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ANALYSIS OF THE VVER-440 AER2 ROD EJECTION BENCHMARK BY THE SKETCH-N CODE

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ABSTRACT

The neutron kinetics code SKETCH-N has been recently extended to treat hexagonal geometry using a polynomial nodal method based on the conformal mapping of a hexagon into a rectangle. Basic features of the code are outlined. Results of the steady-state benchmark calculations demonstrate excellent accuracy of the nodal method. To test a neutron kinetics module for VVER applications, the second AER rod ejection benchmark is computed and the results are compared with the results of the production VVER codes: BIPR8, DYN3D, HEXTRAN and KIKO3D. The steady-state results show that the SKETCH-N code gives an ejected control rod worth close to that of BIPR8 and HEXTRAN. The assembly power distribution is compared with the DYN3D results. Maximum discrepancies of about 5% are found in the power of peripheral assemblies and assemblies with partially inserted control rods. Reasons of these discrepancies are discussed. The transient results: time and value of the power peak and maximum fuel temperature are also close to that of BIPR8 and HEXTRAN. The difference in the maximum fuel temperature between the SKETCH-N and HEXTRAN results is about 100 °C. These differences are mostly due to the differences in the ejected control rod worth due to the different accuracy of applied nodal methods. A numerical experiment confirming this assumption is given. If the ejected control rod worth of the SKETCH-N code is adjusted to the value computed by DYN3D, the transient results of the two codes are very close.

I DESCRIPTION OF THE SKETCH-N CODE

The nodal neutron diffusion code SKETCH-N has been developed for the solution of the steady-state and transient problems in Cartesian geometry [1, 2]. The basic features of the code are summarized as follows:

- diffusion approximation;
- 3D, 2D and 1D reactor models in Cartesian geometry with arbitrary mesh size in any direction;
- arbitrary number of neutron energy groups and delayed neutron precursors;
- transverse-integrated polynomial, semi-analytic and analytic nodal methods with quadratic leakage approximation for spatial discretisation;
- nonlinear iteration procedure for a solution of the nodal equations;
- fully-implicit scheme with analytic integration of the delayed neutron precursors for time discretisation;
- adaptive time step control based on the step doubling technique;
- inverse iterations with Wieland shift accelerated by Chebyshev polynomials for steady-state eigenvalue problems;
- Krylov subspace iterative methods and adaptive Chebyshev acceleration procedure can be used as linear solvers for neutron kinetics problems;
- block symmetric Gauss-Seidel method is applied as a preconditioner;
- internal thermal-hydraulics model for PWR operational transients with single-phase coolant flow;
- interface module based on the message passing library PVM for the coupling with external thermal-hydraulics codes, such as TRAC.

An extensive set of the steady-state and neutron kinetics LWR benchmarks has been calculated to verify the SKETCH-N code [1, 3]. The results show that the SKETCH-N code has acceptable accuracy and efficiency to be used in the LWR safety analysis and design. The code has been coupled with the thermal-hydraulics transient analysis codes J-TRAC (TRAC-PF1) and TRAC-BF1. The assessment of the coupled code systems have been done by NEACRP LWR 3D core transient benchmarks [4, 5]. This version of the code including documentation [2] is freely available from OECD NEA Databank.

The SKETCH-N code has been recently extended to treat the hexagonal geometry [6]. A polynomial nodal method implemented into the code is based on the conformal mapping of a hexagon into a rectangle. The resulting equations are solved using a fourth-order expansion of the transverse-integrated neutron flux into orthogonal polynomials. The transverse leakage is represented using constant neutron currents at the faces of the internal reactor nodes and a linear approximation of the current at the faces of the nodes at the reactor boundary. The results of the steady-state benchmarks have demonstrated excellent accuracy of the method, for all computed problems errors in eigenvalue do not exceed 25 pcm and errors in assembly power are below 2.5 % [6].

II PROBLEM DESCRIPTION

The second Atomic Energy Research (AER) transient benchmark [7, 8] has been developed to test the neutron kinetics capabilities of the VVER-440 3D dynamics codes. The reactor core model is close to the standard configuration of the VVER-440 reactor at the beginner of cycle 1. Four material compositions are defined to simulate different fuel assemblies. The axial and radial reflector is described by the boundary conditions. The transient is initiated by an ejection of the peripheral control rod in 0.16 s at hot zero power of 1.375 kW. The power surge is terminated by the Doppler feedback, which is modelled using a linear dependence of the thermal fission cross section on square root of fuel temperature. An adiabatic model is applied to compute the fuel temperature, thus no heat is removed from the fuel. The modelled rod ejection is highly conservative due to the following reasons:

- total yield of the delayed neutron precursors is reduced to $\beta = 0.005$, which results in the higher control rod worth with relation to β;
- macro cross sections of the control rod absorber are changed to give the reactivity of the ejected control rod of about 2β.

Two seconds of the transient are analyzed.

The benchmark report [8] provides results of four production VVER codes: BIPR8 [9], DYN3D [10], HEXTRAN [11] and KIKO3D [12]. The results contains the reactor eigenvalue, the control rod worth and the power distribution of the initial steady-state condition and the transient data: reactor power, integral reactor power, reactivity, nodal power peaking factor, maximum fuel temperature as data versus time and the power distribution at several time moments. No reference solution is available for this problem up to now, only a comparison with the given results can be done.

III STEADY-STATE RESULTS

A problem has been computed by the SKETCH-N code using a full core representation in radial plane and an axial mesh of 25 cm. A minor modification of the code have been done to simulate the moving delayed neutron precursors, which required due to specific configuration of the VVER-440 control rods containing moving fuel. The adiabatic model of the fuel temperature has been modelled setting to zero the gap heat conduction. Table 1 shows a comparison of the SKETCH-N results with the results of the other nodal codes for the steady-state eigenvalue and the control rod worth. The SKETCH-N code gives the highest value of the control rod worth, which is close to the results of BIPR8 and HEXTRAN. A comparison of the assembly-averaged power distribution with the DYN3D results is given in Fig. 1. The codes show relatively large differences in the power of the peripheral assemblies at the core boundary and in the power of the assemblies with partially inserted control rods. For all other assemblies the differences are below 2 %. The differences in the power of the peripheral assemblies are attributed to the different treatment of the radial leakage in the two codes. The DYN3D code uses constant neutron currents at the node faces, which is similar to the ”flat” leakage approximation of the SKETCH-N code. In the SKETCH-N code, the ”linear” leakage approximation is used for the nodes at the reactor boundary, assuming a linear shape of the neutron current at the node faces. To outline an effect of this approximation we performed a calculation with the ”flat” leakage approximation, where the neutron current is constant for the all node faces. The computed power distribution and a comparison with the DYN3D data is given in Fig. 2. The powers of peripheral nodes computed by two codes are very close in this case.

To show an effect of the axial mesh size the SKETCH-N calculation with the axial mesh size of 12.5 cm was performed. Fig. 3 shows a comparison of the SKETCH-N results with the axial mesh of 25 cm against the SKETCH-N results with the axial mesh of 12.5 cm. The difference in eigenvalue of the two results is 3 pcm. The differences of the power distribution in the assemblies with the control rods are 2-3 %, but the deviations of the SKETCH-N results with the fine axial mesh from the DYN3D results are larger than in the case of the coarse axial mesh. The power of the all other assemblies and the reactor eigenvalue are in a good agreement in the two calculations with the fine and coarse axial meshes, thus the coarse axial mesh of 25 cm was used in the all following calculations.

The radially-averaged axial power distributions of the two codes are very close, the differences are below 1.2 % not only for the steady-state conditions but also for the all time moments of the transient calculations (time = 0.16 s, time of the power peak, time = 2 s).

IV TRANSIENT RESULTS

Transient calculation by the SKETCH-N code were performed using an automatic time step control procedure based on the time step doubling technique. A selected time step size is shown in the Fig. 4. A number of time steps is 668 on the fine temporal mesh and 5 time steps are rejected. The calculation takes 5 minutes and 35 seconds on PC with 600 MHz Pentium III processor.

The highest control rod worth of the SKETCH-N code results in the highest power peak in a comparison with the other codes as shown in Fig. 5. Time of the power peak of the SKETCH-N code is close to that of HEXTRAN. Reactivity versus time is given in Fig. 6. The highest inserted reactivity in the SKETCH-N code also results in the highest integral power as shown in Fig. 7 and in the highest maximum fuel temperature given in Fig. 8. However, the differences in all the results are not very large, for example, the difference between the SKETCH-N and BIPR8 in the maximum fuel temperature is about 100 °C and it is smaller than the differences between the BIPR8 and DYN3D results.

The reactor power peaking factors at several time moments are compared at Table 2. A plot of the power peaking factors of the SKETCH-N and DYN3D codes is given in Fig. 9. The results of the all codes are in reasonable agreement. A short summary of the transient results is presented in Table 3.

In the benchmark report [8], the differences in the transient results of the codes has been attributed to the differences in the nodal solvers resulting in the different control rod worth. To check this assumption we performed the following numerical experiment. The initial position of the control rods has been changed in a such way, that the control rod worth computed by the SKETCH-N code is close to that of DYN3D. The selected control rod position is 58.5 cm from the core bottom, the resulting control rod worth is 0.9744 %, which is close to the value 0.9755 % of the DYN3D code. The power peaking factor of the initial steady-state condition computed by the SKETCH-N is 2.28 against 2.33 of DYN3D. The reactor power versus time of the SKETCH-N, DYN3D and KIKO3D codes are shown in Fig. 10. In this case, the power peak and the time of the power peak computed by SKETCH-N, DYN3D and KIKO3D are close. The maximum fuel temperatures versus time are compared in Fig. 11. These values are also in a good agreement, the difference in the SKETCH-N and DYN3D values at the time 2 s is 40 °C. The presented results confirm an assumption that the differences in the transient results are mostly due to the differences in the accuracy of the nodal methods resulting in the different control rod worth of the ejected rod.

A key safety parameter of the rod ejection transient is an enthalpy injected into the fuel. The reactor-averaged and maximum values computed by the SKETCH-N code are shown in Fig. 12, where a variant with the control rod worth adjusted to the DYN3D value is also shown. The base SKETCH-N calculation results in 180 cal/g of the maximum fuel enthalpy at the time of 2 s, while for the case when the ejected control rod worth is adjusted to the value of DYN3D, the maximum fuel enthalpy is equal to 165 cal/g.

V CONCLUSIONS AND FUTURE PLANS

The second AER VVER-440 dynamic benchmark has been analyzed by the SKETCH-N code. The results of the calculations are compared with the results of the VVER production codes: BIPR8, DYN3D, HEXTRAN and KIKO3D. In the steady-state initial conditions, the reactor eigenvalue, the control rod worth and the power distribution are compared. The differences in the assembly power computed by the SKETCH-N and DYN3D are below 2 % in all the assemblies, except peripheral assemblies at the core boundary and assemblies with control rods. In these assemblies, the differences are about 5 %. The SKETCH-N code gives the highest value of the ejected control rod worth in a comparison with the other codes. As a result, the computed power peak and the maximum fuel temperature are also higher. However, the differences are not large and comparable with the deviations of the all codes. For example, the difference in the maximum fuel temperature at the time of 2 s computed by the SKETCH-N and HEXTRAN is about 100 °C, while the difference between the results of HEXTRAN and DYN3D is about 150 °C. Performed numerical experiment has shown that the differences in the transient results are mostly due to different accuracy of the nodal solvers resulting in the different control rod worth of the ejected rod. An absence of the reference solution even for the steady-state initial condition prevent us from any conclusions on accuracy of the nodal methods used in the codes. The preliminary results of the application of the finite-difference code MAG [13] and finite element code CRONOS [14] to generate the reference solution of this problem are known. However, the both codes require very fine spatial mesh and respectively considerable amount of computer and human resources to complete the analysis. Our future plans include an implementation of the nodal method for triangular geometry into the SKETCH-N code. Thus, a code user will be able to refine an initial hexagonal spatial mesh and to generate a reference solution by the same nodal code.

The results of the transient calculations show that the maximum enthalpy injected into the fuel is sensitive to the value of the reactivity of the ejected control rod. For example, less than 5 % difference in the control rod worth in the two SKETCH-N calculations results in about 10 % difference in the maximum enthalpy injected into the fuel.

The described neutron kinetics model has been implemented into an upgrade of software of the engineering simulator of a VVER-1000 reactor and validation efforts are on the way. Burn-up calculation of 13 fuel cycles of the Unit 2 and 15 fuel cycles of the Unit 1 of Kalinin NPP has already shown a good agreement of the computed results with the measured critical boron concentration and the power distribution of the BIPR7 code. Calculations of the third AER dynamic benchmark for VVER-440 reactor and operational transients of VVER-1000 reactor are planned.

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Table 1: Static eigenvalue in the initial state ($k_{eff,0}$), in the state with ejected rod ($k_{eff,1}$) and static worth of the ejected control rod ($\Delta\rho = 1 - k_{eff,0}/k_{eff,1}$)

Code	$k_{eff,0}$	$k_{eff,1}$	rod worth $\Delta\rho$, (%)	$\frac{\Delta\rho_{\mathrm{code}}}{\Delta\rho_{\mathrm{DYN3D}}} - 1$, (%)
BIPR8	0.99844	1.00867	1.0143	4.
DYN3D	0.99994	1.00979	0.9755	-
HEXTRAN	0.99902	1.00918	1.0069	3.2
KIKO3D	0.99999	1.00993	0.9834	0.8
SKETCH-N	0.99841	1.00872	1.0223	4.8

Table 2: Power peaking factors at the several time moments

Time (s)	0.0	0.16	time of P_{max}	0.4	2.0
BIPR8	2.30	7.76	6.13	5.65	5.29
DYN3D	2.33	7.69	6.53	5.67	5.30
HEXTRAN	2.33	7.77	6.52	5.66	5.32
KIKO3D	2.34	7.78	6.41	5.68	5.30
SKETCH-N	2.31	7.78	6.54	5.61	5.27

Table 3: A summary of the transient results

Parameter	BIPR8	DYN3D	HEXTRAN	KIKO3D	SKETCH
Relative reactor power peak	70.9	63.9	72.4	62.6	78.1
Time of the power peak, (s)	0.24	0.26	0.25	0.26	0.26
Max dynamic reactivity, ($)	-	1.84	-	1.96	2.03
Rel. reactor power at time 2 s	0.50	0.48	0.49	0.48	0.49
Integral power at time 2 s, (MWs)	5944	5554	5912	5563	6185
Max fuel temp. at time 2 s, (°C)	2696	2538	2695	2540	2787

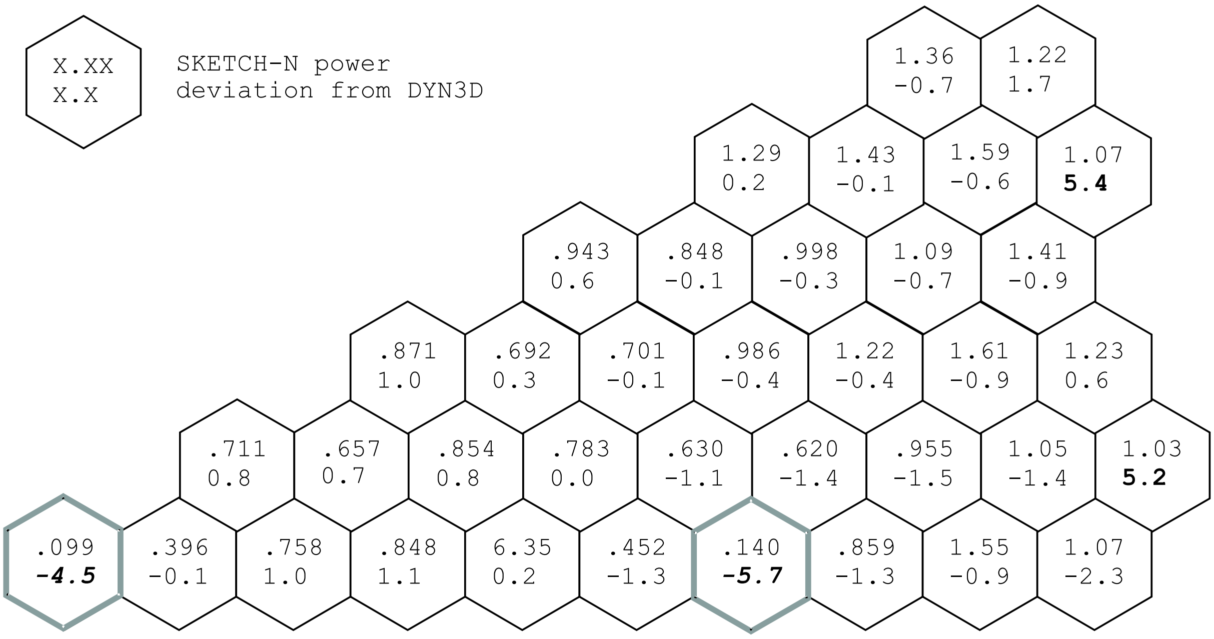

Figure 1: Assembly power of the SKETCH-N code and the deviations from the DYN3D results

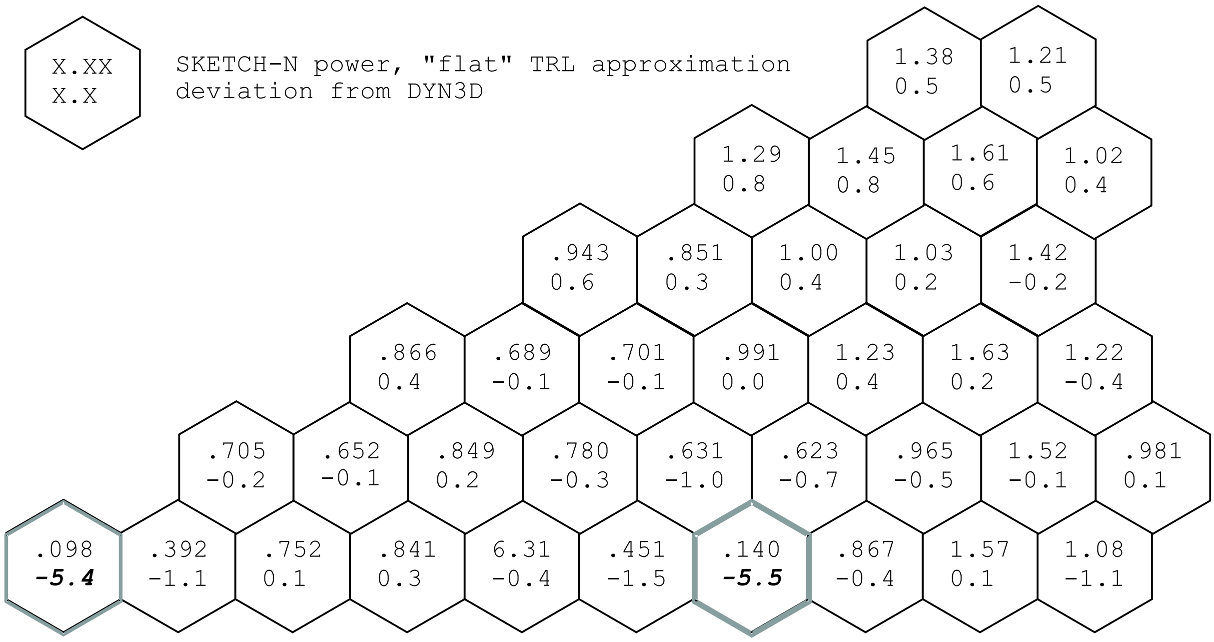

Figure 2: Assembly power of the SKETCH-N code using "flat" transverse leakage approximation and the deviations from the DYN3D results

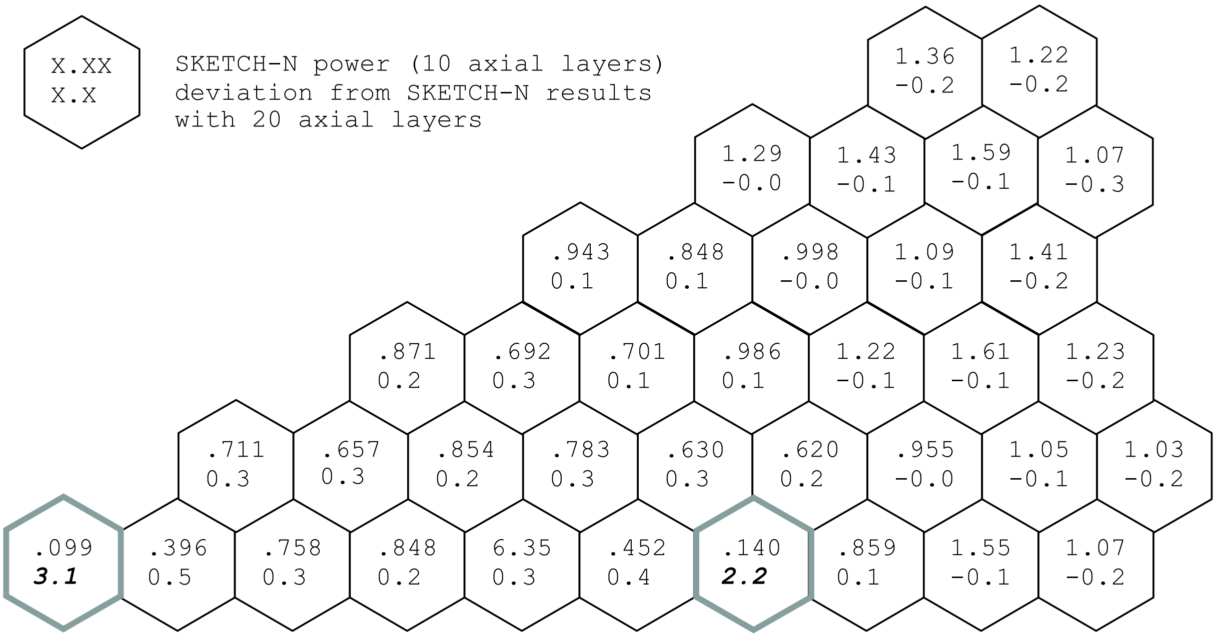

Figure 3: Assembly power of the SKETCH-N code (axial mesh size 25 cm) and the deviations from the SKETCH-N results with the axial mesh size of 12.5 cm

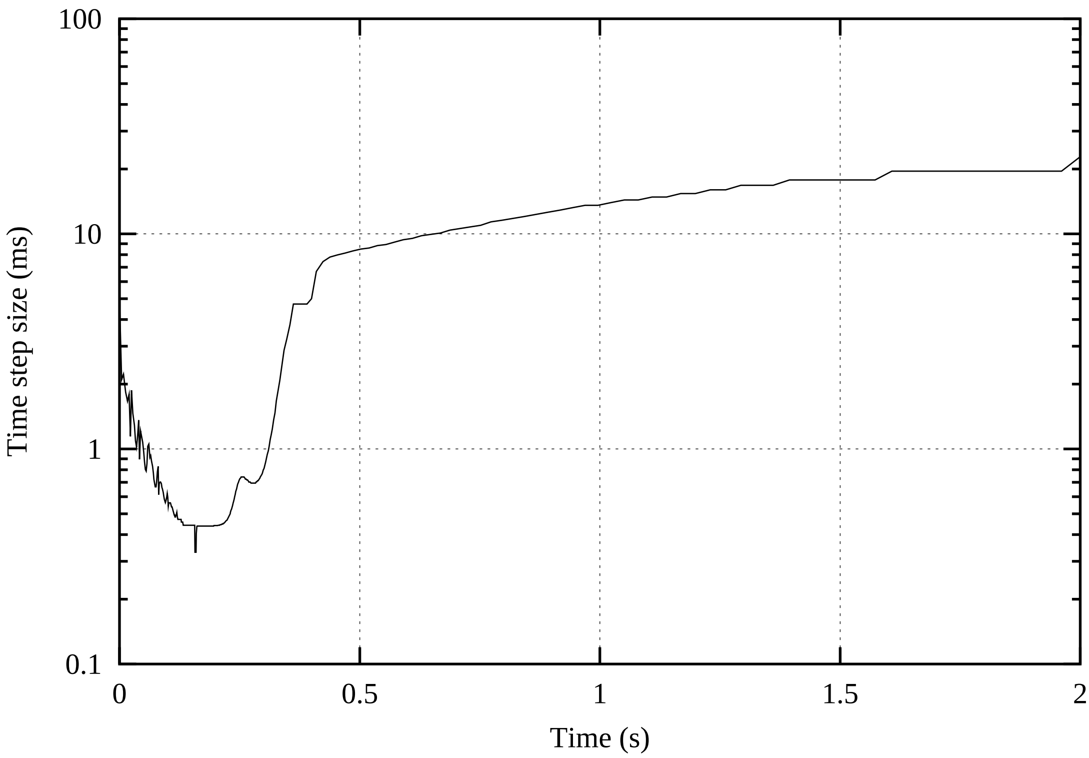

Figure 4: Time step size of the SKETCH-N code

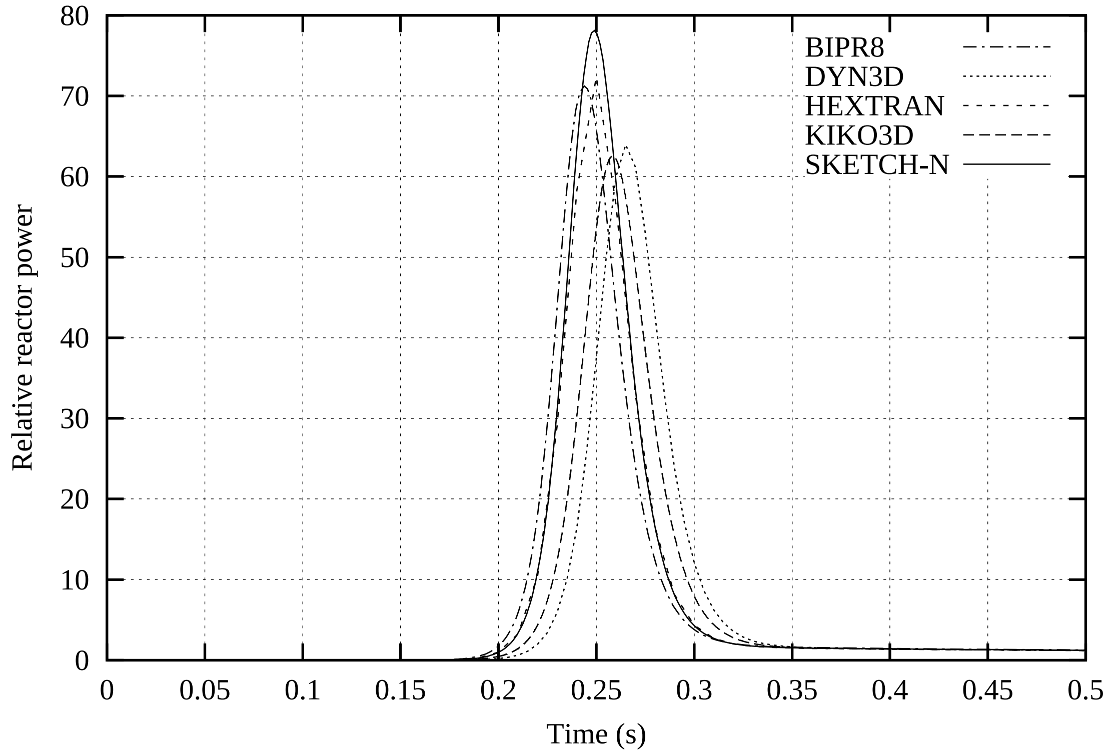

Figure 5: Reactor power vs. time

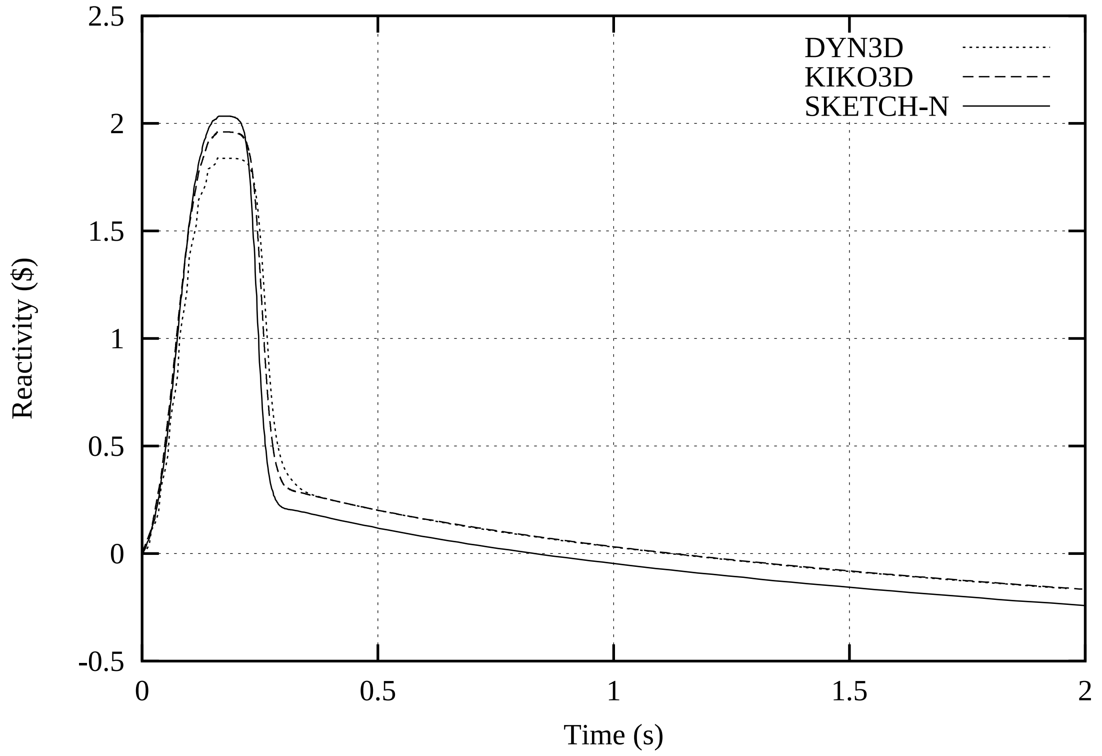

Figure 6: Reactivity vs. time

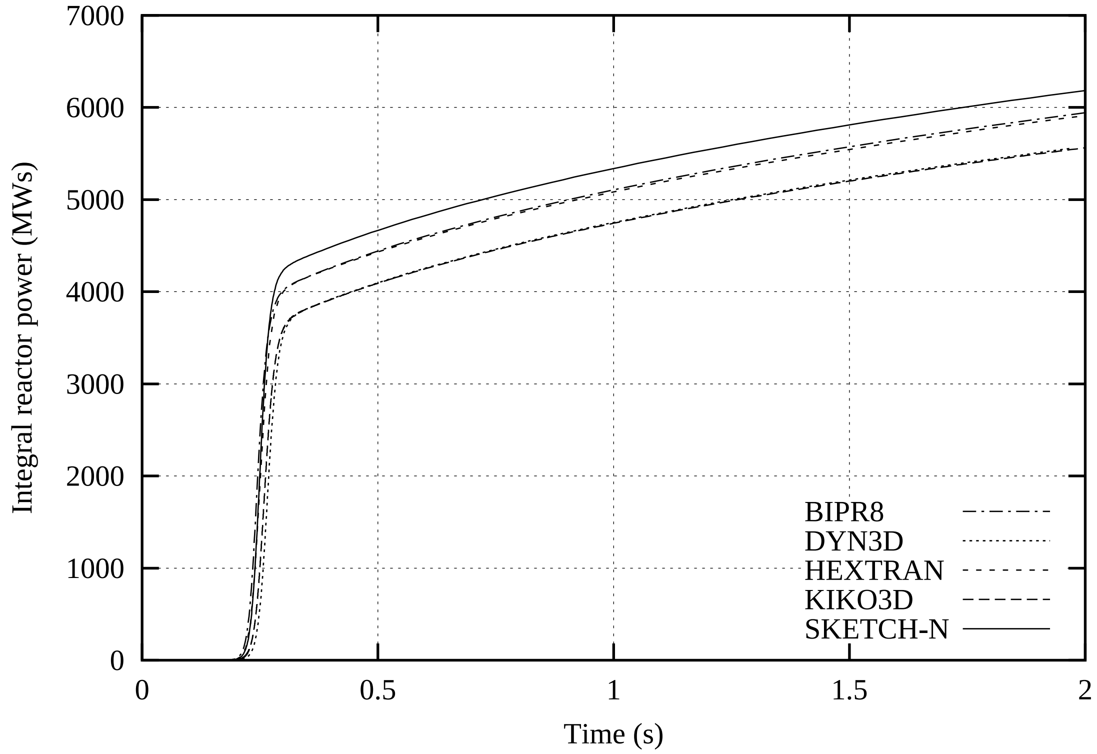

Figure 7: Integral reactor power vs. time

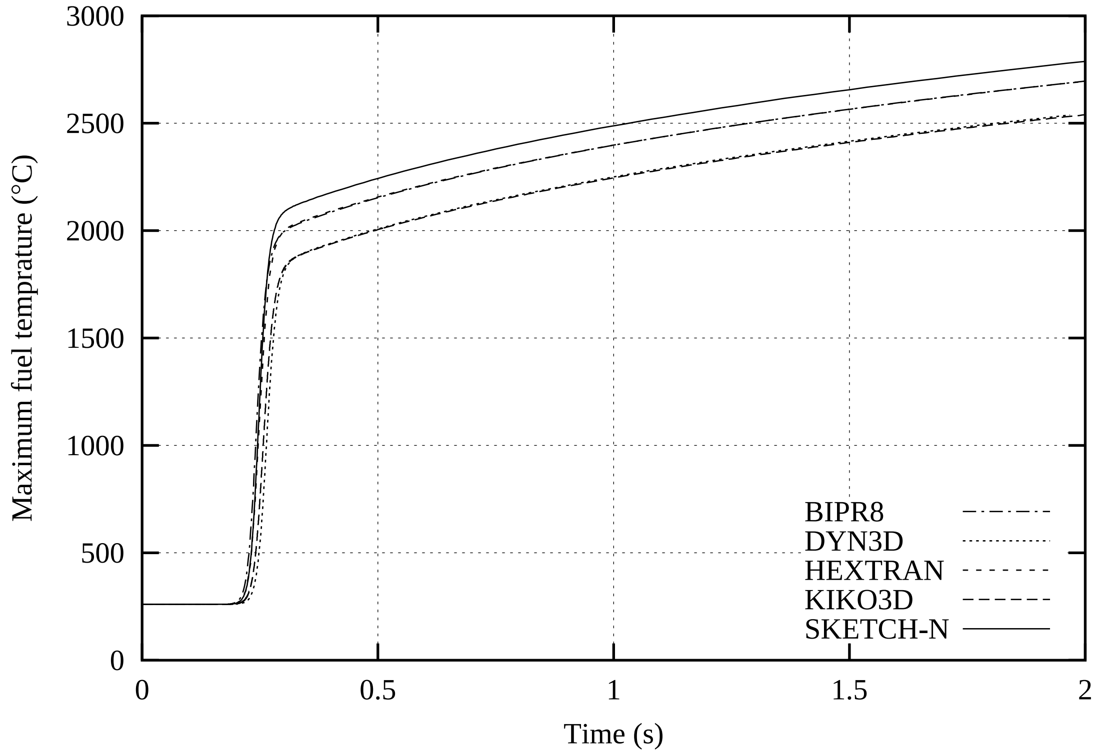

Figure 8: Maximum fuel temperature vs. time

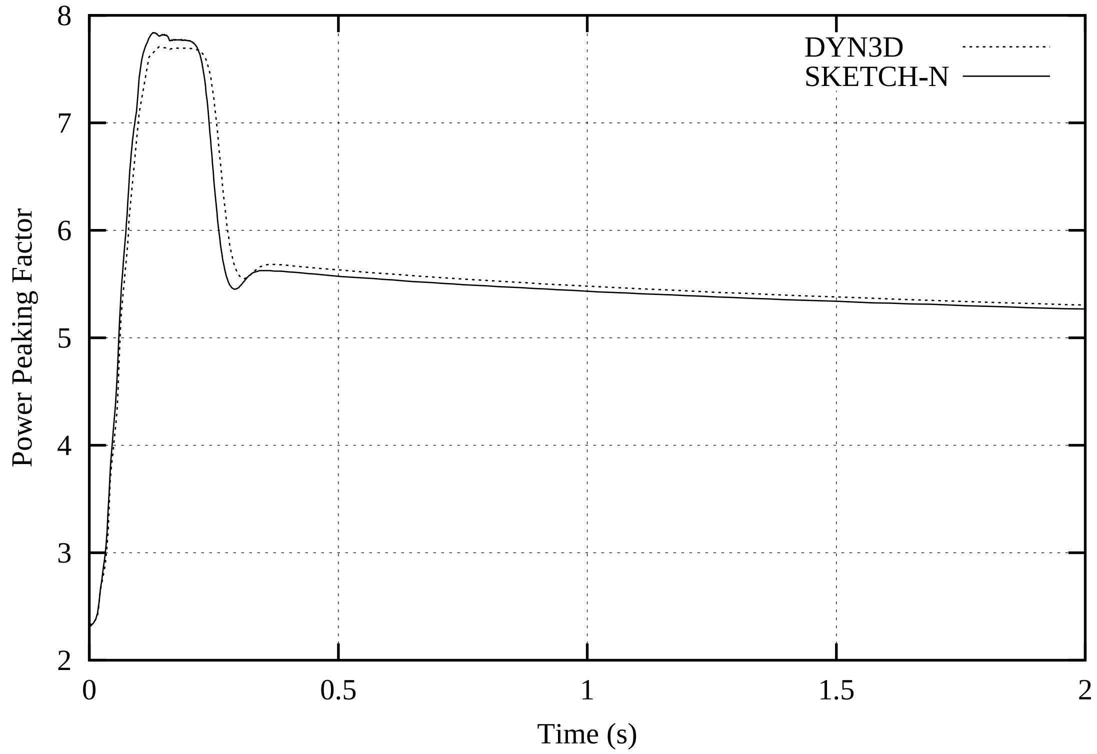

Figure 9: Power peaking factor vs. time

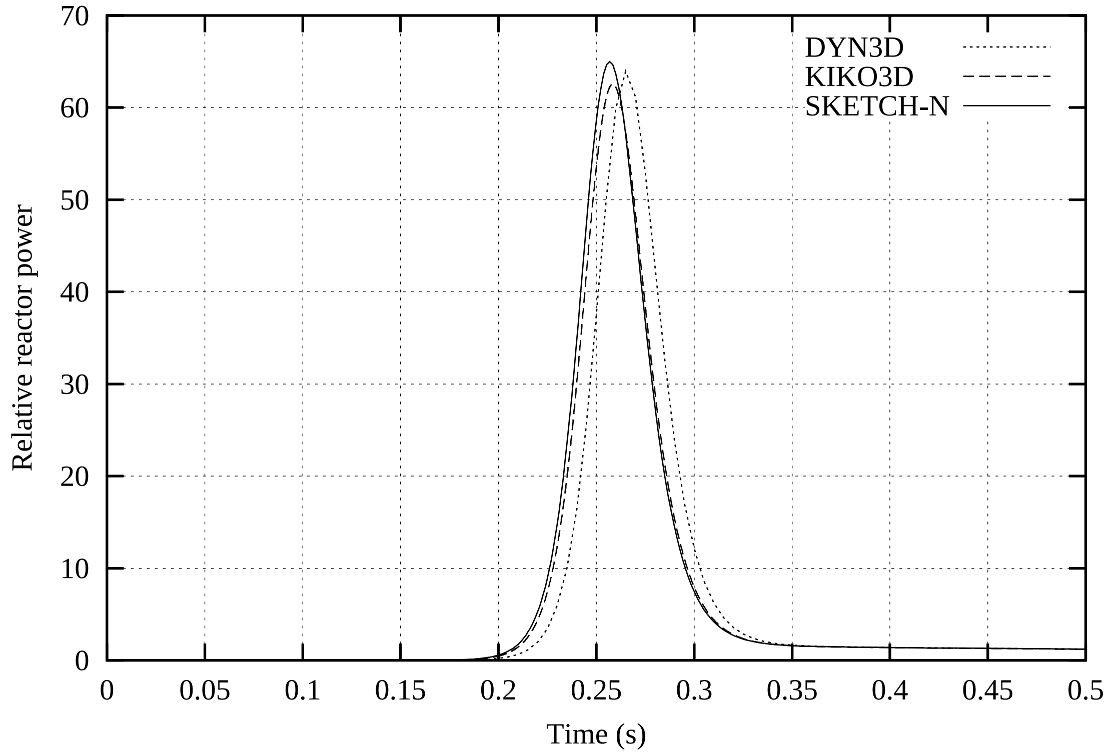

Figure 10: Reactor power vs. time, $\Delta\rho_{\mathrm{SKETCH-N}} \approx \Delta\rho_{\mathrm{DYN3D}}$

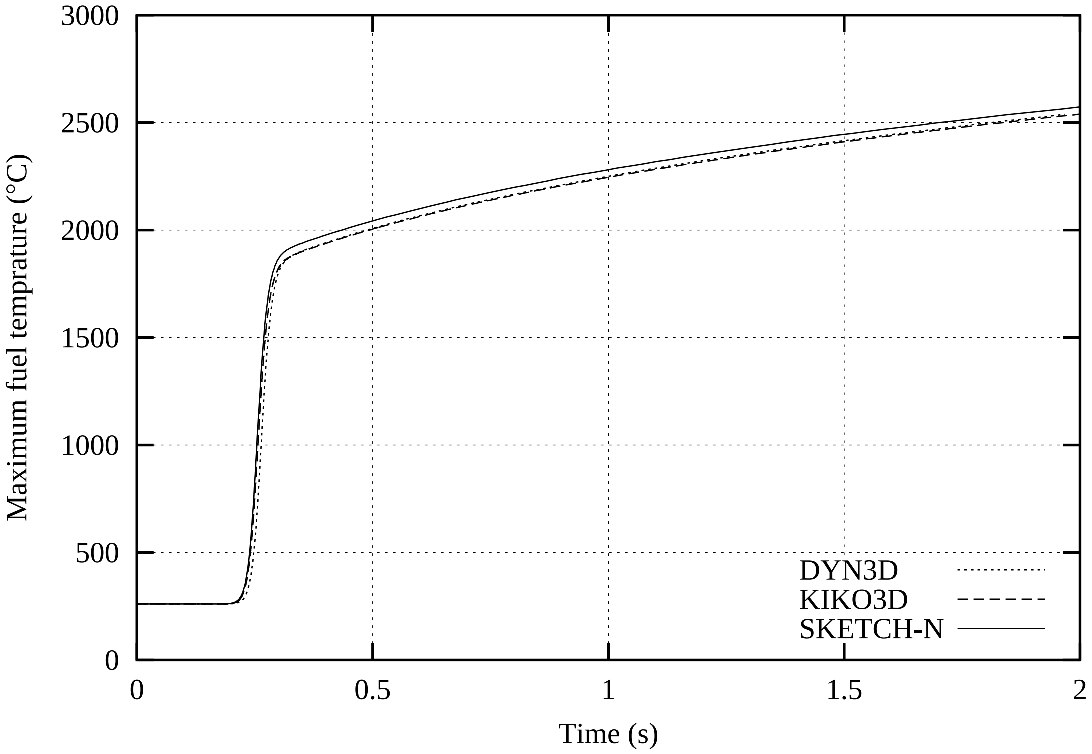

Figure 11: Maximum fuel temperature vs. time $\Delta\rho_{\mathrm{SKETCH-N}} \approx \Delta\rho_{\mathrm{DYN3D}}$

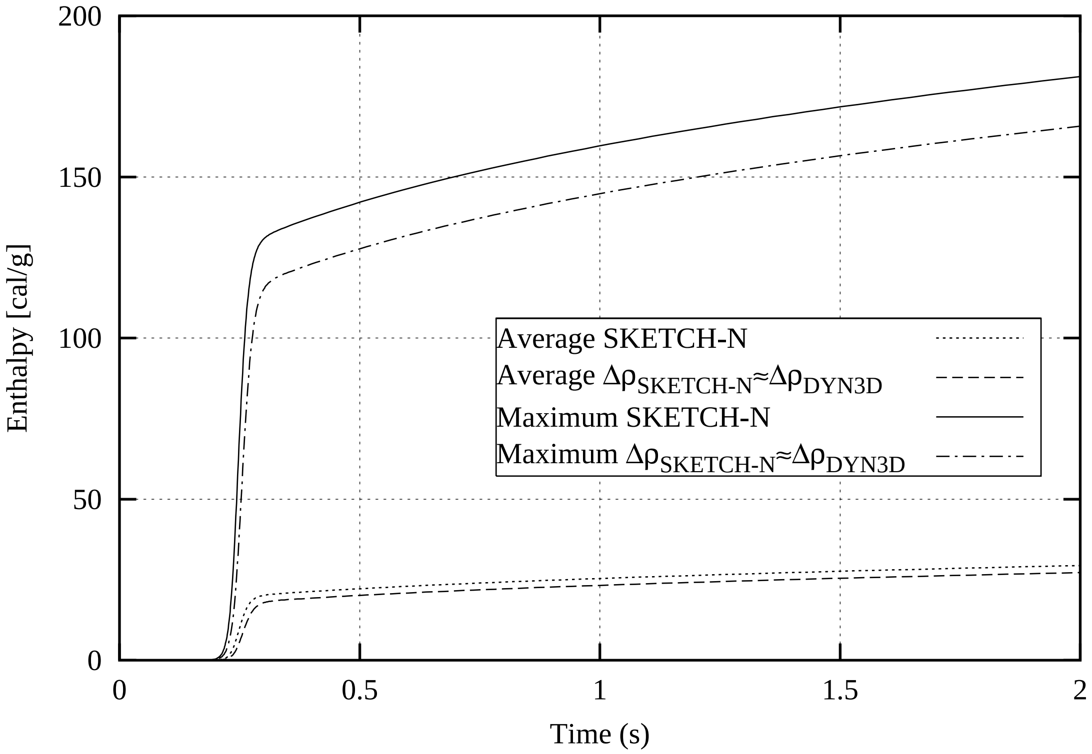

Figure 12: Reactor-averaged and maximum enthalpy injected into the fuel