MADISON EXPERIMENTAL DEVICE DEDICATED TO LWR FUELS STUDIES IN JULES HOROWITZ REACTOR FEEDBACK ON MOCK-UP LOOP TESTS PERFORMED BY IFE HALDEN

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The MADISON device is part of the experimental fleet of Jules Horowitz Reactor and has been designed for experiments focusing on normal operating conditions of fuel in LWR.
IFE has manufactured a full-scale mock-up of the loop to test thermal-hydraulics performances in PWR conditions and the behavior during transients in normal and abnormal operating conditions.
The tests validated the transients for starting and shutting down the loop as well as variations in primary flow, cooling and electrical power.
These tests demonstrate the stability of essential parameters like pressure, flow, temperature. The loop is capable of responding to multiple experimental needs in the future, with a wide range of experimentations and most configuration.
This mock up is providing opportunities to update design and development and test equipment modifications in full scale and will be useful to CEA teams during the design phase of the Madison loop.

1. Introduction

The **MADISON** (**M**ulti-rod **A**daptable **D**evice for **I**rradiations of experimental fuel **S**amples **O**perating in **N**ormal conditions) is part the Jules Horowitz Reactor (JHR) experimental fleet. The MADISON experimental device is a device designed to irradiate fuel rods under nominal operating conditions (steady-state and transient conditions as transients of class 1, ie not leading to cladding rupture).

The Madison experimental device consists of three main parts.

- The in-pile irradiation device, attached to a displacement system in the reactor pool, allowing for the adjustment of fuel rod sample power.
- A shielded cubicle located in the cold compartment adjacent to the reactor pool housing the main parts of the loop that are subjected to radiation. The electrical cabinets and the rest of the loop are close by.
- Underwater lines, reactor pool piping penetrations and ground piping link the in-pile part with the loop.

This high-capacity device will allow irradiation under nominal conditions of Light Water Reactors up to 4 fuel rods simultaneously. For this purpose, the in-pile part of the device, placed on a displacement system, is connected to a loop. This design allows on-line regulation of the fuel linear heat generation rate according to the predetermined experimental protocol independent of the JHR core power.

In support of the design of the MADISON device, a mock-up loop was designed and built by IFE, thus benefiting from the feedback of experimental loop designers and operators and reactor irradiation devices at Halden. This full-scale mock-up loop was designed to validate the thermal-hydraulics operation of the loop, in parallel with studies carried out with the CATHARE calculation code, but also to de-risk the main equipment that will be used on the future MADISON loop at JHR (e.g. high-pressure main pump). The mock-up loop was assembled and arranged in a cubicle with identical dimensions as the MADISON will be at JHR, thus making it possible to evaluate the operability and maintainability of the various equipment.

2. Description of the mock-up

Both mock-up loop systems and the MADISON Loop consists of three main systems:

The High Pressure Circuit (HPC), which maintain the LWR conditions. This circuit is equipped with heaters, exchangers, main pump and high pressure/temperature sensors.

The Low Pressure Circuit (LPC), which supply the HPC with water and with capabilities to which analyze and maintain the water chemistry of the loop. This system consists of:

- Low Pressure system: As well as supplying the HPC system with the required water volume and water quality it will compensate for any HPC loop water density changes during operation of the HPC. Additionally, the LPC will maintain the loop water pressure in the HPC within specified limits by regulating the makeup pumps and the pressure control valves. It will also supply emergency cooling for the experimental device in an accidental situation. Such as a large (pipe) breach upstream or downstream the rig. This is achieved by using two large accumulators (AC-200/201).
- Purification system: The purpose of the purification system (PUR) is to minimize the level of loop water impurities. This is important to prevent corrosion and radioactivity build-up. The main elements of the PUR are two particle filters and a mixed bed ion exchange assembly.
- Water analysis system 1 & 2: The water analysis system 1 (WAS1) will be monitoring the water quality in the water reservoir tank. The WAS1 sensors will be monitoring dissolved hydrogen, dissolved oxygen and conductivity in the water. The water analysis system 2 (WAS2) will be monitoring the loop water downstream the irradiation rig.

The support systems, including intermediate cooling systems, gas supply and liquid and gas effluent systems.

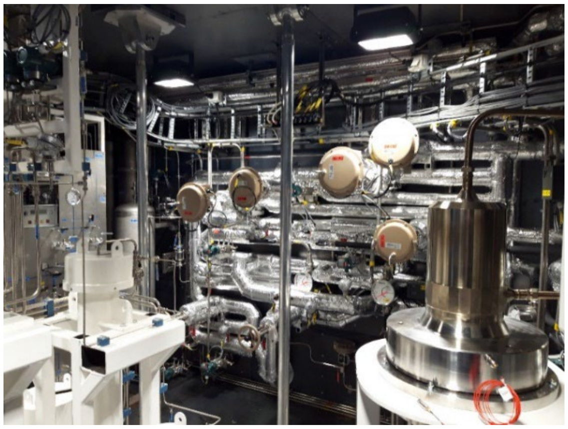
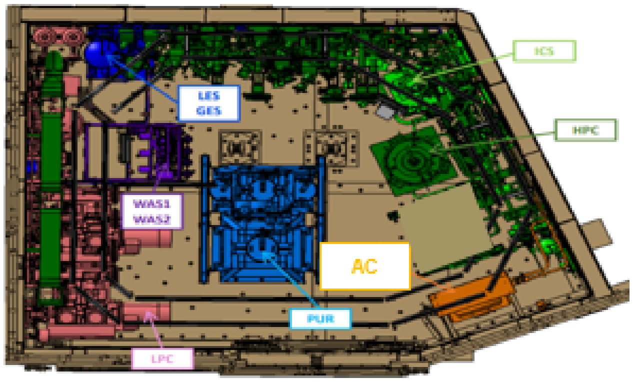


Figure 1: Loop 17 view



LES : Liquid effluent system -
GES : Gas effluent system
WAS : Water analysis system
LPC : Low pressure circuit -
HPC : High pressure circuit
PUR : Purification system
ICS : intermediate cooling
system
AC : air conditioning

Figure 2: Loop 17 overview

The main characteristics of HPC and LPC:

Table I: Main characteristics of HPC & LPC

	Requirements	**Limit**
HPC	Minimum operating flow	0.3 kg/s (1080 l/h)
	Nominal operating flow	0.8 kg/s (2880 l/h)
	Maximum operating flow	1.0 kg/s (3600 l/h)
	Nominal operating pressure: • BWR pressure operation • PWR pressure operation	 70 bar 155 bar
	Nominal operating temperature, rig inlet: • PWR • BWR	 280-330 °C 250-290 °C
LPC	Nominal flow	200 l/h
	Operating pressure range	3-5 bar
	Operating temperature range	30-40°C

3. Summary of Design Process

At the HBWR (Halden Reactor) IFE has a lot of experience in building and running loops, starting in 1986. The MADISON LWR idea started out as a copy of a Halden Loop, but soon developed into something a bit more complex. Constructed with a combination of high and low pressure circuits designed to initially meet both BWR and PWR conditions.
The principle was tested in the HBWR test facility at Halden.

In addition to a complex loop design the MADISON Loop has some extra requirements. The main parts of the loop are to be placed in a Cubicle which dimensions already was decided before the design of the loop. The Cubicle also had holes for mounting equipment on walls, floor and ceiling. The design had to be made following a rigorous process of calculations, procurement and detailed design, meaning dimension on equipment had to be assumed in the early stages.

To solve these challenges IFE had to use different approach than with typical HBWR loops. First the decisions on what had to go inside the Cubicle and what could go outside in the Cold Compartment had to be made in collaboration with CEA. Respecting radiation levels and RCCMRx rules and regulations. After studies using CAD tools areas for the different circuits were made. E.g. two walls for the HPC and ICS circuit, one wall for the LPC, center position for the PUR, etc. This was helpful in the further detailed design of the loop in giving boundaries when working and making it possible to work with smaller portions of the loop. In order to accommodate the already placed holes in the Cubicle walls it was decided to use plates that fit these holes. The equipment and equipment holders could then be fastened (mainly welded) to these plates.

The CAD program used at IFE has a function called “Representations” that switches visibility on objects in the CAD Model. This gave the opportunity to have both the MADISON Loop and Loop 17 in the same CAD model. Even though Loop 17 has less components than the final MADISON Loop. The “Representation” function gave the possibility to draw a CAD model with the knowledge that all the equipment would fit for both loops. Which is especially important with the MADISON Loop.

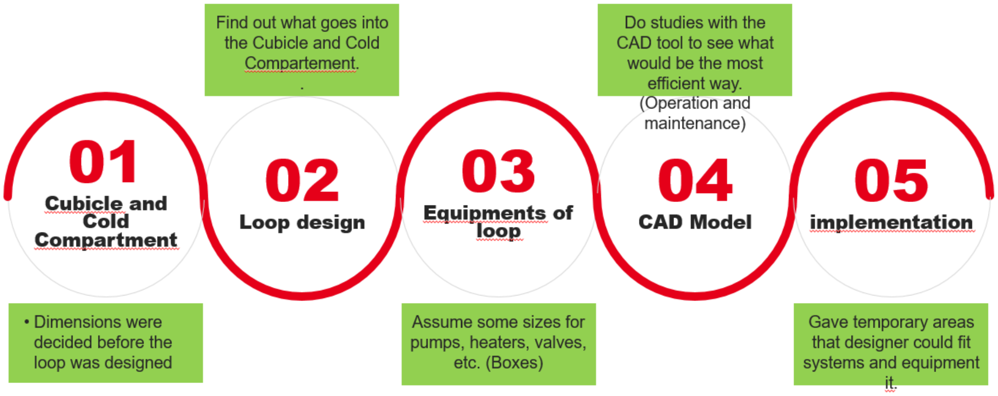


Figure 3: Design process summarized

4. Purposes of the mock up loop

The mock up loop has many purposes at short and long term.

The first goal is to validate the MADISON loop design in as many aspects as possible: thermal-hydraulics performance, equipment selected (good functioning), implementation, I&C, chemistry, etc. This paper focus on the first part: the thermal-hydraulics tests.

This mock-up will be useful for design of the real MADISON loop, which have more requirements for safety and regulation. It will allow for an easier adaptation of the design and lay-out of MADISON-JHR as well as contributing to the risk reduction for its industrial cost estimation.

The long term aim of the mock-up will be:

- To create and maintain competencies of the thermal-hydraulics operating of the MADISON type irradiation loop whilst taking into account the functioning of the loop under PWR and/or BWR conditions.
- To create and improve technical training for the JHR experimentation teams (engineer, technician, electrician, automatician, instrumentalist, chemist...).
- To optimize and test the correct functioning of sample-holders before irradiation.

5. PWR Nominal conditions tests

5.1. Purposes of the loop tests performed

The purpose of these tests is to validate the thermal hydraulics performance of the loop concerning the heating and cooling capabilities, flow and pressure drop capabilities and the ability to maintain stable conditions during normal and incidental conditions.

5.2. Optimization of the loop transients of start-up and shutdown

The transients of the startup of the loop have been optimized in several stages during August and September 2022. The loop has been started in cold conditions, during this stage the primary flow control valves have been tuned. After that, the pressure in the High Pressure Circuit has been increased to 155 bar to check if the performance of the pressure control valve is satisfactory.

The water chemistry has also been checked. The main elements of the purification circuit are two particle filters and a mixed bed ion exchange assembly. This mixed bed ion is used to remove lithium from the water loop. The water analysis systems check the oxygen and hydrogen concentration, the conductivity and the pH. The first system is linked to the main water tank in the Low Pressure Circuit, with the aim of checking the average chemistry of the water loop. The second system is connected, in the Low Pressure Circuit too, but as close as possible to the High pressure circuit in order to detect a possible contamination. There is a double set of oxygen and the hydrogen sensors in each system.

The temperature has been progressively increased to 120°C, 150°C and 300°C to check if the heat exchanger setup is performing as planned.

The critical stage is at low pressure because there is not yet a flexible system in the loop to accommodate a peak of pressure or fluctuation due to the movements of the control valves. The capacity to absorb pressure peaks appears around 120 bar, when the pressure in the loop is higher than that in the gas part of the accumulators.

The figure below shows the startup phases of the loop at the PWR conditions the 30th August 2022.

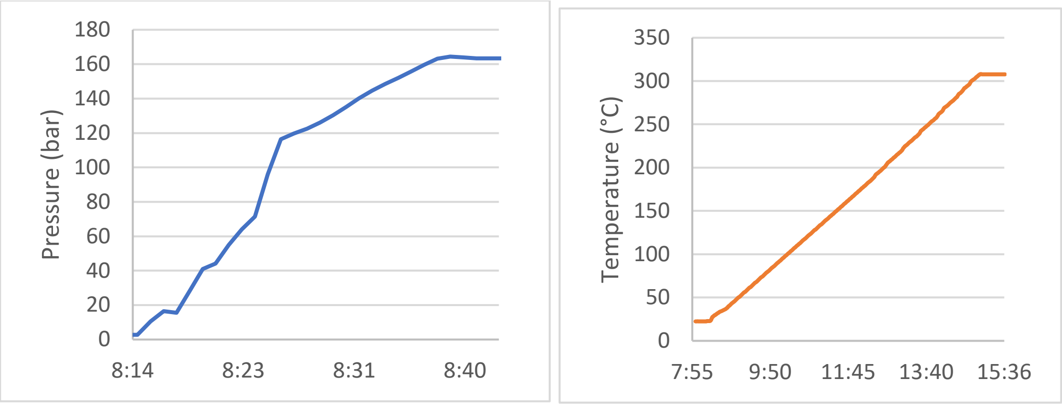


Figure 4: Pressure and Temperature evolution during the startup at PWR conditions

This first tests shows the capabilities of the loop to reach the PWR thermal-hydraulics conditions. The target pressure could be obtained in few minutes, and the temperature evolution is limited in order to reduce the thermal stress of the primary pump.

5.3. Simulation of a power variation

The goal of the test performed on the 19th of October 2022 was to demonstrate that the MADISON loop is capable to maintain stable thermal-hydraulics conditions during power variation of nuclear fuels. The nuclear power variation are simulated by electrical heater (H-104) in the in-pile mock-up.

The figure below shows the transient:

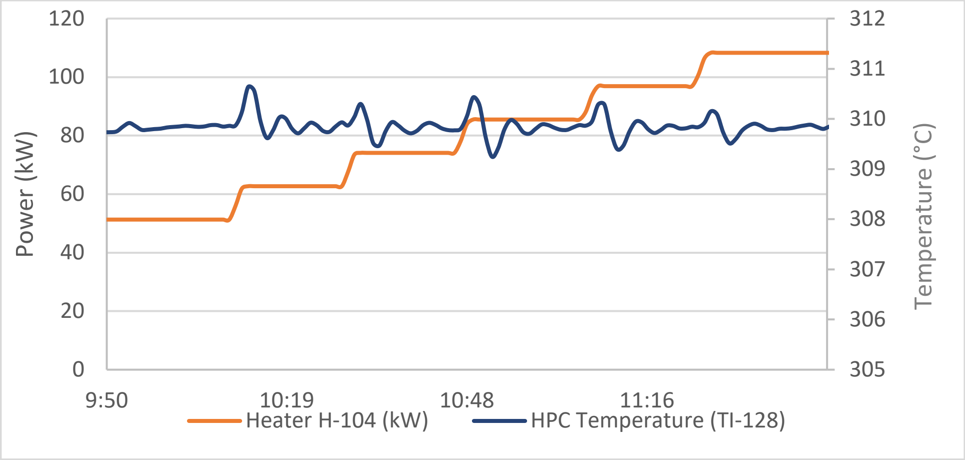


Figure 5: Temperature of High Pressure Circuit during ramps power

The power has been increased from 51 kW to 108 kW by step of 10 kW. The temperature control was very efficient and the temperature was very close to the target, the deviation was less than 1°C.

5.4. Investigate the operating range in term of flow

The MADISON loop is expected to handle different configurations of fuel rods. This will require the capability to adjust the main coolant flow.

On the 20th of October 2022, a test on the range ability of the High Pressure Circuit flow has been performed. At 10:36 the flow reduction started in steps of 400 kg/h down to 1900 kg/h at 11:05. At 13:05, the flow was reduced, first to 1500kg/h then 1300 kg/h and finally 1100 kg/h at 13:40.

During this transient, the heater power was adapted to 63 kW for the highest flow condition and 34 kW for the lowest flow condition.
The transient is showed in figures below:

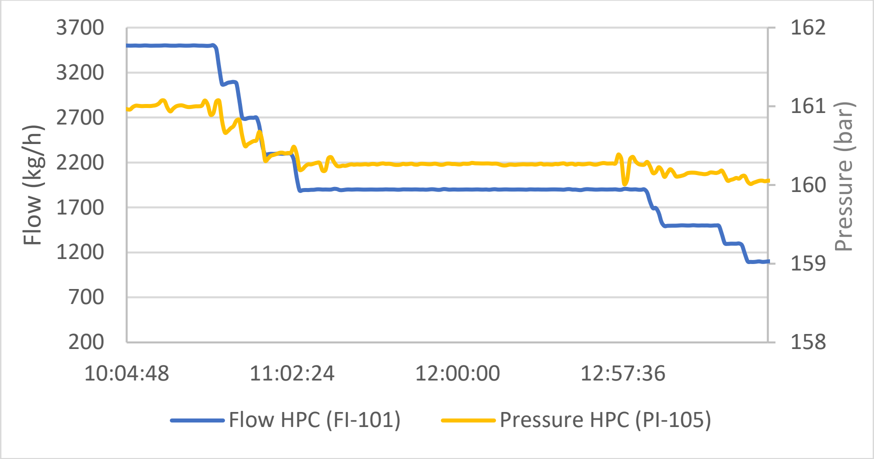


Figure 6: Primary flow transients and pressure evolution

The pressure control was very efficient during the test; the pressure variation was very limited.

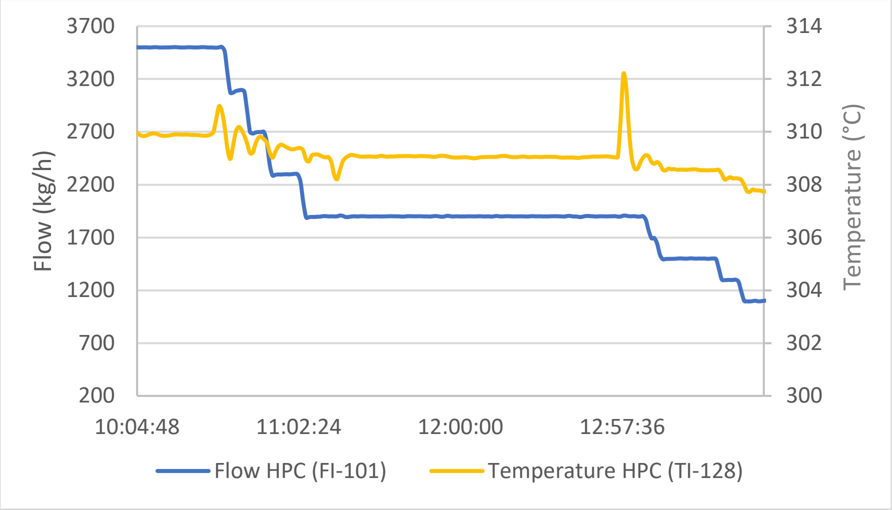


Figure 7: Primary flow transients and temperature evolution

The temperature control was also very efficient during the test, the temperature variation was limited to some degrees.

5.5. PWR conditions – Abnormal and Incidental situations Tests

5.5.1. Electrical power transients

This test simulate the loss of electrical power in the High Pressure Circuit heater H-103. This situation could change drastically the thermal-hydraulics conditions in the circuit and could trigger automatic actions by the device (protection or safety) or by the reactor (SCRAM) if the controlled system is too quick or too slow.

The figures below show the transient performed the 6th September 2022:

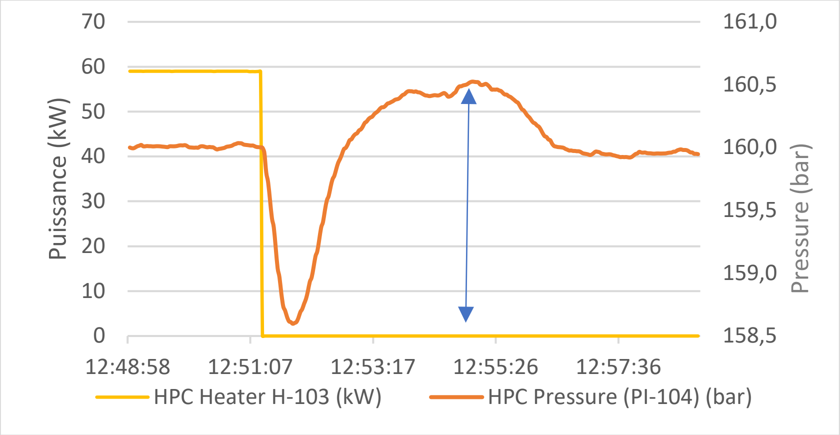


Figure 8: Pressure evolution during the loss of electrical power

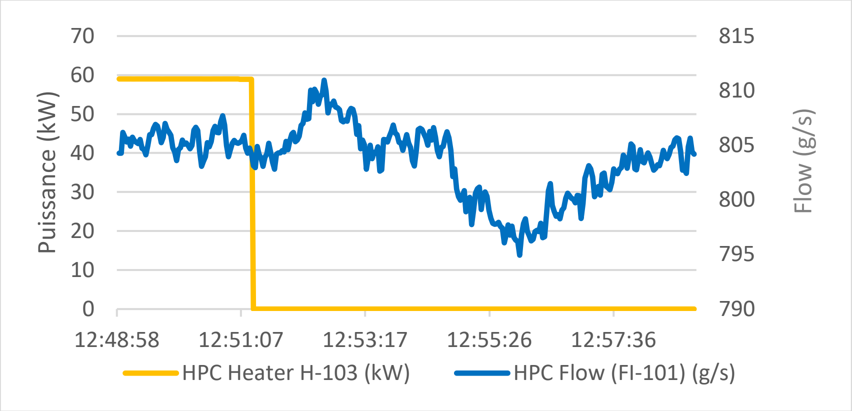


Figure 9: Temperature evolution during the loss of electrical power

The results of this kind of transient shows a low range of variation of loop pressure and flow. The design of the loop appears to be robust to these sudden events on main electrical supply system.

5.5.2. Simulation of a Displacement System Retract

This test simulates an automatic action of protection of the device: the Displacement System Retract of the device. The Displacement System Retract of the device is triggered when the thermal-hydraulics conditions of the High Pressure Circuit (pressure, temperature, flow) or nuclear power generated by the fuel rods are outside its limits.

This action keeps the device away from the core in order to stop the nuclear power generated inside the nuclear fuel rods. To simulate this effect in power drop, a quick disconnection of the heater rig (H104) is done. The heater rig is simulating nuclear power generated in pile part of the device.

The goal of this test is to verify that the flow and pressure transients can be managed without triggering a threshold of the device which in turn triggers an automatic action of the reactor (SCRAM). The loss of electrical heater has been limited at around 2min30s for limited the thermal stress of the main pump. The real transient will be simulated by CATHARE (thermal-hydraulics calculation code) and adjusted with the kinetic obtained during this transient.
The figures below show the transient performed on the 6th September 2022:

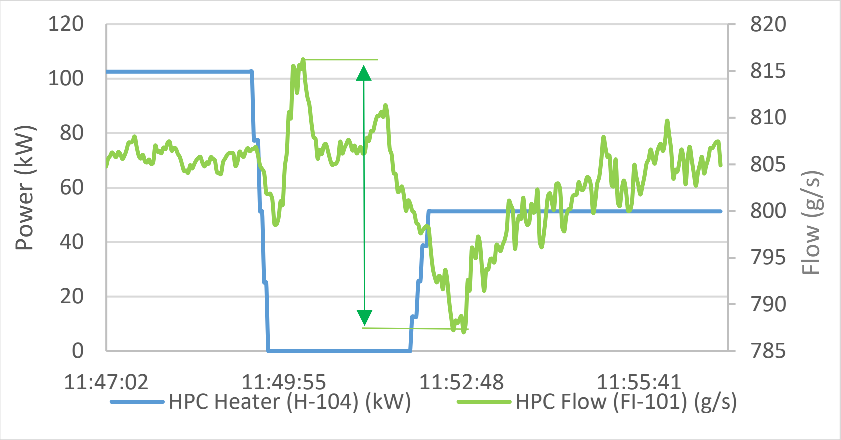


Figure 10: Flow evolution during a Displacement System Retract

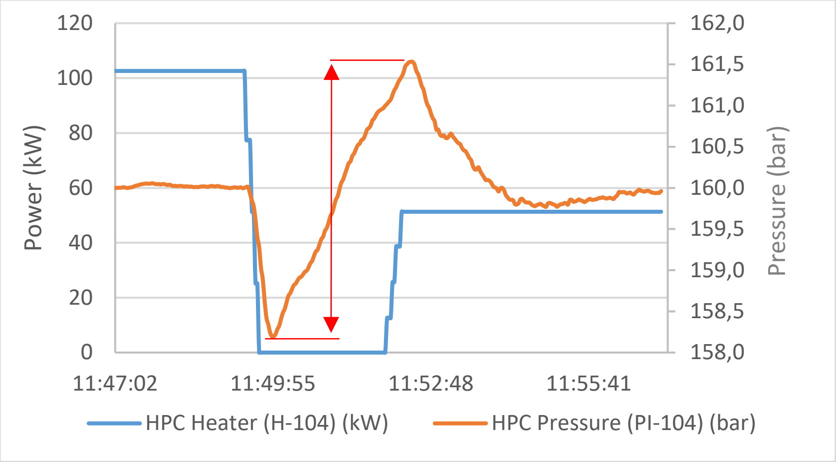


Figure 11: Pressure evolution during a Displacement System Retract

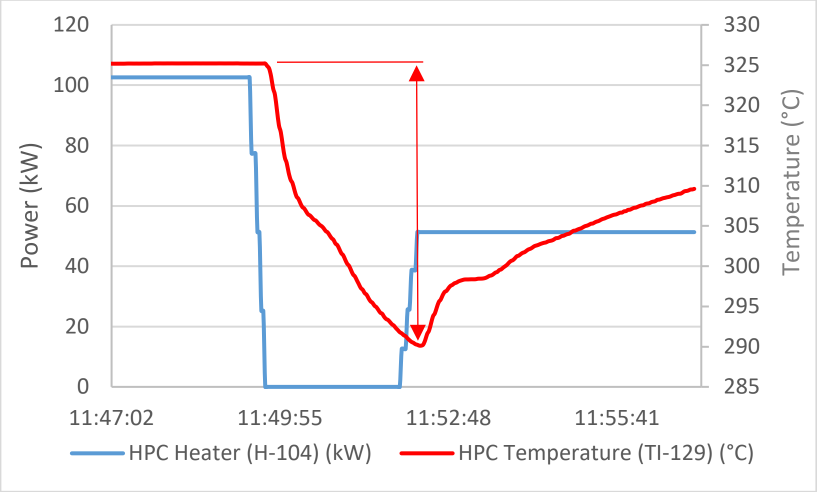


Figure 12: Temperature evolution during a Displacement System Retract

The temperature drop, due to the loss of heater, does not generate a significate perturbation of flow and pressure parameters.

5.5.3. Others Transient relatives to unwanted equipment's failure

Several tests of unwanted positions or actions of valves have been performed and have shown the well-functioning of the loop.

A test of the shutdown of the main pump allowed us to determine the kinetic of flow reduction in order to improve the thermal-hydraulics calculations of these events.

A series of tests consisting of increasing the pressure drop in the Rig Simulator of the in pile part, have shown the capability of the loop to allow multiple configurations of flow and pressure. These tests are important to show the diverse experimental capabilities needed in the Madison Loop. It is expected to be able to handle a range of different Sample Holders.

6. Conclusion

Numerous tests have been conducted to validate the normal operating conditions of the loop, these tests include start-up and shutdown transients of the loop as well as variations in primary flow, cooling, and injected electrical power. These tests also allowed for an estimation of the loop's heat losses.

Incidental situation tests were focused on the shutdown of heating elements and untimely movements of actuators. These include the untimely opening of the bypass valve of flow control valves of the main exchangers, untimely closing of the relief valves to the Low-Pressure Circuit, closure of the secondary valves of the main exchangers, and measurement of the flow decrease of the main pump in case of loss of its electrical supply.

This phase of tests performed in Halden by our Norwegian colleagues of IFE were of interest to design team of CEA in charge of implementing the Madison loop in the JHR Facility.

These tests which aimed to make a preliminary assessment that the loop will have a large capacity and could provide a wide range of experiments. The loop is capable of responding to multiple experimental needs in the future, with a wide range of flow and pressure available for experiments and configurations. The I&C system is intuitive allowing for easy control and operation of the loop and its robustness to transients is achievable.

Furthermore, this mock-up is an exact scale model of the future Madison loop. It provides opportunities to update design and development and test equipment modifications in full scale, including main exchangers to verify the thermal-hydraulic impact against the tests carried out in support of the design in Halden.
It allows to check for layout changes, acquire data and lessons for operations, maintenance (optimize procedures and tools), PID modifications, regulation and operation as well as to train designers of such loops which are quite different from inactive PWR loops.
It is a facility that will help CEA teams with multiple needs during the design phase of the Madison loop.

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