# Advanced Design of ACR-1000® Moderator System

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## Abstract

Advanced design features incorporated in the ACR-1000® moderator system are presented in the paper. The thermalhydraulic behaviour of the moderator flow in the calandria vessel, with 3D computer simulation using the MODTURC_CLAS code, is also discussed. Significantly improved $D_2O$ flow and temperature profiles in the calandria vessel are demonstrated by the simulation results. The moderator flow through the reactor core is reinforced with the natural buoyancy in the region. This results in the $D_2O$ temperature increasing monotonically from the bottom to the top of the calandria vessel. Large subcooling margin is also maintained in the moderator, which prevents sustainable dry-out on the surfaces of the fuel channels.

## 1. Introduction

In the Advanced CANDU®[1] Reactor (ACR-1000®[2]), heavy water ($D_2O$) in the calandria vessel moderates the speed of the neutrons produced by nuclear fission in the reactor core, to promote additional fission reactions. It also serves as a neutron reflector, and a medium for dispersing the soluble neutron poisons for reactivity control. The moderator system is designed as a low pressure, low temperature, closed $D_2O$ circuit to circulate the moderator in the calandria vessel to remove the heat generated in and transferred to the $D_2O$ and to control the temperature of the moderator inventory. In an unlikely event of an out-of-core Loss of Coolant Accident (LOCA) coincident with a Loss of Long Term Cooling (LOLTC), the moderator system also functions as a reactor heat sink.

The main component in the ACR-1000 reactor is a horizontal cylindrical vessel called the calandria, which houses 520 horizontal fuel channels and the $D_2O$ moderator. Each fuel channel consists of a pressure tube (PT) and a calandria tube (CT). Fuel is contained in each PT. The PT is then located inside a CT, separated by an annulus gap. The fuel channels (including PT and CT) are surrounded by the $D_2O$ moderator and supported by the tube sheets at two ends of the cylindrical calandria vessel.

The $D_2O$ in the calandria vessel is circulated through the moderator system for cooling, and through the moderator purification system for chemistry control and poison removal. The moderator system is also connected to the moderator liquid poison system for addition of chemicals used for reactivity adjustment. Helium is provided as a cover gas above all $D_2O$ surfaces. Additional connections are also provided for $D_2O$ collection, $D_2O$ supply and $D_2O$ sampling.

The components of the moderator system consist of two pumps, four heat exchangers (HXs), a head tank, various isolation valves, piping, instrumentation and control components. The system configuration is shown in Figure 1.

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1 CANDU® is a registered trademark of Atomic Energy of Canada Limited (AECL).
2 ACR-1000® (Advanced CANDU Reactor®) is a registered trademark of Atomic Energy of Canada Limited (AECL).

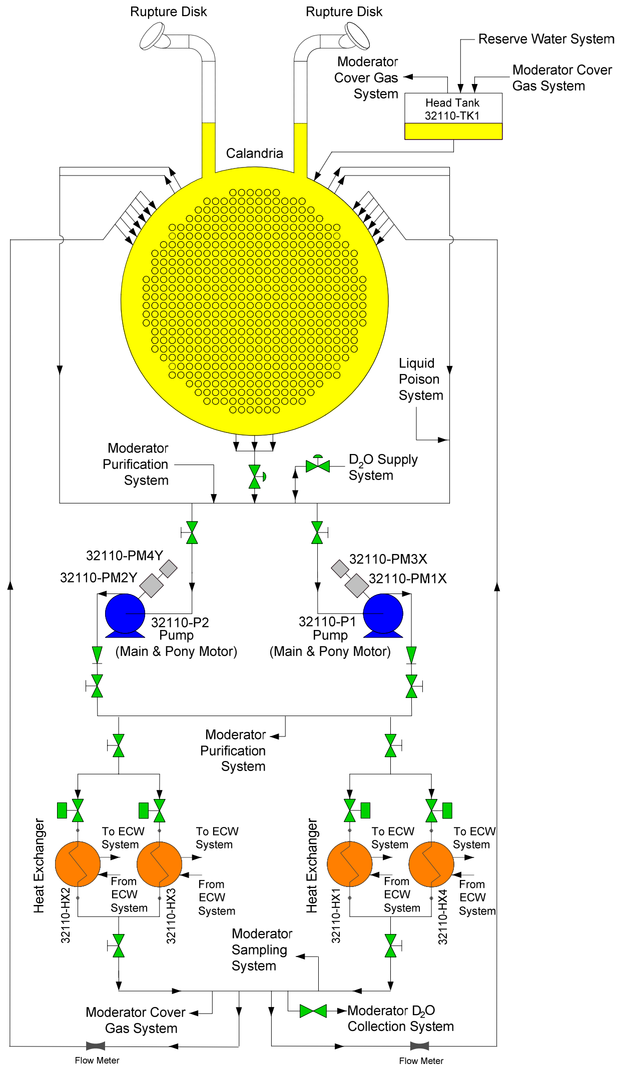


Figure 1 ACR-1000 Moderator System Flow Diagram

Two moderator pumps are connected in parallel, and then connected in series with four HXs. The HXs are also arranged in parallel. This configuration permits the operation of either pump with four HXs. Each moderator pump is equipped with two motors, a large main motor and a relatively smaller pony motor. The main motor drives the pump during the system's normal operation, while the pony motor drives the pump during reactor shutdown and abnormal operating conditions.

The $D_2O$ enters the calandria vessel through twelve downward-pointing inlet nozzles and exits the calandria vessel through four outlet ports located above the inlet nozzles (see Figure 2). The calandria inlet and outlet nozzles are located symmetrical to the calandria's vertical centre plane (X-Z plane), as shown in Figure 3.

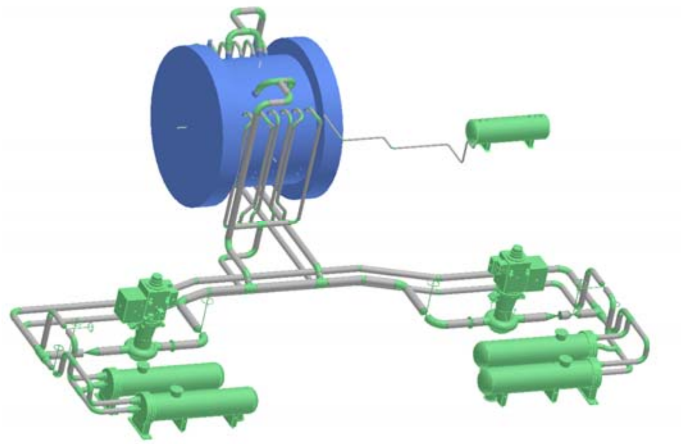

Figure 2 Moderator System Configuration

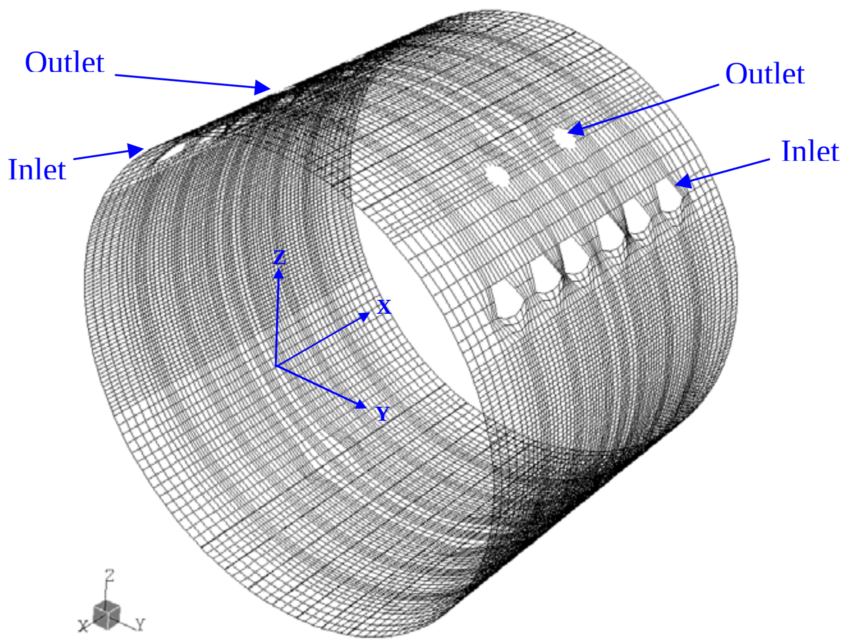


Figure 3 Mesh Model of the Calandria Vessel

After exiting the calandria vessel, the $D_2O$ is pumped by one moderator pump through four HXs. The moderator heat load is removed by the Essential Cooling Water (ECW), which is supplied to the secondary side of the moderator HXs.

Two temperature control valves (TCVs), one small and one large, are provided on the secondary side of each HX (ECW side). During normal reactor full power operation, the small TCVs are fully open, while the large TCVs are modulated to maintain a constant $D_2O$ temperature at the calandria outlet. However, during reactor shutdown or abnormal operating conditions, the large TCVs will be closed automatically, while the small TCVs remain fully open. The majority of the ECW flow is thus preserved for the safety system (i.e., LTC system) in the case of an accident. The small TCVs remain open to maintain a minimum cooling to the moderator.

This paper describes the details of the advanced design features in the ACR-1000 moderator system. It also assesses the thermalhydraulic behaviour of the moderator flow in the calandria vessel, with 3D computer simulation using the MODTURC_CLAS code. Improved $D_2O$ flow and temperature profiles in the calandria vessel are demonstrated, to ensure a large subcooling margin in the moderator.

## 2. Design features of moderator system

The ACR-1000 moderator system is designed based on the proven technology of CANDU 6 reactor, where new advanced design features are incorporated. The main improvements in design are discussed in the following sections.

### 2.1 $D_2O$ flow and temperature distribution in calandria vessel

The moderator system is connected to the calandria vessel via four 14″ calandria outlet ports and twelve 8″ calandria inlet nozzles, located on the upper portion of the calandria vessel (Figure 2). The calandria inlets and outlets are configured to provide a desired $D_2O$ flow, upward through the reactor core, in order to eliminate any temperature hotspots in the moderator.

The calandria inlet has downward-pointing, fan shape diffuser that forces the $D_2O$ to flow downward along the calandria wall. The $D_2O$ from the inlets on both sides of the calandria collides at the bottom of the vessel. It then flows upward through the reactor core, reinforced by the natural buoyancy in the core region. The $D_2O$ flow removes the heat deposited in the moderator and cools the calandria tubes, then exits the calandria through the outlet ports located slightly above the inlet nozzles (Figure 3).

This flow topology in the calandria vessel provides an evenly distributed moderator temperature throughout the reactor core. Three-dimensional computational fluid dynamic (CFD) simulation has been performed to verify the $D_2O$ flow and temperature profiles in the calandria. The detail results of the CFD analysis are discussed in Section 3.

### 2.2 Moderator system as reactor heat sink

The moderator system is also designed to automatically function as a reactor heat sink, in an unlikely case of a postulated LOCA coincident with a LOLTC. After the LOCA, the pump's main motor is tripped, due to loss of class IV electrical power. Subsequently, the pump's pony motor will start automatically with the plant's class III electrical power (diesel generators). The large TCVs on the HX's secondary side are closed upon the reactor trip signal, to re-direct the majority of the ECW flow to cool the LTC system. The small TCVs will be automatically forced to open fully, to maintain a minimal ECW cooling flow to the secondary side of the HXs.

Following a reactor trip upon a LOCA signal, neutronic energy deposition in the moderator drops dramatically. However, if the LTC system becomes unavailable, the temperature of the fuel channel increases rapidly. Eventually, the fuel containing PT becomes hot enough to sag into contact with the CT, due to gravity. The reactor core decay heat is thus transferred, through the contacting PTs and CTs, to the moderator. The moderator system, operating with one pump driven by its pony motor and four HXs (with fully opened small TCVs on the HX's secondary side), removes the reactor core decay heat and transfer the decay heat to the ECW system, and thus maintains the structural integrity of the reactor assembly.

Connections to the Reserve Water System (RWS) are also provided to the moderator system. The RWS supplies the makeup water to the calandria vessel, for some postulated accidents during which the moderator inventory is depleted. The RWS tank, located on top of the reactor building, has a reserved amount of water sufficient to make up for the entire moderator inventory. During the event, the RWS tank will be connected to the moderator head tank, to replenish the calandria vessel by gravity. The RWS makeup water prevents the fuel channels from being exposed. It also provides cooling to the calandria assembly, and thus maintains the structural integrity of the reactor.

## 2.3 Four quadrant design

The ACR-1000 design has adopted a four quadrant separation philosophy in the reactor auxiliary building, as well as physical and functional separation in other areas, to prevent common cause failures from resulting in the loss of fundamental safety functions. An example of separation within a safety system is the four divisions of the LTC system. Subsequently, four divisions are provided in the supporting systems, such as electrical power supply and cooling water systems. The ECW system, which supplies cooling water to the LCT system during plant abnormal operating conditions, is designed with four independent divisions.

The moderator system is cooled by the ECW system during operations. In order not to inadvertently connect the ECW divisions, four HXs are provided in the moderator system. Each moderator HX is connected to an individual ECW division. Each ECW division removes roughly 25% of the total heat load in the moderator during normal operation.

However, each moderator HX is designed with 33% capacity. This guarantees that, even with one quadrant of the plant on maintenance (i.e., one ECW division or one quadrant of the power supply is on maintenance), the moderator system has sufficient design margin for the reactor to operate at its full power. Should there be an accident occurs in one quadrant of the plant, the normal full power operation of the reactor is also not affected.

# 3. CFD simulation of moderator in Calandria vessel

During a postulated LOCA coincident with a LOLTC, the moderator system functions as the reactor heat sink. It removes the decay heat in the fuel that is transferred to the $D_2O$ moderator through contacting PTs and CTs. The moderator system has to maintain sufficient subcooling margin in the $D_2O$, to prevent any CT dry-out. Vapour surrounding a dried-out CT blocks the heat transfer path from the fuel to the moderator, which could lead to severe damage to the fuel channels.

A CFD analysis is performed to assess the $D_2O$ flow and temperature distribution in the calandria vessel. The computer simulation is also used to verify that sufficient subcooling margin exists in the moderator.

### 3.1 Computer code

Three-dimensional CFD computer code, MODTURC_CLAS, is used in the analysis of the thermalhydraulic behaviour of the moderator in the calandria vessel. The MODTURC_CLAS code is a specific version of CFX_TASCflow **Error! Reference source not found.**], with additional subroutines designed for studying the behavior of the moderator in the CANDU design. The numerical method used in MODTURC_CLAS is a fully implicit, co-located, finite volume method with a flux element-based domain discretization. This combines the well-known geometric flexibility of the finite element method with the desirable conservation properties of the finite volume method.

### 3.2 Computer modelling and analysis cases

The calandria vessel consists of the reactor core and a reflector region. Polar grid is used to model the reflector region, with fine mesh in the vicinity of the calandria vessel wall. Non-orthogonal grid is used to model the reactor core. The total number of nodes in the CFD model is around half million. Porous media approach was applied to model the effect of the calandria tube lattice on the flow in the reactor core. In this approach, the fluid momentum loss as it passes over the calandria tubes are calculated using the pressure loss coefficient (PLC) in the momentum equation. The PLC was calculated using empirical equation in reference **Error! Reference source not found.**].

The initial power distribution is proportional to the bundle power map at steady state. The initial calandria inlet $D_2O$ temperature is taken from the energy balance calculation based on the nominal set point of calandria outlet $D_2O$ temperature, heat load and flow rate. The PT/CT contact heat load to moderator is obtained from the results of an ACR-1000 safety analysis for a LOCA coincident with LOLTC.

Four cases are assessed in the CFD analysis. The moderator system operating conditions used in the analysis are listed in Table 1.

Case 1. Moderator system normal operation, with the reactor at its full power and symmetric $D_2O$ inlet flows on both sides of the calandria vessel.

Case 2. Moderator system normal operation, with the reactor at its full power and asymmetric $D_2O$ inlet flows on the two sides of the calandria vessel.

In Case 1, the calandria inlet flows are assumed to be evenly distributed among all inlet nozzles. In reality, however, the inlet flow will be slightly asymmetric, due to differences in piping layout and thus different flow resistances in various inlet pipes. In Case 2, the impact of the asymmetric inlet flows on the $D_2O$ flow and temperature in the calandria vessel is analysed.

Case 3. Moderator system normal operation, with the reactor in a shutdown state, and with reduced moderator heat load and flow (driven by the moderator pump's pony motor).

Case 4. Steady state conditions with conservative moderator heat load from PT/CT contacts following a LOCA coincident with a LOLTC. The moderator system is operating with one pump driven by its pony motor, and four HXs with their small TCVs fully open.

**Table 1 Moderator System Operating Conditions used in CFD Analysis**

| **Parameters** | **Case 1** | **Case 2** | **Case 3** | **Case 4** |
|---|---|---|---|---|
| Heat load ( MW ) | 135.6 | 135.6 | 10 | 32.5/2.5 |
| Inlet flow ( kg/s )<br>(split on two sides of calandria vessel) | 1700<br>(50/50) | 1700<br>(49/51*) | 510.0<br>(50/50) | 510<br>(50/50) |
| Inlet Temperature ( °C ) | 60.07 | 62.08 / 58.38 | 75.3 | 63.5 |
| Outlet Temperature ( °C ) | 80 | 80 | 80 | 80 |

* Estimated based on the piping layout

**Table 2 Asymmetrical Inlet Boundary Conditions for Case 2**

| Nozzle Number | **East Side** | | **West Side** | |
|---|---|---|---|---|
| | ( kg/s ) | ( °C ) | ( kg/s ) | ( °C) |
| 1 | 166.66 | 62.08 | 181.22 | 59.38 |
| 2 | 141.72 | 62.08 | 132.51 | 59.38 |
| 3 | 107.04 | 62.08 | 120.63 | 59.38 |
| 4 | 107.04 | 62.08 | 120.53 | 59.38 |
| 5 | 141.83 | 62.08 | 132.51 | 59.38 |
| 6 | 166.66 | 62.08 | 181.65 | 59.38 |

### 3.3 Results and discussions

For the moderator system normal operation (Case 1), the $D_2O$ velocity and temperature fields in the calandria vessel in the Y-Z plane at X = 1.08 m (this plane cuts through an inlet nozzle, see Figure 3) are presented in Figure 4 and Figure 5. The results show typical flow and temperature distribution in a Y-Z plane where the calandria inlet nozzles are located.

The $D_2O$, after entering the calandria, travels downward along the walls of the calandria vessel. It entrains a large amount of hot $D_2O$ from the reactor core region into the downward flow along the wall. The hot $D_2O$ from the core region mixes and heats up the inlet flow before it reaches the bottom of the calandria vessel. The $D_2O$ flows from inlets on both sides of the calandria then collide at the bottom of the vessel, and move upward through the reactor core. The $D_2O$ flow in the reactor core is reinforced by the natural buoyancy in the region. The flow is symmetrically distributed against the vertical centre plane of the vessel (X-Z plane at Y = 0, see Figure 3).

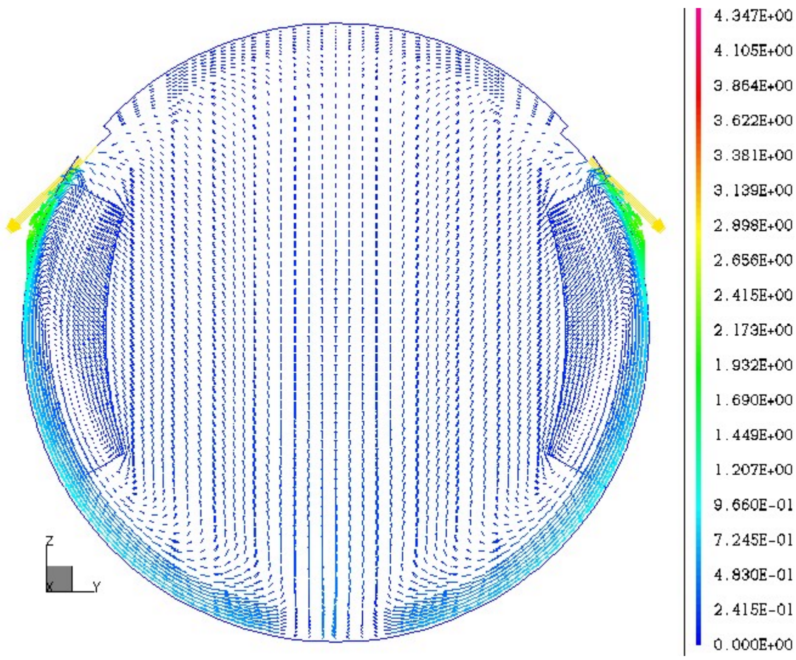


Figure 4 Velocity Field (m/s) in x=1.08 m Plane (Inlet Nozzle Plan), for Case 1

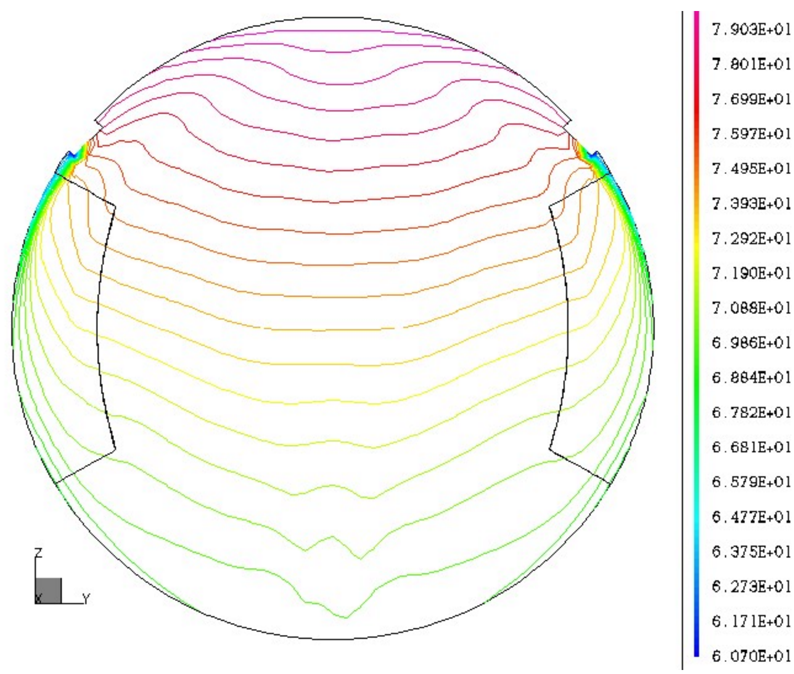


Figure 5 Temperature (°C) Isotherms in x=1.08 m Plane (Inlet Nozzle), for Case 1

The $D_2O$ temperature in the calandria is also symmetrical against the vertical centre plane of the vessel (X-Z plane at Y = 0, see Figure 3), and increases monotonically from the bottom of the vessel to the top, as shown in Figure 5. The inlet flow along the calandria wall is first heated up by the entrained hot $D_2O$ from the core region, by about 10 $^{o}$C. It then picks up more heat while traveling upwards through the centre of the reactor core. The maximum temperature increase across the reactor core, from the bottom to the top, is around 10 °C. The highest $D_2O$ temperature in the reactor core is 80.8 °C, located near the top row of the CTs. The temperature distribution of the moderator indicates a good fluid mixing exists in the calandria vessel. Sufficient subcooling margin (~20 $^{o}$C) is found to exist in the moderator.

For Case 1 to 4, the $D_2O$ flow and temperature profiles at the middle of the calandria vessel (on Y-Z plane at X = 2.97 m, see Figure 3) are presented, qualitatively, in Figure 8, Figure 7, Figure 8 and Figure 9. The simulation results are also summarized in Table 3 for Case 1 to 4, and the main observations are listed below:

1. No flow stagnant areas are found. Some $D_2O$ re-circulations occur at places near the calandria inlet nozzles. The inlet jet flow is strong which entrains a large amount of hot $D_2O$ from the reactor core region into the downward flow (Case 1 to 4).

2. $D_2O$ temperature distribution is stratified from the bottom to the top of the core region, with about 10 °C increases (Case 1 to 4).

3. No temperature hot spots are observed in the reactor core region, due to good $D_2O$ mixing. The maximum $D_2O$ temperature occurs at the top of the reactor core, near the calandria outlets. The maximum $D_2O$ temperature in the reactor core is only 1 °C higher than the calandria outlet temperature (the calandria outlet temperature is controlled during system normal operations) (Case 1 to 3).

4. Asymmetrical $D_2O$ inlet flow in the calandria vessel has been found to have insignificant impact on the $D_2O$ temperature distribution in the reactor core region (Case 2).

5. In the case of a LOCA coincident with a LOLTC (Case 4), the maximum $D_2O$ temperature in the reactor core region is only slightly increased ($\Delta T$ < 1 °C) under the extremely asymmetrical heat load. The $D_2O$ moderator is well sub-cooled, with no dry out conditions (local boiling) observed.

**Table 3 MODTURC_CLAS Simulation Results**

| Parameters | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|
| Maximum $D_2O$ Temperature in Reactor Core (°C) | 80.8 | 80.7 | 80.2 | 81.1 |
| Maximum $D_2O$ Temperature in Calandria Vessel (°C) | 81.7 | 81.4 | 80.3 | 81.3 |
| Average $D_2O$ Temperature (°C) | 73.7 | 74.1 | 78.5 | 73.8 |
| Minimum Subcooling Margin, with 200 kPa(g) Cover Gas (°C) | 58.1 | 58.1 | 58.5 | 57.7 |
| Minimum Subcooling Margin, without Cover Gas (°C) | 22.0 | 22.1 | 22.7 | 21.8 |
| Maximum $D_2O$ Velocity in the core (at X = 2.77 m) (m/s) | 0.39 | 0.37 | 0.10 | 0.15 |

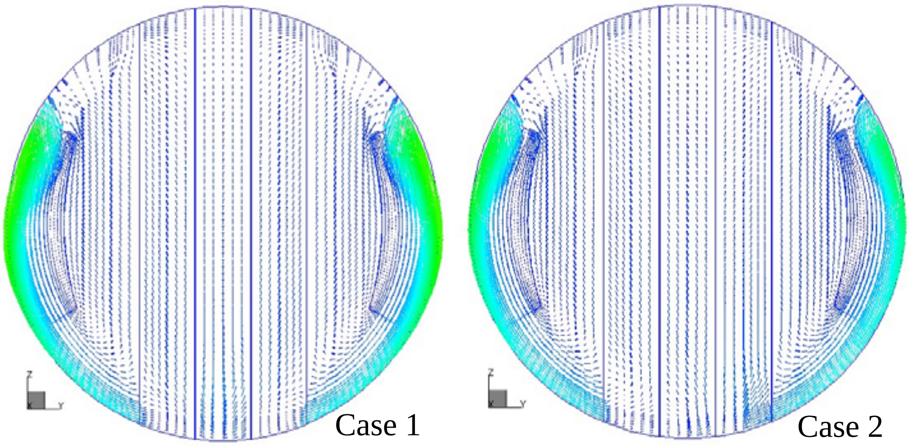


Figure 6 Velocity Fields in X = 2.97m Middle Planes, for Case 1 & 2

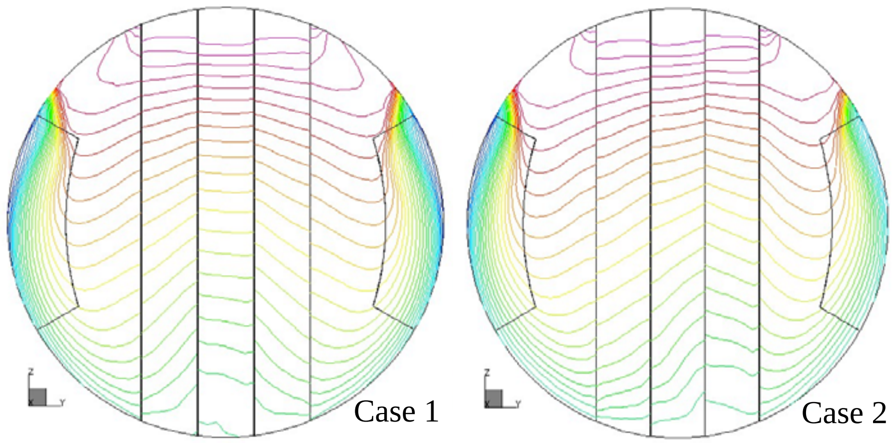


Figure 7 Temperature Fields in X = 2.97m Middle Planes, for Cases 1 & 2

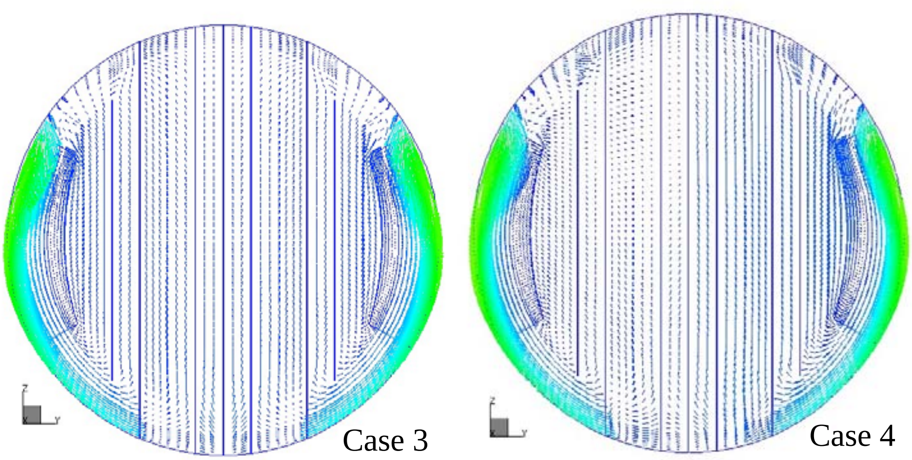


Figure 8 Velocity Fields in X = 2.97m Middle Planes, for Case 3 & 4

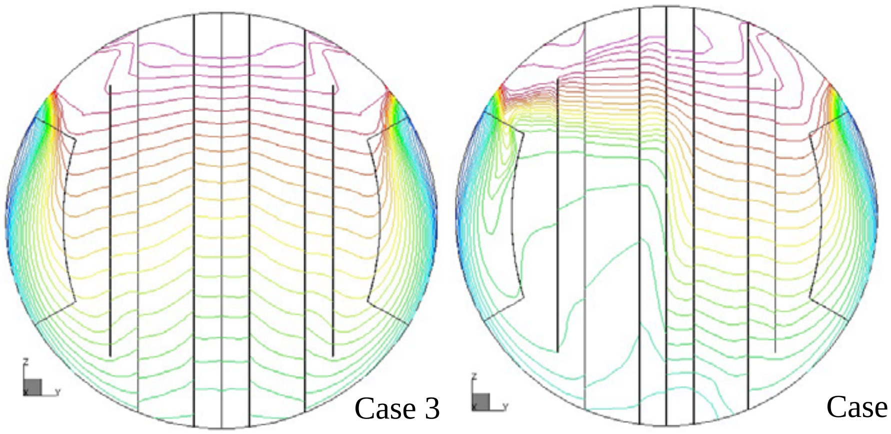


Figure 9 Temperature Fields in X = 2.97m Middle Planes, for Cases 3 & 4

## 4. Conclusions

It is concluded that the ACR-1000 moderator system provides a robust design and stable thermalhydraulic characteristics during both normal operations and abnormal operating conditions. Uniform $D_2O$ cooling flow is observed in the calandria vessel, with stratified temperature distribution from the bottom to the top of the calandria vessel. Large subcooling margin is maintained in the $D_2O$ moderator, which ensures the moderator system's function as a reactor heat sink.

## 5. References

[1] "CFX-TASCflow Computational Fluid Dynamics Software: User Documentation", Version 2.9, AEA Technology Engineering Software, Ltd., 1999.

[2] A. Žukauskas and R. Ulinskas, "Banks of Plain and Finned Tubes", Section 2.2.4 of Heat Exchanger Design Handbook, Hemisphere Publishing Corporation, 1984.