FAST REACTIVITY ACCIDENTS: A COMPARATIVE STUDY

A. C. VERTULLO and M. O. GIMENEZ

Nuclear Safety Group

Bariloche Atomic Center, CNEA, 8400S.C. de Bariloche – Argentina

1. Introduction

In a multiplicative medium as a reactor core, fast reactivity accidents represent one of the initiating events that most dangerous consequences can provoke, leading eventually to severe accidents.
A parametric study has been accomplished in order to acquire knowledge about the role that kinetic parameters play in prompt critical transients from the safety point of view.
Different reactors core have been studied and compared considering LEU and HEU fuels as well as graphite, berylium and D_2O reflected cores.
Calculations have been performed with PARET [1] code and core comparisons also include SPERT [2] and Cabri [3] experimental data.

2. Description of PARET code

The PARET code consists, basically, in a couple neutronics - thermalhydraulics one-dimensional model to predict the evolution of reactivity transients in small reactor cores.
The core can be represented by one to four regions. Each region may have different power generation, coolant mass flow rate and hydraulic parameters as represented by a single fuel pin or plate with its associated coolant channel.
The hydrodynamic Momentum Integral Model in the code, although incompressible, includes a transient void model to estimate the local voids produced by subcooled boiling.
The heat transfer in each fuel element is computed on the basis of a one-dimensional conduction solution in each of up to 21 axial sections.
The plate-to-fluid heat transfer may take place by natural or forced convection, nucleate, transition or stable film boiling and the coolant is allowed to range from subcooled liquid through two-phase regime and super-heated steam.
The code has been modified to include a selection of flow instability, departure from nucleate boiling (DNB), single and two-phase heat transfer correlations and a fluid properties library considered applicable to low pressures, temperatures and flow rates encountered in research reactors [2].
Comparisons of PARET calculations with experimental results have proved that the code is adequate in analysing a wide range of reactor excursions.

3. Parametric study

A parametric study was carried out in order to determine tendencies and sensitivity of research reactor cores to certain kinetic parameters variations, like delayed neutron fraction, β, and neutron generation time, Λ. The selected base case to reference calculations was RA-3 core. It belongs to a reactor sited in Argentina actually being upgraded to 10 Mw operational power with U_3O_8-Al fuels and was considered adequate for the purpose. Main core characteristics are provided in Table 1.
A fast reactivity insertion consisting in a constant reactivity ramp of 1000 pcm in 0.5 seconds was simulated in all the cases. The adopted ramp represents a prompt critical condition for most delayed neutron fractions
The observable parameters are maximum peak power and maximum clad temperature in the hot channel as functions of asymptotical period.

In Figure 1 maximum peak power versus asymptotical period was determined varying delayed neutron fraction. It can be seen that asymptotical period decreases for smaller delayed neutron fraction and consequently the transient reaches higher peak power.

In the same figure neutron generation time variations were also provided. It can be seen that Λ presents a similar behavior than β effective but with a steeper slope. The peak power trends to infinite as Λ decreases.

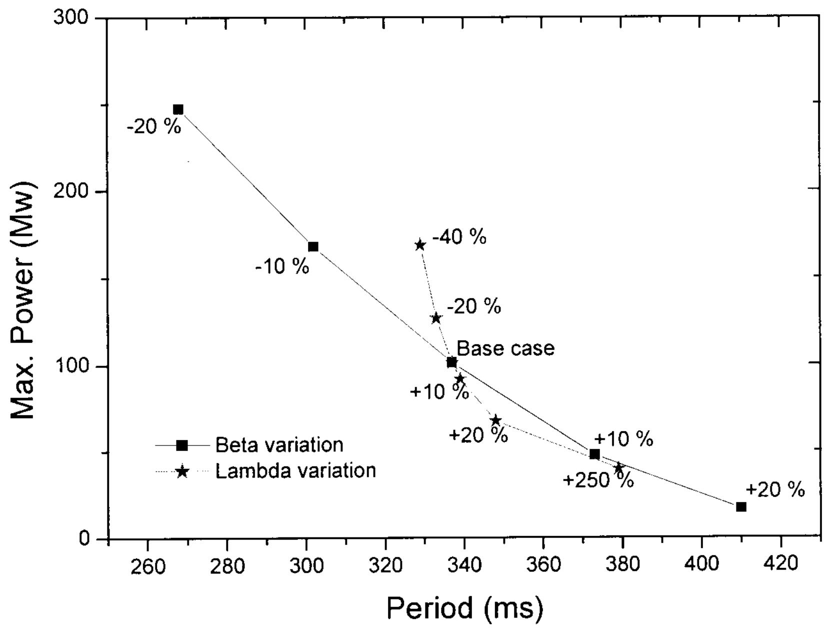

Figure 1- Peak power as function of period and β effective and Λ variations

Maximum clad temperature for hot channel is represented in Figure 2 as a function of period. A 10 % increase in both, β effective or Λ represent lower clad temperatures. This effect has a significant meaning from the safety point of view because temperatures could reach values below damage range, as it is the case with RA-3 core (T<400 ^{0}C). On the contrary when β effective or Λ are decreased, clad temperatures show higher values.

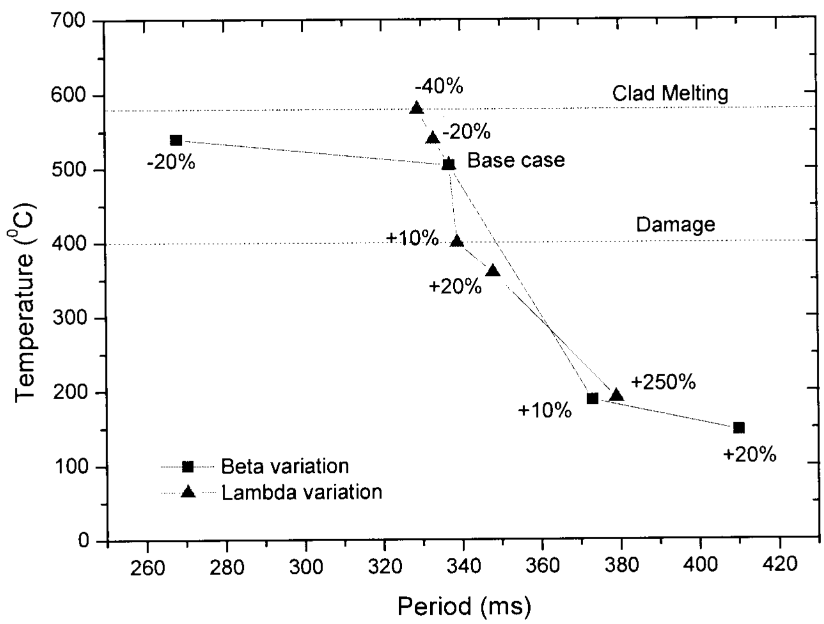

Figure 2- Maximum clad temperature as function of period and β effective and Λ variations

Parameter	SPERT I HEU fuel	CABRI Core HEU fuel	Core 1 LEU fuel	Core 2 LEU fuel	RA-3 Core LEU fuel
Fuel type	U-Al	U-Al	U_3O_8-Al	U_3Si_2-Al	U_3O_8-Al
Plates/Element, Standard, (Control)	24	340 (Core)	19	21	19
Reflector	N/a	N/a	Berilium	D_2O	Graphite
N° Elements Standard, (Control)	32	19	29	16	25
Fuel Thickness, m	0.51×10^{-3}	0.5×10^{-3}	0.7×10^{-3}	0.61×10^{-3}	0.7×10^{-3}
Clad Thickness, m	0.51×10^{-3}	0.38×10^{-3}	0.4×10^{-3}	0.37×10^{-3}	0.4×10^{-3}
Water Channel, m	1.65×10^{-3}	2.12×10^{-3}	2.7×10^{-3}	2.45×10^{-3}	2.7×10^{-3}
Heat transfer area (m^2)	~55	25.1	56.4	26.8	35
U^{235}/plate, kg	0.007	0.011	0.02	0.023	0.0116
Temperature Coefficient, $/°C *	- 0.02528	-0.01149	-0.013	-0.01861	-0.0408
Fuel Temp Coefficient, $/°C *	-------------	--------	-2.56×10^{-3}	-2.580×10^{-3}	-1.95×10^{-3}
Void Coefficient, $/%void *	- 0.3571	-0.7870	-0.2935	-0.2275	-0.3870
Neutron Generation Time, s	50×10^{-6}	58.5×10^{-6}	75E-6	150×10^{-6}	64×10^{-6}
β effective	0.007	0.00783	0.00703	0.0084	0.00768
Hot channel flux/Average	2.5	2.5	3.0	3.0	3.5

* *Average values*

Table 1 - Main characteristics and kinetics parameters of various cores

Parameter	SPERT I B-24/32 HEU fuel	CABRI HEU fuel	Core 1 LEU fuel	Core 2 LEU fuel	RA-3 LEU fuel
Beta	0.91	1.02	0.91	1.09	1.
Neutron Generation Time	0.78	0.91	1.17	2.34	1.
Temperature Coefficient	0.62	0.28	0.32	0.456	1.
Void Coefficient	0.923	2.03	0.758	0.588	1.

Table 2 – Different cores kinetics parameters relative to RA-3

3. Cores comparison

Transient calculations have been done in order to compare the behavior of different cores having in mind results from the previous parametric study.
The scenarios adopted for the simulations were step insertions in the different cores analyzed without flow rate and with 1W of initial power. The inlet temperature was considered 20 ^{0}C for all the case. Transients were self-limited by cores negative feedback coefficients.
Table 2 provides an aid, giving the variation of main kinetic parameters of the different cores adopted in the simulations, related to RA-3 core.
Maximum power as a function of inverse period is represented in Figure 3 for the cores described in Table 1. It can be seen the relevant role that kinetic parameters like β effective and Λ play in relation with the maximum peak power. At slow reactivity insertions, SPERT and Core 1 present the highest peak power values due to their low β and relative low Λ related with the base case (RA-3 core) as well as relative low feedback coefficients. Cabri high enrichment uranium fuels core has a relative smaller Λ and no fuel Doppler reactivity feedback effects but thanks to the large delayed neutron fraction as well as large coolant and void reactivity coefficients presents an intermediate behaviour. Core 2 has the highest kinetics parameters but peak power is not so low as compared with RA-3 core because presents the lowest feedback coefficients.
The change in slope that can be noted in each curve of Figure 3 represented the transition from slow to fast transients. Meanwhile SPERT and Core 1 present the change in slope at approx. 5 s^{-1}, RA-3 and Core 2 present a later appearance of prompt critical (approx. at 20 s^{-1}) due to their larger beta effective. Larger neutron generation time inherent of LEU and D_2O reflected cores give later and lower peak powers, improving reactor intrinsic safety. For example, meanwhile asymptotic periods for a given reactivity step insertion is within the explosive domain for most of the cores compared in the present work, a LEU, D_2O reflected, compact core, is below the critical values mentioned in Borax [4] and Cabri experiments as can be seen in Figure 5. As an example, in CABRI and RA-3 cores (Λ: 59.5–64 μs respectively) the limiting step reactivity insertion is approximately 3 $ meanwhile Core 2 with a neutron generation time of 150 μs requires more than 5 $ to reach similar limiting condition.
Figure 4 shows a different aspect of cores behavior. In this figure maximum clad temperature in the hot channel as a function of inverse period is represented. SPERT and Core 1 present quite similar behavior coherent with the curves in Figure 3. They also have similar heat transfer area as shown in Table 1. Besides the difference in power between both cores, SPERT presents slightly lower clad temperatures due to its lower peaking factor.
In the beginning of fast transient region, Core 2 shows the steepest slope due the compactness of the core. Its heat transfer area is 30 % lower than RA-3 core, this feature explains the difference in clad temperatures.

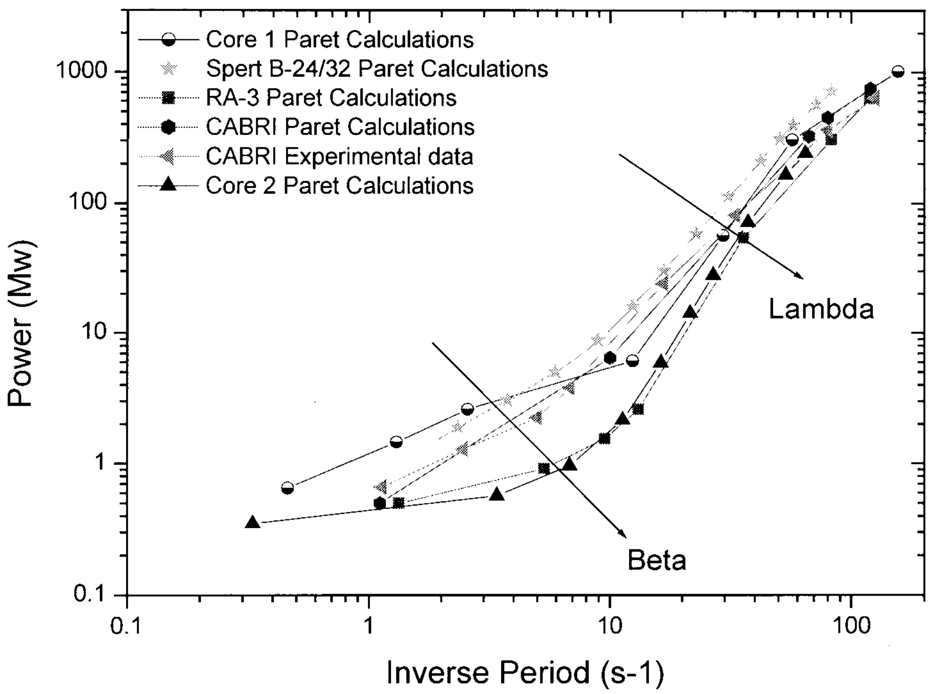

Figure 3 – Peak power vs Inverse period for various cores

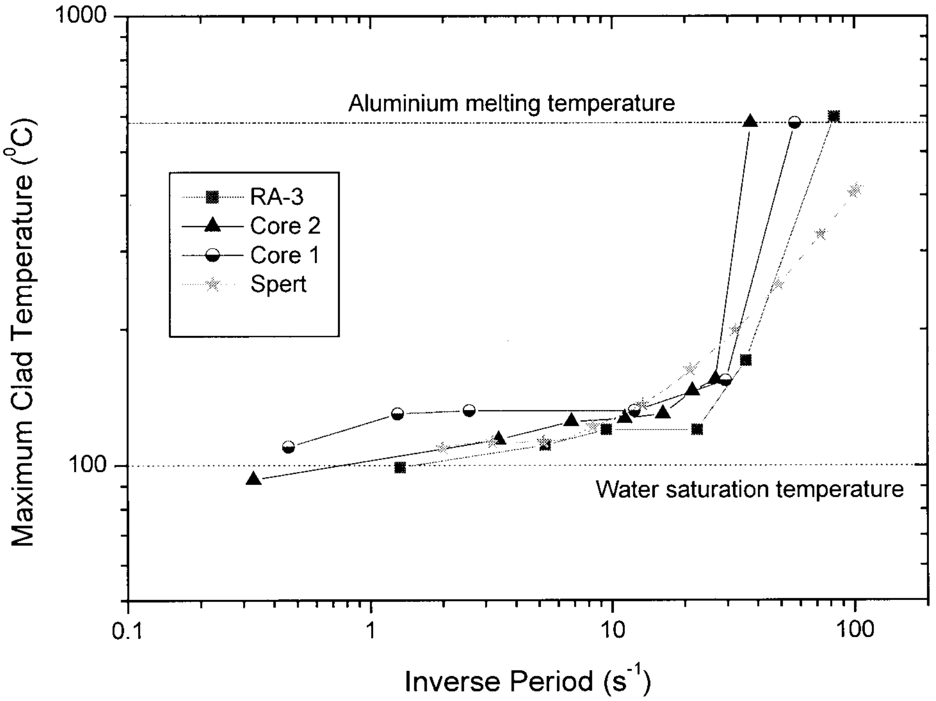

Figure 4 – Maximum Clad Temperature vs Inverse period for various cores

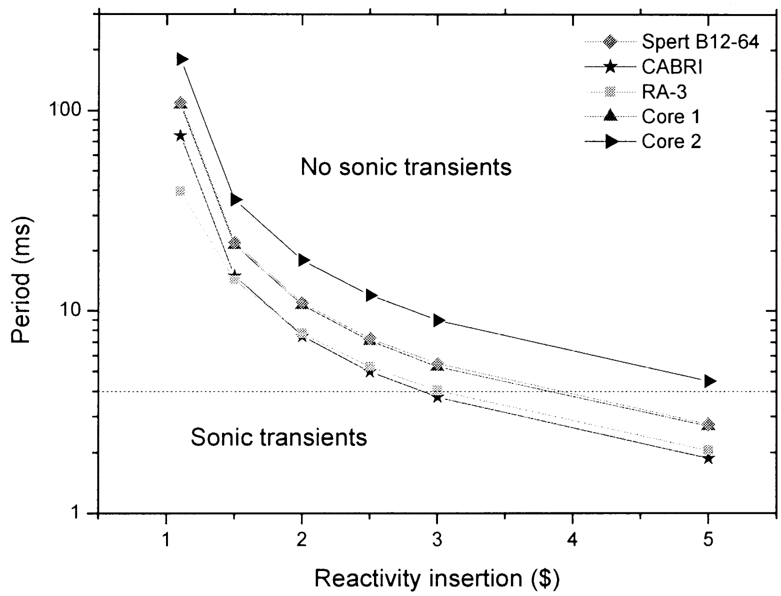

Figure 5 – Period as a function of reactivity step insertion

4. Conclusions

The preceding results show to be in good agreement with conceptual analysis.
In fast reactivity accidents, peak power is considerable more sensitive to relative variation in β effective than in neutron generation time. However an adequate change in design could imply an increment in either β or Λ resulting in later and lower power peaks and consequently could change maximum clad temperature from damage or melting conditions to an acceptable value. As an example, a + 10 % of variation in delayed neutron fractions for a reactivity insertion of 1000 pcm in RA-3 core, lead the clad temperature from 500 to 190^{0}C. It can be concluded that a large delayed neutron fraction could represent an additional passive safety feature besides a better reactor control.
Large neutron generation time due to the heavy water reflector gives a core intrinsic safety condition to explosive accidents. This means that is necessary a higher reactivity insertion to enter a critical domain. Core 2 with a prompt neutron generation time of 150 ms reaches explosive conditions at 5 $, meanwhile the other compared cores are in the same conditions with reactivities of 3 to 3.8 $ and lambdas from 50 to 75 ms
Nevertheless low-enriched uranium fuel presents an additional negative reactivity feedback contribution due to fuel Doppler effect, a LEU core could present higher power and maximum clad temperature than HEU cores due to other factors as low feedback coolant and void reactivity coefficient, due to the core features.
In compact cores, high peaking factors and low heat transfer area give high clad temperatures regardless of eventual lower peak powers.
Some aspects of this comparative study are still uncovered. Further analysis should be done for example, with the release energy associated with the peak power as related with maximum clad temperatures.

3. References

[1] Obenchain, C.F.:" PARET – A program for the analysis of reactor transients". IDO-17282, 1969.
[2] The PARET and the analysis of the SPERT I transients. W. Woodruff. ANL/RERTR/TM-4, Conf-821155, sept 1982
[3] Merchie, F.: " Presentàtion bibliographique des resultats obtenus a CABRI dans le domaine de la securite des reacteurs a eau legere". CEA – CENG, Pi ® 710-87/67, 1967
[4] Abou Yehia H.; Berry J.L.; Sinda T.: "Prise en compte d'un accident de reactivite dans le dimensionnement des reacteurs de recherché" IAEA-SM 310/107, 1989