ATOMIC ENERGY OF CANADA LIMITED
Power Projects, Sheridan Park, Ontario

Lecture 17

Nuclear power symposium

DEVELOPMENT POTENTIAL

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Power Projects

NUCLEAR POWER SYMPOSIUM

LECTURE NO. 17: DEVELOPMENT POTENTIAL OF CANDU REACTORS
DL-115

by

W. B. Lewis

Development arises when a need and a new technique meet. In Canada we hardly need reminding that although the pioneers have passed on to us means of survival in some degree of comfort, not many early residents survived to man's allotted span of three score years and ten that is now an actuarial reality for us. A number of the affluent youth are now clamouring for better quality of life instead of more income, taking food, clean water, power tools, powered vehicles, warmed buildings and even air-conditioning, air depollution, sewage treatment, cultivated fruits and vegetables, for granted. A cold look at the relation of total population, standard of living and prolongation of life shows at once a close relation to consumption of energy. The power demand is predictable a long way ahead since we don't propose genocide, and many babies, children and youths still have a long life in prospect. To meet their power demand and that of their descendants we have available effectively unlimited nuclear energy, but our techniques for harnessing that source are still changing. I would like to remind you of how we have arrived where we are, because it came from a long range crystal ball coupled with experiment and experience. I will read the first two pages of a lecture (DL-37) I gave in Vancouver in 1959 to the Northwest Electric Light and Power Association, away back before B. C. Hydro became public; it was entitled "Planning Canada's Nuclear Programme". It reads:

> "In our programme I am acutely aware that we stand alone. The Canadian full-scale power reactor, known as CANDU, is now an approved project on which tenders have been called for the 220-megawatt turbine generator. This is not the first nuclear generating plant in the world, but it is the first being designed for a refuelling cost as low as 0.8 to 1.0 mill per kilowatt hour.
>
> This does not come about by accident or by a unique scientific and technical brillance at Chalk River, although I am pleased with the scientific standards the staff there have maintained. It comes from a long awareness of the need, or in other words, that proverbial mother of invention, necessity. Consider our position: Canada as a whole has an abundance of water power, coal, oil and natural gas.

" Nuclear power would have to take its place in this setting. Emerging from the war in 1945, the vision of the tremendous potential power in the atomic nucleus and released by the simple process of fission was clear to every physicist. Not everyone was so clear about the difficulties and limitations, and by the time the ideas reached the popular press they included such fantasies as propelling automobiles by nuggets of uranium. The true science had become shrouded in secrecy. Behind the shroud ideas were optimistic and, we would now say, misguided. Very little good uranium ore had been found and the majority view was that there would only be enough to sustain a large power programme for the world if the so-called breeder reactors could be built, but this in turn was considered quite feasible.

These ideas were three-quarters true and that has made it extraordinarily difficult and slow to promote the realization that they pointed in the wrong direction. The practical programme today is not based on breeding, but something close to it, namely fuel regeneration, not primarily to conserve uranium but to avoid handling the intensely radioactive fission products. Such handling, although technically practicable, is too expensive and so is breeding. Everyone now knows that there is a glut of uranium looking for markets.

The Canadian project was fortunate in choosing in 1949 not to aim at breeding. In 1951 we first saw the path we are now following and began to realize the necessity. Between 1951 and 1956 the deviations of our aim were slight and since 1956 every good seems to have come to us on the chosen path.

Before I present the story of how our programme unfolded in the last ten years, (i.e., 1949-1959) let me try to remove any misunderstanding that may exist between us of the aim or vision of the potentialities.

How much would you say it costs to transmit electric power, say, 250 miles? It will, of course, depend on circumstances; how much power, at what voltage and load factor, over icy mountains or over temperate plains. In round numbers it may perhaps be 1 mill per kilowatt hour.

Have you realized that this is just about the same as the total refuelling cost in prospect for the CANDU reactor?

Nuclear power and hydro power have this in common that it is the capital investment that determines the practicality. Moreover the specific cost -- dollars per installed kilowatt -- is liable to be high in small plants. The greatest difference is that hydro power has to be developed where it is found, whereas nuclear power can be developed anywhere that cooling is available. There seems to be no other limit, i.e., other than capital and cooling, to the amount that can be provided.

Nuclear power and water power are perhaps more to be regarded as complementary than as competitive. Niagara Falls provide a good example. By agreement with the U.S.A., during daylight hours in the tourist season 100,000 cubic feet per second must come over the crest of the falls, at other times this may be cut back to 50,000 cubic feet per second. The extra water is divided between the two countries to produce electric power. It happens that the demand for power is greatest in the daytime but, during the summer months, more water is available at night. Ontario Hydro therefore takes the water through its tunnels to Queenston at night and pumps it up into a storage reservoir. Then in daytime when required it comes down extra penstocks through extra turbines. When the total demand increases, the difference between day and night may increase and it might pay to extend such pumped water storage. Because of the low fuelling cost for nuclear power, it does not save much to shut a nuclear power plant down or reduce power during the night; instead the power may be used to pump water into storage.

It seems fantastic to set nuclear power to pump water back up over Niagara Falls for the benefit of the spectacle of the Falls, but it is not so far from economic reality in the context I have outlined. I would not put it beyond range that nuclear power may similarly affect other features of life that we appreciate, such as B.C. salmon, assuming the fateful decisions are not made in the next ten years" (i.e., 1959-1969, and they weren't). "There are other strong reasons for putting all major rivers under control, but in future we should be able to do so without destroying all other amenities because there will no longer be any economic necessity to harness the full potential of rivers for power.

To be quantitative we see the third or fourth reactor of the CANDU type generating 350 MW and costing less than $250/ekW, coupled with a fuelling cost of less than 1 mill/kWh."

Remember, all that was written in 1959. Now to come up to date, I will quote a paragraph from the 1972 Christmas Message from John S. Foster, Vice-President, Power Projects, AECL, to the staff:

"Pickering 3 (a 540 MWe gross CANDU-PHW, and the fourth full scale unit in our CANDU series) was committed in 1967. It was in full service in five years. It reached full power only 65 days after commencement of fuel loading and only 18 days after first critical.

> "*It cost $320/kW*" (*equivalent* to $200/kW in 1959*). "*It can, of course,* be pointed out that the design was very advanced, many items were on order, the construction plant was in place and the construction force was fully mobilized at the time the unit was committed; and the construction and commissioning organizations benefitted from installing two identical units immediately prior to installing Pickering 3. This, however, does not explain Pickering 3 away; on the contrary this gives Pickering 3 its significance. Pickering 3 represents what can be done when people know exactly what they are to do and are poised to do it. It is the basic standard against which future work must now be measured."

That, in fact, fulfils what I was speaking of in 1959, moreover the fuelling cost is certainly less than 1 mill/kWh and can stay that way even if the reactor lives for 60 years.

In what I wish to say here, Pickering can be regarded as the first bud to come into full flower promising to yield a profitable fruit. The most promising bud, however, is the organic coolant with thorium fuel. It could flower before 1990.

I will now return to quoting that 1959 lecture:

> "In 1952 and 1953 our long term philosophy was developed that finally abandoned breeding as unnecessary." (I may interject that the basic idea of the significance of neutrons produced electrically as for example in the ING study was written up in 1952.) "This philosophy, however, had to remain secret until 1957. We were able to present a partial picture at the first United Nations Conference on the Peaceful Uses of Atomic Energy at Geneva in 1955. Dr. John Davis (now our Environment Minister) and I collaborated on a paper on the economic prospects."

At the Second Geneva Conference in 1958 we were able to tell of zirconium pressure tubes, bidirectional natural uranium fuelling to 8,000 MWd/tonne U, and the measurements of the change of reactivity of natural uranium with long irradiation made in the NRX reactor that supported this. We told how the Douglas Point reactor, with 306 tubes 3.25 inch I.D. and a turbine cycle efficiency of 32.8%, would give a net station efficiency of 28%, in the event it was even higher. We discussed the technology of UO_2 fuel and of Zircaloy and of instrumentation for safe control.

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* By the non-residential construction cost index - see Appendix 1.

The final paragraph of that 1959 lecture reads:

> "From the development point of view I expect a demand to arise for full scale power reactors like CANDU at the rate of perhaps one a year. All the time there are improvements in view. We have two other systems being developed, both still using cool heavy water as moderator: in one proposed by the Canadian General Electric Company the coolant is an organic liquid such as used in the Atomics International OMRE, the other system will use superheated steam as the coolant. Both these developments require new materials for strength, corrosion resistance and neutron economy, so there is plenty of work ahead."

Noting that in 1959 I said it was in 1952-1953 that our long-term philosophy was developed that finally abandoned breeding as unnecessary, it seems worth pointing out that it was when Palmer Putnam put together his major work entitled "Energy in the Future" (Van Nostrand, N.Y.) for the USAEC. Nothing quite like it had been done before and I had been invited to comment and found myself tremendously interested, and made a corresponding evaluation for Canada. At that time the leading countries were using close to 1 kW per capita, with Norway and Canada in that position because of their large hydro-electric developments. I made a projection forward to the end of the century and could find no reason to reject the result that we might be then using 5.7 kW/capita. Now we would put it higher since the rate of advance has outpaced all the utilities' forecasts. (See Appendix 2.) Such a power level would be many times the total of our hydro-electric resources, yet is completely trivial when related to uranium as a source.

Figure 1, drawn in 1968, shows what happened to the forecasts. On the left we see the utilities' forecasts for the total electrical capacity in Canada fell rapidly below the actual installations. My forecast for nuclear power was to reach 35 MkW capacity by 1996. No further forecasts had been published then going beyond 1985, but the forecasts made by the Canadian Nuclear Association in 1964 and 1967 showed an increase above my estimates beyond 1976. We may note that the rate of growth of nuclear power in Canada is not as great as that in the U.S.A. and their forecast for 1980 still stands in the neighbourhood of 150 MkW.

Figure 2 reproduces my forecast on an extended scale showing the CNA forecasts of 1971 up to 1990 and some extrapolations indicating we might reach 100 MkW by the year 2000. Even at what may be a low average cost of \$200/kW construction, that represents an expenditure of \$20 billion. My forecast was also concerned to point out the saving in fossil fuel cost which I estimated might be as much as \$300 million a year in 1980. The price of fossil fuel has remained lower than anticipated until recently but is now taking off at a great rate. In 1968 Ontario Hydro indicated that their fossil fuel was costing about 3.44 mill/kWh so the scale on the left of the figure is not far wrong and we see that if power were to develop

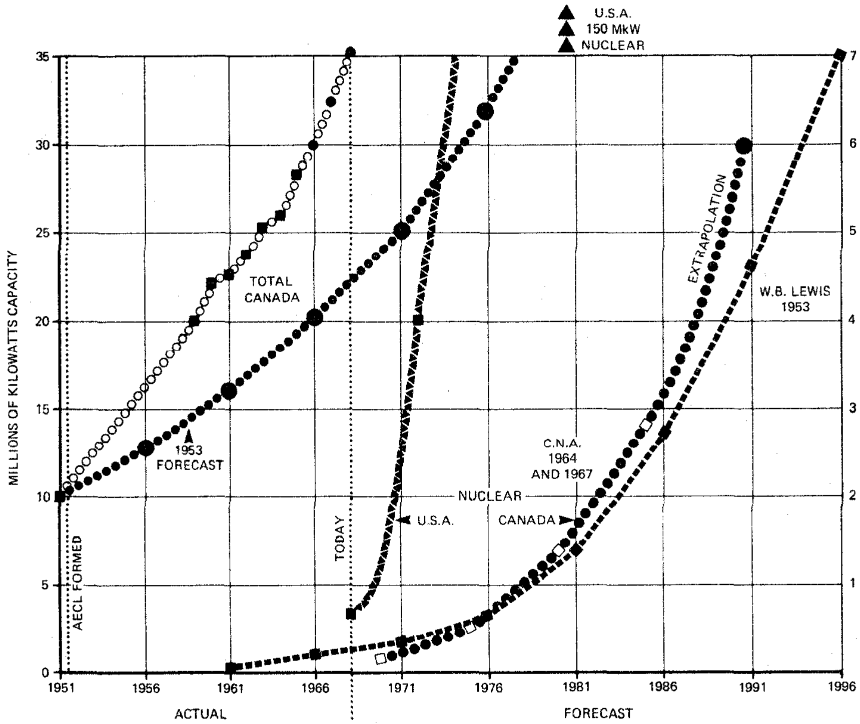

Figure 1 Forecasts of Electric Power

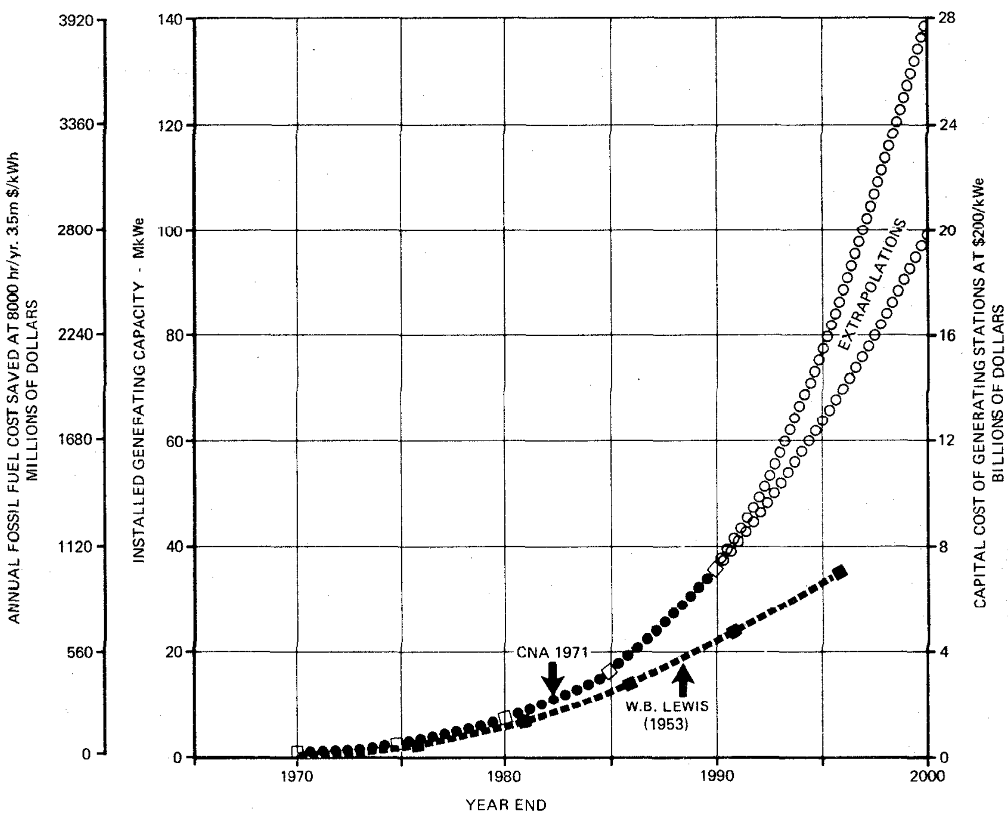

Figure 2 Nuclear Power Forecasts for Canada

using fossil fuel instead the cost of that extra fossil fuel would be $3 billion a year by the year 2000. We must now put this on a world scale and Figure 3, shown at the 1971 Geneva Conference by Alvin Weinberg and Philip Hammond, shows that up to the year 2000 the world population increase is likely to continue to get steeper but within a century it is most desirable that it should be levelled off if we are to live in comfort. We have no grounds for making a prediction but the slide indicates the trends necessary to level off at between 10 and 20 billion people. At present the population is believed to be about 4 billion.

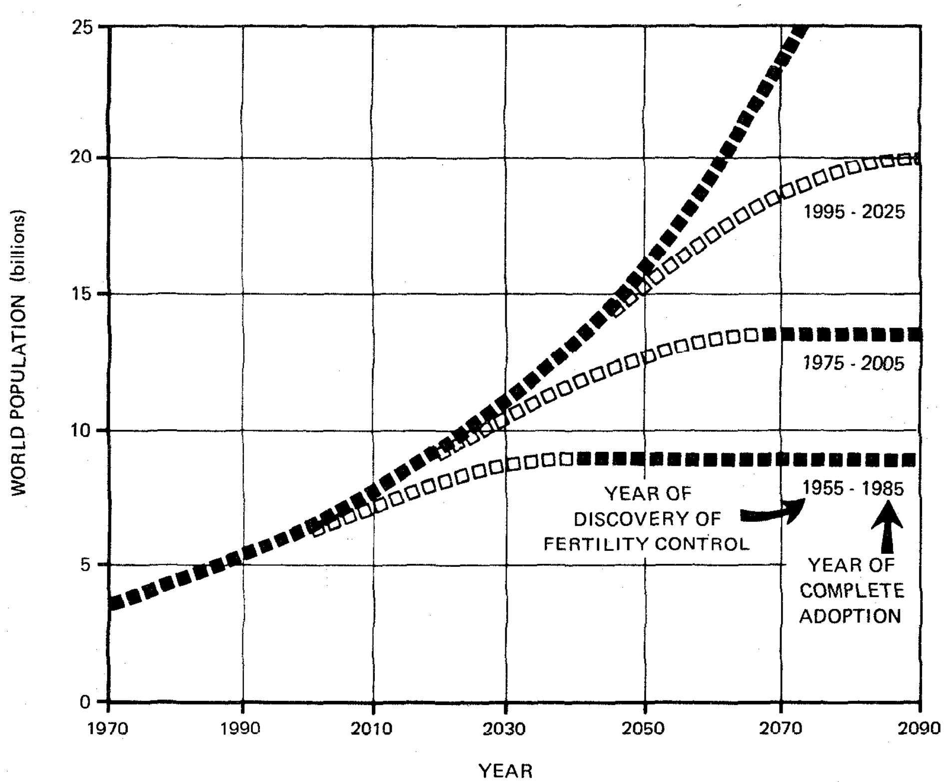

Figure 3 Effect of Momentum in Population Growth

Figure 4, developing one I first used in 1953, supposes that the population in fact levels off at 15 billion, and if we allow them 20 thermal kW/capita, the total heat energy produced is seen to be .18% of that received by the earth from the sun. It does not seem likely that such a small addition would upset the world climate, in fact we do not know whether on its own the earth may swing towards another Ice Age when we might need more heat, or to a period of a melting of the ice caps, raising the levels of the oceans, giving us work to build huge dykes.

WORLD ENERGY FLOW

		RATIO PERCENT
SOLAR RADIATION	1.7×10^{14} kW ON DAY HEMISPHERE	100
HEAT FLOW FROM INTERIOR	2.5×10^{10} kW	0.015
SUGGESTED WORLD DEMAND	3×10^{11} kW	0.18
20 kWt x 1.5×10^{10}	(1.2×10^{11} kWe)	
1966 WORLD ENERGY CONSUMPTION RATE	4.5×10^{9} kW	0.0026
1.2 x kWt x 4×10^{9}		
UTILIZATION OF 1 TONNE NATURAL URANIUM PER YEAR AT 50 MWd/kg	1.37×10^{5} kW	—

Figure 4 World Energy Flow

URANIUM ABUNDANCE

	MILLION TONNES U
TOTAL IN EARTH'S CRUST	> 100,000,000
WITHIN 1 MILE OF LAND SURFACE	2,500,000
IN OCEANS	4,500
CANADIAN LOW COST ORE	0 . 2

FOR FUTURE WORLD DEMAND AT 300 TW

NUCLEAR ENERGY SYSTEM	ANNUAL REQUIREMENT
CANDU - THORIUM + URANIUM (50 MWd/kgU)	2.2 U
CANDU - THORIUM + SPALLATION	≅ 0.2 Th or U
CANDU - THORIUM + FUSION	≅ 0.2 Th or U
BREEDER URANIUM OR THORIUM	≅ 0.2 Th or U

Figure 5 Uranium Abundance

Figure 5 shows how much uranium we have and the effect of supplying the energy from CANDU reactors. Remembering that there is about three times as much thorium as uranium in the world we certainly seem to face no difficulty in the next 10,000 years and should be able to manage for millions of years.

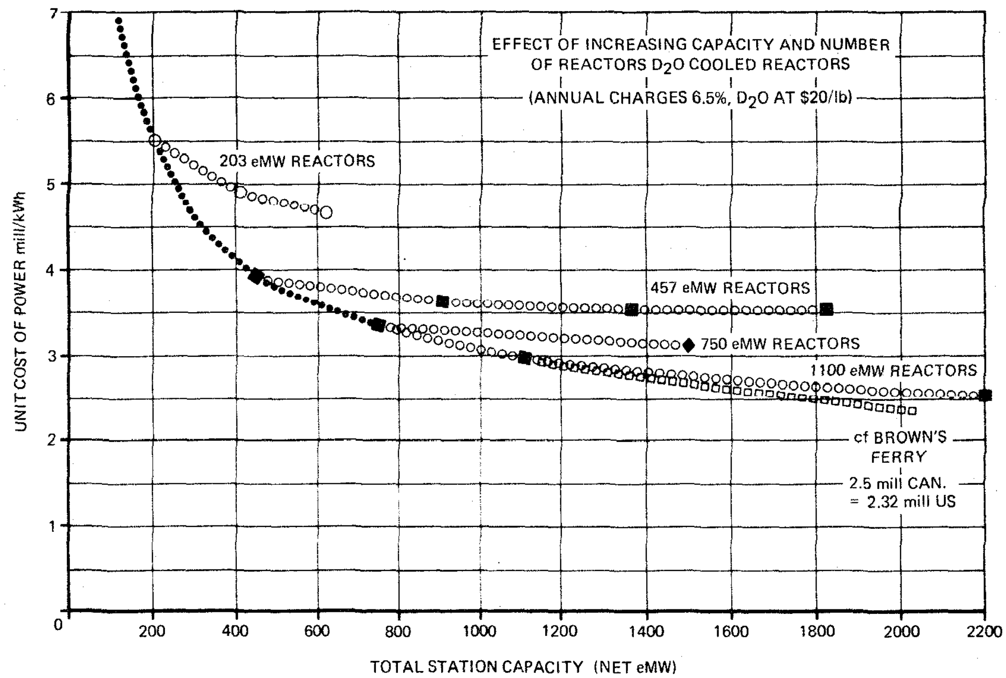

Figure 6 Unit Cost of Power

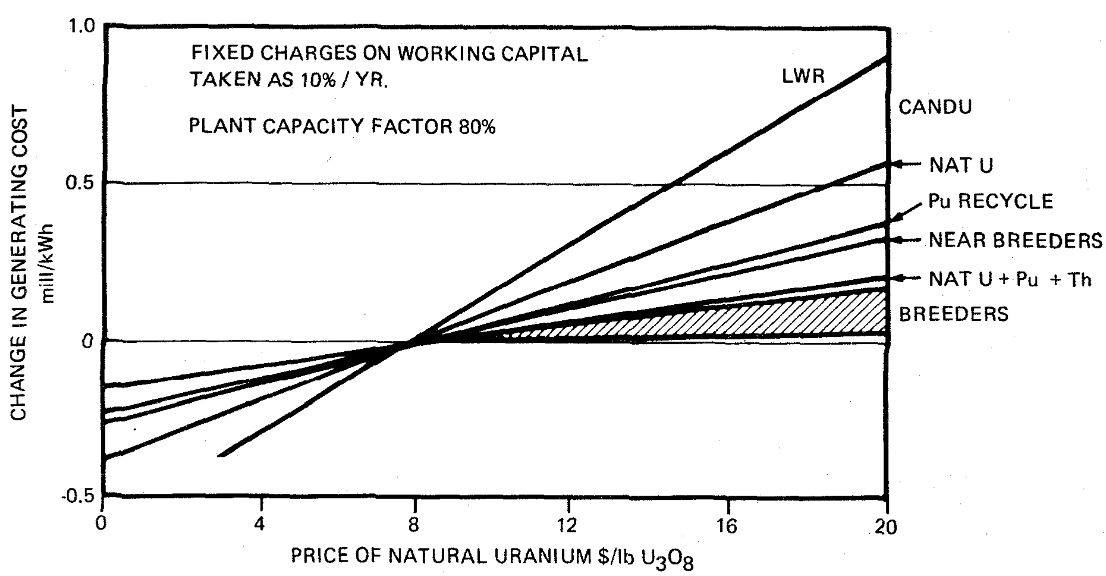

Figure 7 Sensitivity of Generating Cost to Price of Natural Uranium

Turning now to the cost of power, Figure 6 will be no surprise to you. It was first drawn in 1964 but extended slightly to bring in the comparison with the largest planned nuclear power station of the time at Brown's Ferry on the TVA system. However, our own Pickering and Bruce stations are in the same and higher power range. It is important to remember the date because it determines the value of the dollar; it now seems that all the costs should be raised about 50% for 1972 dollars.

On the fuelling cost, Figure 7 is patterned after one presented by Glenn Seaborg in 1966. It shows how the generating cost would increase for an increase in the price of natural uranium. The lines indicate the desirability of getting into recycle with CANDU reactors and also the introduction of thorium.

At the end of 1960 I took another look in the crystal ball for a talk given at the opening of the CIR reactor at Trombay where I developed the evaluation of the cost of neutrons that is directly related to the cost of fissile fuel in all reactors, including breeders, and I showed how the organic coolant at 427°C (800°F) could, with double steam reheat to 650°C (1202°F), give a 45% net station efficiency, Figures 8 and 9, and thorium would give more energy than U-238 per net neutron supplied, Figure 10, and so extend the burnup attainable without the expense of frequent processing of the fission products. All this stems directly from the superior value of η (the neutron yield per thermal neutron absorbed) for U-233 (see Lecture 4 in this series).

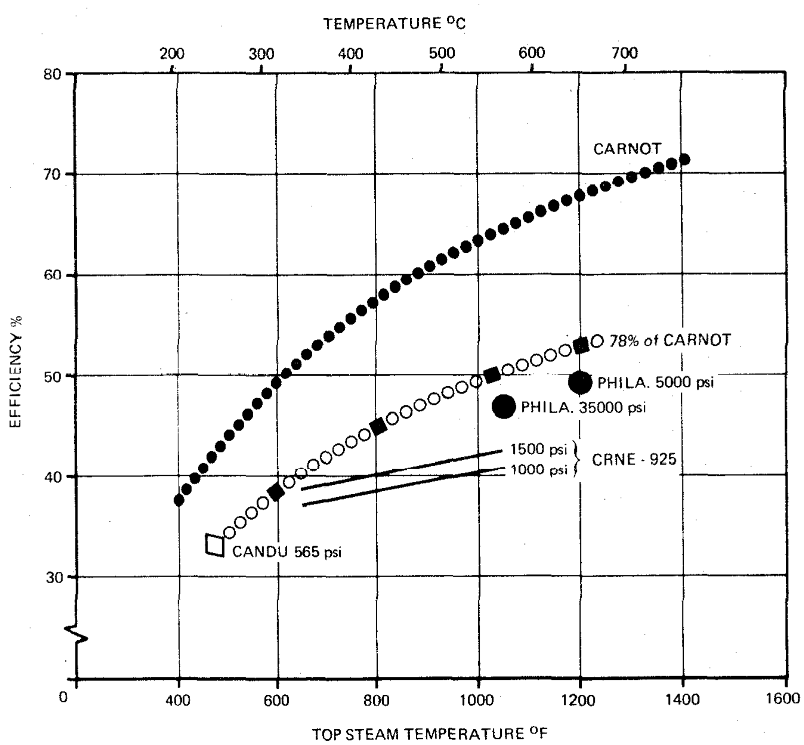

Figure 8 Gross Cycle Efficiency for Exhaust

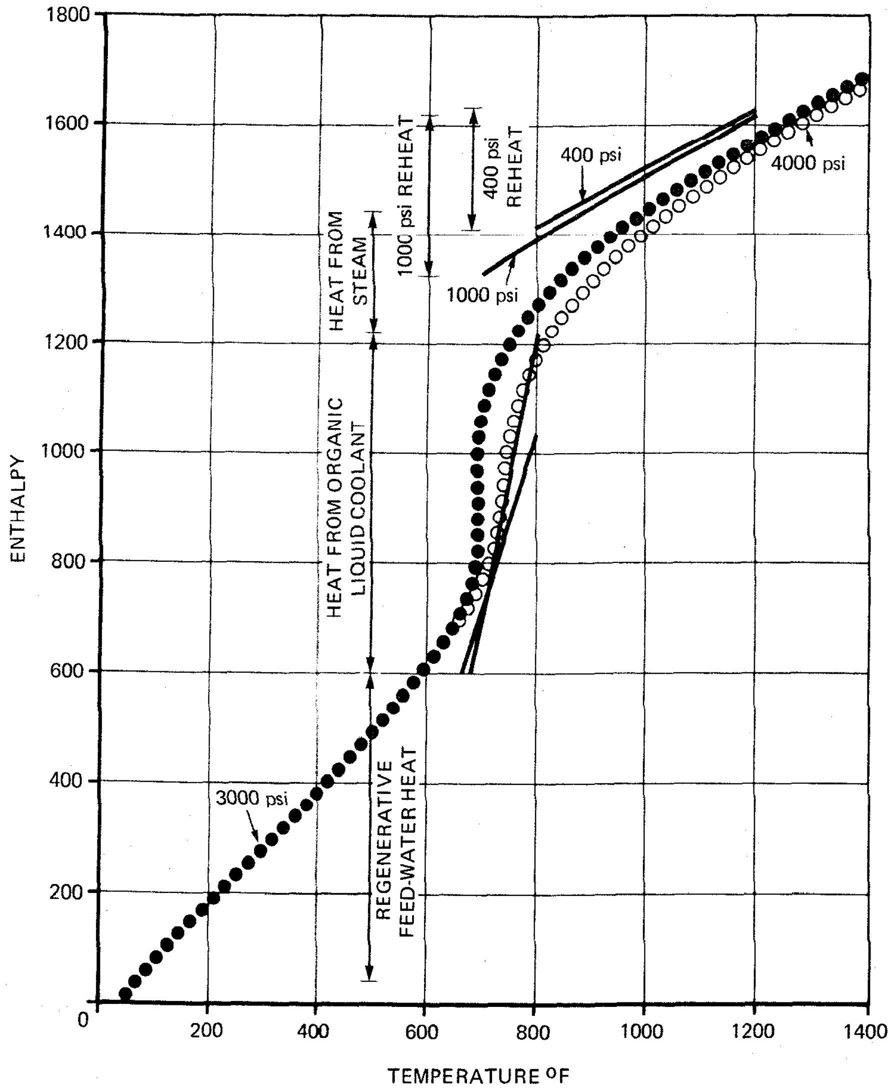

Figure 9 Enthalpy/Temperature °F

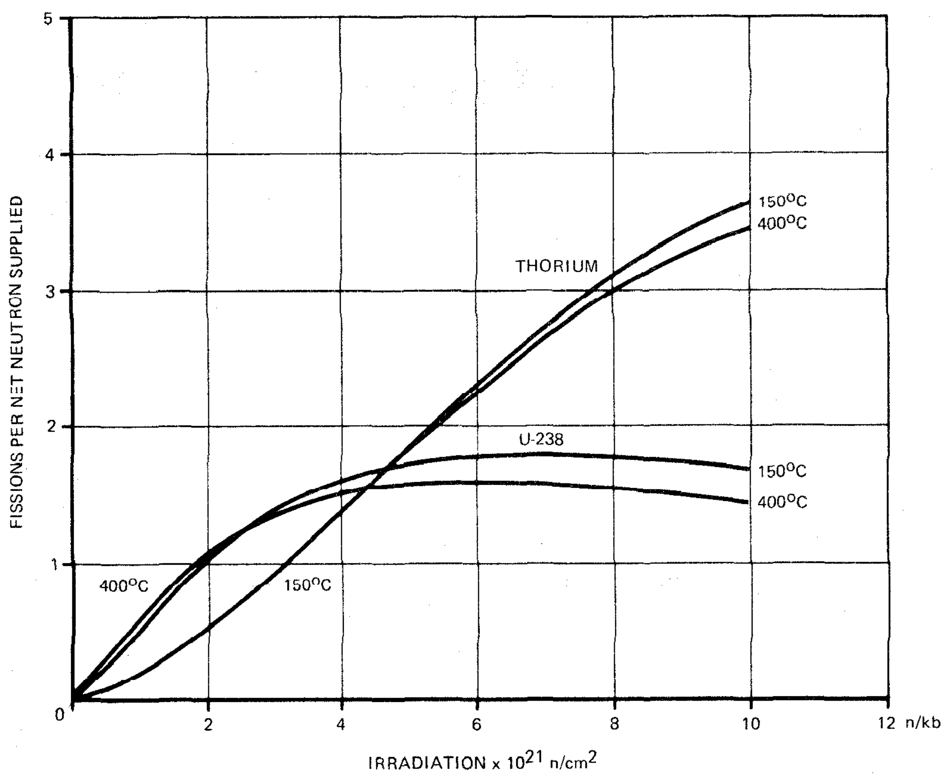

Figure 10 Fissions Per Net Neutron Supplied

Figure 11 shows how the reactivity excess changes for uranium and for thorium. How thorium fits into the picture is interesting. In the original structure of the NRX reactor designed in 1944-45 there was a complete annulus known in secret code as the J-rod annulus for irradiating thorium. Moreover, in September 1946 when I came to Canada to take over from Cockcroft the NRC Atomic Energy Division at Chalk River, he handed me a couple of foolscap sheets outlining the basic prospects making it clear that from what was known of the properties of the fissile nuclei U-235, Pu-239 and U-233, that large-scale power would require fast neutron reactors if plutonium was used, but that U-233 produced from thorium should be satisfactory in the thermal neutron reactors. That property of U-233 of a high yield of neutrons in thermal neutron fission is still the basis of the long-term CANDU prospect. The idea, however, had to contend with moving economic targets. One became well-known between 1955 and 1958. Back in 1955 it had seemed clear to economists that the utilities would be facing rising costs of power because the cost of coal and oil would rise. However, another major change entered the picture and instead of 60 MW(e) being regarded as the largest economic steam turbine, the size and ratings increased to 250 MW(e) and then higher, as we know, to 540 MW(e), 800 MW(e) and 1200 MW(e), with numbers such as 2000 MW(e) spoken of. Improved techniques of mining and hauling coal

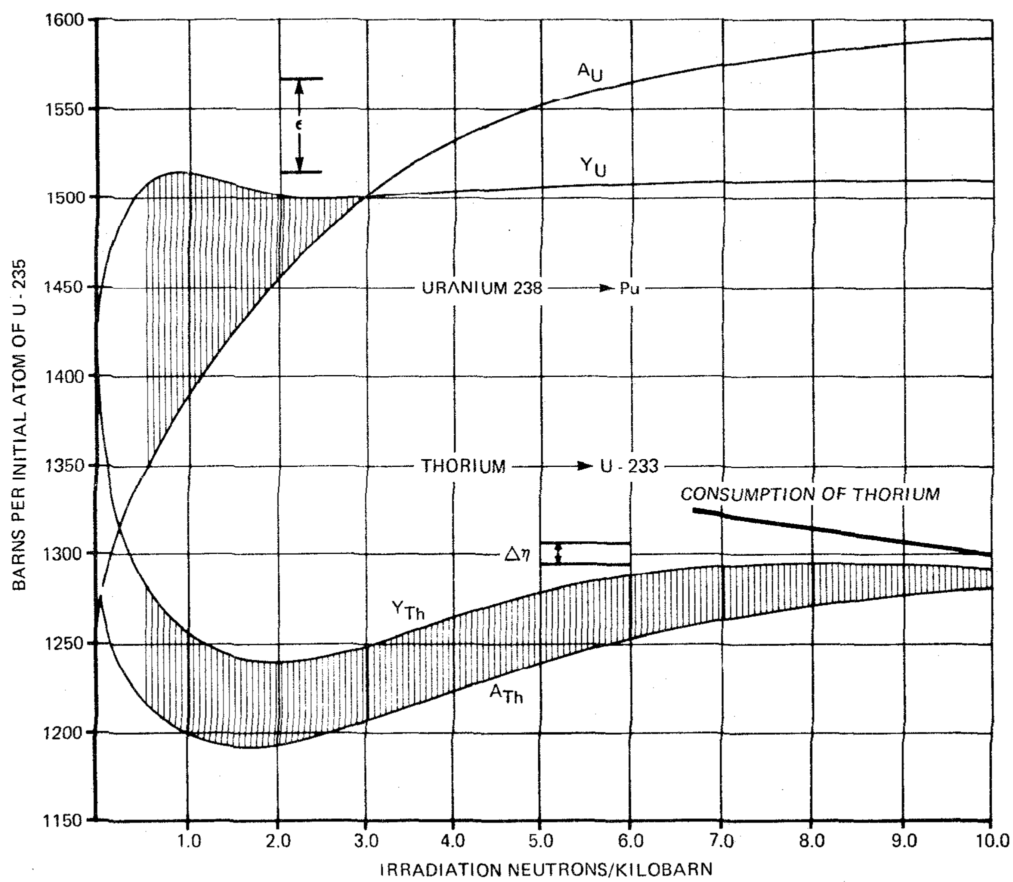

Figure 11 Long Irradiation of Fuels Initially Containing U-235

kept its price almost constant. The prospective cost of generating coal-fired power to Ontario Hydro fell from 7.5 mill/kWh in 1953 to 4.0 U.S. mill/kWh in 1967, since when it has risen. Whereas 200 MW(e) looked economic for CANDU in 1956, by 1959 it was clear that Ontario Hydro would have to aim higher and 450 MW(e) was envisaged, becoming, as you know, 540 MW(e) for Pickering units and now 750 MW(e) for Bruce units. To meet the prospect the pressure tube I. D. was raised from 3.25 to 4.1 inches but we are looking also at 5.25 inches, the size used in the U.K. SGHWR.

Returning to the question of thermal efficiency, it is important to realize that high efficiency reduces not only the fuelling cost but also the capital cost and the amount of circulating water required for cooling. Figure 12 is a revision of Figure 8 showing that a 44% gross steam cycle efficiency could be obtained from 400°C steam in a special cycle labelled LM-3, standing for Lewis and Meikle Cycle 3, one that was evaluated and reported in detail in 1968 and 1969 (AECL-3221). This is important because problems have been encountered

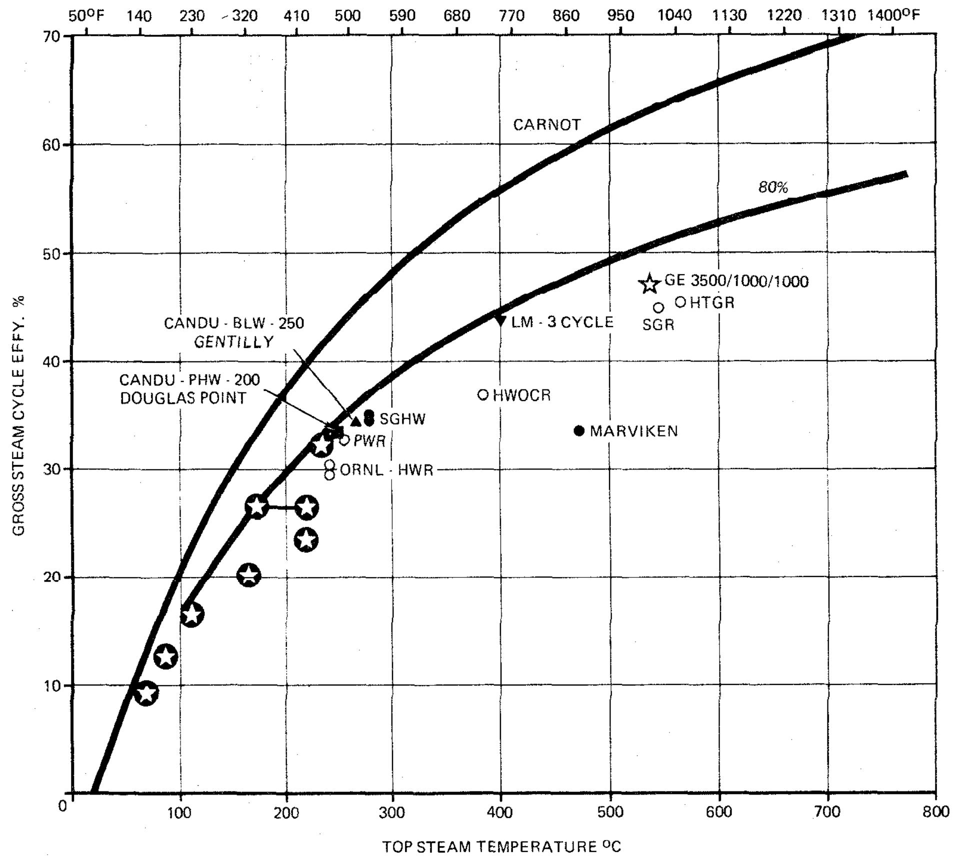

Figure 12 Review of Gross Steam Cycle Efficiencies

with high pressure superheated steam, not only in considering materials for reactor irradiation but also in practice in the steam plants built in 1957 for 650°C (1200°F). Corrosion problems have caused a retreat from such high temperatures. The LM-3 cycle does not involve any reactor superheat and the sole coolant in the reactor can be an organic liquid reaching a maximum temperature of 410°C (770°F). This remains as development potential but as we shall see later experimental results are now very promising that 410°C would be practicable as a top temperature in the organic coolant.

Many people have found the idea of breeder reactors attractive and have indicated that if a fuel is producing more of itself than is consumed, one could afford to pay a high price for it. The snag about this is that one may not be able to afford the inventory. It is therefore very necessary to consider how a fuel cycle can be developed which would have a low inventory cost. I have discussed this intensively in my 1968 report introducing the valubreeder cycle.

The fuel in this case comes in two forms, one is thorium with or without recycled Uranium-233 and the other is uranium at low enrichment. A cost comparison of the valubreeder cycle with several other fuel cycles for similar CANDU reactors is shown in Figure 13. This was the first time that any fuel cycle had been found that could compete in cost with natural uranium.

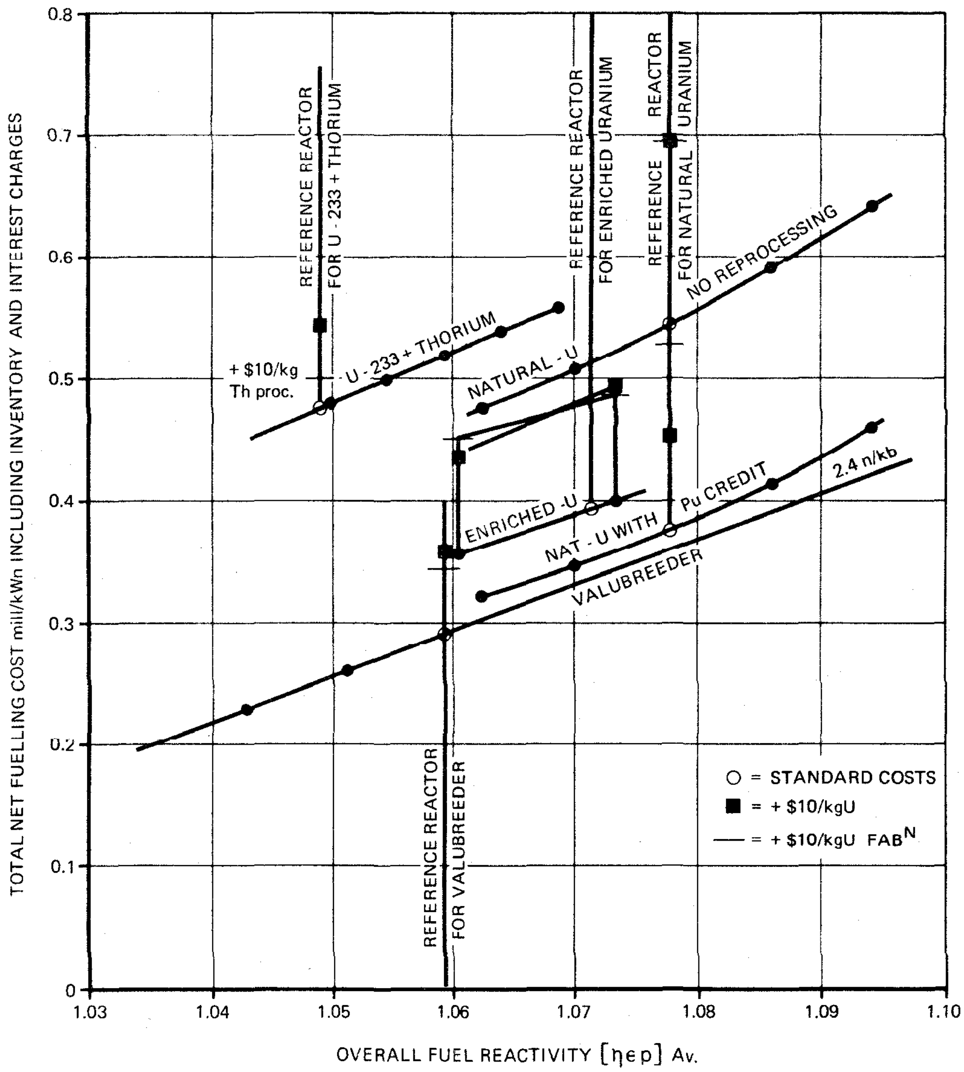

Figure 13 CANDU Fuelling Cost Comparisons

Putting together in 1969 the LM-3A cycle and valubreeder fuel led to a preliminary concept of a 1500 MW(e) reactor with only 370 channels and a moderator vessel just about the same size as used in the Gentilly CANDU BLW 250 MW(e).

On the other hand other fuel cycles involving enriched Uranium-235 and thorium have been studied because they offer the possibility of a higher power density and therefore an even smaller reactor for the same power. For 1500 MW(e) the number of 5 m long channels becomes only 290. The fuel cycle cost is higher but the saving in capital cost of the reactor may prove sufficient compensation. Such cycles were discussed in the paper we presented at Geneva in 1971 with the title "Large Scale Nuclear Energy from the Thorium Cycle". Either the valubreeder or one of these cycles seems to promise the maximum development potential from the CANDU reactor system. More detailed comparisons are given in Appendix 3.

It is difficult to give a balanced impression of how much difference there is between a thorium fuel organic-cooled CANDU and those we have now constructed and operated. On the one hand it is clear that our experience with pressure tubes in heavy water moderator would be much the same. The difference lies in the higher temperatures and the consequent need to establish the performance of fuels under these higher temperature conditions. On the other hand, these high temperatures are considerably lower than experienced in the operation of gas-cooled reactors and prospectively in the sodium-cooled fast breeders. Moreover, considering the development that CRNL put in towards the CANDU-PHW and BLW reactors, the type of work and the magnitude for extending it to organic-cooled reactors seems to call for merely a continuation of similar effort from CRNL and WNRE. There will, however, also be a need to persuade turbine and heat exchanger manufacturers to make some changes to accommodate the LM-3 or similar steam cycle of high efficiency.

Also we should note that the plans call for irradiating thorium fuel to 35 MWd/kg of heavy element. Preliminary experiments indicate that this may be achievable, particularly with the design of fuel outlined in the 1971 Geneva paper and very closely related to the fuels described in the 5th lecture in this series. Concerning fuel development, I would like to quote from the lecture I mentioned that I gave at the opening of the CIR reactor in India for it seems as true today as then:

> "We are not complacent about fuel design, far from it; we realize the key importance of achieving soundly fabricated fuel at low cost. Consequently when any adverse consideration such as hydride embrittlement of the sheathing, cracking of the oxide, irradiation damage, or crevice corrosion, turns up, we investigate it until we are able to set numbers to the effect and design accordingly. While not complacent, we see reason to be confident that we shall not be let down by physical failure of the fuel. The burn-up limit is therefore set by the reactivity limit."

As Mr. Page mentioned in Lecture 5, we in fact did run into some physical failures of fuel in the Douglas Point reactor, but believe that these have been mastered by the introduction of CANLUB fuel. The developments we have in mind for the thorium fuel for longer irradiation use all this experience together with other principles tested in lower irradiations in the experimental reactors. However, we are aiming for very high power output and a long life from the fuel and it seems most desirable over the next 10 years or so to put a considerable effort into the evaluation of several modifications of design so that we understand more fully all the behaviour of the fuel material itself, its sheathing and their interaction. One of the problems we are aware of is the entry of coolant through a small defect in the cladding which, because of the higher temperatures inside, might cause hydriding of the fuel sheathing material. This does not present a problem at the operating temperature but when cooled down the sheath may be excessively brittle and weak. We have some ideas for means of taking hydrogen away from the sheathing and these also need development. I have said that one of the essential techniques we must develop is hydrogen engineering in metals at high temperatures, we most exploit to the full the means of moving hydrogen about so that it does not accumulate where it could cause trouble.

Turning now to the wider scale, there are some operations to be developed, one of those calling for a change from current industrial chemical practice is the management of radioactive wastes. Again, ideas are being developed and I see no reason for any concern, provided steps are taken in the right direction from the start. I regard it as a mistake to seek any permanent disposal for radioactive wastes. Instead it seems very reasonable to call for permanent management. It is certainly necessary to manage the new wastes being produced. Managing the old wastes along with the new wastes makes only a small addition to the work because the radioactive decay of the earlier wastes makes their activity always less than that of the new wastes. It will be necessary to arrange for the materials from which the plant is constructed never to leave the site of the plant. They will need handling as contaminated radioactive material, but the development of such practices seems quite manageable. The idea is developed to some extent in a recent report, AECL-4268, that discusses wastes on an even larger scale than would arise from the 20 thermal kW for 15 billion people that I discussed earlier. This report allows 50 thermal kW for 15 billion people and indicates that a single site should manage the wastes from 300 MkWe generating capacity. One thousand such sites would look after all the foreseen nuclear power generation in the world for the indefinite future; about four such sites might be needed for North America by the end of this century. A site could be opened when there is as little as 6 MkW to be served but the site should be planned on the scale needed for 300 MkW after some thousands of years.

This problem of radioactive wastes introduces the increasing problem of public acceptance. Because nuclear energy was introduced to the world through nuclear weapons, there is abroad among the public what a Time Magazine writer has called "visceral fears". Such fears are very real but are not necessary. There is no evidence that nuclear power, as distinct from nuclear weapons, has been mismanaged; in fact, there is much evidence that the nuclear power industry has an outstandingly good safety record. Moreover, these fears have become extended to low levels of radiation when all the evidence so far is only that high levels of radiation are damaging to life. In order to satisfy public fears much more science needs to be developed and the information spread to the population at large through regular educational processes.

Experience so far with atomic energy workers is encouraging and Figure 14 shows information tabulated in the latest Annual Report from the *Australian Atomic Energy Commission*:

MALE STAFF OF THE UKAEA 1962-1969

CAUSES OF DEATH	ACTUAL	EXPECTED (ACTUARIAL FOR WHOLE POPULATION)
ALL CAUSES	1,467	1,986
ALL CANCERS	379	513
LUNG CANCERS	150	224
LEUKAEMIA	6	13

Figure 14 Male Staff of the UKAEA 1962-1969

Science does not allow us to generalize from such limited information but that must be accepted and incorporated in the general body of science. I have discussed this matter in other lectures and would refer, in particular, to one published in the IAEA Bulletin last September, the substance of which I also gave in my talk in Vancouver last year entitled "Nuclear Energy and the Quality of Life".

Returning to the broad prospect of development potential, we see we have been discussing CANDU reactors and potential CANDU reactors in the context of supplying the energy needs of the whole world for thousands or possibly millions of years. Other reactor systems such as fast breeder reactors may contribute, but to do so they will probably have to establish that they can compete economically with CANDU reactors. Because the scale of the envisaged application is so large, we must not shrink from developments that seem long term and giving no immediate monetary return. Fortunately the industrial development for Canada is a sufficient base for all the development to be supported, moreover coupled with parallel growth of CANDU reactors in India and very probably in other countries as soon as the economic advantages are appreciated, we can look forward to considerable technical developments. As I mentioned earlier, one of the most promising of these is the development of the organic coolant technology together with that of thorium fuel. In the 40 MWt experimental reactor, WR-1 at WNRE, we have found it possible to operate satisfactorily at 400°C, and believe we now understand how to increase this to 410°C or even possibly 425°C. An unexpected bonus appeared in WR-1 operation that it is free from radioactive material transported round the primary coolant circuit. In all the water-cooled reactors this is still an outstanding technical problem; it seems to me to promise a major improvement in reliability and maintainability. We cannot quantify the resulting economic benefit but it must be far from negligible. We may be able to adopt some of the much simpler construction and maintenance techniques that have been developed in the petro-chemical industry.

APPENDIX 1

From 1972 Canada Year Book, pp. 1047 to 1050, we find:

	1959		1970
Non-residential construction			
Cost Index	96.3		156.1
Correspondingly	$200	⟶	$324
	$250	⟶	$405
Consumer Price Index	97.9		129.7
Correspondingly	$200	⟶	$265
	$250	⟶	$331

Further price index changes are shown in Figure A1-1.

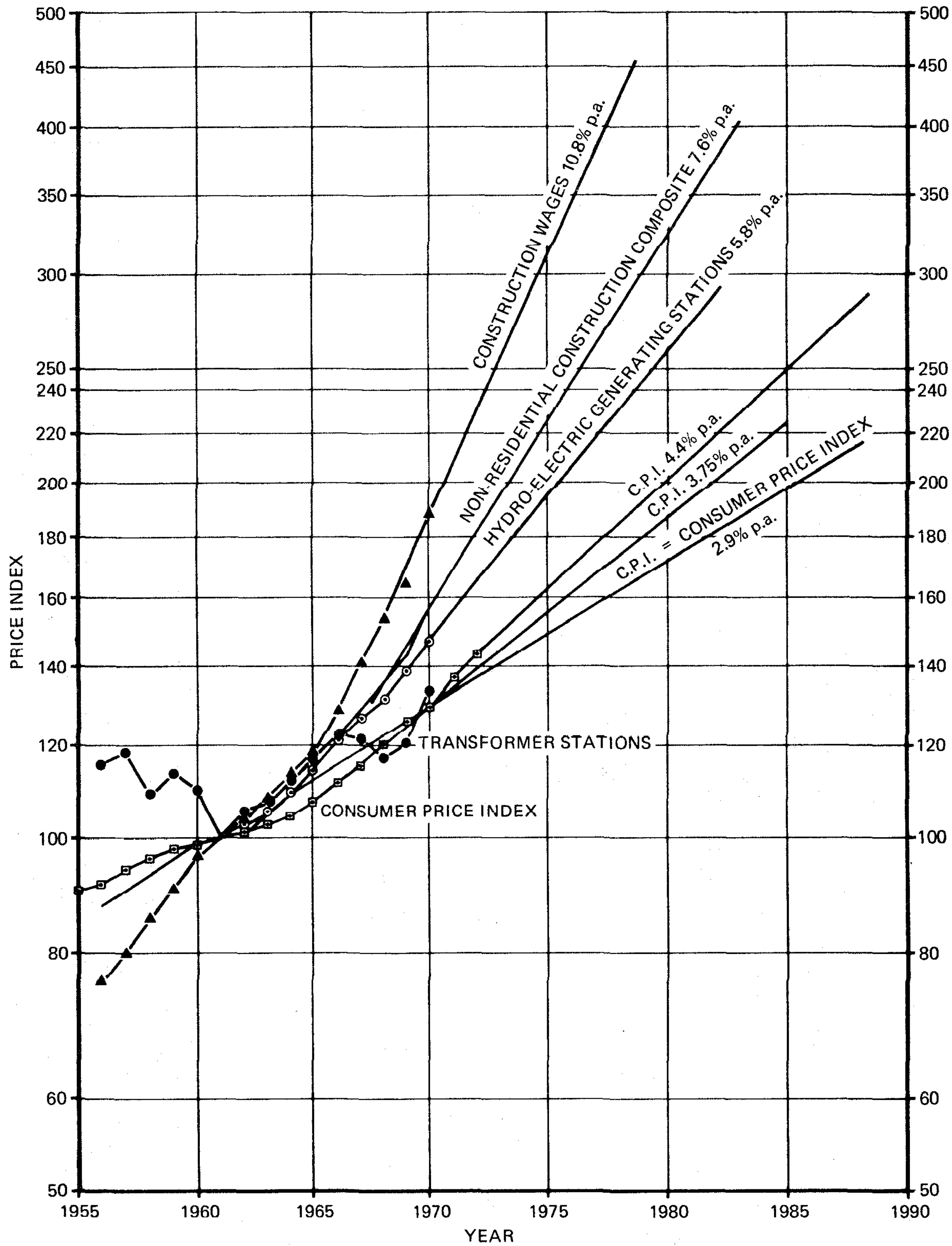

Figure A1-1 Price Indexes From Canada Year Book 1972

APPENDIX 2

Figure A2-1 shows the available information on Canadian net electrical generating capacity, hydro-electric generating capacity, population and gross national product in constant 1961 dollars as given in the Canadian Year Book for 1972 and some earlier years.

Extrapolations at constant annual rates of increase to the year 2000 give:

	Rate	Year 2000	
	% p. a.	Total	kW/capita
Population	1.81	36,305,693	
Net electric generating capacity	5.8	231.7 MkW	6.38
	7.6	369.1 MkW	10.17

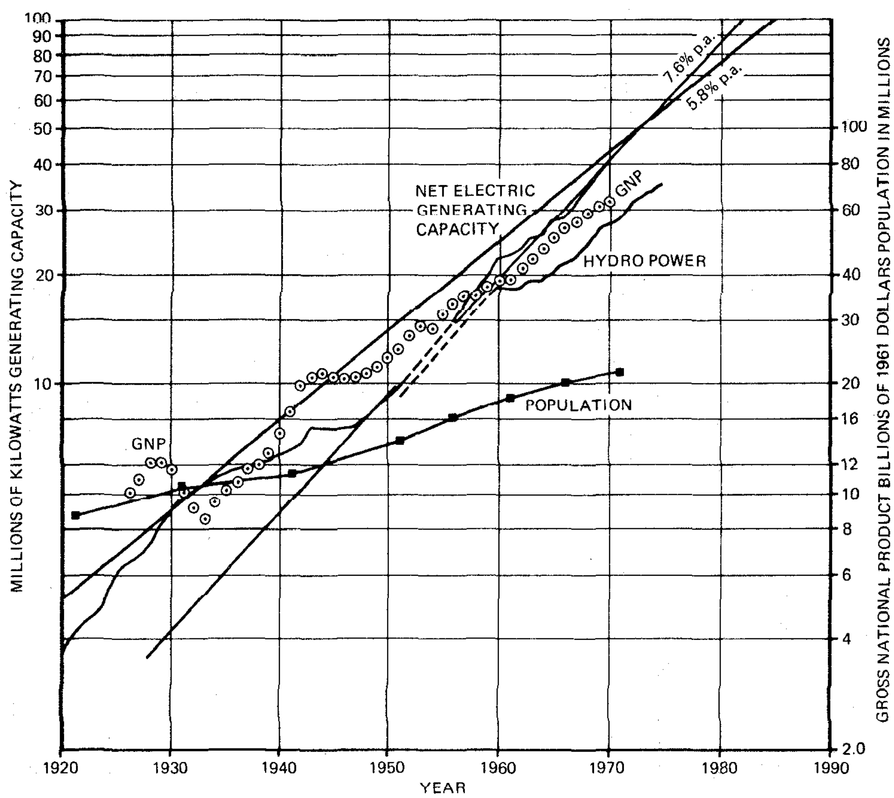

Figure A2-1 Electrical Generating Capacity Population and Gross National Product

APPENDIX 3

It is important to avoid a too short term view in considering CANDU reactor potential. From the economic point of view three major aspects must be considered open to change, namely:

(1) Interest rate on capital

(2) Value and price of U-233

(3) The working substance and its cycle.

Briefly stated, the prospects of change are:

1. Interest Rate

(a) The provision of energy as electricity or otherwise for at least the next century seems likely to demand an increasing fraction of the total available capital. Already it forms so large a component with a relatively long term yield, that is to say, dams and thermal generating stations have a longer useful life than most factories and durables such as aircraft, vehicles, appliances, that some economic considerations indicate that the capital for new installations should come from the revenue of the utilities and from low interest rate loans from governments. Power consumers do not then face paying ever-increasing interest rates.

(b) Keynes in his General Theory of Employment, Interest and Money, argued that in a prosperous economy with full employment the rate of interest could with advantage be very low, while making a clear distinction of the return on capital investment that must provide for wastage, obsolescence and other components. He did not specifically mention the provision for expansion that seems still to be a bone of contention. But, on money rates he wrote (p.376): "Interest today rewards no genuine sacrifice, any more than does the rent of land. The owner of capital can obtain interest because capital is scarce, just as the owner of land can obtain rent because land is scarce. But whilst there may be intrinsic reasons for the scarcity of land, there are no intrinsic reasons for the scarcity of capital."

It seems quite possible that as economic ideas change to meet the changing pattern of investment, low interest rates for power utility capital may be found necessary for prosperity.

2. Value and Price of U-233

The valubreeder cycle shows an increasing gain the better the neutron economy. With U-233 recycle, as breeding is approached, the value of U-233 relative to U-235 would become infinite if it were not for the annual charges payable on a high priced fuel inventory. The actual value of U-233 is then a steep function of the interest rate applicable. The higher the interest rate the lower the value of U-233, and correspondingly of spare neutrons; fuel would be taken to a higher burn-up and the value added would be reduced.

3. The Working Substance

Steam in many ways is not an ideal working substance, but the effort needed to introduce a competitive replacement is extremely high because of the large scale to which steam technology has climbed and the further cost benefits to come from operating on a still larger scale.

Gas turbines using helium and carbon dioxide have some promise. Magneto-hydrodynamics would have advantages if corrosion problems in complex systems of insulators and conductors could be resolved; however, no very promising solution is yet known. Another possibility is a molecularly dis-sociating coolant with or without direct conversion in a recombining fuel cell.

BIBLIOGRAPHY

Lewis, W. B. "Planning Canada's Nuclear Programme", DL-37, Paper presented at the Northwest Electric Light and Power Association, Vancouver, 1959.

Lewis, W. B. "Designing Heavy Water Reactors for Neutron Economy and Thermal Efficiency", DL-42. Lecture presented on the occasion of the formal inauguration of C.I.R., Bombay, India, 1961.

Lewis, W. B. "Energy in the Future - The Role of Nuclear Fission and Fusion". Proc. Royal Society of Edinburgh. (A) 70, 20, 1971/72.

Lewis, W. B. "Prospects for 44% Cycle Efficiency from 400°C (750°F) Steam in Large Electric Generating Stations. AECL-3221, 1969.

Lewis, W. B. "How Much of the Rocks and the Oceans for Power? Exploiting the Uranium-Thorium Fission Cycle". AECL-1916, 1964.

Lewis, W. B. "Heavy Water Reactor Review and Prospect". AECL-2274. Presented at ANS Annual Meeting, Gatlinburg, June 1965.

Lewis, W. B. "The Super-Convertor or Valubreeder. A Near-Breeder Uranium Thorium Nuclear Fuel Cycle". AECL-3081, 1968.

Lewis, W. B. "The Intense Neutron Generator and Future Factory Type Ion Accelerators". AECL-3190. Presented at the IEEE-GNS 15th Annual Meeting, Montreal, 1968.

Lewis, W. B., Duret, M. F., Craig, D. S., Veeder, J. I., and Bain, A. S. "*Large-Scale Nuclear Energy from the Thorium Cycle*". AECL-3980. Paper presented at the 4th United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1971.

Lewis, W. B. "Radioactive Waste Management in the Long Term". AECL-4268, 1972.

Lewis, W. B. "Nuclear Energy and the Quality of Life". IAEA Bulletin, 14, No. 4, 1972.

Tegart, D. R. "Operation of the WR-1 Organic Cooled Research Reactor". AECL-3523. Paper presented at the American Nuclear Society Conference on Reactor Operating Experience, Puerto Rico, 1969.

Lewis, W.B., Duret, M.F., Craig, D.S., Veeder, J.I. and Bain, A.S.

"Large-Scale Nuclear Energy from the Thorium Cycle". AECL-4445. Oral presentation as given at the 4th United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1971.