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A New 3D Consistent 1D Group Constants Representation Scheme

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Abstract

A 1D group constant representation scheme employing tables having independent variables of control rod tip position, fuel temperature, moderator density, and boron concentration is presented. This table functionalizes the current conservation factors (CCF) as well as the conventional 1D collapsed group constants. To test the 1D kinetics model with this 1D group constants representation scheme, steady state and transient calculations for the NEACRP A1 benchmark problem and a SMART bank withdrawal event are performed and compared with 3D reference values. Results show that the errors in k-eff are reduced to about one tenth when using CCF without significant computational overheads. The error in the power distribution is decreased to the range of one fifth or tenth at steady state calculation. During transient, the 1D result shows much closer results to the 3D values than the conventional linear 1D group constants representation. It is expected that the proposed 1D kinetics model with the 1D group constants representation scheme can be used in many practical applications requiring fast execution such as operator supporting system and coupled real time simulation of the system with significantly enhanced solution fidelity.

1. Introduction

In Reference 1, the 1D kinetics model was formulated within the framework of the nonlinear analytic nodal method. It was derived so that the surface and node averaged properties such as fluxes and currents were conserved by using the current conservation factor (CCF). The CCF is generated along with the planar 1D cross-sections prepared through the base 3D code. The 1D cross sections can be obtained through the axial collapsing process which performs the radial flux-volume weighting of 3D cross sections. Since these group constants are functions of state parameters such as fuel temperature, coolant density and boron concentration, several 3D calculations are required to generate planar cross sections at various states. The planar cross sections then need to be properly functionalized for use in the 1D calculations. The representation of 1D cross sections is

conventionally described as a linear function or polynomial function or table interpolation scheme on several state parameters[2, 3]. The control rod cross section is considered as an additive term which comes from the difference between the unrodded set and the rodded set. Adopting the conventional 1D group constants representation, we cannot consider the flux distortion effect when the control rod is partially inserted in the core. This will cause inaccurate results. When the main control of reactor is performed by the control rods, especially in the boron free reactor, the error from partially inserted rod motion will be propagated during transient simulation.

In this paper, a new 1D group constants representation scheme employing tables as a function of a control rod tip position is developed and applied to the 1D kinetics model. The cross section sets for the fuel temperature and moderator density variations are generated for each control rod tip position that is placed at all the axial node interfaces.

In order to verify the 1D kinetics model with the 1D group constants representation scheme, the NEACRP A1 benchmark problem[4] and a SMART[5] bank withdrawal event were calculated and compared with the corresponding 3D reference results.

2. Collapsing 3D Cross Section

In the derivation of the 3D consistent 1D neutronics model [1], the 1D group constants are defined by using the factorization of the flux into two independent functions of the 1D flux(j) and radial shape function(Φ), respectively as the following:

$$f_g(x,y,z,t) = j_g(z,t)\Phi_g(x,y,z,t) \quad . \tag{1}$$

A planar averaged cross-section is defined as:

$$\overline{\Sigma}_{xg} \equiv \frac{1}{A}\int_A \Sigma_{xg}\Phi_g dA, \quad \text{x; type of cross section} \ . \tag{2}$$

The leakage cross-section Σ_{Lg} is defined as:

$$\Sigma_{Lg} = \frac{1}{A j_g}\left(\oint_B J_{gx}dy + \oint_B J_{gy}dx\right) \tag{3}$$

The planar averaged diffusion coefficient is defined as:

$$\overline{D}_g \equiv \frac{1}{A}\int D_g\Phi_g dA \ . \tag{4}$$

The CCF is obtained from the two node flux solution as follows:

$$e_g = \frac{j_g^b(h^b/2) - j_g^t(-h^t/2)}{j_g^b(h^b/2) + j_g^t(-h^t/2)}, \quad g = 1,2 \tag{5}$$

where the superscripts *t* and *b* stand for the top and the bottom nodes, respectively.

The CCF values are generated when the 1D cross-section set is generated from planar collapsed cross-sections. They are used when solving the intra nodal flux distribution in a two node problem kernel of a 1D model[6, 7].

3. 1D Group Constant Functionalization

For general applications of the 1D kinetics code, the following cross section representation scheme which combines a tabular and a polynomial form is introduced:

$$\Sigma(r, T_f, B, x) = x\,\Sigma^U(r, T_f, B) + (1-x)\,\Sigma^L(r, T_f, B)$$

$$\Sigma^i(r, T_f, B) = \Sigma(r, T_f) + (a_1 + a_2\Delta r)\Delta B, \quad i = L, U$$

where

r = coolant density in g/cc,

x = control rod insertion fraction in a node,

Δr = coolant density change from the reference value in g/cc,

ΔB = boron concentration change from the reference value in ppm,

i = index of 1D group constants set,

L = 1D XS set for the node bottom position where CR tip is located,

U = 1D XS set for the node top position where CR tip is located.

In this representation, the base cross sections given in a 2-dimensional table form in which the independent variables are coolant density and fuel temperature. The choice of these two independent variables was dictated by the fact that the coolant density and fuel temperature can vary in a wide range during the transient calculation. The use of tables enables inclusion of the cross term effects and extends the range of application of the cross section set. The boron concentration effect here is separated out because it is presumed that the cross section sets are generated for a given burnup state and that the range of ppm variation around the critical boron concentration at that burnup is small. However, in order to retain accuracy, the density dependence of the ppm derivative of the macroscopic cross section is included. The tables are to be provided for a total of thirteen types of two-group constants. These are transport, absorption, nu-fission, kappa-fission, fission, CCF for two groups and scattering cross section.

4. 1D Group Constants Generation with 3D calculation

In the 1D kinetics model, each plane is treated with a different composition and thus each planar cross section should be obtained from reference 3D steady-state calculations. In the MASTER code[8], the planar collapsing procedure for 1D group constants was already implemented. Also the planar averaged group fluxes and node surface currents are extracted to generate CCF. The GENDA1D utility code is developed to produce the 1D group constants.

Table 1 shows the various core states of MASTER 3D steady-state calculations to generate the 1D cross section table for the SMART core. Three power states are chosen for fuel temperature and moderator density variation calculation to simulate the core behavior. So the tables of 3X3 elements which consist of 3 fuel temperature variation and 3 moderator temperature variation for each control rod group and the control rod position at each node edge can be formulated. The terms dependent on boron concentration are omitted for boron free SMART. Figure 1 shows the MASTER running output which describes the control rod insertion sequence in the third column first row window of Figure 1.

If the control rod is inserted into a node edge, it is possible to reproduce the 3D result with the consistent 1D model using CCF. When a control rod is inserted in the core, then the corresponding rod tip position is determined and each node cross sections in the 1D model is interpolated with the control rod insertion fraction in the node.

As shown in Figure 2, when the control rod is partially inserted in the node k, then the group constants for all nodes are interpolated with the cross section sets k and k+1. The k-th set means the cross sections for all nodes when the control rod is inserted at the bottom edge of node k.

5. Verification of 1D Kinetics Model

In this section, the accuracy of the 1D kinetics model and the table form 1D group constants representation including CCF are verified through the comparison of the 1D and 3D results for the NEACRP A1 benchmark problem and a SMART bank withdrawal event.

5.1 NEACRP Benchmark Problem

This problem shows the core behavior from HZP during 5 seconds transient after a central rod is ejected in 0.1 seconds. The core power dramatically explodes after rod ejection and rapidly decreases due to the Doppler fuel temperature feedback. The 1D group constants are generated at steady states with the A1 control rod insertion depth for the three different power levels. The keff change versus A1 control rod insertion is compared in Figure 3. One can see in this figure that the A1 control rod worth remains essentially unchanged in the described power ranges. The fuel temperature variation and the moderator density variation are performed with those three power levels. The 1D and 3D comparison results are compared in Table 2. The 1D result is very close to the 3D result although the CPU time is only one two-hundredth compared with the 3D computation time. Figure 4 shows the comparison result on the core power behavior. Also the results from two different 1D cross section representation schemes, the conventional linear one [2] and the proposed one, are provided in Figure 4. When the 1D group constants set employing tables as a function of CR tip position is used, the 1D calculation result becomes very close to that of the 3D calculation as shown in Figure 4. Figure 5 shows the core average axial power distribution during the transient. The axial power distributions of 1D calculation agree well with those of 3D.

5.2 SMART Bank Withdrawal Event

The proposed 1D kinetics model was applied to a boron free reactor, SMART. SMART core is composed of 57 fuel assemblies, of which design and performance are based on the 17x17 KOFA. Each fuel assembly holds 264 fuel rods of 8.05 mm in diameter and 2.0 m in active height, 21 guide tubes for control rods and 4 instrumentation thimbles, which are mechanically joined in a square array. In SMART, there are 49 CEAs and the control rods in a bank move together. The locations of all CEA banks in the core are shown in Figure 6.

Banks R4, R3, R2 and R1 are termed the regulating banks and moved in a fixed sequential pattern with the pre-determined overlapping steps. Since soluble boron is not used for the reactivity control during the normal operation, some regulating banks are partially inserted into the core to the critical position. This causes relatively large distortions in the radial and axial power distributions.

The control bank R4 withdrawal event overlapped with the bank R3 is simulated by the proposed 1D kinetics model. Control bank R4 at 80 steps is withdrawn to the fully out position (200 steps) in 90 seconds. Overlapped with control bank R4, control bank R3 at 140 steps is moved to fully out position in 45 second The core power increases due to the reactivity insertion and decreases by the Doppler fuel temperature feedback. But the core power increases more by the continuous bank withdrawal. When the core power reached to 118% nominal power, the scram signal is activated and all control banks are inserted to 0 step in 0.5 second. Figure 7 shows the simulation result for the control bank withdrawal of SMART core. The simulated core power by 1D model is slightly larger than that of the

MASTER 3D result and more rapidly reaches to 118%. But the overall result represents that the 1D kinetics model predicts well the core behavior of bank withdrawal event.

6. Conclusion

The 1D kinetics model with 1D group constants functionalization employing tables as control rod tip position is developed. This model agrees well with that of the 3D reference and also gives more accurate results than the conventional linear group constants model. Thus it is expected that the 1D kinetics model with the 1D group constants representation developed in this paper can be applied to many practical circumstances requiring fast execution such as operator supporting system, safety analysis and reactor real time simulation coupled with system analysis code with significantly enhanced solution fidelity.

7. Acknowledgement

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8. References

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Table 1 Various Core States of MASTER 3D Steady State for SMART to generate the 1D Group Constants

CR ID	CR Tip Position (node bottom edge)	Power * (%)	Table Index of Tf row	Table Index of Dm column
1	ARO	0.0	1	1
		60.0	2	2
		120.0	3	3
		60.0	2	1
		120.0	3	1
		0.0	1	2
		120.0	3	2
		0.0	1	3
		60.0	2	3
	For nz+1, ..,1, repeat each node bottom position until next CR ID appears.	. . .	. . .	. . .
For all CR ID by the CR Insertion Sequence, Repeat until the last CR ID appears.	. . .	. . .	. . .	. . .
Note * : The core state is fixed in each power level for consistent Tf and Dm variation.				

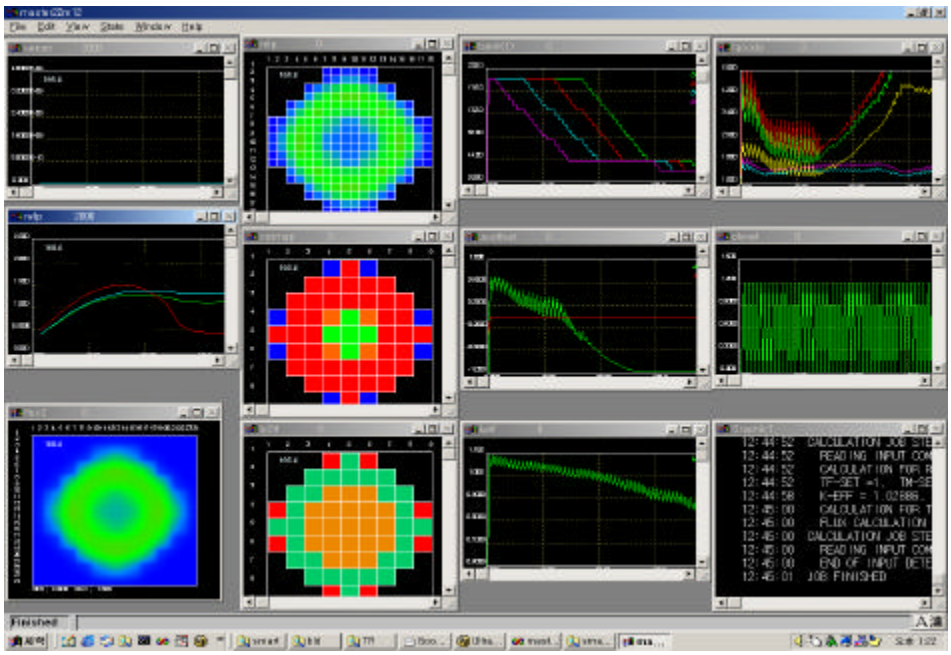
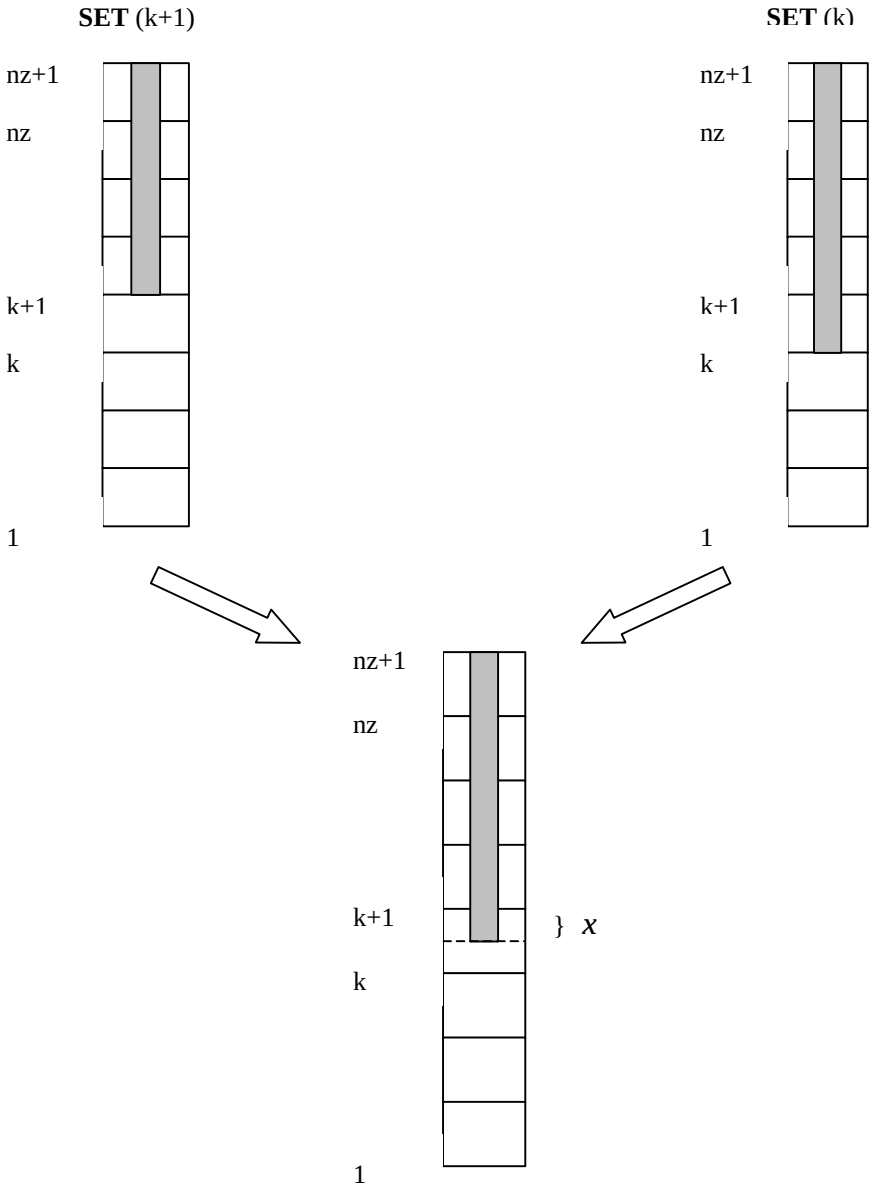


Figure 1. MASTER Output for 1D Group Constants Generation Run for SMART



$$\Sigma(r, T_f, B, x) = x\,\Sigma^{SET(k+1)}(r, T_f, B) + (1-x)\,\Sigma^{SET(k)}(r, T_f, B)$$ for all nodes

where x = control rod fraction in the node k.

Figure 2. 1D Cross Section Interpolation Based on Control Rod Tip Position

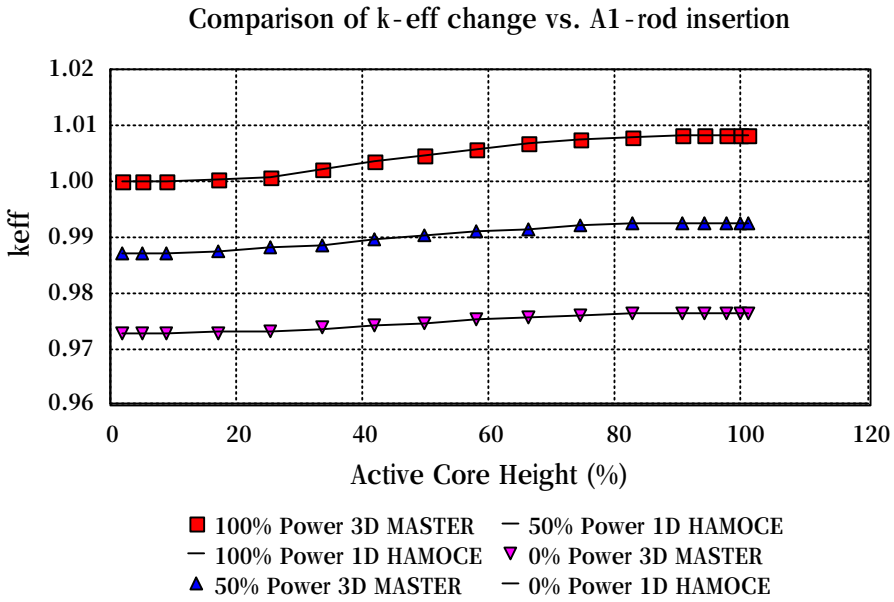


Figure 3. Comparison of k-eff for Various Rod Insertion Conditions in the NEACRP Core

Table 2 1D vs. 3D Comparison of NEACRP A1 Results

Item	3D MASTER	1D HAMOCE
Initial CB (ppm)	561.69	561.56
A1 Rod Worth at HZP (pcm)	827	827
Initial ASI(%)	-1.25	-1.25
Initial peak axial power	1.5012	1.5025
Peak time (sec.)	0.55	0.53
Peak power (%)	125.7	124.7
Power at time=5.00	19.9	18.9
CPU time (sec.)	158.26	0.80

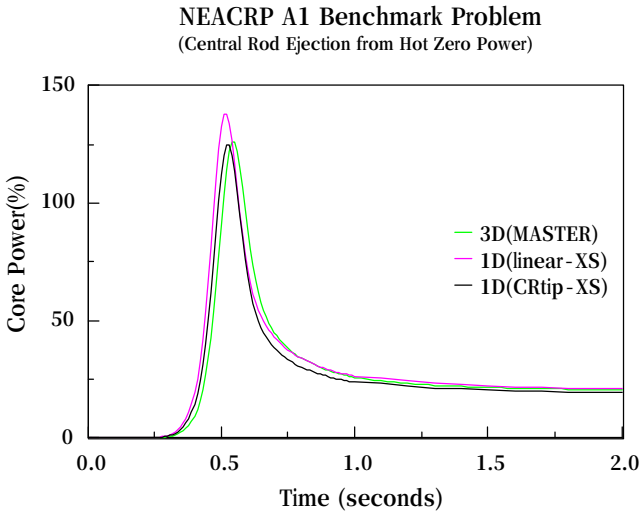


Figure 4　Comparison of Fast Transient Result for NEACRP A1 Problem

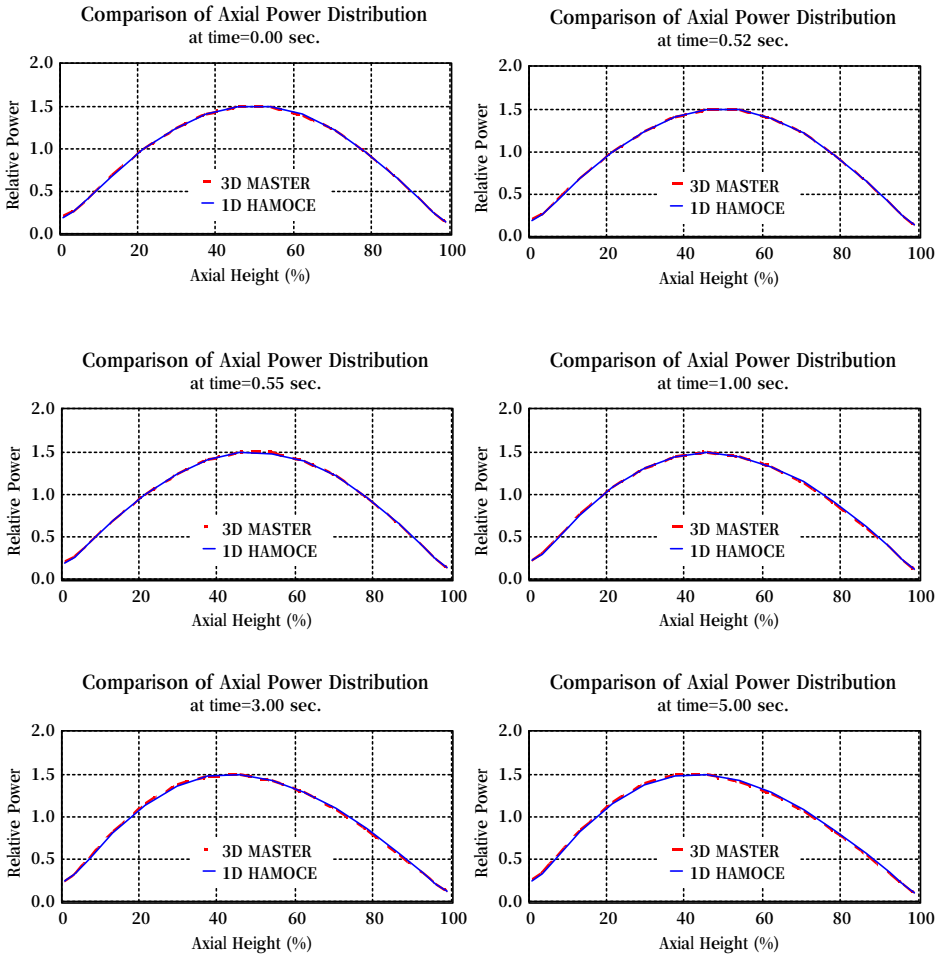


Figure 5　Comparison of Axial Power Distributions for NEACRP A1 Problem

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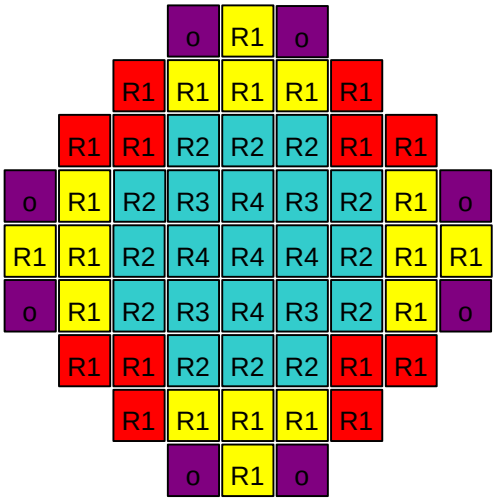

Figure 6 Location of Control Banks in SMART Core

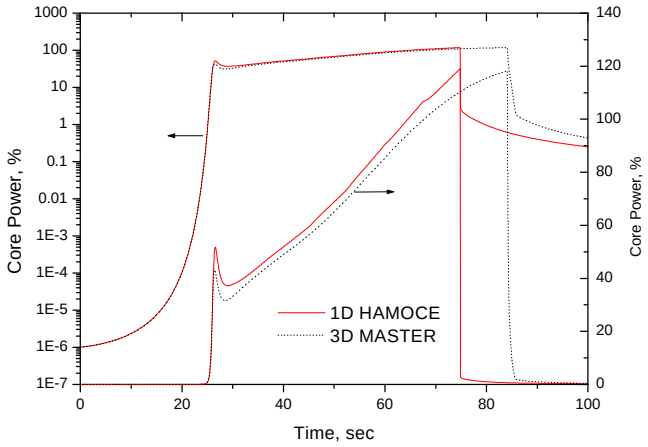

Figure 7 SMART Core Power Behavior in a Bank Withdrawal Event