PROGRESS IN DEVELOPING RESEARCH-REACTOR TECHNOLOGY FOR CANADIAN AND INTERNATIONAL APPLICATIONS

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ABSTRACT

Atomic Energy of Canada Limited (AECL) continues to develop multipurpose research-reactor technology to meet Canadian and international requirements into the next millennium. Considerable progress has been made in refining the concept for a new Canadian Irradiation Research Facility (IRF) that will underpin the evolutionary development of CANDU® (CANada Deuterium Uranium) technology and generate neutrons for basic and applied materials science. Additionally, an IRF-based standardized MAPLE research centre is being developed with various reactor-core options to meet international needs for neutron-beam research plus ancillary isotope production (a 15-MW_t 19-site core), for multipurpose materials testing plus neutron-beam applications (a 30-MW_t 31-site core), and high-flux neutron-beam plus materials-testing applications (a 30 to 40-MW_t complex core with twin 18-site core segments).

INTRODUCTION

There is continuing Canadian and international interest in high-power (>10 MW_t) research reactors because they generate relatively intense fast and thermal neutron fluxes

($\sim 10^{18}$ $n \cdot m^{-2} \cdot s^{-1}$ or more). With few exceptions, only high-power research reactors can irradiate power-reactor fuel assemblies and other in-core components in an environment that represents current light- and heavy-water-moderated power reactors. The minimum (unperturbed) thermal-flux requirement for world-class neutron scattering studies is generally considered to be $\sim 3 \times 10^{18}$ $n \cdot m^{-2} \cdot s^{-1}$ at the beam-tubes, which requires a reactor of at least 14 MW_t. Furthermore, high-power multipurpose reactors designed mainly for materials testing or neutron-beam applications are generally also capable of sufficient radioisotope production to meet regional or international demands.

In Canada, where high-power research reactors owned and operated by AECL have played a central role in the development of the national nuclear program (Hurst, Manson, Critoph, and Petch, 1964), there is a clear need for major infrastructure renewal. AECL does not intend to operate the 135 MW_t NRU reactor beyond 2005. To meet ongoing Canadian requirements for materials testing and neutron-beam applications, AECL is defining the concept for a new national Irradiation Research Facility (IRF) as the successor to NRU. It is also presently supplying two 10-MW_t MAPLE reactors to MDS Nordion for the long-term secure supply of medical radioisotopes. With regard to international requirements, AECL has worked with the Korea Atomic Energy Research Institute (KAERI) to realize its new 30-MW_t HANARO facility (Kim, 1996) and continues to develop MAPLE technology.

MAPLE REACTOR CONCEPT DEVELOPMENT

Since its inception in 1983, the MAPLE concept (Lidstone, 1990) has been developed to meet Canadian and international requirements for high-performance research reactors. MAPLE refers to a family of pool-type reactor facilities that employ a compact, LEU-(Low-Enrichment-Uranium-) fueled, H_2O-cooled core within a heavy-water vessel to furnish neutrons efficiently to various types of irradiation facilities. The MAPLE design is distinguished mainly by the unique reactor assembly, the layout of the primary cooling system, the use of a digital computer system to control all main process systems as well as the reactor itself, and two fully independent shutdown systems. Various configurations of core and irradiation facilities to respond to specific customer requirements can be economically achieved utilizing standard components.

The MAPLE reactor-assembly is an open-tank-in-pool concept that consists of either a simple or a complex core (0.6 m or 0.7 m active fuel height) within a cylindrical D_2O-filled vessel with an inlet coolant plenum below and an open chimney above. MAPLE cores use standard fuel assemblies of 18, 36 or 58 rods that contain 19.75-wt%-enriched LEU fuel meat, in the form of U_3Si_2 or U_3Si dispersed in aluminum, and encased by finned aluminum sheaths. Fuel rods incorporating Gd_2O_3 as a burnable poison are presently under development to provide additional fuel cycle flexibility. A simple core consists of a hexagonal arrangement of typically 19 or 31 fuellable sites, each containing a hexagonal flow tube with a 36-rod driver assembly or a circular flow tube with an 18-rod assembly. The latter provides a surrounding water annulus into which a hafnium cylinder may be inserted for reactor control or shutdown. With a simple core, for example the MX-10 and Mk2 designs, the reactor is H_2O-moderated and D_2O-reflected. For the HANARO reactor, eight sites outside the 31-site central core accept 18-rod assemblies which creates a complex core with mixed H_2O and D_2O moderation. The IRF reactor assembly also has a complex core. It employs mixed moderation with a split-core concept that places three horizontal CANDU fuel test sections between two core segments, each of which comprises an 18-site simple core, plus two sites fuelled with fast-neutron (FN) assemblies containing 58 rods in two rings surrounding a central irradiation thimble.

The primary cooling system cools the core, except for the test loops, using two independent circuits that draw H_2O from two nozzles in an outlet chimney that mounts on the reactor vessel. In each cooling circuit, a pump (or an identical standby unit) forces the water through plate-type heat exchangers and back to the inlet plenum. A fraction of the inlet coolant is discharged directly to the pool to create a flow down the chimney that confines the core flow to the lower part of the chimney thereby preventing activation products from reaching the pool surface. Earlier simple core concepts utilized a single circuit combined with an accumulator tank to provide cooling during the transition to natural circulation. The two-loop design requires isolation between the two loops to allow pump start up and limit reverse flow through a failed loop. HANARO utilizes conventional check valves while the IRF and current reference designs will use a flow diode in each inlet pipe to limit the reverse flow through the circuit and ensure adequate core cooling flow in the unlikely event of a piping failure. This focus on prevention of fuel overheating during loss-of-cooling accident conditions is considered prudent because of the relatively low melting point of aluminum-based fuels compared to the zirconium-clad UO_2 of most power reactors.

The reactor control system operates four control absorbers in the simple core reference design. The split core IRF design will utilize four absorbers in each segment. The hollow-cylindrical hafnium-metal control absorbers are attached to shafts that extend up through the chimney to drive units mounted on a support structure that is located above the pool. Computer-driven stepping motors actuate the control-absorber shafts. A Digital Control System (DCS) uses dual-redundant computer hardware to provide computerized control and monitoring for all reactor systems and experimental facilities. It has two main components, the Digital Control Computer (DCC) for control functions and data acquisition, and the Plant Display System which generates the operator displays, processes operator commands and transmits control commands to the DCC, provides alarm annunciation and acknowledgement, and controls the data logging. As well as the reactor regulation system, the DCS controls the primary cooling system, the D_2O cooling system, the secondary (process) cooling system, the pool water-make-up system and the H_2O purification system. It also provides balance-of-plant monitoring which includes surveillance of safety-systems, various electrical systems, and pool water and gate systems.

In view of the limitations of active safety systems [minimum unavailability of 0.001], the MAPLE concept incorporates two independent diverse shutdown systems. The first shutdown system functions by interrupting the power to the electromagnetic latches in the shaft drives of the hafnium control absorbers and enabling them to fall into the core. Except for the 31-site core, a highly diverse second shutdown system rapidly dumps the D_2O from the region of the reactor vessel neighbouring the core, where it is normally held in place by helium-gas pressure. For the 31-site core, the second shutdown system inserts a second set of hafnium absorbers that are normally hydraulically poised above the core.

The MAPLE containment concept acknowledges the difficulty of ruling out the possibility that foreign material might cause single-channel flow blockage; moreover, reactors that support fuel development inevitably perform certain experiments that cross the threshold of fuel-element failure. Accordingly, the IRF concept (which incorporates high-power fuel-test loops) and the standardized MAPLE research centre rely on a reinforced concrete containment building to house the reactor and its experimental equipment.

MAPLE PROJECTS AND PROGRAMS

The prototype opportunity for MAPLE technology was to build a dedicated facility (MAPLE-X10) for the production of short-lived radioisotopes, such as ^{99}Mo, and transmutation-doped silicon. The reactor was designed to produce a peak unperturbed thermal flux of 2×10^{18} $n \cdot m^{-2} \cdot s^{-1}$ in the D_2O reflector at a power density of 160 $kW_t \cdot L^{-1}$. As of 1993 October, AECL had satisfied all of the requirements for the final stage of construction (installation of the reactor assembly and associated safety-related systems) to the satisfaction of the staff of the Canadian regulator, the AECB. None-the-less, the project was discontinued in November, 1993. However, the facility is now being completed as part of AECL's contract to supply two 10-MW_t MAPLE reactors to MDS Nordion.

A development program (Lidstone, Bishop, Gillespie, and Lee, 1996) was conducted to verify the performance of reactor components and characteristics unique to the MAPLE concept. To support the nuclear design, a network of externally available and in-house physics codes was developed, validated, and applied to characterize the reactivity balance, fuel management strategies, the deposition of fission energy, and the reactor's transient response to system upset. Hydraulic rigs of varying size, from a one-fifth model of the reactor assembly to a full-scale rig that was assembled from actual reactor components (e.g., inlet plenum, grid plate, reactivity-control devices) were built to verify the design of prototype components whose interactions could not readily be predicted. A heat-transfer data base was developed using an electrically heated single-pin experimental rig and verified using a larger electrically heated facility that simulated various types of MAPLE fuel assemblies under normal and accident conditions.

Since 1986, AECL has partnered with the Korea Atomic Energy Research Institute (KAERI) on the realization of the 30 MW_t HANARO multipurpose reactor facility (Kim, 1996). AECL has supplied a MAPLE-type reactor assembly and associated equipment (e.g., control and shutdown mechanisms) to meet KAERI's reactor design requirements. HANARO was designed for performing small-scale fuel and materials tests in support of both light- and heavy-water-moderated power reactors, producing radioisotopes, and facilitating basic and applied research using thermal and cold neutron beams. Following its initial criticality on 1995 February 8, commissioning tests were performed at successively higher power levels leading to routine high-power operation (Kim, Kim, Lee, and Lee, 1996).

Over the past several years, AECL has been assessing future requirements for irradiation facilities to support ongoing CANDU development and to facilitate neutron-based materials science in Canada. Three major CANDU research and development programs require irradiation facilities: fuel and fuel-cycle technology, fuel channel technology, and reactor safety research. With regard to materials science, a recent review (cited in Lidstone, Bishop, Gillespie, and Lee, 1996) concluded that existing Canadian neutron facilities are seriously out of date and recommended that Canada make an immediate commitment to develop a fully equipped reactor-based national source for neutron beam research. The review stressed that a reactor with a full complement of instruments and a flux of 2-3 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$ would meet over 90% of Canadian needs and recommended that priority be given to the acquisition of optimized instruments rather than world leading flux levels.

In response to these Canadian requirements, AECL is developing the dual-purpose IRF described below. The IRF is presently at a pre-project stage whose objective is to assess and optimize reactor performance, to identify and manage the anticipated capital and operation costs, and to prepare the case for the government approvals that are prerequisite to proceeding with formal design and subsequent construction. Thus, no site-specific work has proceeded. However, the AECL Research and Development Advisory Panel has strongly recommended the IRF as the replacement for NRU.

AECL has also continued to develop the MAPLE family of multipurpose reactors to meet other anticipated Canadian and international requirements for isotope production, small-scale materials testing, and neutron-beam applications. The standardized MAPLE (Mk2, Mk3, and Mk4) research-centre concept is described and its anticipated performance is summarized in the following section.

THE IRRADIATION RESEARCH FACILITY

The original stand-alone IRF complex (Lidstone, Bishop, Gillespie, and Lee, 1996) consisted of a reactor containment building with CANDU testing facilities and a neutron beam hall, plus an adjacent guide hall and various buildings for operations, administration, and utilities. In view of its cost ($500M in 1994 Canadian dollars, including costs associated with neutron beam facilities), AECL has evaluated cost reduction options including the utilization of the infrastructure at an existing nuclear site. As a consequence of this study the overall project scope has been substantially reduced to provide essential near-term CANDU R&D and neutron beam applications, plus an expansion capability for irradiation facilities that are desirable in the longer term. Chalk River Laboratories (CRL) has been chosen as the reference site.

The revised reactor building houses experimental facilities and process equipment, provides protection from natural hazards, and acts as a containment boundary. Its size (31 m x 27 m) was established as the minimum necessary to accommodate the reactor process systems and experimental loops (including provision for future loops) on the second floor. This made prudent use of the original design, and avoided a larger reduction in the neutron beam capability. The revised reactor assembly illustrated in Figure 1 provides five beam tubes for neutron scattering instruments in the beam hall (including one that views the cold source), a beam tube for neutron radiography, a cold-neutron source and beam tube for illuminating the cold-guide fan, and a beam tube equipped with thermal guides. A guide tunnel leads through the outside wall to the (30 m x 60 m) guide hall which will accommodate 16 instrument stations. An operations support building adjoins the reactor building on three sides and provides controlled access to all levels of the reactor building and ancillary facilities for that building. The first floor of the facility is illustrated in Figure 2.

As mentioned above, the IRF reactor assembly employs a split-core concept (Figure 1) that places three horizontal CANDU test sections between two driver cores, each comprising an 18-site MAPLE-type core segment plus two fast-neutron (FN) sites.

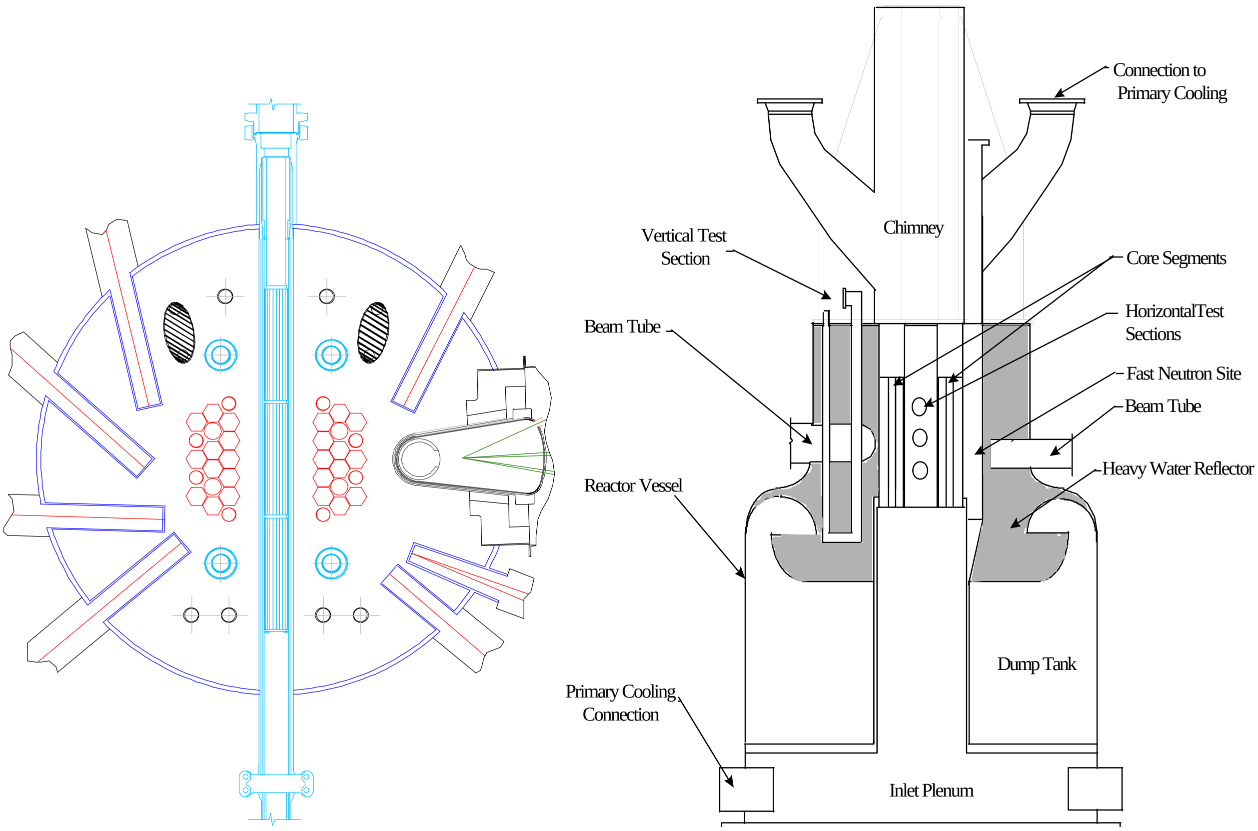


Figure 1

Plan and Elevation of Reactor Structure

The revised IRF experimental facilities comprise:

Horizontal fuel test facilities: three 1.5-m test sections with 2-3 CANDU bundles per test section, connected to two loops initially, with provision for a third loop;

Vertical fuel test facilities: two test sections for multi-element partial bundles, one loop initially connected, with provision for a second loop;

Blowdown test facility (BTF) loop: provision for one blowdown loop system to connect to the bottom horizontal test section;

Materials irradiation facilities: four in-core sites with three or four inserts each, and four fast-neutron sites with four inserts per site or one corrosion loop per site;

Hot cells: one three-compartment cell on the main level of the reactor building and one shielded facility for handling operations for the horizontal test sections;

Neutron beam facilities: eight beam tubes, including one capable of housing a liquid hydrogen (LH_2) cold neutron source and a beam tube for illuminating two thermal-neutron guides.

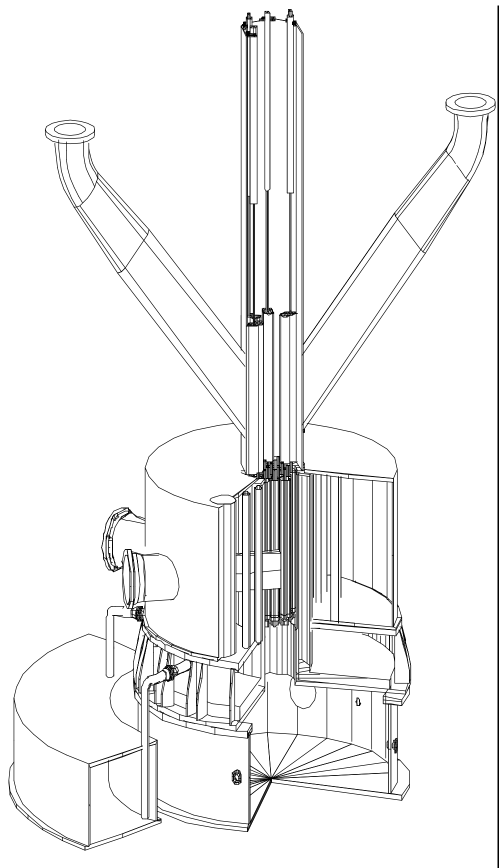
customer requested options are available to meet specific requirements or priorities; for example beam tube or irradiation site size and location. It has also developed various options for containment configurations that can be applied to specific facility applications or facility locations. The reactors in the series are referred to as MAPLE Mk1, Mk2, Mk3, and Mk4.

The reactor, process systems and experimental facilities will be located in a standardised reactor containment building. The control room and essential services will be located in an adjacent building that is environmentally qualified.

MAPLE Reactor Series

The MAPLE Mk1 is based on the MAPLE-X10 reactor which was designed specifically for isotope production. Its application would include materials testing, activation analyses, isotope production and neutron transmutation doping. The Mk1 is equipped with two diverse shutdown systems, disengagement and drop of the four control rods and a partial reflector dump. The reflector dump system actuates by selectively transferring the D_2O from within a “capped-baffle” region near the core to the external tank depicted in Figure 3.

The MAPLE Mk2 reactor assembly shown in Figure 3 uses the Mk1 design modified to incorporate six or more horizontal beam tubes and an array of vertical irradiation sites. Figure 4 presents a typical horizontal layout of irradiation facilities. Three tangential beam tubes (8 mm wide x 14 mm high) are located in the thermal flux peak of the reflector tank for neutron-scattering applications, one 100 mm diameter beam for neutron radiography is located further from the core, and one 200 mm diameter radial beam tube capable of housing a cold-neutron source and neutron guides is located just outside the dump baffle. An epithermal column (lower portion of Figure 4) may be specified to facilitate BNCT research and treatment. Vertical facilities include two hydraulic-capsule sites near the edge of the core, five high-flux isotope-production sites just outside the core and twenty isotope-production sites in the outer reflector.



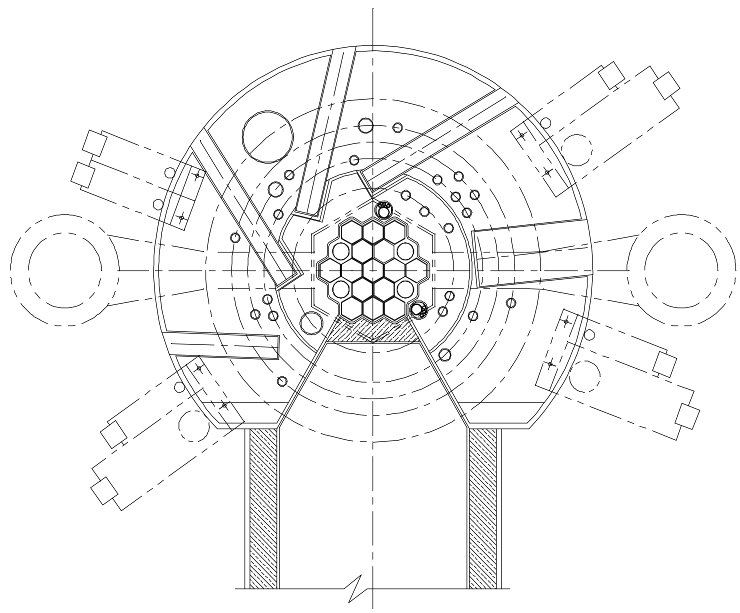


Figure 3 **Figure 4**

MAPLE Mk 2 Reactor Assembly MAPLE Mk 2 Horizontal Layout

The MAPLE Mk2 reactor fully meets international requirements for world-class neutron-beam research at a power output of 14 MW_t. A peak perturbed thermal neutron flux of ~2 x 10^{18}

$n \cdot m^{-2} \cdot s^{-1}$ is available at tangential neutron beam tubes located ~320 mm from the core centre.

At 10 MW_t (which would qualify it for licensing in the USA as a research reactor, rather than a test reactor) a Mk 2 reactor can facilitate wide-ranging multipurpose utilization for neutron-beam research, the production of radioisotopes, and cancer therapy (Lidstone, Bishop, Gillespie, and Lee, 1996). The peak perturbed thermal neutron flux in the reflector is 1.6 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$ which is very high for a LEU-fuelled research reactor of this power level. The reactor is also capable of efficient radioisotope production. Furthermore, a 10 MW Mk2 facility is well suited for the implementation of BNCT following the completion of current clinical trials in the United States and Europe. An advanced epithermal column concept has been defined that uses a D_2O-cooled beryllium column, followed by a D_2O-cooled aluminum column, aluminum-lithium filters, and cadmium and bismuth shields. It is anticipated that full-treatment times of six to ten minutes will be feasible with acceptable limitation of doses to healthy tissue due to photons and fast neutrons.

The MAPLE Mk3 employs a 31-site 30 MW_t core and a larger D_2O vessel than the Mk2 facility to meet materials-testing requirements that favour a high-power-density reactor with in-core irradiation space. The proposed design employs IRF fuel assemblies and reactor-control-system drives in a reactor assembly similar to that supplied for HANARO. The Mk3 reactor will provide several sites in core where the peak fast-neutron flux is ~1.7 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$ in zirconium specimens in IRF-type materials-irradiation rigs. Also, with peak perturbed thermal neutron fluxes of 2-2.5 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$ available, the Mk3 will provide neutron-beam performance that is generally similar to the IRF, HANARO, or the 14-MWt MAPLE Mk2 research centre.

To meet anticipated international requirements for high-flux steady-state neutron sources, the MAPLE Mk4 reactor employs a ~30 MW_t concept that places a region of high thermal neutron flux between two IRF-type split cores. The design concept relies on IRF fuel and other IRF reactor components with minor modifications. The reactor vessel will have two trapezoid-shaped, H_2O-cooled, IRF-type core regions with each 18-site core segment completely fuelled. Horizontal penetrations are envisioned for up to ten beam tubes, four of which (one or two cold-neutron beam tubes and two or three thermal beam tubes) will access the central high-flux region where the peak unperturbed thermal neutron fluxes is about 6-7 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$. For the remaining beam tubes where the unperturbed thermal neutron flux is ~4 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$, the anticipated performance will likely be similar to HANARO or the IRF, that is the perturbed thermal fluxes will be ~2.5-3 x 10^{18} $n \cdot m^{-2} \cdot s^{-1}$.

Facility

The reactor building of the standardized MAPLE multipurpose research centre is a three-story reinforced-concrete structure that contains the reactor and service pools, the reactor hall, shielded rooms for process systems, plus a neutron-beam hall and other utilization facilities such as a BNCT room, fuel-test loop rooms, and irradiation-target handling equipment. The top or operations floor is at the top of pool elevation with access to the reactor and service pools and the process rooms on the floor below. The second floor contains the reactor process systems and an applications area which can be configured to suit the owners requirement. The first or ground floor is allocated to facilities that utilise the beam tubes.

The control room, instrument racks for both the control and safety system, power distribution systems, and cooling water valve rooms are located in a reinforced concrete building that is designed to withstand external hazards such as earthquakes, tornadoes or high winds. The laboratories and administration building is configured according to the owners specific needs.

SUMMARY

AECL is continuing to develop MAPLE technology to meet Canadian and international requirements for high-performance research reactors. The main current focus is on developing the IRF concept to support the evolution of CANDU technology and generate neutrons for basic and applied materials science. AECL is also developing a standardized MAPLE research centre concept for neutron-beam applications, radioisotope production, and materials testing that will use one of four standard reactor sizes.

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