chance for success, it is necessary to enlist the enthusiastic cooperation of appropriate villagers. This means villagers must be involved in selecting the village task to be energized, in selecting the technology, and in determining what village institutions should be responsible for its maintenance and use.

The subject of finding renewable energy sources for Third World rural areas is not just a matter of humanitarian concern for those people. It may directly affect the availability of world energy supplies. Third World rural areas are not significant commercial energy users at present. However, influential leaders in the international community have set a target of eliminating the worst aspects of absolute poverty by the end of the century. The Overseas Development Council has examined the energy consumption of the 25 developing countries that have largely achieved this target to gauge what might happen to energy demand if all developing countries were to do so. Three preliminary important conclusions appear warranted. First, those nations (such as Brazil and Mexico) that have emphasized growth alone are relatively much higher per capita energy users than those countries (such as Taiwan) that have pushed growth with equitable distribution of incomes, or those (such as Sri Lanka) that have focused exclusively on equitable income distribution and have not made such headway on growth. Second, even if all Third World countries follow the relatively energy efficient growth with equity strategy, the goals of eliminating the worst aspects of absolute poverty cannot be met without imposing a claim on world oil resources larger than world oil production will permit. Third, therefore these development goals can only be met if nonpetroleum sources of energy are made available to these rural areas. Under these circumstances, exploring the use of small-scale renewable sources of energy appears to be an attractive path.

References and Notes

1. V. Smil, *Bull. At. Sci.* **23** (No. 2), 25 (1977).
2. The U.S. team, in addition to the authors of this article, included Dr. J. R. Williams, associate dean for research, College of Engineering at the Georgia Institute of Technology; Dr. T. Lawand, director of field operations of the Brace Research Institute, McGill University, Montreal, Canada; Dr. B. Williams, director of the Energy Systems Research Laboratory of R.C.A.; and Dr. P. Reining, Office of International Science of the AAAS. The Tanzanian participants included representatives from the sponsoring council, the Prime Minister's office, relevant ministries and interested organizations, and the University of Dar es Salaam.
3. Calculations such as those in the following pages will be included in a forthcoming NAS publication on the proceedings of the workshop. Although these calculations are based on the work done at the NAS workshop, the particular numbers in this article are those of the authors and have not been checked yet with other members of the workshop.
4. The rate is 0.93 shilling per kilowatt hour. Actually the rate is graduated according to the amount used. The exchange rate is approximately U.S. $1 = 8.2 shillings.
5. The estimates made by the panel for the renewable resource technologies aimed at producing electricity as well as for diesel did not include the cost of power distribution in the village. Such costs are treated in the discussion of extending grid to the villages.
6. In view of the uncertainities in the cost estimates, all numbers are given only to two significant figures.
7. World Meteorological Organization, average of data for June 1966.
8. In this analysis, and those to follow, the cost of generating electricity is compared with the current price to the consumer. The principal justification for this approach is the assumption that the communal nature of the Ujamaa villages lends itself to eventual communal ownership of the generating system—hence the important datum for the villagers is the energy cost.
9. National Academy of Sciences, *Energy for Rural Development* (National Academy of Science, Washington, D.C., 1976). See "Hydropower" in part 2, *"Indirect Uses of Solar Energy,"* for a discussion of the growing use of small-scale hydroelectricity in the People's Republic of China.
10. Tanzanian participants thought that this was reasonable since village labor and materials would be volunteered and hence would not need to be included in the funds budgeted for the project. In a similar situation, techniques in which local labor and materials were used to construct dams and penstocks for installations capable of producing power in tens of kilowatts have been developed in Colombia at the Centro de Desarrollo Integrado "Las Gaviotas."
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12. P. S. Mhina, "A brief description of manufacture and utilization of gobar gas in Tanzania," presented as a Seminar on Appropriate Technology in Small-Scale Industries, 15 to 17 December 1976, Dar es Salaam Technical College [Small Industries Development Organization (SIDO), Box 2476, Dar es Salaam]; A. Mzee, *Pilot Project on Utilization of Gobar Gas in Small I.C. Engines* [Ministry of Water, Energy and Minerals, P.O. Box 9153, Dar es Salaam, Tanzania (1977)].
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The CANDU Reactor System: An Appropriate Technology

CANDU combines a proved reactor, a simple industry, and outstanding potential for resource conservation.

J. A. L. Robertson

The Canadian CANDU (Canada Deuterium Uranium) power reactor does not fit easily into categories of U.S. reactors. Pickering nuclear generating station, which is operated by Ontario Hydro and consists of four 500-megawatt (electric) CANDU reactors, has produced more electricity than any other nuclear generating station, at roughly half the cost of electricity from the available alternative, a coal-fired plant. CANDU reactors are therefore "currently commercial," and comparable to the U.S. light-water reactors. In the United States, however, heavy-water reactors, along with molten-salt and high-temperature reactors, are usually considered as "advanced" because of their low uranium consumption. Neither description does the CANDU reactor full justice. Good neutron economy gives CANDU reactors the ability to operate on a thorium fuel cycle at, or near, breeding. This means that the energy costs are virtually independent of the fuel supply cost, making CANDU comparable to the fast breeder reactor. As a commercially proved reactor able to adapt to changing circumstances, CANDU has a useful role to play in the world's future energy supply.

To a physicist, the essence of a CANDU reactor is its use of heavy water as the moderator. In any thermal reactor the moderator must slow down neutrons efficiently while capturing as few as possible. Both requirements are factored into a figure of merit called the moderating ratio. Table 1 shows how heavy water stands out from other potential materials. To an engineer, pressure tubes are

The author is assistant to the general manager, Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J 1J0.

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Summary. CANDU power reactors are characterized by the combination of heavy water as moderator and pressure tubes to contain the fuel and coolant. Their excellent neutron economy provides the simplicity and low costs of once-through natural-uranium fueling. Future benefits include the prospect of a near-breeder thorium fuel cycle to provide security of fuel supply without the need to develop a new reactor such as the fast breeder. These and other features make the CANDU system an appropriate technology for countries, like Canada, of intermediate economic and industrial capacity.

the major distinguishing feature of a CANDU reactor. In light-water reactors (Fig. 1) there is no distinction between moderator and coolant, and the core is contained within a large, thick-walled pressure vessel. The CANDU moderator, essentially unpressurized and cool, is contained in a reactor vessel (calandria) through which pass some hundreds of identical pressure tubes containing the fuel and coolant. Each tube, made of a zirconium alloy, is about 6 meters long and 10 centimeters in diameter and has a wall 4 millimeters thick.

The pressure-tube design facilitates on-power fueling, achieved by mobile machines which connect to opposite ends of the pressure tube to be fueled [a diagram of the fueling machines, together with further details of CANDU reactors, is provided by Haywood (*1*)]. On-power fueling minimizes the inventory of neutron-absorbing fission products. Heavy water, on-power fueling, and constant attention to neutron economy at all stages of design enable CANDU reactors to enjoy the economies of natural uranium fuel now and the prospect of a near-breeder thorium fuel cycle for the future.

Other attractive features result from these primary characteristics.

1) The use of natural uranium in a very simple fuel design (Fig. 2) provides exceptionally low fueling costs.

2) On-power fueling contributes to a high net capacity factor (the energy actually delivered in a particular period divided by the energy delivered if the unit had operated continuously at its maximum rated output) by eliminating the need for fuel changing during reactor shutdowns.

3) Any fuel assembly that develops a leak during operation can be traced to a particular pressure tube, and even to its position in that tube. On-power fueling allows the leaking assembly to be removed before it can release significant radioactivity to the coolant.

4) The separation of coolant and moderator means that their chemistries can be independently optimized. Specifically, neutron poisons can be added to the moderator to control or shut down the reactor without jeopardizing the corrosion control of the primary coolant circuit.

5) The separate moderator at relatively low temperatures constitutes a very large heat sink capable of absorbing any energy that might be released in postulated accidents. It also facilitates the design of control and shutdown devices.

History

The selection of reactor types for national power systems is not determined by physics alone. The United States, Britain, and Canada cooperated in the wartime development of atomic energy, and all three were aware of the merits of heavy water as a moderator. Indeed, all three have had development programs for heavy-water power reactors, but only Canada has pursued the concept to the commercial stage. History shows why.

Naval propulsion was the first application of nuclear power in the United States. Minimum physical size was the dominant criterion and light-water reactors were a reasonable choice. Enriched fuel was available from diffusion plants built during the war, and construction of the large pressure vessels was within U.S. industrial capability. In Britain the first application was to plutonium-production reactors for a weapons program. Again, long-term economy was not the primary criterion, and gas-graphite reactors were a reasonable choice. In the early 1950's, when both countries recognized an early need for civilian nuclear power, these two reactor types had the tremendous advantages of demonstrated engineering viability and established industrial infrastructure.

In postwar Canada, abundant hydroelectric resources postponed the need for nuclear power and provided a tough economic challenge. (Even in 1977 domestic customers in some parts of Canada pay as little as 2 cents per kilowatt-hour.) The widespread use of hydroelectricity had accustomed Canadian utilities to capital-intensive plants with very low operating costs. It was recognized that a low fueling cost would be crucial to the success of a reactor and that neutron economy was the key (*2*). Heavy water was therefore the first choice for the moderator when Canada began civilian power reactor studies in the middle 1950's. The choice was reinforced by two practical factors: good experience with the heavy water–moderated NRX research reactor (*3*) and successful operation of heavy-water production plants in the United States. These two factors, incidentally, illustrate the mutual benefits of early U.S.–Canadian collaboration. The design of the Savannah River production reactors drew heavily on NRX experience, while the development of the process to supply heavy water to the production reactors helped the Canadian program.

The initial design of our first, 20-MWe, nuclear power demonstration (NPD) reactor (*4*) was similar to that of a light-water reactor. Since scaling up would be limited by the industrial capacity for fabricating large pressure vessels, the advantages of a modular pressure-tube design were becoming apparent. The development of Zircaloy-2 by the U.S. Bettis Laboratory in Pittsburgh, made this concept practicable. Even so, the designers would probably not have had the confidence necessary to base a reactor design on Zircaloy-2 had not Bettis workers been testing the material in NRX as part of a collaborative program. This same collaboration also contributed greatly to an early selection by both groups of uranium dioxide and Zircaloy as fuel and cladding materials, respectively.

The NRX reactor and later the NRU (*5*) and WR-1 (*6*) research reactors played a vital role. Their outstanding capabilities for testing fuel and structural materials have attracted U.S. groups, as well as some from other countries, to conduct development programs. Full-size CANDU fuel bundles can be tested under realistic operating conditions in actual pressure tubes in these experimental reactors.

Operating Experience

The NPD reactor, in operation since 1962, demonstrated the engineering viability of the CANDU design, especially the concept of on-power fueling, which had not previously been attempted for a water-cooled power reactor. Its net capacity factor has exceeded 90 percent for the past 3 years, despite its use to train utility staff and as a test-bed for new fuel designs and other reactor equipment. If NPD's good operation failed to alert the designers to possible problems, the same cannot be said of the 200-MWe Douglas Point prototype reactor (7), which began operation in 1967. Douglas Point's performance has improved substantially over the years, but its greatest contribution, as befits a prototype, has been to identify design and operational improvements for future reactors.

The Douglas Point experience contributed greatly to the exceptionally smooth commissioning of the four Pickering reactors (8) between February 1971 and June 1973. The Pickering net capacity factor to July 1977 has averaged 78 percent; during the last fiscal year (April 1976 to March 1977) all four units exceeded 90 percent and were in the top five of an international table of 67 reactors of comparable size ranked by capacity factor (9).

The fuel for all CANDU reactors consists of short (50 cm) bundles of Zircaloy tubes containing uranium dioxide pellets (Fig. 2). The simplicity of the design and the use of natural uranium result in exceptionally low fuel supply costs. Although the design burnup (energy produced per unit mass of fuel discharged) is much lower than for light-water reactors, the resulting fueling costs (fuel cost per unit of energy produced) are less than half those for any other nuclear station in North America. Pickering's fueling costs have varied from 0.9 mill/kWh in 1973 to 1.2 mill/kWh in 1976 (10, 11). The near-continuous fueling of CANDU reactors serves as a coarse reactivity control and allows the burnup to be measured to a high accuracy (Fig. 3), confirming design estimates (12).

The high capacity factors are partly due to good fuel performance. Of more than 84,000 bundles irradiated at Pickering, less than 0.03 percent have exhibited any leaks (11). In 1971, observation of a slightly higher than average failure rate for Douglas Point fuel led to the identification of a new failure mechanism—and the means of controlling it (13). When a fuel bundle that has had prolonged exposure at low power is subjected to a sudden increase in power its Zircaloy cladding is liable to fail by stress corrosion cracking. This mechanism was responsible for the failure of about 100 bundles in the first Pickering unit to operate, during its first year. Since the introduction of remedial measures in 1972, only about 20 bundles have failed in all four units.

Another common cause of reactor incapacity, boiler leaks, has had very little effect on CANDU reactors. In nearly 50 reactor-years of operation only five tubes have leaked, one each at NPD, Pickering, and Bruce, and two at Douglas Point (14). No failures have been attributed to corrosion, probably because of selection of appropriate materials combined with careful control of the water chemistry on both primary and secondary sides of the boilers. Before the most recent boiler-tube failure at Pickering in 1974, a method for rapidly locating and plugging a leaking tube had been developed; this leak was fixed during a reactor shutdown lasting only 5 days.

Table 1. Merit ratings of potential moderators.

Material	Moderating ratio
Zirconium hydride	49
Organic liquids	60-90
Light water	72
Beryllium	159
Graphite	160
Beryllium oxide	190
Heavy water	
Pure	12,000
99.8 atom percent	2,300

The single most important cause of incapacity at Pickering was an installation error that led to the development of cracks in some of the pressure tubes of two of the reactors. These cracks did not prejudice the safety of the reactors, and there was never any risk to the public or the operating staff from the resulting coolant leaks, which were contained and collected within the reactor vaults. The cost of replacing 69 pressure tubes, including the cost of supplying energy from an alternative source during repairs, amounted to \$75 million. Even after these costs are debited, operation of the Pickering station resulted in a net saving for the utility's customers during the period in question. (During 1976 the saving exceeded \$100 million.) The investigation of the cracking (15) provided not only an immediate remedy to prevent further cracks but also a much better understanding of the process used to roll pressure tubes into end fittings, thereby providing improved techniques for the future.

The demonstrated ability to replace the NRX and NRU calandrias (16) and Pickering pressure tubes provides confidence that even the most radioactive parts of CANDU reactors can be repaired, if necessary.

Other Distinctive Features

The design, construction, and operation of CANDU reactors have other distinctive features.

1) At present, the Pickering station consists of four identical reactor-turbine-generator units, each of which operates independently; a second group of four units is now under construction at the same site (Fig. 4). The multi-unit design has proved most effective in saving costs and in preventing delays in construction and commissioning (8). The period from first critical to full power progressively decreased from 95 days for the first unit to 12 days for the fourth.

2) The design of the reactor and associated equipment was undertaken by the federal agency Atomic Energy of Canada Limited, while the design of the remainder of the plant, the project management, and the on-site construction were the responsibility of the provincial, publicly owned utility, Ontario Hydro. This arrangement exploited the com-

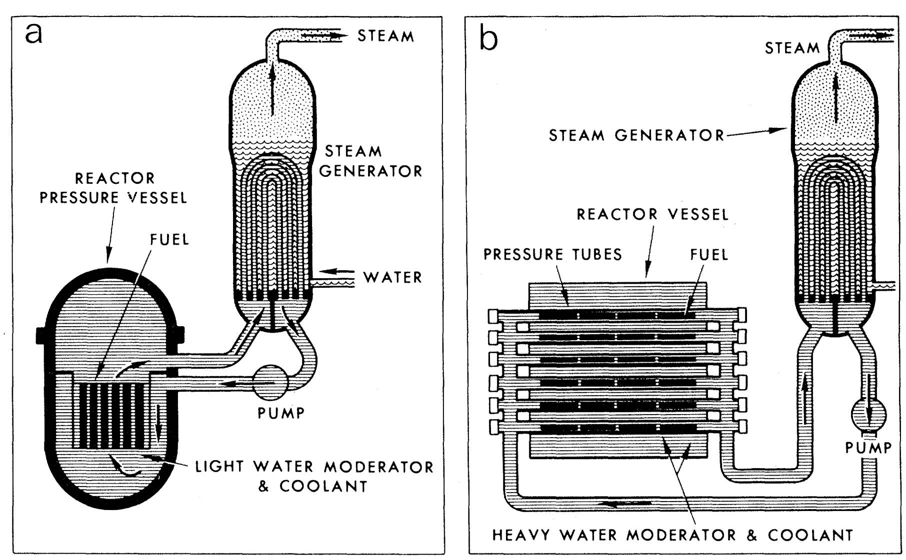


Fig. 1. Schematic diagrams of (a) a light water-cooled, pressure-vessel reactor and (b) a heavy water-cooled, pressure-tube reactor.

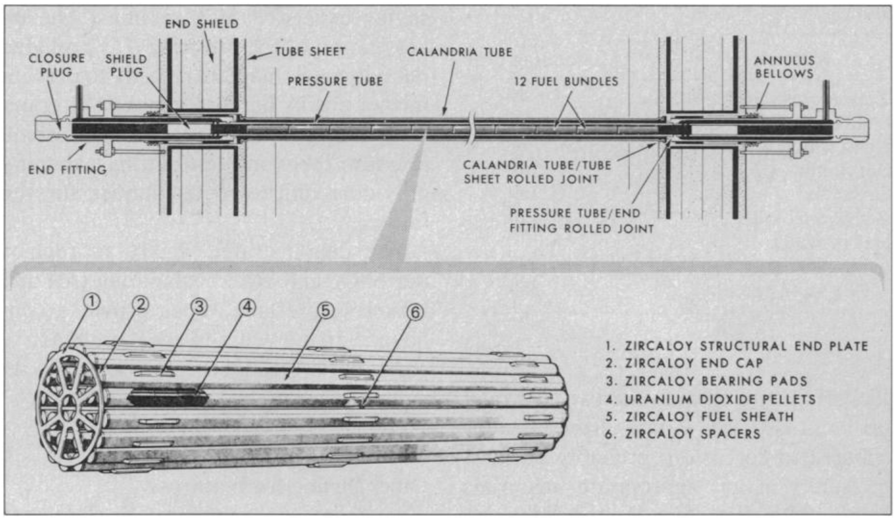


Fig. 2. Individual fuel channel and fuel bundle.

plementary expertise and experience of the two organizations. Although completion of units 1 and 2 was late by a few months according to the original schedule set at the start of construction, units 3 and 4 were completed within schedule (*8*).

3) While each reactor is within its own containment building, the multi-unit design features a negative-pressure containment system that minimizes stresses in the containment building in the event of a loss-of-coolant accident. The four containment buildings are connected through a pressure relief duct to a large vacuum building (Fig. 4) normally held at about 10 kilopascals, which contains a pressure-actuated dousing system for pressure suppression. The same vacuum building will serve the four additional reactors now under construction.

4) The vacuum building, with a 1-m-thick concrete wall, was poured by a slip-form method in 7½ days of continuous pouring. The method has subsequently been further developed for reactor buildings, with the formwork of the roof dome being assembled at ground level and raised with the forms (*9*).

5) CANDU reactors pioneered the use of direct computer control. The operative computer is monitored and backed up by an identical standby computer; if both fail the reactor is shut down automatically.

6) As a result of a strong incentive to prevent leaks of valuable heavy water, significant improvements have been made in "conventional" equipment. As an example, packed-stem valves have been modified so that the packing is maintained in compression by spring-loading (*17*). This very simple modification greatly reduces leakage and thereby minimizes maintenance requirements in areas with high radiation fields.

7) Measures to minimize losses of heavy water also prevent radioactive releases. As a result the present situation is satisfactory; releases from the Pickering station (*18*) have been within the design target of 1 percent of the regulatory requirements based on recommendations of the International Commission on Radiological Protection.

8) Radiation fields that impede maintenance are mostly due to corrosion products in the primary coolant circuit that have been activated in the reactor and subsequently deposited on out-reactor components such as the boilers. Several methods for controlling and reducing these fields without the necessity of removing the fuel or draining the coolant have been investigated (*19*). The most attractive is a mild chemical process in which the cleaning agents are continuously regenerated and the radioactivity is removed in solid form rather than as bulky acid solutions. In 1971 and 1972, fields (behind shielding) at the Douglas Point reactor were reduced sixfold by simple changes in physical and chemical conditions of the coolant, and were subsequently maintained at the reduced level. More recently, the chemical cleaning process was applied during a 3-day shutdown of the reactor to reduce fields in certain areas by a further factor of 6.

9) Exposure to tritium generated in the heavy water of the moderator and coolant is a possible impediment to maintenance work. A new process, combined electrolysis and catalytic exchange (CECE), offers great promise for removing tritium from heavy water and also for upgrading heavy water that contains traces of light water (*20*).

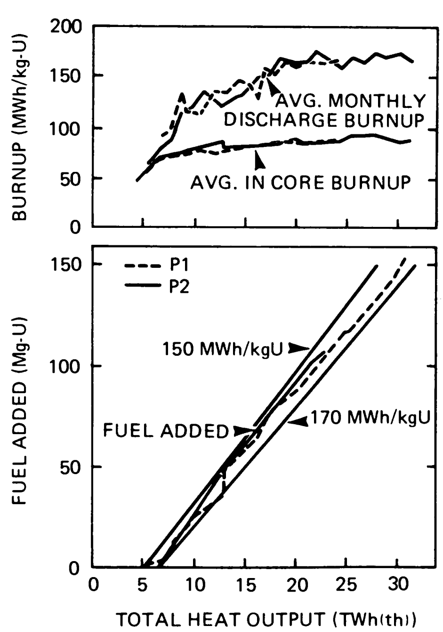


Fig. 3. Fuel consumption and burnup for Pickering units 1 and 2 (*12*).

An Appropriate Technology

The CANDU reactor system is appropriate for countries of intermediate economic and industrial capacity, such as Canada. Producing heavy water is basically simpler than enriching uranium, and commercial heavy-water plants have been built in smaller sizes than would have been possible for uranium enrichment plants.

Serious problems were, nevertheless, encountered in developing a Canadian heavy-water industry (*21*). Perhaps because the process used—countercurrent exchange between liquid water and gaseous hydrogen sulfide—had operated well in U.S. plants, the difficulties of transferring the technology to Canada were underestimated. However, Ontario Hydro's Bruce heavy-water plant has been operating well since 1974, and by 1983, when all plants now under construction are expected to be in full operation, Canada will have a capacity sufficient to support a CANDU installation rate of 3000 MWe per annum. In developing its heavy-water industry Canada has introduced the first application of isotope separation under commercial conditions.

The use of natural uranium facilitated the establishment of a domestic fuel industry, while the short bundles and relatively low burnup allowed volume production at an early stage. Similarly, the production of several hundred pressure tubes, with associated end fittings and calandria tubes, is better suited to Canadian industry than would be the fabrication of a single large pressure vessel. The CANDU calandria is as large as a light-water reactor's pressure vessel but, not having to withstand high pressures, its structure is much simpler and it can be manufactured in Canada. Indeed, about 80 percent of each CANDU generating station can be made in Canada (*22*).

Commercialization of the CANDU reactor system has been achieved at a cost between $1 billion and $2 billion, including demonstration plants. This sum compares favorably with those for other systems, including what has already been spent on fast breeder reactors.

Future Developments

All CANDU reactors, including those under construction and committed, are listed in Table 2. The first three units of the Bruce station are operating, while the fourth is due to be commissioned in early 1979. The present installed nuclear capacity in Canada of roughly 4000 MWe approximates Ontario Hydro's total electrical capacity in 1954, when development of the CANDU system began.

The separation of moderator and coolant offers scope for future developments, while still preserving the essential characteristics of the design. An organic liquid could replace heavy water as the coolant. This would allow higher operating temperatures, and hence higher efficiency, as well as some other advantages. Also, the temperatures would then be high enough to provide high-pressure steam for extracting oil from tar sands and heavy-oil deposits (*23*).

The technical feasibility of an organic-cooled CANDU reactor has been demonstrated by the WR-1 (*6*) research reactor, which has been operating very successfully at the Whiteshell Nuclear Research Establishment in Manitoba since 1965. Much more work on an engineering scale would be needed to make this modification of the CANDU reactor commercially available.

Another possibility is using ordinary light water as coolant, taking the coolant direct to the turbine without an intermediate boiler. The greatest attraction of this approach is that it would mean an appreciable reduction in capital costs at a time when all energy projects are straining capital resources. The technical feasibility of using a light-water coolant in a direct steam cycle has been demonstrated, this time by a prototype reactor at Gentilly in Quebec (*24*).

Despite the prospect of lower costs from the use of alternative coolants, the excellent performance of the Pickering station is likely to make utilities reluctant to change from the heavy-water coolant. Some total unit energy costs (*25*) estimated by Ontario Hydro (Fig. 5) illustrate several significant points. First, oil is just too expensive to compete, apart from any question of its future availability. Second, the Pickering A nuclear generating station and the Lambton coal-fired plant are both four-unit stations of the same capacity and were built at the same time, so they are closely comparable. Recently, the energy costs from Pickering have been about half those from Lambton. Third, a comparison of pairs of nuclear stations, such as Pickering A with Pickering B and Bruce A with Bruce B, shows an annual capital cost escalation rate of about 13 percent, which may cause concern but which is not out of line with other major construction projects. Fourth, because the capital component dominates nuclear energy costs, future increases in fuel costs are likely to have much less effect on nuclear than fossil-fired plants. Projections such as this lead to the expectation that up to half of Canada's electricity can be supplied by nuclear energy by the end of the century, using CANDU reactors of basically the present design.

Fuel Supply

Canada is well endowed with uranium, and present reserves, amounting to about one-quarter of total world reserves (exluding the Soviet bloc, for which data are not available), would be sufficient to satisfy domestic demand well into the next century. However, an increasing worldwide dependence on nuclear energy as oil and gas supplies dwindle has put increasing pressure on Canada to export uranium; the pressure is likely to in-

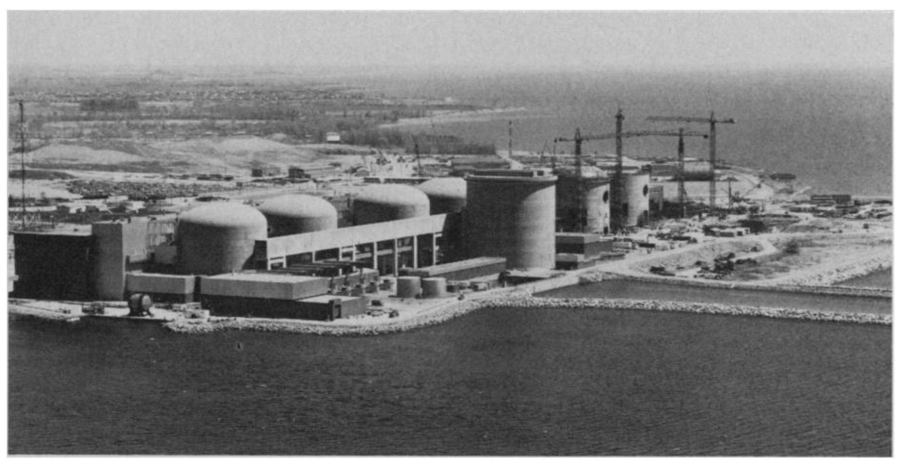


Fig. 4. Two of the four reactor buildings for the Pickering B station under construction next to Pickering A. (The single, large, cylindrical building in the foreground is the vacuum building.)

Table 2. CANDU reactors in operation, under construction, committed, and planned.

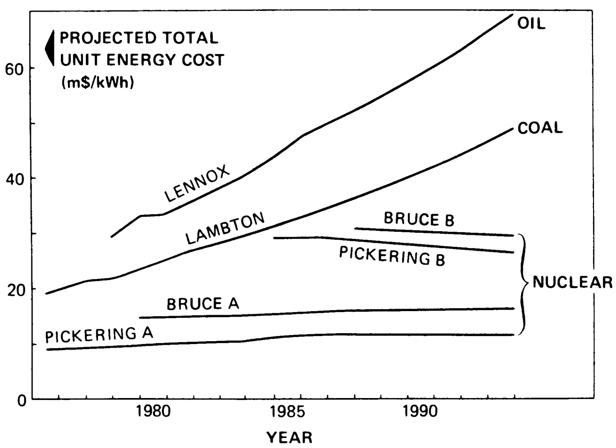
Name*	Location	Power (MWe net)	Nuclear designer†	Date of first power
NPD	Ontario	22	AECL and CGE	1962
Douglas Point	Ontario	208	AECL	1967
Pickering A	Ontario	514 × 4	AECL	1971-1973
Gentilly 1	Quebec	250	AECL	1971
KANUPP	Pakistan	125	CGE	1971
RAPP 1	India	203	AECL	1972
RAPP 2	India	203	AECL	
Bruce A	Ontario	745 × 4	AECL	1976-1979
Gentilly 2	Quebec	600	AECL	1979
Point Lepreau	New Brunswick	600	AECL	1980
Cordoba	Argentina	600	AECL	1980
Pickering B	Ontario	514 × 4	AECL	1981-1983
Wolsung 1	Korea	600	AECL	1981
Bruce B	Ontario	750 × 4	AECL	1983-1986
Darlington	Ontario	800 × 4	AECL	1986-1988
		Total 16,703		

*NPD, Nuclear Power Demonstration; KANUPP, Karachi Nuclear Power Project; RAPP, Rajasthan Atomic Power Project. †AECL, Atomic Energy of Canada Limited; CGE, Canadian General Electric Company Limited.

crease if the introduction of fast breeder reactors in other countries is delayed. To protect domestic interests while recognizing international obligations, the Canadian government announced a uranium policy in 1974. Canadian utilities are assured of at least a 30-year reserve of uranium for all existing, committed, and planned reactors in any 10-year forward period. In return, the utilities must maintain supply contracts for a 15-year forward period, to provide market stability for uranium producers. These arrangements should provide utilities and producers with the confidence needed to make major investment decisions.

From the start, the fueling of CANDU reactors has been based on a once-through fuel "cycle." The prospect of recycling spent fuel, when required to conserve uranium supplies, has always been envisaged, but there is no incentive to do so until it is shown to be economically attractive under conditions that are demonstrated to be safe. The present simplest possible fuel cycle, which does not depend on fuel reprocessing, is likely to be retained as long as uranium remains plentiful and relatively cheap. Thus the Canadian program is much less immediately affected than many others by recent calls for reassessment of fuel reprocessing.

Internationally, there is considerable uncertainty over how much economically recoverable uranium will be discovered during the next few decades and how rapidly production facilities will be installed. There can be little argument that the availability of fuel cycles more conserving of uranium would be welcome, provided that they can be shown to be acceptable on grounds of safety and security. Their availability would contribute to the world energy supply, to the security of the national supply, and to the confidence needed for utilities to commit future plants to nuclear fuel and hence save scarce fossil fuels. The good neutron economy of CANDU reactors permits them to exploit a thorium fuel cycle that is exceptionally efficient in its use of nuclear fuel (*26*). This ability to switch when necessary to a more con-



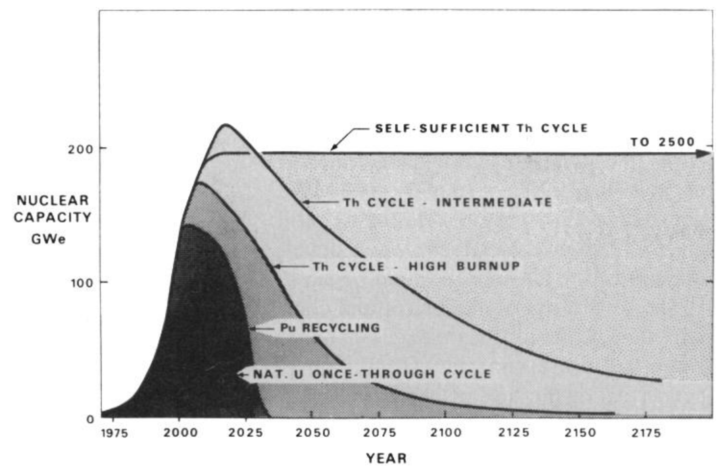


Fig. 5 (left). Projected costs of power from three different fuels (*25*). Fig. 6 (right). Energy that could be obtained from 3×10^5 megagrams of uranium with various CANDU cycles, to illustrate the degree of resource extension possible (*10*).

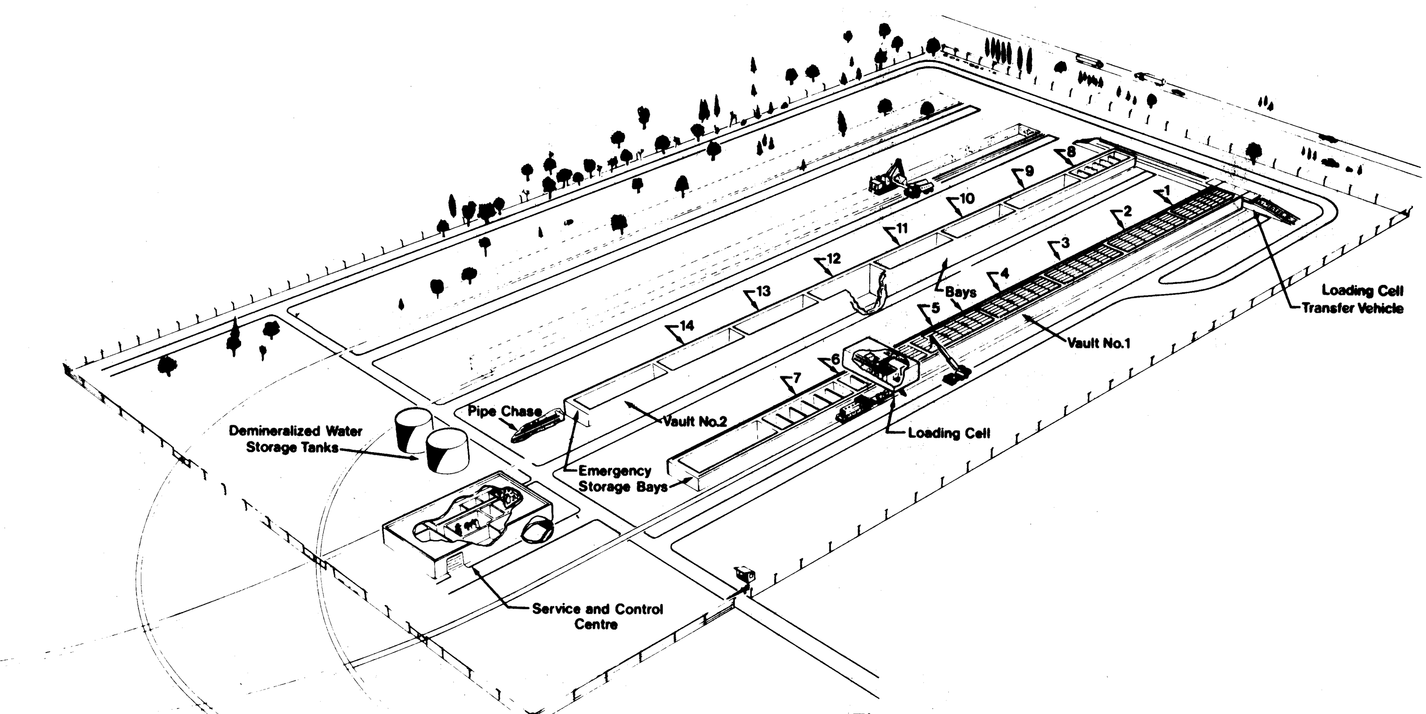


Fig. 7. Possible design for underwater storage of spent fuel.

serving fuel cycle without having to develop a completely new reactor system, such as the fast breeder, is another very attractive feature of the CANDU reactor system.

Current estimates indicate that a "self-sufficient thorium cycle" may be practicable in CANDU with only minimal modifications. At equilibrium, this cycle would require no further uranium and only small amounts of thorium, which is at least three times as abundant globally as uranium. Uranium required to initiate the cycle does not have to be maintained as virgin uranium but can be in the form of spent CANDU fuel. The fast reactor fuel cycle is similar in this respect, and even the amount of uranium needed, 1 to 2 megagrams per electrical megawatt of installed capacity, is roughly the same. Figure 6 illustrates the energy available from various fuel cycles in CANDU reactors, and demonstrates the very large extension in fuel resources possible by switching from the present natural-uranium, once-through cycle to the self-sufficient thorium fuel cycle.

"Electronuclear breeding," the conversion of fertile to fissile material by use of electric power, is of special interest to neutron-economic reactors such as CANDU, where small increases in fissile content can yield disproportionate savings in fuel consumption. The proposed "fusion-fission symbiosis" is probably the best-known example of electronuclear breeding, but it is at least arguable that the spallation process can be applied to produce neutrons and hence fissile material before fusion is available (*27*). Spallation has the obvious advantage that its scientific feasibility has been demonstrated, and demonstration of its engineering feasibility looks promising. In Canada, a relatively small effort has been devoted to spallation for several years, and recently there have been signs of increasing interest in the United States (*28*). Considering the magnitude of the undertaking and the long-term nature of the objective, this subject seems ripe for international cooperation.

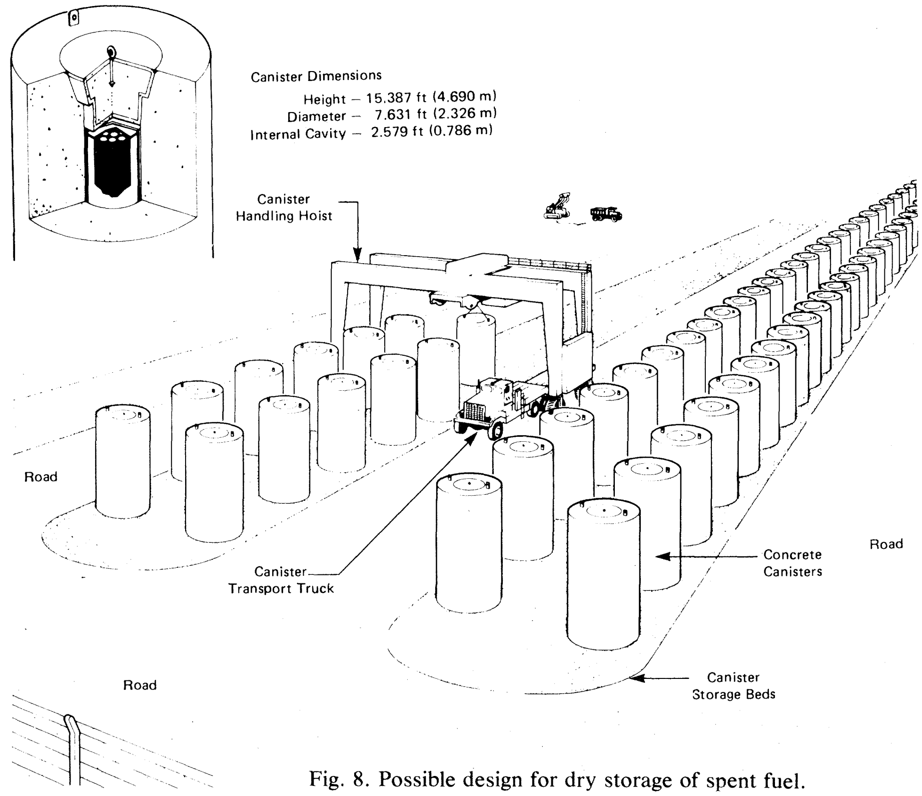


Fig. 8. Possible design for dry storage of spent fuel.

Nuclear Waste Management

The management of nuclear wastes is a subject in which international cooperation is already very effective. Canada's program (*29*) is basically similar to that of most other countries, but has some aspects that usefully complement other programs. Since the CANDU system has assumed once-through fueling from the start, there is underwater storage at each station for 5 to 10 years of spent fuel. A centralized, interim facility for storing spent CANDU fuel safely and securely for periods up to a century is now being considered. The options include underwater storage (Fig. 7), as used at present, or the more passive dry storage. Figure 8 illustrates the concrete canister concept for dry storage: four such canisters are already on test, two with electric heaters and two with spent fuel. Whichever design is adopted, the land requirement is insignificant—5 square kilometers or less—for all Canadian spent fuel expected to the end of this century.

For the permanent disposal of nuclear wastes many countries are considering mined depositories deep underground in stable, dry geologic formations. The Canadian program includes examination of salt deposits, the formation currently favored in the United States, but is devoting more effort to mined cavities in certain granitic, mineralization-free structures that are widespread in the Canadian Shield, which constitutes much of Canada's land mass. The expectation is that both types of formation will prove acceptable, and the world as a whole can only benefit from having a choice.

Canada, in common with other countries, expects to immobilize the wastes in a highly insoluble solid before disposing of them permanently. In 1960, representative separated fission products were dissolved in glass blocks, 50 of which were buried in loose sand below the water table in a controlled area of the Chalk River Nuclear Laboratories (*29*). Monitoring of the very small amounts of radioisotopes in downstream groundwater shows that the blocks are dissolving more slowly than the contained radioactivity is decaying. Similar work is required on other compositions and under other conditions, but these results indicate the potential of this approach to immobilizing the wastes.

The overall objective of the waste management program is to provide safe storage of spent fuel until society determines whether the large amount of latent energy it contains should be exploited through fuel recycling. Methods are being developed and will be demonstrated for the permanent disposal of either the separated wastes or the unprocessed fuel. Parallel work will establish the economics and acceptability of fuel recycling, information that will be needed for reaching a sound decision on the disposition of spent fuel.

International Aspects

The present CANDU fuel cycle, without uranium enrichment or spent fuel reprocessing, is virtually impregnable to any terrorist group seeking to acquire fissile material. If fuel recycling were introduced some increased protection would be advisable, but there would be no need for shipment or stocks of separated fissile material. Any fuel for CANDU reactors, either before or after recycling, would still be very dilute in fissile content, around the 1 percent level. Thus several factors of concern to critics of fast breeder reactors would remain absent from the CANDU fuel cycle.

The absence of enrichment and reprocessing simplifies the international safeguarding of the CANDU system, but the reactor's capability for continuous on-power fueling offsets that advantage. However, techniques and instrumentation for safeguarding CANDU reactors to International Atomic Energy Agency requirements have been developed and are being demonstrated (*30*). A thorough study (*31*) argues that CANDU reactors are no more likely than light-water reactors to be used for the clandestine production of weapons material, while other studies (*32*) have shown that no power reactors are likely to be so misused.

Table 2 includes CANDU reactors that are in operation or under construction outside Canada. Canadian government policy is that nuclear materials and equipment may be exported only to countries that accept full-scope international safeguards. Canada is also participating in the current International Nuclear Fuel Cycle Evaluation, resulting from the seven-nation summit meeting in London in May 1977, to review over a 2-year period methods by which the proliferation of nuclear weapons capability can be impeded without jeopardizing the role that nuclear power can play as a secure source of energy worldwide.

Establishing confidence in international safeguards and associated political measures is of the utmost importance in making available to the world the benefits of nuclear energy. Assuming a successful outcome, the CANDU system has a useful contribution to offer. The major industrialized countries are unlikely to adopt CANDU reactors with once-through fueling, if only because of their massive investment of capital and experience in the infrastructure for their existing systems. However, a growing number of less industrialized countries are beginning to turn to nuclear energy as supplies of fossil fuels dwindle. These countries could well see in the CANDU system the attractive features that have made it an appropriate technology for Canada. The two systems would complement each other in their use of the world's fuel resources. The light-water reactors, leading to fast breeder reactors, could eventually convert and use the world's uranium, while CANDU reactors are capable of extending these resources to include the even more abundant thorium. During the period of once-through fueling, the existence of CANDU reactors with their greater fuel economy will help to reduce the pressure on uranium supplies.

For the longer-term future it is reassuring to have available two distinct systems, each dependent on a different resource base, either of which is capable of supplying the world's energy needs for many generations. Until the commercial availability of alternatives, such as the renewable energy sources or fusion, has been demonstrated, this degree of redundancy could be regarded as essential.

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