Thermal-hydraulics and Decay Heat Removal in GFR ALLEGRO

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Abstract. One of the key issues in the design of the Gen IV GFR ALLEGRO, a helium-cooled experimental fast reactor, is the core cooling in accident conditions, mainly due to the low thermal inertia of the coolant. After a brief description of the reactor, this paper presents the currently adopted approach to decay heat removal, and the analysis of some of the most penalizing pressurized and depressurized scenarios. Starting from the reference design studied up to 2009, the project now explores new possibilities of further development, with a new target nominal power (in the range of 30 – 75 MW thermal) and power density (in the range 50 – 100 MW/m^3), which will be compatible with the safety limits and the design requirements linked mostly to the steel cladded oxide start-up core fuel. The decay heat removal systems (DHR loops), and their main components must be studied under such conditions to check and improve their efficiency in both forced and natural circulation operation.

Key Words: GFR, ALLEGRO, Thermal-hydraulics, Decay Heat Removal

1. INTRODUCTION

The GFR system, a high-temperature helium-cooled fast-spectrum reactor with a closed fuel cycle is one of the six Gen IV systems. It combines the advantages of fast-spectrum systems for long-term sustainability of uranium resources and waste minimization (through fuel multiple reprocessing and fission of long-lived actinides), with those of high-temperature systems (high thermal cycle efficiency and industrial use of the generated heat, similar to VHTR). The advantages of the gas coolant are that it is chemically inert (allowing high temperature operation without corrosion and coolant radioactivity) and single phase (eliminating boiling), and it has low neutron moderation (the void coefficient of reactivity is small). However, there are some technological challenges related to the use of gas coolant in particular for the Decay Heat Removal under accidental conditions. It's low thermal inertia leads to rapid heat-up of the core following a loss of forced cooling. Also, the gas-coolant density is too low to achieve enough natural convection to cool the core at low pressure, and the power requirements for the blower are also important.

The experimental GFR ALLEGRO project [1] is being developed by the V4G4 consortium formed by UJV (Czech Republic), MTA EK (Hungary), NCBJ (Poland) and VUJE (Slovakia) associated with CEA (France).

The objective of this paper is to present the studies carried out by the V4G4 partners on the Decay Heat Removal of ALLEGRO in accidental conditions and some prospective design options for the feasibility of the concept.

2. ALLEGRO

ALLEGRO is an experimental GFR project with the purpose of developing:

- GFR refractory fuels (UPuC SiC-SifC cladding)
- Helium related technologies (components, instrumentation, purification,…)
- Safety technical issues and corresponding safety approach framework.

The main design characteristics of the reactor are summarized in table 1.

TABLE 1. ALLEGRO MAIN DESIGN CHARACTERISTICS

Nominal Power (thermal)	75	MW	Reduced power is being considered in the range 30 – 75 MW.
Nominal Power (electrical)	0	MW	
Power density	100	MW/m^3	Reduced power density is being considered in the range 50 – 75 MW/m^3.
Fuel	MOX/ SS cladding		Start-up core. Feasibility of LEU UOX for the start-up core is being investigated.
	UPuC/ SiCSifC cladding		Long term core.
Type of fuel assembly	Hexagonal wrapper and wired fuel rods		
Number of fuel rods per assembly	169		
Number of fuel assemblies	81		
Number of experimental fuel assemblies	6		
Number of control and shutdown rods	10		
Primary circuit coolant	Helium		
Secondary circuit coolant	Water		Gas is being investigated
Tertiary circuit coolant	Air		Atmosphere
Primary pressure	70	bar	
Core inlet/outlet temperatures	260/516	°C	Should be upgraded for full core refractory fuel.
Number of primary loops	2		
Number of secondary loops	2		
Number of DHR loops	3		Directly connected to the primary vessel
DHR circuits coolant	Helium		
DHR intermediate circuits coolant	Water		
DHR heat sink	Water pool		
DHR exchangers nominal capacity per loop	2,4	MW	
Number of accumulators	3		Filled with Nitrogen

A general description of main ALLEGRO circuits and components is presented in Figure 1.

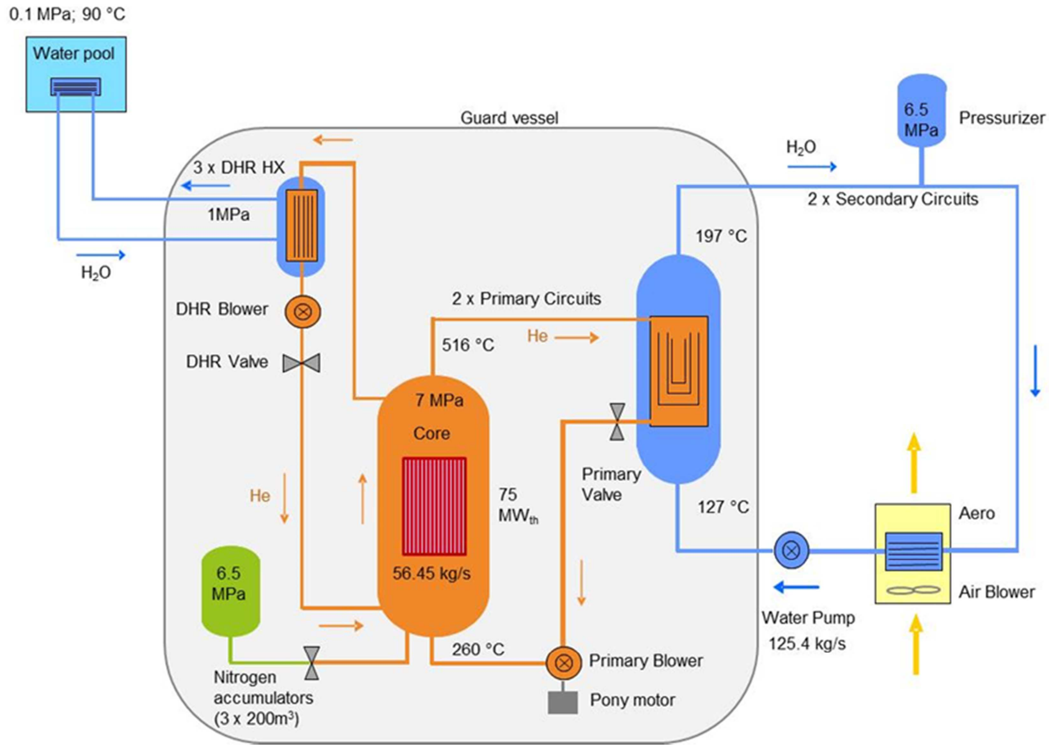

FIG. 1. ALLEGRO main circuits and decay heat removal systems

3. SAFETY ISSUES, DECAY HEAT REMOVAL

The Decay Heat Removal strategy of ALLEGRO considers the challenging case of the occurrence of a small break, natural convection (Station Black Out) with nitrogen injection by the accumulators for the short term of the accident (~1 day) when the decay heat is higher than ~1% of nominal power [2].

This challenge is linked to the very low density of the pressurized helium coolant, which results in a very low thermal inertia on the coolant side. Despite the good heat capacity of the helium, there is low heat removal efficiency under natural circulation.

So, in the process of ALLEGRO feasibility studies a Station Black-Out cumulated with a primary breach transient is postulated.

4. DHR STUDIES

4.1. Reference transient calculations

An extensive work was done on the reference 2009 design related to DHR in accidental conditions using the CATHARE system code. The calculated transients are summarized in the table 2 according to their class:

TABLE 2. CALCULATED TRANSIENTS

CLASS 3 10^{-2}/y - 10^{-4}/y Accidents Plant restart required	CLASS 4 10^{-4}/y - 10^{-7}/y Hypothetical accidents Plant restart not required	DEC Design Extension Conditions
- 3 inch LOCA - LOFA – Loss Of Flow Accident - LOHS – Loss Of Heat Sink (Loss of AIRCOOLER) - Loss Of Off-site Power	- 10 inch LOCA - 10 inch secondary break - Internal break (hot-duct break)	- 24 inch LOCA - Total cross-duct break - Total station blackout. - 10 inch LOCA + GV[1] failure - 1 inch LOCA + Total blackout
Assumed maximum acceptable cladding temperature		
735 °C	850 °C	1300 °C

A total of 39 CATHARE transients' results were analyzed. In those transients that fall into the categories CLASS3 and CLASS4 a single failure criteria was used, while in DEC cases no aggravating events were taken into account. Although, the most representative limit is the maximum cladding temperature, the maximum upper plenum temperature is also considered in the analyses.

The following aggravating events were combined with the initiating events:

- Failure of startup of one pony motor (the other main loop is still active)
- DHR valve is opened (large by-pass through the DHR loop)
- shutdown of both secondary pump (natural circulation in the secondary circuit)
- shutdown of both tertiary blowers (natural circulation in the air cooler, 5% air mass flow rate is supposed)
- Failure of start-up of one DHR blower
- Failure of closure of one primary isolating valve

The simulation results showed that in case of loss of coolant, loss of flow, loss of heat sink, loss of off-site power, secondary break accidents the calculated maximum cladding temperature do not exceed the corresponding values of the given category. Generally, it can be concluded that the worst case aggravating events are the core bypass cases or when only one primary loop is available as a single failure.

It has to be emphasized that these calculations were carried out with best estimate methodology. Nevertheless, more conservative calculations are necessary for licensing. For that reason it is possible that the remaining margin is too narrow in a few DEC cases like: 1 inch LOCA + total blackout, 10 inch LOCA + GV failure, total cross-duct break.

The analysis showed that the maximum cladding temperature value of the internal hot-duct break scenario aggravated by the stop of the blower (pony failure) of the intact loop exceeds the criteria.

In the case of the total cross duct break the transient can be handled with nitrogen injection, but the appropriate signal to start the nitrogen injection couldn't be found. The main difficulty is that nitrogen injection is not necessary in case of a simple LOCA. According to the current concept the injection is activated if both the hot and cold duct is broken and therefore there is

[1] GV: Guard Vessel

a significant core by-pass (DEC). Since the solely use of the pressure signal is not sufficient, the detection of this scenario remains a question of future research.

In addition it has to be mentioned that the pressure loss coefficient at the CATHARE break model is probably too conservative. Further CFD studies are necessary to predict the pressure loss coefficient more accurately.

As a result of these transient analyses - in an iterative process – the following modifications were suggested in the control of CEA 2009 ALLEGRO:

- The pony-motor rotation speed for depressurized transients was increased to 100% of the nominal rotation speed of the primary blowers, in order to obtain an efficient cooling of the core for all the LOCA transients.
- The signal to move from pony-motors to DHR loops was changed: 3% mass flow rate signal was replaced by a 5% rotation speed signal, to better accommodate both large break scenario with negative core mass flow rate and long term cooling using the pony-motors.
- New signals have been added to better detect secondary circuits breaks.
- A new nitrogen injection strategy was elaborated only for DEC transients in depressurized situations: 10 inch LOCA + GV failure, small break with blackout, unprotected loss of coolant and total cross-duct break. For these scenarios, the nitrogen injection provides a sensible improvement of the results.
- The use of a partial closure of a primary valve in case of dissymmetrical transient to decrease surge.

4.2. Investigations on Power and Power density reduction

The original GFR power density of 100 MW/m^3 seems to be too high for ALLEGRO with the MOX fuel.

The main problem with cooling of GFR after a breach in the primary circuit occurs is due to the low density of the coolant at low pressure, so the response of cladding temperature to different backup pressure levels was analyzed.

4.2.1 CATHARE calculations

As a result of the previous transient analysis [3] [4] [5], it was pointed out that some improvements on the design are needed to fulfill the safety requirements. One of the ways considered to reach such objective is to reduce the core power and/or the core power density.This optimization should be done keeping in mind one of the main purposes of ALLEGRO core, to be an irradiator for experimental GFR subassemblies. With this aim, sensitivity studies with the CATHARE code were started by changing the core power from the original 75 MWth to 50 MWth and 26 MWth reduced powers.

The main hypothesis used for such analysis are:

- The axial power profile is unchanged
- The radial peaking factor is unchanged

- The core geometry (volume) is unchanged (this means that the power density is reduced compared to the reference 75 MW case)
- Mass flow rates in the loops are set according to the steady state power
- Heated perimeter of the main heat exchangers are tuned to get the original core outlet temp
- Blower speed is decreased but not tuned (main valve positions are different)
- Gagging scheme is controlled (flow restrictors)

Decay heat used in these calculations is given in Fig. 2

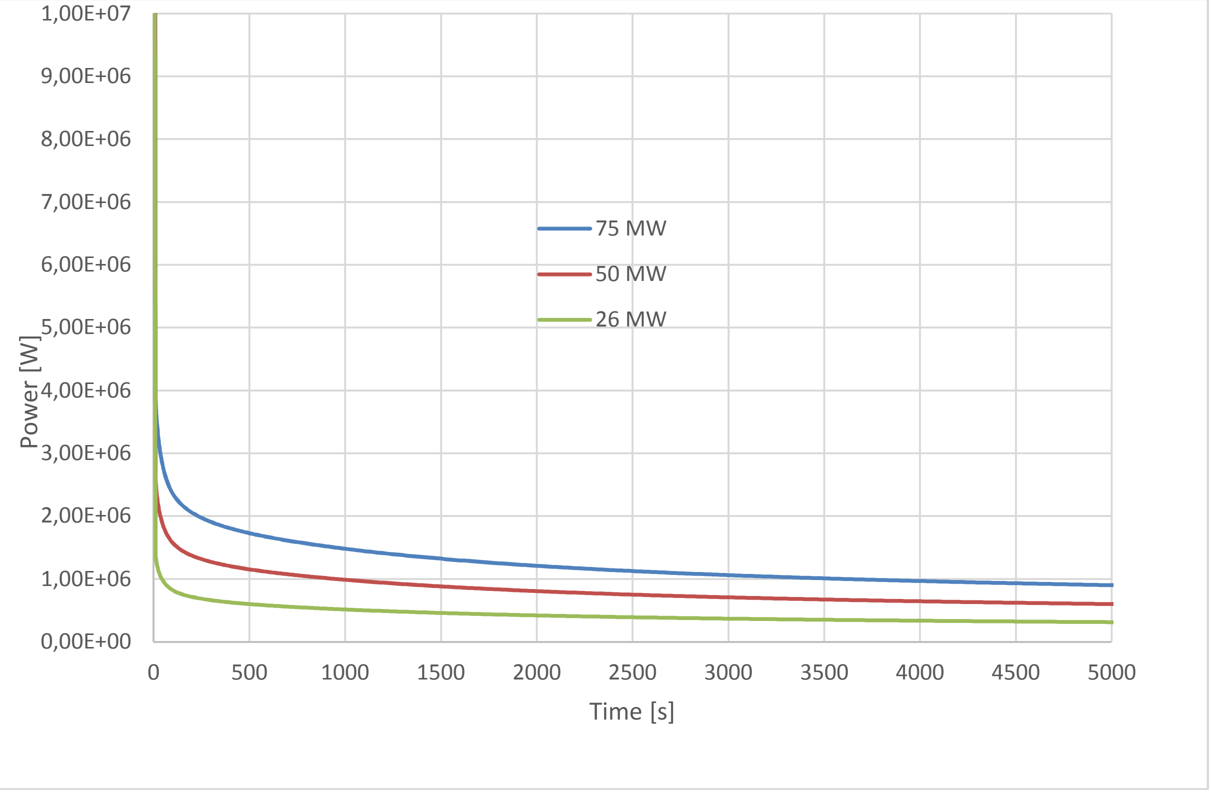

Fig. 2 Decay heat for different initial power levels

4.2.1.1. Transient calculations for 1 inch LOCA + BLACKOUT

Using the conditions above two steady state input decks were created for reduced power. On Fig. 3. the time evolution of the maximal cladding temperatures can be seen for the 1 inch LOCA + BLACKOUT case, where the transients are started from different steady state core powers. As it can be seen, in case of 75MW initial core power the maximum cladding temperature approaches the 1300C melting temperature. (It has to be emphasizing here that in these calculations the uncertainty of the input and model parameters are not taken into account). On the other hand, if the steady state core power is 50 MWth, the PCT[2] value decreases significantly approaching a value of about 900C. When the initial core power is supposed to be 26 MWth then the PCT value has a maximum value less than 600 C. These calculations clearly show the effect an advantage of power density reduction.

[2] PCT: Peak Cladding Temperature

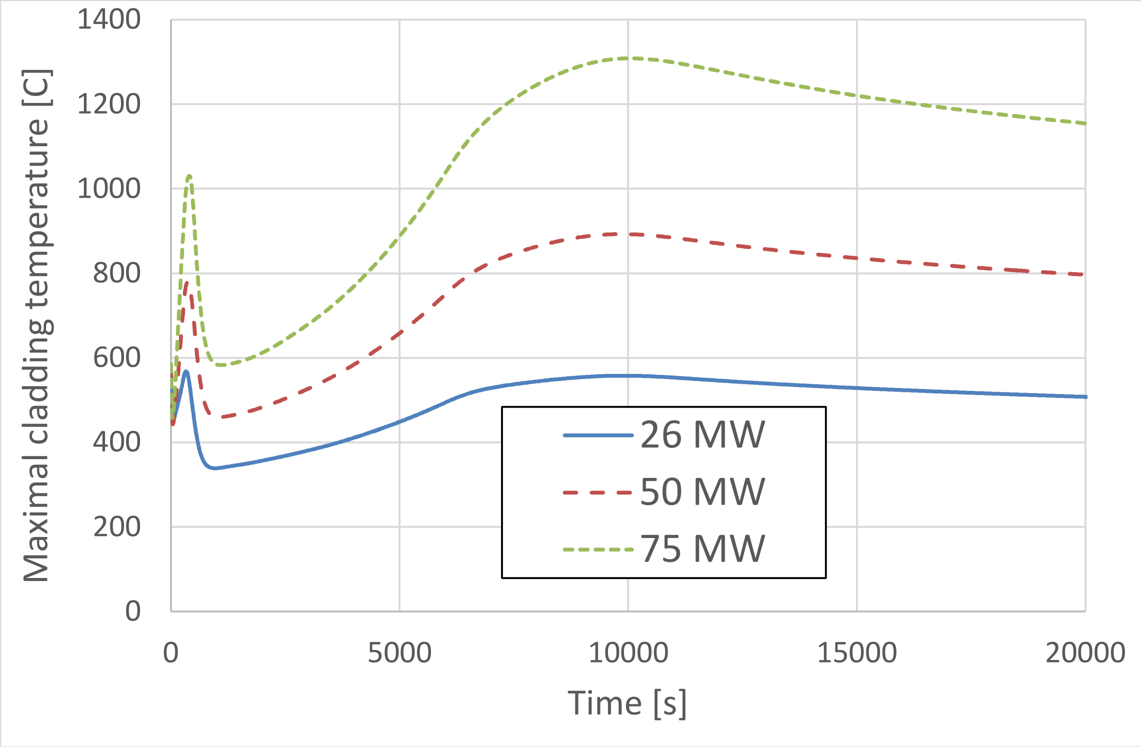

FIG 3. The effect of power and power density reduction on the maximal peak cladding temperature in case of 1 inch LOCA + BLACKOUT.

4.2.1.2. Transient calculations for 3 inch LOCA + BLACKOUT

As it can be seen from the transient analysis of the 3 inch LOCA + BLACKOUT scenario (Fig. 4), it is possible to cool the core if the initial reactor power is 26 MW. It is worth mentioning on the other hand that the detection of the BLACKOUT in the current protection logic is based on the zero DHR blower speed. This means that the nitrogen injection has a significant delay, which has a huge effect to the PCT. For this reason we have the possibility to somehow detect the blackout sooner and the nitrogen injection could be started earlier. This requires the modification of the protection logic.

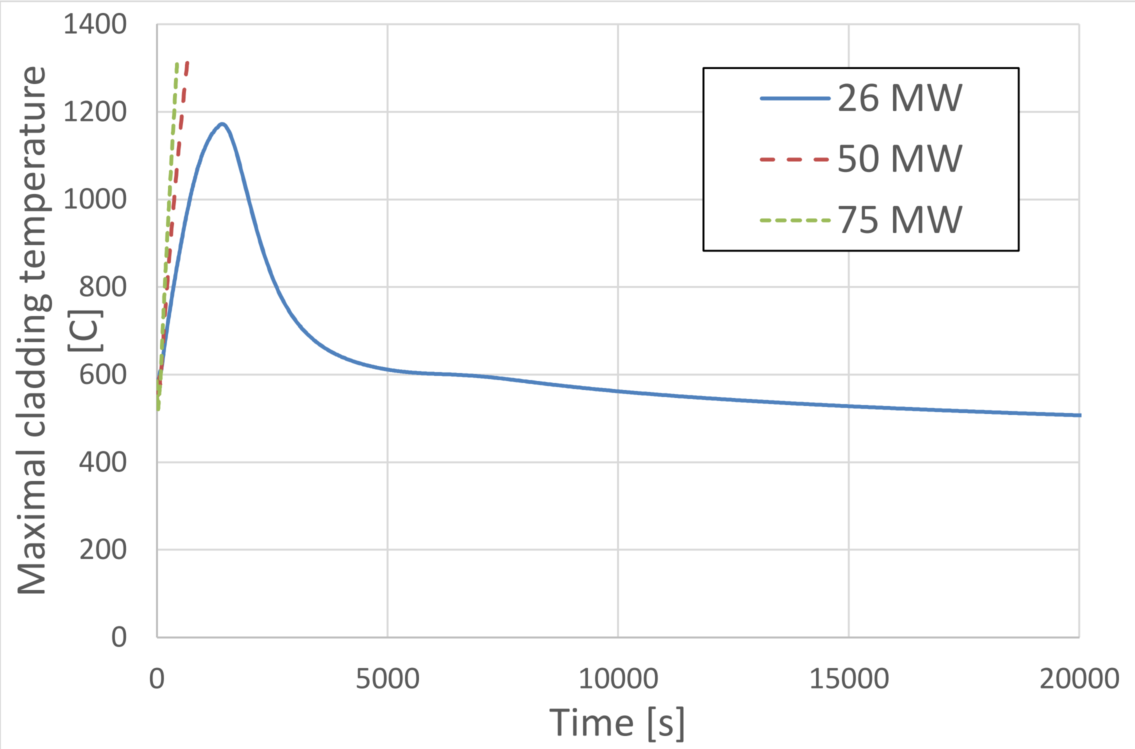

FIG. 4. The effect of power and power density reduction on the maximal peak cladding temperature in case of 3 inch LOCA + BLACKOUT.

4.2.2 MELCOR calculations

A preliminary power reduction sensitivity study was performed on 2 protected scenarios, using MELCOR 2.1.

- LOCA 10” + SBO: Break on main cold duct (no N2 injection to I. circuit)
- LOCA Total cross-duct rupture + failure of pony motors + failure of 2 DHR blowers + no N2 injection to I. circuit

Model of the reactor is based on 75 MWth ALLEGRO 2009 concept with MOX fuel. For the cases with reduced nominal power, nominal coolant mass flow rate was lowered to achieve the same nominal core outlet temperature as for the full power. Studied parameters were:

- Reactor power: 75 & 37.5 MW (100 % & 50%)
- Guard vessel backup pressure (for LOCAs): 0.4, 1.1, 2.1 MPa

Results are shown in Figs. 5, 6 and Table 3.

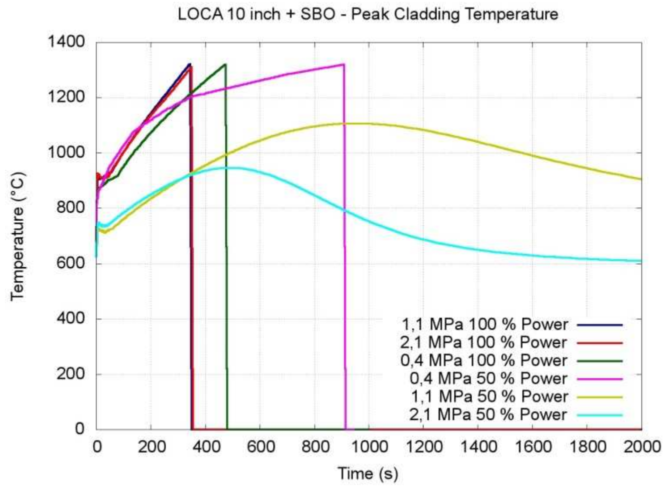

FIG. 5. Comparison of cladding temperatures, LOCA 10".

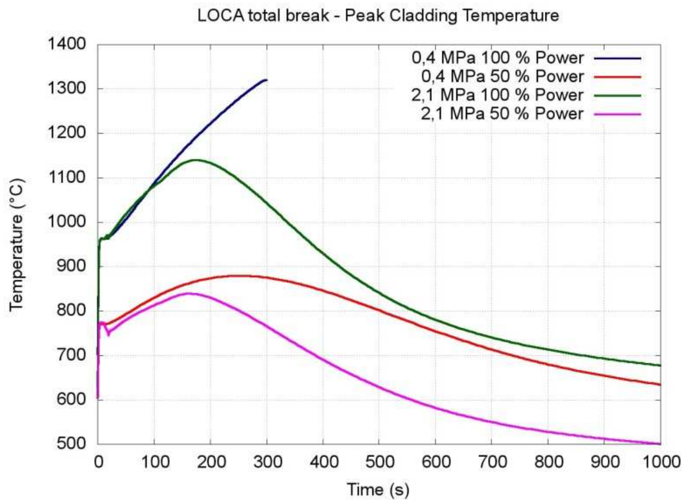

FIG. 6. Comparison of cladding temperatures, LOCA Total.

TABLE 3. SUMMARY OF THE SENSITIVITY STUDY

Scenario	100% Power			50% Power		
	0.4 MPa	1.1 MPa	2.1 MPa	0.4 MPa	1.1 MPa	2.1 MPa
LOCA 10“ + SBO	Melting in 372 s	Melting in 374 s	Melting in 487 s	Melting in 910 s	1124 °C	937 °C
LOCA Total	Melting in 299 s		1147 °C	894 °C		833 °C

Summary of MELCOR results:

- All protected depressurized transients are coolable with GV backup pressure increased to 1,1 MPa and power decreased to 37.5 MWTh (50 %)

In the MELCOR sensitivity study, we used the term "peak cladding temperature". However, MELCOR cannot separate temperatures on the cladding surfaces (inner/outer) and, instead, it gives only one value - average temperature of all the cladding in the respective node. What we call the "peak cladding temperature" in the study is, therefore, the average temperature of cladding in the hottest node of the core.

The sensitivity study with MELCOR showed that all protected depressurized transients are coolable with GV backup pressure increased to 1.1 MPa and power decreased to 37.5 MWTh (50 %).Water ingress combined with SBO has not been acceptably solved so far and water inside the DHR HX cannot be isolated from the primary circuit. Cladding fails due to steam oxidation. The results obtained with MELCOR are being checked by comparison with other computational codes in the framework of a benchmark exercise.

5. CONCLUSIONS

The experimental GFR ALLEGRO project is being developed by the V4G4 consortium formed by UJV (Czech Republic), MTA EK (Hungary), NCBJ (Poland) and VUJE (Slovakia) associated with CEA (France).

One of the key issues related to safety, is the decay heat removal capabilities of the reactor on the most penalizing transients.

To improve the design, studies on the system behavior are being performed with several thermal hydraulic system codes (CATHARE, RELAP, MELCOR) starting from a reference design developed by CEA (ALLEGRO CEA 2009). In addition, benchmarking activities were launched in support to such optimization.

The first preliminary results already available show that a reduction of the core power and power density, could allow to fulfill the safety criteria of acceptability related to the maximum cladding temperatures while maintaining the irradiation capabilities of the startup core.

6. AKNOWLEDGEMENTS

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