COMPARISON STUDY OF HYBRID VS CRITICAL SYSTEMS IN POINT KINETICS

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Abstract

An essential motivation for hybrid systems is a potentially high level of intrinsic safety against reactivity accidents. In this respect, it is necessary to assess the behaviour of an Accelerator Driven System during a TOP, LOF or TOC accident.

A comparison between a critical and sub-critical reactor shows a larger sensitivity for the critical system. The ADS has an unquestionable advantage in case of TOP but a less favourable behaviour as for LOFWS type of accidents. However in the ADS cases, the beam could be easily shut off during the transient. Therefore, a part of the R&D effort should be focused on the monitoring and control of power.

Introduction

In France, the Hybrid systems are dedicated to the elimination of minor actinides and long life fission products according to "the France Act of 1991". The main interest of this type of system is a high potential intrinsic safety level as regards reactivity accidents, in spite of a low dollar value and negative thermal reactions.

In this sense it is necessary to assess the behaviour of a sub-critical reactor piloted by a source during transient of power (TOP), flow (LOF) or current (TOC) and to compare the results with those of a critical system.

The presentation is illustrated by using a PHENIX type fast neutron reactor model with or without source.

Critical and sub-critical system kinetics behaviour

Neutronic kinetics neighbouring the criticality

If $k_{eff} \simeq 1$, or furthermore $\rho * (k_{eff} -1)/k_{eff} \simeq 0$, then the neutronic kinetics are ruled by the effective fraction keff for the delayed neutrons. Typically, the T_d doubling time for the neutronic population according to the reactivity of the following values (1 cent = $\beta_{eff}/100$):

Table 1. **Doubling time according to the reactivity**

ρ (cent)	1	5	10	25	50	75
T_d (s)	700	140	52	14	3	0.7

As long as the reactivity remains well below the dollar, T_d is in seconds. The reactor control is therefore possible and the usual safety systems are operative.

Prompt criticality

If the reactivity ρ is superior to β_{eff}, the neutronic population is therefore ruled by the prompt neutrons. Its evolution is exponential with a doubling time inferior to the tenth of second. The reactor becomes uncontrollable and the usual action time of the safety system, ca. a few hundred milliseconds, can turn out to be inefficient to prevent a criticality accident.

Neutronic kinetics of a sub-critical system

If l represents the prompt neutrons lifetime and S the neutron source - inherent, external or in spallation - then the neutronic population is equal to $\eta = S * l/\rho$.

Dividing the ρ reactivity by an f factor or increasing the S source by the same factor leads to a multiplication by f of the neutronic population. This effect is instantaneous for a sub-critical system of several dollars.

For example, starting at - 2 $, a 1$ insertion finally entails a doubling of the power.

This behaviour is fundamentally different from that of a critical system for which + 1 $ leads to prompt criticality. This advantage is essential.

On the contrary, in a critical system the S source being insignificant, a negative insertion of reactivity entails the interruption of the chain reaction, which is not the case for a sub-critical system whose source remains constant.

Thermal feedback effect

Any temperature modification in a reactor entails a core reactivity variation. The Doppler effect, the concentration variations of the material in the core and the differential core-tank-control rods expansion are the main thermal feedbacks influencing the reactivity. These reactions are called feedbacks as they oppose the initial disturbance, thus playing a stabilising role. The main exception to this rule concerns the draining of a core cooled by a liquid metal, as in the fast neutron reactor. In such a case, the draining effect can be highly positive in certain areas of the core and therefore evaluated in dollars.

For a power reactor, due to the sensitivity of the neutronic flux as regards the reactivity, the thermal feedbacks' role is essential both for operation and safety. In the case of Hybrid systems, the situation is different. On the one hand, as their function consists in burning minor actinides, long life fission products and possibly Plutonium, the feedbacks are weak- notably the Doppler effect and non-differential expansion in absence of control rods. On the other, the sensitivity of the neutronic power as regards the reactivity is lower than in the critical system as shown in previous paragraph 'Neutronic kinetics of a sub-critical system'.

Reactivity accidents

Typically accidents can have two origins:

- The ramps change of reactivity or transient of power (TOP).
- The loss of flow (LOF) which can possibly lead to a TOP in case of coolant draining.

For Hybrid systems piloted by an accelerator, the transient of current (TOC) must also be taken into account.

Triggered by the injection of the whole margin of the current of the accelerator required for the reactor operation over the total cycle time, they can cause a power overshoot.

Transient of power (TOP)

Theoretically, that is to say without prejudging the accident triggering physical phenomenon, we study the critical and sub-critical system behaviour as regards the insertion of a non-protected fast ramp change of reactivity.

As a first example, a ramp change of reactivity of 0.55 $/s is inserted in a PHENIX type core until the fuel melting is achieved. Two calculations are performed, one with k_{eff} = 1, the other with k_{eff}= 0.95 + constant external source.

The mean temperature and the power evolutions are given in Table 2. The following results are obtained [1].

Table 2

	Critical reactor k_{eff} = 1	**Sub-critical reactor k_{eff} = 0.95**
Time before melting	2 s	12 s
Inserted reactivity	1.1 $	6.6 $
P/Po	2.2	1.5

A factor of 6 on the time before melting and therefore on the inserted reactivity is observed between the two systems.

As a second TOP example, we can use the study performed by Rief and Takahashi [2]. The considered reactor, which is sodium cooled, has a power of 1 GW. The chosen operating mode is either critical or sub-critical of - 1 $, - 2 $ and - 3 $. A ramp change of reactivity of 170 $/s is injected in 16 ms, by a total of 2.72 $. The calculation results show that in critical mode, the prompt criticality is achieved 6 ms after the beginning of the ramp with the first power peak of 700 GW at 8.5 ms and a second at 500 GW of 13.2 ms whereas in sub-critical mode, the peaks are respectively obtained at 530 GW for - 1/$, a maximum of 6 GW for - 2 $ and 2.2 GW for - 3 $ at 16 ms. Even if for an initial sub-criticality of only - 1 $ the power peak is close to the peaks obtained in critical mode, the total energy released during power excursion is much lower.

The results presented here concern non-protected transitories of power. As long as the system remains sub-critical, the power increase with the reactivity is considerably slower than in critical mode thus giving a much longer time for the safety systems to react. Furthermore, it is interesting to note that it is unquestionably faster, simpler and more reliable to cut the spallation source rather than to drop the safety rods to stop the chain reaction.

Loss of flow (LOF)

Let us consider a decrease, or even a total loss of coolant fluid flow which could lead to the draining of the core by boiling, if the accident is unprotected.

As a first example, a primary flow decrease from 100 % to 60 % in 10 seconds is simulated in a PHENIX 1 type core. Two calculations are performed, one with k_{eff} = 1, the other with k_{eff} = 0.95 + constant external source.

While considering the same set of thermal feedbacks, we note (Figure 4) a smaller neutronic power decrease in sub-critical (a power increase could even be possible for a core without control bars if the reactivity effect of the coolant is superior to the Doppler effects and fuel actual expansion). The clad and coolant overheating is then faster and broader than for a critical reactor. Although the sodium boiling temperature is not reached, a larger number of clad breakage should be expected.

As a second ULOF example, we can use the study performed by Rief, Magill and Wider [3]. The considered system is a sodium cooled 800 MWe reactor with a draining effect of 4 $. The primary pumps slow down on their inertia by a factor 2 per 12 seconds.

After a few tens of seconds in critical mode, the sodium boiling leads to the core draining, thus making the critical reactor prompt, the maximum power peak reaching 1,800 times the initial power. The accident causes a fast core melting of the explosive type.

In the case of a sub-critical reactor of - 10 $ with external source, the sodium boiling starts 12 seconds after the LOF beginning. In 3 seconds, 4 $ are injected by draining. The power reaches a peak of only 1.5 times its initial value but however remains at a sufficient level after the peak to entail a "slow" core fusion.

It should be noted that for a lead cooled reactor, the clad melting takes place before coolant boiling. Therefore the accidental sequence will be different from that of a sodium cooled reactor.

In principle a ULOF is more favourable for a critical reactor as the coolant temperature increase is slower and weaker. Nevertheless, if the boiling occurs, the consequences following the TOP caused by the draining are more serious.

In comparison to a TOP, the time before the LOF accident is much longer as it is estimated in seconds. The safety system non-intervention probability (rod drop, source shutdown, Diesel take-over, etc.) is therefore much smaller.

Transient of current (TOC)

The reactivity evolution during an operating cycle requires a spallation source adjustment and therefore that of the current of the accelerator, in order to maintain the power at a constant level. The accidental injection of the whole margin of the current of the accelerator can therefore cause a power overshoot.

However the ρ_o sub-criticality level chosen for the reactor operation can be sent in order to prevent core damaging. Indeed, if $\Delta\rho_{TOP}$ is the reactivity variation between the beginning and the end of the cycle, then the instantaneous introduction of the whole accelerator current margin aimed at compensating $\Delta\rho_{TOP}$ entails a power variation equal to:

$$\frac{P}{P_0} = 1 + \frac{D\rho_{TOP}}{\rho_0 + \beta}$$

If P_{max} is the maximum acceptable power required for accident detection during a short period of time, then ρ_o (i.e. k_{eff}) can be set so that P always remains inferior to P_{max}.

Conclusion

If the core is correctly dimensioned to remain sub-critical in any circumstance, then hybrid systems present an unquestionable advantage compared to the critical systems as regards the transitories of reactivity. The power and temperature evolutions are sufficiently slow to allow intervention of the safety system.

In case of unprotected loss of flow (ULOF), the power slump is faster and broader for a critical system than for a hybrid. Nevertheless, if coolant fluid boiling occurs, the consequences following the TOP caused by draining are more serious. Finally, it seems simpler, faster and more reliable, at the same detection level, to cut the spallation source rather than drop the safety bars to stop the chain reaction

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