Decay Heat Removal studies in Gas Cooled Fast Reactor during accidental condition - demonstrator 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 reliable core cooling in accident conditions. The decay heat removal system (DHR loops), and it´s main components must be studied under such conditions, to check and improve their efficiency in the most penalising accident regimes.

The reference design of the ALLEGRO reactor studied up to 2009 is briefly described at the beginning of this joint paper.
In the framework of the collaboration between VUJE, MTA and UJV, the design of ALLEGRO is being improved to increase the decay heat removal capabilities in case of a very unlikely transient of Loss of Coolant Accident cumulated with a Total Station Blackout.
This paper shows the very preliminary results of the investigations on total power and power density reduction, which could allow fulfil the safety criteria of acceptability related to the maximum cladding temperature.
The main problem with cooling of GFR after a break in the primary circuit (LOCA) is due to the low density of the coolant at low pressure, so the response of cladding temperature to different backup pressure level in guard vessel is analysed.
Moreover, the concept of accumulators for injecting nitrogen into the core during depressurized transients, which increases the heat removal by increasing the density of the coolant, is noticed here.

Key Words: GFR, ALLEGRO, Decay Heat Removal

1. Introduction

Demonstrator ALLEGRO, a high temperature helium-cooled fast-spectrum reactor with a closed fuel cycle combines the advantages of fast spectrum systems for long-term sustainability of uranium resources and waste minimization (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).
The ALLEGRO reactor would function not only as a demonstration reactor hosting GFR technological experiments, but also as a test pad of using the high temperature coolant of the reactor in a heat exchanger for generating process heat for industrial applications and a research facility which, thanks to the fast neutron spectrum, makes it attractive for fuel and material development and testing of special devices or other research works.

However, there are some technological challenges related to the use of gas coolant. It is low thermal inertia leading to rapid heat-up of the core following a loss of forced cooling. Also, the gas-coolant density is too low to achieve effective natural convection to cool the core at low pressures. Due to this fact, the studies of decay heat removal from the core in accidental conditions are one of the most relevant issues in ALLEGRO design.

2. Reference design of ALLEGRO reactor

The design of ALLEGRO consists of two helium primary circuits, two secondary water circuits connected to water-air heat exchangers and three decay heat removal (DHR) loops integrated in a pressurized cylindrical guard vessel.
The 75 MW_{th} ALLEGRO reactor shall be operated with two different cores. The starting core with an UOX (Uranium Oxide) or MOX (Mix Oxide) fuel in stainless steel claddings will serve as a driving core for six experimental fuel assemblies containing the advanced carbide (ceramic) fuel. The second core will consist solely of the ceramic fuel and will enable to operate ALLEGRO at the higher target temperature.

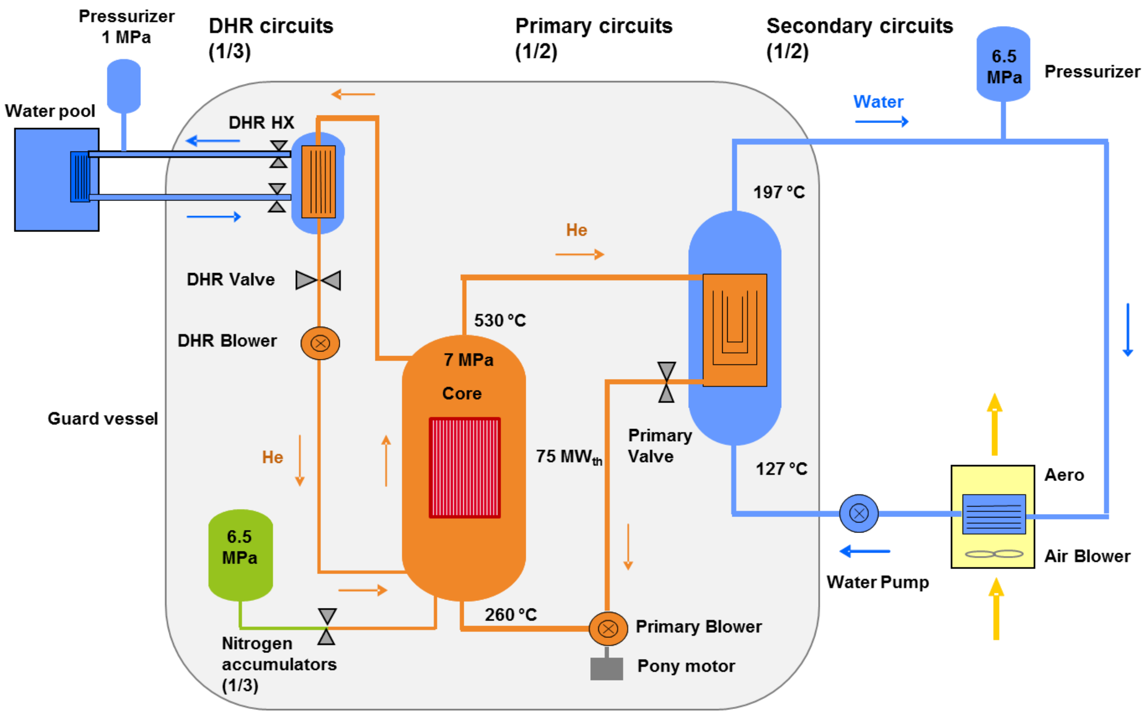

Fig.1: Description of main ALLEGRO circuits and components

3. Improvements of DHR capabilities to reference ALLEGRO design

An extensive work has been done on the reference 2009 design related to decay heat removal in accidental conditions using the CATHARE system code. A total of 39 transients' results calculated by CATHARE code were analysed. It has to be emphasized that these calculations were carried out with best estimate methodology. Conservative calculations are missing and it is necessary to adopt conservative methodology in calculations.

The calculated transients are summarized in the following table according their class and criteria fulfilment:

Transients		Additional failures								
		None	1 Pony motor off	Secondary pumps off	Tertiary blowers off	1 DHR loop valve	1 primary valve	1 DHR loop	1 DHR blower	Guard vessel
Pressurized	Loss of Flow (primary)	✓	✓	✓	✓	✓				
	Loss of Heat Sink	✓					✓		✓	
	Internal break	✓	●	✓		✓				
	Station Blackout	✓	✓			✓		✓		
	Water ingress in the core	✓								
LOCA	Primary 3'	✓	✓	✓	✓	✓				
	Primary 10'	✓	✓	✓	✓	✓				✓
	Secondary 10'	✓	✓	✓	✓	✓	✓			
	DHR loop 10'	✓								
	Crossduct rupture	✓								
	Total section break	✓								
	Primary 1' + SBO	●								

Class 3	Class 4	DEC
10-2/y - 10-4/y Accidents Cladding temperature **> 735 °C**	10-4/y - 10-7/y Hypothetical accidents Cladding temperature **> 850 °C**	Design Extension Conditions Cladding temperature **> 1300 °C**

The evaluation criterion (limit value) of calculated transients is the maximal cladding temperature. The calculations results shows that in case of loss of coolant, loss of flow, loss of heat sink, loss of off-site power, secondary break accidents the calculated maximal 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.

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

- Core design optimization
  - decrease of total power (reference: 75 MW)
  - decrease of power density (reference: 100 MW/m^3)
  - increase of thermal inertia
  - decrease of pressure drop to enhance natural convection
  - cladding material for the start-up oxide core (reference: stainless steel)
- Optimization of DHR systems
  - coupled primary-secondary turbomachines
  - injection systems - gas accumulators (nitrogen)
- Guard containment optimization
  - guard containment + conventional containment building as back-up
  - optimization of guard containment to assure the required back-up pressure to maintain an efficient cooling by natural convection
  - provisions to assure that a double failure (primary circuit and guard containment) is impossible or very unlikely

4. Investigations on total power and power density reduction

As a result of the previous transient analysis, 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 power density.
A sensitivity studies with the CATHARE code has been done by changing the core power (along with power density) from the original 75 MW_{th} to 50 MW_{th} and 26 MW_{th} reduced powers. The representative scenario is 1 inch LOCA aggravated with station blackout.

The main hypotheses 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
- gagging scheme is controlled (flow restrictors)

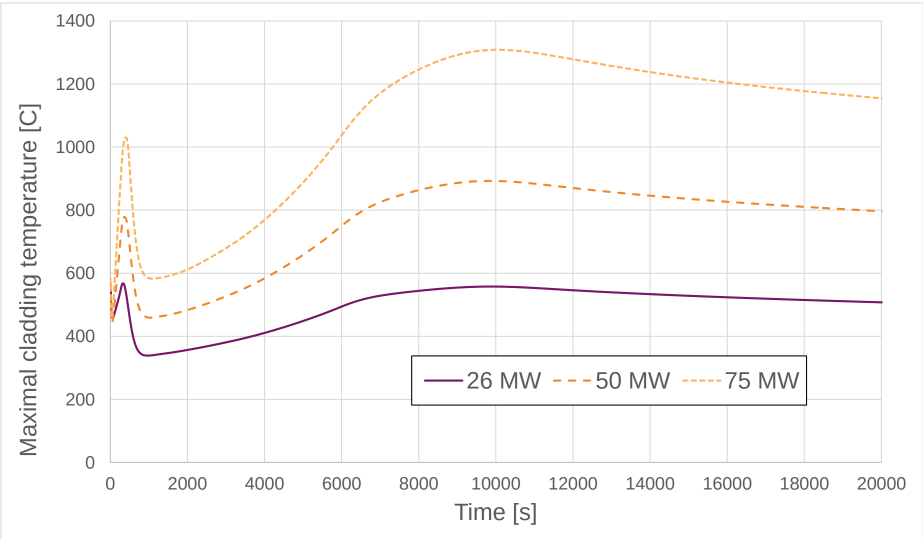

Fig.2: Core power reduction: 1 inch LOCA + blackout (CATHARE calculation)

The figure above shows the time evolution of the maximal cladding temperatures for analysed transients with different (reduced) steady state core power. As it can be seen, in case of $75MW_{th}$ initial core power the maximal cladding temperature approaches the 1300°C (melting point). If the steady state core power is 50 MW_{th} and 25 MW_{th} the peak cladding temperature value decreases significantly to acceptable temperatures. These calculations clearly show the effect an advantage of power and power density reduction.

The main problem with cooling of GFR after a break in the primary circuit is due to the low density of the coolant at low pressure.
The response of cladding temperature to different backup pressure levels was analysed with MELCOR code on representative scenario, which is 10 inch LOCA + station blackout.

	75 MW			**37.5 MW**		
Guard vessel backup pressure	0.4 MPa	1.1 MPa	2.1 MPa	0.4 MPa	1.1 MPa	2.1 MPa
Maximum cladding temperature	Melting	Melting	Melting	Melting	1124 °C	937 °C

Tab.1: Effect of backup pressure: 10 inch LOCA + blackout (MELCOR calculation)

The preliminary results of sensitivity study with MELCOR summarized in table above shows that 10 inch LOCA aggravated with station blackout is not coolable with nominal power even at increased backup pressure. With reduced power, the core is able to cool with backup pressure higher than 1.1 MPa.

5. Nitrogen accumulators

The rationale behind the nitrogen injection is the mitigation of the consequences of certain LOCA situations classified as Design Extension Condition (DEC) cases. The nitrogen injection to the core increases the heat removal by increasing the density of the coolant. It can be used to enhance the cooling provided by the primary blowers, by the DHR blowers or by the DHR loops in natural convection.
There are 3 nitrogen tanks for injecting nitrogen into the core. Each nitrogen accumulator has a volume of 200 m^3 at initial pressure of 6.5 MPa.
The nitrogen injection concept is not fully developed yet and it needs further improvements and optimization. The preliminary calculation shows, that the different transients require different injection pressures. In case of depressurized blackout transient is better to inject nitrogen at higher pressure, while in case of LOCA aggravated with guard vessel failure is better to inject nitrogen at lower pressure.

6. Conclusion

Fast reactors are especially important from the point of view of sustainability of nuclear energy. The Gas Fast Reactor (GFR) has a potential to deliver high temperature heat for industrial processes and is considered as an alternative reactor type to the other type of fast reactors (SFR, LFR).

One of the key issues related to safety of using gases as coolant in a fast reactor is related to the decay heat removal capabilities in accidental conditions due to the lack of thermal inertia of the system and the poor capabilities of gases to remove heat by natural convection.
This issue is being investigated in support to the design of ALLEGRO through the improvement of the core design and the safety related systems and components (lower power density, guard vessel, safety injection accumulators, passive feed of main blowers, etc.).

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