GAS-COOLED FAST REACTORS – DHR SYSTEMS, PRELIMINARY DESIGN AND THERMAL- HYDRAULIC STUDIES

J.Y. MALO*, C. BASSI, T. CADIOU, M. BLANC, A. MESSIÉ[1], A. TOSELLO and P. DUMAZ
CEA/DEN/DER/SESI, CEA Cadarache
[1]1CEA/DEN/DER/SSTH, CEA Grenoble
13108 Saint-Paul-lez-Durance, FRANCE
*Corresponding author. E-mail : jean-yves.malo@cea.fr

Received February 6, 2006

The Gas-cooled Fast Reactor (GFR) is one of the six reactor concepts selected within the framework of the Generation IV initiative and is the reference concept for the Commissariat à l'Energie Atomique (CEA[1]). Two reactor unit sizes have been considered: 600 MWth and 2400 MWth. As far as thermal-hydraulics is concerned, reactor decay heat removal (DHR) proves to be a major issue. The CEA has conducted exploratory design studies to address this issue and a reference solution for the 600MWth reactor has been recommended.

KEYWORDS : GFR, Helium, Decay Heat Removal, System Design

1. INTRODUCTION

The Gas-cooled Fast Reactor (GFR) is one of the six reactor concepts selected within the framework of the Generation IV initiative and has been given high priority in the R&D program on future nuclear energy systems at the *Commissariat à L'Energie Atomique* (CEA) R&D program on Future Nuclear Energy Systems [1,2,3].

Two reactor unit sizes have been considered: a medium size (600 MWth) and a large size (2400 MWth). The main cores characteristics have been identified. Different types of fuel arrangements are envisaged: pins and plates (the latter being the reference concept). The average helium core exit temperature is 850°C, with a maximum fuel temperature of 1200°C (ceramic fuel concept) and a low pressure drop to facilitate natural convection. To design the Decay Heat Removal (DHR) system, the maximum fuel temperature for incident and accident design basis conditions (DBC) has been set at 1600°C.

The use of the circulating gas coolant as the main way to remove the decay heat (forced or natural convection) has been clearly identified. Seeing that the nominal helium primary pressure is significant in the GFR (70 bar), the protected depressurization accident combined with a total loss of power (blackout) has been selected as one of the design transients.

Solutions based on passive systems were first explored, the most obvious solution being a system using natural convection only. A fully passive system has been designed: it consists of three loops (3x100% redundancy) in extension of the pressure vessel, equipped with heat exchangers located at a certain elevation above the core, so that the driving height enables the flow circulation. A "close containment" vessel has been considered in order to limit the loss of pressure after the depressurization accident (the resulting primary pressure is called the backup pressure).

Next, this reference solution was compared to alternative solutions, taking into account lower backup pressures but requiring auxiliary pumping power devices (active or passive).

For all cases, the operating conditions required to avoid exceeding the maximum fuel temperature criterion have been assessed. This particularly concerns a) the backup pressure required to operate in a fully natural convection and b) the auxiliary pumping power required if low backup pressure is considered. A wide range of backup pressures has been studied, from atmospheric pressure to the value related to the natural convection operation.

This paper discusses the exploratory design studies of the DHR system, first examining the pre-sizing of the DHR system using the 1D COPERNIC computer tool (simplified steady-state approach), and then presenting calculations

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[1] French Atomic Agency Commission

performed to validate this preliminary design using both the CATHARE 2 code (steady-state and transients calculations) and detailed analyses of some specific points with the CFD code. The DHR reference solution recommended for the 600 MWth reactor is described.

2. OVERVIEW OF THE GFR PRE-CONCEPTUAL DESIGN

2.1 System Design Status

In a first step, exploratory design studies carried out considering a reactor power of 600 MWth; this choice was mainly driven by the idea of using the GT-MHR Power Conversion Unit (PCU of the Gas-Turbine Modular Helium Reactor, [3]) in order to avoid studying the energy conversion system, limiting our efforts to the reactor core and safety systems.

The main options considered were the following:

- 600 MWth core within a metallic primary pressure vessel,
- PCU vessel connected to the core vessel by a single cross-duct.
- Safety systems based on natural convection.

With these options in mind, a first consistent set of reactor data was issued leading to the reactor schematic diagram in Figure 1.

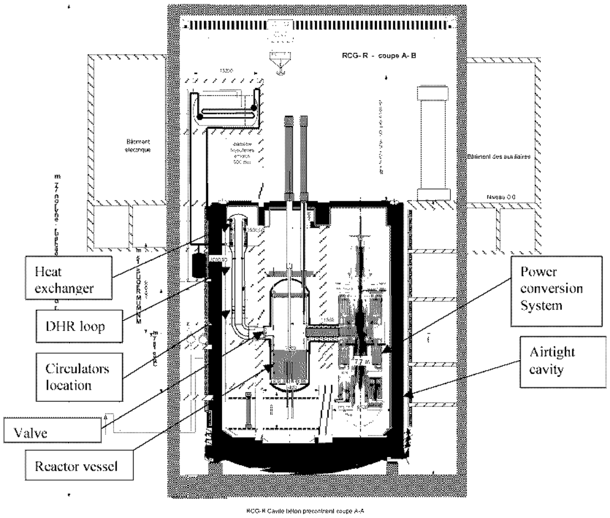

Fig. 1. 600 MWth System Layout

It was discovered at an early stage hat this power level has some significant drawbacks:

- It requires using very challenging fuel elements (only 30% of the matrix for 70% of U,Pu ceramics, see paragraph II.B),
- Its economic competitiveness is questionable (medium size reactor, cost of safety systems).

It was therefore decided to look at a larger power level; 2400 MWth, compatible with the classical “economy of scale” viewpoint. Above all however, the interest of a larger core (with a smaller surface to volume ratio) lies in the fact that a less challenging fuel is required.

With this new reactor unit size, the opportunity was taken to explore the design options considered for the energy conversion system and safety systems.

2.2 Core Design Status

By both coupling core neutronics (zero breeding gain) and core thermal-hydraulics (temperature, pressure drop) constraints, and considering sub-assemblies made of plates with a core power density of about 100 MW/m^3 (Figure 2), it was possible to obtain the core described in Table 1. Here, the fuel element is a CERCER (Ceramic /Ceramic) plate made of dispersed ceramic carbide fuel, (U,Pu)C (70% in volume) within a SiC matrix (30% in volume).

Table 1. 600 MWth Plate Core in Normal Power Operation Conditions

Power	600 MWth / 275 MWe
Core Power density	103 MW/m^3
He Pressure	70 bar
Core outlet temperature	850 °C
Core inlet temperature	480 °C
Nominal mass flow rate	330 kg/s
Fissile height	1.95 m
Fissile diameter	1.95 m
Fissile core row	6
Sub-assemblies (SA)	127
Core fractions (struct., He, fuel)	10, 55, 35%
Fuel plates in one SA	3 x 7
Fuel plate cross section	5,3 mm x 94,3 mm
Gas channel cross section	6,4 mm x 94,3 mm
Core pressure drop	0.4 bar
Mean burn up	5% FIMA
Mean Pu fraction	16.2 % Pu
Maximum fuel temperature	1135 °C

The design trade-off consists in limiting the helium fraction (55% here) while maintaining the maximum fuel temperature below 1200°C and limiting the total core pressure drop. The low pressure drop obtained is a key issue for the safety systems design.

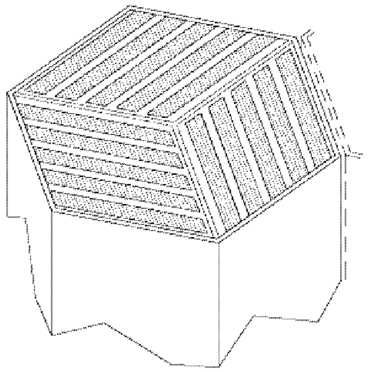

Fig. 2. Plate Sub-assembly

3. DECAY HEAT REMOVAL SYSTEM DESIGN

3.1 Discussion of Possible Strategies

The Decay Heat Removal (DHR) system has a significant impact on the overall reactor architecture.

During the first two years of the project (2001, 2002), exploratory studies were conducted to identify possible solutions. Very quickly, it was revealed that solutions based on core thermal inertia with conduction and radiation to remove heat (like in HTR reactors) were not applicable to the GFR. This is a consequence of the high core power density (100 MW/m^3 compared to 5 -10 MW/m^3 in HTRs) and the limited core thermal inertia. Other solutions were investigated, such as: in-core heat sinks, additional core thermal inertia, heavy gas accumulators, etc. It was finally decided to study more detailed systems relying on helium circulation, based on natural convection as much as possible.

Thus, the main design options are (Figure 1):

- A core design criterion based on a low pressure drop (which facilitates He circulation),
- A DHR design based on protected depressurization accidents combined with a total loss of power (blackout),
- The use of a "close-containment" in order to limit the loss of pressure (backup pressure) after a primary circuit depressurization,
- The use of dedicated DHR loops designed to increase the difference of elevation between the heat exchanger and the core.

The "external" DHR system under investigation is made up of three loops (3x100% redundancy) in extensions of the pressure vessel, as shown in Figure 3 (one loop represented). The choice of three loops is based on safety approach considerations, by assuming that one loop could fail due to an accident initiating event (i.e.: break), while another is supposed to be unavailable (single failure criterion).

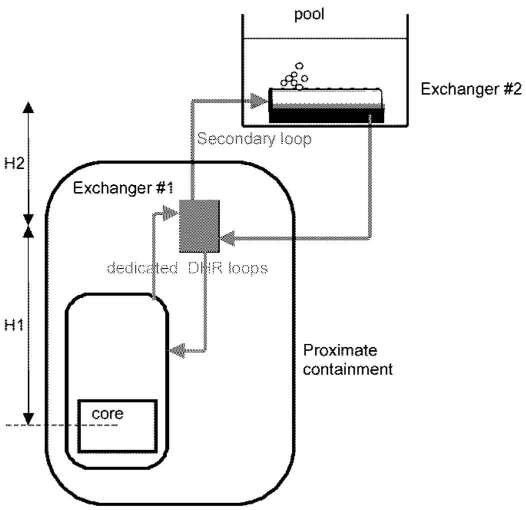

Fig. 3. DHR System

The DHR system consists of a cross-duct piping connected to the reactor vessel. The #1 heat exchanger is made of straight vertical tubes with counter-current flow. The primary helium circulates outside the tube bundle. It has been assumed that the #1 exchanger could be located at a maximum of 15 meters (primary driving height, H1) above the mid-plane of the core (relevant trade-off between natural circulation requirements and a reasonable overall height of the possible close containment). The secondary circuit based on pressurized water (10 bar, always being below the primary pressure to exclude primary system water insertion and being high enough to avoid boiling) is connected to the pool (ultimate heat sink) and can also be based on natural convection (considering a secondary driving height, H2, ≤ 6 m). However, both circuits can also operate with a circulator, generating forced convection in addition to the natural convection. The pool heat exchanger is made of straight horizontal tubes, with the water circulating inside the tubes. The initial temperature of the pool water has been assumed at 90°C.

At the present design stage, the main constraint taken into account in designing the DHR system is to maintain the maximum fuel temperature below 1600°C for conditions encountered in design basis transients. It is worth recalling that, like the 1200°C limit for normal operations, this 1600°C limit will have to be confirmed or changed by the ongoing fuel element R&D.

In other respects, given a) the time after the reactor SCRAM necessary to reach 1600°C in adiabatic conditions (few minutes), b) the energy taken by the gas depressurization, and c) the residual forced convection in the primary system (turbo-machinery inertia), it has been considered that the DHR system could be designed for a power equal to 3% of the nominal power, about 18 MWth (the core decay heat 5 min after the reactor SCRAM using the "ANS+10%" decay heat law). It is worth mentioning that transient calculations using CATHARE have been planned to validate this design option: the objective is in particular to check that during the first 5 minutes of the transient, the core temperature does not exceed the specified limit temperature (see Section 3.3)

3.2 COPERNIC Exploratory Design Studies

Exploratory design studies have been performed using simplified steady-state 1D modeling, with the COPERNIC computer tool (based on Microsoft Excel spreadsheets) [5].

The first objective was to provide a complete pre-sizing of the DHR system. The DHR capabilities have been assessed by identifying the most relevant trade-off between overall system dimensions and the efficiency of the system: the heat exchanger and pipe designs are optimized in order to generate a low pressure drop, making it possible to obtain the most attractive driving height and backup pressure required, or auxiliary circulator power if needed). As the primary and secondary circuits are linked in the modeling by the main heat exchanger, the pre-sizing of the DHR system has been assessed and optimized on a large number of parameters, from the core to the cold source.

The second objective was to assess and compare the required system operating conditions based on a more open strategy and not only on a fully natural convection:

- A fully passive natural convection system (reference solution), used "immediately" at the beginning of the transient (i.e $\approx$5 mn after scram): the minimum backup pressure required needs to be identified. In this case, a "high" value is expected.
- Mixing passive natural/ forced convection systems, based on auxiliary pumping power systems for up to 24 hours and on natural convection afterwards: it is necessary to identify the minimum primary pressure required to operate in a fully natural convection after one day and the auxiliary pumping power required for the first 24 hours. In this case, "low" pumping power (consistent with passive devices) and "moderate" primary pressure are expected.
- A fully active forced convection system, only based on auxiliary pumping power. The advantage of the very low minimum primary pressure required is attractive in terms of the cost of the overall reactor integration (consistent with non-pressurized large containment) but demanding in pumping power. Here, "high" active pumping power is expected for a "long" time: only active systems can be considered.

It is worth mentioning that it has been considered in all these cases that the DHR system should be able to rely on natural convection for a LOF (Loss Of Flow accident).

The COPERNIC calculations, based on a steady-state approach, consist in solving the thermal-hydraulics of the hot channel and iterating them in order to balance the total pressure drop in the circuit with the induced density difference (see Appendix 1). It is worth noting that some lump coefficients were used to calculate the DHR system pressure drop, flow rate and temperatures (cold and hot legs) from core values:

$$\frac{q_{DHR\,system}}{q_{core}} = \frac{\Delta T_{core}}{\Delta T_{DHR\,system}} = \frac{\Delta P_{vessel}}{\Delta P_{core}} = 1.1$$

Because the backup pressure can be varied by modifying the close-containment characteristics (volume, initial pressure), a wide range of backup pressures has been studied, from atmospheric pressure to the value related for the natural convection operation.

For the 600 MWth case, the COPERNIC results concerning the DHR capabilities related to the passive/active strategies are given in Figure 4.

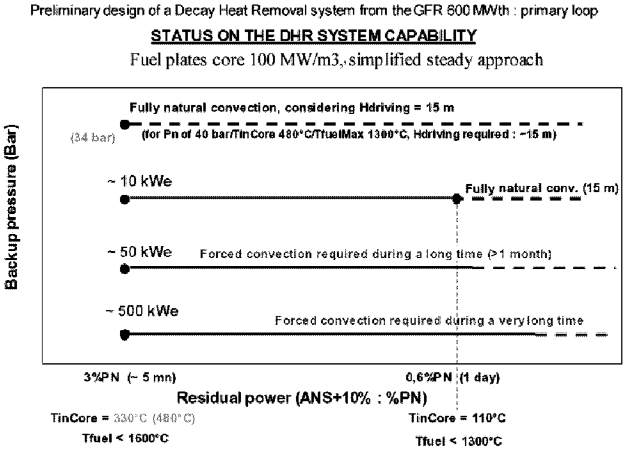

Fig. 4. Summary of DHR System Capabilities for the GFR 600 MWth

The residual power extracted is drawn on the horizontal axis, which can be related to the time scale during the transient period using the "ANS+10%" law. The backup pressure required for the operation of the DHR system is illustrated by the vertical axis,. In the lowest part of the graph, the values of the temperature criterion considered in calculations are recalled, depending on time during the transient (5 minutes or 1 day).

The highest point, related to the fully passive natural convection system, shows that 25 bar should be required to remove the residual power (selected at 3% of the nominal power), considering a driving height of 15 meters. In other respects, it is mentioned that at the pressure level related to LOF (i.e 40 bar, which is the equilibrium pressure after turbo-machinery stop), a driving height of almost 15 meters could be sufficient to remove the same residual power.

For medium back-up pressure (3 to 7 bar), limited pumping power is required (estimated at the beginning of the transient, at 3% of the nominal power), which means that "small" active or passive systems can be used (blowers moved by electrical accumulators, gas ejector/jet pump using additional gas tank). When mixing passive natural/ forced convection systems, a backup pressure of 7 bar should be required to remove the residual power after 1 day following reactor SCRAM (i.e 0.6% of the nominal power) by relying on natural convection only.

For low pressure, forced convection appears to be necessary almost all the time during the transient period (>> month) and the pumping power required becomes significant.

It has been pointed out that most of loop pressure drops occur within the core (80 %). Thus, optimization of the primary loop pressure drops appears quite limited.

The most sensitive parameter was the outlet temperature of the primary heat exchanger (cold leg temperature, which is also the core inlet temperature in the COPERNIC modeling). For 480°C, the required back-up pressure is 34 bar, and for 330°C, this pressure is reduced to 25 bar. Decreasing this temperature is very attractive but, considering all the vessel structures initially at 480°C (especially the core lower axial reflector), 330°C seems to be a good compromise (see Section 3.3, the checking calculations using CATHARE).

Based on this assumption, all DHR loop parameters have been defined. The secondary water loop is characterized by a driving height of 3.7 meters (H2).

The main operating conditions for the reference solution (a fully passive system based on natural convection only) are given in Table 2.

It is worth noting that to obtain the required back-up pressure (25 bar), release of the primary helium inventory (about 5000 kg) is not sufficient, taking into account that the close-containment free volume cannot be lower than 10000 m^3. Therefore, it is necessary to have an initial pressurization of the close-containment atmosphere. Simple mass and energy balances show that this initial pressurization must be above 20 bar, which implies the use of a pre-stressed concrete close-containment (this is the design solution indicated in Figure 1).

Moreover, the preliminary feasibility to use passive devices in the first 24 hours for the mixing natural/ forced convection strategy has been assessed.

Using rough calculations and considering systems based on ejectors connected to compressed air tank, gas reserve required has been estimated at: 150 bar and 200 m^3.

Table 2. Main Operating Conditions of the DHR Reference Solution for the GFR 600 MWth

Primary loop (helium)	
TinCore (°C)	330
ToutCore (°C)	1576
TinMainHeatExchanger (°C)	1463
ToutMainHeatExchanger (°C)	330
Core mass flow rate (Kg/s)	2.78
DHR loop mass flow rate (Kg/s)	3.06
Total pressure drop in the DHR system (Pa)	≈ 190
Secondary loop (pressurized water)	
TinPoolHeatExchanger (°C)	147
ToutPoolHeatExchanger (°C)	110
DHR loop mass flow rate (Kg/s)	115
Main heat exchanger	
Base section (m^2)	4
Height (m)	2.6
Pool heat exchanger	
Base section (m^2)	2
Length (m)	4.4

For the 2400 MWth case, similar figures (as those mentioned in Figure 4) have been obtained, which means that similar capabilities could be considered.

3.3 Validating the 600 MWth Preliminary Design

For this reactor power, the DHR system based on helium natural convection only is considered as the reference. Validation of this COPERNIC preliminary design (0D/1D models) was performed as follows:

- CATHARE stabilized transient calculation (pseudo steady state), at DHR design conditions (3% of the nominal pressure; 25 bar), with a fully natural convection system (complete DHR system modeling). The objective was to check the core heat transfer and pressure drop, and compare the operating conditions of natural convection flows set in motion in both primary and secondary DHR circuits.
- CATHARE transient assessment, by taking into account the effect of the structure thermal inertia. The objective was to check the validity of the initial conditions adopted in the COPERNIC approach, such as the core inlet temperature of 330°C and that during the first 5 minutes in the transient, the core temperature did not exceed the

specified limit temperature.
- More detailed evaluations using 2D/3D CFD modeling.

CATHARE steady-state and transient calculations

As the previous COPERNIC design was based on a simplified steady-state approach, the aim of these CATHARE 2 studies was to verify this design in transient conditions, especially taking into account the structure thermal inertia which can significantly affect the cold and hot leg temperature calculation. The CATHARE 2 version v2.5 was used [6].

Given this study objective, a simplified CATHARE model was used. In particular, the Power Conversion Unit was not considered. The CATHARE model consists of (Figure 5):

- A core model with 2 parallel 1D module used to model the "hot assembly" and remaining core (mean assembly). The radial power peaking factor is 1.1 and the axial peaking factor is 1.36.
- 1D and volume modules to model the primary vessel components, downcomer, lower plenum and upper plenum.
- 1D and volume modules to model the primary/secondary DHR loops and the ultimate heat sink (pool assumed to be at a constant temperature at 90°C).
- Boundary conditions describing the cross-duct conditions (flowrate, temperature and pressure).

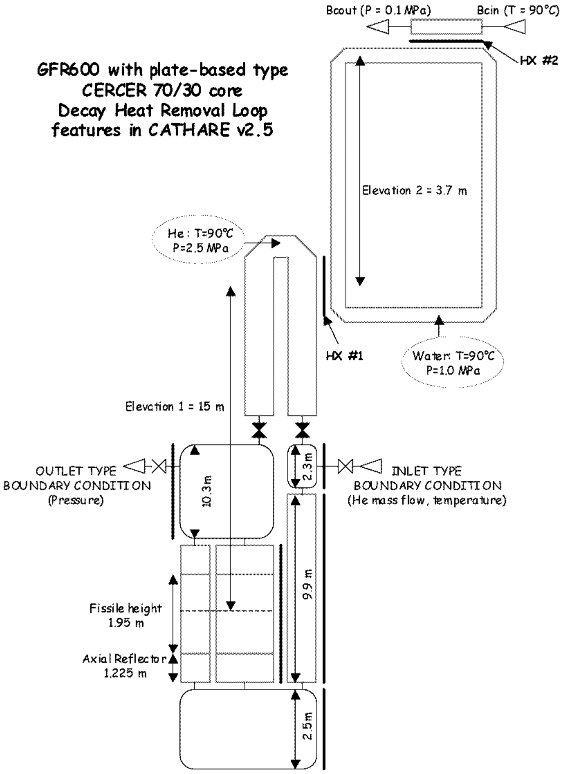

Fig. 5. CATHARE Model

The following calculations were performed:

- Steady-state at the COPERNIC DHR design conditions (1 loop, 3% of the nominal power, 25 bar, no account of vessel structure thermal inertia).
- Transients initiated by a very fast depressurization (large break like a cross-duct rupture resulting in a pressure drop from 70 bar to 25 bar in few milliseconds) with 1 or 2 DHR loops available (depending on the break location and use of the single failure criterion).

Regarding, the first calculation, it can be remarked in Table 3 that agreement is rather good between COPERNIC and CATHARE results. Of course, this is quite normal given the same problem has been modeled with some significant simplifications (then well justified) in the COPERNIC model.

Table 3. Comparison of COPERNIC and CATHARE Results

	COPERNIC	CATHARE 2
Core mass flow rate (kg/s)	2.78	2.83
Core inlet temperature (°C)	330	353
Core outlet temperature (°C)	≈ 1580	1574
Core pressure losses (Pa)	≈ 150	142
Core average Reynolds number	≈ 500	510
DHR primary loop		
Total pressure losses (Pa)	≈ 190	≈ 190
DHR Secondary loop		
Mass flow rate (kg/s)	≈ 115	117
Water inlet temperature (°C)	110	103
Water outlet temperature e (°C)	≈ 150	138

In the second set of calculations, the objective was to assess the overall approach (including the design choice of 3% of the nominal power). The calculation conditions were:

- Core at nominal conditions (600 MWth, 320 kg/s), with the DHR loops isolated (check valve).
- Transient resulting from a reduction in the core flowrate (316 to 0 kg/s) and the primary pressure (70 to 25 bar) in 0.01 s, a reactor SCRAM at t = 0.01 s and the opening of the DHR valves at t = 10 s.

The most penalizing break is a primary DHR loop cross-duct rupture because it results in the failure of this loop. Application of the single failure criterion leads us to assume the loss of a second loop, then to consider one loop only. Our viewpoint is that such a transient initiated by a very large break (cross-duct rupture) combined with the instantaneous loss of the primary helium flow should be classified in Design Extension Conditions (DEC) and, in this case, the single failure criterion does not need to be taken into account: this point is still quite controversial. For the moment, calculations with 2 DHR loops were performed.

In terms of the more penalizing transient (one loop available), the following points must be noted. It was confirmed the thermal effect of the main vessel structures, for example at t = 300 s (time where the decay heat reaches 3% of the nominal power), an outlet core temperature of 1650°C is reached for an inlet DHR HX temperature of 1220°C and an outlet HX temperature of 300°C for an inlet core temperature of 390°C. At the same time (Figure 6), the power released to the secondary loop is 14 MW for a power heating helium of 16,5 MW, the balance being exchanged with structures. Significant radial effects were observed in the core, at t = 300 s, with the maximum fuel temperatures being 1720°C in the "hot assembly" and only 1550°C in the "mean assembly" (figure 7). This means that the distribution of the core flowrate is not optimum for these conditions: the radial flow distribution has been adjusted for nominal conditions.

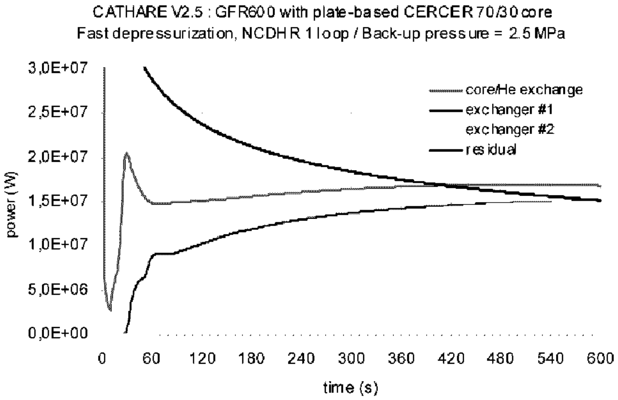

Fig. 6. Powers Exchanged Versus Time

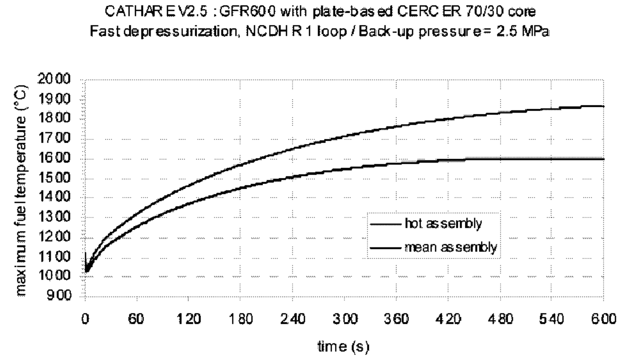

Fig. 7. Maximum Fuel Temperatures Versus Time

Finally, this quite penalizing transient gives a maximum fuel temperature just below 1900°C, thus above the 1600°C limit. The criteria for DEC transients remain to be defined; the logic would be to have further margins compared to DBC criteria.

Assuming 2 DHR loops available, the maximum fuel temperature reached is 1500°C.

It can be concluded that these CATHARE calculations have validated the DHR design issued from the COPERNIC model. In addition to these CATHARE "design" calculations, taking into account a wide range of postulated initiating events (loss of flow, loss of coolant, loss of heat sink, etc.), the related transients were calculated, using a complete system model in this case (including the PCU).

Ongoing CFD calculations using STAR-CD

This study is aimed at confirming that the COPERNIC pre-sizing gives reasonable order of magnitude for the S/A pressure drop. For this purpose, different situations corresponding to the nominal and the DHR conditions are dealt with.

The COPERNIC modeling, mainly based on correlations, is quite simple, especially for complex geometries of the S/A bottom and top parts. The CFD code STAR-CD allows a better representation of the geometry and a precise solving of the mass, energy and momentum balance equations. The models used here are the k-ε High Reynolds model for the turbulent zones and the laminar model for the low Reynolds zones.

Due to the S/A complexity (Figure 8), the straightforward meshing would have led to a large number of meshes, hence a prohibitive computation time.The analysis of the GFR S/A has therefore been made by a two-step approach : the fissile zone and the rest of the S/A (bottom and top neutron shieldings and reflectors). For this latter one, the isothermal and incompressible assumptions are used. For the fissile zone, the properties depend on the temperature and helium is considered as a quasi-compressible fluid.

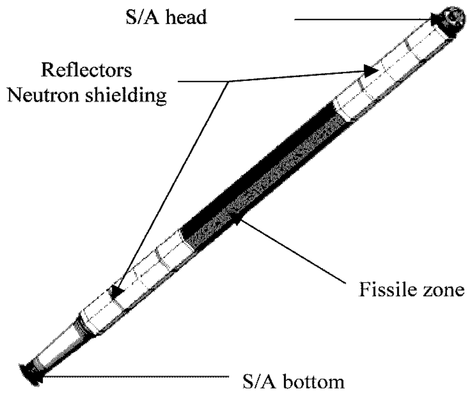

Fig. 8. Overview of a Fuel S/A

The STAR-CD meshing is automatically made of tetrahedral meshes with the automatic STAR-CD mesher. In order to have an established flow at the inlet and the outlet of the element, a flow domain extension is made on both sides in the SolidWorks fluid domain.

The S/A bottom is made of a conical cylinder, the coolant circulates through a convergent and then a conical divergent. The reflectors and neutron shieldings are made of two bi-cones (exterior and interior) with a convergent entry and a divergent exit. The coolant circulates between the two bi-cones. The gas volume fraction is 40 %. The S/A head is a cylinder. The overall meshing of these parts is made of about 200000 cells. Finally, the fissile zone is modeled by two fissile plates and the coolant channel circulates between them. The 2D meshing is made of about 90000 cells. As the calculation in the fissile zone is made for average conditions (fuel power, flowrate), it is worth noting that the pressure distribution could be slightly different in the central S/A since the velocity and the temperature are higher in this region.

As summarized in Table 4, two reactor operating conditions have been considered : the nominal regime under full power and design pressure of 70 bar and the DHR regime, following a depressurization of the primary loop, at 3% of the nominal power, which is roughly the decay heat about five minutes after the reactor scram:

Table 4. Characteristics for the 2 Regimes

	$T_{inlet\,/\,outlet}$ (°C)	$P_{inlet\,/\,outlet}$ (bar)	ρ_{He} (kg / m^3)	$\mu_{inlet\,/\,outlet}$ (Pa.s)
Nominal power (NP)	400	70	4.94	3.38E-05
	850	70	2.978	4.91E-05
3% of NP at 10 bar	330	10	0.804	3.15E-05
	1530	10	0.270	7.23E-05

The boundary conditions are imposed for each element of the S/A. The pressure is given at the outlet and the flowrate at the inlet.

The STAR-CD and COPERNIC results are presented in Table 5 and 6:

Table 5. Pressure Drops (Pa) at Nominal Power Under 70 bar

Te = 400°C Tf = 850°C P=70 bar	STAR-CD Pressure drop (Pa)		COPERNIC Pressure drop (Pa)	Relative difference (%)
	Friction + acceleration	Gravity		
S/A head	860	3.5	2395	63
Neutron shielding	2574	15	11401	5
Reflector	8220	14		
Fissile zone	19892	58	21838	8 .6
Reflector	4780	23	6818	7.6
Neutron shielding	1470	25		
S/A bottom	353	33	390	1
Total	38149 Pa	171 Pa	42842 Pa	10.5 %

Table 6. Pressure Drops (Pa) at 3% of Nominal Power under 10 bar

Te = 330°C Tf = 1530°C P=10 bar	STAR-CD Pressure drop (Pa)		COPERNIC Pressure drop (Pa)	Relative difference (%)
	Friction+ acceleration	Gravity		
S/A head	2	0.3	7	67
Neutron shielding	10	1.3	32	-45
Reflector	34	1.2		
Fissile zone	253	7	245	-10
Reflector	8	3.7	18	0
Neutron shielding	2.2	4		
S/A bottom	0.3	5.3	6	6
Total	319 Pa	23 Pa	308 Pa	-11 %

Considering the global pressure drops in the fuel S/A, the comparison is quite satisfactory. The maximum pressure difference between STAR-CD and COPERNIC is indeed around 10 % for the two regimes, which is judged quite good.

The major difference, noticed in the S/A head, is explained by the fact that COPERNIC but not STAR-CD takes into account the real broadening at the outlet between the upper head and the upper plenum. Another cause of differences between the two approaches could be related to the adequacy of the COPERNIC correlations in the establishing flow region of the different fuel elements. It can be pointed out that the establishing length is quite large in comparison with the height of the fuel elements so that COPERNIC correlations are not well suited for this entry zone.

This study confirms that the total pressure drop in the S/A for the nominal case under the total power is 0.4 bar, which is below the threshold pressure of 0.5 bar originally imposed in the specifications for the 2400 MWth GFR core.

Even though the two approaches give similar results, experiments are required, especially in DHR conditions (laminar flow mainly), where uncertainties in pressure drop calculation could lead to not very well justified DHR options.

3.4 Orientations for 2400 MWth

Very approximate economic evaluations for the GFR design in Figure 1 have shown that the recommended DHR loop design associated with the pre-stressed concrete close-containment leads to a significant increase in investment costs (compared to the HTR case which does require such design). Therefore for the 2400 MWth case, it has been decided to focus studies on medium and low back-up pressure strategies in order to:

- Use a close-containment made of steel,
- Avoid the initial pressurization of this containment.

For such choices, auxiliary pumping systems play a major role in addressing the DHR issue and must be further investigated.

4. CONCLUSIONS

CEA has performed a re-assessment of the DHR issue, by considering a more open natural/ forced convection strategy and by using COPERNIC modeling that includes a large number of parameters involved in the DHR system, from the core to the cold source. The reference solution, based on a fully natural convection system, has been compared to alternative solutions, considering lower backup pressure available but demanding in auxiliary pumping power devices. First validation of calculations using CATHARE transient calculations have confirmed that the DHR pre-sizing strategy based on a simplified steady-state approach with the COPERNIC tool for depressurized core cooldown 5 minutes after scram is consistent with transient calculations. Moreover, it should be noticed that two major points were highlighted by the CATHARE transient assessment: the thermal effect of the main vessel structures for natural convection and significant radial effects affecting the core flowrate distribution at DHR operating conditions. Additional calculation validations using the CFD code are in progress.

For the GFR 600 MWth, the natural circulation solution requires a backup pressure of 25 bar. To obtain this high pressure level, it has been shown that an initial pressurization of the close-containment atmosphere is needed (above 20 bar), which implies the use of a pre-stressed concrete close-containment. This costly solution has now abandoned and it has been decided to prioritize mixing natural/ forced convection systems based on medium and low back-up pressure. These alternative solutions, assessed for the GFR 600 MWth, have shown that limited pumping power is required for medium back-up pressure (3 to 7 bar), which means that "small" active or passive systems can be considered (blowers moved by electrical accumulators, gas ejector/jet pump using additional gas tank). At the current design stage, these preliminary conclusions also seem to be applicable to the GFR 2400 MWth, as both reactor configurations have similar DHR capabilities. As the auxiliary pumping systems will play a part important in future studies, they will have to be further investigated. For example, the effect of such devices on the performance of a wide range of operating conditions, in particular pressure, will have to be assessed (in case of small break, the primary pressure will not immediately reach the final backup pressure).

Generally speaking, the exploratory results presented in this paper also have to be checked, considering in particular:

- Core flow rate distribution in high temperature parallel gas channels. As dynamic viscosity increases with temperature, the higher viscosity in the hot channels leads to lower coolant velocities. This could induce a significant increase of temperatures in these channels, or even a flow excursion
- A complete modeling of the core and vessel to a) avoid as much as possible the use of lump coefficients, b) improve the heat transfer and pressure drop assessments in such mixed convection flows and c) assess possible 3D effects (given the very low level pressure drop in the overall DHR system).

It is worth noting that the thermal-hydraulic design approach for the DHR system will be completed by full-scale experimental characterizations in real conditions, using in particular the HELITE facility at CEA-Cadarache research center [4].

Appendix 1

Simplified Modeling of the DHR System

The calculations based on a steady-state approach consist in solving the following eq. (A1) for both the primary and secondary circuit:

$$\Delta\rho \,.\, g \,.\, \mathbf{HLoop}\ (+\Delta P_{ForcedConv} \text{ if needed}) = \mathbf{\Delta PtotLoop},$$

where:

- $\Delta\rho$. g . Hloop: characterizes the energy provided by natural convection (Pa), induced by the volumic mass difference (kg/m^3) between the hottest and coldest temperatures in the circuit and the driving height (Hloop, meter) between these two temperature levels,
- $\Delta P_{ForcedConv}$: represents the additional energy (Pa) that must be provided if the driving height selected can not ensure the extraction of sufficient residual power relying on natural convection only. The additional pumping power is calculated by:
  $W_{ForcedConv}$ (W) = $\Delta P_{ForcedConv}$. Qv (m^3/s)
- Δ PtotLoop: characterizes the total pressure losses generated in the overall loop (Pa).

The DHR system design is solved according to these main calculation steps:

- From the residual power to be extracted (3% or 0.6% of the nominal power) and the inlet core temperature considered, identification of the core flow rate and core outlet temperature required to avoid exceeding the specified fuel temperature limit (iterative process). The DHR system flow rate and temperatures (cold and hot legs) are then calculated from core values using the following lump coefficients mentioned in Section (3.2),
- Optimization of the heat exchanger design,
- Calculation of the overall pressure losses in the primary and secondary loops,
- Given the driving height, calculation of the backup pressure required in the DHR system to operate in a fully natural convection. In other respects, given backup pressure and in the case where the driving height could not ensure the extraction of sufficient residual power relying on natural convection only, the active pumping power required is calculated. The circulator electrical

power is then estimated considering an isentropic efficiency of 0.8 and an electrical motor efficiency of 0.9.

- Then, the same methodology is applied to solve the secondary loop (given the driving height, identification of the mass flow rate, temperatures, etc.)

It is worth mentioning that no heat exchange apart from the core channels and heat exchanger pipes is considered. Classical correlations are taken into account to assess the heat transfer in the exchangers and the pressure losses in the overall DHR system, such as "Colburn", "Blasius", "Poiseuille" and so on.

The reference GFR 600 MWth core (fuel plate assembly) has been considered (see main characteristics in Table 1):

- Core heat transfer and pressure losses are calculated using a 1D model (axially split into 10 elements). The fuel temperatures in the hot channel are assessed using forced convection correlations related to laminar flow and hydraulic diameter based on the heating wall only. The pressure losses are calculated separately; on the one hand, the fissile part (10 element meshing, increase of the temperature), and on the other hand, the reflectors and shields (isotherm cold and hot parts). Friction factor correlations related to laminar flow and the hydraulic diameter based on the rubbing wall are used (the Dh related to the fissile part is applied to the other parts).

The diameters of the cross-duct piping between the reactor vessel and the exchanger #1 are about 1.15 m for the internal pipe and 1.49 and 1.88 m for the external annular pipe. The total pipe length considered for the pressure losses calculation is given by: 2 x (primary driving height + 4 m). Six 90° bends have been considered. The primary driving height considered is: 15 m (between the mid-planes of the core and the #1 heat exchanger). The #1 heat exchanger is made of straight vertical tubes with counter-current flows. The primary helium circulates outside the tubes bundle. This heat exchanger has been designed using a 0D model, based on the Logarithmic mean temperature difference and using forced convection correlations related to laminar or turbulent flow in tubes bundle. The average pressure losses are estimated from friction factor correlations related to laminar or turbulent flow. A singular pressure drop factor is added for the primary circulation, considering 3 grids of 20% porosity (to maintain the tubes bundle).

The secondary circuit is connected to the pool and consists of:

- The main heat exchanger also linked to the primary circuit (the water circulates in the tubes),
- The pipe connecting the main heat exchanger with the pool heat exchanger; it has a 0.5 m diameter. The total pipe length considered for the pressure losses calculation is: 2 x (secondary driving height + 5 m). Twelve 90° bends have been considered. The selected driving height is less than 6 m (between the mid-planes of both exchangers).
- The pool heat exchanger made of straight horizontal tubes (the water circulating inside the tubes). The heat transfer is calculated using a 1D model (axially split into 10 elements). Forced convection correlations related to turbulent flow are considered for the primary water circulation and natural convection and nucleate boiling correlations for the secondary water pool. The initial temperature of the water pool has been selected at 90°C.

ACKNOWLEDGMENTS

Acknowledgments are addressed to J. Rouault, Head of the Innovative Systems Section (SESI), A. Conti, F. Morin, C. Poette and D. Tenchine from the Reactors Study Department (DER) and various contributors from the Fuel Study Department (DEC).

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