MUSE-4 ANALYSES BY MEANS OF SPATIAL KINETICS CAPABILITIES IN THE ERANOS CODE

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In the frame of the MUSE-4 experimental program the time-dependent detector responses to a short neutron pulse provided by the GENEPI accelerator were analysed in the past by means of the original spatial-time kinetics KIN3D module implemented in the ERANOS deterministic code system. This KIN3D module version employed the usual assumption (common for many diffusion transient codes developed in the past) that the influence of time-dependent effects on the odd-parity flux (that is the neutron current for the lowest angular approximation) is negligible, i.e. Fick's law remains valid even under transient conditions (that disallows using diffusion codes for modelling very fast - compared to neutron lifetime - phenomena, such as neutron waves).

Recently the ERANOS KIN3D module was extended at FZK. In particular, the KIN3D transport options and a new time-discretization scheme were validated with respect to modelling fast source-induced transients. This scheme is free of the aforementioned restrictive assumption that may affect results of transient simulations for very fast events and represents an improvement in terms of accuracy, reliability and robustness.

In this paper results of transient analyses of the MUSE-4 Pulsed Neutron Source experiments performed by means of the new ERANOS KIN3D options are shown and discussed.

I. INTRODUCTION

Accelerator Driven Systems[1] (ADS) are currently under investigation worldwide because of their potential role for incinerating/transmuting plutonium and Minor Actinides (MAs). In order to perform the design and the safety assessment, it is important to develop computation tools able to simulate transients and hypothetical accidents in ADS[2]. In particular the presence of an external neutron source leads to neutron flux distributions and kinetics characteristics different from those of the critical systems. As a consequence the neutron kinetics models for ADS should properly take into account the effect of an external neutron source during a transient[3]. These models have been implemented into KIN3D (Ref. 4), a space-time and energy-dependent neutronics module of the VARIANT/TGV code[5,6], a part of the CEA European Reactor Analysis Optimized System (ERANOS) deterministic code system[7].

A specific feature of the original ERANOS KIN3D version is that only the even-parity (with respect to angle) components of the external source are taken into account. Recently new transport options (Spherical and Simplified Spherical Harmonics, Pn and SPn) and a new time-discretization scheme have been introduced in the KIN3D module in order to take into account both the even and odd parity flux derivative[8].

3D time-dependent calculations with the previous and the new options have been performed by means of the ERANOS KIN3D module in the frame of the zero-power MUSE program[9], carried out at the CEA-Cadarache MASURCA facility to study the neutronics of ADS. Among the main purposes of the MUSE-4 program there was the investigation of the experimental techniques allowing on-line monitoring of the reactivity of an external source driven system at a very low subcriticality level.

In this paper a MASURCA configuration at a very low reactivity level (about -12.5 $) has been considered. The detector responses to a neutron pulse of 0.5μs, provided by the GENEPI pulsed deuteron accelerator, generated at the reactor centre by D-T reactions have been simulated in the frame of the Pulsed Neutron Source (PNS) experiments[10,11,12].

Results of analyses obtained with the different ERANOS KIN3D kinetics options are presented and discussed.

II. KINETICS MODELS IN KIN3D

KIN3D module is the kinetics and perturbation extension of the VARIANT/TGV nodal transport code[5,6]. It includes four kinetics options: point kinetics, improved quasistatic, adiabatic and direct method.

In the point kinetics model the neutron flux is assumed to be separable into a time-dependent flux amplitude function P(t) and in a position-energy-angle shape dependent function ψ(r,E,Ω), which is assumed constant during the transient:

$$\varphi(\mathbf{r},E,\mathbf{\Omega},t) = P(t)\psi(\mathbf{r},E,\mathbf{\Omega}) \qquad (1)$$

The direct option is based on the implicit discretization scheme by assuming that the neutron flux is linear within a time step. In this manner the time-dependent equation can be transformed into a sequence of steady-state problems with an “artificial” source term.

In the improved quasistatic scheme the flux shape is assumed linear during the time step. In this case the flux shape is not updated so often as the flux amplitude. The new flux shape at the end of each time step gives new power profiles and new reactivity coefficients. The adiabatic scheme is similar to the quasistatic one, except that the neutron velocity is assumed to be infinite and the precursors are assumed to be in equilibrium with the flux while performing flux shape recalculations.

A more detailed description of the KIN3D module may be found in Ref. 13.

In the following two Sections the direct method in the original KIN3D module will be briefly described. Then the new implementations will be shortly introduced.

II.A. Direct method in the original KIN3D module

The neutron flux variations in a subcritical system with an external source can be described by the following system of time-dependent transport equations for each energy group g, assuming isotropic scattering and isotropic external source[14]:

$$\frac{1}{v_g(\mathbf{r},t)}\frac{\partial\psi_g(\mathbf{r},\mathbf{\Omega},t)}{\partial t}+\Omega\nabla\psi_g(\mathbf{r},\mathbf{\Omega},t)+ \sigma_{t,g}(\mathbf{r},t)\psi_g(\mathbf{r},\mathbf{\Omega},t)= =\frac{1}{4\pi}\sum_{g'}\sigma_{s,g'\to g}(\mathbf{r},t)\phi_{g'}(\mathbf{r},t)+ +\frac{1}{4\pi}\left[\chi_g(\mathbf{r},t)-\sum_i\chi_{i,g}\beta_i(\mathbf{r},t)\right]F(\mathbf{r},t)+ +\frac{1}{4\pi}\sum_i\lambda_i\chi_{i,g}C_i(\mathbf{r},t)+\frac{1}{4\pi}Q_g(\mathbf{r},t) \qquad (2)$$

$$\frac{\partial}{\partial t}C_i(\mathbf{r},t)=\beta_i(\mathbf{r},t)F(\mathbf{r},t)-\lambda_iC_i(\mathbf{r},t) \qquad (3)$$

where

$$F(\mathbf{r},t)=\sum_{g^i}\nu\sigma_{f,g^i}(\mathbf{r},t)\phi_{g'}(\mathbf{r},t) \qquad (4)$$

$$\beta_i(\mathbf{r},t)=\frac{\sum_{g'}\beta_{i,g'}(\mathbf{r},t)\upsilon\sigma_{f.g'}(\mathbf{r},t)\phi_{g'}(\mathbf{r},t)}{\sum_{g'}\upsilon\sigma_{f.g'}(\mathbf{r},t)\phi_{g'}(\mathbf{r},t)} \qquad (5)$$

with
v_g= neutron speed,
i= delayed neutron family,
$\chi_g(\mathbf{r},t)$= total fission spectrum,
$\chi_{i,g}$= delayed fission spectrum for each family i,
$\beta_{i,g}(\mathbf{r},t)$= delayed neutron fraction for each family i,
λ_i= decay constant for each family i,
$F(\mathbf{r},t)$= fission source,
$C_i(\mathbf{r},t)$= concentrations of delayed neutron precursors for each family i,
$Q_g(\mathbf{r},t)$= external source.

The time-dependent problem is solved under the assumption that, at the beginning of transient, the system will be in a steady-state condition. At each time step the corresponding cross sections and external source files are generated by KIN3D and supplied to the VARIANT code for a new calculation.

A specific feature is that only the even-parity components (with respect to the angle) of the external source are taken into account. As performed in the Variational Nodal Method[5,6] (VNM) the flux ψ is split into even-parity (superscript plus) and odd-parity components:

$$\psi^+(\mathbf{r},\mathbf{\Omega})=\frac{1}{2}\left[\psi(\mathbf{r},\mathbf{\Omega})+\psi(\mathbf{r},-\mathbf{\Omega})\right] \qquad (6)$$

$$\psi^{-}(\mathbf{r},\mathbf{\Omega}) = \frac{1}{2}\left[\psi(\mathbf{r},\mathbf{\Omega}) - \psi(\mathbf{r},-\mathbf{\Omega})\right] \qquad (7)$$

This assumption gives rise to a very good performance of VARIANT code.

The calculation of reactivity and other kinetics parameters (effective delayed neutron fraction, effective source, neutron generation time) in KIN3D is based on the variational nodal perturbation theory technique.

The time-dependent equations are solved with the same approach carried out for solving diffusion transient equations, where Fick’s law is assumed to be valid even during the transient. As a consequence, a different treatment for the time derivative of the even and odd (with respect to the angle) flux components is carried out. In particular the even-derivative of the flux component is discretized by a first order backward Euler scheme, while the odd-time derivative is neglected (the odd-parity flux component is used only for computing the mean neutron generation time). The implementation of this scheme is inaccurate when using an angular approximation of the flux above the first order, i.e. more than the diffusion approximation.

This methodology simplifies the computation scheme. Nevertheless extremely fast phenomena, with a time scale comparable to the neutron lifetime, cannot be treated in an accurate manner. In order to solve this problem new implementations have been introduced in the KIN3D module.

II.B. Extensions of the KIN3D module

The original time dependent model used by VARIANT and KIN3D modules inside the ERANOS platform has been improved[8].

A new KIN3D option allows taking into account the odd-parity flux derivative in the time dependent equations. At the moment this option is available for the direct kinetics model only. The original option has been replaced by a first order backward Euler scheme applied only to the zero order angular term of the flux (i.e. the scalar flux) while all the time derivatives for the higher moments are neglected.

At each time step the KIN3D module computes the odd-parity flux by using the even-parity flux computed by VARIANT, evaluates the corresponding term of the external source and modifies the odd part of the scattering/absorption operator. A more detailed description of the new extensions may be found in Ref. 15.

In order to analyze very fast source transients where the sudden change of the source amplitude leads to neutron flux variations not negligible even at the time scale of the neutron collision time, a second option has been introduced. It is based on a first order backward Euler scheme applied to all even and odd time-derivatives of the angular moments.

This type of approach not only is more accurate when fast transients are considered, but it has also been shown that the accuracy of the scalar flux increases to second order with respect to the time integration[16].

III. MUSE-4 CONFIGURATION SC0 1108/ D-T

MUSE-4 SC0 1108 fuel cells configuration with a D-T external source ($3.3 \cdot 10^6$ neutron/pulse) located at the reactor center has been considered (Fig. 1).

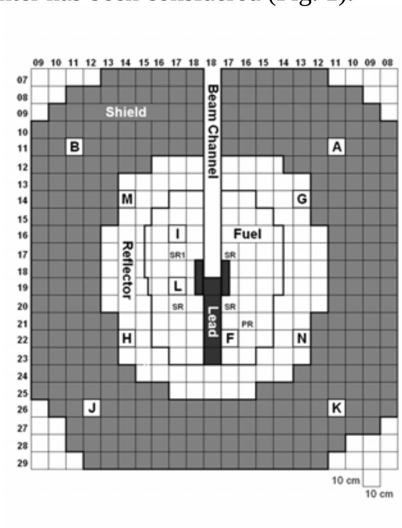

Fig. 1. XY mid-plane view of the MUSE-4 SC0 1108 fuel cells configuration.

Neutron pulses are provided by the GENEPI pulsed deuteron accelerator with frequencies from 50 Hz to 4.5 kHz and less than 1 µs.

Detectors mainly based on ^{235}U fission are located in different positions (Fig. 1) in the core (F, L, I), reflector (G, M, H, N) and shielding (A, B, K, J) regions for detecting the time-dependent responses.

The configuration with 3 Safety Rods (SR) up, SR1 down and Pilot Rod (PR) down is characterized by a meaningful subcriticality level (about -12.5 $). A large amount of experimental results at such subcritical level[11] are available with statistics of the time-dependent results clearly better than those obtained by using a D-D external source.

Moreover in a previous campaign performed by the MASURCA team, the MSM reactivity level was measured in a SC0 1086 fuel cells configuration (very similar to the configuration considered in this paper) with a D-D external source[11]. The MSM experimental results with 3 SR up, SR1 down and PR down and with only PR down were, respectively, -12.53 $ and -1.74 $ (β_{eff}=335 pcm). Since the difference of 0.2 $ between the two configurations with only PR down (MSM experimental result with D-T configuration was -1.95 $), the experimental MSM reactivity for the SC0 1086 fuel cells configuration (-12.53 $, about -4200 pcm) have been considered as reference reactivity for the MUSE-4 SC0 1108 fuel cells configuration.

IV. RESULTS

^{235}U responses to the neutron pulse in different positions in the MUSE-4 SC0 1108 configuration (Fig. 1) to an external source pulse of $3.3{\cdot}10^6$ neutrons/pulse of a duration of 0.5 μs have been simulated by means of the KIN3D module. In the KIN3D calculations the direct and adjoint flux at the beginning of transient come from a steady state VARIANT/TGV calculation.

In this section the results of the direct spatial calculations are shown and discussed. After defining the input data for the module, the effect of the new implementation are shown. Finally the calculated results will be compared with MCNP[17,18] and experimental results[19].

IV.A Definition of the input data

A 33 energy group cross sections calculation has been carried out by means of the ECCO ERANOS cell code[20] by a fine energy group structure collapsing in conjunction with the JEF2.2 nuclear data library[21].

In order to reduce the CPU time in the KIN3D calculations, a 19 energy group structure has been identified having similar reactivity and time-dependent behaviour of the 33 energy groups one. Table I shows that the reactivities calculated in the steady state by means of the transport VARIANT/TGV with the two energy structure are very close, the difference being only about 40 pcm.

TABLE I. 33 and 19 energy groups k_{eff} from transport TGV/VARIANT calculations

Number of groups	k_{eff}	Reactivity (pcm)
33	0.96093	-4066
19	0.96070	-4090

In order to perform the time-dependent calculation the 33 and 19 energy group cross sections have been modified by normalizing the fission source such that the k_{eff} from TGV/VARIANT calculations will be equal to the reference one (k_{eff}=0.95970, ρ=-4200 pcm). Delayed neutron data and the velocities in each energy groups have to be provided by the user.

For yields and delayed neutron spectra data 6 families of delayed neutrons for have been evaluated by using the recommended data[22]. For our evaluations β_{eff}=335 pcm has been set, according to the experiments[11,19].

The mean neutron generation time can be set in the KIN3D module by tuning the input neutron velocities.

Neutron velocities are evaluated by ERANOS system on the basis of the energy limits in each energy group and have been considered equal in each region of the system.

The mean neutron generation time calculated by KIN3D at 33 group velocities has been adopted (Λ=5.1188E-7 sec).

Then 33 and 19 direct spatial calculations with diffusion approximation have been performed. ^{235}U responses are compared in Fig. 2. Results show a very good agreement (maximum difference of few percent). As a result, the 19 energy group structure have been used for our investigations.

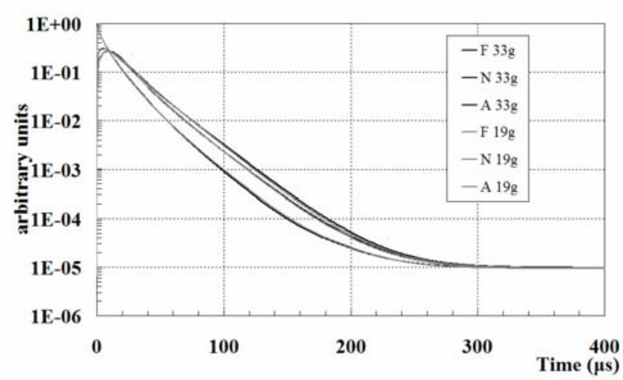

Fig. 2. ^{235}U responses in the positions F, N, A. Comparison between 33 and 19 groups diffusion KIN3D results with direct option.

IV.B Effect of the new implementations

The effect of the new implementations has been initially studied in a 2D MUSE-4 SC0 1108 model (XY mid-plane assessment). The reference reactivity has been obtained by means of the VARIANT/TGV steady-state calculations by normalizing the fission source term.

The transient induced by an external source pulse has been simulated by means of KIN3D spatial direct calculations.

First calculations have been performed in transport and diffusion approximation with the original KIN3D module in order to evaluate the effect of the different approximation in the MUSE-4 configuration under study (Fig. 3). Results are normalized with respect to the maximum fission rate in the detector F.

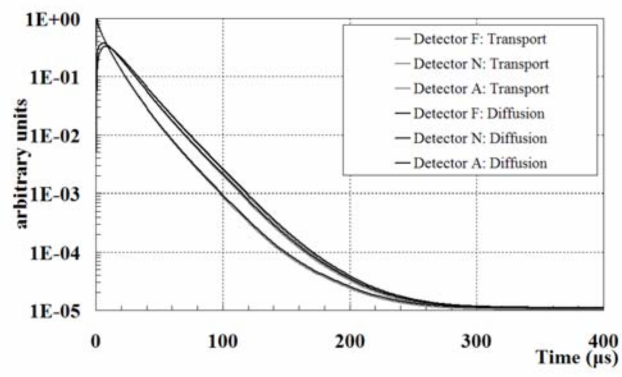

Fig. 3. KIN3D direct calculations in the XY MUSE-4 SC0 1108 fuel cells configuration in transport and diffusion approximation.

Results do not show noticeable differences in this system (at maximum less then 1%). Then transport results have been compared with the corresponding ones coming from the application of the new implementations (Fig. 4). Results are normalized with respect to the maximum fission rate in the detector F.

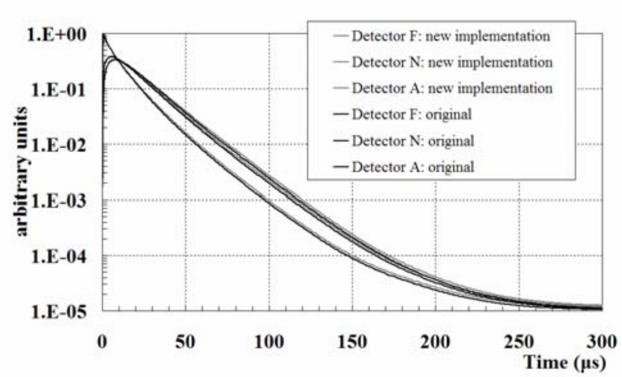

Fig. 4. KIN3D direct calculations in transport approximation with and without the new implementations.

Results show that higher fission rates are obtained if the new implementation is applied. Responses begin to differ after about 50 µs after the pulse. The discrepancies increase up to about 10 % about 100 µs after the pulse (Fig. 5).

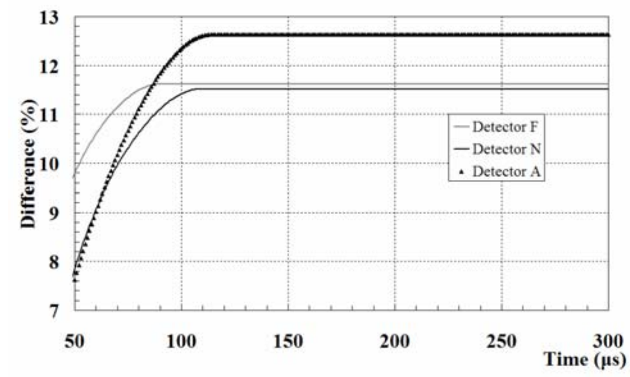

Fig. 5. Percentage difference between the KIN3D direct transport results with and without the new implementation.

The new implementations allow describing in a more precise manner the system behavior during the transient. On the other hand it requires very fine criteria on the convergence and then a little bit more CPU time with respect to the original model.

IV.C. Comparison with the experimental results

KIN3D spatial direct simulations have been performed with 19 energy groups in the MUSE-4 SC0 1108 fuel cells configuration, by extending the results obtained for the 2D MUSE-4 configuration model to the 3D one. Transport approximation and the new implementations have been carried out.

Results have been compared both with the MCNP ones[19] using the ENDF/B-VI library and with the results coming from the application of the Pulsed Neutron Source experiments[11,19].

^{235}U fission rate responses to the external neutron pulse ($3.3 \cdot 10^6$ neutrons/pulse for 0.5 µs) have been evaluated.

Time-dependent KIN3D results with and without the new implementation are compared with the experimental results in Fig. 6.

Results shown in the following are normalized with respect to the maximum fission rate in each detector positions.

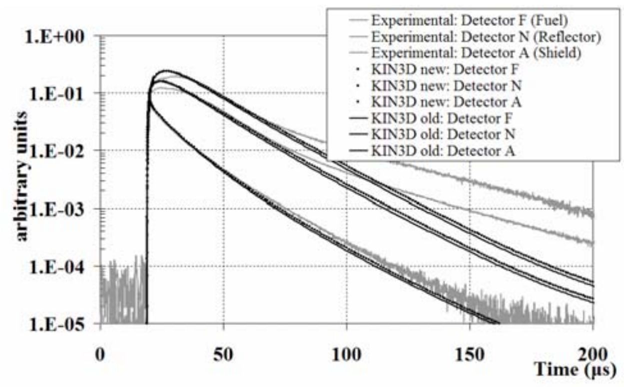

Fig. 6. Comparison among experimental and KIN3D results with and without the new implementations.

Results with the new implementation carried on show higher reaction rates with respect to the original model.

KIN3D results have been compared afterwards with MCNP and experimental results (Fig. 7).

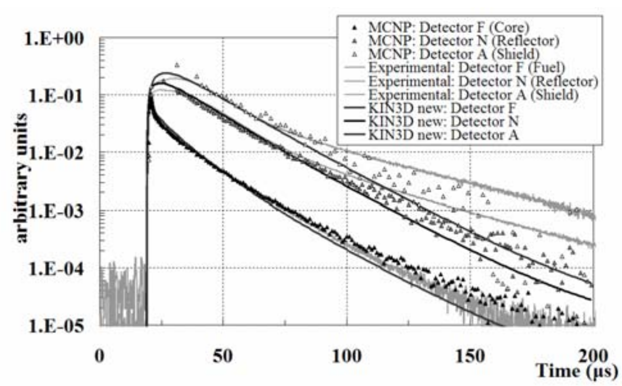

Fig. 7. Comparison among experimental, KIN3D and MCNP detector responses.

KIN3D results show in general a good agreement with MCNP ones. In particular a good agreement with both the experimental and MCNP results can be observed for a short time period in the first part of the responses (up to about 70 μs after the pulse) especially in the reflector and in the shielding regions. The same can be observed in the fuel detector response.

KIN3D and MCNP calculations results seem to provide a coherent picture where PNS α-method could be applied, i.e. far from the source[18].

Experimental results show different 1/τ slopes in the core, in the reflector and in the shielding regions. The presence of different slopes has been discussed in several papers in the frame of MUSE-4 analyses[18,23].

The double exponential behavior shown by experimental results in the reflector and shielding regions is not reproduced by KIN3D calculations.

The origin of this experimental behavior is under investigation.

V. CONCLUSIONS

In order to design and to perform safety studies of the Accelerator Driven Systems the possibility and capability to perform time-dependent evaluations by means of simulation tools represent a very important issue.

With this aim the KIN3D module implemented in the VARIANT/TGV code represents a very powerful and flexible tool. The implicit method on which the module is based allows obtaining fast information concerning the problem under study. Moreover the possibility to use several different kinetics methods allows performing different kind of investigations.

In this paper only the direct method has been considered. Moreover the new implementations recently developed provided the feature to take into account also the odd-parity derivative in the time-dependent calculations. This improvement represents a rigorous approach with respect to the previous KIN3D version. On the other hand the new option is more expensive with respect to the original one in term of CPU time.

Concerning this point new improvements are planned in the future.

The new option has been applied in order to simulate the detector responses to an external neutron pulse in a MUSE-4 experimental configuration at a meaningful sub-criticality level.

Results showed that the KIN3D module is capable to predict the time-dependent behavior in the MUSE core region for a short time period in the first parte of the detector response (up to about 70 μs after the pulse). Moreover a good agreement with MCNP results has been observed in the same time interval. On the other hand the presence of a second exponential behavior in the shielding and in the reflector zones has not been predicted.

Concerning the KIN3D module, because the kinetics options are mainly based on the extensions of the schemes used for critical system analyses, we plan to verify the several kinetics options available in the module and the new implementations in other ADS transient analyses.

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