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CANADA'S STEPS TOWARDS NUCLEAR POWER

by

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1. Canada enjoys a natural abundance of coal, oil, natural gas, water-power and uranium. In the general enthusiasm for nuclear power that marked the first United Nations Conference in 1955 it may not have been noticed that we foresaw (1) a demand for nuclear power in Canada if, and only if, it met the economically competitive range, that, we said, was below 6 mills per kilowatt-hour. This prospective demand arises from the geographical pattern of industrial development in Canada. In other countries also it is likely to be found that a distance as little as four or five hundred kilometres may decide whether the cheapest power is obtainable from uranium or from some other source. When electric power is derived from coal, oil, natural gas or water power its price is highly dependent on transportation costs. Uranium provides a sharp contrast. Even the high costs of bringing uranium from remote regions in the Canadian north affect only the competition between sources of uranium supply, and do not add significantly to the prospective cost of electric power, even when this is very low. Both the prospective market for nuclear power and the availability of uranium are discussed in other papers (2) presented by Canada to this conference, and here I need only mention that a very great abundance of economically available uranium has been discovered so that supply imposes no limit within at least fifty years for the most extravagant nuclear-power projects, not only in Canada but throughout the world.

2. Since the first conference, however, it has become widely recognized that many stages of technical development are required before nuclear power would compete in the low-cost power markets. Competitive sources of electricity limit Canada's objective to this low-cost power and I think we can justifiably claim for the heavy-water, natural-uranium reactor techniques that the steps we have taken have led to most promising results. They have made it clear that we can depend on obtaining an energy yield directly from natural uranium fuel, in the form of a

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relatively inexpensive sintered oxide, as high as 8000 to 10,000 thermal megawatt days per tonne of uranium (3). At such a yield the uranium itself costs less than 1 mill/kWh and total fuelling costs including the cost of fabrication and interest and insurance charges on the whole fuel inventory should not exceed 1.5 mill/kWh. Experiments with UO_2 fuel in the NRX reactor have established (4) that if properly fabricated, a rating as high as 50 thermal kilowatts per metre length is practicable for a single UO_2 rod of any diameter up to 2.5 cm. A fuel bundle of 19 rods could then provide almost 1 thermal megawatt per metre length.

3. The predicted burn-up owes much to a simple but ingenious method of fuelling that was devised in the course of reactor design studies at Chalk River in 1956 (5). In any one fuel channel the process is simple and not novel, having been used in most of the earliest graphite-moderated reactors. The fuel is in the form of short slugs inserted fresh at one end of the channel and progressively moved along until after a full irradiation the spent fuel is discharged at the other end. The innovation lies simply in arranging that in alternate adjacent channels the fuel travels in opposite directions and the system is therefore referred to as bidirectional fuelling.

4. It may be noted that this system is also very simple compared with the recycling system we presented at the first conference (6). No reprocessing of the fuel or recycling of plutonium is involved, and the promise of low cost does not require any value to be assigned to the spent fuel. The spent fuel does, however, contain plutonium that might have a value greater than the cost of extracting it. If so, some credit might be realized.

5. If the reactivity limit of burn-up is evaluated for the bidirectional system simply on the basis of the world's best values for nuclear constants, it is true that 8000 MWD/tonne is predicted, but misgivings might be felt that some unrecognized poisoning effect might exist and prevent its realization. A direct test of long-irradiated natural uranium has therefore been made with much higher precision than that reported at the last conference. The interpretation of such measurements is not, however, simple. The studies are reported in paper 205 to this conference. Collaboration of the United Kingdom formed an essential part of these studies, using the GLEEP reactor at Harwell. The conclusion so far is that somewhat higher irradiations than predicted from the measured values of the nuclear constants seem probable.

6. In 1955 there were many gaps and inconsistencies between measurements of the nuclear constants. New determinations supported by direct measurements to characterize the neutron spectrum are reported in Canadian papers 204, 203, 202, 201 and 187, so that now, as reported in paper 205, the most significant errors lie in discrepant results from

the very difficult measurements of the fission characteristics of Pu-239 and U-235.

7. All these studies just mentioned relate to the changes in reactivity during irradiation. It is, however, also necessary to predict the initial reactivity in reactors not yet built. Further experimental studies have therefore been made on fuel lattices in heavy water, and these are described in paper 212. Collaboration with Sweden and with France in these studies has been helpful and has resulted in a good measure of agreement and a broader basis for predictions. Although these studies are not concluded and further results from experiment and theory are looked for, it is not likely that any significant adverse factors remain to be discovered.

8. Backed by this assurance of reactivity from natural UO_2 fuel in a long irradiation, it is necessary to review the knowledge that leads to the expectation of low fuelling costs in practice. This involves both irradiation experience and fabrication technique and must take account of the statistical probability of premature fuel failures. Such experience is discussed in papers 193, 192 and 194. It may be summarized as demonstrating that, provided the fuel is correctly fabricated and sheathed in a strong Zircaloy can, which can all be done within the economic cost allowance, then no significant overall dimensional change is to be expected. Moreover, the assurance of this is very strong because many irradiations have been carried out, under conditions more adverse than need be used, without any sign of such a dimensional change. The possibility of a failure of a Zircaloy can through corrosion cannot be dismissed with such assurance, but knowledge is being accumulated rapidly and by the time any large reactors are built it is anticipated that a satisfactory technology will have been established. Moreover, even if a Zircaloy can should corrode, there is now a wealth of experience (4) with Zircaloy-canned UO_2 under irradiation and in hot pressurized water to show that the result is not catastrophic and in the proposed type of reactor the faulty fuel would be extracted without even interrupting the operation of the reactor. Only the one faulty fuel slug would be wasted and no operating time lost.

9. Beyond this there is promise through further development of UO_2 fabrication and sheathing techniques (7) that even lower fuelling costs will be achieved, bringing these down from a present estimated 1.5 mill/kWh to 1.0 mill/kWh or even less.

10. The problem of capital costs for heavy-water reactors is not negligible and further improvements are looked for. The most significant advance since 1955 is the introduction of a design in which by avoiding any pressure shell no thick masses of metal are involved, so that it is possible to envisage an indefinitely long life because all parts may be replaced if necessary. Moreover, there is no obvious limit to the size. It may only

need confidence founded on experience to generate a million kilowatts from one reactor, although for an initial full-scale reactor one-fifth of this, or 200 megawatts, has been chosen. Any lower power would significantly raise the specific capital cost, and we have not yet been able to envisage entering the low-cost field competitively with a generating capacity as low as 50 or even 100 megawatts. Competition with other reactors in this range may be achieved by combining heavy-water moderation with the use of an unpressurized organic-liquid coolant as proposed by the Canadian General Electric Company in paper 210 to this conference. Irradiation experience with organic liquids as reactor coolants is, however, still rather limited. Experiments are planned, but we have no results yet to report from Canada. If such a coolant is successful, capital costs may well be lower.

11. As shown in paper 207, the capital cost we have to achieve for the whole station, including the fuel inventory, is about $300 per electrical kilowatt generating capacity for low-interest-rate financing, or about $250/kW for the higher rates applicable to private industrial financing.

12. For this type of plant a typical distribution of the capital costs is given in Table 1.

Table 1.

Distribution of Capital Costs for 200 eMW Power Plant

	$Millions	$/ekW
Reactor and Auxiliaries	10.7	53.5
Building and Plant Services	10.0	50.0
Pumps and Steam Generators	4.7	23.5
Turbo Generators and Auxiliaries	15.0	75.0
Sub-total	40.4	202.0
Heavy Water	11.7	58.5
Fuel Inventory	8.2	41.0
Total Capital	60.3	301.5

13. It may be noted that the reactor and its auxiliaries account for only 18 to 25% of the total, or $54 to $75 per ekW, depending on the proper allocation of costs of the buildings. This may be looked at in

two ways; in the near future it carries the advantage that an error in estimating is not likely to be a large fraction of the total cost, but in the longer term it does not promise very great reductions. These reductions in the longer term must come from increasing the efficiency, including that of the heat exchangers if they remain necessary. Essentially there appears to be no long-term disadvantage from the use of heavy water as moderator, and such designs can take advantage of any improvements in fuel cladding and high-temperature coolants that can be introduced. Experiments to establish such systems are envisaged and will be carried out in experimental loops in the NRX and NRU reactors at Chalk River. The confidence we now have in Zircaloy-clad UO_2 in pressurized water has been derived from such experiments.

14. The capital cost of heavy water itself is not a serious disadvantage because even with unfavourable high interest rates it is repaid in a few years by the fuel cost it saves compared with that for any other moderator. However, if it were possible to produce heavy water more cheaply than the present figure of $62/kg, it would certainly widen the range in which heavy-water power reactors would be competitive. We are continuing to seek improved methods of producing heavy water although we have not yet discovered any very promising method; but neither are we discouraged nor is an improvement essential to the large-scale use of heavy-water reactors for nuclear power.

15. Since the first conference we have completed and brought into use at Chalk River the large experimental reactor NRU rated at 200 thermal MW; this heavy-water natural-uranium reactor is discussed in paper 211 to this conference. The cost proved higher than the original estimate, but the experience has been used in drawing up the estimates for both a 20 eMW demonstration and the full-scale power reactors. It is, perhaps, worth emphasizing the similarity between these proposed power reactors and the original NRX reactor design. The NRX reactor itself has been improved and the improvements are being carried forward in the version being built in India, the Canada-India Reactor described in paper 1704.

16. To review these developments in power-reactor design we must go back to May 1955 when the detailed engineering and construction of a 20 megawatt (electrical) demonstration reactor and power plant was started by the Canadian General Electric Company at Peterborough following a preliminary design reached at Chalk River by a group of engineers mostly seconded by utilities and manufacturing companies. This group formed the Nuclear Power Branch of Atomic Energy of Canada Limited and drew on the experience gained at Chalk River. The proposed reactor (8) was to use natural uranium in heavy water in a rather large steel pressure shell. It was to be pressurized with helium in order to allow displacement of the heavy-water moderator for control and shutdown, thus avoiding the

use of any control rods. This design progressed satisfactorily until March 1957, when the objective was modified.

17. Meanwhile, the Nuclear Power Branch had been reconstituted in May 1955 to study how to meet the economic objective with a full-scale power reactor. The objective as already mentioned was to get below a cost of 6 mill/kWh, in fact to compete with good coal at $9/tonne. The Nuclear Power Branch adopted 5 mill/kWh under the financing system of the Ontario Hydro Electric Power Commission, as their target. This study led to the reactor design reported in paper 208, that is basically similar to the NRX reactor. As in that reactor, the heavy-water moderator is to be at atmospheric pressure in a thin-walled aluminum vessel threaded by thin tubes to provide channels for the fuel elements and their hot coolant. Already since 1950 some of these fuel channels in NRX have carried hot circulating water in tubes that have to be thick enough to sustain the pressure required to keep the water from boiling. Reactivity is controlled by adjusting the level of the heavy-water moderator and in May this year we brought into operation in NRX a system (9) in which drain holes are always open and all control is achieved by the rate at which the heavy water is pumped in. For shutting down NRX we still use six gravity-operated shut-off rods (in addition to dumping the moderator), but for NPD a helium gas-balance system had been designed to avoid the need for these. The same system is proposed for the large power reactor. This results in a very considerable saving in capital cost and there is less that could fail mechanically in operation. Any satisfactory shutdown system has to be absolutely reliable and we have developed an operating system for ensuring this, as discussed later in paragraph 22. 2.

18. The design proposed for the large power reactor differs from NRX in that the fuel channels are horizontal instead of vertical. The reactor vessel is nearly twice as long as in NRX and more than twice the diameter. The number of fuel channels is only slightly increased - about 220 instead of 199 - so the channel spacing or reactor lattice is much more open - about 30 cm - and on a square pattern to improve access for coolant tubes. It is most convenient to allow for thermal expansion, while leaving access for fuelling while operating, by adopting this form of construction in which the coolant channels are brought together by relatively thin pipes connecting to header tubes some distance from the reactor vessel, which can then be independently suspended. (See papers 185, 208, and 209 to this conference.)

19. This design appeared so promising that it was decided to adopt it also for the 20 eMW demonstration reactor NPD although this would set back the completion of this project by 18 months or more to some time in 1961. It should be understood that at this low power, 20 eMW, the capital cost is relatively high and also the fuelling cost because the

attainable fuel burn-up will be less. The purpose of NPD is to provide experience sufficient to demonstrate the practicability of the large reactor and avoid possible costly errors or unnecessary provisions in its design. Providing fuel for NPD will also serve to establish the cost of fabricated fuel.

20. As already mentioned, this design in a 200 eMW size is proposed to meet the economic competition in generating electric power, taking into account both the capital and operating costs. From the pressurized coolant system with the access ports for changing fuel while operating, there may be some leakage of heavy water. This, however, does not represent a loss, for it would escape into a vault lined with a metal vapour barrier. Development work is in progress to study means of minimizing leakage and ensuring efficient recovery so that heavy-water losses may be kept low. Even if leakage occurs into the steam side of the steam generators, the cost of upgrading all the water in the steam system would be acceptable. Very great attention is, however, being paid in design to ensure that such leakage is unlikely

21. An important development towards the pressure-tube type of power reactor is the pressure tube itself. There are several proposals both for hot and for cooled pressure tubes. The distinction between the two arises because the thermal insulation necessary between the hot coolant and the cool moderator may be on the inside or outside of the pressure tube. We have operated a hot Zircaloy pressure tube (10) in the centre of the NRX reactor since March 1957. It has been examined periodically and found to be in excellent condition. The use of such a hot tube surrounded by an insulating gas gap has advantages for construction and replacement. For the same strength, however, a hot tube has to be thicker than a cold tube and this thickness quite significantly affects the fuelling costs. In the design of the 20 eMW demonstration reactor the extra capital cost to compensate for an extra millimetre on the tube thickness has been estimated as $600,000. If the tube were made of stainless steel the figure would be $19,000,000. This, perhaps more than any other feature, serves to emphasize that engineering reactors for truly low-cost power is a specialized field that demands not only development work but also careful analysis. If a cooled pressure tube is adopted, magnesium alloys receive consideration in addition to zirconium.

22. The accident in 1952 in which the NRX reactor was severely damaged (11), has made us pay very special attention to the safety aspects of reactors and we have been led to appreciate a number of subtle principles. The most recent developments are presented in paper 213. Here I will mention three adverse factors and four good design principles to counteract them.

(a) If any single shut-down (or scram) element commands a large reactivity, it is a potential hazard. It must be designed to move freely into the reactor and, under an abnormal condition, it might be thrown out rapidly, thus contributing a rise of reactivity that may be too rapid for compensation by the control system.

(b) Even if a reactor has a negative temperature coefficient, any undue rise of temperature must be recognized, for otherwise it would be promoted by a perfectly working control system.

(c) Operation of almost any reactor at three or four times its power rating could result from a failure of calibration (reduction of sensitivity) of power monitors. If this were sustained for many minutes even a containment structure might be taken beyond its limit.

22.1 To maintain safety against (a) there is the obvious method of subdividing the shut-down elements, or using a moderator dump in a slow-return system, but in addition there is a subtle operating point that a reactor is not safest when shut down, but when the control system has a bank of withdrawn shut-down rods ready for insertion (12).

22.2 Against (b), the strongest protection is a double one, an operating routine used in association with triplicated (at least) control systems (13). The routine can only be applied if the control system has three or more channels, each performing the same function and operating in parallel, such that remedial action results if any two or more channels demand it. The principle is to test the sensitivity and complete functioning of each individual channel on a regular routine without shutting down the reactor. If such tests reveal faults then the tests must be made more frequent, so that the chance of a faulty and unsafe condition existing in all but one of the channels at the same time becomes negligibly small. If no faults are found in many tests, the routine may be made less frequent.

22.3 Against (c) the double principle described to counteract (b) is effective. In addition we have appreciated the valuable part played by water in preventing the spread of radioactive iodine and strontium in the NRX accident. This leads us to exploit water dousing and flooding systems, at all effective points from the fuel itself to any escaping steam or gases. To hold back this safety water supply, a gas-pressure system may be used similar to the gas-balance system used to hold up the moderator in the NPD reactor. Such a system may be specially convenient for gas-cooled reactors.

23. In pursuing this research and development programme directed towards low-cost power, we have taken advantage of the facilities

afforded by the heavy-water reactors at Chalk River to explore and develop techniques that are likely to prove valuable. Examples of successful developments are presented in other papers to this conference and I would draw attention to the relatively cheap and hazard-free fabrication of Pu-Al alloy fuel elements described in paper 191, to monitoring and analysis techniques for heavy water in paper 188, to a fission-product disposal technique in paper 195, the applications of activation analysis in paper 189, studies on the effects of irradiation on steels and irons in paper 190, health and safety experience in papers 184 and 220, and in mines in paper 219. All of these promise to be directly helpful steps towards nuclear power.

24. In conclusion we may consider what the total requirements of heavy water and uranium would be to support an expanding large-scale power programme. The tables show two scales of programme, one that might meet the demand in Canada and one for a larger demand such as may arise elsewhere.

Table 2.

Power System to meet Possible Demand in Canada
based on Heavy-Water Natural-Uranium Reactors
without Recycling

Capacity and Material Requirement

Year	Installed Capacity MkW	Inventory Natural U tonnes	Annual Make-up Natural U tonnes	Inventory Heavy Water tonnes
1966	0.2 - 1.0	90 - 450	30 - 150	170 - 850
1971	0.6 - 1.7	270 - 765	90 - 250	510 - 1445
1976	2.0 - 3.3	900 - 1485	300 - 500	1700 - 2810
1981	4.0 - 7.0	1800 - 3150	600 - 1050	3400 - 5950

Table 3.

Large System
based on Heavy-Water Natural-Uranium Reactors
without Recycling

Capacity and Material Requirement

Year	Installed Capacity MkW	Inventory Natural U tonnes	Annual Make-up Natural U tonnes	Inventory Heavy Water tonnes
1975	100	45,000	15,000	85,000
1985	200	90,000	30,000	170,000
1995	400	180,000	60,000	340,000
2005	800	360,000	120,000	680,000

25. Similar tables were presented (1) at the first conference and also tables of prospective investments in dollars. These latter tend to be misleading and it seems better to remember the specific costs now foreseen per kilowatt of generating capacity given in Table 1 above and to note that improved techniques should lower the costs.

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Other references will be found in the quoted Canadian papers to this Conference, namely papers A/CONF. 15/P/184, 185, 187-195, 201-213, 219-230, 1704.