INTERIM REPORT

OF THE

NUCLEAR STUDY

MOSST Technology Assessment (T.A.) Division
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INTERIM REPORT OF THE NUCLEAR STUDY

Since the advent of the energy crisis, nuclear fission has been presented as the most promising solution to our energy needs. But, during the last few years the ensuing debate over the risk, safety and development of the program has not only slowed the rate of growth of the program, but at times seemed to threaten its very existence. Although this is viewed as unfortunate by some, there is an aspect to the debate which is healthy. Many questions which had previously been discussed only behind closed doors and by technicians have now been aired in public. Regardless of the decisions which will ultimately be made on fuel cycles, waste management, safety and security arrangements, they will be made with the knowledge of a better informed public.

There is, however, a second level of inquiry which underlies these technological questions. These are the basic questions of demand projections and supply mix. All of the issues surrounding energy must be viewed in this context for it is the option for demand growth reduction, and its associated assumptions regarding future demographic patterns, economic growth, and societal values which threaten the nuclear industry even more than the initial questions.

So it is early in an analysis of the issues that any inquiry ceases to be simply technical and must embrace the social aspects as well.

The nature of the public debate on nuclear technology is itself an interesting question. Resistance to new technologies is not a new phenomenon. Outbreaks of machine smashing to preserve jobs occurred in the industrial revolution, and regional interests opposed the building of railways in the nineteenth century. During the last two centuries of increased worldwide innovation, opposition to technical changes seems to have become even more frequent.

The better known cases of public intervention include opposition to water fluoridation, new airports (e.g. Pickering), numerous expressway proposals (e.g. Spadina), moves to tighten regulations on products and substances with undesirable side effects (including DDT, car exhaust, mercury wastes and aerosol spray) and recently in Canada, public intervention against pipeline proposals.

The immediate questions to be asked of the public debate are -- What unique problems has nuclear power presented so that public opposition persists or increases? How representative (of the wider public) are the opponents of nuclear fission? On what social, economic and technological assumptions does the nuclear industry base its claims? Is it possible to compare statistical risks with the enormity of any potential disaster and the benefits of nuclear power?

Perhaps the distinctive feature of nuclear specific risks and problems arises from the combination of the following:

1) the collective nature of variables of the decision;
2) the large population to be potentially affected;
3) large scale and small probability of any accident;
4) the possibility of long-term effects which are as yet undocumented;
5) the association of nuclear power with nuclear weapons; and,
6) the long-term commitment to waste management.

The true significance of these issues can only be realized with respect to some speculative judgment of future developments in our society and institutions. Public debate cannot resolve them but may form a climate of opinion which could assist the government in decisions.

The appropriateness of nuclear electricity and its contribution to entire supply systems is now being called into question. At the most macro level, questions of matching the proper fuel to an appropriate end use shows electricity to be thermodynamically mismatched to some of its daily uses such as space heating. Therefore, a major commitment to nuclear energy is viewed by some as inappropriate and unnecessary.

With respect to a limited research and development budget for energy technologies, critics fear that large scale nuclear development will pre-empt the development of alternative energy sources whose costs and benefits they see as more sensible. As well, these renewable technologies have their own set of social impacts which proponents feel are more in support of future social and demographic trends. They appear to be decentralized, flexible, adaptable to remote locations, less technologically complex, less expensive, environmentally benign, and appropriate in terms of end use. Amory Lovins raises these points in his book "Soft Energy Paths" (1) and concludes that intensive nuclear development should be avoided. However, given the realities of technological and political lead times, it seems that the exploitation of this energy source is assured, at least for the medium term. This study has been undertaken to analyse the implications of this commitment and its extension to the longer term.

The next section of this report deals with the various assessment processes which have been used to set the stage and bring into focus some of the issues of the ongoing debate. The following section deals with the issues themselves which have formed the nexus of the debate. These include:

1) cost and financing
2) uranium supply
3) nuclear plant emissions
4) nuclear power plant safety

5) physical security

6) waste management

7) reprocessing

An attempt will be made to provide a rationale for both sides of the debate and in a concluding section several recommendations are made with respect to filling the gaps in the assessment processes.

THE ASSESSMENT PROCESS

The overall assessment processes normally consider energy resources and energy demands. While the near-term future could be unsatisfactory in many instances with short runs of hydrocarbons being expected, a number of options will lead to satisfactory solutions in the long-run. These options and particularly their systems implications must be identified. Interest then focuses on transitions of today's condition to one option or a combination of options for the long-term future. It is important to consider the constraints for such transitions; if they are understood, the strategies for such transitions can and must be worked out. Capital costs and risk have immerged as major constraints in the consideration of nuclear systems.

The arguments used as pros and cons for the various energy options often do not help to clarify the issue. However, two schools of thought on the general energy strategy have evolved. One school represented by Amory Lovins favours a "soft technology path". This includes using direct solar energy, wind and biomass conversion, and careful resource conservation. The other, represented by the nuclear establishment, favours a "hard technology path", i.e. technological possibility to produce ample energy for all future while avoiding the use of non-renewable natural resource feedstocks as well as avoiding environmental problems.

The nuclear power controversy is an ongoing public debate on a number of issues such as safety standards, health hazards, economic suitability, risks connected with accidents, etc. Conflicting interpretations of assumptions, facts, theories, and likely consequences of nuclear developments are given by those who promote and those who oppose nuclear power.

The areas of confusion and uncertainty are the following:

1) The safety assumptions challenged by a prolonged debate which still continues with shifting emphasis. It ranged from controversial issues on radiation levels, probabilities of accidents, the safety of emergency cooling systems, toxicity of plutonium to problems connected with waste disposal and storage of nuclear material, including theft and sabotage prevention.

2) The second broad area of uncertainty which is just beginning to emerge, concerns the economic assumptions, notably calculations of future energy demand and various versions of calculating the economic rentability of construction and operation of nuclear power plants.

3) The third area of uncertainty is the debate on the licensing procedures and how to set up legislative regulatory standards for adequate public participation in a field in which decision-making and planning processes require considerable technical and scientific expertise. Adequate forms of public participation have yet to be formed.

If one compares the assessment processes, as they have been applied to date in nuclear energy, different statements and recommendations are observed regarding desirable future energy technologies. Even more contrasts are seen in the analysis that different groups use to support their recommendations for hard and soft energy paths.

All methods of evaluation which compare favourable and unfavourable impacts of nuclear energy rest ultimately on how the assessments are made. Thus, they depend, at their foundation, on the type of data used. Very roughly, analysts fall into one of two groups with respect to their philosophy of assessment. The philosophy of the first group springs from the economic-planning theory and views assessment as inference from the market data. The second, which includes sociologists and systems analysts, views assessment as inference from the direct replies to an interviewer's questions. While these views might be taken merely as opposite ends of a continuum, it is of interest to review the different assessment methodologies.

i) Market Approaches

In a free-enterprise economy, it is assumed that the desirability of a commodity is reflected directly in the amount of money people are willing to spend for it at the margin. For direct impacts of nuclear energy, this approach works well. Further the analyst's subjective input is minimized relative to other evaluation techniques, and is relatively easy to discern. Thus, there are strong arguments for its use. Briefly, market approaches first use the set of technological relations to predict impacts along a set of attributes (which are not to be monetary units), then associate levels of impacts on their attributes with monetary values. For example, if an attribute impact was "change of water temperature of 1^{O} C.", one would subsequently associate some monetary cost or benefits with each degree of temperature change. The assignment of monetary units derives from market data either directly or indirectly. A spectrum of econometric techniques has been developed for evaluation of indirect benefits of a nuclear project. The techniques for handling indirect costs are perhaps insufficient for an adequate accounting. Input-Output tables and Cost-Benefit techniques were used by the Task Force chaired by F.C. Boyd of EMR, in the "Nuclear Power Programme Study" of 1974.(2)

The deficiencies of market approaches have often been discussed in the cost-benefit literature. The following summarizes the main points.

1) "Non-market" objectives, such as equity, flexibility in future options, and "balanced" regional growth cannot be evaluated and thus remain external to the analysis of the nuclear option.

2) Some impacts are very difficult to evaluate because existing market mechanisms are distorted or non-existent (e.g. environmental impacts, health impacts, etc.), or for lack of experience with them. For example, the undesirability of thermal pollution can

be only partly captured by its economic implications, similar arguments can be applied to regional development and other impacts.

ii) Direct Assessment

Direct approaches go straight to individuals and by means of questions, simple games, probability and related techniques infer the desirability of impacts of nuclear energy. These approaches have been developed primarily in the litterature of social research and public opinion survey, and in that of applied decision theory. Opinion sampling is well-known, and has many pitfalls and biases. Often the result of opinion surveys are difficult to interpret, only in rare cases do they yield quantitative data. However, they do give the analyst or policy-maker a good general idea of the sentiments of groups involved, as well as identifying interests.

The Canadian Nuclear Association recently surveyed the attitudes of Canadians towards the use of nuclear power in producing electricity.[3] Members of the population aged 18 years and over were selected by sampling techniques from five regions across the country. Personal in-home interviews were carried out with over 2,100 adults during March and April of 1976. The following is a summary of the main findings:

a) Levels of public knowledge concerning the use of nuclear power to produce electricity are very low: just over half (56%) of the Canadian public known about nuclear power. Questions relating to nuclear power were asked only of those who were informed, and the following results apply only to this group.

b) Twenty-one percent of the informed public are opposed and 68% are in favour of the use of nuclear power for generating electricity in Canada. It should be noted, however, that only 63% are in favour of building nuclear power plants in their province, and 40% are in favour of building them in their local area.

At the other end of the spectrum of direct approaches is the method of "preference assessment" which has been developed in the field of applied decision analysis. This approach is oriented toward evoking quantitative statements of preference for impacts and trade-offs among impacts. The method follows from the structure of preference assumed in decision analysis. Professor Keeney of the International Institute of Applied Systems Analysis in Vienna has used decision analysis to assess the environmental impact of nuclear energy.(4)

The strength of direct methods vis-à-vis market approaches is that they allow treatment of impacts, and that they reflect opinions and feelings which are current. Several important deficiencies of direct approaches are listed below.

1) The ordering and even the wording of questions introduces bias replies.
2) Cost constrains the number of individuals interviewed and depth of interviews.
3) Assessment techniques involve statistical methods and therefore depend not only on subjective preferences, but on subjective probability as well.

iii) Supply and Demand Assessment

The assessment of energy resources seems to have been a straightforward matter using mainly trend extrapolation techniques. The major problem for such a technique involves upgrading the data continuously. Some time ago, V. McKelvey, Director of the U.S. Geological Survey,[5] proposed a very sophisticated two-dimensional scheme for plotting resource figures. In this scheme, a distinction is made among various degrees of geological assurances and economic recoverability. This classification has been adopted by many countries, including Canada. The counterpart of the resource supply problem is energy demand and its systems implications. Traditionally, this did not receive much attention; a given demand was accepted and the goal was to find the best way of meeting it by a certain combination of primary energy sources. Recently, demand and supply models for Canada have been built by various groups [6] including F. Gorbet of EMR, R. Hamilton of the University of Calgary and J.D. Khazzoom of McGill University. All of these models provide a breakdown of demand by economic sector and a disaggregation of supply by fuel type. Most often, nuclear electricity is not differentiated from other forms of generation and price elasticity of demand cannot be specified by fuel type. An example of a detailed demand breakdown for Canada is given in figure 1.

With today's limitations and constraints it becomes mandatory to understand energy demand in much greater detail and in other ways than capital costs. Energy conservation is based on this argument and is concerned with energy in respect to its absolute physical resource limits. In support of this energy theory of value, energy analysis, which accounts for the energy content of manufactured goods and services, is an important technique for investigation. Recently, EMR has produced such a study for selected energy production technologies, including a Candu nuclear reactor, examining their net energy output.

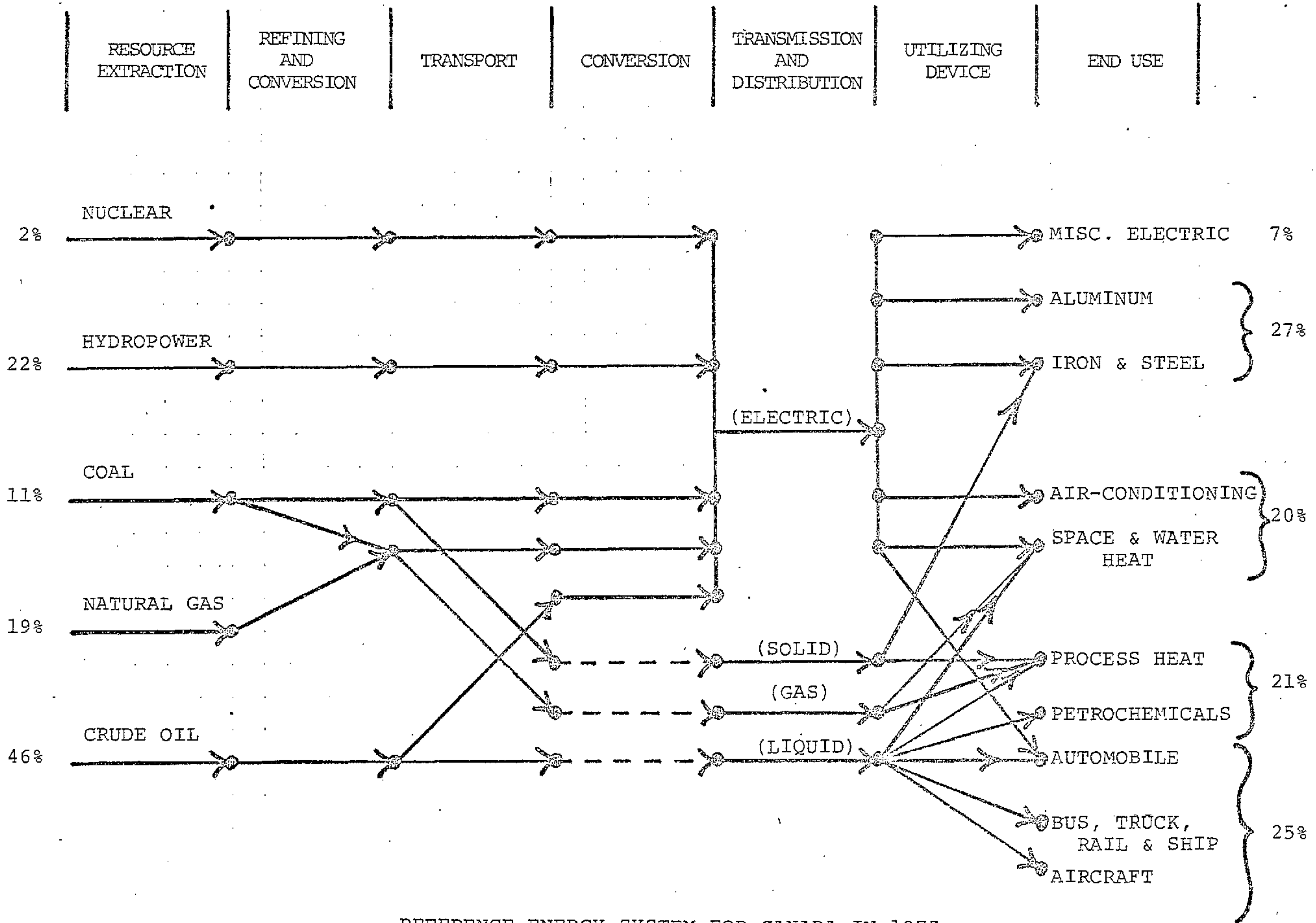
iv) Scenario Writing

Scenarios are hypothetical sequences of events constructed for the purpose of focusing attention on causal processes and decision points. In general, they answer two types of questions.

(1) How might some hypothetical situations come about, step by step?

(2) What alternatives exist for each actor at each step for preventing, diverting, or facilitating the process?

In the Energy field, alternative futures or scenarios are based on different assumptions about economic growth patterns which the society might adopt for the years ahead, and the policies and consequences that each would entail. It is most unlikely that the real energy future of Canada will conform closely to any of the three scenarios described in the next paragraphs which are indicative of the spectrum of possibilities. They are not predictive, but a tool for rigorous thinking.



REFERENCE ENERGY SYSTEM FOR CANADA IN 1975

Fig. 1

The first scenario, "historical growth", (see Figure 2 and Table 1) assumes that the use of energy will continue to grow much as it has in the past. It assumes that the nation will not deliberately impose any policies that might affect the ingrained habits of energy use, but will make a strong effort to develop supplies at a rapid pace to match rising demand.

This energy future is indeed possible, even with domestic resources alone, through the year 2000. It would require very aggressive development of all possible supplies -- oil and gas onshore and offshore, coal, tar sands, nuclear power. If it proved feasible to increase oil imports on a large scale, then the pressure on domestic resources would relax somewhat. Still, the political, economic and environmental problems of getting that much energy out of the earth would be formidable.

The "technical fix" scenario shares with "historical growth" a similar level and mix of goods and services. But it reflects a determined, conscious national effort to reduce demand for energy through the application of energy-saving technologies. The slower rate of energy growth in "technical fix" -- about half as high as "historical growth's" -- permits more flexibility of energy supply, but still provides a quality of life at home, travel convenience, and economic growth that differs little from the historical growth scenario.

The third scenario "improved efficiency for end-use" represents a real break with the accustomed ways of doing things. Yet it does not represent austerity. It combines energy conservation through efficiency (no reduction in services and products), and parallel use of energy resources already potentially available and characterized by considerations of efficiency (e.g., recovery of energy from waste materials and enhanced recovery of oil and gas) . It does not preclude economic growth. This last scenario emphasizes durability, not disposability of goods. It would substitute for the idea that "more is better", the ethic that "enough is best".

All three scenarios share certain characteristics. They all assume household comforts and convenience greater than today's. Every Canadian would have a warm home, a kitchen complete with appliances. He would still drive a car and have a job although he might drive less or have a different job, depending on the scenario the nation follows.

The following table and curves for the first scenario have been computed from information provided by EMR. The curves for the two other scenarios were adapted "to Canadian conditions" from an ERDA Study "A National Plan for Energy Research, Development & Demonstration".[(7)] The soft energy path reflects Amory Lovins' approach.

As shown in the brief outline of assessment processes, there are many gaps to be filled by more information and analysis. The area of energy demand is the weakest link in the process and should be given more attention in the future.

TABLE 1 -CANADA- ENERGY SUPPLY FOR HISTORICAL GROWTH SCENARIO

	1975			2000			2025			
	Q	%		Q	%		Q	%		
Primary Energy Required (Quads - 10^{15} BTUs)	8			16			20			
OIL (1000 barrels/day)	3.68	46	1800	4.65	29	2250	4.0	20	2200	*
NATURAL GAS (also SNG & imported LNG)	1.52	19	1500 (bcF/y)	2.87	18	3000 (bcF/y)	3.2	16	3500 (bcF/y)	**
ELECTRICITY (1) (GWe installed capacity)			60			170			225	
Hydro	1.76	22	37	3.52	22	70	3.8	19	75	
Nuclear (5)	.16	2	3	2.24	14	55	3.8	19	85	
Coal - Thermal (3)	.88	11	20	1.92	12	45	3.2	16	65	
Nuclear Power Plants (2)			1.5			30			50	***
RENEWABLES (1000 b/d oil equivalent)	-	-	-	.80	5	250	2.0	10	1000	
Thermal Electric Coal (millions of tons/year) (4)			28			60			90	=
	8.0	100		16.0	100		20.0	100		

(1) No allowance is made for reserve generating capacity; an allowance of 20% should be added as minimum required installed capacity.
(2) A nuclear plant here has a capacity of 3.2 GWe.
(3) Coal in 1975 includes some oil and natural gas used for electricity generation. That is essentially eliminated by 2000.
(4) 1 Tar Sands plant (100,000 b/d) ≅ 10 million tons of coal.
(5) 1975 78,000 boe/d
2000 1.1 X 10^6
2025 2.1 X 10^6

* cumulative brrls ≅ 60 billion
** cumulative brrls ≅ 240 Tcf
*** $1\frac{1}{2}$ pickerinds per year
= cumulative 3 billion tons

-CANADA-

ENERGY SUPPLY FOR HISTORICAL GROWTH SCENARIO

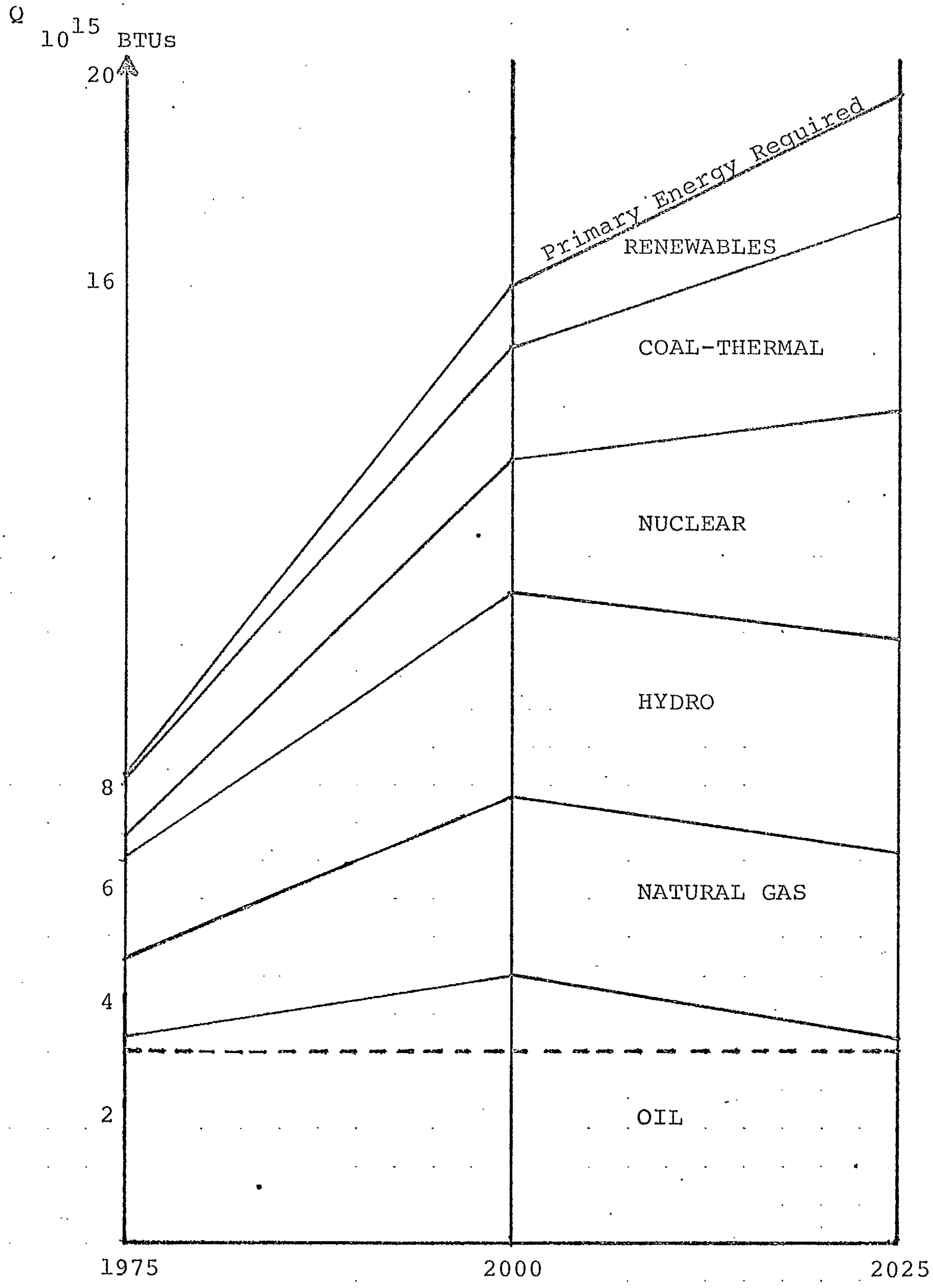


Fig. 2

-CANADA-

ENERGY SUPPLY FOR DIFFERENT SCENARIOS

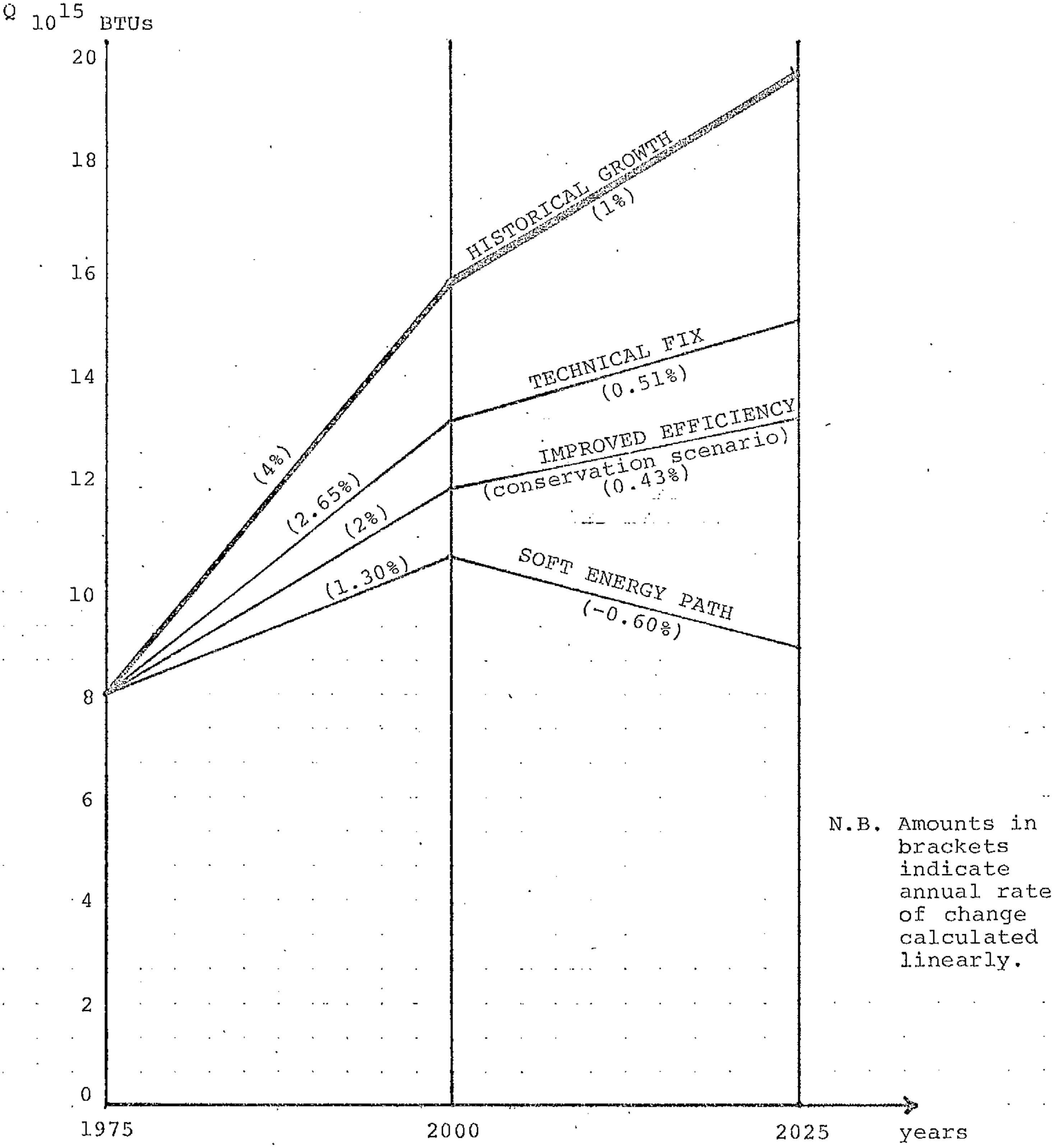


Fig. 3

THE ISSUES: The following section contains a discussion of the controversial technical and social issues surrounding the development of nuclear power in Canada.

Cost and Financing

The costs of any long-term energy development program are difficult to assess since assumptions must be made about future labour and material costs, the cost of fuel and most importantly the costs of capital. The cost estimate which is usually cited for a Canadian nuclear plant is $1,200/MW installed capacity. Capital costs are higher than for conventional plants; however, the lifetime costs per unit of energy are expected to be lower. For example, the 1975 unit energy cost for Pickering A (which includes depreciation, debt service, fuel, maintenance and heavy water) was 9.8 mills /kW-h while fuel alone for Lambton was 12.7 mills /kW-h [8] Ontario Hydro seems confident that, in the long-term, nuclear is the most efficient way to produce base load electricity since it is less sensitive to future price increases of fuel. Compared to the American system, the lower fueling costs of CANDU offset higher initial capital costs even when heavy water production costs are included. Higher interest rates will erode this advantage. Critics also add that hidden costs such as basic research in governments and universities, waste management, decommissioning, and operation of regulatory and monitoring agencies also add considerably to the unit energy costs and ought to be considered in a comparative analysis.

In a net energy study done by Energy, Mines and Resources it was shown that in a static analysis for a 1020 MW CANDU Reactor, the payback period for the energy investment is less than 2 years at 80% capacity. The most energy intensive input was the heavy water which accounted for up to 69.2% of the total or over one year's annual production of electricity for generation of the initial charge.[9]

Conclusions to be drawn from this are that by increasing the plant lifetime, net energy gain can be improved. As well the Canadian system is shown to be more expensive (energy and dollar wise) to construct owing to heavy water costs but cheaper to operate since no fuel enrichment is needed. These points can influence timing of construction and rates of growth.

Aside from the actual cost and unit energy cost, the financing of such large debts as that which Ontario Hydro plans to undertake, leads to criticism. With the Ontario government's announcement that the expansion program would have to be cut back by $6.5 billion, it became clear that long-term capital has become an increasingly scarce resource which must be allocated over competing demands. Major projects must be rationally timed, not competing for the same scarce capital.

Uranium Supply

One of the most technically disputed areas is uranium supply, and its implications for fuel cycles and export limitations.

The uranium industry has a sort of boom and bust history beginning with large scale developments in the 1950's due primarily to the military program in the U.S. Following this, there were the doldrums of the 1960's during which time stockpiling was carried out to prevent collapse. Since the 1973 oil embargo, the industry has again been expanding to meet world requirements. Canada has been a major supplier (30% of the total market) along with S. Africa, Gabon, Namibia. Recently, Australia has agreed to begin production.

Policies for export of Canadian uranium were revised in 1974 to ensure adequate supplies for our own facilities. A 30-year supply of reserve fuel for all plants existing and planned within a 10-year period must be protected to allow our own development program to reach its potential. As well, contracts for uranium must be maintained 15 years in advance for all Canadian reactors. The Atomic Energy Control Board now reviews all export contracts annually and any contract may only be signed for up to 10 years.

Fuel must be supplied to the CANDU reactor at the rate of 5 tons of uranium oxide per MW per 30 years lifetime, assuming the reactor is run at 80% capacity. The demand for uranium can be calculated from the projections of installed capacity and export commitments. AECL projections show 14,700 MW will be installed by 1986 and 60,000 MW by 2000. This is just one of many energy futures, and by comparison to previous projections, conservative in nature. Export agreements now in effect total 110,000 tons.

The supply of uranium has been estimated according to price per lb of U_3O_8 calculated over various levels of certainty. These supply figures reflect even more uncertainty than the demand estimates since they depend on geologic as well as economic variables. These estimates based on the Uranium Resource Appraisal Groups 1975 assessment are shown below. [10]

TABLE 2

1975 Estimates of Canada's Recoverable Uranium Resources

	Short Tons U_3O_8		
Mineable	Measured	Indicated	Inferred
Up to \$20/lb U_3O_8	82,000	107,000	226,000
\$20 to \$40/lb U_3O_8	14,000	22,000	111,000
	96,000	129,000	337,000

Using these 1975 estimates and comparing these with the AECL projections for reactor capacity and export commitment about 50% of the Canada's current estimated uranium resources are left uncommitted.

Other questions can be asked about rates of extraction. Annual production estimates of 11,500 tonnes for Canada by 1985 and 12,700 by the early 1980's were made based on the Appraisal Group's Assessment. Some of this production is for export and although export policies have been tightened up, as world capacity expands more pressure will come to bear on Canada as a uranium exporter. It has been argued that exporters should have guarantees that the commodity or its fissile offspring remain within the countries of the Nuclear Non-Proliferation Treaty. However these guarantees are difficult to honour and it is this aspect as well as concern about environmental degredation and long-term supply prospects for Canada which are being considered at the Cluff Lake Hearings in northern Saskatchewan. At these hearings and others such as the Windscale enquiry for the British Nuclear Fuels Reprocessing Plant, the key elements of supply uncertainty, and its links to fuel cycle and export policies, and the dichotomy between the location of risks and benefits in the fuel cycle, point to fuel availability as a weak point in the consideration of present fuel cycle technology as a long-term option.

Nuclear Plant Emissions

The radiation released from the routine operation of CANDU reactors is not thought to constitute a serious health hazard. In fact, the release of radioactivity from a same-sized coal-fired plant is often more than from a nuclear station.

Canadian regulations are based on International Commission for Radiological Protection (ICRP) standards which put maximum whole body dose at 500 millrem/person/year for occupational workers. The release to the public must not exceed 1% of this limit, and in fact, the average radiation dose to the public around Pickering attributed to the reactor has been ~.003 millirem/year. In comparison, the background radiation in Toronto is about 100 millirem. At each site, release limits are derived from various radionuclide groups taking into account possible emmission paths, general population densities around a site, and local meteorological conditions.

However, operating practices were at one time far less sophisticated and discovery of low-level radiation from land fill in Port Hope has aroused much public reaction. The likelihood of any increased health risk is still being debated but radioactivity provokes a level of public concern unmatched by other equally serious health or environmental hazards. Whether Port Hope was the motivation for a new approach to public accountability or rather, the last straw, it brought to light the future consequences of even today's standards being inadequate.

It is the radioactivity release associated with a non usual occurrence that still is of most concern, and brings into question station safety and siting practices.

Controversy presently surrounds the decision in Ontario not to subject the Ontario Hydro Darlington site to the provincial Environmental Assessment and Review process since it had been under consideration before the new law was passed. Environmental groups such as Pollution Probe are challenging the omission of this project as a precedent and further are challenging the demand estimates of Ontario Hydro which justify the construction plans. Again, public opinion is not clear as spokesmen for both sides present their views.

One of the more important analyses in any environmental report is the impact of thermal discharge. Waste heat is produced in the generation of electricity as described by the loss of "exergy".(11) Although ways are being sought to capture and utilize this waste heat, nuclear stations in particular discharge much heat into surrounding water bodies. Thermal discharges form a plume which extends up to 5 km from the station. The long-term cumulative impact of such discharges is uncertain but increased temperatures are thought to change fish patterns. As well, radionuclide levels will increase. According to AECL estimates, all the thermal discharge from the electric power stations planned for 2000 would cause the surface temperature to rise by $.5^{O}F$ which is less than the yearly variation in the Great Lakes. However, this heat is discharged near the shore where most biological activity such as fish spawning takes place. In rivers, if the thermal discharge occupies a major portion of the cross-section, fish migration may be impeded. Thermal impacts are also a problem with other types of electrical generation and industrial processes.

Nuclear Power Plant Safety

The CANDU system is thought by some to be the safest system in the world since the configuration and nature of the fuel precludes the possibility of an explosion.

The most serious type of accident is the loss of coolant accident where the enormous heat release by the fission process could cause a core meltdown and a release of highly radioactive material.

The dramatic increase in reactor size in the late 1960's increased the uncertainty about the integrity of the containment shield in the event of a core meltdown. This turned attention to the role of the emergency core cooling system in preventing accidents.

August 1974 saw the release of the Rasmussen report done for the USAEC by consultants under Prof. Rasmussen of MIT. It was widely acclaimed as a major advance in application of fault tree probability analysis of component failures in complex systems.

The Rasmussen Reactor Safety Study took into account for the first time both consequences and probabilities of catastrophic accidents in light water reactors. Some specific results of RSS are:[12]

1) The probability of core meltdown is 5×10^{-5} per reactor year which is larger than previous AEC estimates of 1×10^{-6}. This is average for the types of reactors being built in the US (BWR & PWR).

2) For each reactor type the categories of radioactive release following core meltdown and the probability of each is ascertained. This shows that core meltdown does not necessarily lead to large releases.

3) For each release class, expected consequences are calculated in 6 categories - prompt fatalities, prompt injuries, delayed cancers, delayed "thyroid nodules". genetic defects and property damage. Weather patterns, population densities and radiation dose methodologies were used in calculating these results.

There have been many challenges to the methodology used in the R.S.S. Critics have stated that the analysis leading to core meltdown probability is inadequate on the following grounds:

Completeness

It is impossible to know whether fault tree analysis has identified all failure modes. This is agreed but it is argued that the most important modes have been included.

Design Adequacy

Probability and fault tree analysis cannot deal with reactor design inadequacy as distinct from statistical failure of components. Unsuspected design inadequacy is often responsible for accidents in the aircraft industry.

Human Failure

As used in the R.S.S., probability and fault tree analysis do not deal with certain types of human error, including willful acts and sabotage. The R.S.S. is in effect a statistical study of a perfectly designed machine with the only sources of failure lying in the statistical malfunction of components and statistically quantifiable operator errors.

None of the criticisms are directed at the quality of analysis done in the R.S.S. within the framework of probability and

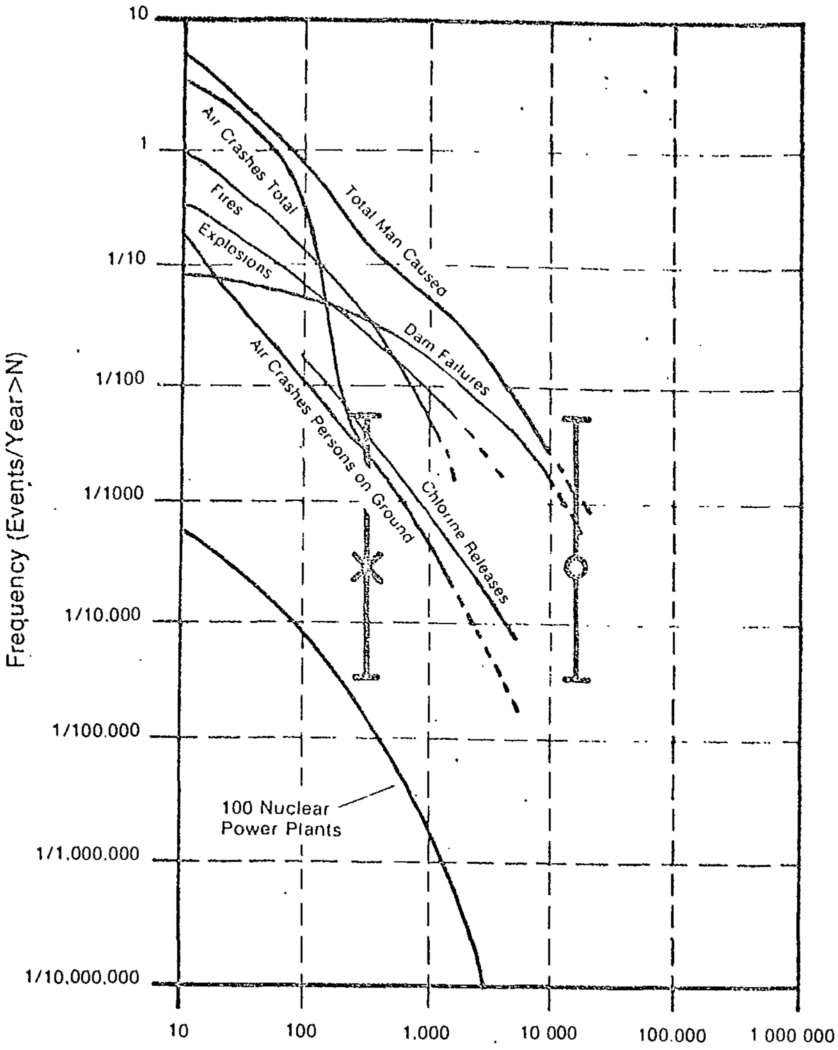


Fig. 4

Nuclear and Non-Nuclear Accident Probabilities and Consequences—AEC Estimates and APS Corrections

The curves represent the frequency of different types of accidents, nuclear and non-nuclear, as a function of the number of fatalities as given in the Rasmussen report. The curve labeled "100 Nuclear Power Plants" (50 boiling water and 50 pressurized water reactors) includes only early fatalities, *not* delayed deaths due to cancer.

Two error bars have been added to this basic figure which appeared as Fig. 6.1 in the Summary volume of the Rasmussen report. The frequency range is that calculated in the Rasmussen report for the occurrence of a 'reference accident'* assuming the existence of 100 pressurized water reactors. This accident was assigned a probability between 1 in 20,000 and 1 in 2 million per reactor year in the Rasmussen report.

The point 'X' on the left-hand error bar indicates the *total* number of fatalities, 372 (62 early and 310 delayed from cancer), from the 'reference accident' as calculated in the Rasmussen report. Using the Rasmussen report's probability estimate, but including the corrections to the estimated number of cancer deaths calculated in the APS study, gives the point '0' or 10,000 to 20,000 cancer deaths.

*A pressurized water reactor core meltdown with a release of radioactivity to the atmosphere almost as great as if there were no containment building at all fault tree analysis. Sceptics view the results as the reasonable lower bounds on accident risk and some have suggested that the methodology could be patched up or more conservative error limits introduced.

For the first time a wide public was made aware that judgements about reactor safety were based on estimated probabilities and that there was considerable disagreement among scientists and engineers both on probability estimates and potential effects of an accident.

In Canada, the Atomic Energy Control Board licences and inspects all reactors and facilities. Strict safety codes and standards are applied to the design, manufacture and construction and operation of all equipment. The AECB also receives regular reports on effluents discharged during plant operation. An integral safety feature of the CANDU system is the two part independent control system computer which has the facility to correct errors outside the regular control system. Other safety features which are noted are the heavy construction of the reactor building, the air lock system, and the venting of the building into an adjacent vacuum building if the pressure builds.

Physical Security

Security policy and procedures for obtaining an AECB licence are well established. These include the security of nuclear materials in use, transit or storage; the security of nuclear facilities; the training of staff; the protection of relevant information and the development of contingency plans for security breaches. The two most apparent security hazards are the sabotage of a nuclear station by a take over of the control room or by an explosion, and the diversion of nuclear materials. Mock sabotage attempts have been staged to bring to public attention the inadequacy of present security arrangements.

The CANDU system uses natural uranium fuel (.7% U_{233} - 99% U_{238}) which has no weapons potential until it is enriched. However, the amount of plutonium produced per unit of output in the Candu system is significant, although true weapons grade plutonium requires a shorter exposure of the fuel bundle to the reactor. Furthermore, the plutonium produced is in association with other radioactive material in the spent fuel, so is virtually inaccessible to the non-technical public.

According to security specialists, the ends to be achieved by sabotage or destruction of a power station could be more easily met by stealing military weapons or by dispersing nuclear dust through centralized services or activities. However, any increasingly centralized capital intensive energy system implies growing vulnerability to malicious disruption. It is this aspect and a growing distrust of the unchallenged future of institutions which raises concern for all large energy developments.

Waste Management

The topic which has received most public debate is that of waste management. Management of radioactive wastes involves two steps; short-term storage and long-term storage or ultimate disposal of waste.

CANDU fuel bundles weigh 44 lbs and produce the equivalent of electricity of 500 tons of coal. There are 4680 bundles of fuel in a Pickering size reactor and about 40/day/station are replaced.

Presently in Canada spent fuel is stored on site in water filled bays. This is considered a short-term procedure. While enough storage capacity for a reactor lifetime does not yet exist at every site, it can be built at a moderate cost.

The options for long-term storage are concrete canisters, centralized bays, and geological storage in salt mines and stable rock formations. Some experiments with metal and concrete canisters are being carried out at the Whiteshell Nuclear Research Establishment.

Most countries' plans call for enclosing the wastes in a glass matrix before permanent storage. Burial of wastes after one year would cause a significant rise in temperature which declines with time. This decrease in heat release is critical to the timing of matrix solidification since glass devitrifies after 700° C.

To date West Germany is the only country to implement geological storage. Waste is stored in the abandoned Assa salt mine. One important problem has been discovered with burial in salt. Salt has a greater thermal conductivity than rock and the temperature rise after 40 years of storage is 85° C. Because the delicate salt water balance is a function of temperature, such temperature increases cause the water to migrate towards the buried canisters. This water buildup occurs at the rate of 2-3 litres per year, or

25 litres in the first 25 years. Since the canister temperature is over 100° C. the water will vapourize and could be vented. This leaves hydrochloric acid which erodes stainless steel leaving the glass cylinder.

In Canada the primary candidate for long-term storage are rock formations known as plutons which have been unaffected geologically for more than 250 million years. Reportedly, at least 10,000 plutons exist in the Canadian shield. AECL intends to have a geological storage site selected by the early 1980's and a demonstration site operable soon thereafter.

Canadian nuclear experts proposed that Canadian long-term storage must include a provision for retrievability, pending a decision on fuel reprocessing or other methods of boot strapping to advanced fuel cycles.[13] What actually constitutes waste, as opposed to a valuable resource for future fuel cycles, has been the main point of discussion. If reprocessing is initiated, geological storage is also preferred for disposal of these high-level wastes.

Critics argue that geological storage or disposal is an unproven strategy and constitutes a lethal legacy for future generations. The moratorium they advocate on future nuclear developments is based partly on the lack of proven storage to contain wastes for the extended time period required. Given that there are already wastes accumulated and that sufficient safety is a relative position, such a moratorium could not, of course, include development of waste management program.

Reprocessing

Consideration is now being given to the feasibility and desirability of fuel reprocessing in Canada. The advantage seems quite apparent; the lengthened lifetime of uranium supplies, of carefully staged. Proponents contend that the fuel cycle must be closed so that technologies for fuel fabrication and reprocessing can remain in step with reactor technology and meet their mutual requirements. However, the critics contend that by reprocessing we are exposing ourselves to another set of risks in handling and transporting waste fuel, and are building up even greater quantities of wastes. Finally, they contend that the technology to be used has continued to be proven unsuccessful.

The other potential for danger in reprocessing is the incentive for terrorists to acquire the plutonium for bombs since during the process plutonium exists in a concentrated form. There would be however, many obstacles to this undertaking. In power reactors Pu_{240} is formed as well as Pu_{238} which makes it difficult to assemble a supercritical mass of plutonium without an inefficient premature explosion. Also, weapons grade plutionium requires a much shorter fuel exposure to the reactor, and diluting plutonium oxide with alpha emitting isotopes creates a strong deterent to hijacking. Not withstanding these arguments it is still possible to construct a crude bomb from the fissile fraction of reprocessed fuel. Although bombs can also be constructed from fissile elements in other fuel cycles· the increased potential for terrorist acts is still cited as a fundamental criticism of reprocessing·

The technology which has been used for recovering uranium and plutonium from the spent fuel of power reactors is the Purex process. This process employs TBP (tributyl phosphate) dissolved in a kerosenelike hydrocarbon as a separating agent. The efficiency and economic viability of the Purex process depends on the design of the solvent extraction apparatus. The innovation of mixer settlers and centrifugal contractors have improved the operation.

Fuel reprocessing is mandatory to move to advanced fuel cycles such as Thorium U_{233}. The self-sufficient Thorium U_{233} cycle opens up a virtually unlimited energy resource since a certain generating capacity once started on the cycle can operate on a consumption of thorium which is about 1% of the consumption of uranium on the present "once through" amount of power available. The amount of power which can be generated is only three times that which can be generated on the once through uranium cycle. This is a consequence of the requirement of uranium for the starting fissile material.

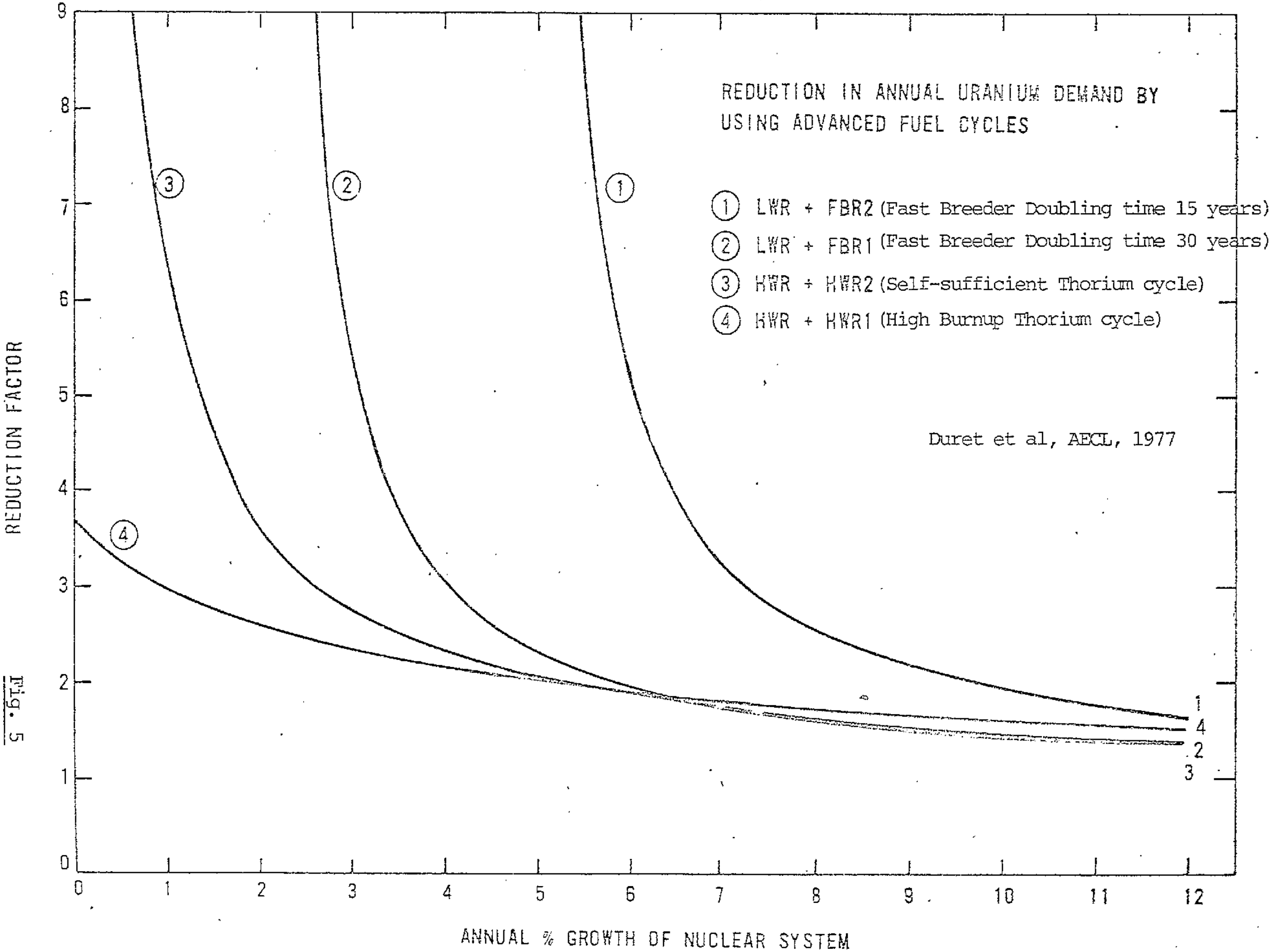
Consequences of the characteristics of the cycle are that it provides users with assurance of virtually unlimited fuel supply and makes operating costs insensitive to the price of uranium, but it does not materially reduce uranium requirements during periods of substantial growth in capacity. This latter consequence also applies to fast breeder reactors unless the doubling time of the cycle is less than the doubling time of the demand for energy.

Inventory requirements or start up requirements for converter reactors such as the present CANDU system constitute a relatively small proportion of the total lifetime fuel requirements.

The opposite is true of advanced fuel cycles, especially if the conversion rate is > 1. The inventory requirements are the only requirements, and uranium demand remains sensitive only to expansion rate. For high system expansion rates (10% or greater) which are characteristic of the initial introductory phase of nuclear power, the gain to be obtained by the introduction of advanced fuel cycles is minimal because of inventory requirements of plutonium.[14] Technological aspects aside, the single most important aspect to ensure the success of an advanced fuel cycle is the reduced growth rate of the nuclear system itself.

The improvement in resource extension becomes greater as the growth rate is reduced. Thus advanced fuel cycles are most useful when the expansion rate is relatively low. The growth rate at which dramatic reductions in fuel requirements can be made depends on which fuel cycle is implemented as can be seen on the following diagram.

The apparent constraint in the system is fissile material. This can be obtained not only by the conversion of U_{238} to Pu_{239} in the reactor or by spiking the system with enriched uranium, but by other means outside the fission process. One is to use the neutrons generated in the fusion process to convert fertile material to fissile material. Another process, one which is being researched by AECL, is the spallation process.(15) In this process a proton beam is used to bombard heavy elements, such as lead and cause them to produce free neutrons. This is an attractive neutron source since each proton can release up to 50 neutrons which in turn can be absorbed by fertile material around the target to produce fissile material. AECL believes it is possible to actually embed this target within a reactor and by combining it with a high voltage proton linear accelerator to produce fissile material insitu. This avoids all the problems of transporting and reprocessing plutonium and fabricating active fuel bundles. The costs of such a system have not been estimated and all of the engineering problems have not been solved, however, as with other advanced fuel cycles, the figure of $250/kg of natural uranium fuel appears to be the price at which such systems become competitive.



REDUCTION IN ANNUAL URANIUM DEMAND BY USING ADVANCED FUEL CYCLES
① LWR + FBR2 (Fast Breeder Doubling time 15 years)
② LWR + FBR1 (Fast Breeder Doubling time 30 years)
③ HWR + HWR2 (Self-sufficient Thorium cycle)
④ HWR + HWR1 (High Burnup Thorium cycle)
Duret et al, AECL, 1977
REDUCTION FACTOR
ANNUAL % GROWTH OF NUCLEAR SYSTEM

Fig. 5

CONCLUSIONS AND RECOMMENDATIONS *

The growing demand for energy and the considerable size of the financial commitments for capital projects make long-term energy forecasting increasingly mandatory, both on a national as well as on a global basis. Yet forecasts are difficult to make because of the complexity of the structure of energy demand. The problem of energy demands are partly technological in nature, but the variety and the plurality of energy use and in particular the fundamental differences between energy use and energy services lead into open-end considerations that cannot be handled by technology alone. The total of energy requirements and the actual mix of fuels will depend on economic growth patterns, forms of utilization and conservation practices. For example, broad scale successes on the conservation front would provide lead time for the implementation of new technologies.

Improper or untimely decisions will come to bear more and more heavily upon society as a whole. The decision which has to be made is where we want to be in the next 50 years and then by working backwards to set up the incremental steps for getting there. In short, one has to define a desirable future and move into it; not

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* For this analysis, major reports from AECL, the Porter Commission, the World Energy Conference, the Coalition for Nuclear Responsibility and Amory Lovins as well as American papers such as the Rasmussen Report, ERDA studies and some of the popular literature have been examined.

just evolve into some future by extension of current technologies.

It is recommended that further work should go into the development of the scenarios outlined on page 13. More analysis should be directed towards improving and extending the critical assumptions made in these scenarios. These scenarios do not represent unvarying commitments for the future conduct of either development or implementation actions. Rather, they may result in modifications to the current R&D priorities.

Recommendations have already been made and adopted with respect to the restructuring of the AECB. The separation of promotional and commercial functions from the regulatory and licensing ones and addition of responsibilities for public hearings may ease the debate on safety conditions by allowing more frequent public questioning. Further, by providing a dichotomy between the two functions which often seem in conflict, a more comprehensive and far sighted control may be gained over licensing and regulatory procedures for all stages of the fuel cycle and technology transfer.

It appears that the public debate no longer focuses on the safety and security problems of specific nuclear plants but includes a more fundamental examination of energy demand projections, growth rates and fuel substitutability. With respect to nuclear facilities, the unresolved problems seem to be "backend loaded" e.g. problems of waste management, as well as the ongoing concern for long-term uranium supplies.

Recently, AECL has been given approval to proceed and specifically develop methods for storing of spent fuel. However, the greater question of the storage of reprocessed waste is still undecided, although the capability to handle such waste impinges on advanced fuel cycle decisions. Another recommendation of this study would be to direct funding of Research and Development into these two areas so that a well-timed disposal program is co-ordinated with future fuel cycle developments. At no cost should the present "once through" fuel option be discounted. The work on a complementary disposal program for this option must soon be completed.

Advanced fuel cycle programs must be investigated as one of many options for long-term energy supply. The biggest variability will be the timing for transition from the present system with a rational use of finite resources. The many possibilities now under consideration must be properly cost-accounted to assess their economic competitiveness at various uranium prices. As well the engineering feasibility has yet to be proven for some aspects. For advanced fuel cycle and near breeder reactors, putting safety questions aside, the financial implications of developing such systems have not yet been fully documented.

In conclusion it seems appropriate that MOSST should undertake similar assessments of societal, economic, and environmental factors of other energy supply systems.

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