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# LOWER PLENUM HOLES FOR RESEARCH REACTOR CORE FLOODING - A PROPOSAL TO IMPROVE THE SAFETY IN DESIGN

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## ABSTRACT

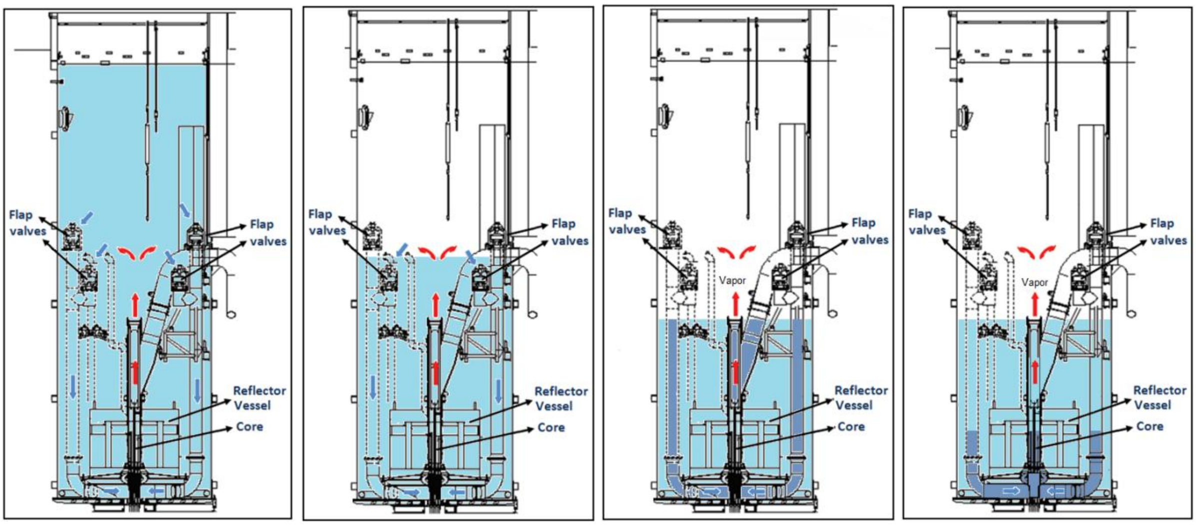
Modern and high power pool type research reactors generally operate with upward flow in the core. They have a chimney above the core, where the heated fluid is suctioned by the pumps. It passes through the decay tank and is sent to the heat exchangers for the cooling and returns to the core. The pipes inside the reactor pool have passive valves (natural circulation valves) that allow the establishment of natural circulation between the core and the pool for the decay heat removal, when the pumps are inoperative. These valves also have the siphon-breaker function in case of Loss of Coolant Accidents (LOCA), avoiding the pool emptying. In some reactors, these valves are located above the core chimney to facilitate the maintenance. When a LOCA causes a water level below these valves, they loose the natural circulation function. If the water level is the same of the chimney top, the available fluid for the core cooling is only that contained in the chimney and core, and a significant quantity of water in the pool is unavailable for core cooling. To bypass this problem during the reactor design phase, the inclusion of small holes of 10 mm of diameter on the lower plenum lateral side is proposed. These holes will allow a flow path between the pool and the core. Theoretical calculations were performed and analyzed for different drilling configurations: 4, 6 8, and 10 holes. A theoretical analysis of the estimated leakage rate during normal operation and evaporation and replacement rates during a hypothetical LOCA were performed. The calculation results showed that the four configurations analyzed are able to supply the water evaporated from chimney. An experiment is being proposed to validate the theoretical calculations and the considered hypotheses.

## 1. INTRODUCTION

In modern and high power pool type research reactors, the primary coolant systems generally have upward flow in the core. They have a chimney above the core, where the heated fluid is suctioned by the pumping system. Then, the coolant passes through the decay tank and is sent to the heat exchangers for the cooling and returns to the core. The pipes inside the pool have passive valves (natural circulation valves) that allow the establishment of the natural circulation between the core and the pool, for the decay heat removal when the pumps are inoperative. These valves also have the siphon-breaker function in case of Loss of Coolant Accidents (LOCA), avoiding the pool emptying. In some research reactors, these valves are placed below the core level, as in the 100 MW Jules Horowits reactor [1], which is under construction in France. In other research reactors, they are placed above the core level, as in

20 MW Opal reactor [2], already operating in Australia, the RA-10 of 30 MW under construction in Argentina [3], and the RMB reactor [4] , also of 30 MW in project in Brazil. The valves placed below the core, have as advantage the possibility of utilization of all pool water volume for the core cooling, when a Loss of Coolant Accident (LOCA) occurs, but as disadvantage the access for maintenance. The valves placed above the core have as advantage the ease of access for maintenance, but as disadvantage the non-use of large volumes of water for the core cooling in a LOCA. It is important to mention that these research reactors have emergency makeup water systems, which act in case of LOCAs.

Fig. 1 shows an illustration of the behavior of the four natural circulating valves (flap valves) placed above the core as will be used in RMB. The four valves were placed in pairs, in the two primary return pipes inside the pool. The two higher have the additional siphon-breaker function and the other two in a lower level. In Fig. 1, four different situations are showed: Fig. 1-A shows a normal system pumping shutdown condition; Fig 1-B after a LOCA in the primary pipe, with the water level below the siphon-breaker valves; Fig.1-C the same accident but with the water level below the second natural circulation valves and at the top of chimney; and Fig. 1-D the beginning of core uncovering level [5] and [6].



**A** **B** **C** **D**

**Figure 1: Natural circulation valves above the core.**

It can be observed after a LOCA, Fig. 1-B, that the two siphon-breaker valves lost their natural circulation function, but the other two continue with this function. When the level is below the second valves and at the top of chimney, Fig. 1-C, these valves also lost their natural circulation function, and there is no communication between the core and the pool water. In the Fig. 1-D, the core begins to uncover and there is a significant quantity of water in the pool that is not used for core cooling.

Fig. 2 shows the four natural circulation valves (flap valves) above the core, but with the presence of holes in the lower plenum lateral side [5] and [6]. These holes are being proposed as an alternative to use the large volume of the pool water, when a LOCA causes a water level below these valves. The same conditions of previous case are considered, such as: (2-A) normal system pump shutdown condition; (2-B) after a LOCA in the primary pipe; (2-C) the same accident but with the water level below the second natural circulation valves and at the top of chimney; and (2-D) the beginning of core uncovering level [5] [6].

One can observe in Figs 2-C and 2-D that for levels below the natural circulation valves, the holes allow communication between the water of pool and the core, maintaining it flooded and cooled.

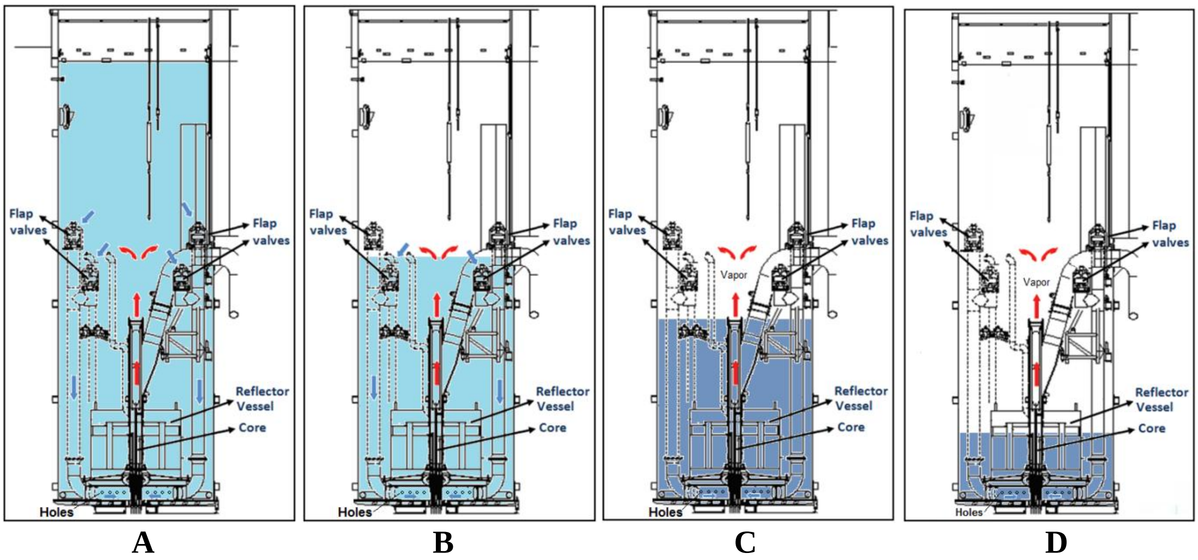


**Figure 2: Natural circulation valves above the core with lower plenum holes.**

In this work, the inclusion of holes on the lower plenum lateral side is proposed, like in the Fig. 2, to keep communication between the core and the pool water, after a LOCA. In Section 2, the theoretical analysis of leakage flow rate through the holes during the reactor normal operation and the evaporation and replacement flows rate through the holes, during a hypothetical LOCA is presented. In section 3, an experimental test section to validate these theoretical calculations is proposed.

## 2. THEORETICAL ANALYSIS

Holes of 10 mm of diameter on the lower plenum lateral side, with four different drilling configurations: 4, 6, 8 or 10 holes are proposed. The diameter of 10 mm is the same of the perforated plate inside of this plenum. Fig. 3 shows an illustration of the RMB reactor during the normal operation condition with the primary pumps operating and the four circulating valves closed, but with a leakage in the primary total flow through the core due to the holes. In Fig. 3, the core flow ($Q_C$) and the leakage flow ($Q_L$) can be observed. $Q_L$ is the flow through the holes resulting in a reduction in the core flow. In Table 1, it is presented a theoretical analysis of total leakage flow rate and the relations with the total flow rate for RMB Core Cooling System (CCS). Four drilling configurations are proposed for the same head loss conditions, leakage flow by hole and hole velocity. Reynolds and Euler numbers are also presented. Pressure inside the plenum ($P_0$) is obtained from [7]. A singular pressure drop coefficient for the orifices ($k_{or}$) of 2.72 (from the diagram 4.18 of [8]) was used. The velocity in the holes was estimated in 14.9 m/s (4.21 $m^3$/h per hole) considering a hole pressure drop of 3.0bar.

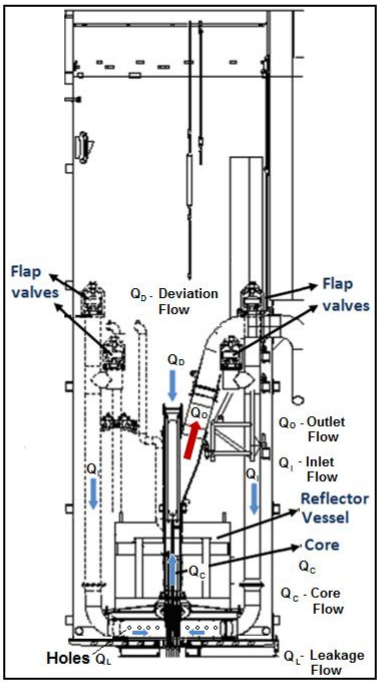


**Figure 3: Holes leakage flow during normal operation**

Table 1values are a preliminary estimate. For 10 holes configuration (larger holes number analyzed), it is expected a leakage flow of 42 m3/h, correspondingto1.4 % of total core flow of3110 m3/h. For the 4 holes (smaller holes number analyzed) is expected a leakage of 17 m3/h, or only 0.5 % of the total core flow. In Table 1, it is verified that the decrease in the holes number causes a directly proportional reduction in the leakage flow. The leakage flows are very small when compared with total core flow and no significant effect are expected on the core cooling.

In Fig. 4, it is shown an illustration of the replacement and evaporation flows during a hypothetical LOCA. Table 2 shows the estimated calculation of these flows. The evaporation flow is caused by the core decay heat and was estimated by the equation attributed to Way-Wigner [9], considering the end of a reactor continuous operation condition for 300 days. A latent water heat of vaporization of 2260 kJ/kg was used. The replacement flow is that established by the communicating vessels principle, to compensate the difference in height caused by the core water evaporation. It was considered the same pressure drop coefficient for the orifice ($K_{or}$= 2.72). The replacement flows are supplied for the four configurations analyzed. Table 2 also provides the decay times in hours ($T_{dec}$) and decay energy ($E_{dec}$) in kJ, estimated for this study. It was considered in a very conservative way, the immediate emptying of the reactor poll, until the top of chimney level.

**Table 1: Estimated calculations of the pressure drop and leakage flow in the holes.**

| Core Coolant System (CCS) – RMB Reactor | | | | |
|---|---|---|---|---|
| Lower plenum holes | | | | |
| Core flow in CCS ($m^3$/h) ($Q_c$) | 3110 | 3110 | 3110 | 3110 |
| **Number of holes** | **10** | **8** | **6** | **4** |
| Hole diameter (mm) | 10 | 10 | 10 | 10 |
| Hole area ($m^2$) | $7.85 \times 10^{-5}$ | $7.85 \times 10^{-5}$ | $7.85 \times 10^{-5}$ | $7.85 \times 10^{-5}$ |
| Flow velocity (m/s) | 14.9 | 14.9 | 14.9 | 14.9 |
| Leakage flow per hole ($m^3$/h) | 4.21 | 4.21 | 4.21 | 4.21 |
| **Total leakage flow ($m^3$/h) ($Q_L$)** | **42.1** | **33.7** | **25.2** | **16.8** |
| **$Q_L$ / $Q_c$ (%)** | **1.4** | **1.1** | **0.8** | **0.5** |
| Pressure $P_o$ (bar)g | 4.24 | 4.24 | 4.24 | 4.24 |
| $R_e$ | $1.48 \times 10^{+5}$ | $1.48 \times 10^{+5}$ | $1.48 \times 10^{+5}$ | $1.48 \times 10^{+5}$ |
| Eu | 1.36 | 1.36 | 1.36 | 1.36 |
| Hole pressure drop coefficient ($K_{or}$) | 2.72 | | | |
| Hole pressure drop - DP (bar) | ($K_{or}$*Rho*$v^2$/(2*$10^5$)) | | | |
| DP (bar) | 3.0 | 3.0 | 3.0 | 3.0 |

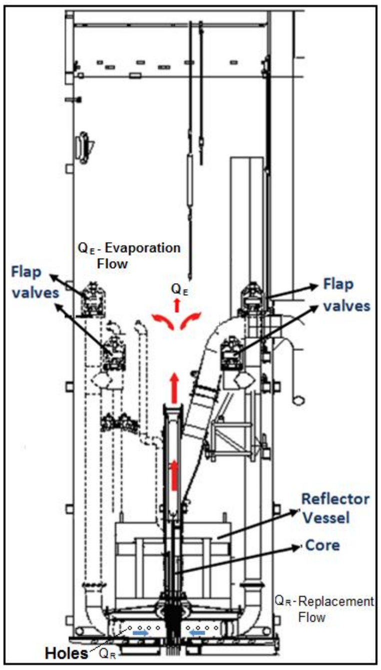


**Figure 4: Replacement and evaporation flows during a LOCA.**

**Table 2: Evaporation and replacement flows in a LOCA.**

| $T_{dec}$ (h) | $E_{dec}$ (MJ) | $Q_E$ ($m^3$/h) | ΔH (cm) | $Q_R$ 10 holes ($m^3$/h) | $Q_R$ 8 holes ($m^3$/h) | $Q_R$ 6 holes ($m^3$/h) | $Q_R$ 4 holes ($m^3$/h) |
|---|---|---|---|---|---|---|---|
| | | | 0 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1 | 7.6 | 0.65 | 1 | 0.76 | 0.61 | 0.46 | 0.30 |
| 2 | 8.5 | 0.45 | 2 | 1.07 | 0.86 | 0.64 | 0.43 |
| 3 | 9.3 | 0.40 | 3 | 1.32 | 1.05 | 0.79 | 0.53 |
| 4 | 10 | 0.36 | 4 | 1.52 | 1.21 | 0.91 | 0.61 |
| 5 | 11 | 0.34 | 5 | 1.70 | 1.36 | 1.02 | 0.68 |
| 6 | 12 | 0.32 | 6 | 1.86 | 1.49 | 1.12 | 0.74 |
| 7 | 12 | 0.31 | 7 | 2.01 | 1.61 | 1.21 | 0.80 |
| 8 | 13 | 0.30 | 8 | 2.15 | 1.72 | 1.29 | 0.86 |
| 9 | 13 | 0.29 | 9 | 2.28 | 1.82 | 1.37 | 0.91 |
| 10 | 14 | 0.28 | 10 | 2.40 | 1.92 | 1.44 | 0.96 |

Fig. 5 shows the replacement and evaporation flows curves for the four configurations studied.

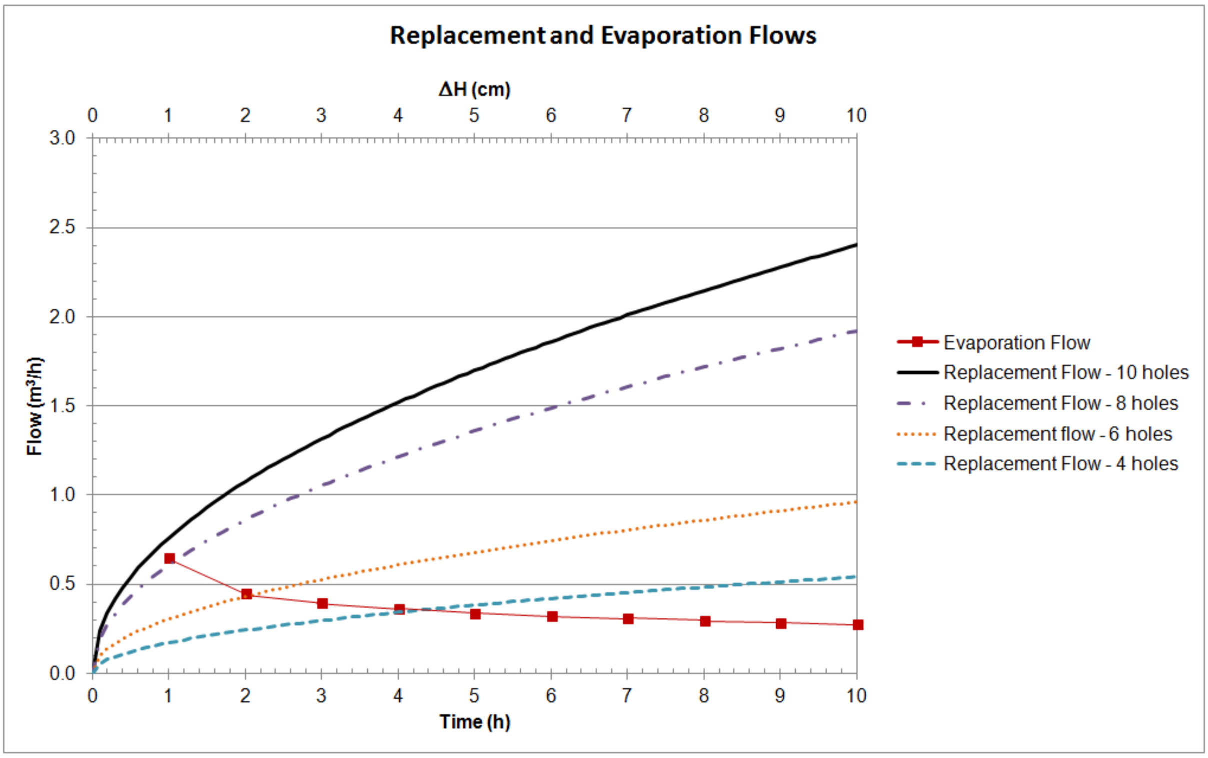


**Figure 5: Evaporation and replacement flows for four drilling in a LOCA.**

From Table 2 and Fig. 5, it is observed that in the first decay hour an estimated evaporation flow of 0.65 $m^3$/h, which is gradually reduced with time. A comparison of this evaporation flow rate in the first hour showed the it will be supplied with a DH of 0.8 cm for the 10 holes configuration, with 1.2 cm for 8 holes, 2.1 cm for 6 holes and with 4.6 cm for 4 holes. Thus, it was observed that the 4 configurations can supply satisfactorily the chimney evaporation flows. For the verification and validation of the theoretical calculation, it is being proposed an experimental test section. The experiment presentation is done in the Section 3

## 3. PROPOSED EXPERIMENT

Fig. 6 shows a schematic representation of the experimental test section proposed to simulate the holes in the lower plenum lateral side. The section will be installed in the Thermal-Hydraulic Laboratory of the Nuclear Engineering Center of IPEN.

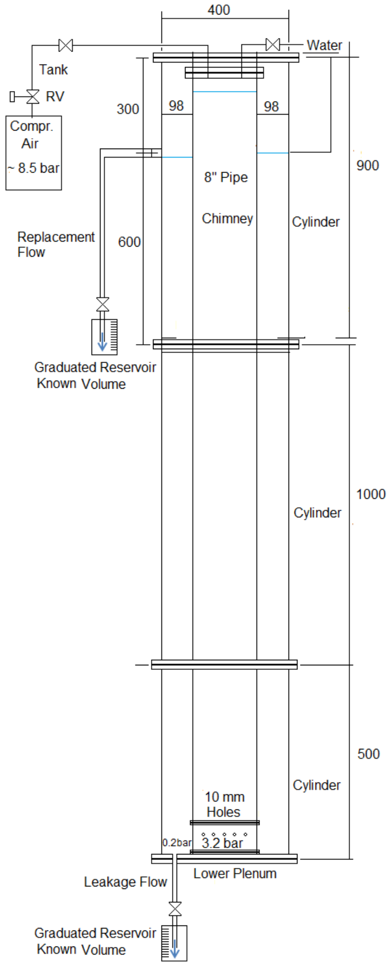


**Figure 6: Lower plenum holes experiment schematic representation.**

The test section is formed by an aluminum cylinder of 400 mm internal diameter and 2100 mm height. Inside of the cylinder, there is an aluminum pipe of 8” diameter and 2100 mm length that simulate the RMB chimney. The lower part of the aluminum pipe has a flanged section to simulate the RMB core lower plenum. This flanged section has 10 holes of 10 mm, to simulate the holes, which have internal threads for the closing by PVC plugs, allowing the simulation of 10, 8, 6, or 4 holes. The internal 8” pipe is filled with water and pressurized by an air compressor. The pressure in the lower plenum interior will be adjusted in 3.1 bar, obtained by a regulating valve and measured by a Validyne differential pressure gauge. The pressure in the external side of lower plenum is 0.2 bar, due to the hydrostatic height of the water in the cylinder. The difference of 3.0 bar between the lower plenum internal and external points is the same of the theoretical calculation of the section 2 (Table 1) and also that expected in RMB. The lower part the section has a water outlet, for the measure of the leakage flow. This outlet will be connected to a graduated reservoir with known volume. The upper part of the section has another water outlet, for the measure of the replacement flow, also connected to a reservoir with known volume.

## 4. CONCLUSIONS

In this wok, the inclusion of holes of 10 mm of diameter on the lower plenum lateral side, with four different drilling configurations: 4, 6, 8 or 10 holes was studied and proposed. The theoretical leakage flow through the holes during the reactor normal operation and the evaporation and replacement flows rate through the holes, during natural circulation condition after a LOCA, for each one of these four cases, were estimated. For the configurations analyzed, the flow leakages are very small when compared with the core flow and no significant effects are expected on the core cooling and its safety. The four drilling cases analyzed showed to be adequate and sufficient to keep the RMB core cooling and are important for the better use of the pool water. The holes have passive safety characteristics (no mobile parts). Due to their dimensions, local pressure and water quality, the probability of the holes clogging is very small.

An experimental study of the holes in a test section simulating the core lower plenum of the RMB, to validate the theoretical calculations and the considered hypotheses, also was proposed. The experiment will be performed in the Nuclear Engineering Center of the IPEN, for the simulation and validation of the estimated leakage, replacement and evaporation theoretical flows for proposed configurations.

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