THE ARCHEOS HEAT UNIT TO DECARBONIZE THE HEAT MARKET WITH PROVEN TECHNOLOGIES

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Abstract

The ARCHEOS SMR is under development in the CEA. Currently under conceptual design phase, the ARCHEOS objective is to decarbonize the heat market in Europe for low temperature applications such as food industry, pulp, paper and chemistry. In 2024, a new structure regrouping industrial partners will host the ARCHEOS development.

ARCHEOS is a Light-Water Reactor powering 50MW of heat to industrial networks. The main compromise on the ARCHEOS design, allowing reaching the economic target, is the supply temperature around 150°C. The reactor operates below 15 bar and uses new inherent safety feature.

The thermal hydraulic design use natural convection on the primary and secondary circuits for normal operation. The primary circuit is an integrated vessel connected to compact heat exchangers directly linked to the vessel. A second vessel containing the secondary volume is around the primary vessel and contains a hot zone and a cold zone separated by a thermocline. The secondary circuit is thus in natural convection between the primary/secondary heat exchanges and the thermocline.

This particular design leads to new thermal hydraulic operation of the reactor and a very high degree of safety: various accidents studied for LWRs do not exist for ARCHEOS and a thermal inertia will absorb the vast majority of postulated accident for ARCHEOS.

1. INTRODUCTION

European industries using heat are vastly using gas with major disadvantages: the volatility of its price and the carbon impact. Several solutions are investigated but none should be able to address a large part of the market:

- The biomass may be at its peak in different countries and may be kept for crucial uses such as high temperature heat or biofuels,
- The geothermic energy needs a very particular environment,
- The heat pump are very competitive for temperatures below 100°C but need residual heat at a higher temperature to have a sufficient performance and to be competitive above 100°C.

ARCHEOS is a PWR dedicated to the decarbonisation of the heat market. As a true compromise between an easy-to-develop technology SMR and a large market, ARCHEOS will power 50MW up to 150°C and will specifically answer industrial needs between 100 and 150°C. With its simple design, ARCHEOS could be the first heat SMR available on the European market that will also need other technologies to pursue its decarbonisation on other markets.

The market targeted by ARCHEOS includes food industry for drying processes and sterilization, and several industries that require steam such as tyre production, pulp industry or wood processing. As ARCHEOS is a nuclear unit, it still requires a high initial investment and should operate with a load factor above 50% to be competitive. That is why ARCHEOS does not primarily target district heat even if it could be an annex market on specific sites.

In Europe, several hundreds of sites could host an ARCHEOS unit in a plug-and-play configuration: these sites need around 50MW over 75% of the year at a temperature between 100 and 150°C.
Actually designed starting from the market needs, ARCHEOS has four main objectives:

— Inherent safety that will be above passive safety. The heat market, contrary to the electricity one, spreads all over the European territory and need to have onsite production unit. Thus, on new areas will site ARCHEOS units, near the heat users. The inherent safety will ease the public acceptation and the safety processes;
— Simplification of the nuclear unit. The major example is the absence of energy conversion system to focus on heat. Furthermore, ARCHEOS design allows evacuating spent fuel few hours after the unit stops so that there is no spent fuel pool. On another side, the use of natural convection reduce the use of pumps and increases the reliability of the operation. This high simplification allows an easy safety process and decreases the heat production cost to be highly competitive;
— Ease to site and develop ARCHEOS. As a new way to decarbonize present factories, an ARCHEOS site has a very limited impact: the industrial heat users won't need to change their way to operate. ARCHEOS does not need a cold source and thus do not use water from the environment. The site size will be below 10 000 m^2. This ease to site is one of the main criterion to be accepted by industrial end users. The ease to develop meets the industrial need to decarbonize fast. ARCHEOS has very limited technological and regulatory risks by reusing already existing systems. For example, the fuel is standard PWR fuel, limited to 5% enrichment;
— Fast to develop. As mentioned before the decarbonisation is urgent. However nuclear unit need time to be developed and we decided to comply to the present regulatory requirements so that the certification of ARCHEOS in France and then in Europe will arrive in 2029.

ARCHEOS is currently during its pre-conceptual design phase and should be led by a new industrial structure at the beginning of 2025 with the CEA and industrial partners.

2. GENERAL DESIGN

All these objectives led to a new innovative design for ARCHEOS. The primary circuit is included in a reactor vessel containing the core, the Control Rod Drive Mechanism (CRDM), the pressurizer, the heat exchanger and a down-comer. To operate in natural convection with around 4 meters of elevation between the core and the heat exchangers, we decided to design innovative compact plate heat exchangers with the benefit of a compact reactor vessel size associated to low level pressure drops (from both sides of the heat exchanger). The primary circuit operates at full power at around 135°C for core inlet, and 175°C outlet. ARCHEOS operates in free boron conditions in normal operation and thus every fuel assembly has control rods. The core contains 45 classic LWR assemblies (17x17 rods) of 1.6m height, enriched below 5%. The core is designed, in accordance with the market, to operate for 10 years before reload.
The secondary circuit is composed on a large metallic vessel around the primary vessel and pipes between the vessel and a secondary/tertiary heat exchanger. The secondary circuit is slightly over-pressurised in relation to the primary circuit so that it will remain monophasic liquid in any conditions, with a natural and passive radiological containment. Mechanical stress induced by pressure gradient between primary and secondary side is highly reduced. The secondary vessel contains a thermocline between a hot zone in the upper part and a cold zone in the lower part. The secondary circuit flowrate operates in natural convection between the thermocline and the heat exchangers, specificity that makes this mode of operation unique for a pressurised water reactor. Thermal power extraction is given by a classic forced circulation circuit with pumps and heat exchangers. This circuit is used to take hot water from the top of the secondary volume and send it to secondary/tertiary heat exchangers. After cooling, secondary water is returned to the secondary vessel, below the thermocline level. With this configuration, the heat exchangers do not need to be integrated into the reactor vessel, and the possibility of a pipe rupture has no significant consequences for core cooling. The closer the primary and secondary circuits are to equilibrium, the less likely it is that such an event will occur.
An In-Refuelling Water Storage Tank (IRWST) is located above the secondary volume and is used during the maintenance phases. The IRWST is also used as an Ultimate Heat Sink (UHS) for several accidental conditions: the residual power is evacuated from the secondary volume to the IRWST. The submerged safety exchangers operate in natural convection so that there is no need of large power backup onsite. In extreme case, particularly

in the event of a lower rupture of the secondary vessel leading to a significant drop in liquid water level, isolation valves can be opened for mixing water pool and secondary water inventory, as a diverse system device for residual heat power extraction function. There is no direct primary cooling function, as the entire primary circuit system is immersed into the secondary circuit inventory, with both natural convection mode in any conditions with the primary heat exchangers, and direct thermal conduction from the reactor vessel. Even the innovative pressurizer's natural cooling function makes a contribution to incidental reactor cooling management.
The tertiary circuit is made of the heat exchangers and a customer heat network deserving several end-users.

TABLE 1. Temperature and pressure of circuit systems

Circuit	Hot temperature (°C)	Cold temperature (°C)	Pressure (bar)
Primary	175	135	14
Secondary	155	115	14.5
Tertiary	150	110	Depending on the network

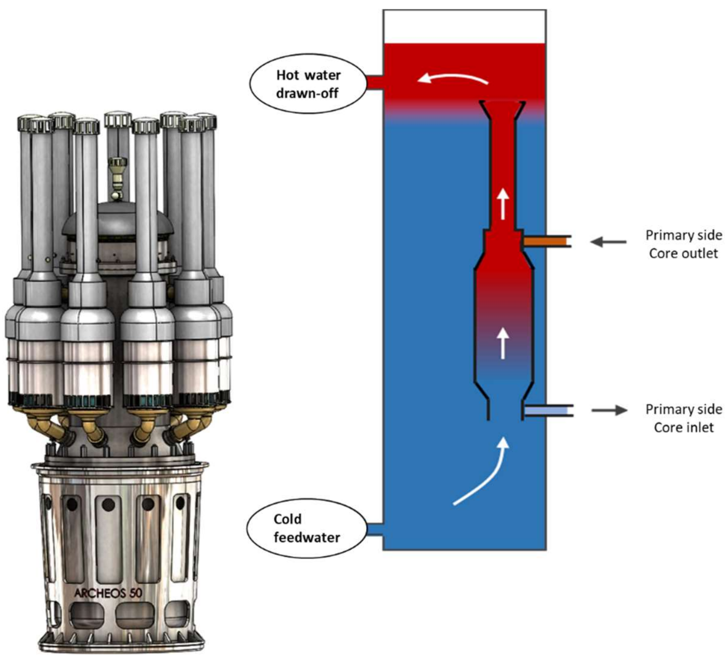

FIG.1. ARCHEOS vessel (on the left), temperature separation in the secondary volume (right)

3. THERMAL HYDRAULICS STUDIES

Design studies to define the operating concept were carried out using the CEA's COPERNIC pre-design tool [1]. The natural primary and secondary circulation loops were modelled as a function of core power parameters, singular and regular pressure drops in the core and primary/secondary heat exchangers. The plate heat exchangers were sized according to the manufacturing possibilities for these components, the total footprint of the reactor block, and the maximum permissible pressure drops to maintain a reasonable elevation of the reactor vessel. In a second step, CATHARE model [2], [3] of primary and secondary circuits have been developed, as well as the extension of the forced secondary level. The limitation in the representation of the large 3D secondary volume with respect to 0D-1D modelling of the CATHARE thermo-hydraulic code led us to extend the modelling to the use of CATHARE 3D [4], but also to CFD tools that are better able to represent the 3D physics and stability of the thermocline in secondary circuit volume. Future developments are also envisaged, based on coupling system code and CFD, of the CATHARE 3/Neptune type, in order to better represent the evolution of the primary and secondary circuits associated with a large stratified 3D volume. Operating, cold start, reactor shutdown and load variation studies were modelled using the CATHARE 3 tool, and led to specific regulation studies to ensure stable power operation while delivering the required temperatures to the customer circuit. Operating parameters are monitored and controlled at different power levels using the following control tools: - a set of heaters and pressuriser coolers for primary operating conditions, a main flow control valve for the primary circuit before the exchanger inlet, a set of regulating valves to adapt the secondary natural flow outlets, and a variable-speed or adjustable-flow pump for the secondary forced circuit. Traditionally, reactor power is adjusted using the control rod insertion position map. An example illustrating the CATHARE studies is shown in figure 2, with a start in "cold" condition, i.e. at the uniform secondary cold temperature. The reactor gradually goes from zero power to nominal power, then to half power, then back to full power. The graphs show the evolution of inlet and outlet temperatures for each circuit.

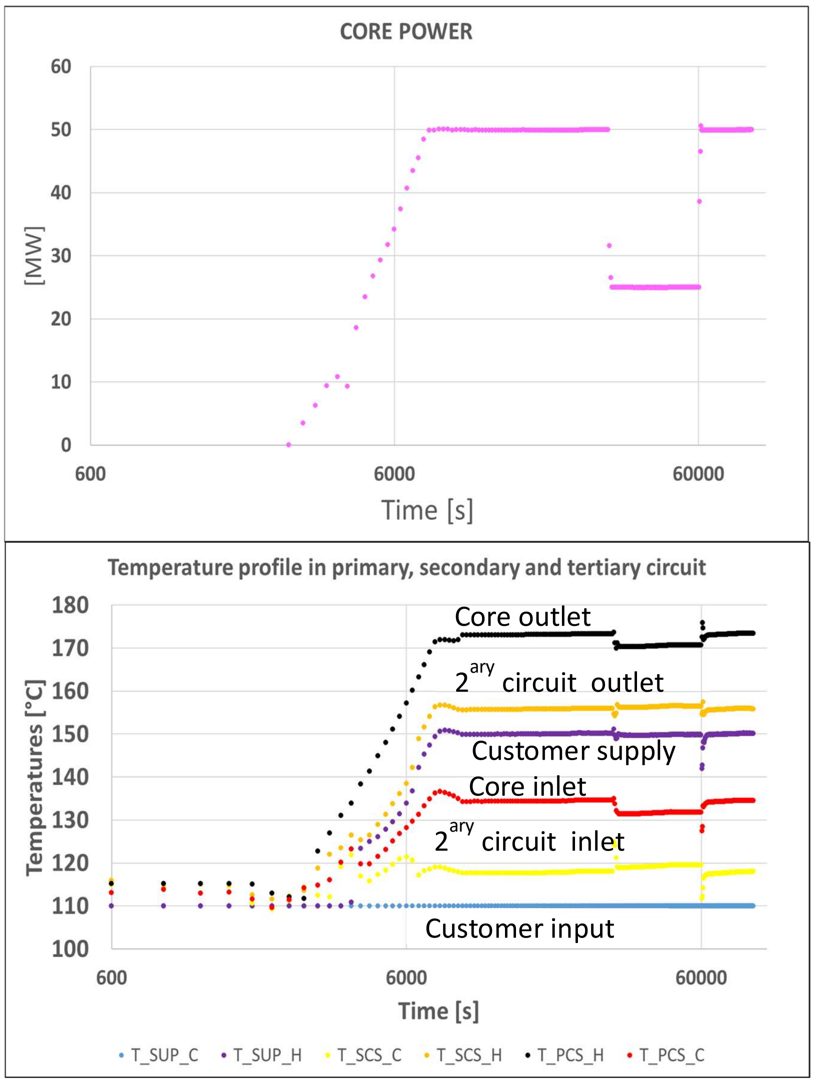

FIG.2. ARCHEOS: CATHARE transient scenario from cold start, full power, 50% reduction scale, and full power final step

Other illustration concerns CFD simulations. The objective is to model the heat exchange that will occur between the primary loop issued from the core and the secondary circuit that will develop in the large volume by natural convection. Note that the primary and secondary fluids are hermetically separated, and that the secondary fluid circulating in the heat exchanger is provided by the water filling the volume of the secondary circuit in which

the reactor is immersed. The thermal gradient separating the hot from the cold water in this vessel is then evaluated.
A 2D approach is first adopted and the geometry is simplified. The heat exchanger is represented using a dual stream model in which the heat transferred from the hot leg to the cold leg is tabulated. The STAR-CCM+ software is used to carry out the CFD simulations. It is based on the finite volume method for solving the Navier-Stokes equations [5]. The modelling uses a turbulent flow and the heat transfer methods.
The CFD approach is used to confirm the analytical calculations in the CATHARE modelling performed independently. The behaviour of the plate heat exchanger is well reproduced and can then be used for simulation. Steady state and transient states can be run for the pre-design calculations of the secondary circuit.

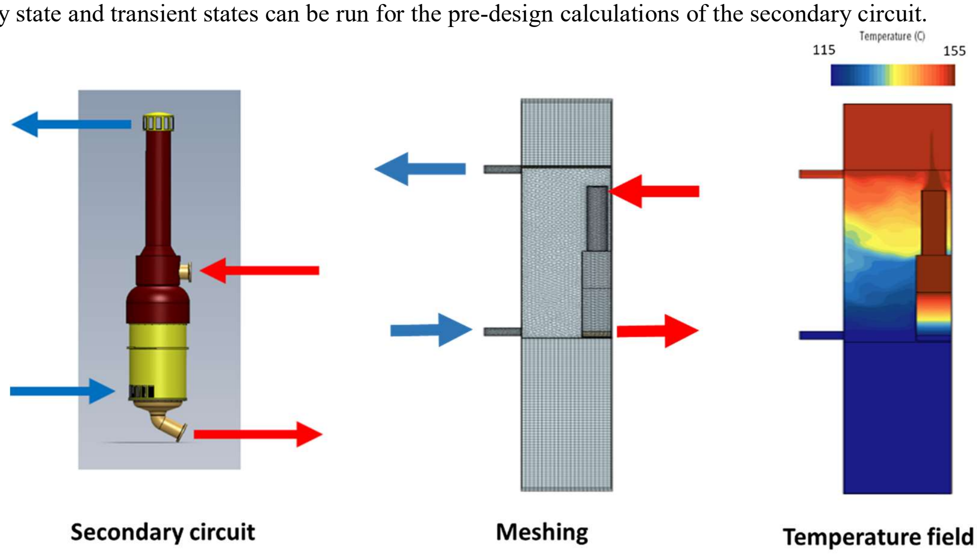

FIG.3. CFD calculation with STAR CCM+ of ARCHEOS secondary plenum temperature

3. SAFETY

The specific ARCHEOS design leads to new safety features modelled with the CATHARE code. The main safety system of ARCHEOS is the secondary design that brings major inertia for all operating conditions, and decoupling mode between the supply circuit and the reactor core. Most initiating events considered in AOO (Anticipated Operational Occurrences) [6] as sudden thermal power rise or stop, are completely diluted with a minimal impact for the reactor core. In case of a LOOP (Loss of Offsite Power), thermal inertia of the secondary volume combined with the elevated position of the thermocline leads to a very reduced pressure drop requirement first, and several hours of period of grace before deciding to start safety cooling operation mode, or going back to normal operation. Thus, in the hypothesis of continuing a scenario of total electrical loss, an almost infinite grace period is provided by the large volume of the ultimate heat sink (IRWST). The initiating events likely to induce a strong variation in reactivity in the core have an extremely reduced probability (close to the physical impossibility of occurrence) thanks to the following characteristics of the reactor: - presence of internal control rods with impossibility of cluster ejection, - maximum speed of movement of the rods reduced by design, - a boron-free circuit involving no risk of injection of clear water, - no cold shock resulting in a rupture of steam pipes. The completely submerged situation of the primary circuit in the secondary circuit cancels any significant consequence of an accident of loss of primary coolant. In the hypothesis of the rupture of the secondary vessel, two scenarios are possible depending on the position of the break:

- Upper break leads to a final mixing with pool inventory, with a shot time boiling mode for the secondary circuit, without any consequences on primary side. Specific mechanical studies are led to verify the absence of significant stress on the structure of the pool with such event. Residual power is extracted through the final ultimate heat sink inventory of IRWST.
- Lower break on the reactor pit environment leads to a rapid level drop of the secondary liquid level, and a boiling mode event, without any consequences on the reactor core during several hours. In this type of situation, the drop in the liquid level no longer allows the dedicated safety cooling means to be used, and a procedure for mixing the secondary volume and the water from ultimate heat sink is then put in place.

Dedicated to the safety residual power extraction, the ARCHEOS unit needs: batteries to operate valves and control of the reactor state; the heat exchangers in the IRWST mentioned above; isolating valves to connect the secondary volume and the IRWST in case of the failure of the previous exchangers to add a large water inventory to the inertia already provided by the secondary volume. Uncontrolled rod withdrawal have to be managed with a sufficient anti-reactivity provision with other rods. As a diversified way to shut down the unit, emergency boron injection is possible in the primary circuit. Finally, protection against extreme events of the external aggression type (plane crash, external malicious acts, and extreme climatic events) is also studied, in particular thanks to specific configurations of access to sensitive areas close to the reactor, and by reinforced means civil engineering. All the incidental and accidental conditions studied, from minor Anticipated and Operational Occurrences (AOO) or Design Basis Accident (DBA) category 2 events, category 3 and 4 design basis accidents, as well as events falling into the Design Extension Conditions (DEC-A) type category, make it possible to consider the **physical impossibility of a severe accident (Design Extension Condition category B) occurrence**.
With the total absence of radioactive rejects, and absence of requirement of an exclusion protective zone around the site, that will be part of the inherent safety included in the ARCHEOS design.

4. ARCHEOS SITE

The overall ARCHEOS site contains two zones. A first one, the most secured, containing the reactor building and a maintenance building and the second containing non-nuclear buildings.

The first zone comprises:

- A reactor building that should resist to external events such as earthquakes or plane crashes (in red in FIG. *2*). The reactor building contains the primary and secondary circuit and the safety systems. This building is the major part of the overnight cost of the ARCHEOS site;
- A maintenance light building (in green in FIG. *2*) designed to host the largest components before being sent into the reactor building at the commissioning phase and designed to receive the fuel casks (fresh and spent);
- Between the two buildings a transfer hatch to carry the components from one building to the other and a Dry air cooler to condition the systems.

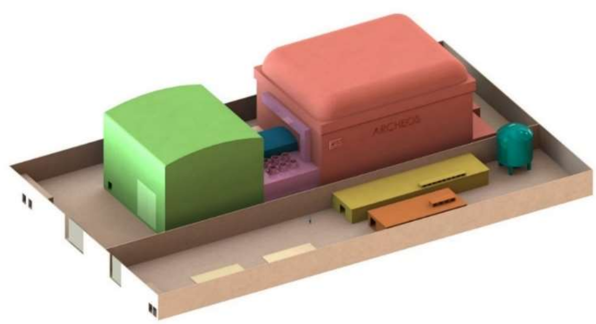

FIG. 2. ARCHEOS site, view of the maintenance and reactor buildings

Two buildings are located in the second area. The first one to host the secondary/tertiary exchangers, shut down circuit system, and the devices to control the power, pressure, temperature and activity of the heat sent on the network. The second one is dedicated to the management of the water pool, chemistry, inventory, cooling mode.
The handling phase occurs during the ten-year in-depth inspection period. The handling machines are brought and installed for the handling campaign. As shown in the figure below, the main heavy lift coupled to the doweling machine allows the upper dome of the secondary tank to be removed to place it at the bottom of the pool. The upper block of the reactor tank, including the exchangers, is thus unbolted and removed to also be installed at the bottom of the pool. Classic assembly handling is then carried out, with placement in a transport castle for immediate evacuation.

5. CONCLUSION AND PERSPECTIVES

The ARCHEOS project is being developed by several CEA departments, for the design of the core, fuel, specific heat exchangers, and operating and safety thermo-hydraulics. In parallel with these developments, economic viability and market studies are being carried out within the IDNES project, as well as civil engineering studies. A thesis is scheduled in the near future to study in greater detail the specific operating features of the reactor, immersed in a large secondary volume which gives the concept a degree of operating safety and tolerance to incidental random events that is totally unprecedented compared with competing concepts.

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