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MAPLE-MNR: PRELIMINARY THERMALHYDRAULICS STUDIES

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ABSTRACT

McMaster University has outlined the incentives for replacing the present 30-year old McMaster Nuclear Reactor (MNR) core with a core of MAPLE design. Briefly, such a renewal of MNR would provide experimental facilities with significantly higher thermal neutron fluxes. This involves a relatively low cost, since the present MNR cooling and auxiliary reactor systems would be retained. In this paper, preliminary thermalhydraulics studies are presented.

INTRODUCTION

The McMaster Nuclear Reactor (MNR) is a 5 MW, MTR-type, open-pool research reactor. It consists of a rectangular matrix core which contains the fuel assemblies and special sites for the irradiation of samples. The core, its support structure, and the control and reactivity mechanisms are suspended in the pool from a moveable manbridge spanning the pool. Cooling water is drawn downward from the reactor pool through the core to the primary cooling system via an outlet in the pool floor.

It has been proposed to replace the MNR with a new, Canadian designed, 5 MW reactor core known by the acronym MAPLE (Multipurpose Applied Physics Lattice Experimental). This reactor is identified as MAPLE-MNR to distinguish it from the 10 MW MAPLE-X reactor being designed by Atomic Energy of Canada Ltd. (AECL) for installation at its Chalk River Nuclear Laboratories. The MAPLE-MNR reactor is closely patterned on the MAPLE-X reactor. It is intended to install the MAPLE-MNR and its control system into the existing biological shielding and containment building, using the existing cooling and heating systems, etc. This will significantly reduce the design and construction costs, and may keep licensing requirements to a minimum. In this work, some highlights of the preliminary thermalhydraulic studies will be presented based on the proposed MAPLE-MNR core. These are: (1) Numerical flow simulations of the chimney inside the existing MNR swimming pool by the MAPL3D code [1]; (2) Numerical flow simulation of the primary cooling system using the SPORTS-M [2]; and (3) Identification of possible cooling modes under loss-of-forced flow conditions.

MNR PRIMARY COOLING SYSTEM

In the proposed implementation of a MAPLE reactor core into the MNR reactor system, all of the in-pool components would be replaced. The original primary and secondary cooling systems would be retained, with the exception of components which may need to be renewed (such as the main pump) or slightly modified.

Figure 1 shows a schematic of the primary cooling system which is used in the present MNR, and will be used in the proposed MAPLE-MNR. Elevations of the primary system components are not reflected in this figure - the bottom of the heat exchanger is actually at core level.

Demineralized light water coolant passes from the core to a holdup tank, where short-lived radionuclides, such as N-16 are formed by activation of the coolant, decay. After a holdup time of 5 to 10 minutes, the coolant is pumped through two heat exchangers and back to the core. The coolant passes through several monitors for operational as well as safety control, such as a flowmeter and temperature sensors.

In contrast to the MNR and MAPLE cooling systems, the MAPLE-MNR system is an open loop in which the chimney water drains directly into the holdup tank before being pumped back through the heat exchangers.

MAPLE MNR REACTOR

Figure 2 shows the schematic of the MAPLE-MNR reactor core and chimney, which are connected by the coolant inlet and outlet piping to the original MNR primary cooling system. The same pool outlet (directly below the core) and inlet (pool floor a few meters away) as used with the MNR would be retained. Most of the primary system piping is encased in concrete for radiation shielding and for the protection of pipe integrity.

In Figure 3, a side view of the pool inlet piping is shown. A characteristic feature of the MAPLE design is the 10% bypass flow that is required to prevent coolant that has passed through the core (and as a result contains radionuclides) from reaching the pool surface. The bypass flow is pulled down the chimney, and is routed with the core discharge into the primary cooling system piping via the chimney suction outlets.

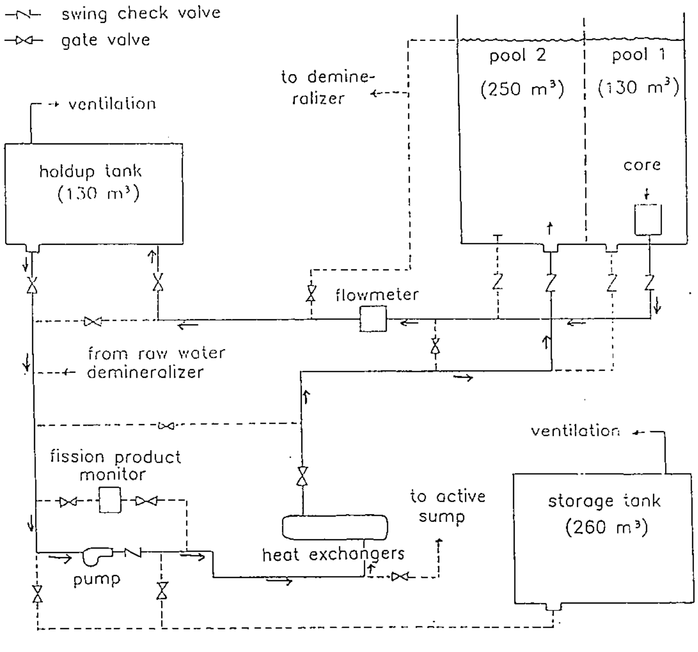

Figure 1 Schematic of primary cooling system of McMaster Nuclear Reactor.

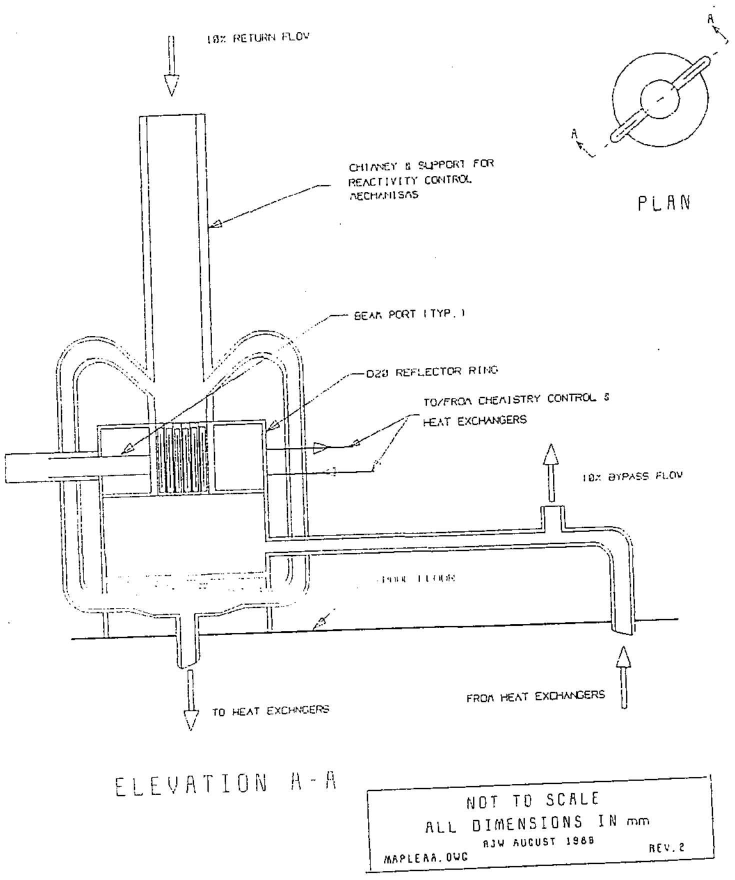

Figure 2 Schematic of proposed MAPLE-MNR core.

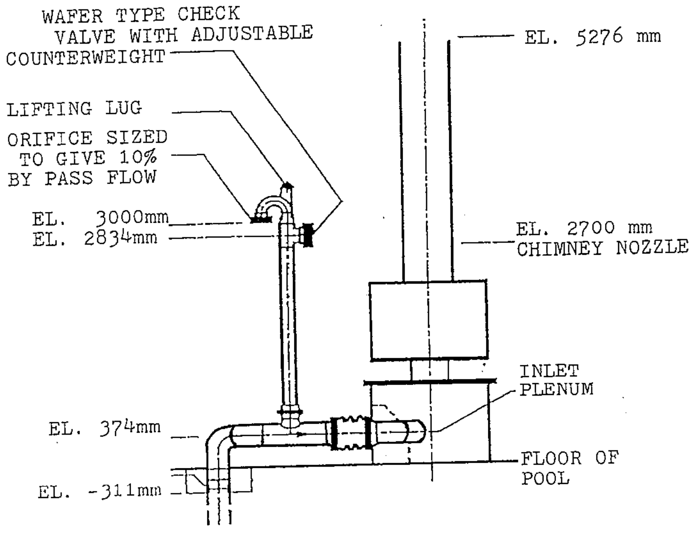

Figure 3 Primary coolant inlet piping in pool.

The bypass flow is drawn off the inlet flow through a vertical pipe, as indicated in Figure 3. There is also a safety check valve located along this pipe. The check valve is closed under normal operating conditions and opens when the primary system pressure drops below a given point according to the setting of counterweights. This is an important safety feature which will give pool water access to the core under reduced flow conditions, so that natural convection may take place.

Under reactor shutdown conditions, the level of radioactive decay heat that must be removed can be up to 6% of the maximum reactor power. Removal is either by normal forced circulation through the primary cooling system, or by natural circulation if the primary system is disabled.

A tank of heavy water (D_2O) surrounds the fuel to provide moderation and reflection of neutrons. When the reactor is operating, this D_2O doughnut is especially rich in thermal neutrons. For that reason, the D_2O doughnut is penetrated by several experimental beam tubes. The D_2O tank will require an independent cooling system, since it absorbs about 0.25 MW at 5 MW operation from heating by neutrons and gamma-rays. The moderator system must be closely monitored for buildup of tritium.

The MAPLE core consists of 36-pin fuel assemblies for use in standard lattice sites, and 18-pin assemblies for use in reactivity control sites. The bundles proposed for the MAPLE-MNR are 60 cm long and contain 19.7% U-235 in a U_3SiAl alloy dispersed in an aluminum matrix and sheathed with finned aluminum.

The reactivity control for the MAPLE reactor core consists of control rods and shutoff rods. These rods are held in position by hydraulic cylinders or electromagnets which release the rods in the event of a power failure. The rods are enveloped by shroud tubes that are permanently positioned within the chimney.

THERMALHYDRAULICS OF THE PRIMARY COOLING SYSTEM

The major concern was whether or not the present primary cooling water pump, heat exchangers and piping system could meet the requirements of the new reactor. As part of this study the existing primary heat transport system attached to a MAPLE was modeled with the SPORTS-M thermalhydraulic code [2,5].

SPORTS-M is a computer code that performs steady state and transient thermalhydraulic analysis of piping networks. The governing equations used in the code are the conservation equations of mass, momentum and energy together with the equation of state for a one-dimensional transient flow of a homogeneous two-phase mixture. A heat transfer package and radial heat conduction module are coupled to the hydraulic modules. The heat transfer package contains correlations that address all the heat transfer regimes of a boiling curve. The correlations are coupled with a radial heat conduction model for a single fuel pin that solves the transient heat conduction equation by a fully-implicit finite-difference scheme.

Table 1 lists the segment names used in the MAPLE-MNR model and the description of the portion of the primary cooling system that the segment models. Figure 4 shows the idealization of the MAPLE-MNR primary cooling system. A'*' in the segment name indicates a wild character that represents the flow path. The characters chosen to represent the three flow paths are: 'R' for the reactivity control sites, 'D' for the 36-pin driver fuel site and 'A' for the zirconium irradiation module sites. Details of the hydraulic modelling can be found in Ref. [3].

Axial power distributions for the driver and reactivity control sites were obtained from Smith [5].

TABLE 1

SEGMENT DESIGNATIONS USED IN THE MAPLE-MNR MODEL

COUTP	"chimney outlet pipe", the portion of chimney where the lines to the delay tank join the chimney.
DCOUT	"double chimney outlet", the two eight inch lines leading from the chimney to the diffuser and "T" near the pool floor.
FITGS	"fittings", the diffuser and "T" combining the chimney outlet flow into a single 10 in. line.
SCOUT	"single chimney outlet", the 10 in. line running from the piping "T", to the delay tank inlet. (excluding valve 10)
VLV10	"valve 10", the gate valve used to regulate the flow from the pool to the delay tank.
DTNKU	"delay tank up", the delay tank from the floor to the surface of the tank. (1/2 of the total delay tank volume)
DTNKD	"delay tank down", the delay tank from the surface to the floor of the delay tank. (1/2 of the total delay tank volume)
PMPIN	"pump inlet line", the line running from the delay tank to the pump suction flange.
PSRES	"pump stopped resistance", a dummy segment used for modelling natural convection circulation.
PUMP	"pump", the pump segment.
PDISC	"pump discharge line", the 10 in. line running from the pump centerline to the heat exchanger inlet.
HTEX	"heat exchanger", the heat exchanger segment.
HXOUT	"heat exchanger outlet", the 10 in. line running from the heat exchanger outlet to the point where the bypass line connects (bypass takeoff).
*LINE	"inlet line", the core inlet line running from the bypass takeoff to the inlet plenum.
*INPL	"inlet plenum", the inlet plenum.
*GREG	"grid region", the region under the reactor core adjacent to the grid structure under the D_2O tank.
*GRID	"grid plate", the grid plate, cup, hanger bar and bottom end plate for the fuelled sites.
COR36	"core 36-pin", the 36-pin driver fuel sites.
COR18	"core 18-pin", the 18-pin driver fuel sites.
CORZR	"core ZR", the zirconium irradiation module sites.
*TOP	"flow tube top", the flow tube top from the top end plate to the top of the flow tube for the fuelled sites.
*LCHM	"lower chimney", the portion of the chimney between the top of the flow tubes and the point on the chimney where the lines to the delay tank join the chimney.
BYPAS	"bypass", the bypass line from the bypass takeoff to the orifice plate.
ORFIC	"orifice", the orifice plate
POOLT	"pool top", the portion of pool adjacent to the chimney between the orifice plate and the chimney top.
UCHIM	"upper chimney", the portion of chimney from the chimney top to the portion of chimney where the lines to the delay tank join the chimney.
LSEG	"last segment", a dummy segment used for convenience.

The SPORTS-M fuel conduction model is a one-dimensional model and cannot accurately predict the two-dimensional nature of the MAPLE-MNR fuel fins. The sheath radius of the SPORTS-M model was chosen so that the finned and unfinned sheath mass were equivalent. This means that the heat transfer surface area of the model is less than the actual surface area, therefore the predicted flux will be higher than the actual flux. The thermal-hydraulic results are therefore considered to be a conservative prediction.

A summary of the calculated MAPLE-MNR steady state thermalhydraulic parameters is given in Table 2. The numerical predictions indicated that the onset of nucleate boiling (ONB) for the hottest part in each fuelled segment is predicted to be within maximum allowable levels.

TABLE 2

THERMALHYDRAULIC SPECIFICATIONS FOR MAPLE-MNR

	PARAMETER	VALUE	
		Driver sites	Control/Shutdown sites
CORE	Total Power (MW)	3.15	1.85
	Coolant Inlet Temperature (°C)	35.0	35.0
	Coolant Outlet Temperature (°C)	49.47	45.59
	Coolant Mass Flow Rate (kg/s)	52.18	41.89
	Grid Plate Inlet Pressure (kPa abs.)	205.526	205.592
	Flow Tube Outlet Pressure (kPa abs.)	171.139	171.082
	Pressure Drop (kPa)	34.387	34.510
	Coolant Velocity over fuel assembly (m/s)	1.90	3.93
	Maximum Surface Heat Flux (MW/m^2)	0.689	1.333
	Maximum Fuel Sheath Temperature (°C)	96.5	100.4
	Maximum Fuel Centerline Temperature(°C)	109.6	125.7
	Maximum ONB Ratio	0.635	0.650
CORE	Total Coolant Flow Rate (kg/s)	94.09	
ZIRCONIUM IRRADIATION MODULES	Coolant Flow Rate (kg/s)	6.38	
	Ave. Coolant Velocity (m/s)	0.773	
BYPASS FLOW	Coolant Flow Rate (kg/s)	12.18	
	Coolant Velocity in Pool (m/s)	0.0017	
HEAT EXCHANGER	Number of Heat Exchangers	1	
	Heat Removal Rate (MW)	5.0	
	Primary Coolant Mass Flow Rate (kg/s)	112.65	
	Primary Coolant Inlet Temperature (°C)	45.66	
	Primary Coolant Outlet Temperature(°C)	35.0	
	Pressure Drop (kPa)	103.13	
PUMP	Number of Pumps	1	
	Mass Flow (kg/s)	112.65	
	Suction Side Pump Pressure (kPa)	128.13	
	ΔP Across Pump (kPa)	190.33	
	Pump Head (m)	19.6	

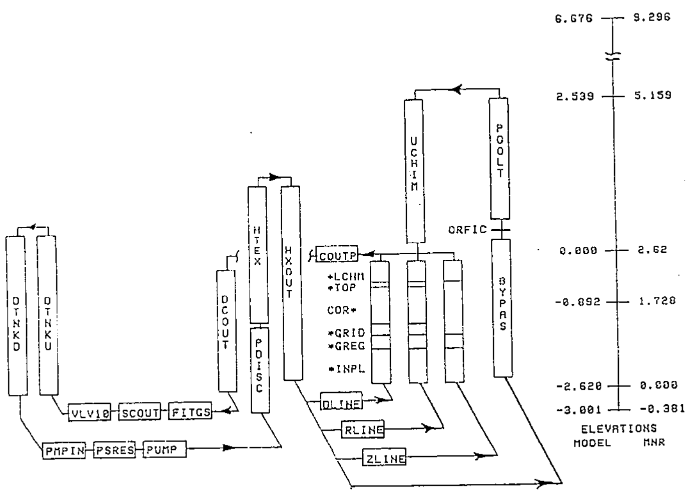

Figure 4 Idealization of MAPLE-MNR primary cooling system.

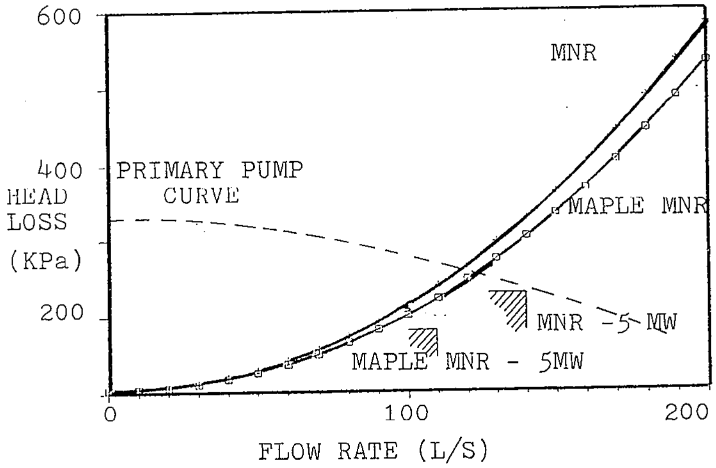

Figure 5 Primary cooling system resistance curve.

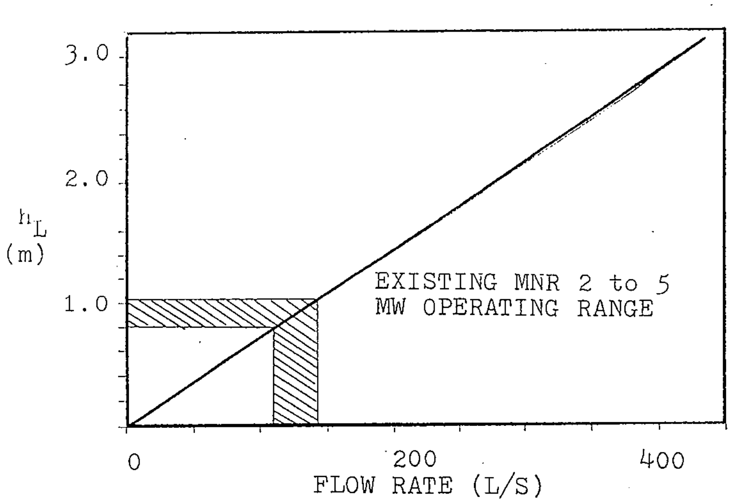

Figure 6 The holdup tank water level as a function of system flowrate.

Figure 5 shows an estimated system resistance, head loss vs. flowrate, curve both before and after the additional pipework has been added. It can be seen that the new piping does not add significantly to the present system resistance. The original MNR pump head loss vs. flow curve has been superimposed in Figure 5 for illustration purposes.

Figure 5 indicates that the primary water pump, providing it is brought up to its full specification with the addition of a new impeller, would be more than capable of handling the flow requirements of the MAPLE reactor at 5 MW power. The fact that there is no increase in flow required also suggests that the existing holdup tank will be adequate to provide the delay times necessary and, as there is now, leave plenty of capacity in hand. Figure 6 shows the holdup tank water level plotted against system flow for a delay time of 300s. The present MNR 2MW operating flow, the predicted MAPLE-MNR 5 MW operating flow calculated by SPORTS-M and the original MNR 5 MW flow are shown for comparison purposes. Since the tank is built between the inner and outer walls of the reactor building, modification to it would be an expensive proposition. However, as can be seen from Figure 6, this is unlikely because there is sufficient spare capacity to meet the minimum delay requirement of 300s for flow rates up to nearly 450 l/s. This is approximately 400 percent greater than the flow predicted by SPORTS-M for the MAPLE-MNR operating at 5 MW.

In summary, the results indicate that the flow areas and fluid velocities in the system do not exceed those that we have now for 5 MW operation. The factor of safety in terms of the ONB is approximately 30 percent so that the probability of fuel dryout is low.

CHIMNEY DESIGN AND POOL DEPTH

As mentioned previously, one of the few major changes in the new MAPLE-MNR reactor compared to the existing MNR is the reversing of direction of the core cooling water flow.

Having made the decision for upward flow it is then necessary to prevent the short-lived radionuclides from rising to the pool surface where the high energy gamma radiation could become a hazard.

This has been accomplished using a chimney design, Figure 2, which draws off the upward cooling outflow directly as it leaves the core. A bypass flow (approximately 10 percent of total flow) enters the pool directly and is then drawn from the pool down the chimney where it recombines with the core flow near the suction outlets. The verification of this concept has been handled by the MAPL3D code [5]. This study was undertaken to confirm that a reduced chimney height, to 2600 mm from 3000 mm, was sufficient to confine the outflow from the core within the chimney. To demonstrate this, flow patterns in the chimney and the reactor pool were calculated under a variety of conditions. The effects of chimney height, pool diameter, suction outlet elevation, bypass flow ratio, boundary velocity magnitudes, and nonuniform velocity profiles at the core outlet were examined

The major assumptions and idealizations made in the simulations were:

(1) the turbulent viscosity was calculated at each node based on the local values of the velocity and density, ρ, and the core-exit diameter as a length scale from:

$$\mu_t = 0.01\rho \text{ (local velocity)(core-exit diameter).} \qquad (1)$$

This model was to account for mixing of the three interacting streams (core, suction and countercurrent flows) in the chimney and satisfied the scaling laws derived in [1]. As shown in reference [1] the model predicted the experimental results from the 1/5-scale MAPLE hydraulic facility at the

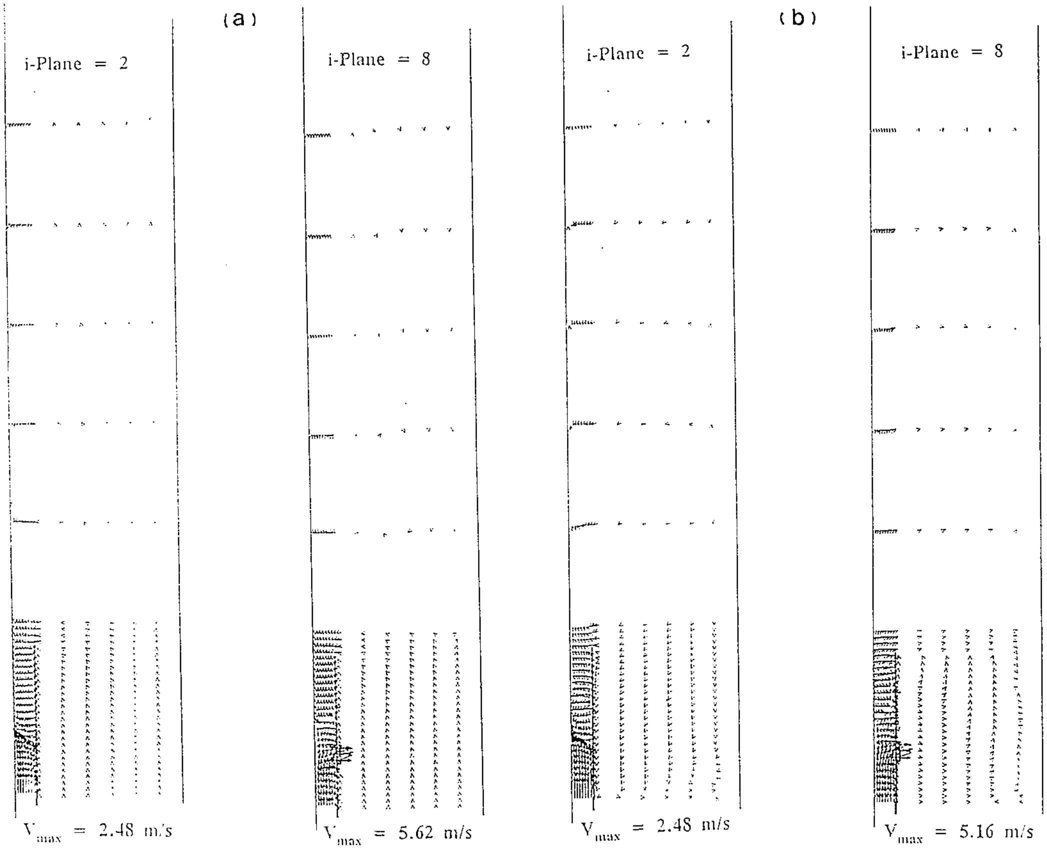

Figure 7 Predicted flow patterns in chimney and pool with (a) no bypass flow, (b) 10% bypass flow.

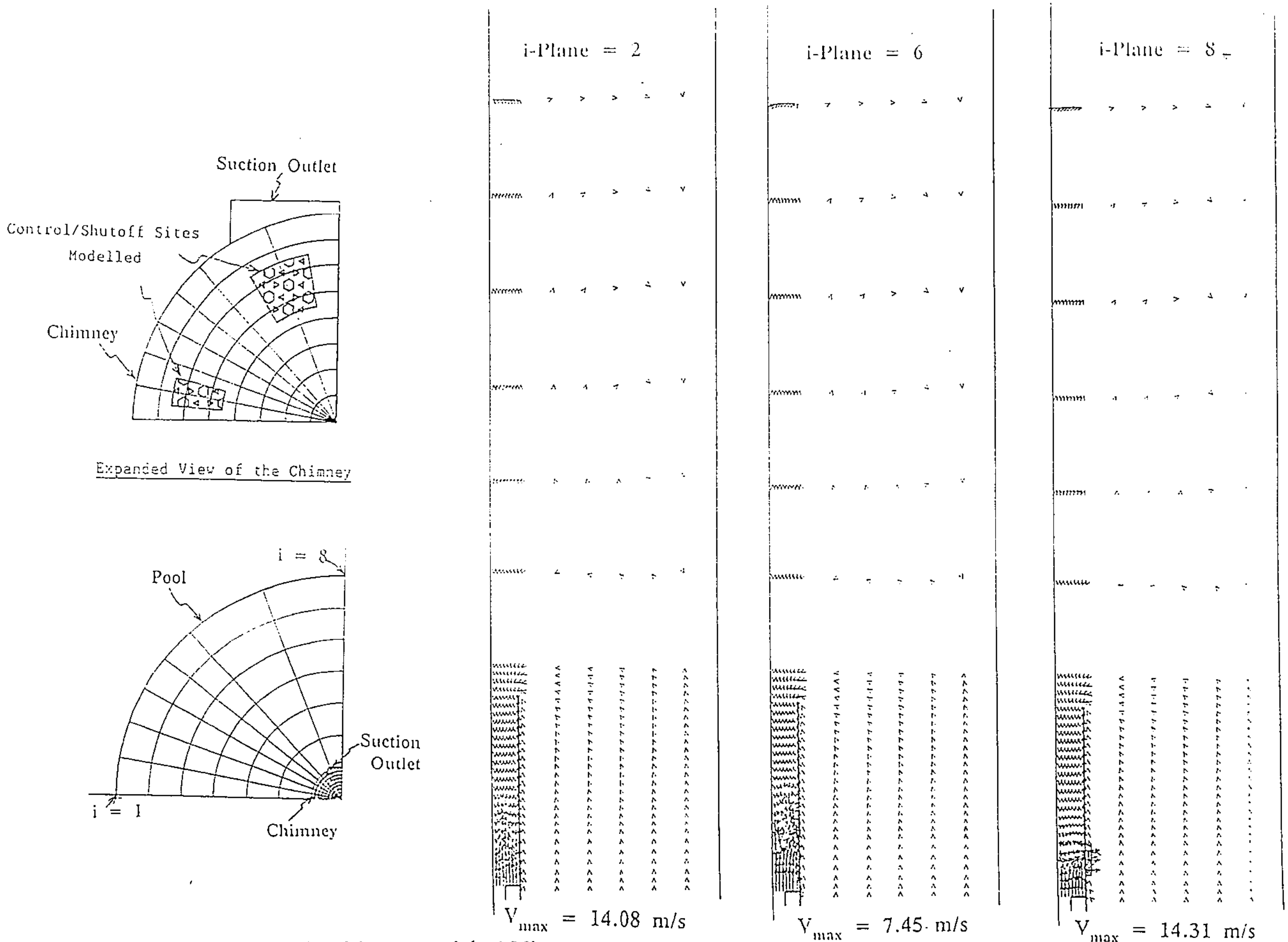

Figure 8 Predicted flow patterns inside chimney with 10% bypass flow with nonuniform core velocity and the flow velocities at the boundaries.

AECL-RC Whiteshell Nuclear Research Establishment reasonably well.

(2) the chimney, the core and the pool in MAPLE-MNR were represented as coaxial cylinders in cylindrical coordinates such that the actual flow areas of each were maintained.
(3) the flow was at steady state and isothermal. The isothermal assumption was found to be reasonable for high-flow conditions, since the buoyant force was relatively small in comparison with other forces from the core, suction and bypass flows.
(4) components and piping obstructing the flow in the chimney and pool were not included in the model. Since the suction outlets are located above the top of fully withdrawn position of the control/shutoff shroud tubes in MAPLE-MNR, predicted flow patterns were considered representative above this position. This assumption was considered reasonable since the high-flow core-jet velocity entering the chimney decayed very little between the top of the reflector tank and the suction outlets.

MAPL3D was used to model the volume above the top of the reflector tank, since the flow patterns in the chimney and pool were the main items of interest. In view of the symmetry of the flow, it is sufficient to model only one quadrant of the system. Thus, two boundaries of the calculation domain consisted of symmetric planes. The inlet flow conditions were explicitly specified at the core exit and the annulus between the inside of the pool wall and the outside of the reflector tank wall such that global mass flow was conserved. A constant, uniform or nonuniform velocity profile at the core exit was specified.

All the internal walls in the pool and chimney were modelled by modifying the corresponding convection-diffusion coefficients so that the neighboring nodes across the wall did not influence each other. Wall shear stresses were determined using a logarithmic velocity profile near the wall.

The initial flow velocity fields were set to zero for the simulations. The converged steady-state solution was independent of the specified initial conditions.

To examine the effect of bypass flow, a case was simulated under no bypass flow conditions. The predicted flow patterns in the chimney and pool under no bypass flow conditions are shown in Figure 7a. Figure 7b shows the plot of velocities which were scaled in relation to their magnitudes. A comparison with no-bypass-flow-to-bypass-flow ratio of 10% reveals that the flow patterns near the suction outlets are similar between the two cases. However, without bypass flow, the fluid in the chimney "leaks out" through the central region of the chimney and returns down through the inner edges of the chimney to make up the mass flow balance. The leaking velocity was predicted to be small and was of the order of 10^{-1} to 10^{-2} m/s (compared to the core velocity of 2.5 m/s and the suction velocity of 5.2 m/s).

The effect of flow velocities at the boundaries with a nonuniform core-velocity profile is shown in Figure 8. To show the effect of velocity magnitudes at the nonuniform flow boundaries, the flow velocities at the boundaries were increased to three times. A bypass flow ratio of 10% was used. The velocity magnitudes were predicted to change, but the flow patterns were unchanged regardless of the magnitudes of velocities at the boundaries.

From the numerical results, the following conclusions were drawn:

(1) the 2.6-m chimney height is sufficient for full containment of the core jet within the chimney at a bypass flow ratio of 10%;
(2) when the core jet is contained in the chimney, the vortex stretching height is unaffected by chimney height, pool diameter or suction outlet elevation (only within limits);
(3) similar flow patterns in the chimney result regardless of the magnitudes of the velocities at the boundaries for both uniform and nonuniform velocity profile at the core exit;
(4) a nonuniform core-velocity profile results in a higher vortex stretching height than a uniform core-velocity profile for a bypass flow ratio of 10%;
(5) under conditions of no bypass flow, a small amount of the core jet leaks out of the chimney top but it returns back into the chimney top.

In summary, the results indicate that a 2600 mm chimney height is adequate for full containment of the core outflow. Additionally these results provide a high degree of confidence in the chimney concept since downward flow was shown to exist under a broad variety of conditions.

ASSOCIATED SAFETY CONSIDERATIONS

Some detailed analysis has already been carried out regarding safety features of the MAPLE reactor. However, the integration of a MAPLE core into an exiting reactor is unique, and warrants an independent study. In Ref. [6] the feasibility of such an integration is reviewed from a safety standpoint. Reactivity and cooling related accident scenarios are considered, and recommendations are made for future safety studies of the proposed MAPLE-MNR reactor. These recommendations take into account recent studies that have been carried out elsewhere for MAPLE reactors, as well as the particular needs of the MNR host system.

Abnormal reactivity and cooling conditions include loss of control, loss of power and/or pumping, and loss of coolant and/or moderator. The primary concern in these scenarios is core overheating with the subsequent release of highly radioactive fission products. The MAPLE design has the advantage that the direction of flow is conducive toward natural circulation of coolant through the core. Furthermore that the core design ensures negative temperature and void reactivities.

The recommendations for the next stage of study include:

- the modelling of natural circulation of MNR pool water to ensure adequate passive cooling of decay heat;
- the investigation of subchannel flow conditions such as the point of onset of significant void and the critical heat flux;
- the modelling of operational transients such as loss of power;
- the study of effects by the D_2O moderator system on the core reactivity and cooling.

These and many other detailed studies would be carried out during the licensing and safety research study period of the proposed MAPLE-MNR.

CONCLUDING REMARKS

Preliminary results show that:

(1) the onset of nucleate boiling (ONB) for the hottest part in each fuelled segment was predicted to be within maximum allowable levels for the present range of the flow rate.

(2 the existing primary cooling water system is adequate to handle the MAPLE-MNR cooling requirements up to an operating power level of 5 MW.

(3) the preliminary design of the chimney on the MAPLE-MNR reactor has been shown to prevent short-lived radionuclides from rising to the top of the pool. As well, it acts as the support for the reactivity control and shutdown mechanisms.

(4) the pool natural circulation is expected to be a major cooling mode under loss-of-forced flow conditions in the primary cooling system.

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