Passive Safety Design Optimization for 600 MWth GCFR

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ABSTRACT

Within the 6th Framework Program of the European Community on the subject of the Gas-Cooled Fast Reactor (GCFR) different designs of the GCFR were investigated. One of the assessed designs was a 600 MWth reactor with the containment guard vessel. Passive safety design optimization for the mentioned GCFR design is presented in this paper.

In the GCFR it is difficult to remove the decay power using only passive ways due to the small core size and high power density. Decay Heat Removal (DHR) loops based on natural circulation are present in the GCFR design, however they are most efficient at high reactor pressure. The current DHR strategy is to use auxiliary system cooling in the first 24 hours of the accident and natural circulation cooling thereafter. A possible design modification has been studied in order to allow the GCFR decay heat removal using only passive systems. Therefore, a concept of injection of a heavy gas into the reactor pressure vessel during accident conditions has been investigated.

A model of the GCFR has been built for the SPECTRA code, including the reactor vessel, the Power Conversion Unit (PCU), the decay heat removal loops, the containment (guard vessel) and the reactor building. The model has been verified by comparing results with results of CATHARE calculations for the large break and the small break LOCA scenarios.

Furthermore, CO_2 tanks were added and analyses repeated for small and large break LOCAS, as well as a complete guillotine rupture of the cross-duct between reactor vessel and PCU, and on one of the DHR loops. Sufficient cooling has been observed in most of the analyzed cases. An eventual oxidation of the SiC cladding by CO_2 has been taken into account in analyses. In most cases the cladding oxidation was negligible.

The performed analyses showed that the designed system allows a change of the current DHR strategy of auxiliary system cooling in the first 24 hours of the accident and natural circulation cooling thereafter. That is, with the addition of the heavy gas injection into the reactor vessel, the natural circulation cooling is sufficient to ensure core cooling from the onset of a LOCA.

KEYWORDS

Gas-Cooled Fast Reactor, passive safety, design optimization

1. INTRODUCTION

The Gas-Cooled Fast Reactor (GCFR) is a nuclear reactor design [1], which features a fast spectrum with a closed fuel cycle and minimizes the production of long-lived radioactive waste [2]. Furthermore, it makes it possible to utilize fissile and fertile isotopes more efficiently than thermal spectrum reactors. GCFR uses a direct closed conversion cycle with recuperator and inter-cooling. The turbomachinery and the heat exchangers are enclosed in a separate vessel, called the Power Conversion Unit (PCU). A potential fuel candidate is a dispersed ceramic fuel (U,Pu)C-SiC organized in prismatic blocks.

From the point of view of waste minimization, the GCFR core becomes more efficient if the power density is high. The value of 103 MW/m^3 has been set as a reference by CEA [2]. Due to the small core size and high power density of the GCFR, it is difficult to remove the decay power using only passive systems. Conduction through the core shroud and radiation from the Reactor Pressure Vessel (RPV) surface, effective in the High Temperature Reactors (HTR)/Pebble Bed Modular Reactors (PBMR), is not useful for the GCFR as a result of the small core size.

Three independent Decay Heat Removal (DHR) loops based on natural circulation are present in the GCFR design. At the inlet to each DHR loop is a check valve. During normal operation there is a considerable pressure drop over the reactor core; the pressure above the core is lower than the pressure in the downcomer and the DHR valve remains closed. In case of a Loss of Flow Accident (LOFA), the turbomachinery stops and there is no forced flow through the core. Consequently there is no core pressure drop. In such a case the DHR valve opens, the hot gas enters the DHR inlet pipe, flows up to the DHR Heat Exchanger (HEX), and the DHR starts up in the natural circulation operation. However, the DHR loops are only efficient if there is a high reactor pressure. At low pressures the loops are insufficient because of very low density of helium and thus small density difference, which provides a driving force too small for natural circulation. Therefore, the GCFR needs active systems to remove decay heat in case of low pressure, such as a Loss of Coolant Accident (LOCA). Each DHR loop has a blower, which in such cases provides a forced circulation cooling.

A possible design modification has been studied in order to allow the GCFR decay heat removal using only passive systems. A concept of injection of a heavy gas into the RPV during accident conditions has been investigated. In order to enlarge the fluid density in accident conditions it has been proposed to position the CO_2 tanks next to the DHR loops. In addition, an increase of Reynolds number provides some decrease of friction pressure loss and increase of heat transfer coefficient. Therefore, during LOCA the heavy gas is injected into the downcomer side of the DHR loops due to opening of the check valves.

This paper describes results obtained for the modified system with enhanced passive safety. Analyses were performed using the SPECTRA code [3], an in-house developed general purpose thermal-hydraulic code. It can model thermal-hydraulic behavior of nuclear power plants, including reactor cooling system, emergency and control systems, containment and reactor building of various reactor types like BWR, PWR, HTR. It can also be used to assess thermal-hydraulic response of non-nuclear plants, for example cooling systems of chemical reactors. Verification and Validation (V&V) of the code was performed [4] following the recommendations set by the ANS guidelines [5] for the V&V of scientific and engineering computer programs for the nuclear industry. The GCFR design version considered in this work features a vertical shaft PCU and the containment, also called the Guard Vessel (GV) [6].

2. SPECTRA MODEL OF GCFR

The SPECTRA model of GCFR includes all important parts of the system; RPV with the core divided into three axial sections and three radial rings, the PCU, three DHR loops, the containment and the reactor building [7]. The nodalization is shown in Fig 1.

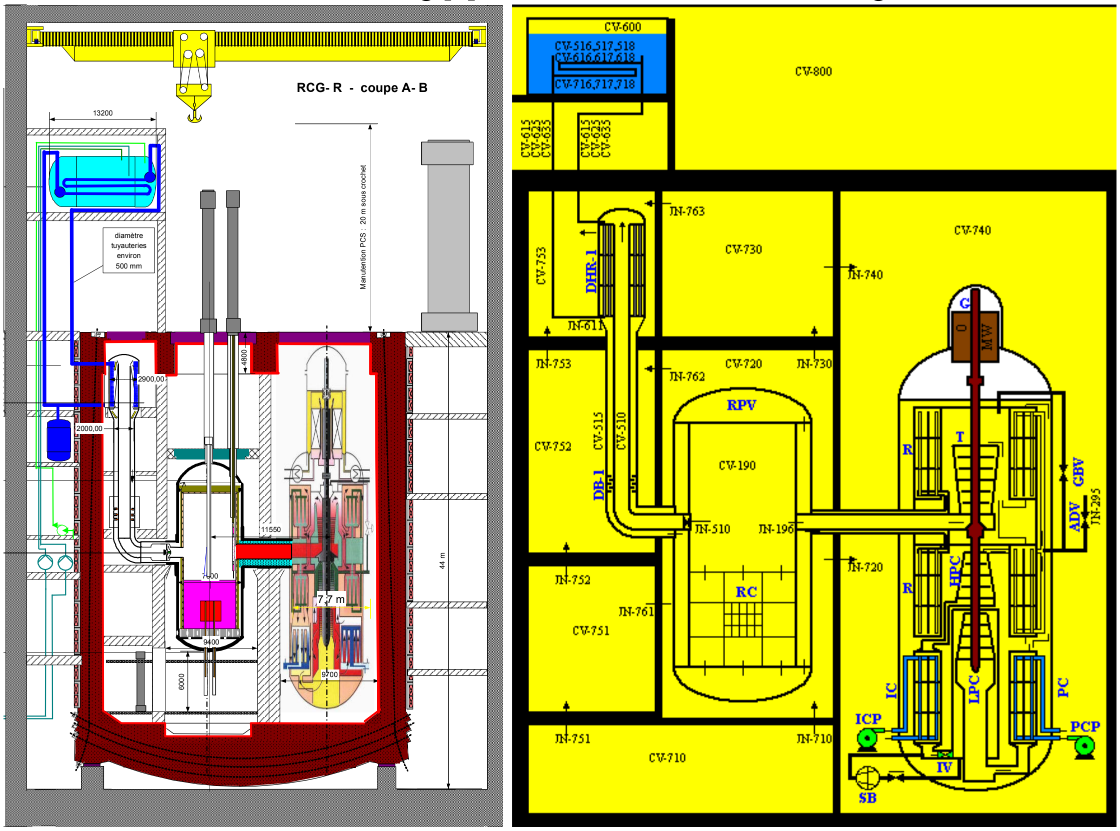

Fig 1 Schematic overview of the containment and the reactor building (left) and SPECTRA model of GCFR (right).

The turbomachinery nominal parameters were taken from the GCFR data [2], while the detail data such as turbine and compressor maps were assumed based on data for typical helium turbines and compressors. Also modeled were the heat exchangers of the DHR primary to intermediate loops and from intermediate loops to DHR pool.

The valves present on the inlet of the DHR loops were modeled as check valves with a fixed opening and a closing pressure. The opening pressure differences were assumed to be equal to 100 Pa, 120 Pa and 140 Pa, for the DHR-1, DHR-2 and DHR-3, respectively in order to assure sequential activation of these units.

An Automatic Depressurization Valve (ADV) was placed on the PCU to prevent long term bleeding of CO_2 in the containment. During small break scenarios CO_2 will be injected when the Reactor Vessel is at about 4 MPa. The blowdown will continue until the RPV pressure reaches about 0.4 MPa and a mixture of helium and CO_2 will be lost through the break. An ADV has been designed with an opening setpoint just above the heavy gas injection setpoint p = 4.2 MPa and large flow area D=0.2 m compared to the heavy gas injection area D=0.04 m. In this way it is assured that the blowdown is finished before a serious amount of heavy gas is injected.

3. VERIFICATION OF THE SPECTRA GCFR MODEL

Two LOCA scenarios have been analyzed and compared with results obtained with the CATHARE code [8]. These are:

- Large Break LOCA, D = 250 mm
- Small Break LOCA, D = 25 mm

In both cases the break was located on the PCU duct.

For both large and small break LOCA four cases were considered. For the first three cases the containment and reactor building models were not used. Instead, the pressure downstream the break was fixed at different levels in order to be consistent with the analyses performed with CATHARE code [8]. The last case was performed using the full model, including containment and reactor building. The four cases are:

- Fixed back-pressure of 1.50 MPa
- Fixed back-pressure of 1.00 MPa
- Fixed back-pressure of 0.75 MPa
- Full model (including containment with a volume of 49400 m³ and reactor building)

For each scenario one out of three DHR loops was assumed to be available. Results of the simulations are shown in Fig 2 and Fig 3. Note, that the maximum cladding temperature is only a rough approximation due to roughly nodalized axial power and temperature profile in the core.

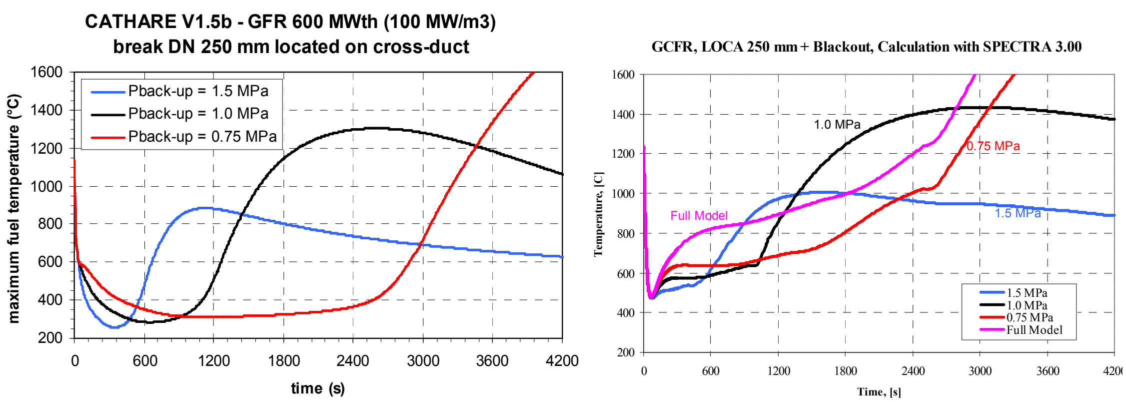

**Fig 2 Left: Maximum fuel temperature, LOCA D=250 mm - CATHARE results [8];
Right: Maximum fuel temperature, LOCA D=250 mm - SPECTRA results.**

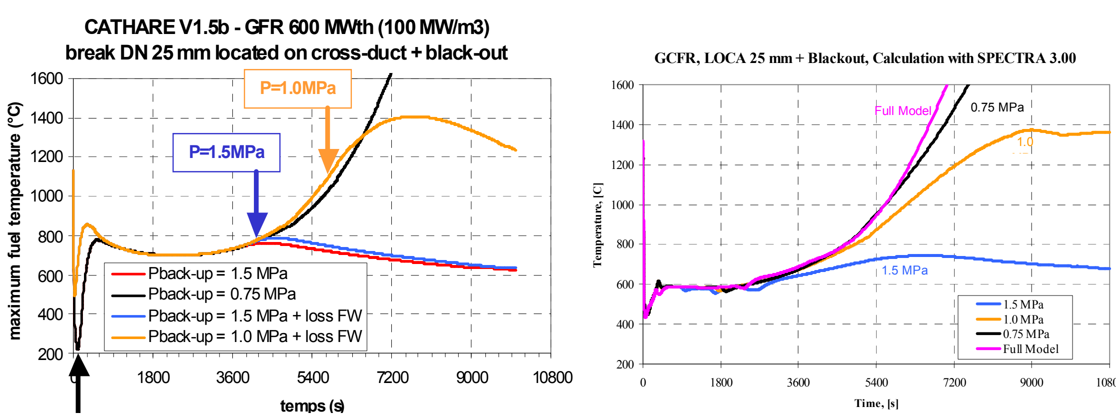

**Fig 3 Left: Maximum fuel temperature, LOCA D=25 mm - CATHARE results [8];
Right: Maximum fuel temperature, LOCA D=25 mm - SPECTRA results.**

For large and small break LOCA CATHARE and SPECTRA code give similar results, which can be summarized as follows:

- Good cooling is observed for the backpressure of 1.50 MPa.
- High fuel temperatures are observed for the backpressure of 1.00 MPa.
- Fuel overheating with T>1600ºC occurs for the backpressure of 0.75 MPa.
- The results obtained with the full model are the most conservative, with the highest fuel temperatures. This is a consequence of a low RPV pressure (0.39 MPa) used in this case. This is nevertheless a typical containment pressure for post LOCA conditions, so the DHR system should be designed to be operable at these conditions.

The differences in the results obtained by CATHARE and SPECTRA code are a result of assumptions made during building of the GCFR model in SPECTRA. Certain assumptions, as for example in the case of turbine and compressor maps, were necessary, where the detail description of the systema or the applicable data was not been available.

Comparison shows that the SPECTRA results obtained with the containment and the reactor building model are most conservative and this model will be used in the next sections for the design optimization for passive safety.

4. DESIGN OPTIMIZATION FOR PASSIVE SAFETY

A heavy gas injection system is proposed as design optimization for passive safety. CO_2 has been selected as a suitable heavy gas as the molar weight of CO_2 is eleven times higher than of Helium. The system has been designed to provide an effective cooling of the reactor vessel under all LOCA conditions [9]. The layout of the proposed CO_2 system is shown in Fig 4.

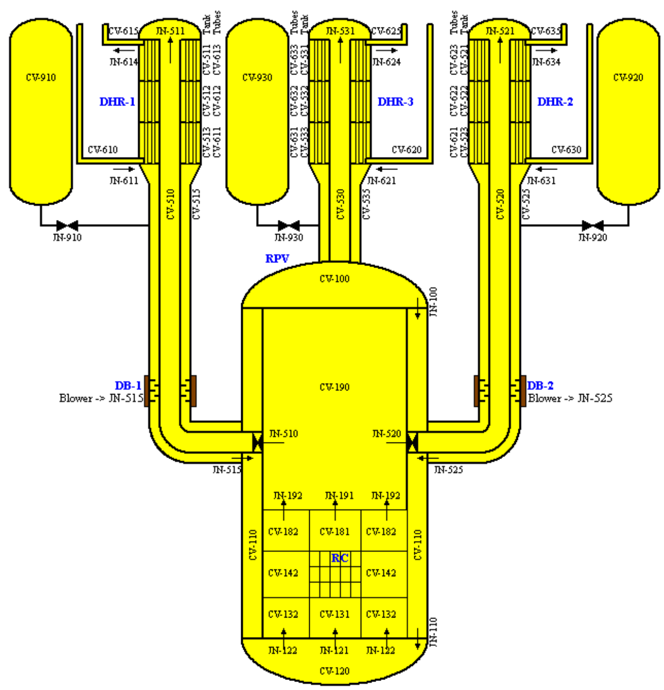

Fig 4 DHR loops with CO2 tanks.

The system consists of a CO_2 tanks with a volume of V=143 m^3 connected to each of the three DHR loops through a check valve. The CO_2 pressure was selected as 4.0×10^6 Pa. During normal operation the RPV pressure is about 7.0×10^6 Pa and the check valves remain closed.

When the check valves open CO_2 is first injected into the downcomer side of the DHR loops. This promotes natural circulation by creating higher fraction of the heavy gas in the downcomer side than in the riser side, where CO_2 enters significantly diluted after mixing with the RPV gas. Such conditions exist during the whole injection period. When the injection is terminated the circulating gas is gradually mixed to produce a uniform mixture in the RPV and the operating DHR loops. By then the CO_2 volume fraction must be sufficient to provide natural circulation that will remove the decay heat.

The GCFR design with the CO_2 injection system is referred to as the System Optimized for Passive Safety (SOPS). Analyses of LOCA scenarios, showing the performance of this system under a variety of LOCA conditions are shown in the next section.

Eventual oxidation of the SiC cladding by the CO_2 and O_2 coming from the containment are considered. The carbon oxidation reactions are: $C + CO_2 \rightarrow 2\ CO$ and $C + O_2 \rightarrow CO_2$. The first reaction is endothermic, with energy consumption of 170.5 kJ/mol [10], corresponding to the reaction energy of -14.2×10^6 J/kg$_C$. The second reaction is exothermic, with energy generation of 393.3 kJ/mol, corresponding to the reaction energy of $+32.8\times10^6$ J/kg$_C$.

The reaction kinetics of the SiC oxidation by O_2 is approximated based on data from [11] by the following equation [7]:

$$R_{O2}(T, p_{O2}) = 0.47 \cdot \exp\left(-\frac{16410}{T}\right) \cdot \left(\frac{p_{O2}}{10^5}\right). \tag{1}$$

Here, R_{O2} is the reaction rate, T the temperature, and p_{O2} the oxygen partial pressure. No data was found for SiC oxidation by CO_2. It is expected that the CO_2 reaction will be much slower because of significantly smaller oxidizing potential of CO_2 compared to O_2. Therefore an assumption that CO_2 oxidation rate is the same as the O_2 oxidation will provide very conservative results and the CO_2 reaction is therefore calculated from the same reaction kinetics formula as the O_2 reaction.

5. LOCA ANALYSES FOR THE OPTIMIZED SYSTEM

The large break LOCA (D=250 mm) and the small break LOCA (D=25 mm) cases that had been analyzed with the original design and are shown in section 3, were analyzed again with the SOPS. Furthermore, a very small break (D=10 mm) on the RPV - PCU cross-duct, a small break (D=25 mm) near the CO_2 injection point and a large break (D=250 mm) near the CO_2 injection point were investigated in order to verify whether the SOPS works properly when a large part of the injected CO_2 is being lost through the break during the blowdown phase. Also analyzed were a guillotine rupture of the cross-duct between the RPV and the PCU and a guillotine rupture of a single DHR loop.

Large LOCA D=250 mm

A seventy minutes analysis has been performed. The maximum fuel temperature remained below 1000ºC, which is below the acceptable limit of 1600ºC. Therefore, any fuel damage is avoided. The results are shown in Fig 5.

In addition flows through the system and CO_2 concentrations were analyzed. At the end of the calculation the flow through the DHR-1 was 18 kg/s and the flow through the core was about 14 kg/s. The core bypass flow passing through the shroud and reflector was 1.6 kg/s and the flow through the PCU about 2.8 kg/s. Furthermore, despite the single CO_2 tank gas injection, the CO_2 concentrations in the system are high and are above 80% volume fraction. The large concentration of heavy gas is the reason for the large natural circulation flow through DHR-1 and the good core cooling.

Small LOCA D=25 mm

A three hour analysis has been performed for this case. Also for a small break LOCA the maximum fuel temperature remains below 1000ºC ad any fuel damage is avoided (Fig 5).

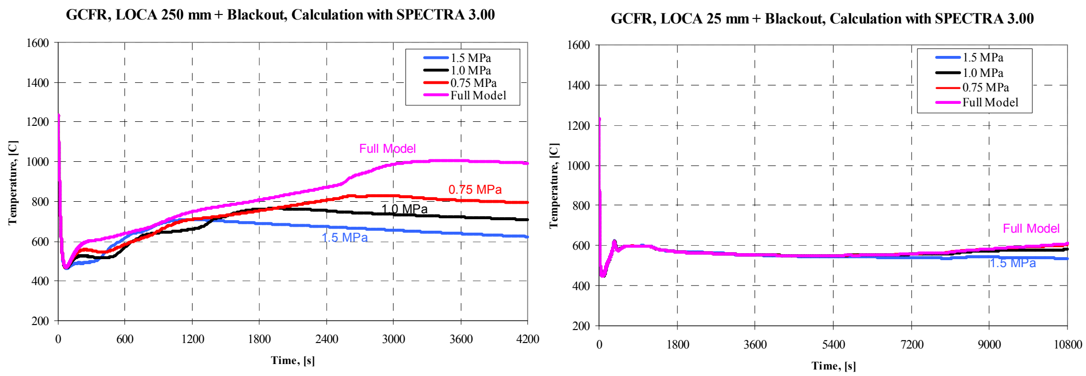

Fig 5 Left: Maximum fuel temperature, LOCA 250 mm, SOPS.
Right: Maximum fuel temperature, LOCA 25 mm, SOPS.

Very Small LOCA D=10 mm

A small LOCA with D = 10 mm located on the RPV-PCU duct has been analyzed to verify SOPS performance under very small break. Two cases were considered; with disabled ADV and with normal ADV operation. In both cases the maximum fuel temperature remains below 1000ºC (Fig 6) and the fuel damage is avoided.

The ADV opening results in higher CO_2 concentrations in the reactor vessel, because it prevents "bleeding" during the slow depressurization process. At the end of the analyzed period at 10 hours the CO_2 concentration in the RPV is about 60% in the case with the ADV opening and about 20% without the ADV opening. The temperatures are nevertheless lower without the depressurization as the effect of high reactor pressure dominates over the CO_2 effect.

Small LOCA D=25 mm Near the CO_2 Injection

In this case the break was located on the downcomer side of the DHR-1 loop. Two cases were considered; with and without the depressurization. In the case without depressurization the CO_2 concentration in the RPV is much lower due to a slow "bleeding" of the injected gas through the break. In the case with ADV there is a rapid depressurization of the primary system when the ADV opens at about 800 s. Therefore the slow "bleeding" of CO_2 does not occur and there is significantly more CO_2 inside the reactor vessel.

In the case without depressurization, the maximum fuel temperature of about 1000ºC is encountered at about 23,000 s. In the case with depressurization, the maximum fuel temperature of about 1050ºC is encountered at about 3,000 s (Fig 6). Fuel damage is avoided in both cases.

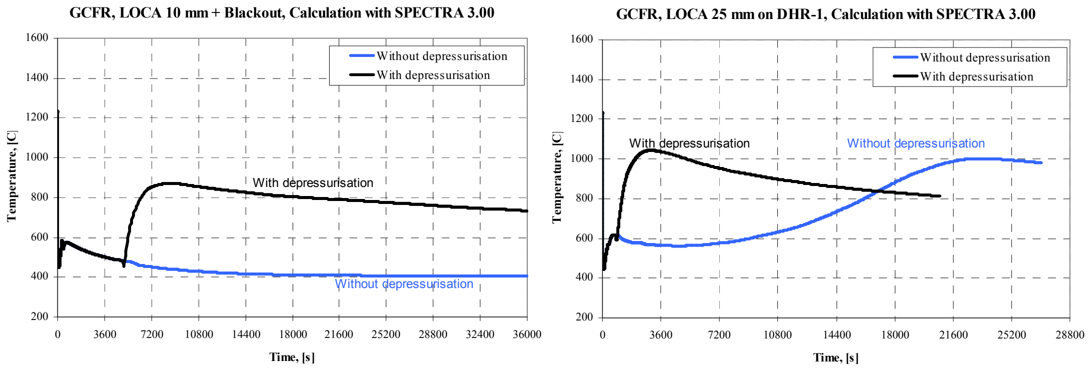

Fig 6 Left: Maximum fuel temperature, LOCA 10 mm, SOPS.
Right: Maximum fuel temperature, LOCA 25 mm, near CO_2 injection.

Large LOCA D=250 mm Near the CO_2 Injection

In this case the break was located on the downcomer side of the DHR-1 loop. Three cases were considered; without depressurization, with depressurization through the ADV where the ADV once opened remains open and with depressurization through the ADV where the ADV opens for half an hour only.

Without depressurization more CO_2 is lost in the early phase and the final CO_2 concentration is about 70%. With depressurization the peak CO_2 concentration is about 80%. However, if the ADV remains open, there is a strong draft created by the break and the open ADV, which mixes the RPV gases with the containment and therefore dilutes CO_2 present in the RPV (Fig 7). Therefore, permanently open ADV gives somewhat higher fuel temperature in the later phase of the accident. The maximum fuel temperature is about 1250ºC for the case without depressurization. For the cases with depressurization the maximum temperature is about 1200ºC (Fig 7). Fuel damage is avoided in all cases.

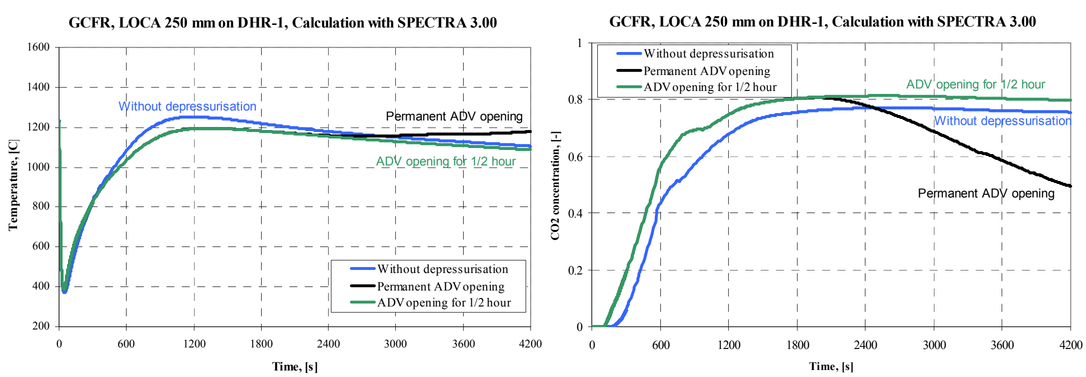

Fig 7 Left: Maximum fuel temperature, 250 mm, near CO_2 injection.
Right: CO_2 concentration, LOCA 250 mm, near CO_2 injection.

Guillotine Rupture of RPV-PCU Duct

As one of the most severe LOCA cases a complete guillotine rupture of the RPV - PCU duct is considered. This kind of break is not only large in size, but it leaves the reactor vessel open from both sides of the core. Because of two large openings in the RPV, a strong draft is created through the RPV, which results in mixing of the RPV gases with the containment gases. CO_2 will be mixed and distributed approximately uniformly between the RPV and the containment volumes. A large amount of CO_2 must be supplied in order to obtain the gas mixture sufficiently heavy to create natural circulation.

Three cases were considered. In the first case only one out of the three DHR loops is available. For the second calculations two CO_2 tanks (the tanks located on DHR-1 and DHR-2) were assumed to be available. In the third case both DHR-1 and DHR-2 loops were assumed to be fully available. Results are shown in Fig 8.

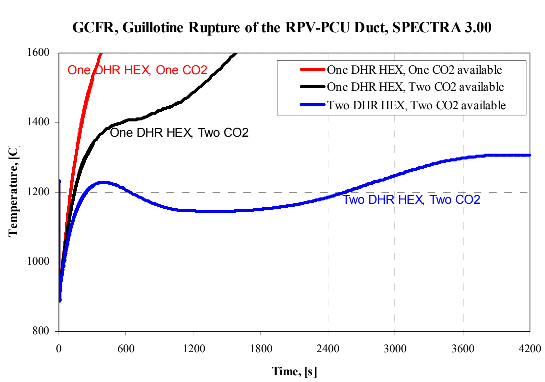

Fig 8 Left: Maximum fuel temperature, rupture of the RPV-PCU duct.
Right: CO_2 concentration, rupture of the RPV-PCU duct.

Because of a large opening on both sides of the vessel, the gases are well mixed. The final CO_2 concentrations in the RPV are the same as in the containment (Fig 9). For the third case the final CO_2 concentration is about 20%. In the second case the CO_2 concentrations are even slightly higher but because only a single heat exchanger (DHR-1) is available, the decay heat removal is insufficient. In the third case the power removed by the DHR approximately matches the core decay power.

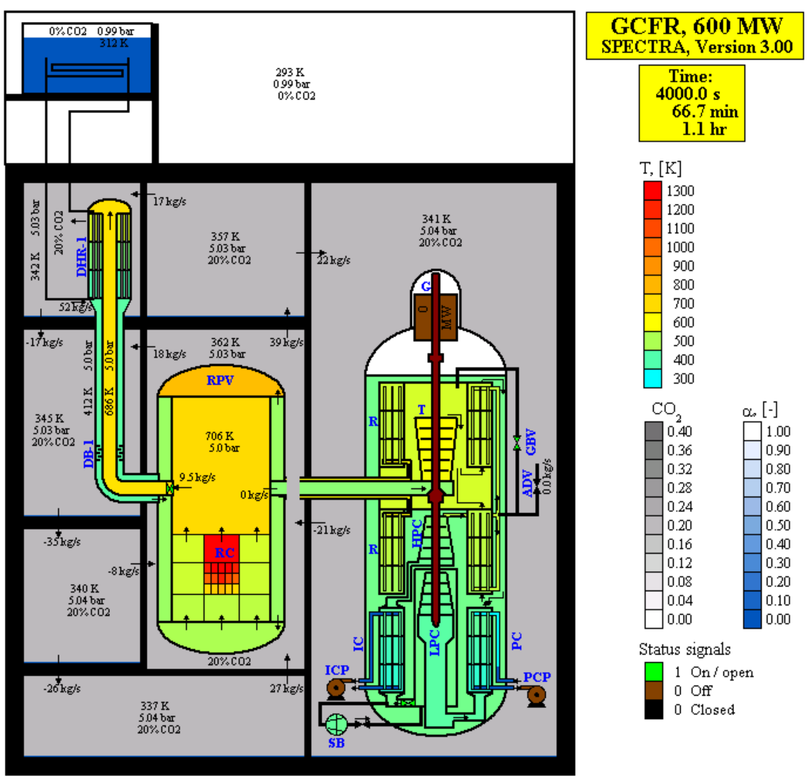

Fig 9 Containment CO_2 concentrations at t = 4000 s. PCU duct rupture, Case 3.

An important aspect of this particular scenario is a very large core bypass flow. The flow through both DHR loops is about 19 kg/s. The flow that is passing the core is only about 6 kg/s. About 12 kg/s is circulating through the open duct and 1.2 kg/s is passing through the reflector. However, because of the low CO_2 concentrations and the large core bypass it is very difficult to cool the core. The successful cooling can be achieved, if two out of three DHR loops are available.

Guillotine Rupture of DHR Duct

As a second severe LOCA case a complete guillotine rupture of one of the DHR ducts DHR-3 is considered. This break is similar to the break on the RPV-PCU duct. The break leaves the vessel open from both ends, creating a strong draft, which results in mixing of the RPV gases with the containment gases. Therefore, injection of CO_2 from a single tank is insufficient and only cases with the injection from two tanks were analysed for the present scenario.

Three cases were considered. In the first case one DHR loop (DHR-1) and two CO_2 tanks (on DHR-1 and DHR-2) are assumed to be available. For the second calculations both DHR-1 and DHR-2 loops were assumed to be fully available. In the third case both DHR-1 and DHR-2 loops and all three CO_2 tanks were assumed to be available. Results are shown in Fig 10.

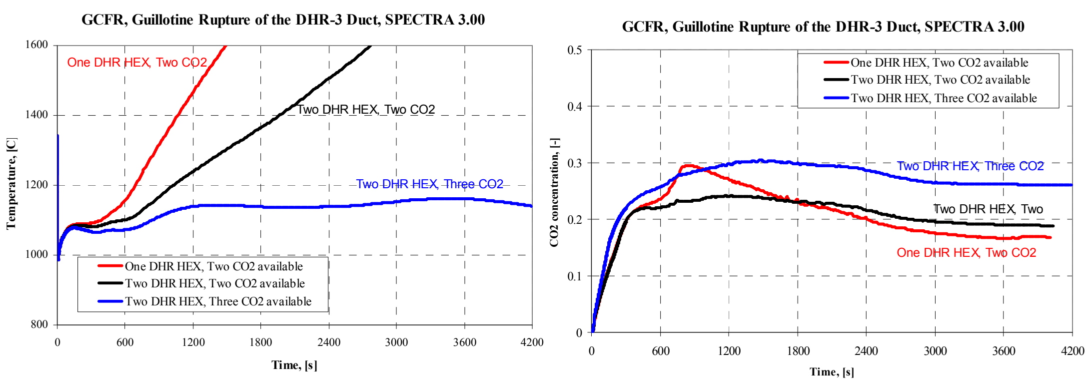

Fig 10 Left: Maximum fuel temperature, rupture of the DHR-3 duct.
Right: CO_2 concentration, rupture of the DHR-3 duct.

Similarly as in the RPV-PCU duct rupture, the core cannot be cooled with one DHR heat exchanger, when two CO_2 tanks are injecting. However, in the present scenario even the availability of two heat exchangers and two CO_2 tanks is not sufficient. The main reasons are:

- In the present scenario the RPV - PCU connection is intact and the PCU, initially filled with helium, acts as a continuous supplier of the light gas to the RPV. Therefore the RPV helium concentrations are higher in case of the DHR duct rupture than in case of the PCU duct rupture.
- In the present scenario there are two large openings from the vessel; one through the ruptured DHR duct and one through the PCU duct. There is a significant natural circulation flow through these two connections. Consequently the flow that passes through the core is small.

The core may be cooled with the present scenario if all the systems are available. This is shown in the case with two DHR heat exchangers and three CO_2 tanks working. The CO_2 tank on the DHR-3 is injecting the heavy gas into the containment. This is sufficient to increase the CO_2 concentration in the RPV to 26% (Fig 11), which is sufficient to keep the core cooled.

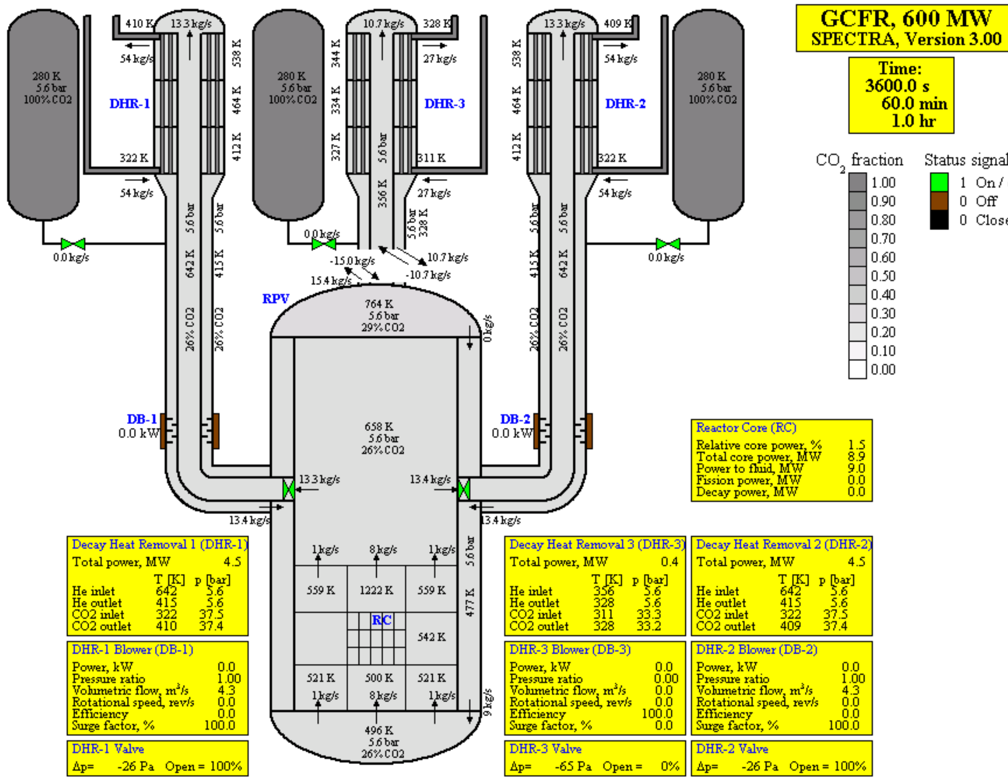

Fig 11 CO2 concentrations at t = 3600 s. DHR-3 duct rupture, Case 3.

Summary of the Calculated Results

Calculated results are summarized in the Tables 1 to 3.

Table 1. Summary of scenarios - availability of safety systems.

Case	HEX / CO2(*) DHR1	DHR2	DHR3
Large LOCA, *D* = 250 mm, on the RPV-DHR duct	Y / Y	N / N	N / N
Small LOCA, *D* = 25 mm, on the RPV-DHR duct	Y / Y	N / N	N / N
Small LOCA, *D* = 10 mm, on the RPV-DHR duct	Y / Y	N / N	N / N
Small LOCA, *D* = 10 mm, on the RPV-DHR duct + depressurisation	Y / Y	N / N	N / N
Small LOCA, *D* = 25 mm, near the CO_2 injection	Y / Y	N / N	N / N
Small LOCA, *D* = 25 mm, near the CO_2 injection + depressurisation	Y / Y	N / N	N / N
Large LOCA, *D* = 250 mm, near the CO_2 injection	Y / Y	N / N	N / N
Large LOCA, *D* = 250 mm, near the CO_2 injection + depressurisation	Y / Y	N / N	N / N
Large LOCA, *D* = 250 mm, near the CO_2 injection + depressurisation + closure of ADV after ½ hour	Y / Y	N / N	N / N
Guillotine rupture of the RPV-PCU duct, 1 DHR, 1 CO_2 available	Y / Y	N / N	N / N
Guillotine rupture of the RPV-PCU duct, 1 DHR, 2 CO_2 available	Y / Y	N / Y	N / N
Guillotine rupture of the RPV-PCU duct, 2 DHR, 2 CO_2 available	Y / Y	Y / Y	N / N
Guillotine rupture of the RPV-DHR duct, 1 DHR, 2 CO_2 available	Y / Y	N / Y	N / N
Guillotine rupture of the RPV-DHR duct, 2 DHR, 2 CO_2 available	Y / Y	Y / Y	N / N
Guillotine rupture of the RPV-DHR duct, 2 DHR, 3 CO_2 available	Y / Y	Y / Y	N / Y

(*) HEX - Heat Exchanger on the DHR loop, Y=available, N=not available
CO2 - CO_2 tank on the corresponding DHR loop, Y=available, N=not available

Table 2. Summary of LOCA results - pressures and maximum fuel temperatures

Case	Pressure p, MPa	Max. T and timing	
		T, ºC	t, s
Large LOCA, D = 250 mm, on the RPV-DHR duct	0.44	~1000	3,500
Small LOCA, D = 25 mm, on the RPV-DHR duct	0.44	~980	24,000
Small LOCA, D = 10 mm, on the RPV-DHR duct	1.8 (0.34)	<600	36,000
Small LOCA, D = 10 mm, on the RPV-DHR duct + depressurisation	0.42	~850	8,000
Small LOCA, D = 25 mm, near the CO_2 injection	0.44	~1000	3,000
Small LOCA, D = 25 mm, near the CO_2 injection + depressurisation	0.42	~1050	23,000
Large LOCA, D = 250 mm, near the CO_2 injection	0.43	~1250	1,200
Large LOCA, D = 250 mm, near the CO_2 injection + depressurisation	0.43	~1000	1,300
Large LOCA, D = 250 mm, near the CO_2 injection + depressurisation + closure of ADV after ½ hour	0.43	~1000	1,300
Guillotine rupture of the RPV-PCU duct, 1 DHR, 1 CO_2 available	0.45	>1600	400
Guillotine rupture of the RPV-PCU duct, 1 DHR, 2 CO_2 available	0.50	>1600	1,500
Guillotine rupture of the RPV-PCU duct, 2 DHR, 2 CO_2 available	0.50	~1300	4,000
Guillotine rupture of the RPV-DHR duct, 1 DHR, 2 CO_2 available	0.51	>1600	1,500
Guillotine rupture of the RPV-DHR duct, 2 DHR, 2 CO_2 available	0.51	>1600	2,700
Guillotine rupture of the RPV-DHR duct, 2 DHR, 3 CO_2 available	0.56	~1150	3,600

Table 3. Summary of LOCA results - cladding oxidation during the analysed period.

Case	CO_2 fraction, %	Oxidation	
		Thickness, m	Oxidant
Large LOCA, D = 250 mm, on the RPV-DHR duct	82	0.4×10^{-5}	CO_2
Small LOCA, D = 25 mm, on the RPV-DHR duct	34	0.9×10^{-5}	CO_2
Small LOCA, D = 10 mm, on the RPV-DHR duct	20	~0.0	-
Small LOCA, D = 10 mm, on the RPV-DHR duct + depressurisation	63	0.7×10^{-5}	CO_2
Small LOCA, D = 25 mm, near the CO_2 injection	34	0.8×10^{-5}	CO_2
Small LOCA, D = 25 mm, near the CO_2 injection + depressurisation	76	2.3×10^{-5}	CO_2
Large LOCA, D = 250 mm, near the CO_2 injection	76	3.7×10^{-5}	CO_2
Large LOCA, D = 250 mm, near the CO_2 injection + depressurisation	49	3.2×10^{-5}	CO_2
Large LOCA, D = 250 mm, near the CO_2 injection + depressurisation + closure of ADV after ½ hour	80	3.0×10^{-5}	CO_2
Guillotine rupture of the RPV-PCU duct, 1 DHR, 1 CO_2 available	10	23.0×10^{-5}	CO_2 , O_2
Guillotine rupture of the RPV-PCU duct, 1 DHR, 2 CO_2 available	28	7.0×10^{-5}	CO_2 , O_2
Guillotine rupture of the RPV-PCU duct, 2 DHR, 2 CO_2 available	20	2.7×10^{-5}	CO_2 , O_2
Guillotine rupture of the RPV-DHR duct, 1 DHR, 2 CO_2 available	17	30.0×10^{-5}	CO_2 , O_2
Guillotine rupture of the RPV-DHR duct, 2 DHR, 2 CO_2 available	19	15.0×10^{-5}	CO_2 , O_2
Guillotine rupture of the RPV-DHR duct, 2 DHR, 3 CO_2 available	26	2.7×10^{-5}	CO_2 , O_2

It can be seen that in all analyzed scenarios except for the guillotine break of the RPV - PCU duct or the DHR duct, the SOPS provides good core cooling using natural circulation only, when one out of three DHR loops is available. Furthermore, except for the 10 mm break without depressurization, the RPV pressure is equal to the containment pressure and is about 0.4 MPa. The SOPS ensures good cooling at such low pressure while in the original design the pressure of at least 1.0 MPa was required.

A guillotine rupture of the RPV - PCU duct or a guillotine rupture of the DHR duct present a large damage to the system and the core coolability cannot be achieved using one DHR loop only. For the guillotine rupture of the RPV-PCU successful cooling is possible if two DHR loops are available. For the guillotine break of a DHR duct successful cooling is possible if two DHR heat exchangers are working and three CO_2 tanks are injecting gas.

Table 3 shows the oxidized layer thickness and the main oxidant. The oxidation results are expected to be conservative since the O_2 oxidation data has been used to model the CO_2 oxidation. It can be seen that except for the cases where fuel damage occurred, the oxidized thickness was low in the order of 10^{-5} m. The oxidation by CO_2 may be avoided by replacing CO_2 by another gas. Argon with its molar weight of 40 has a similar weight as the CO_2 and could therefore be a good replacement. Because the molar weights of both gases are very similar, the natural convection in the system is likely approximately the same when Ar is applied instead of CO_2, however, the capability to remove heat from the system may differ. Furthermore, oxidation by O_2 can be reduced by applying an inert containment, such as the containment of a typical BWR. In an inert containment the oxygen content is typically reduced to about 5%. This will reduce the chance of O_2 oxidation and significantly reduce the reaction rate.

6. CONCLUSIONS

A model of the GCFR has been built for the SPECTRA code. The model includes the Reactor Vessel, the Power Conversion Unit, the Decay Heat Removal Loops, the containment (Guard Vessel) and the reactor building. The model has been tested by comparing results with results of CATHARE calculations for the large break and the small break LOCA scenarios.

In order to enlarge the fluid density in accident conditions it has been proposed to place CO_2 tanks next to the DHR loops. Multiple LOCA analyses, including small and large breaks, as well as a guillotine rupture of the RPV-PCU duct and the DHR duct have been analyzed. It has been concluded that the heavy gas injection system, designed within the present study, allows changing of the current DHR strategy of “auxiliary system cooling before 24 hours and natural circulation cooling thereafter”. It has been shown that with the heavy gas injection natural circulation cooling is sufficient to ensure core cooling from the moment of LOCA - the analyses were made assuming simultaneous LOCA and station blackout. Therefore the active systems are not necessary to provide core cooling.

The analyses described in this report were made using a preliminary design of the GCFR with vertical shaft and the Guard Vessel. Currently different designs are being considered. The results of the presented analysis might still be applicable for other design options provided that the following conditions are fulfilled:

- The density of the gas mixture in the reactor vessel in the GCFR design is not smaller that that in the present analyses. This means the pressure after LOCA must be at least as high as the one obtained in the present design (about 0.4 - 0.5 MPa) and the injected gas must be as heavy as the one assumed here (CO_2, molar weight of 44). Therefore the results of the present study will not be applicable for the designs that would lead to a lower pressure, such as the designs without the Guard Vessel.
- Currently used CO_2 may be replaced by other equally heavy or heavier gas. For instance, Argon can be used or other heavier gases may be considered.

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