INGENIERÍA E INNOVACIÓN

THERMOHYDRAULIC ANALYSIS OF AN ISOLATION CONDENSER SELF-REGULATING BY NON-CONDENSABLE GASES (SIRIO FACILITY)

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Advanced nuclear power plants must improve safety to prevent core damage and ensure reactor integrity by implementing passive safety systems that do not require human actions and an external power source. One of the main passive systems being implemented in new power plant designs are passive DHR (Decay Heat Removal) systems (e.g. isolation condenser), whose function is to passively remove the decay heat from the core by natural convection in the event of an accident.

The DHR systems present a significant challenge in reactors cooled by liquid metals since if the temperature of the coolant drops below its freezing temperature, it solidifies, so the natural circulation stops and the core decay heat cannot be removed. The European project PIACE (PASSIVE ISOLATION CONDENSER) project has the goal of study the use of non-condensable gases inside the Isolation Condenser (IC) as a way to regulate the cooling, since the presence of non- condensable gases induce a heat transfer degradation. For this purpose, an experimental facility, SIRIO, scaled on the PDHR of the ALFRED lead-cooled reactor, is being built.

A thermal-hydraulic model of the SIRIO facility for TRACEv5p5 code has been developed from the RELAP5-3D thermal-hydraulic model of the facility. The model contains both, the Steady State branch to bring the facility to ALFRED operating conditions, and the IC branch, which contains the innovative Isolation Condenser connected in the lower head to a tank of non-condensable gases, to reproduce the behavior of the ALFRED DHR system. Simulations with TRACEv5p5 and RELAP5-3D codes have confirmed that the innovative IC with non-condensable gases is able to passively remove the decay heat power and prevent the molten salt to reach a temperature corresponding to the lead freezing.

INTRODUCTION

The DHR system presents a significant challenge related to the cooling ratio since although a rapid cooling initially seems an advantage, it can cause serious problems. In reactors cooled by liquid metals or molten salt, it is mandatory that the temperature of the coolant does not drop below its freezing temperature in order to avoid solidification of the coolant; and in light water reactors, a high cooling ratio can cause irreversible damage to the structural materials.

SIRIO FACILITY

SIRIO experimental facility is "power-to-volume" scaled 1:47 on the DHR system of ALFRED, reactor. The scaling factor is obtained from the ratio between the volume of ALFRED reactor NC gas tank (6 m^3) and the volume of SIRIO facility NC gas tank (0.127 m^3). The "power-to-volume" scaling is characterized by the following elements:

- Power density is kept constant, so volumes are scaled in agreement with thermal power.
- Height is kept constant.
- Operational pressure is kept constant.

	Decay Power	Total active surface (m^2)	Thermal flux (kW/m^2)	Total volume (L)	Power density (kW /L)
ALFRED	2625	244.18	10.75	8059.3	0.3257
SIRIO	55	5.2666	10.443	173.37	0.3172
Ratio	47	47	~1	47	~1

Table 1. Scaling of ALFRED to SIRIO facility.

SIRIO facility is 30 meters high. The primary cooling fluid (lead in the ALFRED reactor) is replaced by a molten salt pool in which each SG tube is submerged, representing the SIRIO facility heat source. The facility mainly consists of 3 branches, a steam generator and 2 pools (Figure 2): HX Branch, IC Branch, Common Branch, Steam Generator, IC pool and HX pool. Their description is introduced below.

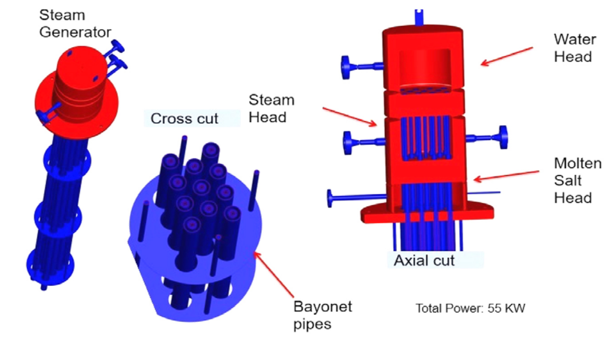

Figure 1. SIRIO Steam Generator.

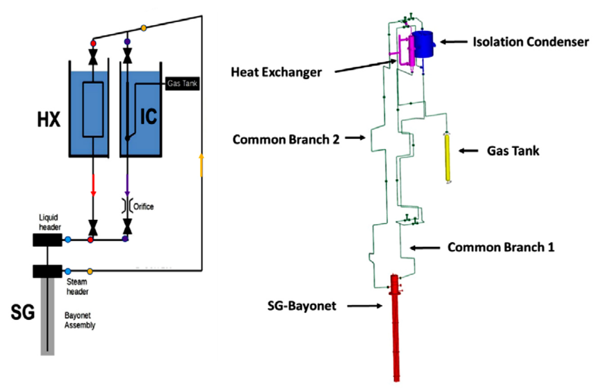

Figure 2. SIRIO facility. Red - HX branch; Blue – Steam Generator branch; Orange – Common branch 2; Violet – IC branch.

- HX Branch: It has the mission of bringing the facility to the Steady State, which is used as the starting point of the SBO sequence. The HX consists of two pipes, that exchanger heat with the HX Pool to reach the Steady State conditions at 180 bar. HX is completely isolated when DHR begins the operate.
- IC Branch: The IC, which is 0.68 meters, is a shell and tube heat exchanger containing a tube, a top head and a bottom head. The top header, which is connected to the steam line, has the function to uniformly distribute the mass flow, therefore it can be accounted in terms of volume and neglected in terms of heat transfer. The bottom head connects the IC with the gas tank. An orifice with a diameter of 5 mm is installed downstream of the IC to avoid non- condensable gases go to the SG. IC-branch contains an upstream valve and a downstream valve that allow isolating the Isolation Condenser during the Steady State. IC is completely isolated when the HX is working.
- Steam Generator: it includes eleven bayonet-tubes (Figure 1), which are completely submerged in a pipe filled with molten salt. The outermost of this pipe is uniformly heated from the outside with electrical heater of a power of 5000 W. This allows a natural convection towards the molten salt, reproducing a similar heat flux trend along the SG height relative to ALFRED.

  The SG element is a set of coaxial pipes welded on different plates on the steam generator header. The feedwater enters from the top, the feedwater header, in the inner tube of the SG bayonet-tubes, reaches the end of the tube bundle, reverses its direction and upflows in the annular space between the outer tube and outermost tube. The steam finally exits the bundle again from the top, reaching the steam header. The water descending the component in the downcomer is heated by the ascending water in the annular section. The phenomenon is the regenerative heat transfer. Sensibility studies showed that more that 80 % of regenerative heat transfer takes place on the top 3 meters of the SG bayonet-tubes where the steam exits in the annular region. To avoid this phenomenon, there is a double wall in the first 3 meters of the inner part of the SG. One of these walls is 6 meters, while the other is only 3. The annular region between the double wall is left open and is filled with static water during operation, acting as an isolation barrier.
- Common Branch: IC and HX share the part of the feedwater line (D 1”), which is the tube between the IC outlet valve, the HX outlet valve and the SG. They also share the steam line (D 1”1/4.), which is the tube between the Steam Generator, the IC inlet valve and the HX inlet valve.

Isolation Condenser operation

When the transient phase begins the HX isolation valves are closed, then the facility pressure increases as a result of water boiling in the SG. Later, when the pressure reaches 190 bar, the upstream IC valve opens allowing the steam to enter the Isolation Condenser pushing the non- condensable gases into the gas tank connecting to the bottom IC header.

Due to the large difference temperature between the steam and the IC walls, which are at room temperature, the steam starts to condense quickly and then, the line below the IC is being filled by the condensed water. 65 seconds after opening the upstream IC valve, the downstream IC valve opens and the liquid stored in the piping below the IC is drained by gravity into the SG. The water flow by natural circulation along the loop is ensured by the water column, while the fluid boils inside the SG and condenses in the IC.

In the long-term phase it is necessary to reduce the power removed from the molten salt in order to prevent freezing. The IC cooling control is passively carried out by the non-condensable gases and it is based on the total pressure equilibrium between the tank and the IC loop. As the decay heat decreases with the time also the pressure decreases, allowing the non-condensable gases, previously stored in the tank, to expand and move towards the IC. The gas deteriorates the heat transfer, reducing the power removed and then the system pressure decreases.

SIRIO TRACEV5P5 MODEL

The model consists of two loops: HX-loop and IC-loop (Figure 3), with 36 hydraulic components. The model also contains both HTSTRs and Pipe Walls. HTSTRs components have been used to model the heat transfer between several facility components: the molten salts and the SG; the annular riser and the downcomer; the HX and the HX Pool; and the IC and IC Pool. Besides, the steam line and the condensate return line, connecting the SG to the HX and to the IC, have a very small diameter and a large height, necessary to achieve the natural circulation. These dimensions mean that the heat losses through the walls are considerable and have an important influence on the total energy balance of the facility, so it is mandatory to model these heat losses. For this purpose, the pipe wall option in the PIPEs components input has been used instead of HTSTR.

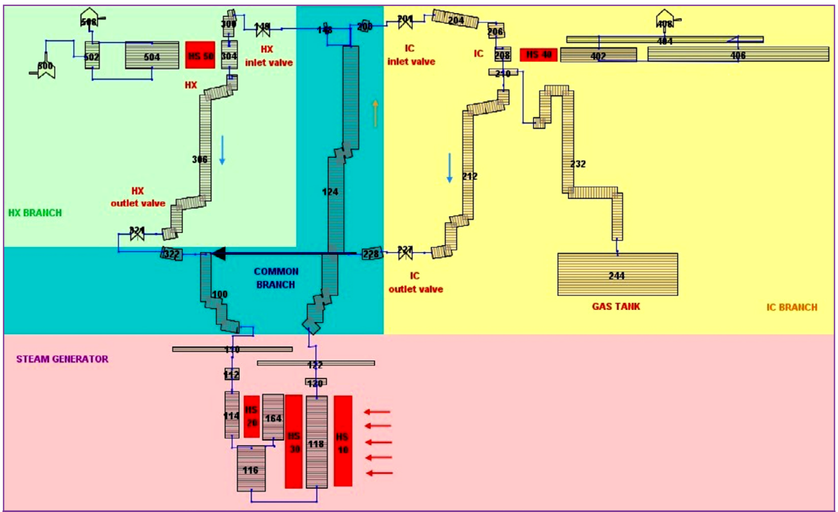

Figure 3. SIRIO-UPM model for TRACEv5p5 code.

Parameter	RELAP5-3D	TRACEv5p5	Dev.
SG Power (kW)	54.98	54.96	0.04%
HX Power (kW)	49.81	49.21	1.20%
Heat Losses (kW)	4.80	5.03	4.79%
Average temperature of the molten salt (K)	633.20	632.55	0.10%
Pressure (P-148) (bar)	180.53	179.41	0.62%
Mass Flow rate (V-149) (kg/s)	0.077	0.078	1.30%
HX Pool Mass Flow rate (kg/s)	0.021	0.02	4.76%
SG Annular Riser Inlet Void Fraction (P-118/10)	0.26	0.32	23.08%
SG Annular Riser Outlet Void Fraction (P-118/60)	0.76	0.81	6.58%

Table 2. SIRIO-UPM model for TRACEv5p5 code. Steady State results.

The molten salt heating system have been implemented in the model through a series of control blocks that consider the heat provided by the heating system, the power removed by the SG and the thermal inertia of the molten salts. The average molten salts temperature is calculated by means of a power balance between the incoming and the extracted SG power.

STEADY STATE RESULTS

The model includes a steady-state control, which regulates the temperature of the molten salts so that the power in the SG is 55kW (7% of ALFRED reactor initial decay heat). During the Steady State phase, the system adopts the HX Pool as the main heat sink, removing about 50 kW, with a mass flow rate of 0.02 kg/s. The remaining fraction of power, about 5 kW, is removed by the cooling power through the pipe walls. During Steady State, the IC branch is isolated and filled with non-condensable gases at room temperature and at 110 bar.

The steam from the SG begins to condense at the bottom of the HX tubes (P-304/10), just at the level, 0.62 m, where the HX Pool is full of water (P-504/04). The fluid coming from the HX is subcooled liquid that once it has passed through the SG downcomer (P116/30) increases the temperature to saturation conditions. The fluid enters the annular riser saturated with a void fraction of about 0.2 and ascends until the SG steam header with a void fraction of 0.8. Therefore, the steam into the SG tubes, submerged in the molten salts pool, never reaches superheated steam conditions. (Table 2. Figures 4 & 5).

STATION BLACK OUT SEQUENCE

The starting point for the simulation of the SBO sequence is the previous Steady State phase described above. It is necessary to take into account that the IC branch is at atmospheric temperature and the steam in the SG and in the steam

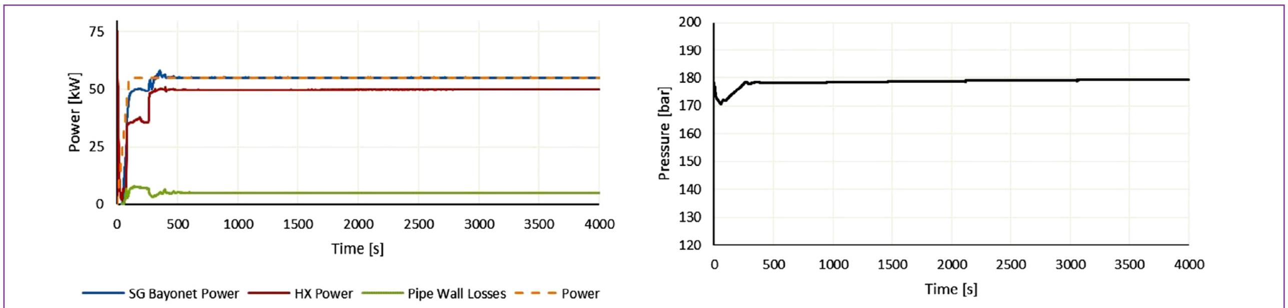

Figure 4. SIRIO-UPM model for TRACEv5p5 code. Steady State. Power balance (left) and top facility pressure (right).

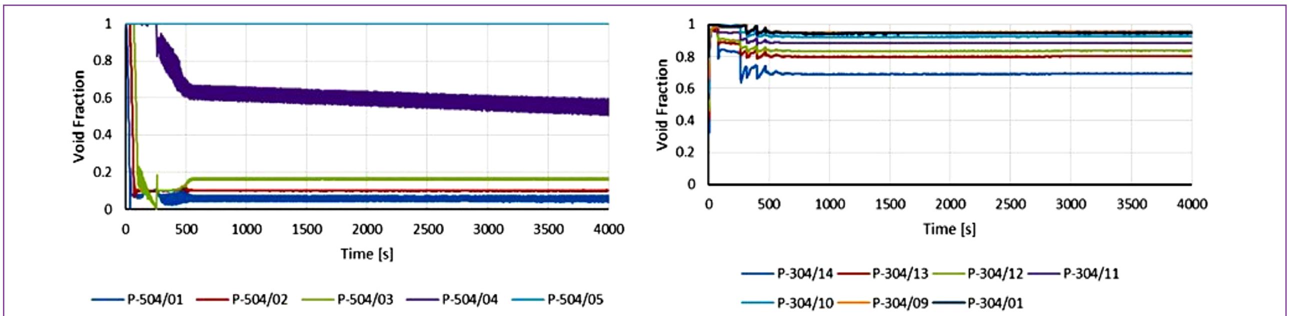

Figure 5. SIRIO-UPM model for TRACEv5p5 code. Steady State. HX Pool void fraction (left) and HX void fraction (right).

Event	Conditions
Upstream and downstream HX valve closes	4000 s after the beginning of the simulation
Upstream IC valve opens	P-148 pressure = 190 bar
Downstream IC valve opens	65 s after the upstream IC valve opens
Initiation of the decay heat curve	6000 s after the beginning of the simulation

Table 3. SBO sequence events.

line is at very high pressure and temperature. This causes a strong depressurization when the IC isolation valve is opened. Normally, nuclear power plants operate with the upstream IC valve open, so that the ICs have a similar pressure to that of the vessel (BWR) or the steam generator (PWR). To perform a realistic simulation, during the first 2000 seconds of the SBO sequence, the power of the heat source is kept constant, at 55 kW, to account for non-negligible heat capacity of the cold side. At 2000 seconds after the beginning of the SBO sequence, the power of the heat source begins to decrease following the decay heat curve of ALFRED reactor.

At 4000 seconds after the beginning of SBO sequence, both the upstream valve and the downstream valve on the HX close. Then, the SG is isolated from both, the IC and the HX, causing the pressure to rise rapidly up to the upstream IC valves set-point, 190 bar. The downstream IC valve opens 65 seconds after the upstream IC valve.

Once the HX valves are closed, the pressure rises rapidly because the main heat sinks (HX and IC) are isolated, so the steam can only be cooled by heat losses through the pipe walls. The pressure takes 92 seconds to reach 190 bar, and then the inlet IC valve opens, and the inventory from the steam line with a temperature of 634 K enters the IC branch, that is at 303.15 K. This causes a pressure to drop to 148 bar 176 seconds after the upstream IC valve opens. Subsequently, the pressure increases again because the power transmitted to the fluid in the SG is much greater that that removed by the IC and by the pipe walls. At 6000 seconds, the decay heat curve simulation begins, so the SG power reaches a lower value than the IC Power. This it makes that the pressure begins to decrease again (Figure 6).

From the 6.500 second to approximately the 8.000 second, the power removed in the IC is higher that the power absorbed by the fluid in the SG. It causes that the pressure decreases rapidly in this period of time, allowing the non-condensable gases to expand from the gas tank and migrate to the colder region of the IC branch (Figure 7). Due to the presence of non-condensable gases, the efficiency of the heat transfer between the IC branch and the IC Pool begins to degrade. Therefore, the removed power decreases which causes the slope of the pressure curve to decrease.

The behavior of the mass flow follows the behavior of the pressure, showing two peaks (Figure 8): one when the upstream IC valve opens reaching a value of 2.7 kg/s, and the

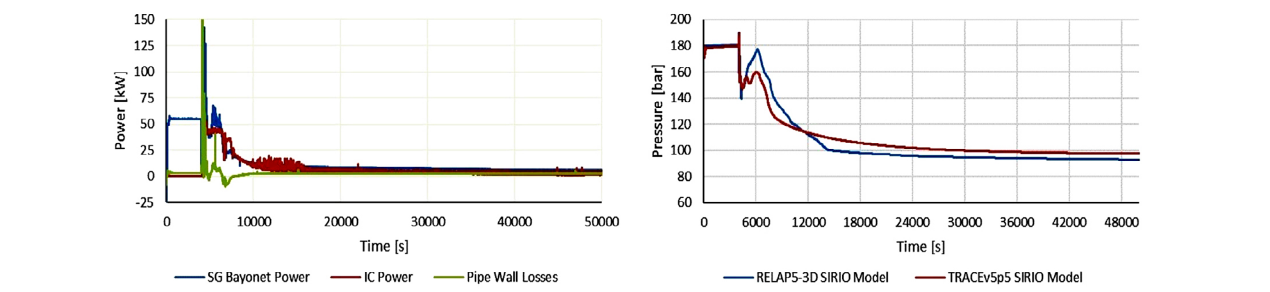

Figure 6. SIRIO-UPM model for TRACEv5p5 code. SBO sequence. Power balance (left) and top facility pressure (right).

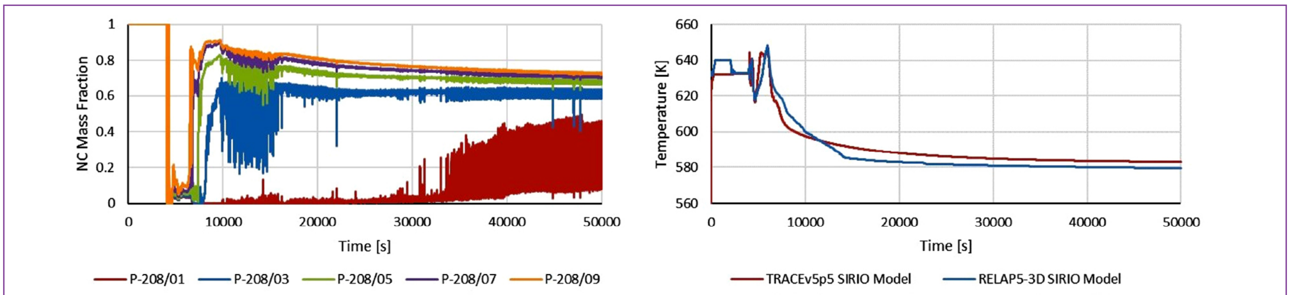

Figure 7. SIRIO-UPM model for TRACEv5p5 code. SBO sequence. Concentration of NC gases in the IC (left) and Avg. Salt temperature(right).

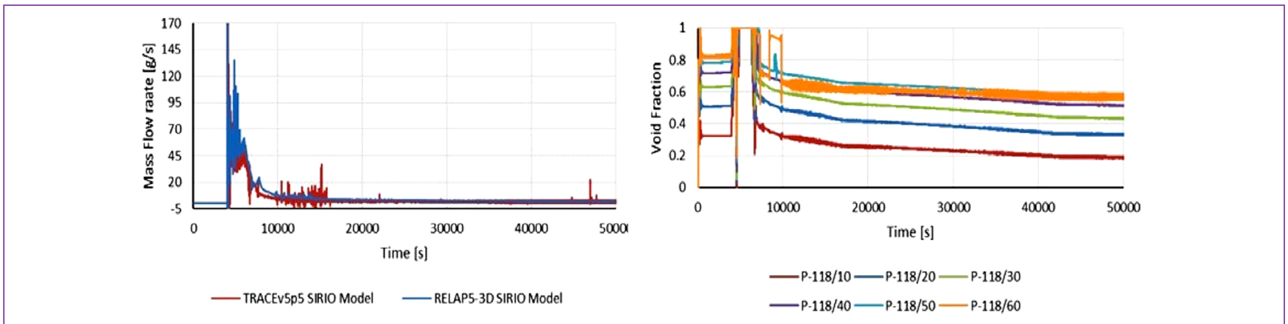

Figure 8. SIRIO-UPM model for TRACEv5p5 code. SBO sequence. IC inlet valve mass flow rate (left) SG void fraction (right).

other one when the pressure increase at 6.000 second, reaching a value of 46 g/s which later it stabilizes at 2 g/s. It is possible to notice that the steam coming out of the SG steam head is at saturation conditions during the whole simulation, however, the fluid at the inlet of the SG annular riser is subcooled liquid.

CONCLUSIONS

- The Steady State results of the SIRIO-UPM model for TRACEv5p5 code conform to the values predicted by the RELAP5-3D code.
- The SBO sequence results of the SIRIO-UPM model for TRACEv5p5 code also presents a similar behavior to that predicted by RELAP5-3D code.
- Simulations with TRACEv5p5 and RELAP5-3D codes have confirmed that the innovative IC with non-condensable gases is able to passively remove the decay heat power. Besides, it also prevents the molten salt (simulating the primary lead coolant of the Alfred reactor) to reach a temperature corresponding to the lead freezing.

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