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THE ADVANCED MAPLE REACTOR CONCEPT

LE CONCEPT DE REACTEUR AVANCE MAPLE

R. F. Lidstone, A. G. Lee, G. E. Gillespie, H. J. Smith

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RÉSUMÉ

Les sources de neutrons à haut flux continuent de présenter de l'intérêt au Canada et dans le monde en tant que soutien des essais de matériaux de réacteurs de puissance avancés, des progrès nouveaux dans les applications des faisceaux de neutrons extraits et de la production commerciale de radioisotopes choisis. On a développé le concept de réacteur avancé *MAPLE* pour satisfaire à ces besoins. Le réacteur avancé *MAPLE* est un nouveau réacteur à D_2O à coeur fermé utilisant du combustible d'uranium faiblement enrichi en barres dans un coeur annulaire compact pour produire des flux maximals de neutrons thermiques de $1x10^{19}$ $n \cdot m^{-2} \cdot s^{-1}$ dans le réflecteur et des flux maximals de neutrons rapides de $3x10^{18}$ $n \cdot m^{-2} \cdot s^{-1}$ dans un montage d'irradiation central à puissance thermique débitée de 50 MW. On minimise les frais d'investissement et les frais de développement supplémentaires en employant la technique de réacteur *MAPLE* au plus haut degré possible.

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ABSTRACT

High-flux neutron sources are continuing to be of interest both in Canada and internationally to support materials testing for advanced power reactors, new developments in extracted-neutron-beam applications, and commercial production of selected radioisotopes. The advanced *MAPLE* reactor concept has been developed to meet these needs. The advanced *MAPLE* reactor is a new tank-type D_2O reactor that uses rodded low-enrichment uranium fuel in a compact annular core to generate peak thermal-neutron fluxes of 1×10^{19} $n \cdot m^{-2} \cdot s^{-1}$ in the reflector and peak fast-neutron fluxes of 3×10^{18} $n \cdot m^{-2} \cdot s^{-1}$ in a central irradiation rig with a thermal power output of 50 MW. Capital and incremental development costs are minimized by using *MAPLE* reactor technology to the greatest extent practicable.

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CONTENTS

1. INTRODUCTION

Over the next ten to twenty years, a major expansion in the utilization of intense neutron fields is anticipated, subject to the availability of an appropriate mix of medium-, high-, and ultra-high-flux neutron sources. At the leading edge in terms of flux intensity, an ultra-high-flux neutron source such as the proposed Advanced Neutron Source (ANS) facility [1,2] is needed to generate neutron fluxes approaching 1×10^{20} $n \cdot m^{-2} \cdot s^{-1}$ for difficult experiments in condensed-matter physics, for certain materials irradiation studies, and for the large-scale production of transuranium isotopes. Considering the saturated utilization of the existing high-flux reactors at Grenoble, Brookhaven, and Oak Ridge, new facilities with peak available neutron fluxes of 0.5 to 2×10^{19} $n \cdot m^{-2} \cdot s^{-1}$ will substantially augment the world's capability in materials testing for advanced fission and fusion reactors and in advanced basic and applied research using extracted neutron beams. Furthermore, the real key to global access to the peaceful benefits of nuclear science and technology is an international network of modern medium-flux (peak fluxes of 1 to 5×10^{18} $n \cdot m^{-2} \cdot s^{-1}$) neutron sources to facilitate practical applications in areas ranging from neutron scattering and nuclear physics in support of national research programs, to materials testing and manpower training in support of power-generation programs, to materials analysis and the production of key radioisotopes in support of medicine, industry, and agriculture.

Notwithstanding the exciting pace of development in accelerator technology [1,3], fission-based systems are likely to continue to dominate the overall population of neutron sources for the next decade or two. While accelerator-driven spallation sources are regarded as somewhat less difficult to site than comparable fission-reactor sources, their capital and operating costs are substantially higher than conventional reactor sources [1]. Moreover, the research and development program required to establish an ultra-high-flux facility is judged to be "moderately large" for a spallation source, compared to "modest" for the current ANS concept [1].

The need for advanced neutron sources has long been recognized in Canada. Between 1963 and 1967, Atomic Energy of Canada Limited (AECL) study teams investigated the accelerator-based ING (Intense Neutron Generator) concept [4,5] whose objective was to generate peak unperturbed thermal neutron fluxes of about 1×10^{20} $n \cdot m^{-2} \cdot s^{-1}$, which would have yielded a factor of 25 improvement over the best performance since achieved in the NRU reactor.

During the past several years, AECL has been developing the new MAPLE multipurpose reactor concept [3,6,7] designed to generate peak thermal neutron fluxes of up to 3×10^{18} $n \cdot m^{-2} \cdot s^{-1}$ in its heavy water reflector at a nominal thermal power level of 15 MW_{th}. AECL will produce key short-lived radioisotopes such as ^{99}Mo commercially, and will demonstrate MAPLE technology in the prototype 10-MW_{th} MAPLE-X10 facility now being constructed at its Chalk River Nuclear Laboratories.

Also, the Canadian Institute for Neutron Scattering (CINS) has recently made recommendations to the Natural Sciences and Engineering Research Council (NSERC) regarding the new and upgraded facilities necessary to sustain neutron scattering research in Canada [8]; the recommendations featured the near-term upgrading of the McMaster Nuclear Reactor with a 5-MW_{th} MAPLE reactor and the study of mid-term options to strengthen Canadian access to high and ultra-high neutron fluxes, including a MAPLE-based high-flux neutron source. McMaster University is currently seeking NSERC funding for the MAPLE upgrade. Additionally, AECL has just commissioned studies to compare an advanced D_2O-cooled MAPLE reactor with an accelerator-based neutron source as prospective successors to NRU.

2. A NEW CANADIAN HIGH-FLUX NEUTRON SOURCE

To date, the MAPLE program has focused on the development of a modest-cost multipurpose medium-flux neutron source to meet contemporary requirements for applied and basic research using neutron beams, for small-scale materials testing and analysis, and for radioisotope production. The basic MAPLE concept incorporates a compact light-water cooled and moderated core within a heavy-water primary reflector to generate strong neutron flux levels in a variety of irradiation facilities. Its major design features are:

1) **Compact, Light-Water-Cooled and -Moderated Core** - The MAPLE core volume is limited to about 63 litres (nineteen 600-mm long fuel assemblies), which results in the generation of very strong fast and intermediate neutron fluxes within the core and the availability of unusually strong thermal neutron fluxes at irradiation facilities in the core and surrounding reflector. For example, the peak unperturbed thermal neutron flux is 4×10^{17} $n \cdot m^{-2} \cdot s^{-1} \cdot MW^{-1}$ in a central flux trap and 2×10^{17} $n \cdot m^{-2} \cdot s^{-1} \cdot MW^{-1}$ in the heavy-water reflector.

2) **LEU-Silicide Fuel Particles Dispersed in Aluminum Rods** - MAPLE fuel meat is LEU (low-enrichment-uranium, about 19.7 weight percent ^{235}U in total uranium) U_3Si particles dispersed in an aluminum matrix; it is coextrusion clad with aluminum to form finned rods. This fuel has been developed by AECL as part of the international RERTR (Reduced Enrichment for Research and Test Reactors) program for use in the NRU, MAPLE-X10, and other MAPLE reactors.

3) **Heavy-Water Primary Reflector** - The MAPLE reactor concept employs heavy water as the primary reflector. Heavy water provides optimum transmission of neutrons from the core to the horizontal beam ports and various vertical facilities used for neutron activation analysis, radioisotope production, etc.

4) **Customized Beam-Tube Arrangement** - A variety of beam-tube arrangements can be accommodated in the MAPLE reactor assembly. The number and orientation of the beam tubes are adjusted to meet the specifications and requirements of facility users.

5) <u>MAPLE Safety Features</u> - The MAPLE design relies on diverse safety measures to assure protection of operating staff and members of the public in the event of conceivable accidents. For example, the core is deliberately undermoderated so that all important reactivity coefficients are appropriately negative. Also, one reactor shutdown system is physically separated and the second is functionally isolated from the reactor regulation system, and fuel changing can proceed without the need to disable the control or shutdown systems.

In view of the renewed Canadian interest in a high-flux neutron source, the MAPLE group has begun to explore advanced concepts based on AECL's experience with heavy-water reactors. The overall objective is to define a high-flux facility that will support materials testing for advanced power reactors, new developments in extracted neutron beam applications, and/or production of selected radioisotopes. The design target is to attain similar performance levels to HFR-Grenoble, HFBR, and HFIR in a new D_2O-cooled, -moderated, and -reflected reactor based on rodded LEU fuel. To minimize capital and incremental development costs, the design concept uses MAPLE reactor technology to the greatest extent practicable.

The main performance goals for the new advanced MAPLE_D_2O reactor are a peak thermal neutron flux of about 1×10^{19} $n \cdot m^{-2} \cdot s^{-1}$ in the heavy water reflector and a peak fast-neutron flux of 2×10^{18} $n \cdot m^{-2} \cdot s^{-1}$ in an central irradiation facility for a core configuration in which the maximum linear fuel rod rating is less than 120 $kW \cdot m^{-1}$.

3. DESCRIPTION OF THE MAPLE_D_2O REACTOR

The MAPLE_D_2O reactor (Figures 1 and 2) is a tank-type reactor employing heavy water for cooling, moderation, and reflection. A 19-site MAPLE grid plate structure is installed within the stainless-steel tank (3.0 m tall by 2.2 m diameter) to form an inlet plenum/lower reflector in the bottom metre of the tank. Hexagonal zirconium-alloy MAPLE flow tubes, lengthened to accept 1.0-m long fuel assemblies, thread and lock into the grid-plate sites; non-fuel modules such as irradiation rigs may be similarly attached to the grid plate. Heavy water from the primary heat exchangers enters the lower reflector region of the tank and is forced upwards through the flow tubes to cool the fuel. It then mixes in an outlet chimney and passes through apertures to the primary reflector region connected via exit nozzles and outlet piping to the primary coolant pumps. The main reactor specifications are presented in Table 1.

Table 1 also has the fuel specifications. The MAPLE_D_2O fuel assembly uses 1000-mm lengths of NRU-type U_3Si-Al fuel rods in a 60-rod fuel assembly; however, the standard NRU sheath thickness is reduced from 0.76 mm to 0.38 mm. The performance of the U_3Si-Al fuel rods has been excellent, with up to 93 percent burnup of the initial fissile material being achieved at very high linear power ratings (up to 100 $kW \cdot m^{-1}$) with acceptable swelling behavior and no defects. For low-burnup fuel, maximum linear power ratings of 120 $kW \cdot m^{-1}$ have been found acceptable.

Hafnium absorber blades are inserted immediately outside the core for reactivity control, generally following the contours of the core. When deployed, the absorber blades isolate the fuel from the heavy water outside the core. The principal reactor shutdown system hydraulically actuates a set of six U-shaped absorber blades that fit around the corner sites of the 19-site core. A set of six V-shaped absorber blades is normally operated by the reactor regulating system using stepper motors to position mechanically driven absorber shafts; a second independent shutdown can override the regulating system by releasing magnetic latches to insert its reactivity-control absorbers.

The reactor regulating system uses a digital computer system to initiate and maintain selected reactor flux and power levels and to acquire, record, and display process information. Its automatic-control algorithm effects reactor changes in minimal time from the current setpoint while avoiding overshoot and the violation of rules governing minimum reactor period and maximum acceptable rate of absorber withdrawal.

The reflector tank is penetrated vertically by appropriate fuel-test loops, cold and/or hot sources, and irradiation rigs, and horizontally by a set of zirconium-alloy beam-tubes. It is expected that most MAPLE_D_2O beam tubes will be rectangular in cross section; the nominal specification is 150 mm high by 60 mm wide.

To limit beam-tube lengths while reducing neutron and γ fields to acceptable levels, the reactor tank is closely surrounded by a thick (600-mm) thermal shield whose average composition, by volume, is seventy percent iron and thirty percent water. At a thermal power level of 60 MW, the radiation fields are reduced to 25 $\mu Sv \cdot h^{-1}$ by an additional 1350 mm of ilmenite concrete. Accordingly, typical distances from the nose of the beam tube to the working face are approximately 3 m.

4. MAPLE_D_2O STUDIES

4.1 Physics Studies

Scoping calculations for the MAPLE_D_2O reactor were performed for two alternative core configurations - eighteen fueled sites with the central site unfueled and twelve outer sites fueled with the central seven sites unfueled. The 3DDT three-dimensional multigroup diffusion code [9] was employed with two neutron energy groups, a thermal group with $E \leq 0.626$ eV and a fast group with $E > 0.625$ eV. Cell-averaged cross sections were prepared using the supercell option of the WIMS-CRNL code [10] to model the cell of interest in its local environment and an 89-group library derived from the ENDF/B-V data file.

The scoping calculations confirmed that the twelve-site annular core incorporated sufficient reactivity margins to support a practical fuel cycle and could attain the targetted fast-neutron flux in a central rig. For the same maximum linear fuel rating, the twelve-site core generated substantially better peak thermal neutron fluxes in the reflector - 49 percent higher than the eighteen-site core. Accordingly, no efforts were made to achieve higher fluxes by flattening the power shape of the eighteen-site core, and subsequent calculations focused exclusively on the flux-trap arrangement formed by the twelve-site core.

Additional 3DDT calculations were performed for 30-MW and 50-MW twelve-site cores using the following five neutron-energy group structure:

FAST	$E > 0.8$ MeV
GROUP 2	9 keV $< E <$ 0.8 MeV
GROUP 3	4 eV $< E <$ 9 keV
GROUP 4	0.626 eV $< E <$ 4 eV
THERMAL	$E <$ 0.625 eV

The same WIMS-CRNL modelling strategy was to prepare the cell-averaged cross sections for 3DDT. The 3DDT calculations were verified by repeating the fresh-core calculations with the MCNP code [11], which uses a general-geometry package and Monte Carlo theory to solve the transport equations in three dimensions with minimal compromise in the realism of the modeling. MCNP relies on a continuous-energy library based on the ENDF/B-V data file.

Table 1 shows the computed reactivity balance for the twelve-site core at 50 MW. The excess reactivity in a fresh core is 177 mk. The estimated short-lived fission-product load is about 51 mk. Allowing 25 mk for beam ports and irradiation sites in the heavy water reflector, and 8 mk as a reserve, the expected core lifetime is 40 full-power days. The corresponding average fuel burnup is estimated at 22% ^{235}U for a whole core replacement scheme. Alternative fuel management schemes will be investigated in future studies.

Figure 3 shows the 3DDT-computed radial distribution of the fast and thermal neutron fluxes at 50 MW for the horizontal plane of maximum thermal flux. The unperturbed peak thermal flux is 1.2×10^{19} $n \cdot m^{-2} \cdot s^{-1}$. For three 60 mm x 150 mm tangential beam tubes at distances of 100 mm, 150 mm, 200 mm from the core wall, the MCNP-computed perturbed thermal fluxes are 9×10^{18} $n \cdot m^{-2} \cdot s^{-1}$, 1.0×10^{19} $n \cdot m^{-2} \cdot s^{-1}$ and 9×10^{18} $n \cdot m^{-2} \cdot s^{-1}$, respectively; the average computed ratio of perturbed to unperturbed flux at the beam tube noses is 0.85.

Figure 4 shows the axial thermal neutron flux distributions for 50 MW at distances of 120 mm and 500 mm from the core edge. The flux skewing is caused by deployment of the regulating-system absorber blades to the core midplane; accordingly, the horizontal beam tubes should be located somewhat below the core midplane to minimize flux shifts during the operating cycle. At 500 mm from the core edge, the peak unperturbed thermal flux is roughly 4×10^{18} $n \cdot m^{-2} \cdot s^{-1}$, which corresponds to the maximum available in NRU, and the flux length at half peak extends over about 1.3 m. Hence, although the effect of fueled sites in the reflector have not yet been evaluated, the outer reflector regions appear suitable for high-pressure, high-temperature fuel test loops. Furthermore, it is planned to investigate the prospects for creating local regions of elevated fast flux for materials-damage studies via fast-neutron loops nearer the reflector flux peak.

Fast neutron fluxes that could be produced in a central materials irradiation facility have also been investigated. For a zirconium-walled rig displacing a cylinder of heavy water 1000 mm long by 90 mm diameter, the fast (> 0.8 MeV) neutron flux in a strongly absorbing steel rod is estimated to be 2.4×10^{18} $n \cdot m^{-2} \cdot s^{-1}$. This flux level is comparable to that available in a major facility such as OSIRIS which generates fast neutron fluxes of 2×10^{18} $n \cdot m^{-2} \cdot s^{-1}$ in a cylindrical volume 520 mm long by 30 mm diameter at a power output of 70 MW_{th}.

4.2 Shielding Studies

A brief survey of MAPLE_D_2O shielding requirements was conducted using the one-dimensional discrete-ordinates transport code, XSDRNPM-S [12] and the SCALE 27n-18γ cross-section library [13]. Spherical geometry was assumed with S_{16} angular quadrature, and P_3 anisotropic scattering. The MAPLE core was represented by a spherically homogenized (volume preserved) core with the central island assumed to be voided. The thickness of surrounding D_2O, the tank wall and shields was preserved in the calculations. Peak heating in the concrete and the neutron and γ fields at the shield surface were estimated for a range of concrete and thermal shield thicknesses.

For a thermal power output of 60 MW_{th}, peak heating rates in the concrete are less than 1 $W \cdot L^{-1}$ for thermal shields thicker than 0.26 m. For the same power output and a total doserate of 2.5 $\mu Sv \cdot h^{-1}$, the required thickness of ilmenite concrete is 1.71 m for a 0.40-m thick thermal shield and 1.35 m for a 0.60-m thick thermal shield. The radiation fields at the shield surface are predominantly due to γ radiation (ignoring the effects of shield penetrations); the neutron contribution to the overall dose rate is less than one percent.

4.3 Thermalhydraulics Studies

MAPLE_D_2O fluid-flow and heat-transfer requirements were assessed with a one-dimensional thermalhydraulics code [14] that analyzes transient and steady-state conditions for piping networks associated with pool-type and low-pressure tank-type reactors. The heat-transfer package contains correlations that describe all the heat-transfer regimes of a boiling curve. A fully implicit finite-difference scheme is used to solve the transient heat-conduction equation for a single fuel rod. The finned rods were conservatively modelled by choosing the sheath outer radius to preserve the total sheath mass.

The coolant flow requirement was determined by limiting the maximum operating heat flux for a fuel rod with a linear power rating of 120 $kW \cdot m^{-1}$ to less than two-thirds (actually 58 %) of the heat flux at the point of onset of nucleate boiling. For an inlet pressure of 1.0 MPa and an inlet temperature of 38°C, the required flow velocity is 12 $m \cdot s^{-1}$, which implies a core mass flow of about 420 $kg \cdot s^{-1}$. The corresponding peak fuel temperature is 218°C and the estimated outlet pressure is 370 kPa.

5. CONCLUSIONS

This assessment of the MAPLE_D_2O concept has identified a viable new concept that can be developed to play several roles:

- provide a successor to NRU. The reference annular core concept produces thermal fluxes that exceed those currently available in NRU by a factor of three to five at about half the thermal power output. Fast-neutron fluxes three times higher than the best achievable in NRU can be generated in a larger irradiation volume than is feasible in NRU.
- enhance the global availability of high-flux neutron sources. The reference concept produces comparable accessible thermal neutron fluxes to those achieved in ILL, HFBR and HFIR.
- complement the proposed ANS reactor by enabling the building of similar instrumentation for a compatible facility generating ten to twenty percent of the targetted ANS conditions.
- extend the current MAPLE reactor family via a high-powered multipurpose reactor design for materials testing, radioisotope production and extracted neutron-beam applications.

This preliminary study of the MAPLE_D_2O reactor shows that a 12-site annular core meets all major requirements for a high-flux multipurpose reactor facility. As the study is based on a cursory examination of the performance potential, more detailed investigations are required to gain a better understanding of its capabilities. Accordingly, AECL is further exploring the feasibility of developing this promising concept.

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TABLE 1

MAPLE_D_2O SPECIFICATIONS

General			
1.	Reactor type	Tank type; low-enriched (19.7 %) uranium fuel; heavy-water cooled, moderated, and reflected	
2.	Nominal power	50 MW	
3.	Purpose	extracted neutron-beam applications; advanced materials testing; radioisotope production	
Reactor Physics			
4.	Core Parameters	k_{eff} = 1.215	
5.	Thermal neutron flux	Maximum in island: in reflector:	1.0×10^{19} $n \cdot m^{-2} \cdot s^{-1}$ 1.2×10^{19} $n \cdot m^{-2} \cdot s^{-1}$
6.	Reactivity balance	Burnup Xe & Sm Experiments Reserve	91 mk 53 mk 25 mk 8 mk
Core			
7.	Shape & dimensions	Irregular hollow hexagon, 1000 mm high, maximum diameter 400 mm	
8.	Number of subassemblies	12 hexagonal zirconium-alloy flow channels, 77.6 mm (externally) across the flats, 1.6 mm thick, containing 60-rod fuel assemblies	
9.	Lattice	Hexagonal, pitch approx. 80 mm	
10.	Core fissile load	Approx. 10.6 kg ^{235}U	
11.	Power density	Average 750 $kW \cdot L^{-1}$ Maximum 1300 $kW \cdot L^{-1}$	
12.	Operating cycle	40 d	
13.	Burnup	Average 22 % of initial ^{235}U	
14.	Moderator	Heavy water	
Fuel Assemblies			
15.	Subassemblies	60 rods plus central support shaft in a hexagonal array, pitch 9.5 mm	

TABLE 1 (cont'd)

16.	Form & Composition	NRU-type U_3SiAl rods coextrusion clad with finned aluminum alloy; fuel meat 5.48 mm diameter by 1000 mm long; cladding thickness 0.38 mm; six fins per rod 1.02 mm high by 0.76 mm wide; Enrichment 19.7 % ^{235}U in U, by weight;
17.	Uranium content	0.88 kg ^{235}U; 4.47 kg U
Core Heat Transfer		
18.	Heat transfer area	Total 22.9 m^2, including fins
19.	Heat flux	Average 2.18 $MW\cdot m^{-2}$ Peak 3.77 $MW\cdot m^{-2}$
20.	Fuel rod temperatures	218°C maximum in fuel 138°C maximum at clad surface
21.	Coolant	heavy water
22.	Core flow	Velocity 12 $m\cdot s^{-1}$ Total mass flow 420 $kg\cdot s^{-1}$
23.	Coolant pressures & temperatures	Inlet 1000 kPa, 38°C Outlet 370 kPa, 57°C
Control		
24.	Regulating system	Single PROTROL (industrial PC-based) digital control computer; six V-shaped Hf absorber blades attached above to stepper-motor-driven shafts; blade surface 92 mm wide by 1100 mm high; total reactivity worth 307 mk
25.	Shutdown System #1	Six U-shaped Hf absorber blades attached above to hydraulically-actuated shafts, blade surface 138 mm wide by 1100 mm high
26.	Shutdown System #2	Magnetic-clutch override of regulating system
Reflector		
27.	Material & dimensions	heavy water surrounding core, 2.2 m diameter by 3.0 m high
Reactor Vessel		
28.	Material, form & dimensions	Stainless-steel right-circular cylinder, 2.2 m inner diameter by 3.0 m high, 12 mm thick

TABLE 1 (cont'd)

Experimental Facilities		
29.	Horizontal beams	Six to nine rectangular zirconium-alloy tubes, 60 mm wide by 150 mm high; Accessing thermal neutron fluxes of 8×10^{18} $n \cdot m^{-2} \cdot s^{-1}$ to 1.0×10^{19} $n \cdot m^{-2} \cdot s^{-1}$
30.	Cold source	To be specified, possibly a liquid hydrogen-deuterium mixture optimized for a cylindrical source of 200 mm diameter,
Shielding		
31.	Radial	600 mm thermal shield: 70% iron, 30% water; 1350 mm ilmenite-concrete biological shield
32.	Radiation fields	gamma: 20 $\mu Sv \cdot h^{-1}$ neutron: less than 0.2 $\mu Sv \cdot h^{-1}$

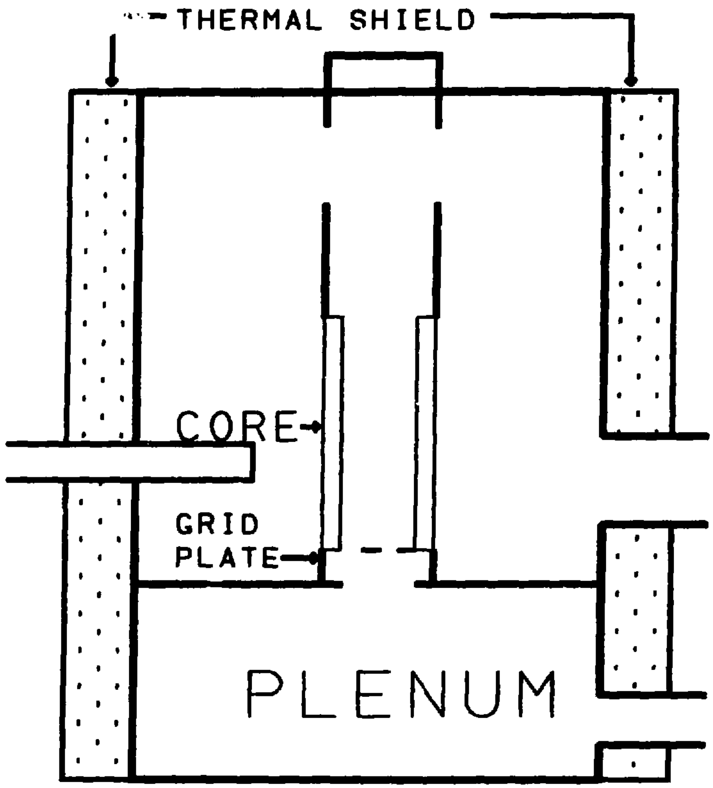

Figure 1: Vertical MAPLE_D_2O Layout

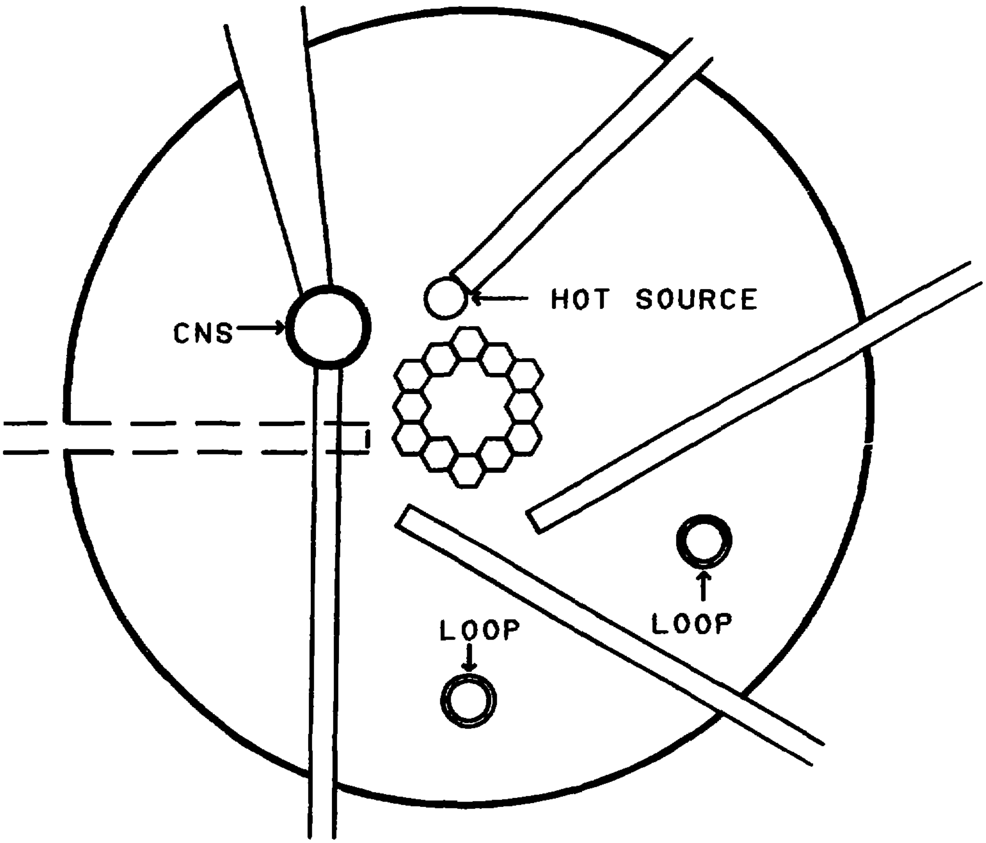

Figure 2: Horizontal MAPLE_D_2O Layout

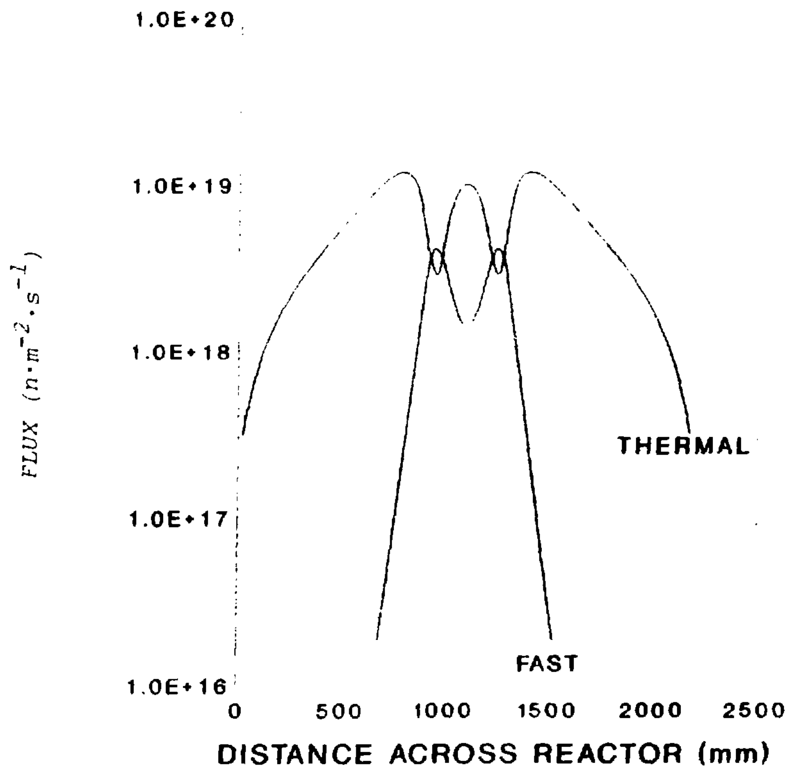

Figure 3: MAPLE_D_2O Radial Neutron Flux Distributions at 50 MW

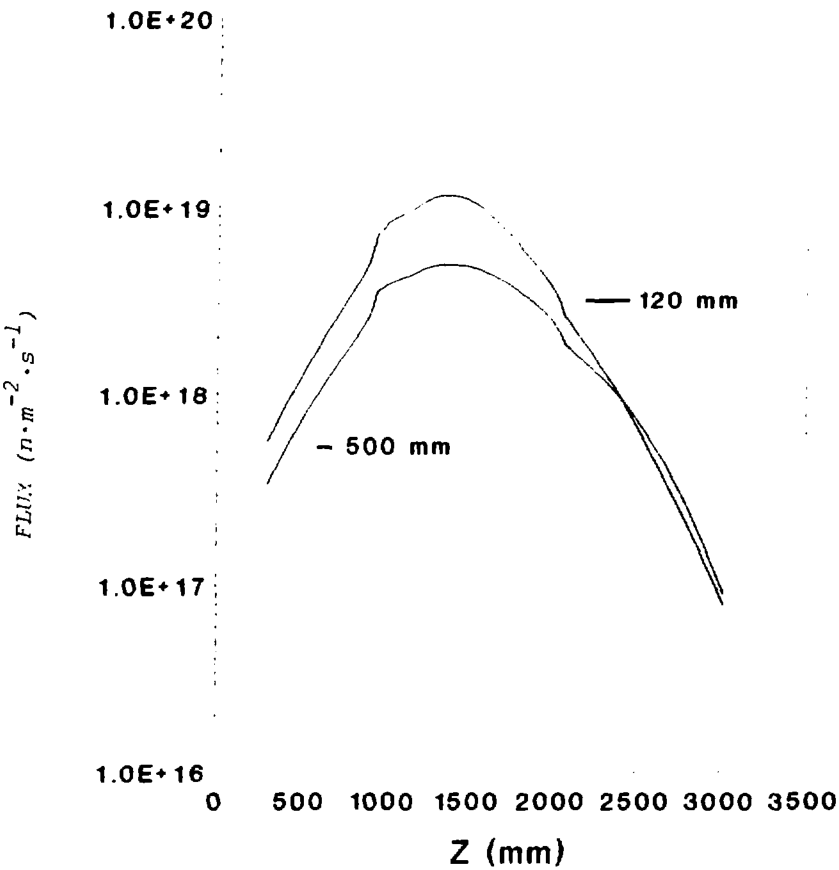

Figure 4: MAPLE_D_2O Axial Thermal Flux Distributions at 50 MW

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