# Passive shutdown device for Gas Cooled Fast Reactor: Lithium Injection Module

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## *Abstract*

In this paper a passive reactivity control system for a Gas Cooled Fast Reactor is proposed. The Generation IV GCFR features a core with a relatively high power density, and control of transients and adequate shutdown under accidental situations must be assured for safe operation. Using a passive shutdown device rules out the possibility of unprotected transients. The proposed devices work by the passive introduction of $^6$Li into the core (Lithium Injection Module). Control is by the outlet temperature of the coolant gas in the fuel assemblies, employing a freeze seal. The proposed devices can be integrated into the regular control assemblies. A total of four LIMs is proposed in the core. Thermohydraulic calculations were done using the CATHARE code for a 600 MWth GCFR, for 2 types of transients: a loss of flow, and a control rod withdrawal. The calculations show that activation of one LIM is sufficient to keep the reactor power bounded, while activation of all LIMs in the core will shut down the reactor. The passive LIM devices are able to exclude unprotected transients in the GCFR core.

***KEYWORDS: Gas Cooled Fast Reactor, Passive Safety, Lithium Injection Module, Transient Thermohydraulics, Passive Reactivity Control***

## 1. Introduction

One of the six reactor types proposed in Generation IV [1] is the Gas Cooled Fast Reactor (GCFR). Currently several design options are investigated by various groups throughout the world. The GCFR designs share several reference design features:

- Core power density around 100 MW/m3 (cf. HTR 5 - 10 MW/m3, PWR 100 MW/m3, LMFBR 300 MW/m3).
- High temperature operation with an outlet temperature of 850°C, using helium coolant.
- Fully ceramic core, with the possible exception of the diagrid and parts of the reflector. The preferred materials are SiC for structures and cladding, and $Zr_3Si_2$ for the reflectors.

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- Ceramic fuel, using a mix of UPuC in a SiC matrix. Absence of blankets to improve proliferation resistance.

The combination of high core power density (for a gas cooled system), and low thermal inertia in the core, lead to the possibility of rapid temperature excursions. To increase safety margins, design measures are taken, e.g. application of dispersed fuel in ceramic cladding (high retention of fission products), high-melting ceramic structures, and low void effect. In all fast reactors, core restructuring due to excessive temperatures may lead to reactivity accidents [2]. An adequate, highly reliable SCRAM system is therefore necessary. In this paper research is presented targeting the development of fully passive emergency shutdown systems for GCFR. Using fully passive devices rules out the possibility of unprotected transients, i.e. the neutron chain reaction is automatically stopped for off-nominal conditions.

## 2. Passive reactivity control: options and constraints

To shut down a nuclear reactor, three options are generally available:

1. Introduce a parasitic absorber
2. Increase leakage from the reactor
3. Remove the fuel, or reshape the fuel into a less reactive configuration (possible in mobile fuel reactors, e.g. molten salt reactor, pebble bed reactor)

In this paper a device for passive introduction of an absorber (option 1) is presented. The first decision to be made for passive devices is the reactor property on which it is to operate. The first proposals that we investigated used the core pressure as the governing parameter. This was motivated by the fact that a Loss Of Coolant Accident (LOCA) in the high power core would have severe effects. However, it was soon learnt that pressure-operated devices were not practical for several reasons. First, there will be a pressure holding system on the primary circuit, which will keep pressure more or less constant. Secondly, depending on the Power Conversion System, power output may be controlled by flow or inventory adjustments, leading to pressure fluctuations. And, last but not least, pressure operated devices need to be disarmed in case of an intended depressurization. All these issues make pressure operated devices not very practical.

It was decided to design passive devices using the core outlet temperature as the governing parameter. The rationale for this choice is the following: an accident is basically an unintended mismatch between power production and power removal from the core, and any accident will thus manifest itself as a change of outlet temperature, assuming that the inlet conditions are not directly affected by the accident. The activation temperature can be tuned by using a material with the required melting point. The activation temperature can have some margin over the maximum temperature during normal operation and intended transients. For the proposed passive shut down devices to be succesfully integrated into the design of the nuclear reactor, several demands and constraints are taken into account:

- The passive device is intended to ensure shut down under accidental conditions when all other active control systems (have) fail(ed).

- The device should be small enough to not interfere with other control systems in the reactor, and should preferably be integrated into the regular control assemblies. The assemblies housing passive devices should not be higher than regular assemblies.
- The reactivity of the passive devices should be so large that activation of only one device will introduce a sufficient amount of negative reactivity.

In the following the neutronic design of the passive devices is discussed. All calculations presented in this paper concern the GFR600, a 600 MWth Gas Cooled Fast Reactor studied within the European GCFR-STREP. Some basic design parameters are given in table 1. The GFR600 fuel assembly is illustrated figure 1. The GFR600 core contains 112 fuel assemblies, 6 control assemblies, 3 shutdown assemblies, and is surrounded by 210 reflector assemblies ($Zr_3Si_2$ reflector).

**Table 1:** GFR600 core parameters. The generation time $\Lambda$ and $\beta_{\text{eff}}$ are obtained from a cell calculation, the Doppler and void coefficients were obtained from Monte Carlo (KENO-6) calculations

| *Reference data for GFR600* | |
|---|---|
| Power [MWth] | 600 |
| Coolant | He |
| Power density [MW/m$^3$] | 103 |
| Specific power [W/gHM] | 45 |
| $T_{\text{core,in}}$ [°C] | 480 |
| $T_{\text{core,out}}$ [°C] | 850 |
| Core H/D [m] | 1.95/1.95 |
| $p$ [MPa] | 7.0 |
| Fuel type | plates |
| Fuel material | UPuC + MA |
| Struct. material | SiC |
| Refl. material | $Zr_3Si_2$ |
| *Dynamic parameters* | |
| $\Lambda$ | 7.5e-7 s |
| $\beta_{\text{eff}}$ | 373.3 pcm |
| Doppler coefficient | - 0.6 pcm / K |
| Void coefficient | 396 pcm (= 1.06\$)[a] |

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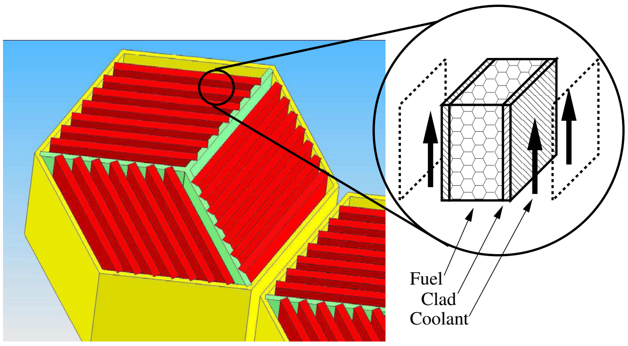
[a] between 70 and 1 bar

All neutronic calculations were done using the CSAS26 module in SCALE 5 [3]. In this model, the fuel assemblies are represented by cell-homogenized mixtures (i.e. self-shielding is taken into account). The reflectors are represented as homogeneous mixtures without any lattice effect, and the absorbers are modeled in their actual geometry, using a cell-calculation to correct the cross sections for effects of absorber self-shielding.

**Figure 1:** GFR600 fuel assembly. The light coloured wrapper and central mechanical restraint are made of SiC. The darker fuel slabs contain the fuel mixture clad with SiC. Each assembly contains 21 fuel plates. The fueled length is 1.95 m, the overall length of the assembly about 4 m. The overall volume fractions are 55 vol% helium, 10 vol% SiC for structures and cladding and 35 vol% fuel/matrix (70 % UPuC/30 % SiC).



## 3. LIM: Lithium Injection Module

To make a temperature controlled passive introduction of reactivity, a device with a freeze seal is chosen. Once the freeze seal melts due to overheating, an absorber is irreversibly released into the core. To identify the nuclide with the highest negative effect on $k_{\text{eff}}$, a unit cell calculation was done using the sensitivity and uncertainty module TSUNAMI-1D in SCALE 5. The result is given in table 2.

**Table 2:** Reactivity effects of nuclides in a GFR600 cell calculation using TSUNAMI-1D. The reactivity effect is expressed in $d\lambda/dN$, i.e. the change in reactor eigenvalue as a function of the number density of the isotope.

| Isotope | $\frac{d\lambda}{dN}$ |
|---|---|
| Eu-151 | -1.40 |
| B-10 | -0.942 |
| Gd-155 | -0.921 |
| Eu-153 | -0.827 |
| $^6$Li | -0.366 |

Because Eu (natural composition 47.8% Eu-151, 52.2 % Eu-153) and B-10 have the highest effect, the compounds $Eu_2O_3$ and $B_4C$ were initially selected for further evaluation. Both these compounds are solid at GFR600 temperatures, so they could be introduced by gravity into the core in the form of small spheres or rods. In both cases, the materials are maintained at the hot side of the reactor, and this may be detrimental to the operation of the device. For example, it is possible that the small spheres fuse together in the high temperature environment, preventing their flow into the core. Therefore, $^6$Li was finally selected because it is liquid at GFR600 operating conditions. The resulting device is similar to the LIM (Lithium Injection Module) proposed for the RAPID reactor [4].

A preliminary design was made of an assembly with a LIM: 7 SiC tubes are filled with $^6$Li in case of off-nominal conditions. A total of 4 LIMs are present: one in the central assembly and 3 in the inner three regular control assemblies. The storage tank containing the $^6$Li during normal operation is located in the bottom of the assembly, and should not have a very large volume to allow integration into the assembly. In activated mode, the Li should occupy the fueled length of the core (1.95 m). The inner diameter of the pins is 22 mm, giving a required volume of $^6$Li of 5200 cm$^3$. If the storage tank occupies all available surface of the assembly, it will be approx. 22 cm high. But to allow for the regular control mechanisms, the $^6$Li storage tank should not occupy all available surface in the assmbly, so a tank height of 45 cm is chosen. Good shielding is maintained as the lower shielding is some 120 cm high. The 7 SiC tubes occupy some 13.7% of the volume of the assembly, so enough room is left over for the regular control mechanisms.

**Table 3:** The effect of the proposed LIM with 7 SiC tubes, $r_{\text{in}}$=1.1 cm, $r_{\text{out}}$=1.2 cm. For a fresh core, the effect amounts to -6.8$ if 4 LIMs are activated. When the burnup reaches 10%, the effect of the LIMs is somewhat lower.

| Core configuration | k$_{\text{eff}}$ | $\Delta\rho$ |
|---|---|---|
| Fresh core | | |
| Reference, 4 x 7 tubes | 1.02572 ± 0.00026 | - |
| $^6$Li in 4 x 7 tubes at 70 bar | 0.99964 ± 0.00029 | -6.81$ |
| Avg. burnup 9.33 % FIMA | | |
| Reference, 4 x 7 tubes | 1.01194 ± 0.00021 | - |
| $^6$Li in 4 x 7 tubes at 70 bar | 0.99045 ± 0.00023 | -6.16 $ |

The LIM is illustrated in figure 2. The 7 SiC tubes are connected to a plenum at the very top of the assembly. From this plenum, tubelets are protruding sideways into the hot outlet gas stream of the neighbouring fuel assemblies. These tubelets contain a small freeze seal from a material with the required melting temperature. The freeze seal should have a small volume to make sure it responds adequately to a temperature increase. If one of the freeze seals ruptures, the $^6$Li shoots into the core. To enable this, the storage tank should be pressurized above the normal system pressure during normal operation. The 7 tubes with $^6$Li are equipped with small SiC pistons, to seal off the tube to prevent the $^6$Li from spraying into the core after activation.

From figure 2 it is seen that it is advantageous if the column of Li can be suspended into the fuel zone, because the required volume of $^6$Li is smaller. The column of Li can be pushed up by the helium from below if the diameter of the tube is small enough. For Li, the maximum inside diameter of the tube to allow this capillary effect is some 27.2 mm [4]. Therefore, the inner diameter of the tube is chosen as 22 mm.

## 4. Transient thermalhydraulic calculations

A simplified thermalhydraulic model of the GFR600 core was made using the CATHARE code [5]. A detailed description of the power conversion system does not exist, therefore the inlet and outlet of the reactor are described as boundary conditions. The fuel plates are modeled as flat plates in which power is produced. The CATHARE model has 6 fuel elements, each representing one ring of fuel assemblies. The axial power profile has a cosine shape with a power peaking of 1.3, radial power peaking is 1.15. Bypass flow in between the fuel elements, as well as flow in the reflector, are currently not modeled. The fuel elements are equipped with flow gags to get a uniform outlet temperature of 850°C. Heat exchanges between the vessel and

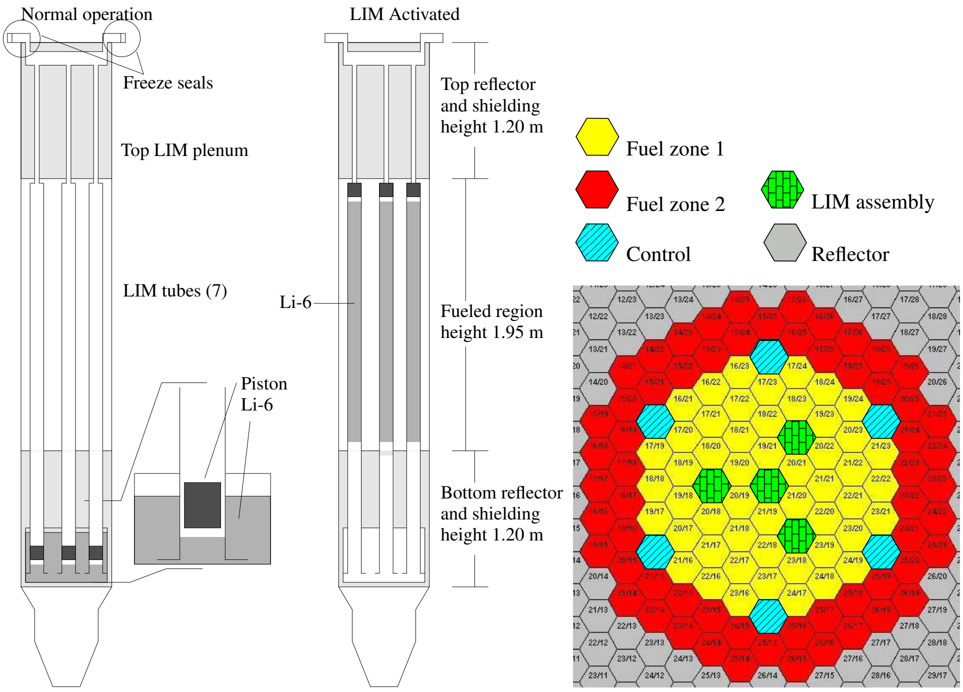


**Figure 2:** Rough design of a Lithium Injection Module (LIM), activated by a freeze seal (not to scale). The height of the storage tank is some 45 cm. When the LIM is activated, the small SiC pistons seal off the tubes to prevent the $^6$Li from spraying into the reactor. The pressure in the storage tank is slightly above the reactor operating pressure. On the right hand side the core layout is given with the locations of the LIM assemblies.

the surrounding environment are not taken into account, due to a lack of detailed design. The primary circuit is equipped with 3 redundant DHR circuits. The DHR circuits contain a heat exchanger located 15 m above the core midplane. The heat is transferred to liquid water on the secondary side. Under pressurized conditions, the DHR circuit relies on natural circulation of the primary helium and secondary water. The DHR circuits are isolated during steady state by valves on the cold side.

The LIMs are each connected to their six neighbouring fuel assemblies, with the freeze seal protruding into the hot outlet gas stream of the fuel assemblies. From this configuration some important design issues are identified:

- If a localized transient occurs, one LIM be activated, and the power goes down. The other LIMs will not be activated, unless the transient inserts more reactivity than the worth of one LIM.
- LIM assemblies could potentially be used to detect flow blockage in individual assemblies, but then at least one LIM should be connected to each fuel assembly.
- Core-wide transients are detected by all LIMs. To make sure the largest number of LIMs are activated at the same, the freeze seals should be as uniform as possible. Again, if one LIM is activated, the other LIMs will not be activated.

Given the simplified primary circuit description, two relevant core-wide transients were calculated:

1. A loss of flow at constant pressure. An initiating event for such a transient would be the (faulty) activation of the turbocompressor braking system.
2. Ramp insertion of reactivity, 0.9$ of reactivity is introduced linearly, either over 20 seconds (faulty withdrawal of control rod), or in 1 second (control rod ejection). Pressure and flow are maintained.

For the neutronic power the well known 6-delay group point kinetics equations are used. Doppler feedback is taken into account based on the average fuel temperature in all fuel assemblies. The void coefficient is calculated from the average pressure in the fuel region of the core. All transients were calculated assuming that either 4 LIMs are activated (-6.8$), or 1 LIM (-1.7%) is activated. The exact worth of each LIM depends on the position in the core, but this is not taken into account. A third calculation was done, activating 1 LIM with a smaller worth (-1.2$). A schematic of the CATHARE model of the core, and the entire circuit is given in figure 3.

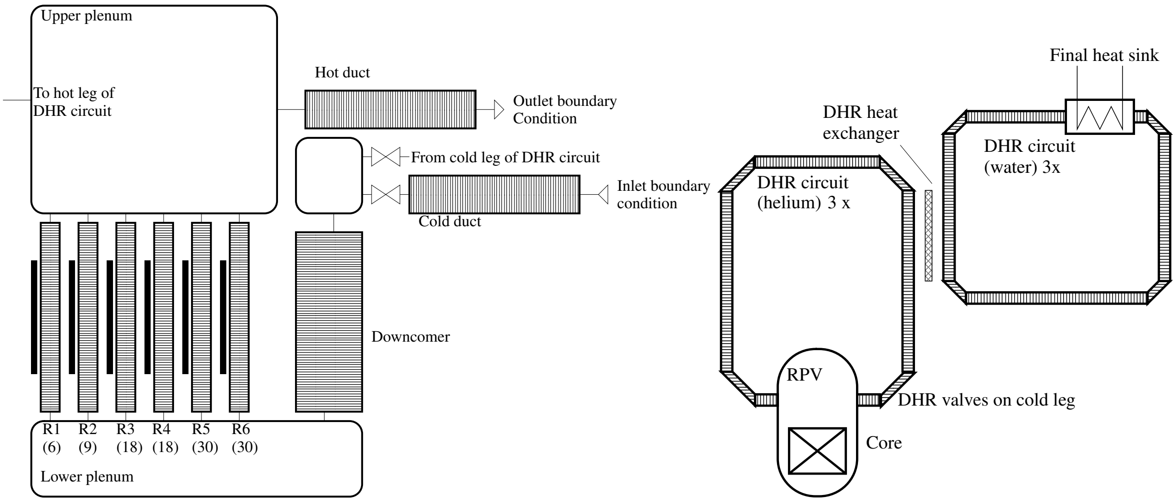


**Figure 3:** Illustration of the CATHARE model of the GFR600 primary system. R1 through R6 are the 6 rings of fuel assemblies, the number in brackets the number of fuel assemblies per ring. The black structures represent the fuel plates. The DHR circuits are represented as simple pipes (concentric ducting). Under pressurized conditions, no blowers or pumps are used in the DHR circuits.

## 5. Results of transient simulations

### Loss of Flow

In all calculations, the mass flow decreases as $\frac{1}{1+t/\tau}$, with $\tau = 10$ s. Activation of 1 LIM is sufficient to shut down the reactor, whether it introduces -1.2$ or -1.7$. In the beginning of the transient, the fuel temperature increases, and power decreases immediately by Doppler feedback. After activation of the LIMs, there is a large prompt jump down in power, followed by a decrease governed by the slowest delay group and decay power. If 4 LIMs are activated, the first jump down is larger (prompt jump behaviour, the power step being proportional to the amount of reactivity introduced). This results in lower temperatures during the rest of the transient. When the coolant mass flow reaches 5% of steady state value, the turbine is isolated and the DHR circuit is opened. In the graphs this is visible as the 'hump' around 5200 s. Under pressurized conditions, the DHR has adequate heat removal capacitiy: the outlet temperature of the core decreases steadily under natural circulation.

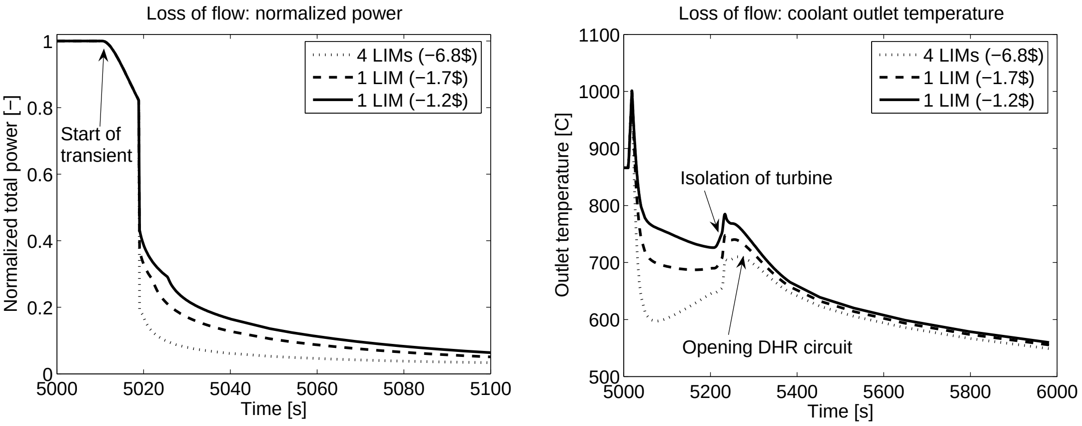


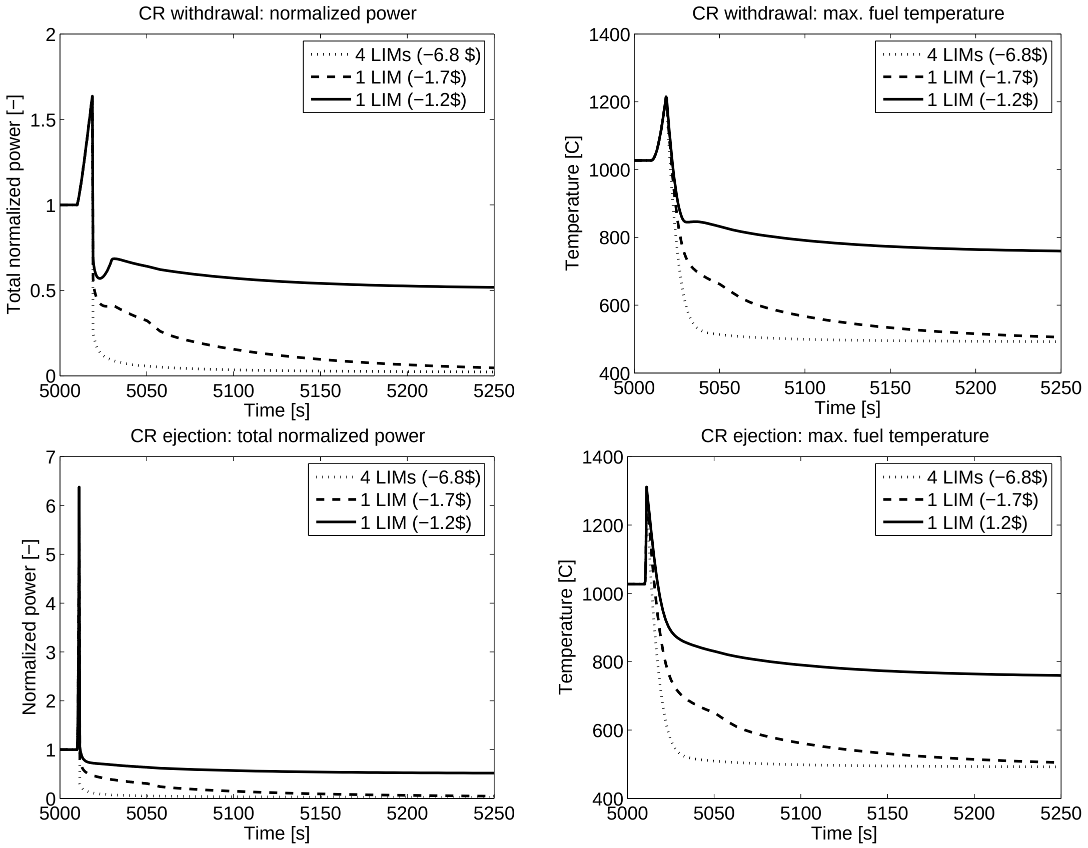
**Figure 4:** Loss of flow results. In the two figures the normalized power and the helium outlet temperature are given. Note the difference in power just after activation of the LIMs: introducing more negative reactivity reduces the power faster. The hump in the right hand figure is caused by the isolation of the turbine, followed by the opening of the DHR system. Note the different time scale on the figures.

From this calculation, it is concluded that a fully passive device, such as a LIM would be an adequate shutdown system, even if the LIM worth is not very high (-1.2$) and only 1 LIM is activated.

### Ramp reactivity introduction, control rod ejection

For this scenario, the results are summarized in figure 5. In all cases, 1 LIM would be sufficient to limit the reactor power. If 1 LIM is activated, -1.7$ (or -1.2$) of reactivity is introduced, and together with the 0.9$ due to CR movement and the Doppler feedback, a net reactivity is established close to zero. If all 4 LIMs are activated, the reactor is shut down. The low-worth LIM (-1.2$) cannot shut down the reactor, instead $\rho = 0$ is obtained at a temperature below operating temperature (positive reactivity contribution from Doppler feedback). For a LIM-worth of -1.7$ the reactor is shut down: in this case, the Doppler reactivity would have to compensate (-1.7$ + 0.9$ =) -0.8$, corresponding to a temperature decrease of almost 500°C of the fuel. Whether the control rod is removed gradually or (almost) instantaneously does not make much difference on the transient behaviour. In the case of CR ejection, the power peak is very large, and very short. Since pressure and flow are maintained during the transient, the energy deposited in the fuel and structural materials can be removed efficiently. Even though the fuel temperature does not reach extreme values, this kind of accident causes concern for the possibility of fuel assembly degradation by thermal shock.

In figure 6 the reactivity is illustrated for the cases where -1.7$ or -1.2$ is inserted. The CR, Doppler and total reactivity are given. Notice that if the strong LIM is activated (-1.7$), the temperature of the fuel decreases considerably, giving a positive Doppler contribution of some +0.5$. If the 'weak' LIM is activated the overall reactivity approaches zero quite quickly. It



CR withdrawal: normalized power

CR withdrawal: max. fuel temperature

CR ejection: total normalized power

CR ejection: max. fuel temperature

**Figure 5:** Results for the withdrawal of a control rod (+0.9$). In the upper row ('CR withdrawal') the rod is withdrawn in 20 seconds. In the bottom figure, the rod is withdrawn in 1 second ('CR ejection'). Notice that in both cases the reactor is shut down if more than -1.7$ is inserted. If -1.2$ is inserted, the reactor power stabilizes at about 50% of the nominal power. This behaviour is almost independent on the withdrawal rate of the control rod.

is mainly due to the prompt jump behaviour of the PK-equations that in that first, short period of negative reactivity, the power decreases very quickly. It should be noted that in the current calculations the inlet condition was maintained at steady state values. If the inlet temperature is reduced, the positive Doppler contributions may be larger.

From this calculation it is concluded that LIMs are effective to shut down the reactor, even if a large reactivity is accidentally inserted. If 1 LIM is activated, the reactor may not be shutdown completely, but the power production is controlled. The transient considered here gives a design envelope for the required LIM reactivity: one LIM should at least be able to counteract the largest accidental introduction of reactivity, which is a design parameter (control rod (drive) design). A loss of coolant will also introduce positive reactivity (see table 1), but the associated temperature increase of the coolant will cause negative Doppler feedback.

## 6. Conclusions

In this paper a passive shutdown device for a Gas Cooled Fast Reactor is proposed, based on the passive introduction of liquid $^6$Li in a special assembly if off-nominal conditions occur. Two transients are calculated: a loss of flow, and a faulty control rod withdrawal. For the Loss

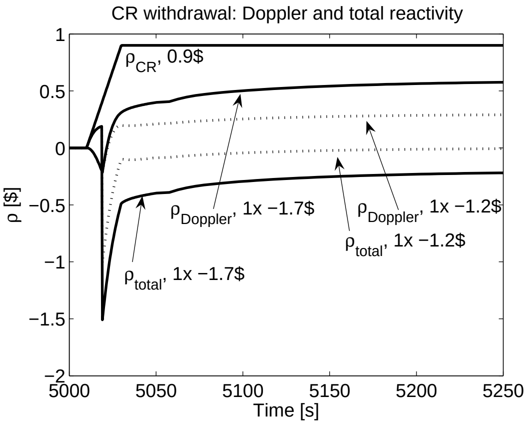


**Figure 6:** Transient reactivity contributions during the control rod withdrawal, for the 2 cases where only 1 LIM is activated. If the 'weak' LIM is activated, the total reactivity approaches zero quite quickly. The difference between LIM worth (-1.2\$) and CR worth (+0.9\$) is provided by positive Doppler feedback. When the strong LIM (-1.7\$) works, the Doppler contribution is larger, but the overall $\rho$ remains negative.

of Flow transient, activation of 1 LIM (of 4 present) is sufficient to shut down the reactor, while maintaining safe temperature margins on the fuel. For this kind of transient, a LIM worth of about 1\$ would be sufficient for adequate shutdown. For the control rod withdrawal, activation of 1 LIM is sufficient to prevent damage, but the reactor will not be shut down completely. If 4 LIMs are activated, the reactor is shut down. Although one LIM would suffice to control the reactor, redundancy may call for more LIMs.

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