SMALL CANADIAN REACTORS FOR HEAT, ELECTRICITY, RESEARCH AND ISOTOPES

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ABSTRACT

The world's exploitation of nuclear energy has so
far been dominated by the production of electricity,
using base-load plants having one or more reactors,
each with an installed capacity of anywhere from
about 100 to 1300 MW of electrical output. However,
changes in energy prices and technological develop-
ments during the past fifteen years are now providing
opportunities for much smaller reactors, with up to
30 MW thermal output. Small reactors currently being
developed in Canada are well positioned to exploit
these opportunities, for the production of heat and
electricity, and for nuclear research and the pro-
duction of radioisotopes.

INTRODUCTION

Nuclear power plants are currently supplying about
15% of the world's electricity. In Canada, CANDU
power plants are supplying about 13% of the country's
(40% of Ontario's) electrical needs. By 1992, more
than 20% of Canada's (65% of Ontario's) electricity
will come from nuclear plants. Most of this electri-
city is being supplied by base-load plants with one
or more reactors, each capable of producing anywhere
from 100 to 1300 megawatts of electrical power.
These large power reactors are making an important
contribution to the world's electrical supply, and
are expected to make an even greater contribution in
the future. However, because of changes in the price
of energy supplies and technological developments
during the past fifteen years, much smaller reactors,
with up to 30 MW thermal output, are now beginning to
find application in a wide variety of areas. This
paper will describe recent developments in Canada
that are leading to a range of new small reactors for
the production of heat and electricity, and for
nuclear research and the production of radio-
isotopes.

SMALL REACTORS FOR HEAT AND ELECTRICITY

While the contribution of nuclear energy to the
world's electrical supply is substantial, its con-
tribution to the total world energy supply is still
only modest since less than 30% of the world's pri-
mary energy consumption is used to generate electri-
city. Another 30% of the world's primary energy
consumption is used as low-grade heat, mainly to heat
buildings, and this represents a large potential
market for nuclear fission energy. Another potential
market is the supply of electricity for areas remote
from electrical distribution systems. Both of these
areas represent major opportunities for small
reactors if certain economic and technical criteria
can be met. Recent developments in small reactors
described below suggest they will be able to meet
these criteria.

A major study on the use of small reactors for the
production of heat and electricity was carried out in
Canada in the mid-1960s. (1) That study identified
several potential applications for small reactors:

- industrial process heat, requiring power levels up
  to about 30 MWt

- electricity for remote mining complexes, with power
  requirements in the 5 to 30 MWe range

- electricity for small, remote villages in northern
  Canada, with power requirements in the 0.5 to
  1.0 MWe range.

Another application discussed at that time was in
rail transportation, to replace diesel locomotives.

Although the market appeared fairly large for
these various applications, small reactors could not
compete with fossil-based power sources because

- the capital cost was significantly greater than the
  competition, which was usually oil-fired diesel
  generators, and

- the operating costs were not low enough to overcome
  the capital cost differential, mainly because of
  the low cost of fossil fuels.

The conclusion reached in the study was that if
small reactors were to become competitive, the cost
of the reactor fuel would have to decrease signifi-
cantly, or there would have to be a technological
breakthrough that would enable such reactors to be
built without complex control and safety systems, and
to operate completely automatically, without
operators, something unheard of at the time.

It must be remembered that oil was only about
$3 per barrel (Can.) at that time, so the competition
was very tough. Since then the price of oil has
reached over $40 (Can.) per barrel and while it is
currently only about $25 (Can.) per barrel, some
experts predict it will reach $40 (Can.) per barrel
before the year 2000. Furthermore, the required
technological breakthrough of unattended operation
has been achieved, with the successful development
and demonstration of the SLOWPOKE reactor concept,
and it is this concept that forms the basis for the
new SLOWPOKE Energy System currently being developed
by Atomic Energy of Canada Limited (AECL).

The SLOWPOKE Energy System

The SLOWPOKE Energy System (SES) is a heat genera-
tion and distribution system based on the SLOWPOKE
heating reactor. (2) It is being developed mainly as
a source of heat, but it can also be used to generate

electricity. The system is derived from the highly successful SLOWPOKE-2 research reactor (3), a 20 kWt unit developed at the Chalk River Nuclear Laboratories (CRNL). Eight of these reactors are currently in operation, seven in Canada and one in Jamaica. They are mainly used for nuclear research and training, and have operated very reliably. The unique feature of these reactors is that they are licensed to operate unattended, with remote monitoring, for up to 72 hours at a time. Unattended operation is possible because the reactor has negative temperature and void coefficients of reactivity, limited excess reactivity and restricted access to the core by the users. Consequently, the reactor does not require an automatic shutdown system, neutron ionization chambers, or low-power startup instrumentation. The reactor is controlled automatically by a single, motor-driven absorber rod responding to a self-powered neutron detector.

Because the reactor is so simple and safe, users of the facility have been licensed as operators without formal training in reactor technology, although they must be qualified in radiation protection procedures. Reactor users do not have access to the core and are not permitted to handle the reactor's enriched uranium fuel.

The excellent operating experience with the SLOWPOKE research reactors (over 60 reactor-years) provides the foundation for the SLOWPOKE heating reactor, which is designed to operate at 10 MWt. It incorporates the key technical features of the research reactor, namely, operation at atmospheric pressure, natural-convection cooling, remote monitoring instead of an on-site operator, and unquestionable safety.

The SLOWPOKE heating reactor core consists of uranium oxide fuel elements, similar to those used in CANDU fuel bundles, but using 4.9% enriched uranium instead of natural uranium. Each fuel element is 0.5 m long and contains 0.5 kg of uranium. For an annual load factor of 50%, the fuel bundles comprising the core would be replaced every six years.

The reactor core, coolant riser duct and heat exchangers are installed in a water-filled pool inside a steel-lined concrete vault, as shown in Figure 1. The pool water serves as both the heat-transfer medium and the radiation shield.
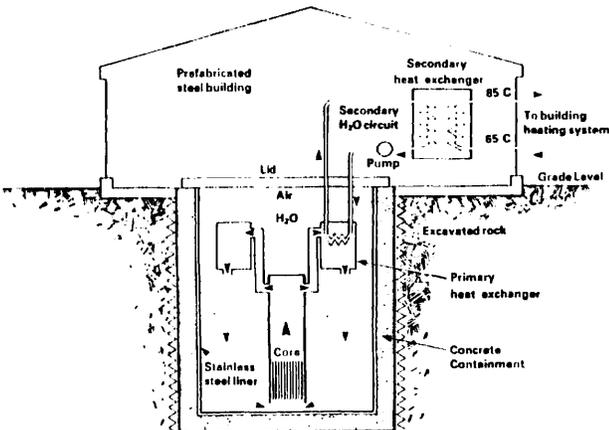

FIGURE 1: THE SLOWPOKE ENERGY SYSTEM

Primary heat transport from the reactor core is by natural circulation of the pool water through plate-type heat exchangers. The secondary circuit delivers heat to the building heating system, via a secondary heat exchanger.

In applications where electricity is required, the heat is transferred to pressurized Freon. The resulting Freon vapour is expanded through a single-stage turbine, which drives the electric generator. Such organic Rankine engines typically have thermal-to-electrical conversion efficiencies of 5-10%.

To compensate for fuel burnup, four absorber plates are used for periodic core reactivity adjustments by an operator. In addition, a central absorber rod is used for automatic control of the pool water temperature. The rate of removal of all absorbers is limited by the speeds of their electric motors, and by a timer requiring manual reset.

A liquid-absorber system can shut the reactor down over a period of five minutes. The gadolinium nitrate absorber solution flows into the pool by gravity, via two temperature-activated valves. These valves require no external power supply and are set to open automatically at a core outlet temperature of 98°C. The temperature sensors and valves for the liquid-absorber shutdown system are fluidic throughout, and therefore fail-safe.

Pool water is continuously pumped through ion-exchange columns to maintain water chemistry and control corrosion. The ion-exchange column can also remove fission products from defective fuel and, if required, the gadolinium nitrate in the liquid shutdown system.

The reactor pool is covered by an insulated lid, enclosing a gas space over the pool. The air and water vapours are continuously circulated through a purification system and hydrogen recombiner. After filtering and monitoring, a fraction of the circulating cover gas is released to the atmosphere.

The fundamental factor underlying the reactor design is inherent safety. The primary goal is to meet all Canadian regulatory requirements in a manner that permits operation of the unit for extended periods of time, without an operator in the reactor building. To achieve this goal, the SLOWPOKE heating reactor has been designed to provide radiological protection by utilizing inherent properties and processes that obviate the need for complex instrumentation and control systems, and specially engineered systems. The following are the main safety features:

- A pool-type reactor that operates at atmospheric pressure, and thereby avoids the need for a reactor pressure vessel. Thus, a loss of coolant due to depressurization is impossible.

- Natural circulation of the coolant, which ensures cooling of the reactor core without the need for pumps.

- Double containment of the pool, with the gap between the two containment structures being monitored for leakage. This gap can also be filled with water to test for leakage through the concrete vault.

- A fully redundant control system.

- A slow rate of reactivity change, which allows the use of slow-response control and shutdown systems.

- Negative fuel temperature reactivity coefficient, which provides inherent self-regulation of reactor power.

- Negative reactivity coefficient of water density (due to temperature rise and bubble formation), which would limit the power transient following a loss of regulation.

- A large pool volume at 68°C, which would delay core temperature rise following a loss of secondary cooling. Consequently, any thermal transient would take hours to reach equilibrium and never exceed a safe temperature limit.

- A heat pipe immersed in the pool, which guarantees indefinite cooling after shutdown to remove decay heat, even without electrical power.

All essential instruments will be monitored at one or more remote locations and a licensed operator will always be on call. A single remote monitoring centre could manage the heating and ventilating requirements of many systems in a number of locations.

Several barriers are used to prevent fission pro-oducts from being transferred from the reactor to the outside environment:

- The uranium oxide fuel, which is a diffusion-resistant ceramic that would retain most of the fission products.

- The zircaloy sheaths around the fuel elements, which are vacuum-sealed and designed to withstand the stresses resulting from fuel expansion, fission-gas pressure and the mechanical loads that occur during refuelling.

- The double pool-containment system, comprising the pool water contained in a steel vessel without penetrations, and the reinforced concrete vault.

- The steel cover plate, which keeps the top of the pool isolated from the building environment.

To prove that the design goals can be met, a 2 MWt demonstration reactor (called the SDR) has been built at AECL's Whiteshell Nuclear Research Establishment (WNRE). The main purpose of the SDR, shown in Figure 2, is to demonstrate that the reactor can be operated safely and reliably without an operator in the reactor building. The SDR replicates all the features necessary to validate the design of the 10 MWt SLOWPOKE heating reactor. Operation of the SDR will

- validate the computer models used to simulate the performance of the commercial units, using steady-state and transient tests covering the full range of anticipated operating conditions

- gain experience in monitoring and controlling radioactive emissions from the reactor

- demonstrate the consequences of a fuel-sheath failure, for fully irradiated fuel.

SLOWPOKE
DEMONSTRATION REACTOR

Key to cutaway
1. Core (4 bundles)
2. Control rod
3. Hot riser duct
4. Primary heat exchanger
5. Cover plate
6. Water purification system
7. Secondary heat exchanger
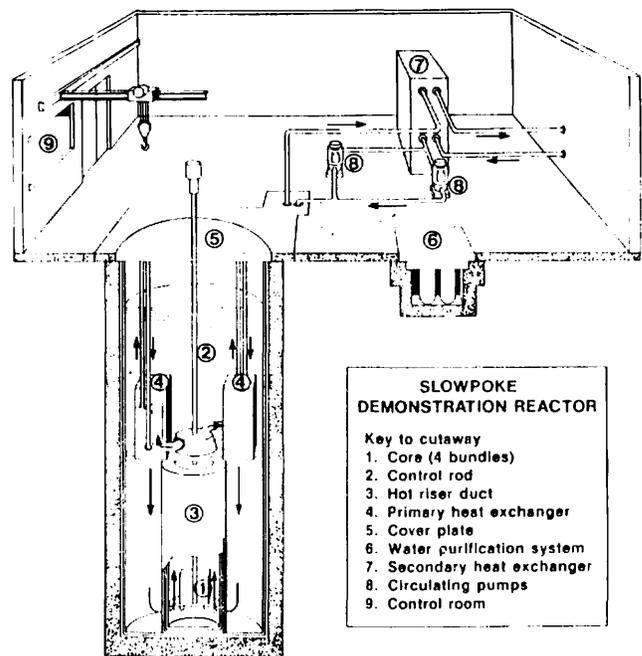8. Circulating pumps
9. Control room

FIGURE 2: THE SLOWPOKE DEMONSTRATION REACTOR

Following the test program, the SDR will be used as a full-scale demonstration of building heating and electrical generation. To demonstrate building heating, some of the buildings at WNRE will be heated by the SDR. Subsequently, a 200 kWe organic Rankine engine will be connected to demonstrate the capability for electrical generation.

Because the reactor can operate unattended, the operating costs are quite modest, so that the unit cost of heat supplied by a SLOWPOKE Energy System can be as low as 1.2 cents/kW.h, depending on the unit size and load factor. (4) This makes such a system competitive with conventional heating systems in most regions of Canada, even in urban areas. Indeed, with such low-cost heat, even the low efficiency of a Rankine engine could produce 800 kWe at 22 cents/kW.h, when operating at a load factor of only 60%. Although not competitive with base-load electricity produced by CANDU reactors, there are many areas not connected to an electrical grid where such costs are acceptable. The most promising areas of application for the SLOWPOKE Energy System are commercial and industrial complexes, such as apartment buildings, hotels, shopping centres, factories and mining operations. Given that about 30% of all the energy consumed in the world is used to heat buildings the potential market is very large indeed.

The Nuclear Battery

As noted above, the SLOWPOKE heating reactor produces electricity at a relatively low efficiency, since the maximum temperature of the primary coolant is only about 90°C. This makes it uneconomical for some applications requiring electricity only. However, AECL is developing, in collaboration with the

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Los Alamos National Laboratory, a new compact electrical generator, called the Nuclear Battery, that offers the promise of safe, reliable and economical electricity for many remote applications, such as weather stations and radar installations, ocean-bed oil production, underwater vessels and electrical supplies for small isolated villages.

The basic features of the Nuclear Battery are shown schematically in Figure 3. The reactor core is solid, consisting of blocks of graphite moderator in which the enriched uranium fuel is embedded. Thus, the fuel is surrounded by a heat sink capable of absorbing and dissipating large quantities of heat. The high heat capacity of graphite ensures that thermal transients can only occur slowly, while its good thermal conductivity maintains a uniform temperature across the core. Because graphite is less efficient than water in thermalizing fission neutrons, a high ratio of carbon to uranium atoms is required to achieve a critical system. Consequently, the power density is very low.
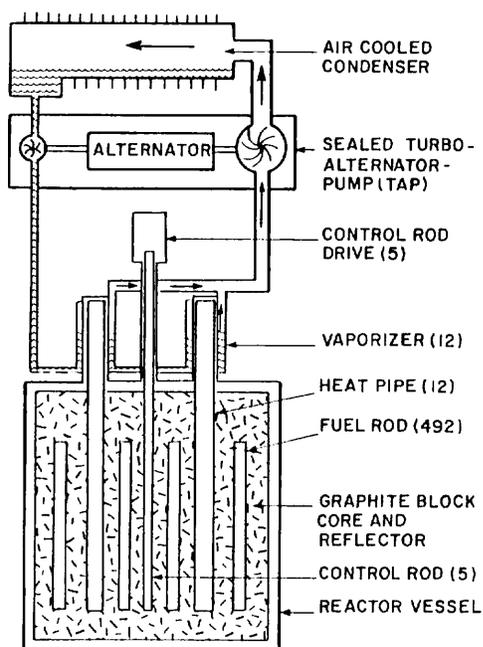

FIGURE 3: THE NUCLEAR BATTERY

Labels in figure:
AIR COOLED CONDENSER
ALTERNATOR
SEALED TURBO-ALTERNATOR-PUMP (TAP)
CONTROL ROD DRIVE (5)
VAPORIZER (12)
HEAT PIPE (12)
FUEL ROD (492)
GRAPHITE BLOCK CORE AND REFLECTOR
CONTROL ROD (5)
REACTOR VESSEL

To achieve maximum long-term reliability and minimize costs, the initial fuel charge is designed to provide the fuelling requirements for 10 to 20 years, depending on the operating power level. The fuel forms being considered are TRISO silicon oxycarbide coated-particle fuel, like that used in the Fort St. Vrain high-temperature gas-cooled power reactor in the United States, or zirconium-alloy-clad uranium carbide fuel elements similar to those used for more than 10 years in the organic-cooled WR-1 research reactor at WNRE. These fuel forms have better fission-gas retention than UO_2 and provide the primary barrier to the release of fission products. The fuel power ratings and peak fuel

temperatures are much lower than those encountered in large power reactors, and maximum fuel burnups are well within the range of demonstrated experience. The total energy output from the system is therefore limited only by the excess reactivity available to provide the required fuel burnup, and not by fuel performance considerations.

Heat transport from the reactor core to the power conversion system is provided by heat pipes installed in axial holes drilled in the graphite core blocks. The heat pipes extend above the top surface of the reactor, and terminate at the other end in the lower axial reflector. The use of heat pipes provides a passive means of extracting the heat from the core at high temperatures, and eliminates single-point failure modes, since the reactor can continue to provide full power output with a small fraction of the heat pipes in a failed state. The current heat-pipe design features a low neutron-absorbing zirconium alloy tube 6.1 cm in diameter. The heat pipes contain a small quantity of potassium and operate at about 500°C, with sub-atmospheric internal pressure.

The graphite core rests on ZrO_2 ceramic supports within an Incoloy or steel-alloy containment vessel. The containment vessel provides a second barrier to the release of fission products. A gap of about 5 cm between the core and the vessel is filled with thermal insulation, which serves to minimize thermal losses from the core and reduce the temperature at the vessel surface. There is a similar gap of 5 cm between the containment vessel and the surrounding radiation shield. Circulation of air through this latter gap maintains the vessel at its design temperature and cools the inner surface of the shield.

The containment vessel is backfilled with helium gas and maintained at a pressure slightly above one atmosphere. The helium improves the heat transfer across clearance gaps in the core, e.g. between the graphite blocks and the heat pipes, and provides an inert atmosphere. Monitoring of the helium system provides a continuous indication of containment vessel integrity. A reservoir of helium gas is provided to limit the consequences of a containment vessel leak. The helium cover-gas system also provides a means of removing gases and moisture evolved during initial core heat-up and a controlled method of purging the core environment through a filtered cleanup system. Periodic sampling of the helium would verify the extent of fission-product containment by the fuel.

The reactor core contains five or more reactivity control devices in the form of cylindrical rods containing boron carbide (B_4C) pellets. These control rods are used to start up and shut down the reactor, regulate the operating temperature and compensate for long-term reactivity losses due to fuel burnup. The rods are driven by stepping motors located on a shielded platform above the core. The control-rod housings form part of the containment envelope. Both the rate of rod withdrawal (rate of reactivity insertion) and the maximum extent of withdrawal (maximum excess reactivity) are limited by physical means. During normal operation only one control rod will actively regulate the reactor temperature; the remaining rods will be positioned near the upper end of their travel. A cold shutdown state can be achieved even if one of the control rods

malfunctions and cannot be reinserted. Control rod reinsertion may be accomplished by gravity release, positive drive action by the stepping motors or, in special circumstances, by manual action. For higher power applications, burnable poisons may be used to provide passive long-term reactivity control, and thereby limit the maximum available excess reactivity.

Because the Nuclear Battery provides useful heat at temperatures of about 500°C, it offers the prospect of very good Carnot cycle efficiency. Net conversion efficiencies of better than 20% are achievable using a toluene (C_7H_8) organic Rankine cycle power-conversion system. The principal advantage of the regenerative organic Rankine cycle is that it is capable of providing the highest efficiency of any power conversion technology at the lowest possible heat source temperature. The safety advantages of this choice are that high conversion efficiency reduces the inventory of hazardous fission products while minimum core operating temperatures increase the margins to material damage during accidents.

The advantages of organic working fluids include excellent mechanical lubrication properties and very low activation in the presence of radiation fields. Very high reliability has been demonstrated for similar engines using Freon at much lower operating temperatures. Toluene has the broadest base of experience in the temperature range of interest since it features good resistance to thermal decomposition, in addition to acceptable thermodynamic properties. Toluene also has a low freezing point of -95°C, which makes it ideal for arctic applications.

The reactor core, vaporizers and control rods form a single module that is suspended and enclosed within a vault of solid construction. The vault provides a degree of impact protection for the core and could be sealed to act as a tertiary containment envelope. The vault is enclosed within a building structure or vessel compartment that has restricted access.

Because of the flammability of toluene, the organic Rankine engine will be designed as a hermetically-sealed unit. It will be housed in a leak-tight enclosure situated outside of the reactor vault, and equipped with fire detection, alarm and protection systems.

As with the SLOWPOKE heating reactor, the Nuclear Battery is being designed to operate unattended, for periods up to about one year in duration. Remote monitoring of all essential parameters would be provided on a regular basis from a central manned location.

The ability to operate the Nuclear Battery unattended is based on its self-regulation characteristic and other inherent safety features described below.

The constant presence of the graphite heat sink ensures that the fuel rods cannot overheat and release their fission products, even if the heat removal capacity of all the heat pipes were lost. Moreover, the core possesses a strong negative temperature reactivity coefficient that provides self-regulation of power output, to balance the available heat removal capability. The natural tendency of the reactor is, therefore, to act as a constant temperature heat source, with the temperature defined by the reactivity control system. Consequently, the thermal power output automatically decreases to a low level in the event of loss of heat-pipe cooling, even if the control rods become stuck in position and cannot shut the reactor down. In this case, the core and fuel temperatures are maintained near their normal operating values. Reactor shutdown decay heat can always be safely dissipated by passive conduction from the graphite reflector through the insulation and containment vessel to the environment without the need for forced circulation of cooling air along the exterior vessel surface. Passive decay-heat removal in this manner is practical because the decay heat loads are quite low. Indeed, the decay heat load quickly drops to a level below that of the normal thermal losses through the vessel at full power.

Loss of reactivity control (due to control rod withdrawal) would produce a brief overpower transient followed by the establishment of a new equilibrium at a higher core temperature. The core thermal power can only match the available heat removal capability at the equilibrium condition. A large margin to fuel damage exists during an overpower transient because the initial design fuel ratings are very low. A further consequence of the low fuel ratings and low core power density is that xenon-induced transients are also quite small. For these reasons fast shutdown and emergency core cooling systems are not required.

The probability of release of fission products from the reactor core is very small due to the relatively small fission-product inventory compared to a large power reactor, and the high-temperature retention characteristics of the fuel. For example, the TRISO fuel particles can retain their fission products up to 1400°C whereas the highest core temperature that can be sustained neutronically is about 950°C.

The Nuclear Battery is currently at an early design stage. It is expected that a demonstration unit will be built at WNRE to demonstrate the inherent safety features of the concept and its capability to operate unattended for extended periods. Another important aspect of the demonstration program will be confirmation of the conversion efficiency and reliability of the organic Rankine cycle for the production of electricity. While the demonstration unit will be designed to produce only a few tens of kilowatts of electrical power, the concept should be capable of being scaled up to about 400 kWe, with no major design changes.

Other Concepts

Other small reactor concepts are currently being pursued in Canada. One of these is a light-water cooled, enriched-uranium fuelled reactor to supply heat and electricity for the SAGA-N commercial submarine, being developed by International Submarine Transportation Systems of Halifax for underwater exploration and maintenance activities. (5) The planned reactor power is 1.0 to 1.5 MWt, with an electrical output of 100 kW. Some waste heat will also be recovered for use in the submarine and to heat diving suits. An organic Rankine cycle using Freon is proposed for the electrical supply. Unlike the SLOWPOKE Energy System, which uses natural

circulation cooling, the primary coolant in the SAGA-N system will be pumped through the Rankine cycle evaporator.

Another small reactor concept being explored by AECL would employ a solid beryllium oxide (BeO) moderator and liquid lithium (Li) as the coolant. This combination would result in a more compact power source than the graphite-moderated Nuclear Battery, but would have very similar self-regulating and safety features. The use of a circulating liquid coolant system would enable the decoupling of the organic Rankine cycle power conversion system from the reactor heat source. Thus, the toluene could be vapourized in a simple tube-in-shell heat exchanger located outside the radiation shield where it would be protected from radiolytic decomposition. Such a compact reactor could be attractive for applications in space.

THE MAPLE REACTOR FOR RESEARCH AND ISOTOPES

It is now well accepted that if a country wishes to have full access to the benefits of nuclear science and technology it must have a multipurpose research reactor. For countries planning to utilize nuclear power, the acquisition of a research reactor is a proven way to develop the essential expertise and technology. This is particularly true if the aim is to localize power-reactor technology, since a high-flux research reactor enables the testing of reactor fuel and other key components of nuclear power plants. For countries not planning early exploitation of nuclear power, the ability to produce neutrons can provide many benefits: the production of radioisotopes for use in medicine, industry and agriculture; the non-destructive analysis of materials and components; and research and training in nuclear science and technology.

Canada has always been a world leader in the development and utilization of high-flux research reactors, starting with NRX in 1947, followed by NRU in 1957 and the organic-cooled WR-1 reactor in 1965. Those reactors have all been recognized as leading reactors of their type. They all used heavy water as the moderator, which resulted in large in-core volumes that allowed the testing of full-size nuclear power plant components. In recent years, however, the capital cost of such large reactors has become prohibitive. In response, AECL has developed the MAPLE family of research reactors, which can provide superior reactor performance at modest cost. (6) These new MAPLE reactors combine the features of the large heavy-water research reactors NRX, NRU and WR-1 with those of the SLOWPOKE-2 and MTR-type light-water research reactors, to yield a highly versatile facility with outstanding performance.

The basic features of the MAPLE research reactor are shown in Figure 4. The reactor assembly consists of three main parts: the inlet plenum (and lower support structure), the calandria vessel, and the chimney. Vertical flow tubes penetrate the calandria vessel and delineate three regions:

- a central light-water cooled, light-water moderated core region

- an intermediate light-water cooled, heavy-water moderated core region
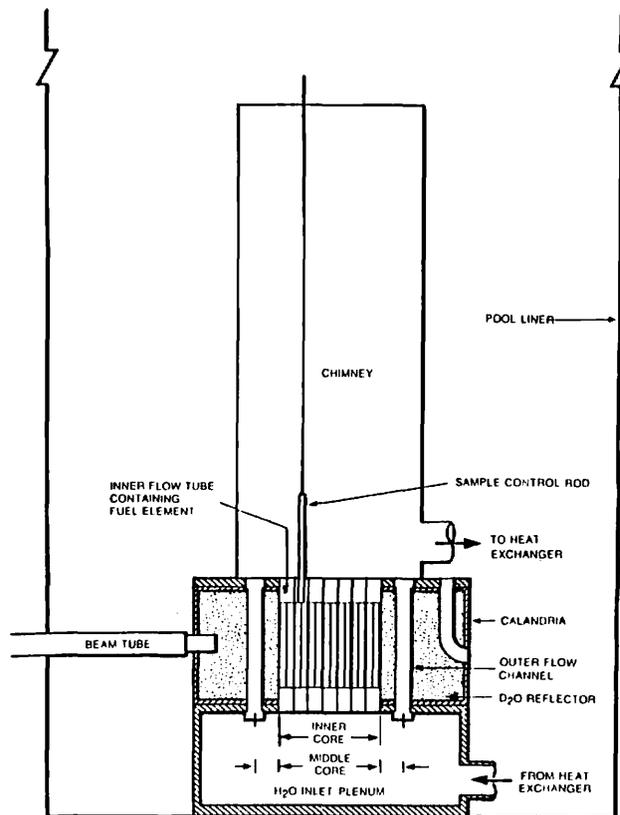
- an outer heavy-water reflector.

FIGURE 4:   THE MAPLE RESEARCH REACTOR

This three-region design enables the MAPLE reactor to provide the flux advantages of a compact light-water moderated reactor, and the flexibility and spacious experimental volumes of a heavy-water moderated reactor. The layout of the calandria vessel, shown in Figure 5, can accommodate a wide range of fuel configurations and a wide variety of irradiation facilities.

The central core region contains 29 fuellable flow channels. It is cooled and moderated by light water, to achieve as high a neutron flux as possible per unit power output. At power levels of about 10 MW or more, this core region provides an irradiation environment that is a reasonable simulation of a light-water power reactor. It also facilitates CANDU fuel testing in combination with accelerated endurance tests of CANDU components, such as zirconium-alloy pressure-tube materials. Peak fast and thermal neutron fluxes of about 3×10^{14} n.cm^{-2}.s^{-1} are available in the central core region at a thermal power output of 20 MW.

While the central region may be completely fuelled to obtain maximum fuel burnup, a compact loading of 14 to 19 fuelled sites can be used to maximize the fast neutron flux in the core and the epithermal and thermal fluxes in in-core and reflector facilities. Such a core loading would enhance the production of isotopes, such as ^{99}Mo/^{99m}Tc, which result mainly from resonance neutron capture in a ^{98}Mo target. It would also provide a peak unperturbed thermal neutron flux of up to 5×10^{13} n.cm^{-2}.s^{-1} in a central flux trap and a peak unperturbed thermal flux
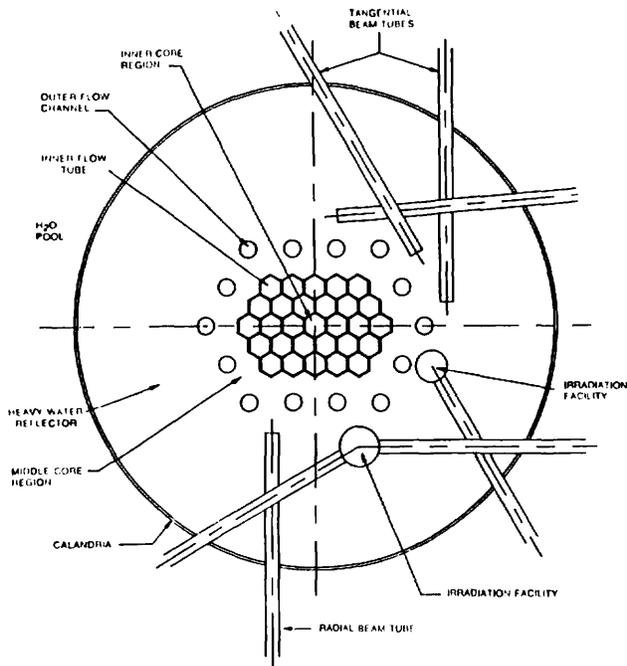
FIGURE 5: TYPICAL ARRANGEMENT OF MAPLE REACTOR BEAM
TUBES AND IRRADIATION FACILITIES

in the reflector of about 2 to 2.5×10^{13} n.cm^{-2}.s^{-1} for each megawatt of thermal output, thereby enhancing the facility's utilization for materials testing and neutron-beam applications.

The intermediate-core region consists of a ring of 14 fuellable flow tubes installed in the heavy-water tank. This light-water cooled, heavy-water moderated region is operated in conjunction with the central core to provide irradiation conditions that closely approximate a heavy-water power reactor environment. Rig and loop facilities can be installed in the heavy-water tank to provide fuel and materials testing in this simulated CANDU reactor environment. The ability to simulate both light-water and heavy-water reactor environments greatly increases the MAPLE reactor's versatility. Furthermore, by selectively fuelling the intermediate region, the neutron and gamma-ray fluxes delivered to specific irradiation facilities in the outer reflector region can be tailored to meet program requirements. Beam tubes may be operated in the radial or tangential mode, as shown in Figure 5, by adjusting the fuel loading in the intermediate and central core regions.

The spacious outer reflector region can accommodate many experimental facilities, such as horizontal beam tubes, irradiation holes, rabbit tubes, etc. The use of heavy water as the reflector ensures optimal performance of tangential beam tubes, which are preferred over radial beam tubes for most applications. The heavy water reflector typically delivers to tangential beam tubes thermal neutron fluxes 20 to 40 percent higher than would a beryllium reflector. However, beryllium is used as a reflector in MAPLE where its properties are superior to those of light or heavy water. Beryllium modules may be installed in the central core region to provide

fuelling flexibility and to tailer the neutron spectrum in irradiation facilities.

The MAPLE reactor uses low-enrichment uranium (LEU) fuel, with an enrichment level between 5 and 20 weight percent. The rodded fuel assemblies are similar to those used in large power reactors, which will allow operations personnel to gain valuable experience in the operating characteristics of this type of fuel. Furthermore, the use of rodded fuel permits a wide range of fuel-assembly configurations. Standard fuel assemblies contain 36 rods, but may contain fewer rods to adjust the ratio of fuel to moderator, or to fit around a special irradiation facility. For example, 18 rods form a control assembly, for use in reactivity-absorber positions.

Two types of fuel are available for use in MAPLE reactors. The first, recommended for reactors operating at up to 10 MWt, consists of UO_2 pellets enriched to between 5 and 8 percent in ^{235}U, contained within zirconium-alloy cladding. The second fuel type, for reactors operating above 10 MWt, comprises a uranium-silicide-aluminum dispersion co-extrusion-clad with aluminum.

The cooling of the MAPLE reactor core is achieved via forced upward flow. This greatly reduces the volume of coolant that must be delayed to manage the upward migration of ^{16}N and other short-lived activation products. It also offers greater fluid flow and hence superior heat transfer capability. It also avoids flow reversal during the transition from forced to natural circulation.

The light-water primary coolant flows up through the core from the inlet plenum. After passing through the core, the water is drawn from the chimney through horizontal nozzles and is pumped to plate-type heat exchangers located in an adjacent equipment room. About 90% of the water is returned directly to the inlet plenum. The remaining 10% is passed through a delay tank to allow the ^{16}N to decay before being returned to the pool. By rerouting 10% of the coolant flow, a quantity of pool water is drawn into the top of the chimney, thus creating a small downward flow that controls the upward migration of ^{16}N, and other short-lived activation products. Natural convection provides adequate flow to remove residual heat from the fuel following a reactor shutdown.

The reactor assembly and the pool liner act as double containment for the primary coolant. The probability of a loss-of-coolant accident is very small because two independent barriers must fail before the reactor core can be drained.

The reactivity balance of the MAPLE reactor is controlled by two separate, diverse, independent systems: the regulating system and the protective system. Each system interacts with the reactor core via its own set of up to four hafnium absorber rods. All absorber rods enter the core from above, through the chimney. This improves safety by reducing the number of pool penetrations at or below core level. The protective system absorbers are operated hydraulically and drop into the core when the water pressure in a hydraulic cylinder is released by opening electrically-operated solenoid valves. The regulating system absorbers are actuated by cable drives that pass over pulleys at the top of the chimney and then go to stepping motors located in protective housings on the side of the reactor pool.

The reactor protective system employs the traditional two-out-of-three analogue logic and simple, modular design to ensure high reliability and availability. Three fission chambers provide signals to independent amplifier systems that generate linear, logarithmic and period information.

The MAPLE reactor uses a digital regulating system, which has several safety, operating and economic advantages. Reliable and economical systems are commercially available that use uncomplicated control software and have interface devices for almost every application. Sophisticated control schemes can be readily implemented and modified to accommodate changes to the experimental programs, which minimizes the potential for human error.

Depending upon local regulatory requirements, a closely coupled low-leakage pressure containment structure housed in a vented conventional building may be located around the reactor pool. This would avoid the large expense of a pressure containment building while providing containment against potential releases of fission products.

Taken together, the design features of the MAPLE reactor result in a product with exceptional performance. This arises mainly from the coupling of a unique compact light-water cooled core and a spacious reflector that exploits the combined advantages of heavy water and beryllium. The proven rod-type fuel assemblies, based on zircaloy-clad UO_2 or aluminum-clad U-Si-Al dispersion, provide an unusual degree of freedom in core configuration to meet a wide range of irradiation requirements. The arrangement of beam tubes may be customized to suit customer preferences for radial, tangential or convertible tube orientation, and for hot or cold neutron sources. The inherent safety features of the MAPLE reactor are combined with state-of-the-art passive and active engineered safety systems to set a new standard for pool-type research reactors.

A demonstration reactor of the MAPLE type, called MAPLE-X, is being built at CRNL. The MAPLE-X reactor will have a thermal power output of about 20 MW and will be used to demonstrate all the essential features of the MAPLE family of research reactors, as well as produce radioisotopes for AECL's Radiochemical Company. The reactor is expected to begin operation in 1989.

CONCLUSION

While nuclear energy is making a significant contribution to the world's electrical supply, there are many other areas where it could contribute to supplying the world's energy and other needs. Many of these areas can be serviced by small reactors and Canada is currently developing several small reactor concepts that will enable it to exploit these opportunities. Thus, the future for small reactors both in Canada and worldwide appears to be quite promising.

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