DEVELOPMENT AND APPLICATION OF A FAST RUNNING MODEL FOR THE DESCRIPTION OF COOLANT MIXING INSIDE THE PRESSURE VESSEL OF PRESSURIZED WATER REACTORS

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ABSTRACT

An efficient semi-analytical model for the description of the coolant mixing during stationary and transient processes inside the reactor pressure vessel (RPV) of pressurised water reactors (PWR) has been developed. This model is based on the technique of linear superposition of response functions on Dirac impulse shaped perturbation functions. In the model, the RPV is represented formally by a group of transfer systems (for each combination of inlet nozzle position and fuel element position one) with one input and one output each. An experimental way of obtaining the transfer properties is shown on the example of the German PWR KONVOI. The validation of the model against experimental data from the 1:5 scaled coolant mixing test facility ROCOM is presented.

The semi-analytical coolant mixing model has been used in combination with the 3D reactor dynamics code DYN3D for the analysis of a hypothetical boron dilution event after start-up of the first main coolant pump in a generic four-loop PWR. The model provides realistic time-dependent boron concentration fields at the core inlet. By varying the initial slug volume it was found, that for the given core configuration slugs of less than 20 m^3 do not lead to a re-criticality of the shut-off reactor. Calculations with the bounding slug volume of 36 m^3 show, that the corresponding reactivity insertion does not lead to safety relevant consequences.

1. INTRODUCTION

In hypothetical accident scenarios connected with asymmetric perturbations in the primary circuit of a nuclear power plant (NPP) like overcooling of one loop due to a steam line break or local boron dilution events, 3D effects have to be considered. Usually, the computational analysis of such scenarios is performed within three off-line coupled steps, each of them carried out independently. First of all, a thermohydraulic analysis of the transient is carried out by means of an advanced thermohydraulic system code. From that calculation, boundary conditions are derived for an analysis

of the 3D mixing processes inside the reactor pressure vessel (RPV) using a computational fluid dynamics (CFD) code. The results of this calculation (temperature or boron concentration distribution at the core inlet) are used in a 3D neutron kinetics analysis of the reactor core behaviour.

Recently, 3D neutron kinetics core models have been coupled with advanced thermohydraulic system codes. To be able to turn from the above described three step off-line approach to a fully coupled analysis of the whole process, the implementation of a model is necessary, which links the thermohydraulics of the system code with the thermohydraulics of the core model, simulating the mixing processes in the RPV in a realistic way. Due to the long computation times the direct integration of CFD-modules into reactor safety analytical tools is not practical at present. For that reason, a fast running semi-analytical model for the simplified description of the coolant mixing inside the RPV has been developed. In this paper, the development, validation and the application of that model is presented.

2. DEVELOPMENT OF THE FAST RUNNING COOLANT MIXING MODEL

The part of the RPV from the inlet nozzles through the downcomer and the lower plenum up to the core inlet is considered as a highly non-linear system with multiple inputs and outputs. The inputs are time-dependent functions of the coolant velocity, enthalpy and boron concentration at each of the inlet nozzles. In general, these functions can be independent at the different inlet nozzles. The output signals are the same quantities at each fuel element position.

The RPV can be treated formally as a set of transfer systems (one for each combination of inlet nozzle and fuel element position) with one input and one output signal (boron concentration or coolant temperature) each. These systems have different transfer properties which are determined by the flow field and turbulent mixing being strongly dependent on geometrical details of the flow domain. That means, that the transfer properties are different for various reactor types and different hydraulic processes.

In the current paper, the derivation of the model for the start-up of the first main coolant pump (MCP) after flow stagnation is described. For that special case the number of inputs to the system reduces to one.

The disturbance of such a system by a Dirac impulse is an appropriate method to explore these unknown transfer properties. A disturbance of the system by a function of any form (for instance: a slug of coolant with lower boron concentration) can be represented by superimposing a sequence of

such Dirac impulses. The system response at each fuel element position is obtained by superimposing the responses to the different Dirac impulses with the same coefficients used for representing the input. That approach presumes, that the global non-linearity of the transfer from the input to the output can sufficiently be treated by superimposing of mainly linear responses to Dirac impulses of the concentration at different times of the instationary process (pump ramp).

The transfer properties can be determined experimentally or by CFD. In this work, an experimental approach has been applied. For that purpose, experiments at the ROCOM (Rossendorf Coolant Mixing Model) test facility [1] were carried out.

This experimental facility was designed and built especially for the investigation of coolant mixing phenomena in the downcomer and the lower plenum of the German 1300 MW KONVOI reactor. The facility is a 1:5 linearly scaled model (Fig. 1). The model represents the original reactor with all constructional details in the given scale, beginning from the cold leg at 1 m (5 m in the original) before the entry into the RPV and including the inlet nozzle, the downcomer, the lower plenum, the perforated drum up to the core support plate including the corresponding penetrations. The facility is operated with demineralized water at room temperature and is equipped with different wire-mesh sensors [2]. The working principle of these sensors is based on the measurement of the conductivity. Salt solution is used as a tracer changing the conductivity of the fluid. Water with different conductivity simulates the differences in the boron content or temperature. Particularly, the measurements of two of the four installed wire-mesh sensors are used for the determination of the transfer properties. The sensor located in the reactor inlet nozzle of one loop (Fig. 2, pos. 1) measures the input signal to the above introduced systems. The mixing device, located at the injection position, ensures that the injected water is equally distributed over the cross section. The other sensor provides the concentration at each fuel element inlet position at the lower core support plate (Fig. 2, pos. 4). For analytical presentations, dimensionless mixing scalars with a time resolution of 0.05 s are derived from the measuring data. These scalars are defined as follows:

$$\theta_i = \frac{\sigma_i - \sigma_0}{\sigma_P - \sigma_0} \tag{1}$$

where i is the current measurement position; σ_i the conductivity at that position, σ_0 the conductivity of the water before the experiment and σ_P the conductivity of the injected slug.

To get the pulse responses, experiments were performed injecting the tracer solution over a short time (nearly 0.1 s) into the loop with the starting pump. It has to be taken into account, that due to the considered pump start-up process the transfer behaviour changes in time. Therefore, the time position of the injection in the pump start-up ramp has been varied in the different experiments. The impulses

of three experimental series are shown on Fig. 3a, the responses to these impulses measured at a certain fuel element position are shown in Fig. 3b. As can be seen from Fig. 3a, the transfer behaviour of the above introduced systems were exposed to an input signal, nearly being a Dirac impulse.

For an adequate representation of a slug, the limited number of experimental impulses is not sufficient. Therefore, additional interpolated impulses were inserted between the experimental ones. The responses are then calculated by interpolation between the neighbouring experimental responses.

The time course $F(t)$ of the slug concentration to be modelled at the reactor inlet can be reconstructed from n impulse functions as follows:

$$F(t) = \sum_{j=1}^{n} a_j \cdot g_j(t) \tag{2}$$

where $g_j(t)$ is the time course of the j^{th} impulse, a_j is a coefficient, weighting the contribution of the j^{th} impulse to the requested slug. The number n depends on the volume of the slug to be modelled. The coefficients a_j are obtained as solution of a least squares deviation problem between measured and approximated slug. An example for the combination of experimental and interpolated impulses is shown in Fig. 4 together with a demonstration of the slug reconstruction.

Supposing, that the system response can be superimposed, the transient course of the mixing scalar at each fuel element position can be derived in a similar manner using the same coefficients a_j. The time course of the mixing scalar $H_k(t)$ for each k of the 193 fuel element positions can be calculated by:

$$H_k(t) = \sum_{j=1}^{n} a_j \cdot h_{kj}(t) \tag{3}$$

where $h_{kj}(t)$ is the time course of the j^{th} answer function at the corresponding fuel element position k.

The described superposition technique is the main part of a calculation program, called Semi-Analytical Perturbation Reconstruction (SAPR) model.

3. VERIFICATION OF THE FAST RUNNING COOLANT MIXING MODEL

Several hypothetical accident scenarios are discussed, where due to the start-up of the first MCP after flow stagnation, a slug of lower borated coolant could be driven into the RPV. A numerical analysis of such a hypothetical boron dilution event in a German PWR was performed by Reinders [3]. From

that work, the following boundary conditions were derived for generic experiments at the ROCOM test facility:

- Flow stagnation in the initial state
- Start-up of the first MCP by linear increase of the pump frequency from 0 to the nominal value within 14 s
- Injection of water with high conductivity into the pump ramp

The experiments were carried out without density differences, because the criterion for neglecting the density differences between borated and unborated coolant outlined in [4] is fulfilled a few seconds after pump start-up.

The normalized coolant velocity in the loop with the starting pump is shown on Fig. 5. In each of the remaining three loops with switched-off coolant pumps, a reverse flow establishes, which reaches about 10 % of the flow rate in the starting loop (see Fig. 5). The tracer simulating the coolant with lower boron content passes the wire-mesh sensor in the inlet nozzle (Fig. 2, pos. 1) from 7 to 14 s. This corresponds to an initial slug position behind the MCP. The dimensionless mixing scalar according to equ. (1) averaged over the cross section at the sensor position is given in Fig. 5, too.

These boundary conditions were used as input for a calculation with the semi-analytical model SAPR. The curve of the mixing scalar averaged over the cross section at the reactor inlet (Fig. 5) is the basis for the reconstruction. The quality of the reconstruction is the same as in the example shown on Fig. 4.

Additionally, by help of the CFD code CFX-4 a calculation was carried out using the experimentally obtained slug form as boundary condition. Therefore the semi-analytical model can be compared with the experimental data and the CFX-results.

Turbulent fluctuations of the flow field have been observed in earlier experiments [1]. Therefore, the experiment was repeated several times to average over these fluctuations. The results of the single realisations were used to carry out a statistical analysis of the experimental data.

Fig. 6 shows the transient course of the average value of the mixing scalar at the core entry. The confidence interval of two standard deviations (95.4 %) is shown, too. The curve calculated by the SAPR-model shows practically the same behaviour like the experimental one. The maximum is reached at the same time. In the later part of the transient, the calculated concentration is slightly higher than the measured one, but always inside the confidence interval. In the CFX-calculation, the

concentration increases more slowly and the maximum is reached later. In the further course, the CFX-values are also inside the confidence-interval (lower boundary). The transient course of the maximum value is shown in Fig. 7. That maximum value or the minimum boron concentration is an indicator for possible reactivity insertion during a transient. In the experiment as well as in the calculations, the maximum value is determined at each time step over all fuel element positions. Therefore the position can vary, which has also an influence on the width of the confidence interval of the experimental data. In both calculations, the course of the maximum concentration at the core inlet is very close to the experimental data. After reaching the maximum in time, the value calculated by the SAPR-model belongs mostly to the upper part of the confidence interval, the CFX-value to the lower edge.

Table I summarises a quantitative assessment of the calculated data in comparison to the experiment. The comparison of the maximum values reached at each fuel element position during the transient shows, that the values for 129 fuel elements (more than 60 % of all positions) belongs to the experimentally determined confidence interval of 95.4 %, 68 of them even to the narrow interval of one standard deviation (68.3 %).

Table I Key parameters of the comparison

	SAPR-model	**CFX-calculation**
Number of fuel elements, which maximum belongs to the 68.3 % confidence interval of the experiment	68	20
Number of fuel elements, which maximum belongs to the 95.4 % confidence interval of the experiment	129	45
Total number of fuel elements	193	

In addition to this table, the transient course of the mixing scalar at one fuel element position from the outer part and one from the middle of the core is shown in Figs. 8 and 9. The turbulent fluctuations are significant only in the later part of the transient, when the maximum of the deboration front already passed the corresponding fuel element position. As can be seen, the fluctuations are higher in the outer part of the core. For both fuel element positions, the curves calculated by the SAPR-model are mostly inside the confidence interval. The maximum values are reached practically at the same time. Only for about two seconds around the maximum at the inner fuel element position and shortly after reaching the maximum at the outer fuel element position the calculated transient value is outside of the 95.4 % confidence interval. Both curves, calculated by CFX increase more slowly. The maximum value reached during the transient at the outer fuel element position is smaller in the CFX-calculation than the experimental one and the value calculated by the SAPR-model. In the later phase of the transient (after reaching the maximum in time at the corresponding fuel element position), both CFX-curves are inside the confidence interval.

4. BORON DILUTION ANALYSIS USING THE SAPR-MODEL IN COMBINATION WITH THE DYN3D CODE

The 3D neutron kinetic core model DYN3D [5] has been developed in the Institute of Safety Research of the Forschungszentrum Rossendorf. DYN3D has an extensive verification and validation [6, 7] basis and is widely used for the analysis of reactivity initiated accidents in light water reactors with Cartesian and hexagonal fuel assembly cross section geometry [8, 9].

The analysis presented here has been carried out for the begin of an equilibrium fuel cycle of a generic four-loop pressurized water reactor. The macroscopic cross section library needed for the core calculations has been generated by the 2D neutron transport code CASMO. The library contains cross section sets dependent on burn-up and the thermo-hydraulic feedback parameters in a range of variation being relevant for the transient under consideration [10]. The reactor is assumed at hot zero power in a subcritical state. The xenon- and samarium-distributions correspond to the full power state. All control rods are inserted, except one, which sticks at fully withdrawn position. This control rod is located in the core region, where the minimum boron concentration during the analysis of the transient has been predicted. The coolant in the lower plenum has a temperature of 192 ^{o}C and a boron concentration of 2200 ppm. The initial subcriticality of this state is determined by a steady-state DYN3D calculation with -7787 pcm.

In correspondence with [3], it is assumed, that the slug of unborated coolant, which has been created during a hypothetical boron dilution event, is located in the loop seal behind the MCP. The switching-on of the MCP in the loop with the slug drives the slug to the core inlet. On this way, the unborated coolant is mixed with the highly borated coolant in the downcomer and lower plenum. The mixing is modeled using the SAPR-Model. This is applied both to the mixing of boron as well as to the temperature mixing. Because it is not obviously, which distribution gives the maximum reactivity effect, the distribution of the boron and temperature at the core inlet at two time points have been extracted from these calculations (one temperature and boron concentration value for each fuel assembly position). The first distribution corresponds to the time point of the total minimum boron concentration reached during the analysis, the second one is time point of the minimum of the boron concentration averaged over the whole core entry cross section. The initial slug volume used as input to SAPR has been varied during the analyses between 0 m^3 and the bounding volume of 36 m^3 [3] in steps of 4 m^3 (see table II). The slug contains no boron and has a temperature of 210^{o}C in all cases.

For each case of boron and temperature distribution, a stationary core calculation for the hot zero power state described above has been carried out by means of DYN3D. In these calculations, the inlet

distribution is extended over the whole height of the core, that means, an uniform axial distribution is assumed. Table II summarises the results of these calculations. For each distribution, the reactivity inserted by boron dilution, the summary reactivity and the minimum boron concentration are shown. Although the summary boron content in the whole core is lower in the calculation with the second distribution (at time of minimum of the average value), in all cases except one the calculation with the total minimum in boron gives an higher reactivity insertion into the core. That means, that the local distribution has an higher influence on the reactivity than the summary boron content in the core. For two calculations, the time point of total minimum boron concentration at the core inlet coincides with the time point of the minimum of the boron concentration averaged over the whole core entry cross section. Therefore, the results are the same for these time points.

Table II Results of stationary core calculations

Initial Slug Volume [m^3]	**Time of total minimum**			**Time of minimum of the average value**		
	Inserted Reactivity [pcm]	**Summary Reactivity [pcm]**	**Min. Boron Concentration [ppm]**	**Inserted Reactivity [pcm]**	**Summary Reactivity [pcm]**	**Min. Av. Boron Concentration [ppm]**
1	172	-7615	2064	168	-7619	2149
4	1043	-6744	1619	1035	-6752	1953
8	3756	-4031	1104	2554	-5233	1702
12	6751	-1036	655	4750	-3037	1446
16	8903	+1116	377	6424	-1363	1216
20	9468	+1681	298	7777	-10	1041
24	9925	+2138	178	9925	+2138	887
28	10319	+2532	94	10319	+2532	754
32	11197	+3410	0	11625	+3685	638
36	12427	+4640	0	12328	+4595	547

From the stationary calculations follows, that an initial slug volume of less than 16 m^3 does not lead to a recriticality of the core. Therefore, only the cases with higher initial slug volumes are of interest for a transient analysis.

The first transient calculations have been carried out for the initial slug volumes of 16 and 20 m^3. The SAPR-Model provides the time-dependent boron concentration and coolant temperature at the inlet into each fuel assembly. In the DYN3D-code, the fuel assemblies are modelled as isolated parallel thermohydraulic channels.

The MCP reaches its full mass flow rate about 15 s after the switching-on. Due to the non-working MCP's, in each of the three other loops a reverse flow of about 10 % is established. The boron front reaches the core bottom about 12 s after switching-on the MCP. This time is the starting point for the

transient core calculations. The average coolant velocity is 0.45 m/s at that time and enhances up to 0.65 m/s during the next seconds.

Earlier analyses of boron dilution events showed a significant influence of the description of the boron front on the behaviour of reactivity and nuclear power in transients with low fluid velocity [9, 11]. In connection with these analyses, a special model, based on a particle-in-cell (PIC) method for the description of the boron transport through the reactor core has been developed. Using the PIC-method for the boron transport in the core allows to select a time step width, which satisfies the requirements of the interaction between neutron kinetics and thermohydraulics. Numerical diffusion is fully suppressed.

Fig. 10 shows the dynamic reactivity during the transient for the 16 m^3 and the 20 m^3 cases. As can be seen, the dynamic reactivity in the 16 m^3 -case remains always below the zero-line. This is connected with the fact, that the slug has a finite length, what was not taken into account in the stationary calculations extending the minimum inlet distribution of the boron concentration in axial direction. The slug of 20 m^3 leads to a significant reactivity insertion into the core, a value of nearly 2 $ is reached. That results in a power peak of more than 6500 MW (Fig. 11). Then the power excursion is stopped by the Doppler feedback. The limited integral energy release due to the small half width of the power peak did not lead to a significant enhancement of the coolant temperature, boiling did not occur.

With more than 7000 MW, the magnitude of the power peak is only slightly higher in the calculation with the bounding slug volume of 36 m^3 (see fig. 12) than in the previous calculation. The Doppler feedback stops the further power increase, too. Contrary to the 20 m^3 case, the power peak occurs even before the boron concentration has reached its minimum. Because the positive reactivity insertion is continued after the power peak, typical secondary power peaks are observed. As can be seen from fig. 13, the radial power distribution over the reactor core is very heterogeneous. At the location of the power maximum, coolant boiling with a maximum void fraction of up to 70 % occurs for a short time. However, no heat transfer crisis was obtained, so that the cladding temperatures keep below 260 °C (fig. 14) and no safety relevant limitations are violated.

CONCLUSIONS

A semi-analytical model for the description of the coolant mixing in the downcomer and the lower plenum of PWRs based on response functions to Dirac shaped impulses has been developed. Experimentally determined pulse responses are used. The model has been applied in combination with

the 3D neutron kinetic core model DYN3D for the analysis of a hypothetical boron dilution event. The model provides realistic boron concentration fields at the core inlet. By varying the initial slug volume it was found, that for the given core configuration slugs of less than 16 m^3 did not lead to supercriticality in static calculations. Transient calculations with higher slug volumes revealed a further conservatism of the static analysis. Only an initial slug volume of 20 m^3 leads to a power increase of the shut-off reactor in the calculation. According to these calculations, even a reactivity insertion up to 2 $ connected with the 36 m^3 slug did not lead to safety relevant consequences. The power excursion is controlled by the Doppler feedback.

This parameter study performed for a generic PWR is a demonstration of the capabilities of the mixing model SAPR in combination with the neutron kinetic core model DYN3D. In case of the application of the mixing model to a certain reactor, the bounding initial slug volume for a specific scenario has to be determined and then used as input to the mixing model.

The consideration of realistic assumptions concerning the coolant mixing in the RPV preserves a great amount of inherent safety of the reactor. Earlier analyses with conservative coolant mixing assumptions provide supercriticality even for smaller slug volumes.

A proper description of the boron transport through the core in case of transients with low coolant velocity is absolutely necessary to calculate the neutron kinetic behaviour of the core in a right manner. Otherwise the numerical diffusion distorts the boron front and the reactivity insertion is smoothed artificially.

In the near future, the model is to be implemented into the coupled code DYN3D/ATHLET. That would allow to carry out analyses of the whole plant behaviour.

ACKNOWLEDGEMENTS

The projects this paper is based on are funded by the BMWi (German Ministry of Economics) and are registered with No. 150 1216 and 150 1225.

The authors thank Dr. D. Lucas (FZR) for implementing the PIC-Method into the core model DYN3D.

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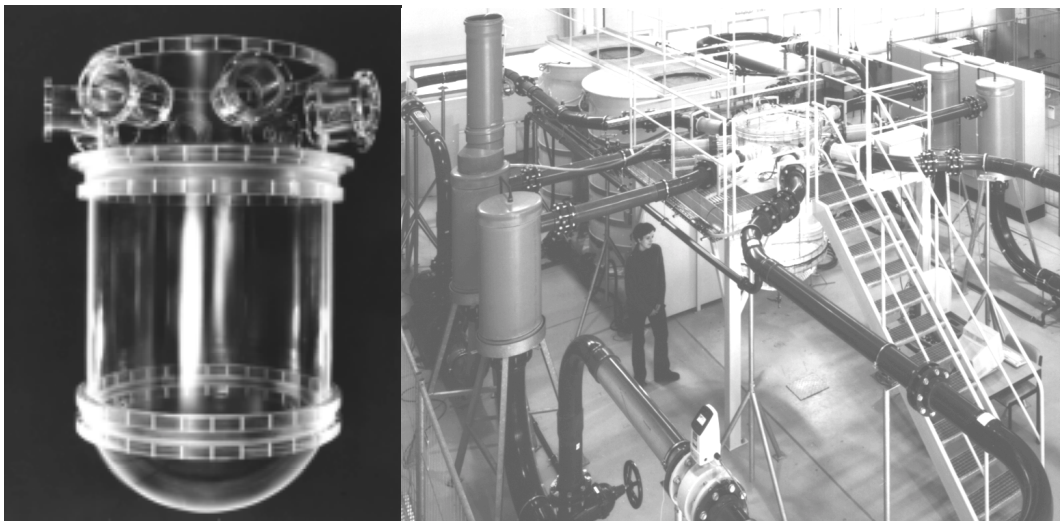

Fig. 1 Test facility ROCOM

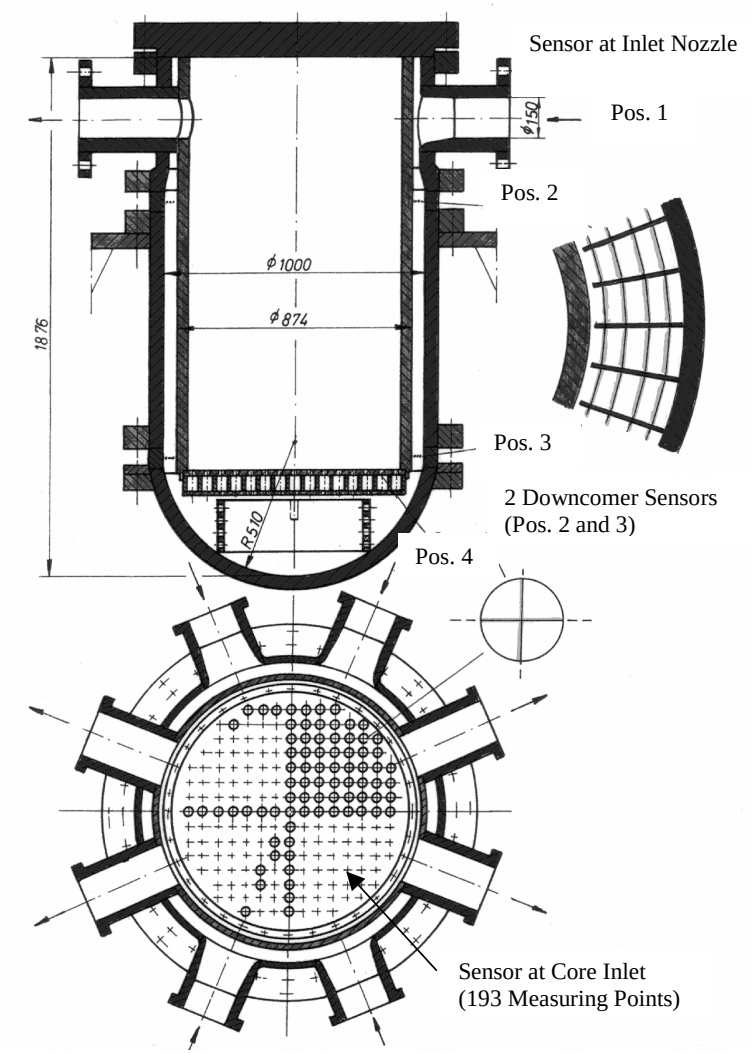

Fig. 2 Positions of the wire-mesh sensors in the test facility

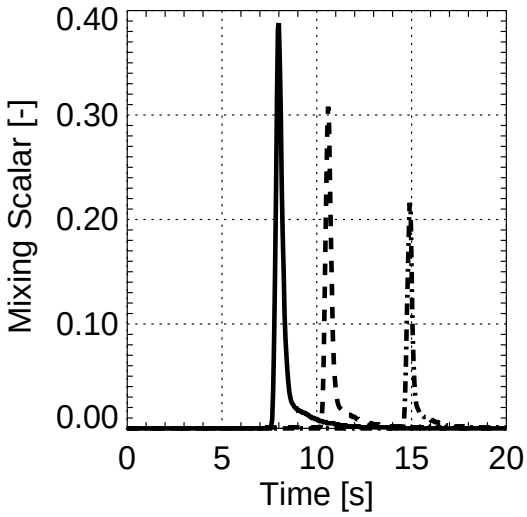

Fig. 3a Examples for the experimental impulses

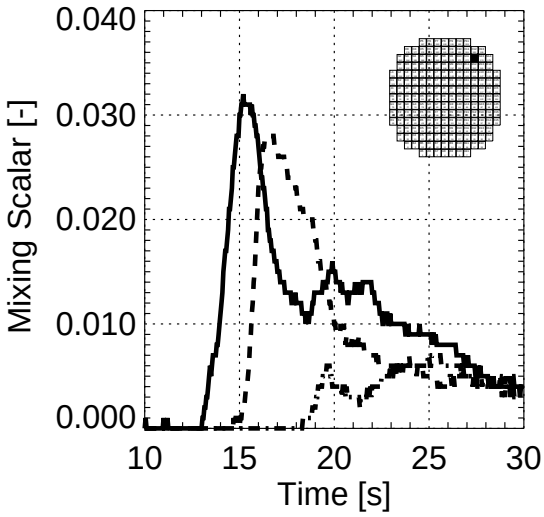

Fig. 3b Mixing scalars (answer to 3a) at a certain fuel element position

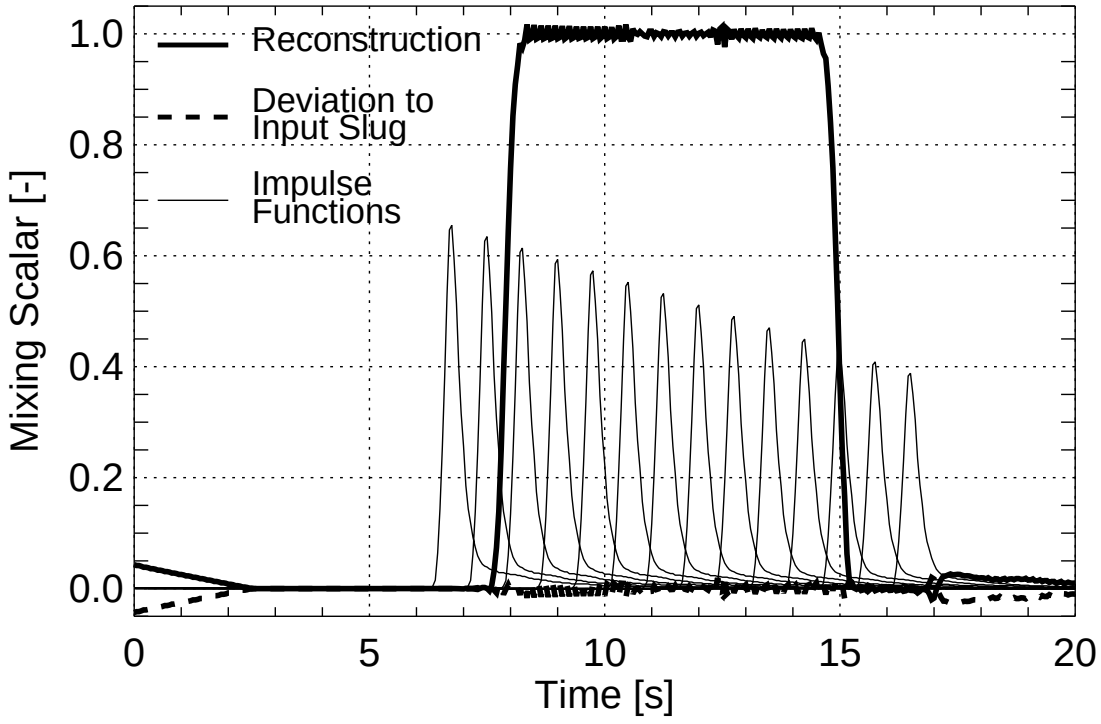

Fig. 4 Demonstration of the slug reconstruction procedure by experimental and interpolated impulses

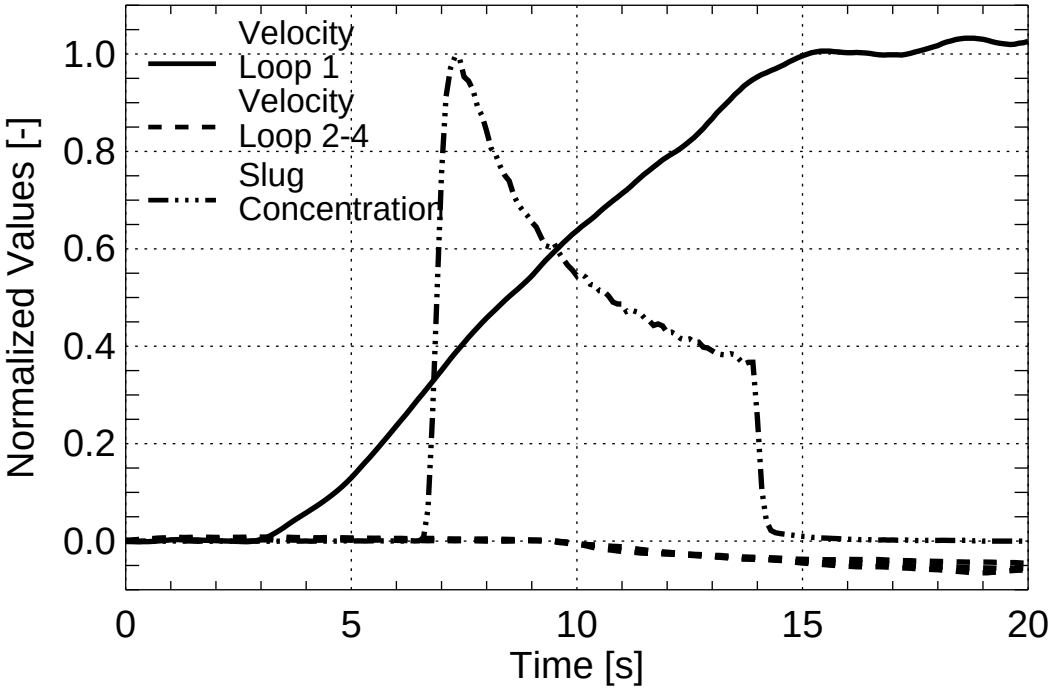

Fig. 5 Normalized coolant velocity and created slug during the experiment

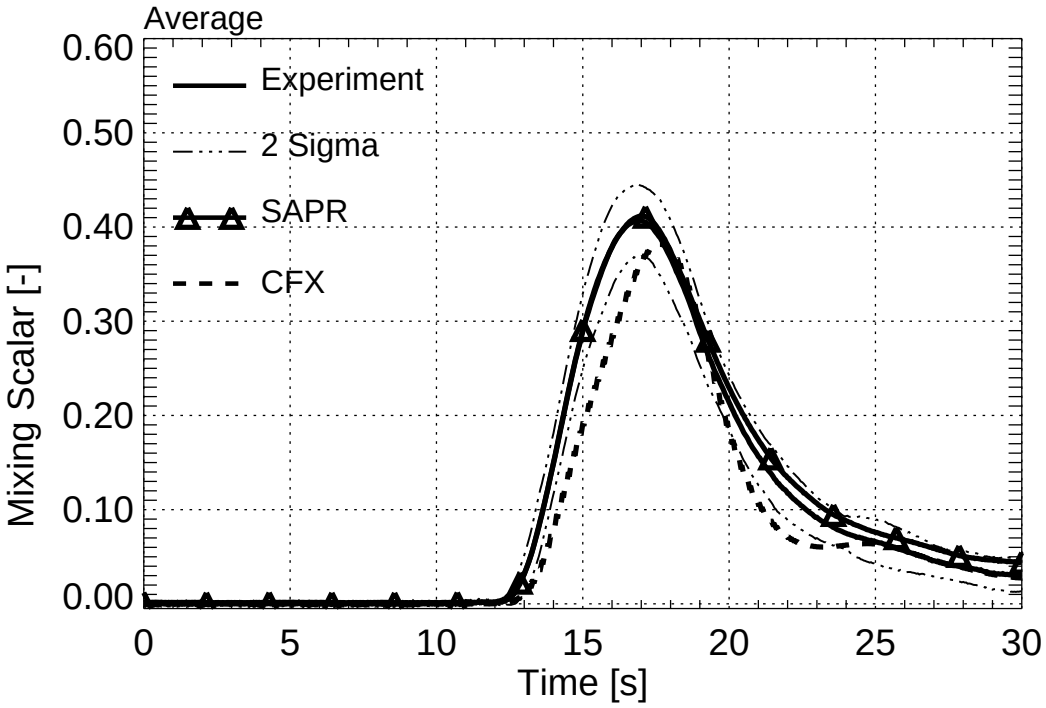

Fig. 6 Average of the mixing scalar at the core entry in comparison between experiment, semi analytical model (SAPR) and CFX-calculation (with confidence interval of 95.4 %)

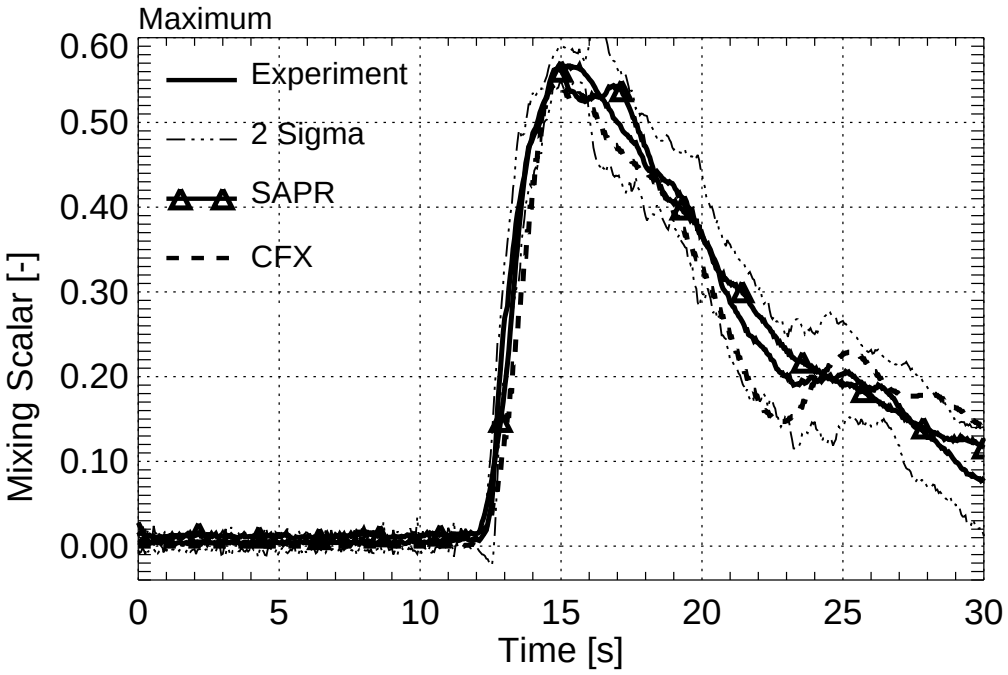

Fig. 7 Maximum of the mixing scalar at the core entry in comparison between experiment, semi-analytical model (SAPR) and CFX-calculation (with confidence interval of 95.4 %)

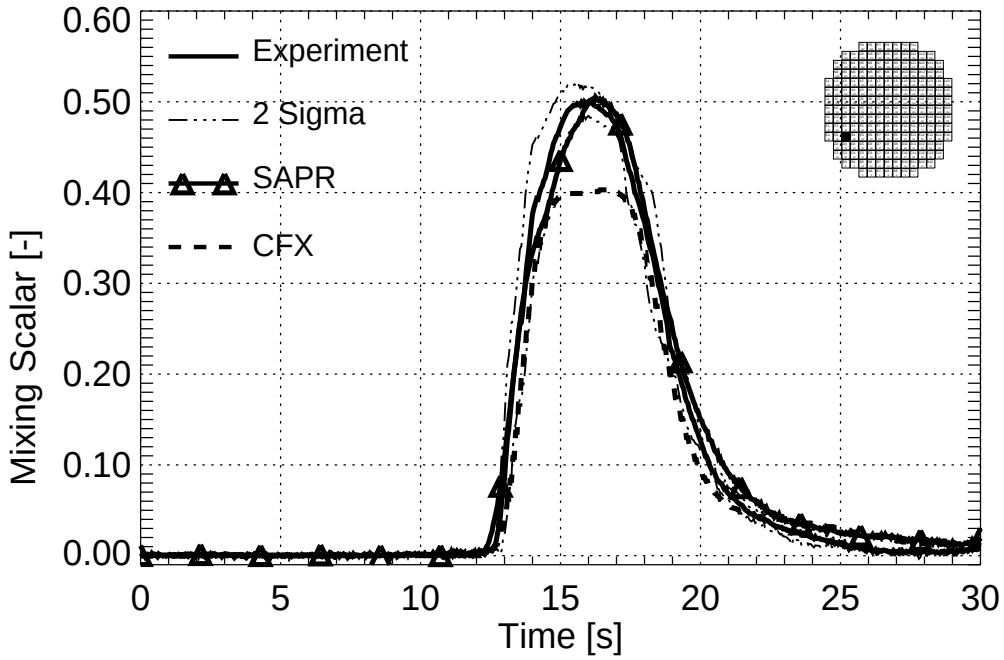

Fig. 8 Mixing scalar at a fuel element position in the outer part of the core in comparison between experiment, semi-analytical model (SAPR) and CFX-calculation (with confidence interval of 95.4 %)

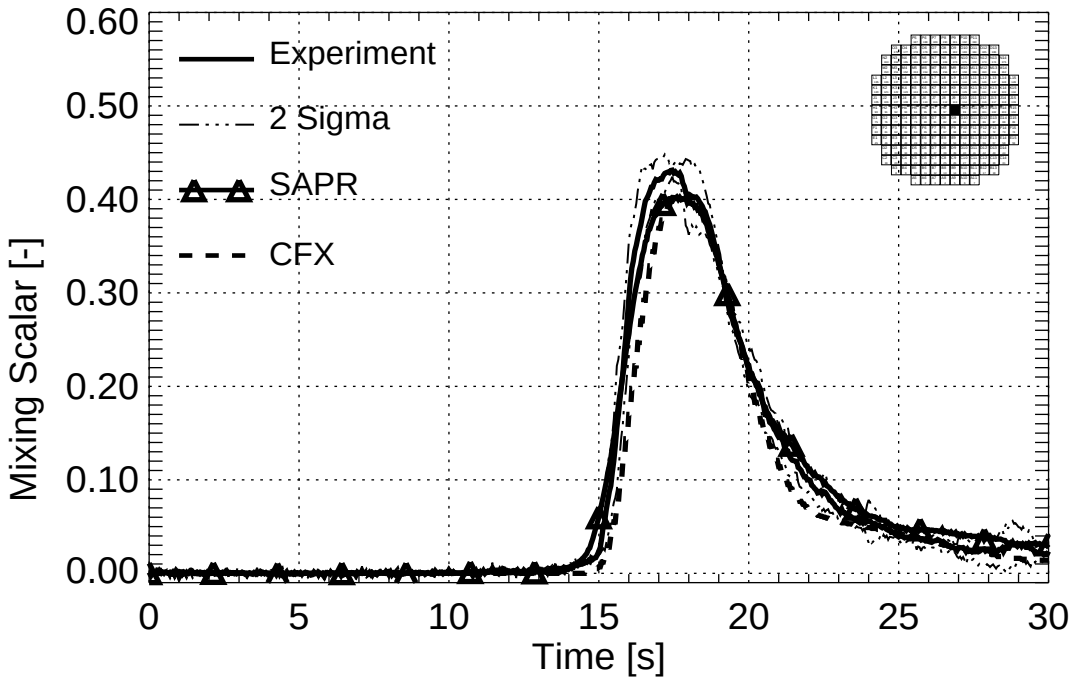

Fig. 9 Mixing scalar at a fuel element position in the inner part of the core in comparison between experiment, semi-analytical model (SAPR) and CFX-calculation (with confidence interval of 95.4 %)

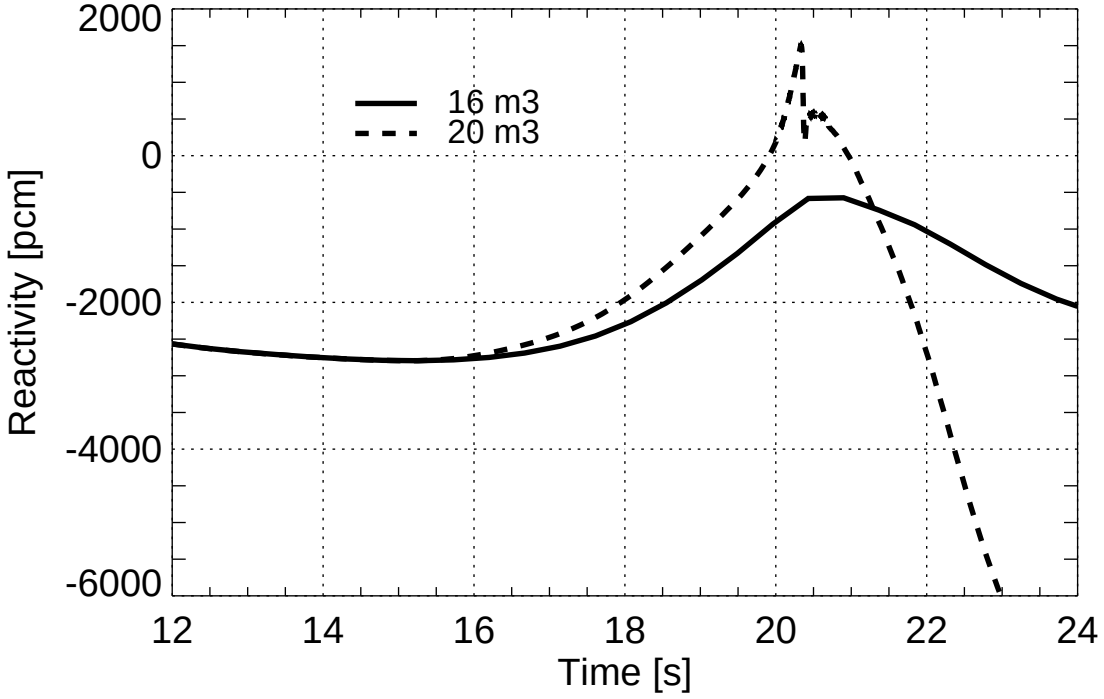

Fig. 10 Dynamic reactivity in the case of injection of a 16 m^3 and a 20 m^3 unborated slug

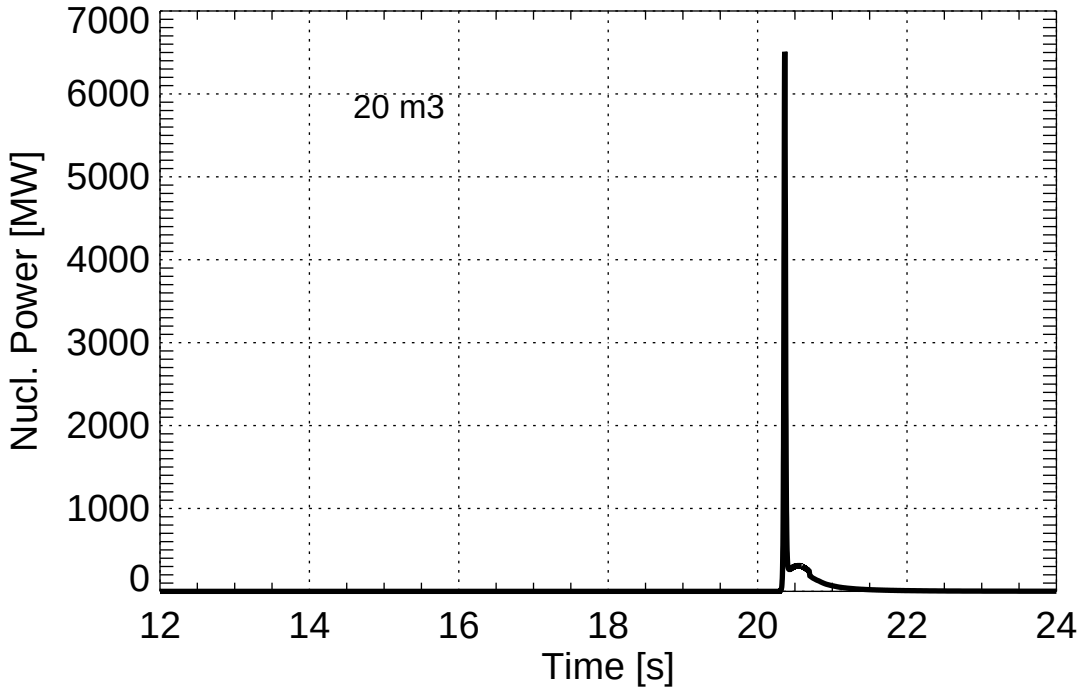

Fig. 11 Nuclear core power in the case of injection of a 20 m^3 unborated slug

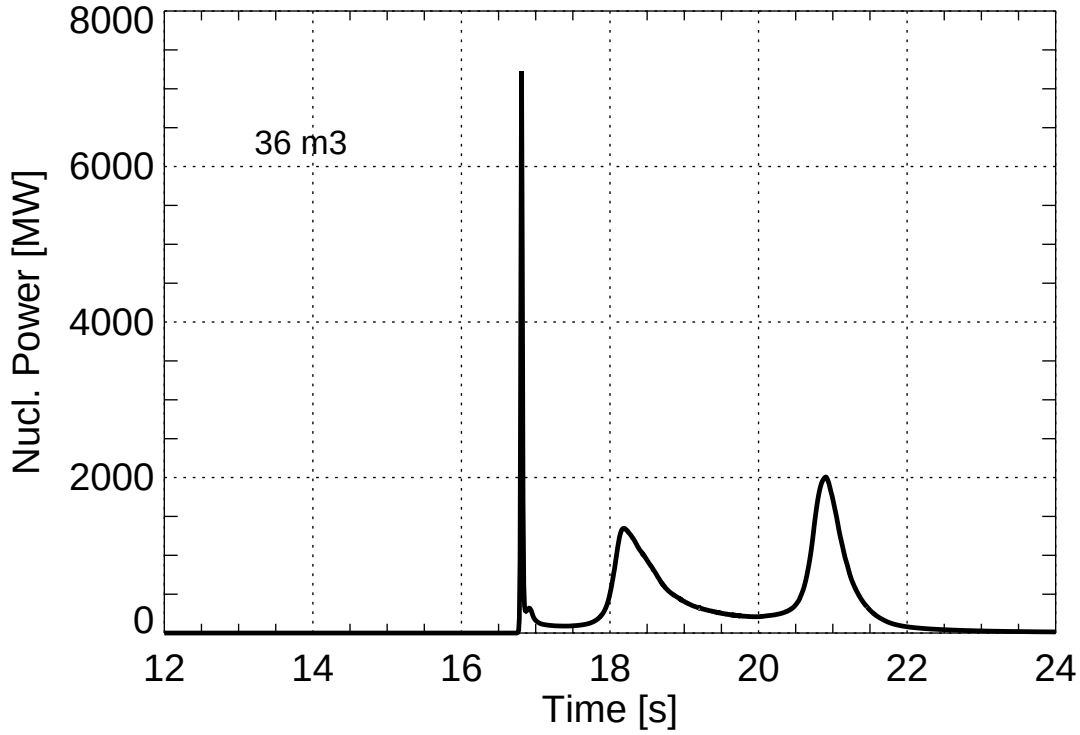

Fig. 12 Nuclear core power in the case of injection of a 36 m^3 unborated slug

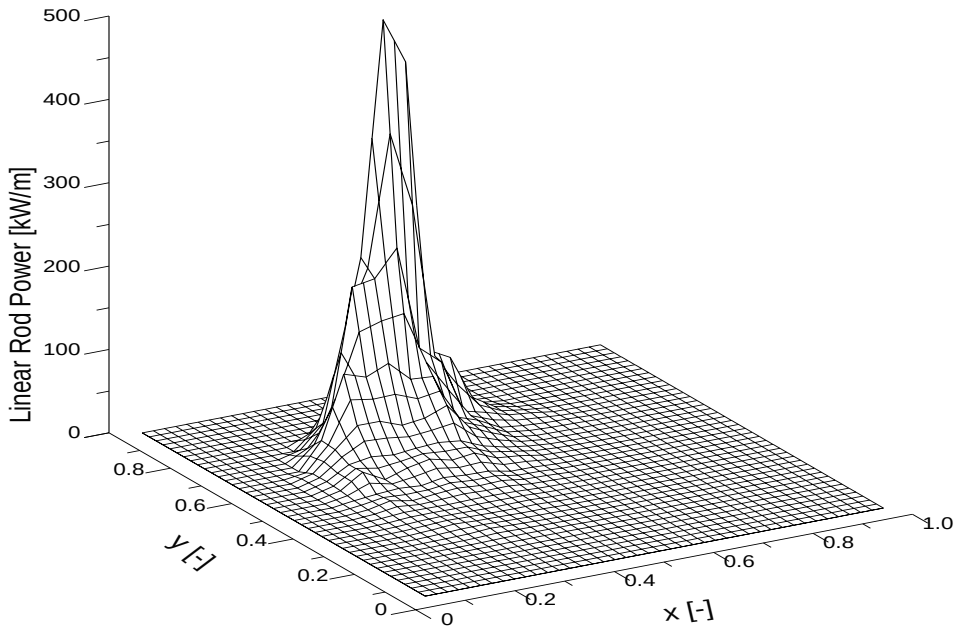

Fig. 13 Radial distribution of the linear rod power density in the moment of maximum power (36 m^3 case)

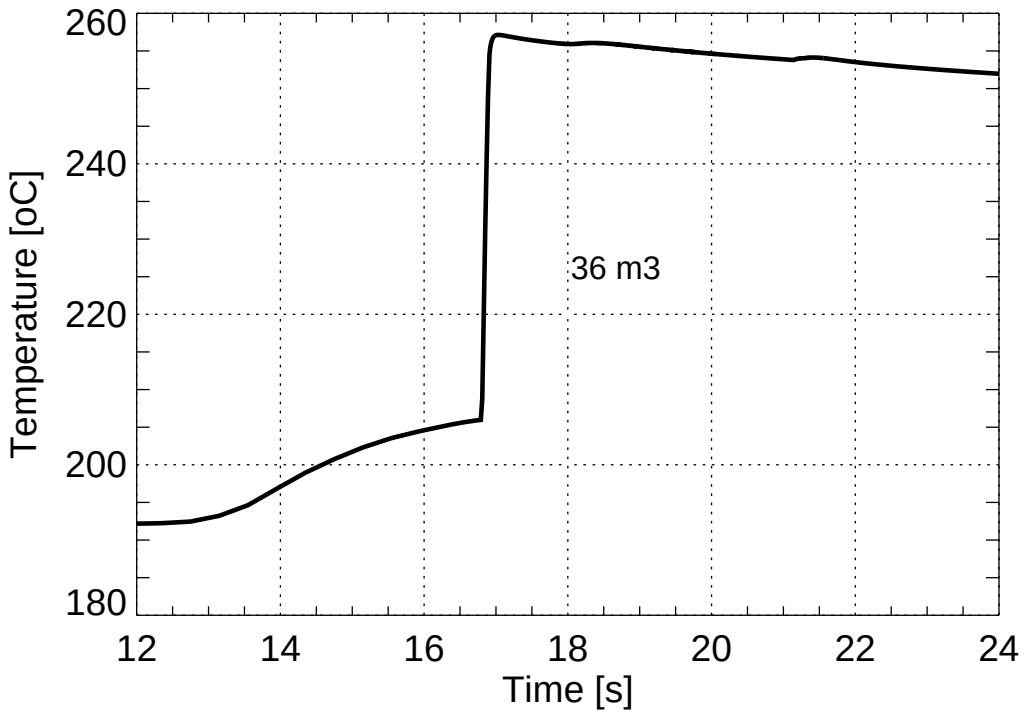

Fig. 14 Maximum cladding temperature in the case of injection of a 36 m^3 unborated slug