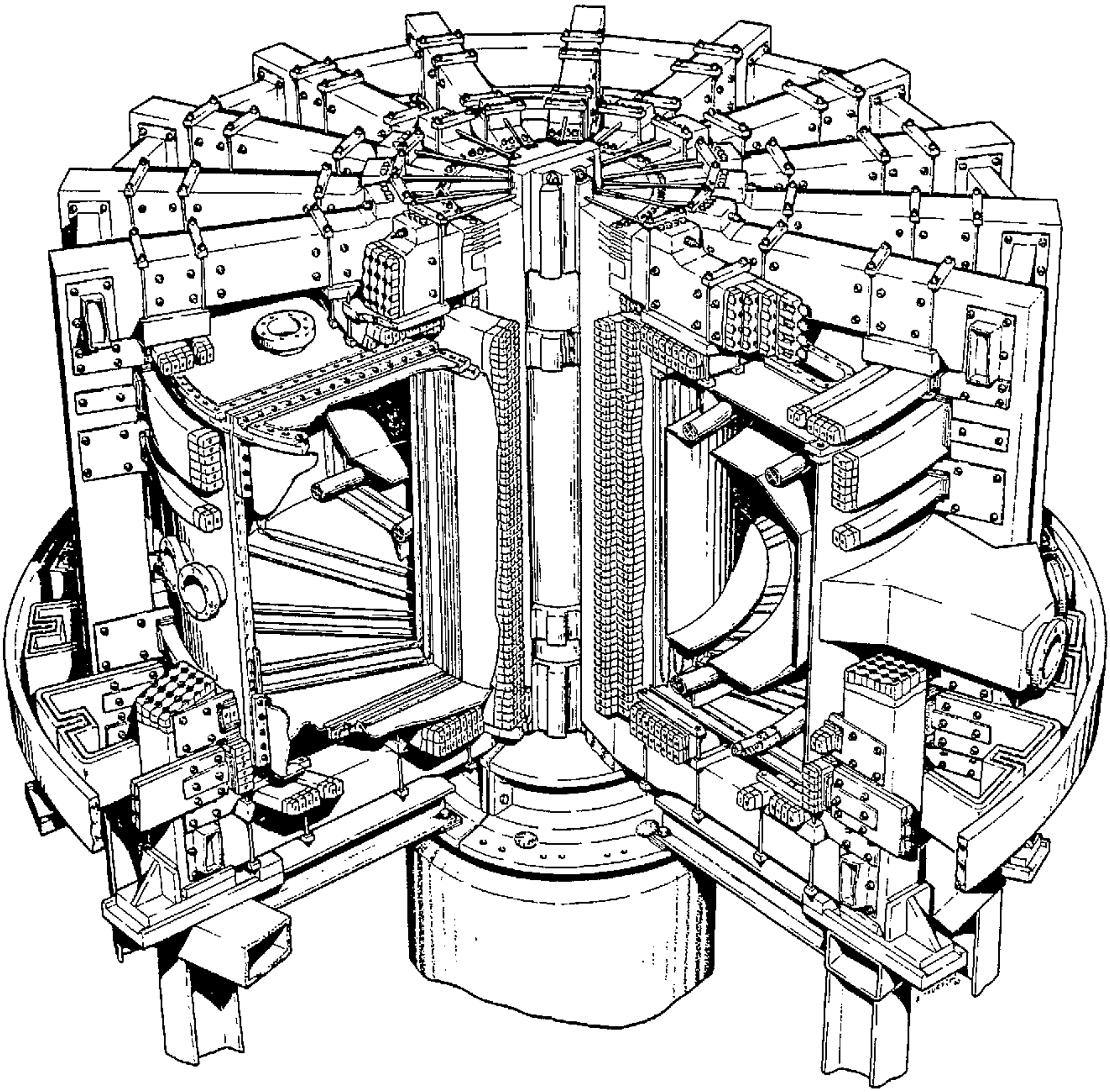
PLASMA

Plasma current	280 kA
Average electron density	3×10^{19} m^{-3}
Average electron temperature	450 eV
Maximum ion temperature	500 eV
Energy confinement time	5 ms

Source: IREQ et al, Tokamak de Varennes National Facility - Executive Summary and Final Report, October 1980, p. 4.

M.P. Backynski, 'Developments in Fusion Energy in Canada', Physics in Canada, November 1981, p. 117.

T.S. Brown, 'Canadian Fusion Program', June 1982, Tables 2 and 3.



TOKAMAK DE VARENNES

de Varennes will be $37.4 million ($20 million of which will be capital costs) and will be shared equally between NRC and IREQ. In order to carry out the design, construction and research program, a consortium of five organizations, under the project direction of IREQ as the operating agent, was formed: IREQ, INRS-Energie, Université de Montréal, Canatom and MPB Technologies. Construction and commissioning are scheduled for completion in the latter half of 1984.

The Tokamak de Varennes is designed as a small fusion experimental device for studying certain characteristics of fusion-grade plasma in a Tokamak magnetic confinement configuration. (See 'Tokamak de Varennes'). The heart of the facility will be a stainless steel, donut-shaped structure about the size and shape of a large tractor tire, wrapped and threaded by tons of copper. It will operate semi-continuously, with powerful currents surging through its coiled electromagnets for 30 seconds to create a complex choreography of associated magnetic fields. Hydrogen gas will be released into the vessel's vacuum to create a plasma. At a temperature of 5 million ° C (sufficient to test the confinement), the plasma will be confined by the magnetic forces, causing it to spiral in helix fashion around the vacuum chamber. The device will not be a source of energy: when operating, it will drain energy from the electrical grid at about the same rate as a small town. No fusion reaction is intended or will occur: the fuel used will only be ordinary hydrogen and not the hydrogen isotopes necessary for fusion. The magnets will only be powerful enough to test the pulse technology: full-scale fusion reactors must use superconducting magnets cooled to near absolute zero. There will, therefore, be no need for equipment and facilities with remote handling and shielding to protect the personnel.

The most important experiment will be to develop a multiple pulse train for the magnets that confine the plasma. Instead of trying to keep a single magnetic field intact for several seconds, fast switching will create a series of alternating magnetic pulses. The series of pulses, which individually may be only 1,000th of a second long, could create a powerful magnetic field that is possible to sustain for up to 30 seconds. This quasi-continuous mode of operation would enable investigations to be made on a host of important scientific and technical aspects such as fast plasma current reversal, plasma impurities control, electro-technical materials problems and the facility/electrical grid interactions. In addition, it will require the use and development of advanced diagnostics and sophisticated instrumentation, such as X-ray spectroscopes and infrared lasers.

The Tokamak de Varennes will constitute the narrowly focussed specialization of the Canadian fusion R&D program within the broad area of magnetic confinement technology. As discussed below, it satisfies the four criteria previously indicated for specialization: international interest, indigenous Canadian advantage, national cooperation, and interim industrial benefits.

The first specialization criterion is that the real interest to foreign fusion programs must be sufficiently high to make international collaboration and exchanges attractive and likely, leading to a Canadian access to world fusion knowledge and know-how. A unique feature of the device will be the engineering capability to operate in a semi-continuous mode because of its sophisticated power supply. Up to now, all other Tokamaks have operated in a single pulse mode - short pulses of at most one second; but the next generation of engineering test reactors will run for tens of seconds and a commercial fusion reactor will operate continuously. The Tokamak de Varennes, however, will be capable of terminating a pulse very quickly and in a controllable fashion and immediately starting another. Even though the individual pulses are very short, the total pulse train will be sustainable for 30 seconds. This is of particular interest to foreign fusion programs in a number of ways. The physical characteristics of fast pulse termination are unknown but are obviously important for attaining high duty cycle operation. The plasma and wall will start to approach thermal equilibrium with consequences of obvious interest for materials endurance, impurity buildups and energy losses, magnetic coil heating, and many other similar engineering problems. The project will also provide useful data on how to directly connect a fusion reactor to a large electrical grid. In addition, the advanced diagnostics and instrumentation required will be of considerable foreign interest.

Thus, the Tokamak de Varennes is an international scale experimental project in fusion research that promises to result in a significant Canadian contribution to the world's fusion knowledge. Richard Bolton, the project director, has said: 'It's a matter of filling in chinks in a vast international mosaic.'[50] Brain Gregory, a project scientist, has asserted: 'We're not trying to compete with the big boys; but we do expect to answer some questions they'll find very interesting.'[51] Indeed, the project has already attracted a considerable degree of interest in the foreign fusion community, and is expected to give Canada access to the results of international research efforts.[52]

The second specialization criterion is that there must be an indigenous Canadian advantage in the area. The Tokamak de Varennes will exploit several special Canadian capabilities. First of all, it will be located at Varennes, thirty miles southeast of Montreal where the high voltage lines that transmit power generated at Churchill Falls and Manic-Outardes plug into the Hydro-Québec electric grid. Access to a high-voltage power transmission line is a great asset for a fusion experiment. In contrast, researchers at the Princeton Plasma Physics Laboratory

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[50] Wallace Immen, 'Canadian fusion goals: to contain fuel reaction', Globe and Mail, Friday, May 21, 1982, p.9.

[51] Sean McCutcheon, 'Tokamak de Varennes - Towards nuclear fusion power', NRC Science Dimension, March, 1981, p.18.

[52] M.P. Bachynski, 'Developments in Fusion Energy in Canada', Physics in Canada, November, 1981, p.117.

have to slowly accumulate power in enormous flywheels until they have enough energy for a single pulse.

The participating partners in the project consortium have a unique range of existing expertise and skills. IREQ is one of the largest electrical utility research laboratories in North America, with a recognized capability in electrotechnology at its High Power Laboratory. The two universities (Québec and Montréal) have basic physics and diagnostics expertise and the two private firms involved (Canatom and MPB Technologies) have proven high technology experience and ability.

The third specialization criterion is that it must be a program of national cooperation. The Tokamak de Varennes project involves federal and provincial government bodies, universities and private companies. The total cost of the project is jointly funded on an equal basis by NRC and IREQ. Moreover, like all of Canada's national facilities, the Tokamak de Varennes will be available for use by the larger scientific and engineering community, both within Canada and abroad, for advanced research and technological development.

The fourth and last specialization criterion is that it have a high probability of interim industrial benefits. With a deliberate emphasis on the near-term (next ten years) potential for industry, the Tokamak de Varennes project will maximize its Canadian industrial content, have direct impacts on the development of Canadian industrial capability, generate a considerable potential for industrial spin-off benefits, and improve the access of Canadian industry to foreign fusion technology markets.

The project is making a conscious effort to maximize its Canadian industrial content, and has been prepared in some cases to pay a reasonable premium in order to ensure such Canadian content. The estimated Canadian industry/utility involvement or

Table 39. Estimated Canadian Industry/Utility Participation in Tokamak de Varennes

(1980 millions of dollars)

1. Construction - 3 years	Capital Costs:			Design Engineering and Administration		
	Total	Industry/Utility		Total	Industry/Utili	
Subsystem	$	$	%	$	$	%
Tokamak (including magnetic coils & vacuum vessel)	4.0	3.2	80%	0.5		
Electrical Power	5.3	4.3	80%	1.2		
Diagnostics	2.5	1.3	50%	1.0		
Instrumentation & Control	2.0	1.0	50%	1.0		
Experimental Area Services	1.0	1.0	100%	0.3		
Building and Facilities	0.2	0.2	100%	-		
Project Management	-	-	-	1.0		
Total	15.0	11.0	73%	5.0	3.3	65

2. Operations - 4 years

(1980 millions of dollars)

'Steady-state' operating costs	Total	Industry/Utility	
	$	$	%
annual	4.5	2.0	44
initial 4 years	18.0	8.0	44

Source: IREQ et al, Tokamak de Varennes National Facility-Executive Summary and Final Report, October 1980, p. 15

IREQ et al, Tokamak de Varennes-Industrial Impact, October 1980, p. 16-17.

participation over the first seven years will be of the order of $22 million or 58%: capital costs $11 million (73%); design, engineering and administration $3 million (65%); and operating costs $8 million (44%). (See Table 39.)

The project will have direct impacts on the development of Canadian industrial capability. (See Table 40.) The unique project management experience gained will assist industry to manage other projects. The development of a number of engineering design skills will be required, resulting in an engineering capability applicable to many other fields. Canadian industry will develop capabilities in several technologies (with actual hardware fabrication experience), including, in particular, a wide range of instrumentation and controls. Lastly, the experience gained in developing technology for operation by a direct power grid connection will potentially put Canadian utilities at the forefront of future world users of fusion electricity.

The potential of industrial spin-off benefits (additional sales or commercial exploitation) from the engineering and technological capabilities developed by industry on the project is considered to be high and extensive, but difficult to quantify. The economic utility resulting from industrial contracts would have a highly beneficial impact on contracting firms, spreading out through many aspects of the firm's activities in the form of value added, economic potential, increased sales, cost savings and improvements in cost calculation, cost and project control and quality standards and quality control. Based on the experience of the European Organization for Nuclear Research (CERN), in which a spin-off ratio of 4.2 was indicated, a Canadian industrial realization of about $46 million from the $11 million capital expenditures having Canadian content would result from the Tokamak de Varennes Project. Moreover, as evidenced by the NRC's Industrial Research Assistance Program (IRAP), a program designed specifically to increase industrial spin-off can substantially improve the 'pay-off' or benefit ratio.

Table 40. Impact of Tokamak de Varennes on Development of Canadian Industrial Capability

Project Management Development

Engineering Design Skills:

- Magnetic system engineering
- Vacuum system design
- Power system engineering
- Control and circuit engineering
- Overall systems design and integration
- Computer techniques, stress and thermal analysis

Specific Technologies:

- Magnetic field coils
- Directors, liners, limiters
- Vacuum vessels, pumps and ports
- Power supplies
- Structures
- Instrumentation and controls (including automatic data acquisition systems)
- Services (ducting, cooling, cabling, heat exchangers communications, etc.)
- Diagnostic instrumentation:
  - Voltage Loop & Rogowski Coils
  - Magnetic Flux Coils
  - Magnetic Field Coils
  - 2mm Microwave Interferometer
  - 8mm Divertor Interferometer
  - Microwave Scattering
  - Microwave Radiation
  - x-Ray Pulse Height Analysis
  - Hard x-Ray System
  - Crustal Spectrometer
  - x-Ray Wave Detector
  - Slow Neutral Detector
  - Residual Gas Analyser
  - Surface Analysis Station
  - Scannable Thomson Scattering
  - Small Angle Thomson Scattering
  - TV Thomson Scattering
  - CO_2 Laser Scattering
  - CO_2 Laser Fluctuation
  - Infrared Laser
  - Grazing Incidence Monochrometer
  - Infrared TV Camera
  - Soft X-Ray Spectrometer
  - Charge Exchange Ion Temperature
  - Fast Ion Diagnostic Experiment
  - Neutron Counter
  - Plasma TV
  - Monochromators
  - Bolometers
  - Divertor Energy Analyzer
  - Langmuir Probes
  - Pellet Injection

Utility Technology and Experience with direct power grid connection

Source: IREQ et al, Tokamak de Varennes - Industrial Impact, October 1980, p. 17-18.

The project would also improve the access of Canadian industry to the foreign fusion technology market - an industrial market that is now in excess of $1 billion and that could be of the order of $3 billion by the year 2000. Since the project incorporates some advanced design features that foreshadow characteristics to be found in future engineering test fusion reactors, the design and manufacturing experience gained has credible long-term implications. Areas in which international recognition and interest could be obtained include the operation of demountable toroidal field coils at steady state, divertor technology for impurity control under quasi-steady-state plasma operation, the surface studies in a long-pulse environment, long-pulse operation and coupling to the electrical grid, and the development of advanced diagnostic instrumentation. Such developments would aid Canadian industry as a potential supplier for certain high technology requirements for international fusion projects. The principle Canadian industry sectors that might have such opportunities to compete are electrical utilities and high power electrical equipment manufacturers, mechanical engineering and manufacturing companies, electronics and data handling firms, instrumentation companies, the nuclear engineering industry and special materials suppliers. (See 'The Tokamak de Varennes Project: Canadian Companies and Developing Capabilities'.)

Thus, as indicated above, the Tokamak de Varennes Project fully satisfies the basic criteria established to be a specialization of the Canadian fusion R&D program within the magnetic confinement area. It will, therefore, serve to establish the necessary scientific expertise and technological capacity to keep open the fusion power option for Canada.

Materials/Engineering: The Fusion Fuel Technology Project

In the broad area of fusion materials and engineering, the Canadian Fusion Program is concentrating in fusion fuel technology

THE TOKAMAK DE VARENNES PROJECT:
CANADIAN COMPANIES AND DEVELOPING CAPABILITIES

A number of Canadian companies have already become actively involved in the designing, engineering and component manufacturing required for the Tokamak de Varennes Project. More companies will become involved before the construction phase is completed in two years time. Already, however, these companies are developing certain industrial capabilities in specific technological areas - capabilities that will be directly relevant to enabling these companies to compete for similar work in other fusion device programs and to achieve spin-off applications in non-fusion areas. This is concretely illustrated in the following partial list of selected Canadian companies now involved in the Varennes work and of some of the technological capabilities they are developing from this work.

Canadian Companies	Developing Technological Capabilities
Canadian General Electric Brown Bovire Canada	high power switching technology
Canatom	- heat transfer in supercurrent accelators - general engineering design in fusion systems, including large magnetic and vacuum chambers
Canadian Vacuum Systems	very large, complex vacuum systems
MPB Technologies	- laser diagnostic instrumentation - computer interfacing systems (CAMAC)
Ultra High Vacuum Instruments	vacuum transfer equipment

and, more particlarly, in tritium technology. Materials and engineering work is applicable and relevant to both of the fusion approaches - magnetic confinement and inertial confinement. Such work will be a crucial element in the next stage of fusion development - proof of technical or engineering feasibility. The requirements and problems involved here open up vast fields of research wherein significant scientific contributions can be made. Lastly, the materials/engineering area offers perhaps the most promising and significant means of developing industrial capabilities and providing industrial benefits.

In January of 1980, a one year contract was let by NRC to DSMA ACTON LTD., a Toronto firm of engineering and advanced technology consultants. The study was jointly funded by NRC and Ontario Hydro, and was undertaken in collaboration with Ontario Hydro, the University of Toronto and McMaster University. It was directed to evaluate concepts for a national Fusion Engineering and Materials Development Program for Canada and to indicate, from the most promising alternatives, a preferred focal technology that would best meet Canada's scientific, industrial, technical and financial requirements. The report[53], submitted in January of 1981, provided a comprehensive analysis of a dozen major program options and identified fusion fuels, in particular tritium technology, as the optimal narrow specialization to pursue. The recommended program goal was to establish R&D activities leading to the development of an industrial base in fusion engineering in Canada - a base that would subsequently enable Canada to supply tritium related sub-systems for the international prototype and fusion power reactors to be built in the next two decade. The proposed technical program consisted of four inter-related elements, with tritium as the common theme and central focus: fusion fuel systems, materials development, equipment development and safety

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[53] DSMA ATCON LTD., Conceptual Study for a National Fusion Engineering and Materials Development Program, NRC, January 1981.

Table 41. Proposed Technical Program Elements in Fusion Fuels Technology

Fusion Fuel Systems

Fuel purification (removal of non-hydrogenous material, preparation to a physical state suitable for further processing)
Fuel production (lithium technology, hydrogen extraction)
Isotope separation (adjustment of hydrogen isotope concentrations)

Materials Development

Hydrogen-materials interactions:
- hydrogen metallurgy (surfaces, diffusion, hydrides)
- ceramics and organics (electrical insulators, sealants and paints, surface treatments and cleaners)
- irradiation effects (damage analysis, swelling, resistant materials

Equipment Development

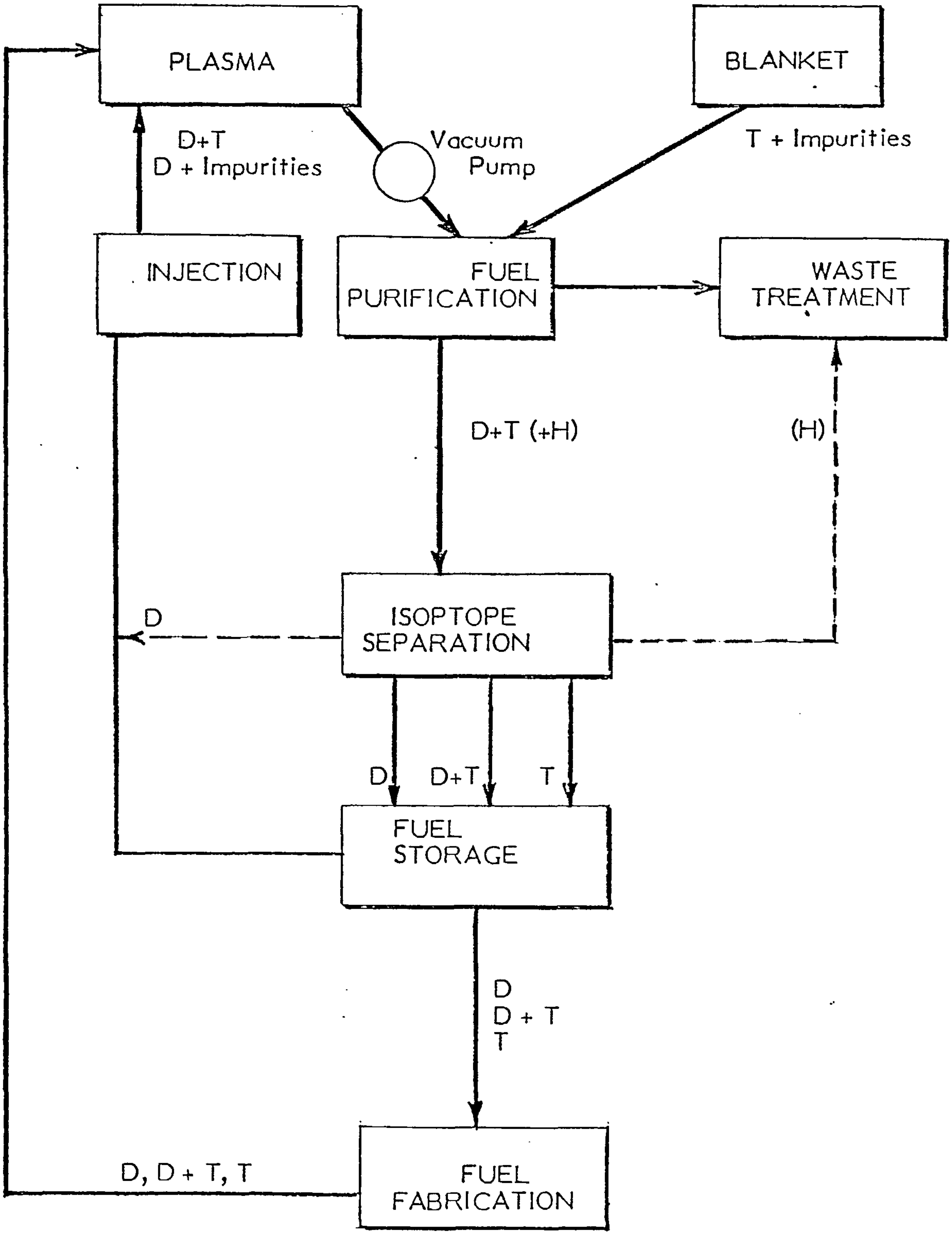
Instrumentation (tritium detectors, hydrogen monitors)
Hydrogen compatible components (valves, seals, pumps, containers, personnel protective clothing)
Testing and certification (in hydrogen isotope environments, at high and low temperatures, of mechanical properties under simulated conditions)
Remote maintenance and handling (fuelling systems, blanket replacement, devices, emergency repairs, welders, inspection devices)

Safety and Environment

Monitoring (techniques, requirements, inventory control, machine and personnel protection)
Safety (decontamination, accident analyses, safety systems)
Biology and health physics (tritium mobility, biological effects, siting implications, occupational and public health safety)

Source: DSMA ATCON LTD, Conceptual Study for a National Fusion Engineering and Materials Development Program, NRC, January 1981, p. 40-51.

Figure 20. Fusion Fuel Processing System



H = hydrogen D = deuterium T = tritium

Source: DSMA ATCON LTD, Conceptual Study For a National Fusion Engineering and Materials Development Program, NRC, January 1981, p. 59.

Table 42. Fusion Devices and Tritium

Reactor Type	Facility	First D-T Burn	Tritium Inventory	Tritium Consumption	Tritium Production
Research Tokamaks	TFTR	1986	<10g	negligible	zero
	JET	1986	<10g	negligible	zero
Mirrors	MFTF	?	small	negligible	zero
Laser	NOVA	1988	<1g	negligible	zero
	ANTARES	1988	<1g	negligible	zero
Engineering Tokamaks	FED	1992	20kg	60g/day	40g/day or zero
	JET 11	?	20kg		
	INTOR				
Energy Producer	STARFIRE	2020	60kg	300g/day	300g/day

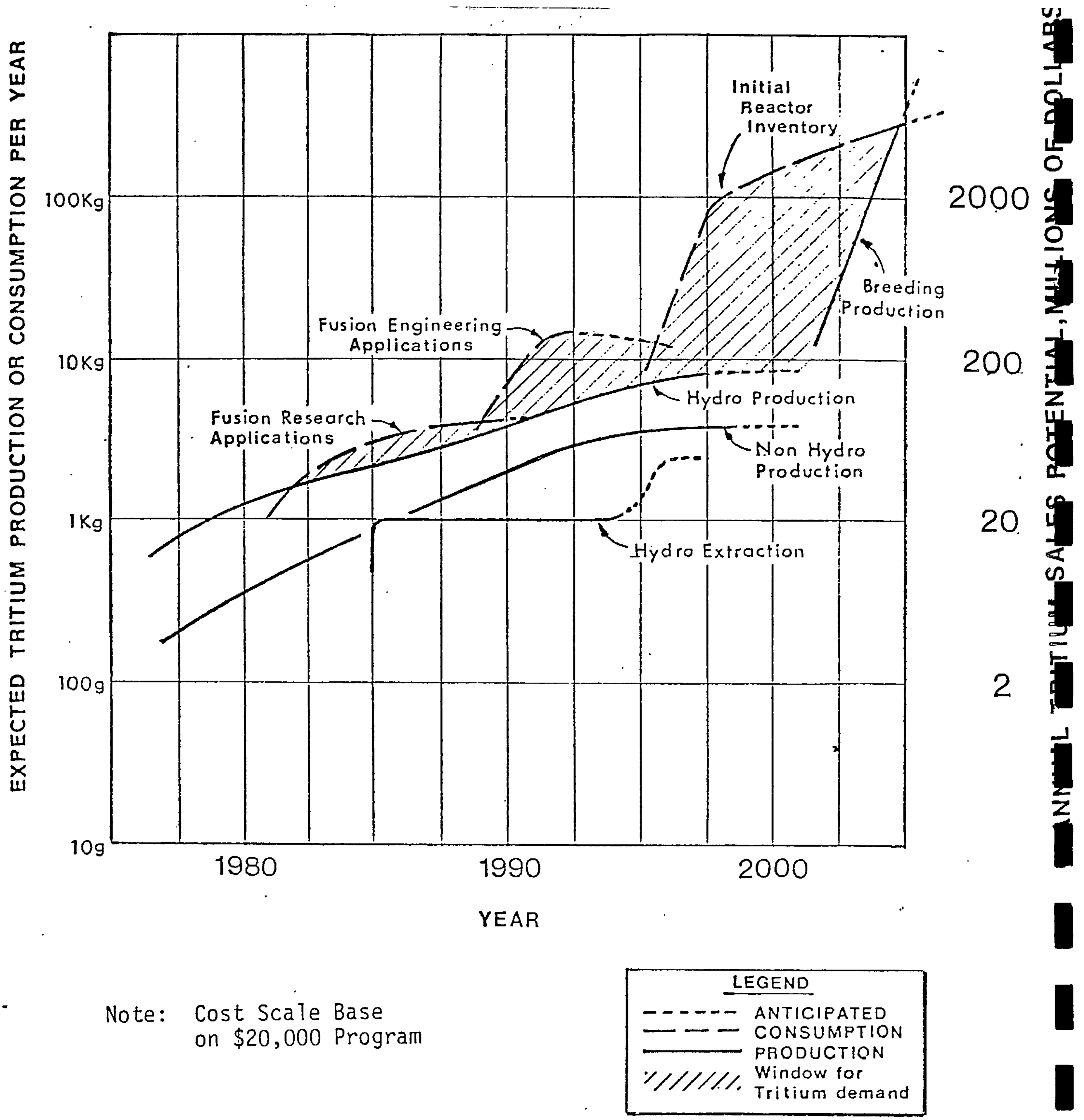
Source: DSMA ATCON LTD, Conceptual Study for a Nationa Fusion Engineering and Materials Development Program, NRC, January 1981, p. 58.

and environment. (See Table 41 and Figure 20.)

This choice of tritium-fusion fuels as the narrow focus for a Canadian R&D program in the fusion materials/engineering area resulted from a number of considerations. There will be an international need for tritium in the period 1985-2000 for experimental fusion devices around the world. (See Table 42.) Such devices will be based on the deuterium-tritium fusion reaction. Before 1985, little tritium will be needed, since the first fuel burnup in TFTR and JET are not scheduled before 1986; but by the end of the century, the annual world tritium demand is expected to be around 100 kilograms. Beyond 2000, fusion reactors are expected to breed their own tritium requirements. (See Figure 21.) The 100 kilograms of annual tritium demand by 2000, however, would, at $20,000 per gram, mean a sales potential in that year of about $2 billion. From the 1985 startup of its tritium removal system for the Pickering nuclear station, Ontario Hydro will become a significant tritium producer: a cumulative tritium production from 1985 to 2000 of almost 30 kilograms which would be worth $300 million at the current U.S. selling price of $10,000 per gram for relatively small amounts, or $3 billion at the estimated actual total production cost of $100,000 per gram. (See Figure 22.) Thus, this window of tritium demand in the period 1985 to 2000 provides a unique and significant sales opportunity for Canada to capitalize on its tritium supply.

Moreover, this tritium supply could be used as the means to develop a world class expertise for Canada in tritium technology for fusion R&D. Canada is already an existing world leader in tritium production through its fission program: the CANDU nuclear power reactor produces about 200 grams of tritium per year per 1 GWe, as a by-product in its heavy water moderator. The current Canadian expertise in tritium mainly resides in Ontario Hydro and AECL, and involves the extracting, monitoring and safe handling of tritium. Specific areas to be investigated include detritiating the heavy water moderator, the biological effects on man of

Figure 21. Expected World Annual Tritium Consumption and Production Rates and Sales Potential



Note: Cost Scale Base
on $20,000 Program

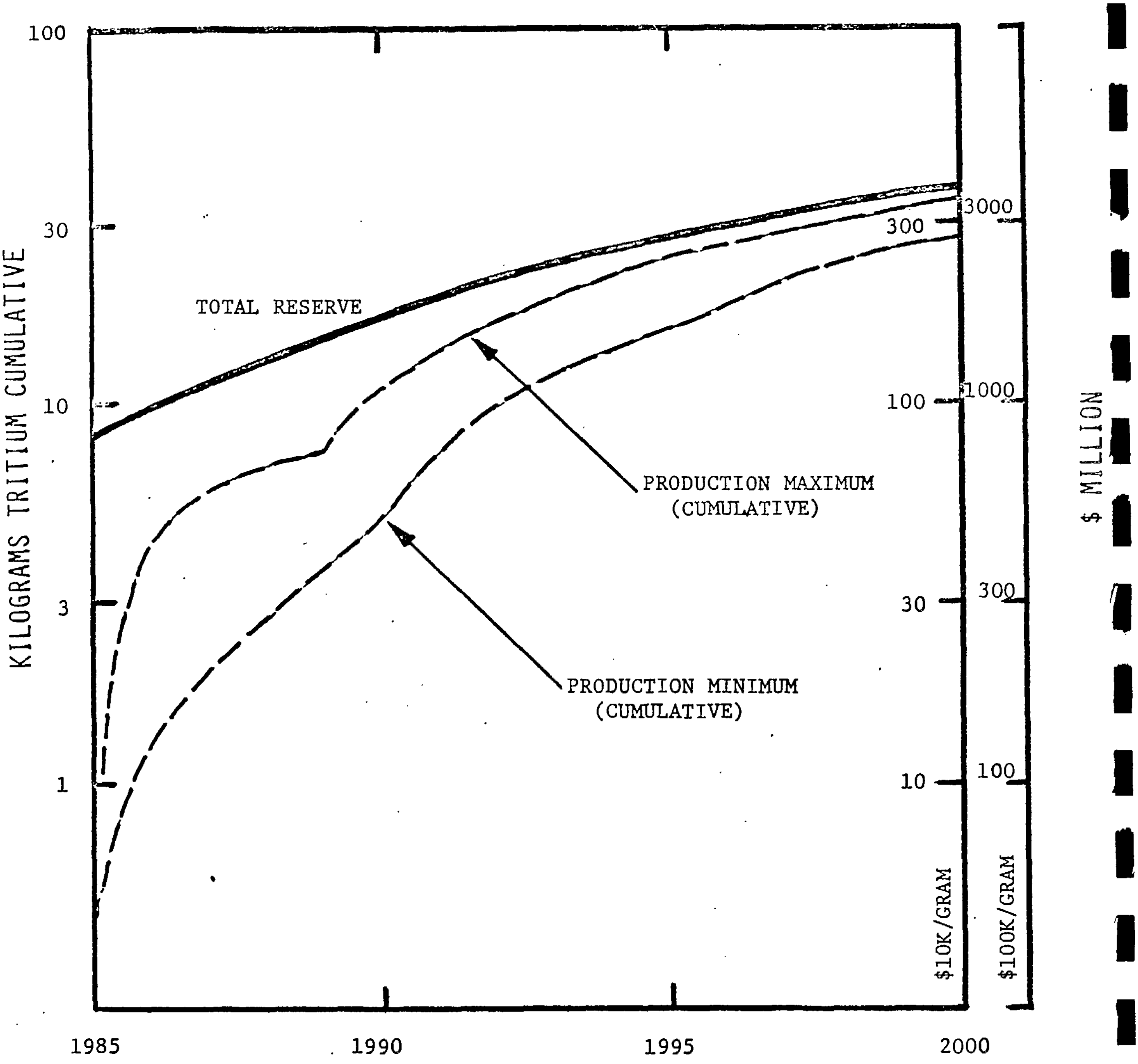
Source: DSMA ATCON LTD, Conceptual Study For a National Fusion Engineering and Materials Development Program, NRC, January 1981, p. 60+ 155.

tritium, tritium storage in solids in the form of tritides as a possible high density storage system, and remote manipulation devices and procedures. The technical expertise needed to manage tritium as a CANDU waste product, and the technical expertise needed to manage tritium as a fusion fuel, are mutually supportive and complementary.

This background of special Canadian advantages because of a large tritium inventory and existing tritium expertise provides Canada with a tritium head-start and a unique opportunity to develop a world class expertise and capability in fusion-related tritium R&D. This would provide Canadian industry with the potential to supply a number of special tritium systems and components to foreign fusion devices being planned over the next two decades. Appreciable foreign interest in such systems has already been expressed (It should be noted that tritium is classified by many nations as a strategic material for military applications). In the U.S. fusion program, the expenditures on tritium system components could reach $50-100 million per year in the next decade. American and European fusion plans call for the construction of capital facilities that wll total many billions of dollars, of which perhaps 10% will constitute tritium handling systems and hardware. It is clear, therefore, that a substantial world market exists for tritium technology, and that the design and supply of system components for such technology will become a lucrative export market for Canadian industry. There is a strong likelihood that bilateral and multilateral agreements could be reached with other countries, thereby promoting Canada's fusion fuel role in collaborative development programs. In addition, the potential for industrial spin-off benefits would tend to be high, with applicability over time to non-fusion technology areas - such as the tritium-related aspects of the fission program, environmental knowledge and management, and the hydrogen-based energy economy for the future being proposed for Canada.

For these reasons, it was announced in May of 1982 that the

Figure 22. Ontario Hydro Tritium Reserve and Production 1985-2000



Note: The dollar scales represent the current US selling price for relatively small amounts ($10K per gram) and the estimated actual total production cost ($100 K per gram).

Source: T.S. Brown, 'Canadian Fusion Program', June 1982.

chosen specialization of the Canadian Fusion Program within the general fusion area of materials and engineering would be a Fusion Fuels Technology Project whose primary goal would be to establish Canada as a world leader in tritium management. To establish the project, an initial 5 year expansion phase would include a funding level of $.5 million in the first year, rising to $5 million in the fifth year, for a total cumulative cost of $20.6 million. The constant operating level, to be reached in 1986, is $7 million per year. These costs are being shared as follows: 50% from NRC, 25% from Ontario Hydro and 25% from the Ontario Ministry of Energy. Ontario Hydro is the operating agent for the project. The specific activities that are being initiated in the first year of the project include fuel purification and clean-up, material and equipment development (barriers, pumps), remote operations, testing and certification, monitoring instrumentation, biology and health physics. Unlike the Tokamak de Varennes Project, this project does not involve the establishment of a single major facility. It will be a program of contracted out R&D work performed at existing institutions and facilities. The major recipients of such work are likely to be Ontario Hydro, AECL, IREQ, the University of Toronto's Institute for Aerospace Studies and other universities and industries across Canada.

The Fusion Fuel Technology Project satisfies the basic criteria for specialization in the National Fusion Program. The tritium supply and the associated tritium technology developed will be of real international interest for the next generation of fusion devices in foreign fusion programs. The project has already attracted such interest from the U.S., Euratom and Japan. The significant Canadian contribution to be made in this area will make international collaboration and exchanges abroad likely, leading to a Canadian access to world fusion knowledge and know-how. Indigenous Canadian advantages are involved: the Ontario Hydro tritium supply inventory and the existing Ontario Hydro-AECL expertise in tritium handling. The project will be one of national cooperation, with funding being shared by NRC, Ontario

THE FUSION FUEL TECHNOLOGY PROJECT:
CANADIAN COMPANIES AND DEVELOPING CAPABILITIES

Although the tritium R&D project was formally announced only six months ago, a growing number of Canadian companies are becoming involved in developing tritium capabilities. These capabilities could be developed to make these Canadian companies real competitors in the world fusion market for tritium related abilities and components. A partial list of selected companies that are currently involved is provided below, together with indicated technological capabilities being developed. It should be remembered, however, that more companies are becoming involved very rapidly and that there are very good prospects for developing these and other capabilities as the project gets fully underway.

Canadian Companies	Developing Technological Capabilities
SPAR DSMA ACTON LTD. Canadian General Electric	assorted tritium handling technologies, including remote handling aspects.
CAE	remote handling/maintenance equipment
Canatom Monserco Sindrex Ontario Hydro AECL	tritium monitors (personal, area & surface) in real time and discriminate aspects
Noranda Electrolyzer	fusion fuel exhaust stream equipment
VHV Instruments	tritium valve technology
AECL	tritium health and environment tracing including modelling pathways analysis

Hydro and the Ontario Ministry of Energy and with contracted-out R&D work for government, industry and the universities. Lastly, the project will have a high probability of interim industrial benefits: the sales opportunity from 1985 to 2000 in the supply of tritium to the international market; the industrial capability developed to supply tritium components and sub-systems for engineering prototype and future fusion reactors around the world; and the high potential for considerable industrial spin-off benefits in non-fusion areas. (See 'The Fusion Fuel Technology Project: Canadian Companies and Developing Capabilities'.) In these ways, the Fusion Fuel Technology Project, with the tritium technology specialization, will serve to establish the necessary scientific expertise and technical capability within the materials/engineering fusion area, and thus contribute to keeping open the fusion power option for Canada.

Inertial Confinement: The Proposed Laser Fusion Project

The third broad fusion area being proposed for a Canadian R&D effort is inertial confinement technology. The chosen specialization being suggested within this area is a laser fusion project focussed on high-power, pulsed gas laser technology and the associated ultra-fast, high-resolution, optical diagnostic instrumentation.[54] What appears to be involved here is a possible national laser fusion facility centred on carbon dioxide (CO_2) lasers; it will probably be established around the existing NRC program.

A final decision on this project, however, has not yet been made and awaits completion of a detailed planning exercise. Early in 1982, a $150,000 contract was let by NRC to MPB Technologies Inc. to study and make recommendations on a possible inertial confinement program for Canada: the rationale, the focal point for scientific and technical directions, and the resources

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[54] T.S. Brown, 'Canadian Fusion Program', June 1982, p.16.

THE STUDY ON THE ESTABLISHMENT OF A CANADIAN INERTIAL CONFINEMENT FUSION PROGRAM

CONTRACTOR MPB Technologies Inc.

COST $150,000

COMPLETION DATE March 31, 1983

PURPOSE To consider, outline and document a detailed Inertial Confinement Fusion (ICF) Program for Canada, including its rationale and scientific and technological directions, and to estimate the projected financial and human resources required.

OBJECTIVES

1. Outline a detailed science and technology program which is to be the focal point for a Canadian ICF effort including: objectives of the program, the initial technical content and guidelines for a continuing program, those aspects which are uniquely Canadian or where Canada can make a major contribution, and the role and contribution of the Canadian ICF program in relation to the national international effort.

2. Outline the resources (with associated costs) which will be required to carry out the ICF program such as: potential compression driver systems, laser development equipment, target production systems, diagnostic equipment, computational requirements, and technical support facilities.

3. Identify the capability in Canada to carry out the proposed program in ICF including: the available scientific and technological expertise, the ability of the universities to train people in this field, and the available industrial infra-structure to serve this area.

4. Prepare a report including conclusions and recommendations.

NOTE: Plans to study estimated industrial benefits will be considered after the ICF program has been defined. Such an industrial benefits study is very important and has to be done. A good case for ICF requires a narrowly defined program and attractive industrial benefits. A fair idea of how the program of work is shaping up is necessary in order to undertake such a study. It is possible that this study could commence in the fall of 1982. The study objective could be to estimate the industrial benefits -- short term (next 10 years) and longer term (30 years) benefits -- which can reasonably be expected to result from the establishment and operation of the ICF program: the estimated potential industry involvement, the impact on development of Canadian industrial capability, identification of spin-off benefits, impact on the ability of Canadian industry to gain access to foreign know-how and foreign markets, and other impacts.

required. (See 'The Study on the Establishment of a Canadian Inertial Confinement Fusion Program'.) The final report is expected by March 31, 1983. Based on its terms of reference, the study will include the basic rationale or justification for such a program and will relate it directly to the specialization criteria of international interest, Canadian advantage, and national cooperation. (The last criterion, interim industrial benefits, will be addressed in another study.) In addition, it has been indicated that the study will consider different driver systems, not just lasers, as the possible specialization area.

One obviously wants to avoid making a premature judgement or decision on the matter before the detailed planning information is available. Clearly, there are a number of critical points which, presumably, the MPB Technologies study will address. In particular, it needs to come forward with convincing arguments on the extent of the actual need for such a Canadian R&D effort in inertial confinement generally, in laser fusion specifically, and in CO2 lasers more specifically. To date, at least, this need has not been established. The serious concerns underlying this assessment are expressed below.[55]

First of all, it should be noted that a CO2 laser focus in Canadian fusion R&D has been repeatedly suggested by the fusion

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[55] These concerns have resulted from a review of the current literature on inertial confinement. The three most important reference sources used were:
J.S. Geiger and G.A. Bartholomew, 'A Review of the Prospects for Fusion Breeding of Fissile Material', AECL, October 1981, particularly Chapter 5 'Inertial Confinement - Laser Beams' p.87-109 and Chapter 6 'Inertial Confinement - Particle Beams' p.111-146;
DSMA ATCON LTD., Conceptual Study for a National Fusion Engineering and Materials Development Program, NRC, January 1981, particularly Appendix D 'Description of Program Options - Laser Drivers and Particle Beam Drivers', p.D10-12, D15-16; and Appendix E 'Selection of the Recommended Program Option';, p.E1-9;
John Lawson and Derek Beynon, 'Heavy ions beam in on fusion', New Scientist, August 26, 1982, p.565-568.

studies of the last decade. Indeed, the early Project Fusion Canada study of 1974 recommended such a focus - at a time when the development of lasers for inertial confinement fusion was only in its infancy. But a full and detailed rationale for such a Canadian focus has never actually been presented. This suggests the possibility that it has continued to be promoted as the optimum specialization more out of the sheer momentum of a view once held, than out of a careful assessment of its actual merits and drawbacks as these have developed over time. This element of inertia in the thinking on inertial confinement should not be overlooked.

This is especially so today when one actually looks at the current status of inertial confinement vis-à-vis magnetic confinement, and the implications that this may have for the Canadian fusion R&D program. Inertial confinement is certainly, at the present time, a much less likely prospect for becoming a viable and practical approach to actual fusion power than the Tokamak and other magnetic confinement possibilities. The Tokamak approach remains the leading world contender, with the best prospects. It is now confidently expected that the proof of scientific feasibility will be achieved in the next two or three years in the American TFTR Tokamak, or in other similar devices now coming on stream around the world - the European JET, the Russian T-15, and the Japanese J-60. The result is that the emphasis in the world Tokamak fusion program is now clearly shifting to the engineering phase.

In sharp contrast, the inertial confinement approach is very much of a long shot. It was, in fact, a relatively late starter, with serious experimentation not beginning until the late 1960's. Development tended to be hampered by the restricted security classification imposed on much of this early work, and by the need to develop high power lasers. Experimental results in the seventies continued to encounter a host of new and unexpected difficulties and to reveal factors that have rendered inertial confinement far more difficult than originally believed (e.g. the light absorption process involving the generation of fast superthermal electrons and scattering diseffects, the thermal energy transport process, pellet design problems, material thermal stress, etc.) In contrast to the outlook in the early 1970's, which held that a laser driver delivering a few kilojoules of energy would yield scientific breakeven, the current view is that a minimum driver energy of more than 100 kilojoules, at a wavelength in the near ultraviolet range, will be required to reach this milestone. As yet, the energy released is only a very small fraction of the energy invested in the driver. Although there are some expectations that proof of scientific feasibility may be achieved by 1990 - a few years later than the Tokamak proof - in facilities now being built (the NOVA at the Lawrence Livermore Laboratories, the Antares at the Los Alamos Laboratories and the PBFA 11 - the Particle Beam Fusion Accelerator - at the Sandia Laboratory), these are very probably unrealistic expectations. The state of the art is definitely not mature enough to take scientific feasibility as a certainty - or to move significantly towards engineering feasibility. The expected conditions suitable for a fusion power reactor based on inertial confinement are extremely demanding and hardly seem within near-term reach: a high pellet density that is over a thousand times the density of the solid fuel or tens of times the density of lead, a temperature beyond 10 million °K., a pulse energy in excess of 200 kilojoules, a driver efficiency of at least 10, a pulse power of the order of 10 M Joules, pulse durations in the 10 nanosecond (a billionth of a second) range, very short wavelengths in the ultraviolet region, and an energy gain of almost 200. It is clear that much more study needs to be done to obtain a better fundamental understanding of the basic science involved in inertial confinement, especially on the mechanisms of light absorption and heat transportation and their dependence on wavelength and pulse length.

Moreover, given this rather primitive state of knowledge and the new difficulties and problems generated by scientific activities, it is not surprising that there has been a considerable change of thinking over time as to which particular driver approach is likely to be the optimum one to develop in order to realize actual fusion power in the inertial confinement arena. The initial R&D effort concentrated entirely on lasers, and only recently has it been broadened to include the various charged particle beams. A brief survey of these basic alternatives is presented below.

A laser simply takes in a weak light beam, amplifies it and puts out a powerful light beam as the needed energy carrier - a process that is in principle similar to the one by which a magnifying glass uses sunlight to focus heat on a price of paper that then burns. Of the laser drivers, the CO2 gas laser and the neodymium (Nd) glass laser have been the best understood and the most readily scaled up and, for these reasons, have dominated the field so far.

The CO2 gas laser has a number of attractive features - a high efficiency (around 20%), an energy scalability, a possibly high repetitive rate, a high power handling capability and a possible solution to the cooling problem in laser drivers. These features indicate that the CO2 laser is a serious contender that currently shows promise in evolving to satisfy reactor requirements. The problems that exist at this stage, however, are considerable and are such as to cast doubt on its successful application. Its wavelength is thirty times greater than the estimated optimum one required. The laser-plasma interaction (the physical process governing the coupling of the laser radiation and the plasma) poses many difficulties. Backscattering instabilities constitute a dangerous energy loss mechanism. A substantial amount of irradiating laser energy appears as superthermal electrons. Thermal energy transport through the critical density is strongly inhibited. The development of advanced pellet configurations will be required. And, of course, there is a major need to increase the power in the laser driver. At present, the largest CO2 laser is the Helios at Los Alamos with 8 beams, 20 terawatts (TW) of peak power and 10 kilojoules (kJ) of energy. This will be followed in 1984 by the Antares, also at Los Alamos, with ten times the number of beams, and ten times the peak power and energy (Table 42).

The other major laser driver under investigation is the neodymium (Nd) glass laser. Because it is more flexibile and more advanced than the CO2 laser, it continues to be a favourite driver for scientific study. But its low efficiency (0.2%), its restrictive operation of about one pulse per ten minutes, and its poor power handling capability appear to make it technically impossible and unsuitable for commercial energy production. The most powerful Nd glass laser is the Shiva at the Lawrence Livermore Laboratories with 20 beams, 30 TW of peak power and 10 kJ of energy. NOVA II, to be completed in 1990, will entail 20 beams, 300 TW of peak power and 300 kJ of energy.

Other laser driver alternatives, however, do exist. The krypton-fluoride laser is the only near ultraviolet laser, and offers efficiencies of up to 60%. Although it offers tens rather than hundreds of kioljoules of energy, the krypton-fluoride laser is a candidate as a driver for a laser inertial confinement reactor. The argon fluoride laser, one in the ultraviolet region of the spectrum, is also a possibility. The halogen gas excimer laser has shorter wavelengths and offers more favourable energy coupling performance characteristics, but at present remains a low energy (one kJ) driver.

It may be too early at this time to choose the particular laser driver system to be used in an actual fusion reactor. Indeed, given the need for a more complete understanding, the odds for even achieving a net energy gain from the laser route may be judged at the present time as very small.

Table 42. World Inertial Confinement Fusion Lasers

Country	Type and System	Date	No. of Beams	Power Amplifier	Peak Power (TW)	Energy (kJ)	Energy (J/c[illegible]^2)
Canada	CO$_2$-COCO II	1973	2	15 cm	0.12	0.02	0.7
China	Nd	1977	6	7.0 cm	0.6		
	CO$_2$	1980	1			0.02	
France	Octal	1979	8	10.8 cm	2	0.7	
Japan	Nd-Gekko II	1975	2	6.5 cm	0.4	0.2	3.1
	Nd-Gekko IV	1977	4	10.8 cm	4	2	
	Nd-Gekko XII-M	1980	2	20 cm	7	3	5.5
	Nd-Gekko XII	1983	12	20 cm	40	20	5.3
	CO$_2$-Lekko II	1977	2		0.5	1	
	CO$_2$-Lekko VIII	1981	8		10	10	
U.K.	Nd	1980	6	10.8 cm	2	1	1.8
	Nd-Helen	1979	2	18 cm	1	1	2.0
USA-LLL	Nd-Argus	1976	2	20 cm	3	1.1	1.8
	Nd-Shiva	1978	20	20 cm	30	10	1.6
	Nd-Nova	1984	10	46 cm	100	100	6.0
	Nd-Nova II	1990	20	46 cm	300	300	9.0
	KrF-Rapier	1979	1	10x10 cm^2		0.025	0.0[illegible]5
LAL	CO$_2$-Helios	1978	8	35 cm	20	10	1.3
	CO$_2$-Antares	1984	72	30x35 cm^2	200	100	1.3
	CO$_2$-SPTF	concept	200	46x46 cm^2		1000	2.4
Rochester	Nd-Zeta	1978	6	9 cm	3	1.2	3.1
	Nd-Omega	1980	24	9 cm	30	10	6.6
KMSF	Nd-Chroma I	1979	2	14 cm	2	1	3.2
NRL	Nd-Paros II	1978	2	10.5 cm	1.4	1.3	7.5
Sandia	HF-Phoenix II	1980	1			1.7	
USSR	Nd-Kalmar	1971	9	4.5 cm	0.3	4.2	
	Nd-Delfin	testing	216	4.5 cm	10	2.9	
	Nd-UMI-35		32		10		
	CO$_2$	1977				2.5	
	I	1976				0.2	
W. Germany	I-Asterix III	1977	1	17 cm	1	1	4.4

Legend: CO$_2$ - carbon dioxide gas
Nd - neodymium glass
KrF - krypton fluoride

LLL - Lawrence Livermore Laboratories
LAL - Los Alamos Laboratory
KMSF - KMS Fusion Inc.
NRL - Naval Research Laporatory

Source: J.S. Geiger and G.A. Bartholomew, 'A Review of the Prospects for Fusion Breeding of Fissile Material', AECL, October 1981, p. 93.

In the mid-1970's, in light of the growing difficulties with lasers, attention was directed to using particle accelerators as fusion drivers - drivers which would use an intense beam of charged particles as the energy carrier. Such particles appeared to be more efficient than lasers in turning the input energy into output energy. The first particles investigated were electrons, but the problems associated with them soon became apparent. The field generated by the electrons in the beam severely limited the current that the beam could carry. The excessive range of electrons in the pellet meant that the centre of the pellet became prematurely heated. In fact, from what has been learned, it is difficult to envisage electron beams in a fusion power system. This now seems the least viable of the particle beam approaches and has been assigned a low priority for development in other countries.

It was then hoped that light ions, with energies of 10 MeV, would prove to be superior to electrons and research was undertaken on this approach. However, a total current of several million amps was required, and there proved to be a number of severe problems in getting the ion beam from the source to the pellet in the proper relationship, and in achieving high pulse repetitive rates and frequencies.

The latest particles to be studied are heavy ions, which come either from inductive linear accelerators or from conventional heavy ion linear accelerators. Energies as high as 10 GeV can be obtained, thereby reducing the current requirement a thousand fold. Such beams can operate at a high frequency and at a high repetitive rate. Substantial progress appears within reach in energy scalability, power efficiency and beam-pellet coupling. Although heavy ion beams seem to be the current front-running particle approach, it is not even near to achieving the required beam power and energy pulsed power required for a fusion power reactor, and it still requires a large and extensive research program before even getting near the possible demonstration of scientific feasibility.

The most promising particle beam driver will ultimately become the central element of an inertial confinement engineering test facility only if it competes favourably against the most promising laser driver. Neither lasers nor particles, however, appear to be close to meeting the necessary requirements for such a facility. The relative attractiveness of the various possibilities and their ranked ordering have tended to fluctuate considerably as scientific studies progress, and as many extremely difficult problems have surfaced over time to reveal the severe drawbacks of various alternatives. It certainly appears to be much too early to make a sound technical judgement and to say with any confidence and certainty which approach will eventually provide a viable path to a fusion reactor - if any. At this stage, therefore, it may be unwise to bet significantly on any of these approaches.

Given that inertial confinement fusion is far away from proof of scientific feasibility, it may not be advisable for the Canadian Fusion Program to undertake a significant program in this area. It is premature at this time to decide whether lasers or particles represent the best alternative.

Another area of serious concern in inertial confinement is that much of the work involved has potential military applications and, as such, is under a security classification. Inertial confinement work has always been pursued for military as well as energy reasons. Indeed, from its earliest days, laser fusion research has been directed primarily to military ends, and remains largely a military concern. For this reason, the world laser fusion effort is heavily concentrated in the USA and the USSR. In the American program, for instance, of the over $200 million devoted to inertial confinement development in fiscal year 1981, a significant part came from the defense budget.

This weapons potential, and the security classification it entails, may prove to be a serious roadblock to the further possible development of this field in Canada. It may limit Canada's opportunity for international collaboration since the main candidate would be the US, and the US might not be very open to such collaboration in this sensitive area. Moreover, since this connection to nuclear weapons design and testing is unique to inertial confinement, and does not exist in magnetic confinement, it may be worthwhile, particularly from a public opinion point of view, for Canada to avoid an involvement in this area. Inertial confinement is largely being developed around the world because of its military applications, and this rationale may be difficult to support in the Canadian context. On the other hand, it is such a long shot, that it may be difficult to justify on an energy basis alone.

The main reason usually advanced for why Canada should specialize in CO2 laser fusion work is that we already have a considerable expertise in high power lasers and in diagnostics for inertial confinement. (In contrast, Canada has no significant activity in the particles area, although some aspects of AECL's accelerator development program and the TRIUMP cyclotron may be relevant.) There is a recognized advantage in the international reputation Canada holds as a world leader in laser development. Several research 'firsts' have been recorded by Canada and significant contributions made: the development of lasers, laser interactions with materials, plasma-laser coupling processes, energy transport in laser irradiated targets, and diagnostic techniques using Canadian made lasers (e.g. ultra-fast, pica-second streak cameras).

The laser-plasma group in the Division of Physics in NRC pioneered the development of CO2 lasers (COCO II) and continues to extend the capabilities of the system. Current work relevant to inertial confinement includes the development of high power, nanosecond pulse technology for CO2 lasers; the investigation of laser-plasma interactions to understand the radiation-plasma coupling process and the behaviour of the superthermal particles; the development of optical diagnostics and sophisticated measuring tools such as X-ray and infrared spectrometers, ultrafast cameras, microscopes and particle detectors; and the study of other potentially useful laser systems such as dye lasers and excimer lasers.

A number of university groups across Canada are involved in fundamental laser development studies. The primary (but not sole) system under investigation is the CO2 laser, with theoretical modelling and experimentation of the dynamic processes involved in the major study areas of absorption, transport, parametric instabilities and diagnostic systems for the measurement of plasma parameters. The main groups involved include INRS Energie of the Université du Québec at Varennes, the Universities of Alberta (KrF), B.C., Toronto and the Ecole Polytechnique at the Université de Montréal.

Canada has also developed several small high technology companies which are directly servicing, developing, producing and marketing CO2 gas lasers. Such firms include Lumonics Research Ltd. of Ottawa, Gentec Inc. of Quebec City, RCA Ltd. of Ste. Anne de Bellevue, MPB Technologies of Montreal and Laser Fusion Ltd. of Concord, Ontario. This existing industrial capability could be enhanced through a laser fusion R&D effort, through the need to supply optical components, laser modules and target chambers. Moreover, the development of laser systems for fusion power could find wide application and potential spin-off benefits in several non-fusion areas - the machining, drilling and welding of pipelines or massive structures, and the fields of medicine, communication and survey/alignment equipment.

This existing Canadian base of scientific expertise and industrial capability represents the foundation upon which one could develop a laser fusion R&D effort in Canada. This might well constitute an indigenous Canadian advantage - one of the specialization criteria. Significant interim industrial benefits and spin-offs might also be forthcoming. A full judgement on these aspects, of course, will have to await their detailed presentation in the planning study now underway. It should be noted, however, that such benefits are important and necessary prerequisites for a Canadan fusion R&D effort in this area but are not sufficient by themselves to justify such an effort. What must be firmly established first is the need for the Canadian Fusion Program to encompass the inertial confinement area and the importance of the CO2 gas laser speciality in that area.

From the discussion above, it would seem that there may be legitimate grounds for not undertaking an effort in inertial confinement beyond the present level of activity - although the findings of the MPB Technologies study could reverse this view. This tentative conclusion is largely based on the current status of inertial confinement, on the limited resources that will be available for fusion R&D as a whole, and on the existence of what may be more attractive alternatives. Two leading fusion scientists from the Lawrence Livermore Laboratories, for example, indicated to the Lefebvre Special Committee on Alterative Energy and Oil Substitution that Canada should seriously consider making a world fusion contribution in the field reversed magnetic mirror area - one that involves a very compact system, that is extremely interesting from a physics standpoint and that can be investigated at this point in time on a relatively small scale.[56] This is only to suggest that, if a third specialization focus is to be given to the Canadian Fusion Program, then there may well be real alternatives to a focus within inertial confinement and these alternatives should be carefully considered before an inertial confinement decision is made.

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[56] Richard Post and John Emmett, testimony to the Lefebvre Committee, December 10, 1980, Minutes No. 35, p.40 and 44.

THE FUSION-FISSION HYBRID

A typical fusion reactor operating on a deuterium-tritium reaction would have a lithium blanket that absorbed the released neutrons to produce tritium, and that used the heat to generate electricity. This kind of reactor, whose specific purpose is to generate electricity, is called a 'stand-alone' fusion reactor.

What a fusion reactor could produce most naturally and easily, however, is a prodigious amount of energetic neutrons. Instead of being used to generate electricity, these neutrons could be used to produce fissile fuel. The fusion reactor would have a blanket of fertile material (Th232 or U238) which, when it absorbed neutrons, would 'breed' fissile material (U233 or Pu 239). This fissile material could, after processing, then be used and burned as a fissile fuel in a fission reactor. This kind of fusion reactor, whose specific purpose is to produce fissile fuel, is called a 'fusion breeder'.

A 'fusion-fission hybrid' system is one that consists of a fusion reactor and a fission reactor in a symbiotic relationship. There are two types of such hybrids. One is a fusion breeder that produces the fissile fuel which is then taken away and used in a separate fission reactor. The other is when the fusion breeder and the fission reactor are joined together as a single entity that produces both fuel and power.

It is commonly held that the first commercial application of a fusion reactor may be as a supplier, not of net energy, but of neutrons used to produce fissile fuel material. Since a fusion breeder is required to produce neutrons rather than net energy, its engineering requirements could be at least an order of magnitiude less severe than that of a stand-alone fusion reactor. A fusion breeder could therefore be expected to become technically and commercially developed earlier. This would permit an earlier industrial participation in fusion reactors and would enable nuclear fusion to act in the short-run as a valuable adjunct to the fission power system. A fusion breeder could also act, because of the experience gained from it, as the logical stepping stone toward the development of the stand-alone fusion reactor at a later date.

A fusion-fission hybrid might, however, encounter some serious drawbacks. There might be a considerable economic penalty in operating a fusion breeder below the engineering energy breakeven point. A combination of fusion and fission could drag fusion into the midst of the nuclear fission controversy - something that fusion development should attempt to avoid. Furthermore, alternative sources of neutrons such as the accelerator breeder and the fast breeder reactor, appear to be technically more advanced than the fusion breeder, and therefore might be realized sooner. And, finally, there must be a real demand for such fissile material in advanced fission fuel cycles or reactors for the fusion breeder to be actually needed.

Source: J.S. Geiger and G.A. Bartholonew, 'A Review of the Prospects for Fusion Breeding of Fissile Material', AECL, October 1981.

Another alternative that has been widely and repeatedly suggested as a worthwhile activity for Canada is the fusion-fission hybrid (see 'The Fusion-Fission Hybrid'). Indeed, the Science Council of Canada's energy study of 1975 recommended that 'Canada should initially concentrate on fusion as a neutron source for use in breeding fissile material rather than on fusion as a net energy generator. In this way our involvement in fusion technology could become a natural long term adjunct to our nuclear fission power program'.[57] The first practical and commercial application of fusion power in Canada could well be as a neutron source to improve the utilization and expand the supply of fuel for the CANDU fission reactor operating on an advanced fuel cycle. Canada is, in fact, particularly well-suited for such a symbiotic system. The CANDU reactor produces fusion fuel - tritium - as a byproduct of its operation, and could therefore supply a fusion reactor with its needed fuel (and, as a result, greatly simplify the design of the fusion reactor, since tritium breeding within a lithium blanket would not be required). The fusion reactor in turn is rich in the production of neutrons which can be used very effectively in an advanced fuel cycle CANDU reactor. A fusion reactor, for instance, could have a lithium blanket breeding U233 from Th232 for use as a fuel in a CANDU reactor operating on a thorium fuel cycle. In this situation, a single fusion reactor could fuel between 30 and 40 CANDU reactors of a similar size - making the CANDU about 1.5-2 times better in combination with a fusion reactor than would be a conventional light water reactor.[58]

Thus, the CANDU reactor appears to offer a unique opportunity for a fusion-fission hybrid system. Such a system may add an attractive flexibility to both parts of the hybrid, and be a technically and commercially viable proposition well before a stand-alone fusion reactor. If so, then Canada could be in a

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[57] Science Council of Canada, <u>Canada's Energy Opportunities,</u> March 1975, p.108.

[58] Richard Post, testimony to the Lefebvre Committee, December 10, 1980, Minutes No. 35, p.40.

position to develop a competitive edge in introducing and supplying fusion power systems. Although AECL is in the midst of evaluating the basic electronuclear breeding possibilities of accelerator breeding and fusion breeding, the eventual development of a hybrid fusion-CANDU symbiotic relationship might be considered as a main element in the Canadian Fusion Program and as a possible alternative focus to the one in inertial confinement. Certainly a recommendation to develop a laser fusion specialization will need to show that this is more beneficial and worthwhile for Canada than pursuing the fusion-fission hybrid concept.

In summary, the apparent third specialization of the Canadian Fusion Program - a laser inertial confinement fusion project focussed on the development of CO2 gas laser technology and diagnostic instrumentation - has not been decided yet and is now the subject of a detailed planning study. At this stage, however, it appears that such a specialization may not be warranted or justified. This specialization concept was proposed a decade ago and has continued to be advanced without a hard and realistic assessment being made since then as to its actual merits and drawbacks. Inertial confinement is certainly at the present time a far less likely prospect for becoming a viable and practical approach to actual fusion power than the Tokamak and other magnetic confinement possibilities. Inertial confinement is still mired down in considerable and growing scientific difficulties that seriously call into question whether this appraoch will achieve scientific feasibility. Given the problems that have developed, and the uncertainties that continue to exist, it is likely too early at this point to judge which particular driver alternative (lasers or particles) will, if ever, turn out to be the optimum one for realizing fusion power. Inertial confinement work is also heavily burdened with potential military applications and security classification. Although there is in place an existing Canadian base of scientific expertise and industrial capability in CO2 gas lasers, this in itself is not a sufficient justification for the proposed specialization effort. Moreover, it has yet to be clearly demonstrated that a laser fusion specialization is more beneficial and worthwhile for the Canadian Fusion Program that would be other possible alternatives, such as developing the fusion-fission hybrid concept.

It is therefore concluded that a totally convincing case for Canada undertaking a specialization in a laser fusion project has not been made to date and that it is not at all obvious that the Canadian Fusion Program should in fact include such a specialization. A final decision on this matter will only be possible after the detailed planning study has been completed, but such a decision must take into account the serious concerns raised above.

International Collaboration

Besides the specialization areas described above, another important component of a Canadian Fusion Program is international collaboration.

If the program objectives of the Canadian Fusion Program are to be realized, the specialization areas undertaken must result in formal agreements for bilateral exchange with appropriate foreign fusion centres. Although the Tokamak de Varennes Project and the Fusion Fuel Technology Project have only been initiated within the last two years, some concrete achievements, noted below, have already been made in establishing international collaboration.

The Tokamak Project has attracted considerable international interest. As a direct result of the announcement of this project, a formal standing offer was made by the Princeton Plasma Physics Laboratory for Canada to participate in the operation of the Plasma Divertor Experiment (PDX) machine. This would involve Canadian scientists working directly on PDX and could be a valuable Canadian entrée to this major fusion facility and to its successor - TFTR. Due to a lack of funds, however, this offer has not been taken up to date. An informal arrangement has been made, however, for a joint experiment that involves the provision of a beam tube port on PDX for the application and testing of a laser-fluorescence, diagnostic instrument which is being developed for the Varennes Project. Another offer has been received from the Massachusetts Institute of Technology (MIT) to install the diagnostic equipment on its fusion machine, the Alcator. An agreement has been signed with MIT for IREQ scientists to obtain background experience and training by working directly on Alcator. It is expected that other opportunities will develop, especially as the completion of the construction phase of the Varennes Tokamak approaches, and certainly as the actual R&D operational program gets underway.

In the Fusion Fuel Technology Project, Ontario Hydro is part of a consortium formed by McDonnell Douglas to carry out a fusion fuel study for the Electric Power Research Institute, the joint research institute for the American electric utilities. The study, entitled 'Assessment of Technical Risks and R&D Requirements for a Magnetic Confinement Fusion Fuel System', will be a technical assessment of the engineering options of fusion fuel subsystems. It will be a nine month effort costing $250,000 and is scheduled to be completed by January of 1983. It is hoped that Canada will be able to meet some of the R&D requirements that will be identified in the study.

Talks are now in progress with the Los Alamos National Laboratory on the possibility of Canada providing a tritium commissioning and operating manual for use in the Tritium System Test Assembly, now under construction there. Negotiations are now taking place for a Canadian involvement in the $270 million Fusion Materials Irradiation Test Facility at Hanford, Washington - a project that is being considered as a joint construction and operation effort of the US, Japan and Euratom. Canada has, in fact, been specifically invited to join the negotiating group of this project.

Opportunities are being pursued for a Canadian involvement in the tritium related aspects of TFTR, especially in terms of modelling pathways of tritium hazards to the environment (an area in which Canada has a recognized capability) and remote manipulation aspects of tritium handling. It is very likely that Canada will obtain the modelling contract and that an aggressive Canadian bid will be made on the design of at least one of the remote manipulation devices involved.

Ontario Hydro has also made two other arrangements with the US. The Argonne Laboratory near Chicago has asked Canada to assist in the tritium related work being done for the American INTOR design studies. In addition, the University of Wisconsin is undertaking design studies for a German national fusion machine, and has sought to involve Canada on the tritium aspects involved.

Ontario Hydro is also discussing with JET representatives at Culham (U.K.) several tritium areas. Canada will likely offer to do some tritium pathways analysis. JET is very interested in possibly obtaining a Canadian tritium supply. The JET facility must include a complete tritium handling and removal system that will cost about $17 million. Although it was assumed that France, as a consortium member, would be providing this system, the JET people are now seriously considering the possibility of a Canadian role in this area. Canada may therefore put together a complete proposal that could place it on the bidders list.

Exploratory talks are also occurring with Japan on tritium matters. To date, however, Canada is simply making fact-finding visits to Japan in order to identify specific opportunity areas that could be pursued.

Although the tritium project was only announced within the last six months, it is clear that there has already been considerable progress and movement in the area; that a substantial amount of international interest in the project has been forthcoming; and that the future prospects for the project, especially in the short-term, appear to be significant.

In addition, negotiations are now going on with the US Department of Energy for the establishment of a formal US-Canada bilateral agreement on fusion R&D - a blanket agreement which may be finalized within a year or two. Such an agreement is expected to pave the way for the participation of Canadian industry in US fusion programs by providing the general framework for such participation. It is clear that this agreement is being pursued only because Canada has recently established real, active fusion R&D projects - the prerequisite basis for possible collaboration. Meanwhile, working groups have been set up within the US Department of Energy to oversee any US-Canada joint steps that may be taken in the interim. Indeed, the fact that a bilateral agreement is being negotiated has opened doors for such interim arrangements.

Other international contacts also exist. Cooperation between the University of Alberta and the Lawrence Livermore Laboratories on krypton-fluoride lasers is in progress. MPB Technologies Inc. has received a contract from the US Department of Energy for work on hot electron effects. The University of Toronto's Institute for Aerospace Studies has joint contracts with the JET service group concerning the properties of surface coatings for first wall protection, and with Gulf Atomic of San Diego for materials testing in the fusion context.

Another aspect of international collaboration is a Canadian involvement in multilateral organizations and agreements in the fusion area. Since membership is contingent on 'a major fusion research effort' being in place, Canada is not yet a member of the International Fusion Research Council (IFRC) of the International Atomic Energy Agency. There is real hope, however, that, as the two Canadian fusion projects get established, Canada could earn a seat on this important fusion body. This would be a significant breakthrough milestone for Canada on the world fusion scene. Preliminary discussions towards this end have already taken place. Informal indications are that there is an IFRC interest in a Canadian membership now. The first stage will likely consist of a Canadian participation in the INTOR design working groups as a proof or test of a meaningful Canadian fusion contribution. Canadian participation in these working groups and in other IAEA internal fusion activities is being pursued. Important milestones would be Canada sitting on these working groups within two years, and, then, after a few years, gaining a membership seat on the IFRC.

Canada is a member of the Fusion Power Coordinating Committee of the International Energy Agency and has signed two Implementing Agreements. The first one is on TEXTOR (Torus Experiment for Technology), a Tokamak device in Julich, West Germany, designed for the study of plasma-wall interactions and impurity problems. By contributing about $250,000 and five scientist-years to its construction, Canada has obtained a right to 7% of the machine time; has gained a working familiarity with the German program; and has greatly improved its prospects for future equipment and instrumentation sales. The use of TEXTOR by Canadian scientists and companies will provide a valuable entry point to the European fusion program.

The second agreement is on 'Radiation Damage in Fusion Materials' under which Canada, Japan, Euratom and the US are exchanging information and reference materials to correlate and establish a common data pool for fusion materials damage. Joint radiation experiments and scientists exchanges are also being planned. The only real Canadian involvement to date, however, has been the attendance at meetings by an AECL officer working under a sub-contract from NRC. Additional Canadian participation, however, has not been pursued, due to a lack of funds; only about

TABLE 43- RECOMMENDED MINIMAL BUDGET FOR CANADIAN NATIONAL FUSION PROGRAM

(All units in 1979, millions of Canadian Dollars)

FISCAL YEAR	79/80	80/81	81/82	82/83	83/84	84/85	85/86	86/87	87/88
• Federal Funds for National Fusion Program	0.3	3.0	6.0	9.0	12.0	15.0	12.0	12.0	12.0
• NRC In-house Laser Fusion Group	0.9	1.2	1.5	2.0	2.0	2.0	2.0	2.0	2.0
• Total Federal Funds	1.2	4.2	7.5	11.0	14.0	17.0	14.0	14.0	14.0
• Other Sources of Funds for National Fusion Program*	0.7	1.8	6.5	12.0	14.0	8.0	3.0	3.0	3.0
• TOTAL	1.9	6.0	14.0	23.0	28.0	25.0	17.0	17.0	17.0

*Includes: Provincial Governments/Utilities/Foreign, etc.

Source: NRC Advisory Committee on Fusion-Related Research, 'A National Fusion Program for Canada,' March 1980.

$15,000 of Canadian funds has been spent to date. This is, however, a critically important area since it involves laying the basic ground rules for internationally accepted specifications in materials production. An up-to-date and thorough understanding of these specifications as they are developed is essential if Canadian industry is to be able to provide actual bids on materials production in future fusion devices.

International collaboration must also involve a planned program of exchanging scientific and engineering personnel - so that Canadian personnel could participate in major foreign fusion projects such as TFTR and JET, and their personnel could participate here. Canada should also monitor closely the developments related to the INTOR project and, if it appears that it might be revived as a possible international venture, Canada should prepare itself to be in position to be a candidate as host. Meanwhile, Canada should explore with the US whether there is a role Canada could play in the development of the Fusion Engineering Device or other facilities.

Since the Canadian fusion R&D effort must be undertaken in terms of international collaboration in order for Canada to make a valuable contribution and to gain access to the world fusion knowledge and know-how, it is extremely important that this program element be developed as much and as far as possible. Significant accomplishments have been made to date and further opportunities must be seriously pursued and successfully exploited if the Canadian Fusion Program is to achieve its goals and objectives.

Funding

In 1979-80 Canada spent almost $3 million (1979 Canadian dollars) on fusion R&D: $300,000 in federal funds for the National Fusion Program; $900,000 for the in-house laser fusion group at NRC; $750,000 of NSERC funds for university fusion

CANADIAN FUSION PROGRAM PLAN

Sub-Program	Title/Objective/funding	1983/84	1984/85	1985/86	1986/87	1987/88
Magnetic Confinement	TOKAMAK DE VARENNES - To evaluate the physics and engineering feasibility of a reversible-current Tokamak	①	② $\boxed{3}$	④		⑤ →
	- Funding ($ M Budget year)	12.6	6.9	8.2	9.0	9.9
Inertial Confinement	LASER FUSION - To evaluate the physics and engineering feasibility of gas lasers as drivers for microimplosions	⑥	$\boxed{7}$	⑧		⑨ →
	- Funding ($ M Budget year)	2.5	4.8	10.2	14.5	10.8
Materials/ Engineering	FUSION FUEL TECHNOLOGY - To develop components and consulting expertise for the management of tritium as a fusion fuel.	$\boxed{10}$			⑪	$\boxed{12}$ →
	- Funding ($ M Budget year)	2.9	4.5	6.6	7.7	8.5
	TOTAL PROGRAM 3.4 - Total Funding ($ M Budget year)	18.0	16.2	25.0	31.2	29.2

TABLE 44

KEY:
1. Delivery of Tokamak components completed
2. First Plasma
3 Decision on 5-year operating agreement with Hydro Quebec
4. Full operating capability reached
5. Complete measurements of principal characteristic of reversing current
6. Complete scientific and technicala plan including industrial benefits analysis
7. Decision on 5-year, facility-construction agreement with provincial partner.
8. COCO II up-grade completed
9. Complete construction of laser fusion facility
10. Decision on 4-year fusion fuel program implementing agreement with Ontario Ministry of Energy.
11. Complete selection of sub-specialties for program
12. Decision on 5-year operating agreement with Ontario Hydro and Ontario Ministry of Energy.

Source: T.S. Brown, 'Canadian Fusion Program', June 1982 related activities; and $700,000 from Provincial Governments and utilities. Since the world fusion funding in that year amounted to over $2 billion, this Canadian level of support was not considered to be a serious contribution to the international fusion research effort.

In 1979 the NRC, based directly on funding recommendations made from its Advisory Committee, indicated that a minimal budget for the Canadian Fusion Program in the three specialization areas over the five year period from 1980/81 to 1984/85 should total almost $100 million, of which about one-half would be federal funds. (See Table 43.) After 1984/85 and the end of capital fund requirements for the major facilities involved, a steady state operation for the following three years would be at an annual level of $17 million: $6 million for magnetic fusion, $4 million for materials and $7 million for laser fusion. (This level of effort in each of the specialties was determined by the size of the research team that was deemed necessary in order to establish a world presence for Canada.)[59] This is, in fact, very much in line with what a leading American fusion scientist suggested would be an adequate funding level in order for Canada to make a real contribution to the world fusion effort: 'I think expenditures on the order of $10 million or $20 million a year could have the effect you are looking for ... Typically, I would say in any one of the areas a couple to several million dollars a year would be necessary to be able to strongly contribute to it'.[60]

With the establishment of the Tokamak de Varennes Project in 1981, and the Fusion Fuel Technology Project in 1982, a more definite forecast and timing of actual fusion funding is now possible. Table 44 outlines the future funding plan for the Canadian Fusion Program as presented in June of 1982, together

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[59] T.S. Brown, 'The Canadian Fusion Program', June, 1982, p.10.

[60] John Emmett, testimony to the Lefebvre Committee, December 1980, Minutes No. 35, p.29-30.

Canadian Fusion Program as presented in June of 1982, together with a list of critical decision milestones to be faced. Total fusion funding over the next five fiscal years (up to and including 1987-88) is expected to be $120 million: $50 million in the Tokamak de Varennes, $40 million in laser fusion and $30 million in fusion fuel technology. Approximately one-half of this funding will be from the federal government and one-half from the provincial governments or their electric utilities. Moreover, additional funding support would be required if further positive decisions are taken at the future milestone dates indicated: in 1984 on the construction of a laser fusion facility; in 1985 on an operating agreement with Hydro Quêbec on the Tokamak de Varennes; and in 1987 on an operating agreement with Ontario Hydro and the Ontario Ministry of Energy on the fusion fuel project. (It should be noted, however, that no fusion-related NSERC grants are included in these estimates, and that an inertial confinement effort in a laser fusion project with a special facility is assumed.)

Thus, the current funding plan for the Canadian Fusion Program appears to satisfy the minimal effort needed to establish Canada as a serious fusion research actor - an effort that could develop a Canadian expertise and leadership role from which to make a significant contribution of value to the international fusion development program. Depending on developments over the next few years, additional fusion funding may be proposed but this will only be decided at the appropriate time and in light of the experiences gained and the outlook then prevailing. The only fusion research project in this funding plan still left to be decided upon is the inertial confinement specialization. As indicated previously, however, such a project, at this time, may not be clearly justified.

4. CONCLUSIONS

Based on the preceding account of the policy principles and program elements of a Canadian fusion R&D effort, the following conclusions can be reached.

(1) In order to meet the energy needs of the next century and beyond and to sustain a position of energy self-sufficiency in the long-term, Canada should keep open the fusion energy option by establishing the necessary scientific expertise and technological capacity to develop fusion power, when and if such development becomes desirable or necessary in the future.

(2) Because a totally foreign dependency on fusion technology in the future is undesirable, and because a totally independent and full-scale indigenous program on fusion development is impractical, a Canadian fusion R&D program must be based on the cornerstone of international collaboration. This will enable Canada to gain access to the scientific knowledge and technical know-how of the world fusion program, and to therefore develop a Canadian industrial capability to manufacture components and materials for a fusion power system either at home or abroad.

(3) To gain such access, however, Canada must have an established domestic fusion R&D program capable of making a significant contribution of real value and interest to the world fusion effort. This program and contribution must be realized within the decade if Canada is to join the international fusion community, since the engineering stage of fusion development now being entered into will soon restrict the possibility of new fusion entrants. To date, significant progress has been realized in achieving collaborative arrangements with other countries in the existing program elements, although still further arrangements should be pursued and realized.

(4) The primary objective of a Canadian fusion R&D program in the 1980's, therefore, should be to establish and maintain a domestic scientific and technical capability as the basis for achieving international collaboration with foreign fusion programs.

(5) This requires that Canada must concentrate or specialize in narrowly focussed technical areas in fusion R&D. Such specialized areas must be of real international interest; must be based on some indigenous advantage or existing expertise; must be undertaken through national cooperation involving all the relevant sectors; and must result in substantial interim industrial benefits.

(6) The Tokamak de Varennes Project is the established specialization of the Canadian Fusion Program in the magnetic confinement area. This project fully satisfies the specialization criteria.

(7) The Fusion Fuel Technology Project with a focus on tritium supply and handling is the established specialization of the Canadian Fusion Program in the materials/engineering area. This project also appears to satisfy the specialization criteria.

(8) The third specialization of the Canadian Fusion Program is proposed in the inertial confinement area - with a laser fusion project focussed on the development of CO2 gas laser technology and associated diagnostic instrumentation being put forward. A final decision on this project has not yet been made and awaits the completion of a detailed planning study now underway. At this stage, however, a convincing case has not been presented as to the actual need for a Canadian R&D effort in inertial confinement generally, and in CO2 gas lasers fusion specifically. Inertial confinement is clearly far behind magnetic confinement on the road to developing fusion power. Given the considerable scientific difficulties it faces, inertial confinement may not even prove to be scientifically or technically feasible. In light of the

uncertainties that continue to exist, it is too early at this point to judge which particular driver alternative (lasers or particles) will, if ever, be most capable of realizing fusion power. Inertial confinement work is also heavily burdened with potential military applications and security classification. Although there does exist a Canadian scientific expertise and industrial capability in CO2 gas lasers, this in itself does not constitute a sufficient justification for the proposed specialization. Moreover, it has not been clearly shown that a laser fusion specialization is more beneficial and worthwhile for Canada than other possible alternatives, such as the fusion-fission hybrid concept. For these reasons, the proposed laser fusion project must be seriously questioned as an appropriate R&D specialization of the Canadian Fusion Program.

(9) The current funding plan for the Canadian Fusion Program in the three specialization areas indicates expenditures over the next five fiscal years (up to and including 1987-88) of $120 million - one-half from the federal government and one-half from the provincial governments or their electric utilities. This appears to satisfy the minimal effort needed to establish the required Canadian scientific expertise and technical capability in fusion energy. This funding plan, however, includes $40 million for an inertial confinement project specializing in CO2 gas laser fusion - a project that has yet to be approved and that, at this time, can not be clearly justified.

G. OVERALL CONCLUSIONS AND RECOMMENDATIONS

This concluding segment of the paper presents the general context in which long-term energy R&D policy options should be considered; and sets out certain conclusions and recommendations on the extent to which Canada should pursue R&D on advanced fuel cycles for the CANDU system, and R&D on nuclear fusion.

1. Long-Term Energy R&D Policy Options

Energy is a critically important element in the future development of an industrial society. Current energy production, however, is largely based on the hydrocarbon fossil fuels - oil, natural gas and coal. Due to their limited supply, these fossil fuels will not indefinitely be able to provide the growing energy needs of the world. At some point in the future, these conventional energy sources will become physically unavailable or economically and socially unacceptable. New alternative sources of energy will then be required.

If society is to be freed from its vulnerable fuel dependency, and if its energy needs over the long term are to be sustained, then its sources of energy will need to be renewable or essentially inexhaustible in nature. They must therefore be obtained from a widely available and abundant fuel base. At the present time, there are few such essentially inexhaustible energy sources with this potential. In order that they may be available when needed in the future, however, these long-range energy alternatives require a considerable program of continuing scientific and technical development over a long period of time.

The great uncertainties inherent in such development, though, must be recognized. Given the long lead times involved and the many variables that will come into play, it is not possible to pinpoint exactly when such alternatives will be required, to confirm their eventual economics with confidence, or to evaluate fully all of their likely consequences. Such answers can only be acquired over time as the development effort progresses. Moreover, these uncertanties suggest that it would be advisable to avoid, if possible, a reliance on only one long-term alternative since, for whatever reasons, it may not work out to be the best alternative.

Canada's long-term energy concerns are to meet its energy needs in the next century and beyond, and to sustain an energy self-sufficiency position over the long-term. Canada, like the rest of the world, will need to make the inevitable energy transition away from dwindling hydrocarbons to essentially inexhaustible energy sources. Canada should attempt, therefore, to place itself in a flexible position to make realistic decisions at the appropriate time in the future, concerning these energy sources. To do so, Canada will need to keep open certain basic options in these areas so that it will be able to decide, if required in the future, whether or not to adopt these energy technologies. If this flexibility is not maintained, Canada's future energy choices may be severely constrained. What is required to avoid such constraints is a continuing effort to develop the needed competence in the science and technology of these energy sources.

Keeping open such long-term energy options is a necessary and proper function of the federal government's energy R&D program. Although shorter-term R&D focussed on more immediate energy problems must obviously be pursued and predominate, it is necessary to ensure that these long-term R&D needs are also adequately supported on a continuing basis. The horizon of interest for Canada's current and planned energy R&D effort should not be limited to next year or to the next decade, but should also extend into the next century. The energy R&D concerns should be not only with the energy problems of this generation, but also with the energy problems of the next generation. A far-sighted perspective, therefore, calls for the federal government's energy

R&D portfolio to consist of a healthy mix of short-term and longer-term R&D problems and activities.

> Recommendation No. 1: The federal government should seek to keep open certain longer-term energy options - options involving essentially inexhaustible fuel supplies - by supporting a necessary level of relevant R&D in these areas.

2. CANDU Advanced Fuel Cycles

The CANDU nuclear reactor is an important Canadian energy technology. Designed, developed and manufactured in Canada, it is a leading Canadian high technology product that contributes towards our goal of energy self-sufficiency. It provides an increasing share of our electricity needs, and is capable of meeting far more of these needs as they grow in the future. It represents an economic source of electricity in Ontario today, and will likely become more economically attractive in the future and in certain other areas of Canada. In terms of reliability and performance, CANDU consistently surpasses its foreign counterparts and it requires significantly less uranium fuel - about 20% less - than these other reactors.

One long-term energy option for Canada is the use of advanced fuel cycles in the CANDU reactor. With only a modest modification of its basic reactor design, CANDU has the potential to use advanced fuel cycles that would result in up to an 80% savings in the amount of uranium fuel required. In contrast, a light water reactor could only be brought, with advanced fuel cycles and with sustantial basic design changes, to achieve about a 30% uranium savings. A fast breeder reactor could improve uranium use some 60 or 70 fold, but entails the development of a totally new reactor. The CANDU nuclear reactor, therefore, is a unique reactor that can, without major modifications, use advanced fuel cycles, achieve substantial uranium fuel savings, and extend the nuclear fuel base.

At this time, however, such advanced fuel cycles are not likely to be required from a resource viewpoint, or economically competitive for some time to come. Canada's existing uranium resource base, together with the continuing resource additions that can be expected in the future, is capable of meeting the long-term fuel requirements of the domestic nuclear power program and of maintaining Canada's position as a leading uranium exporter. Advanced fuel cycles will only become economically competitive if and when the uranium price increases to four or five times the current price level in constant dollar terms - a situation that is unlikely to develop for at least another four or five decades.

At the present time, therefore, the full development of advanced fuel cycles is neither demanded by the current uranium resource situation nor warranted by economic considerations. Given the continuing uncertainties over the long term and the many factors involved, however, this assessment could change in time. It would thus be desirable for Canada to position itself so that, if required by the evolving situation, it could decide to proceed with advanced fuel cycles. It would, therefore, be advisable for Canada to undertake an adequate R&D effort in order to keep open its policy options for future decisions on the demonstration and deployment of advanced fuel cycles. Such an R&D program would take advantage of the unique characteristics of the CANDU reactor and of Canada's existing scientific expertise in the nuclear field.

<u>Recommendation No. 2</u>: Canada should keep open the CANDU advanced fuel cycles option by undertaking a modest R&D program with funding up to a ceiling of approximately $10 million per year for about ten years -- with these funds to be drawn from within the existing budgetary allocation of AECL. This activity would provide the basis for an expanded program should the need for such a program arise at some time in the future (e.g. should the price of uranium increase considerably). A full review of the R&D program should be made at the end of five years.

Although the precise definition of the elements of an optimum R&D program on advanced fuel cycles are best left to the appropriate scientific experts to suggest, certain general orientations and surrounding conditions can be suggested.

First of all, while the R&D program should explore the range of advanced fuel cycle possibilities, it should seek, as one short-term goal, to complete the necessary research work required for a low-enriched uranium (LEU) fuel cycle. Although it is not as uranium conserving as other advanced cycles based on plutonium and thorium, and does require an enriched uranium supply either from abroad or from within Canada, LEU does offer a number of distinct advantages, and is of more interest to Ontario Hydro at present than the other cycles. Moreover, only a modest research effort for only a few years is required to make this cycle technically available for introduction into the CANDU reactor. This would likely require a firm decision from an electric utility to proceed with the LEU and an appropriate resolution of who should incur the R&D costs involved.

In addition to this, a comprehensive knowledge base should be developed in Canada on the sensitive areas of advanced fuel cycles - environmental impacts, waste disposal, safety aspects, and non-proliferation considerations. This is required in order to determine with assurance the likely consequences involved in adopting advanced fuel cycles.

Such future decisions will likely be marked by controversy, with the public acceptability factor being a prime consideration. For this reason, it will be important that there is developed over time a solid public understanding about the nature of the R&D program and the results it achieves, and about the likely implications of advanced fuel cycles (especially in the sensitive areas previously mentioned).

One caveat which should be attached to the advanced fuel cycle R&D program is that it should not be undertaken at the expense of other essential efforts in nuclear R&D, such as waste disposal, reactor safety, and the decommissioning of nuclear facilities. This on-going work is vital to the success of the existing CANDU program, and no resources should be diverted from it to the advanced fuel cycles effort. The funds for the latter should come from elsewhere within AECL.

The advanced fuel cycle R&D program should be national in scope, involving participants from the relevant sectors - the nuclear electric utilties, the nuclear manufacturing industry and the university sector. Although AECL, with its existing scientific expertise in nuclear energy, would clearly be the leading actor, other interested groups and individuals should be involved in the R&D program so as to give it a national flavour.

Further, it would be highly advantageous if the R&D program was undertaken as an international co-operative venture between Canada and one or more foreign countries, and such a possibility should be thoroughly investigated. This collaboration could result in significant benefits: a sharing of the costs involved, the stimulation of interest in the CANDU reactor, the connection of Canada to a larger reactor market, and the gaining by Canada of marketing skills for its technology. This would also ensure that

Canada does not undertake R&D in this area in isolation from the efforts and interests of the rest of the world.

Recommendation No. 3: The R&D program on advanced fuel cycles should involve the following elements:

- the necessary, remaining research work required for the low-enriched uranium (LEU) fuel cycle to become technically feasible (once a utility decision to proceed with the LEU and a resolution of cost responsibilities are made);
- an appropriate emphasis on the sensitive aspects concerning the environment, waste disposal, safety and non-proliferation;
- an accompanying public awareness effort on the nature of the program, its intended results and likely implications;
- a national effort involving AECL and the other relevant sectors, such as the nuclear manufacturing industry, universities, and electric utilities; and
- an international cooperative venture between Canada and one or more foreign research partners.

Recommendation No. 4: An interdepartmental task force, to be composed of AECL, MOSST, EMR and EA, should immediately be formed to investigate the possibilities of international collaboration in R&D on CANDU advanced fuel cycles. In examining these possibilities, the task force would consult with possible foreign research partners, and assess their potential for collaboration on the basis of the following critiera:

A foreign research partner for collaboration in this field should have;

- a potential domestic nuclear reactor market of significance;

- proven international marketing skills;
- an expertise and capability in associated technologies or processes;
- an established base of nuclear R&D personnel; and
- a real interest in undertaking a collaborative effort, including a sharing of the costs.

The task force would report to ministers on whether or not there is a potential for collaboration in this area, and, if the potential exists, whom the most appropriate partner would be.

3. Nuclear Fusion

Nuclear fusion also represents one of the few essentially inexhaustible energy sources with the potential to provide a solution to long-term energy supply needs. It offers considerable advantages over nuclear fission in terms of environmental impacts, safety aspects and risks of nuclear weapons proliferation. Although it is too early to make a reliable and confident assessment, fusion might well become an economically competitive energy technology in the future.

For these reasons, fusion power development is now being actively pursued by the industrialized countries of the world. This international effort will be very long and very costly. Fusion research progress to date indicates that the scientific feasibility of the fusion reaction will almost certainly be demonstrated within the next couple of years, but that a commercial fusion reactor will likely not be available for introduction before the year 2030.

If fusion power becomes necessary in the future in order to meet Canada's energy supply needs, a total dependency by Canada on importing foreign fusion technology would be undesirable. It would render the goal of sustained energy self-sufficiency impossible, entail considerable balance of payments costs, and make it difficult for Canadian high technology industry to participate in the design/construction of a fusion system. Moreover, Canada's international reputation and standing as a technologically advanced nation would be seriously undermined. On the other hand, a totally independent and full-scale indigenous R&D effort by Canada in fusion power development would be impractical, given the massive amounts of money over a very long period of time that would be involved.

> <u>Recommendation No. 5</u>: Canada should keep open the fusion energy option for the future by establishing the necessary scientific expertise and technological capacity to develop fusion power when and if such an option becomes technically available and economically attractive.

A Canadian fusion R&D program must involve a significant level of international collaboration. In fact, such collaboration should be a keystone of the Canadian program. This collaboration will enable Canada to gain access to the scientific knowledge and technical know-how of the foreign-based fusion programs, and to better develop a Canadian industrial capability to manufacture components and materials for fusion power systems. To gain such access, however, Canada must have an established domestic fusion R&D program capable of making a significant contribution of real value and interest to the world fusion effort -- that is, our R&D activities should be concentrated in certain specialized areas and based on some indigenous advantage or existing expertise. This contribution must be realized within the decade if Canada is to join the international fusion community, since the engineering stage of fusion development, now being embarked upon, will soon restrict the possibility of new fusion entrants.

Recommendation No. 6: The Canadian fusion R&D program should involve a considerable level of international collaboration so as to permit access to world fusion knowledge as it develops. In order for Canada to make a significant contribution to the world effort, it should undertake fusion R&D in certain specialized areas. These specialized areas:

- should be of real international interest;
- should be based on some indigenous advantage or existing expertise;
- should be undertaken as a national effort involving all sectors; and
- should provide substantial interim industrial benefits.

Two major specialization projects in the Canadian Fusion Program have been established to date and are currently underway: the Tokamak de Varennes Project in the magnetic confinement area and the Fusion Fuel Technology Project in the materials/engineering area. The Tokamak Project, totalling almost $40 million to late 1984, involves a small experimental Tokamak device operating in a quasi-continuous pulse mode for the study of certain characteristics of fusion-grade plasma. The Fusion Fuel Technology Project, totalling $20 million to 1986, involves R&D on the management of the fusion fuel, tritium. Both projects appear to satisfy the specialization criteria for Canadian fusion R&D: they are of international interest and will provide a valuable contribution to the world fusion effort; they are based on existing Canadian advantages or expertise; they are projects of national cooperation involving several sectors; and they promise considerable interim industrial benefits. Both projects hold good prospects for meeting the purposes and goals of the Canadian Fusion Program.

Recommendation No. 7: Full support should be given on a continuing basis to the Tokamak de Varennes Project and the Fusion Fuel Technology Project, including the current funding plan over the next 5 fiscal years (up to and including 1987-88) of approximately $50 million and $30 million, respectively (with equal shares coming from the federal government, and from the provincial governments and their electric utilities). A full review of these fusion projects should be made at the end of this five year period.

It has been repeatedly suggested that inertial confinement become the third specialization of the Canadian Fusion Program. It has further been proposed that such an effort would focus on the development of carbon dioxide gas laser technology and the associated diagnostic instrumentation. A final decision on this proposed area of research has not yet been made, and awaits the completion of a detailed planning study now underway. At this stage, however, a convincing case has not been presented as to the actual need for a Canadian R&D effort in inertial confinement generally, and in fusion from gas lasers specifically.

Inertial confinement is clearly far behind magnetic confinement on the road to developing fusion power. Given the considerable difficulties it faces, inertial confinement is a long way from the demonstration of scientific feasibility. Further, in light of the continuing uncertainties, it is too early to judge which particular driver alternative (lasers or particles) will, if ever, be capable of realizing fusion power. Additionally, inertial confinement work is heavily burdened with potential military applications and security classification. Although a Canadian scientific expertise and industrial capability do exist in carbon dioxide gas lasers, this in itself does not constitute a sufficient justification for the proposed specialization. Moreover, it has not been clearly shown that a laser fusion project is more beneficial and worthwhile for Canada than other possible alternatives, such as the fusion-fission hybrid concept.

For these reasons, the proposed laser fusion project must be seriously questioned as an appropriate R&D specialization for Canadian fusion R&D.

> Recommendation No. 8: An adequate case has not been made for the proposed inertial confinement project, involving gas lasers; this project should, therefore, not be approved at this time.

Finally, it should be noted that AECL has had a modest R&D program on advanced fuel cycles for some years now, and that the work on the Tokamak de Varennes Project and the Fusion Fuel Technology Project is well underway. In other words, what this paper is recommending is not a dramatic departure from what is happening now. It suggests that the advanced fuel cycles program be kept within a modest ceiling that is not much above the present level of effort, and that the two established fusion projects be fully supported over time, as presently intended. It also suggests that there is no reason to allocate more than this to these areas at present, given the economic and scientific uncertainties attached to them. However, if in the future uranium prices increase signficantly, or considerable scientific and engineering advances are made in the fusion area, then it may become appropriate for Canada to undertake significant additional efforts with respect to advanced fuel cycles or fusion. For the present, though, the suggested funding levels represent a reasonable level of activity.

As indicated in the paper, it is believed that these R&D programs to keep open the long-term nuclear policy options are legitimate and worthwhile courses of action for Canada to take in addressing its long-term energy needs. If one or the other is not pursued, this would considerably narrow Canada's future energy options and limit our future flexibility. Such would not be a wise course to follow.