RESEARCH REPORT

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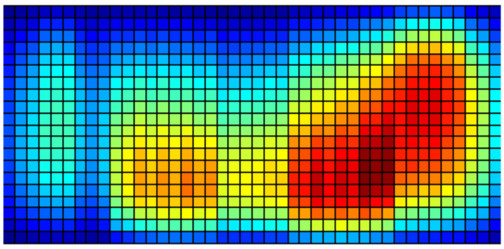

TRICOT 2010/SAFIR

Extensions to TRAB-3D / SMABRE in 2009

Authors: Anitta Hämäläinen, Hanna Räty, Malla Seppälä

Confidentiality: Public

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Customer, contact person, address SAFIR2010 Research Programme (VYR,VTT)	Order reference
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The main features of coupling have been programmed mainly by the SMABRE developer before middle of 2008. After that the status of the different code versions and options were checked, and identification of modifications leading to deviating results with different code versions and coupling types were reported. Latest studies and developments have focused purely on the internal coupling. The deviation of numbers of fuel assemblies and fluid channels is programmed and several smaller improvements have been realized.

As test cases calculations on a pump seizure transient has been calculated for an EPR type reactor and control rod ejections for the high pressure light water reactor, HPLWR. The simultaneous development with a special HPLWR model has enabled useful cross-checking and application for internal coupling, even though a peculiar oscillation behavior appearing in the HPLWR needed some effort. The test case calculations with EPR and HPLWR are reported here to show the capabilities of TRAB-3D/SMABRE. After some new validation cases and checking the earlier modeled BWR features, internal coupling will be ready for final reporting and updating of the manuals.

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Signatures	Signatures	Signatures
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Contents

1 Introduction

The objective of the subtask TRAB-3D/SMABRE of SAFIR2010/TRICOT project is to improve the thermal hydraulics in the reactor dynamics computer code, TRAB-3D, by coupling it internally to the SMABRE code. TRAB-3D /1/ is a reactor dynamics code with three-dimensional neutronics and one-dimensional thermal hydraulics in a core and in a BWR circuit. The code can be used for transient and accident analyses of boiling water reactors (BWR) and with its core model coupled to SMABRE, also for pressurized water reactors (PWR). The system code SMABRE /2/ models the thermal hydraulics of light water reactors. Both codes have been entirely developed at VTT. TRAB-3D and SMABRE have earlier been connected with parallel coupling. /3/

Main advantages of internal type of coupling are possibilities to handle coolant flow reversals in core flow channels as well as modeling of cross flows in an open reactor core like EPR. Also the porous media model could be used for the thermal hydraulics to simulate 3-dimensional hydraulics. On the other hand, the possibility of describing flow 3-dimensionally in the core necessitates a new approach to hot channel calculations.

The basics for internal coupling were created for BWRs in the EMERALD project as a part of the SAFIR-Programme /4-6/. In TRICOT, the work has continued for the PWR /7-8/. The internal coupling of TRAB-3D and SMABRE needed large modifications and new modules especially into SMABRE, which should still have all the old calculation capabilities with parallel coupling left in it.

The main features of coupling have been programmed mainly by the SMABRE developer before middle of 2008. After that the status of the different code versions and options were checked, and identification of modifications leading to deviating results with different code versions and coupling type were reported /8/. Updating the code manuals /9/ is still waiting some clarifications raised up during this process.

Latest studies and developments have focused purely on internal coupling. The deviation of numbers of fuel assemblies and fluid channels is programmed and several smaller improvements have been realized. The EPR and HPLWR reactors have been used for the test cases. Even though the HPLWR is not included in the SAFIR project, the main findings and test case calculations are reported here to show the capabilities of TRAB-3D/SMABRE.

2 Internal coupling of TRAB-3D/SMABRE

TRAB-3D /1/ is a reactor dynamics code with three-dimensional neutronics coupled to core and circuit thermal hydraulics. The code can be used for transient and accident analyses of boiling (BWR) and pressurized water (PWR) reactors.

The system code SMABRE /2/ models the thermal hydraulics of light water reactors. Both codes have been entirely developed at VTT. The progress of coupling is described in /4-8/.

Already at the 90’s, when at VTT the 3-D neutronics code HEXTRAN was coupled with the SMABRE code through parallel coupling, division of the core and also the pressure vessel to parallel channels has been a typical procedure to describe the reactors for the coupled codes, even if it is not necessary for calculation of all transient types. Typically the number of parallel channels in the pressure vessel and in the core is at least equal to the number of the circulating loops.

In internal coupling TRAB-3D performs the neutronics calculation, SMABRE will take care of the hydraulics calculation of the whole cooling circuit including the reactor core, and the heat transfer calculation may be carried out by either code by the user's choice. On the other hand in parallel coupling TRAB-3D performs the core hydraulics and heat transfer, and the coarse SMABRE core hydraulics with fewer channels than in TRAB-3D are solved in parallel.

Several TRAB-3D/SMABRE code versions reported in /8/ have been reduced to two versions which are used for all calculations regardless of the used coupling type. Another current code version is intended for supercritical conditions. After combining the developed features and findings from the HPLWR version to the traditional one, the results are the same with both versions e.g. for the EPR test cases, as it should be.

3 Extensions to TRAB-3D/SMABRE

The checking of several new and old options of the coupled code reported in /8/ has been continued. In this process some mistakes were found in new features implemented for internal coupling in calculations of heat structure temperature profiles. In internal coupling it is possible to carry out the heat transfer calculation of fuel rods either in SMABRE or in TRAB-3D. Thus the heat structure calculation has been upgraded in SMABRE concerning the normal heat structures. Possibility of modeling with several radial mesh points in heat structures affects the calculations of transients in which different thermohydraulic conditions exist in different sides of a two sided heat structure. This affects also calculations with the parallel coupling and probably improves the stability of results e.g. in a steam line break transient. The two sided heat structures are mainly encountered in the modeling of the steam generators and the pressure vessel.

Power generated in the fuel assemblies is in the stand-alone SMABRE input given directly to each core heat structure separately. The axial power profile is determined by these values and kept the same even though the absolute values may change while using point kinetics or in decay heat period. In parallel coupling with TRAB-3D the stabilization of the beginning of the coupled calculation depends only on input variables. In the first version of the internal coupling the initial axial profiles in SMABRE were assumed to be equal, and problems were encountered. As a new feature developed for HPLWR modeling the number of axial profiles may be defined by the user This improves the accuracy of the initial values and decreases the steady state calculation time for all internally coupled applications.

As a part of HPLWR-project, new material properties are included in SMABRE. These are created from a large international data base, which is used to create the polynomes for suitable ranges of pressure and temperature. For the subcritical transients the new material properties were tested for an EPR test case and no significant differences were found.

The SMABRE point kinetics was modified in order to take account the fluid temperature in the moderator channels for feed backs in HPLWR. This feature is ready for use for internal coupling and 3-D calculations.

In the stand-alone used SMABRE and with parallel coupling it has not been necessary to take into account the deviating number of fuel assemblies and fluid channels. In parallel coupling the deviating numbers of assemblies or channels have typically been between the codes, TRAB-3D and SMABRE. In the first version of the internally coupled code system the option to include many fuel bundles in one flow channel was deemed obsolete, and all analyses were thought to be carried out with one channel per fuel bundle. Therefore the original developer of the coupling did not carefully distinct between treatment of assemblies or channels in loops. Later it was realized, however, that in some applications, and code comparisons this option would be needed. Basics for this has now been realized for TRAB-3D/SMABRE. The opposite, modeling of several fluid channels connected to same assemblies, needed e.g. for modeling of modern BWR fuel, may need some more effort and will be realized in connection with the BWR capability tests. Also application of the two sided heat structures connected to internally coupled core island or cross flows may be modeled.

4 EPR application

The PWR test case for the coupling is in a geometry resembling the EPR reactor core with 241 hydraulic channels and 20 axial core nodes. The modeled fuel is a typical PWR fuel. In this application the number of loops is 4, the number of pressure vessel sectors and their respective SMABRE channels is 8 and the number of core channels in SMABRE is 17. The whole primary loop and the secondary loop from the feedwater tank to the turbine valves have been modeled in SMABRE. The model is quite similar to, but not exactly identical to the model of the EPR plant. As a dynamic test case a pump seizure transient has been performed.

Several new and old options of the coupled code reported in /8/ have been tested. Even though in the up to now used test cases in the EPR application modeling with fewer fluid channels than fuel assemblies is not meaningful, the extension has been checked and tested with EPR. The Figures 1-3 show the differences in EPR test cases calculated with either 241 or 17 channels. The time histories of the case don't differ significantly. Figure 1 shows the differences in the initial power profile with 241 and 17 fluid channels and Figure 2 the differences in inlet mass flow. The differences in inlet mass flows are quite large, about 12 %. This indicates for the parallelly coupled SMABRE input that modeling of the center channel and its loss coefficients with 9 fuel assemblies should be better described. As in the mass flows, small differences may be seen in the middle of the core in maximum fuel temperatures, too, Figure 3.

Test runs of the original 241 fluid channel model of EPR with all the improvements made to internal coupling were performed. The Figures 3 and 4 shows the differences in the test case, main circulation pump seizure. The Figures indicate that at least no major errors are evident in the extensions to the code. The peaking factors are about equal at the maximum power and although they differ after that, the power level is then already very low.

Already in /7-8/ good results were reported in comparing the core distributions for fission power, channel mass flows and fuel temperatures with stand-alone TRAB-3D and internal coupling, and also when using parallel coupling. For slightly deviating results the explanations and main internal options causing the differences between the old and new versions of code have been found out and reported. These options will be included in the input. Thus the validation calculations and further improvements will be easier to perform.

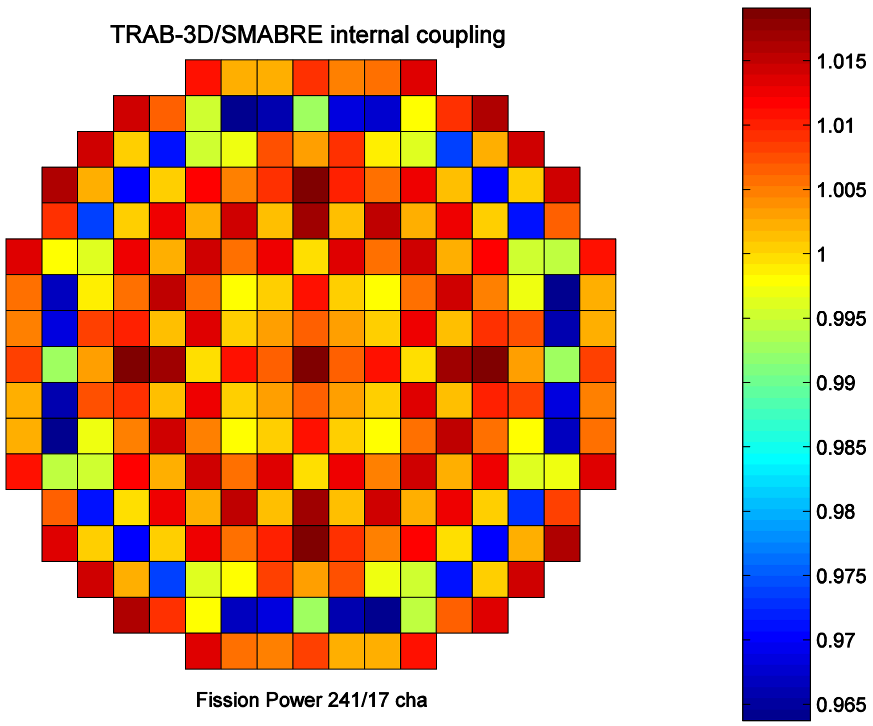

Figure 1. Steady state relative power distributions with 241 / 17 fluid channels in TRAB-3D/SMABRE.

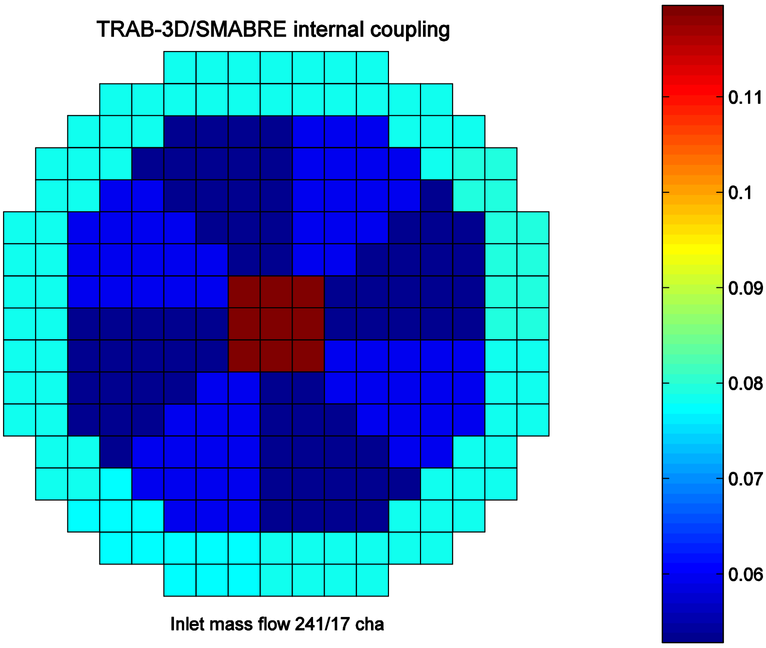

Figure 2. Steady state relative inlet mass flow distributions with 241 / 17 fluid channels in TRAB-3D/SMABRE.

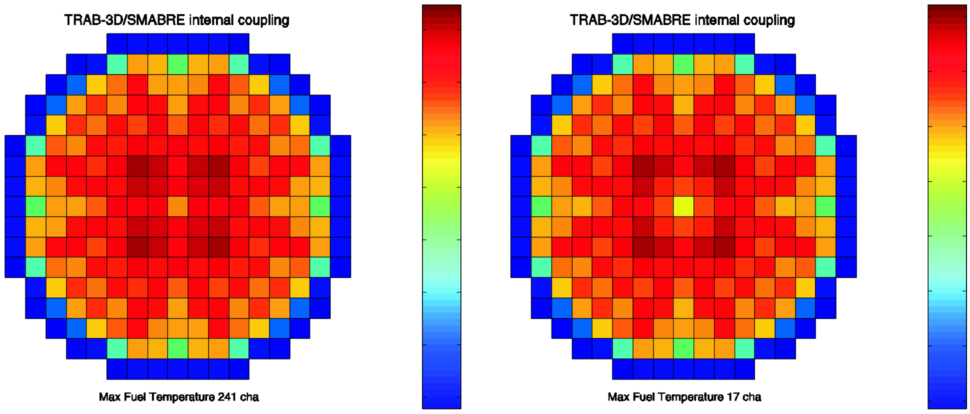

Figure 3. Steady state maximum fuel temperature 241 and 17 fluid channels in TRAB-3D/SMABRE version using internal.

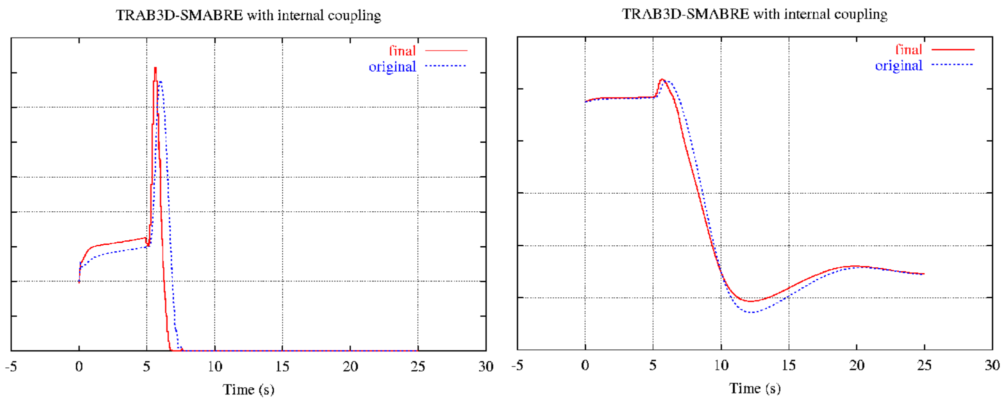

Figure 4. Average void fractions and maximum equal quality at core outlet in pump seitzure transient of EPR with TRAB-3D/SMABRE internal coupling with latest improvements.

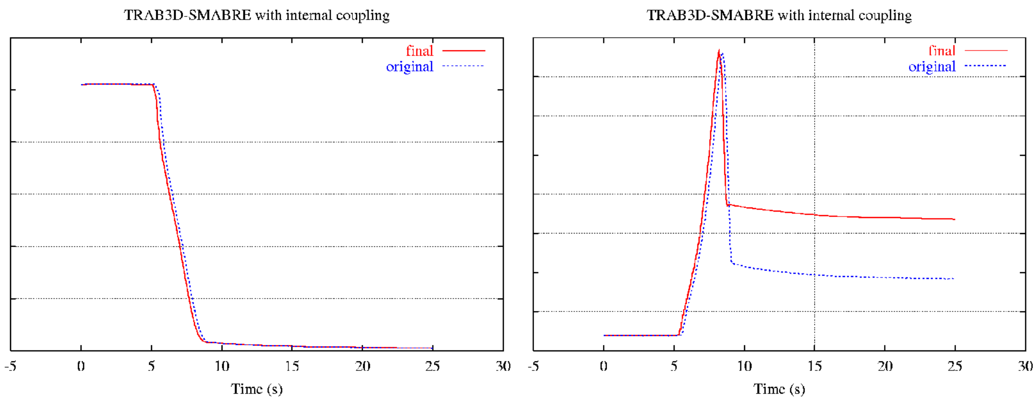

Figure 5. Fission power and fission power peaking factor in pump seitzure transient of EPR with TRAB-3D/SMABRE internal coupling with latest improvements.

5 HPLWR-application

The internal coupling of TRAB-3D/SMABRE makes it possible to use the code for analyzing the supercritical pressure HPLWR reactor. Actually, internal coupling instead of parallel coupling is necessary because of the special design of the HPLWR core with its up- and downward flow channels. The development of the HPLWR version has been performed simultaneously with the internal coupling. Even though the modeling of features caused by the supercritical pressure is performed in another project, this has created a useful cross-checking possibility for both code versions.

The main idea for the HPLWR version is to extend the capability of the code to supercritical conditions. Thus in the HPLWR project new material properties have been implemented in the code and they may be used also for the general TRAB-3D/SMABRE.

The HPLWR has in an EU project been analyzed with several system codes. The SMABRE point kinetics was modified in order to take account the fluid temperature in the moderator channels for feed backs. The results got better and more stabilized with these modifications. In the EU-project several transients have been calculated with SMABRE point kinetics /9/ and were compared e.g. to the RELAP-5 calculations performed in PSI Switzerland.

The point kinetics model of the three way core of the HPLWR-model for SMABRE consists of three fluid channels in the core one after another in such a way that there is only one flow path through the core. In one of the channels the flow is directed downwards and there are two lower plenums and two upper plenums (Figure 6). The number of fluid channels in TRAB-3D/SMABRE calculations has been 156 or 1404. In the HPLWR three –way core design there are nine fuel assemblies in each of the 156 fluid channels. The total number of fuel assemblies is 1404. Due to the problems encountered in HPLWR, also a core island of 3 fluid channels was created for internal coupling.

Already in the steady state calculation of HPLWR with SMABRE, in which the core island is created, difficulties were encountered in the form of an oscillation behavior with a growing amplitude in pressure and consequently in other parameters too. These oscillations are created in the extra upper plenum and lower plenum inside a core flow path, nodes 5011 and 7821 in Figure 6. The core calculation is fine until the oscillation around the core starts to affect it. Oscillations exist with different number of flow channels and also with large loss coefficients. The mass errors calculated with SMABRE are not huge during the oscillations. The phenomenon was studied in several ways, e.g. a 3 channel model was created for HPLWR. This enabled direct comparison between results from the stand-alone SMABRE calculation with only 3 flow channels and results from calculation of internal coupling mode where the core island consists of 3 channels. In these studies the problem was identified to the ‘extra’ lower and upper plenums inside the core flow paths and it was considered to be specific to HPLWR case. The internal coupling used in TRAB-3D/SMABRE may not be applicable directly for this kind of core construction because there are some features in the coupling which may not be used for ‘extra’ lower and upper plenums having totally different pressures and mass flows. On the other hand, also the HPLWR construction and behavior is not totally clear.

The above mentioned problem was ‘solved’ by using small connections from upper plenum to these ‘extra’ upper and lower plenums for stabilizing the pressure and by using very small time steps, 0.0021 s. In this way, together with a long enough steady state calculation, the CRE, control rod ejection, was analyzed with TRAB-3D/SMABRE and results with 1404 flow channels were reported in /9/. Compared to the calculations performed in KFKI with the KIKO3D-ATHLET coupled code, the results were reasonable and the results of the two codes were very close to each other.

In HPLWR CRE the ejected rod consists of five control rod. The positions of ejected rods are marked with red in Figure 7. The rods are located in channels with flow direction top to bottom, shown in Figure 8 with core channel initial mass flows. The ejection time is 1 s. In these calculations no radial distribution of temperature in the fuel rods is assumed.

In the TRAB-3D/SMABRE calculations only simplified feed backs from the moderator and gap channels are used. Here, the model to improve the feed backs for point kinetics will be expanded for internal coupling and 3-D calculations. Furthermore, the direct heat transfer from moderator channels to the core flow channels has not been modeled. This has been covered by increasing the feed water temperature. The model for two sided-heat structures in the core island for heavy reflector of EPR may be used here.

In Figure 9 the fission power in the transient is depicted. The differences between 3, 156 and 1404 channels cases are surprising small. The maximum fission power is 3185, 3207 and 3203 MW, respectively. In all cases the power level equalizes to about the same slightly higher level than the initial power. The differences are also quite small in the peaking factors of fission power at the time for maximum power level (Figure 10, 11). Otherwise the results indicate the natural differences with different number of fluid channels. Differences between 156 and 1404 channel cases are small in average fluid density (Figure 12) and in fuel average temperature (Figure 13) as well for cladding temperatures. The results of 3 channel deviate significantly from 156 or 1404 channels in the cladding temperature (Figure 14). Also the location of maximum cladding temperature is not same for the 3 channel model and the other two models. This is the results of larger fluid volumes to stabilize the heat input.

In Figure 15 the axial fission power profiles are shown. The positions of ejected rods are clearly seen in the lowest figure where increase of the fission power is highest and relation between maximum and initial profiles are peaked. The maximum powers are met in the nearest channel where also initially the highest power exists. Relation of axial profiles between 156 and 1404 channels at the time of maximally peaked profile are shown in Figure 16. The differences are at most 4 % between the 156 or 1404 channels. The power distribution in the radial direction after CRE is shown in Figure 17, its relation to the initial profile in Figure 18 and its relation to the 1404 channel model in Figure 19.

The HPLWR-CRE results indicate that the multichannel extension to TRAB-3D/SMABRE works properly in the test case. Comparison to the Hungarian ATHLET/KIKO3D results indicates the same. In CRE the thermal hydraulics don't play a significant role but on the other hand asymmetrical phenomena pulls out the possible mistakes and inconsistencies. In HPLWR-application the checking of several options dealing with calculation stability programmed into the code have increased understanding of the internal coupling. Also the special and larger volumes in the lower and upper plenum have uncovered some inconsistencies between SMABRE and TRAB-3D modeling of these geometries.

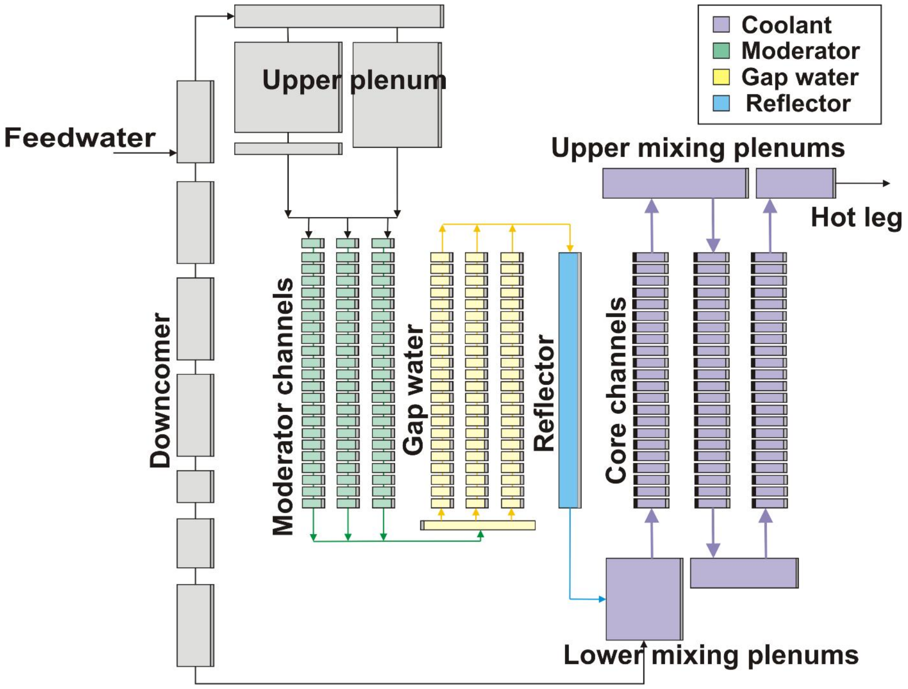

Figure 6. SMABRE nodalization for HPLWR pressure vessel and three-way core. The moderator channels and gap water is flowing between the core channels.

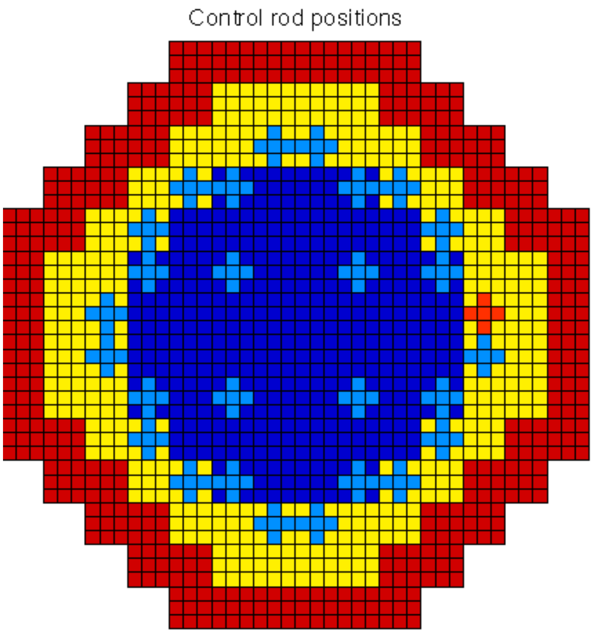

Figure 7. Cross section of HPLWR three-way core and positions of control rods in the core.

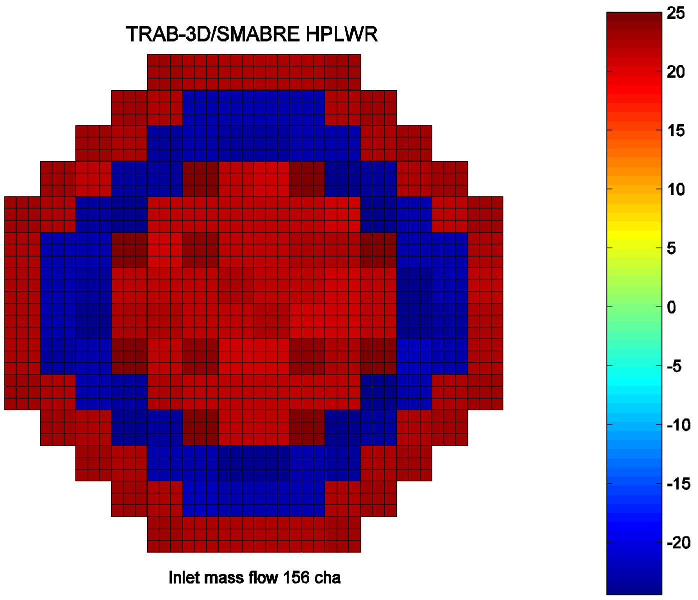

Figure 8. Channel inlet mass flow at core bottom in the HPLWR- three way core with 156 fluid channels.

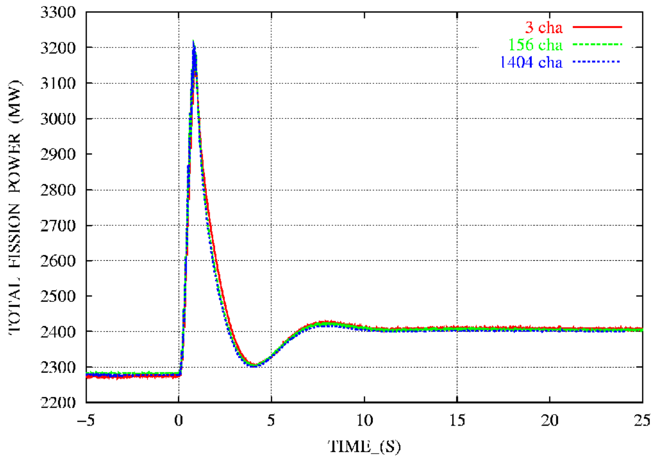

Figure 9. Total fission power of HPLWR core in CRE transient with 3, 156 and 1404 flow channel models.

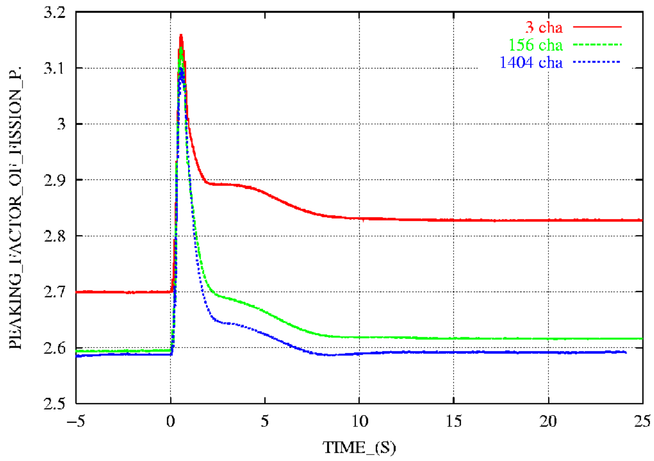

Figure 10. Core peaking factor of fission power in HPLWR core in CRE transient with 3, 156 and 1404 flow channel models.

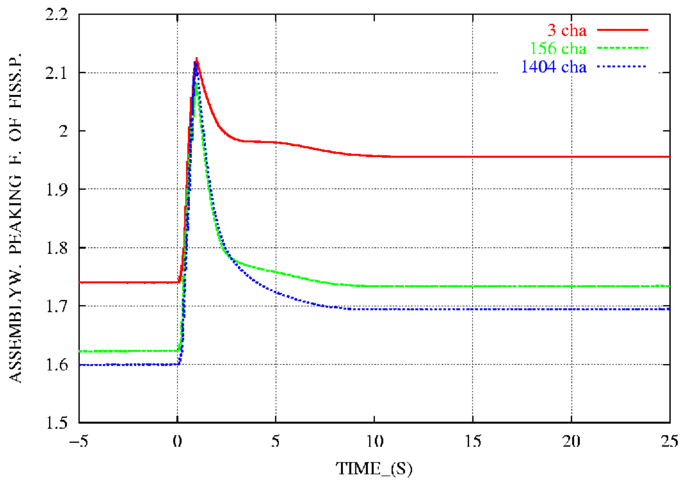

Figure 11. Assembly wise peaking factor of fission power in HPLWR core in CRE transient with 3, 156 and 1404 flow channel models.

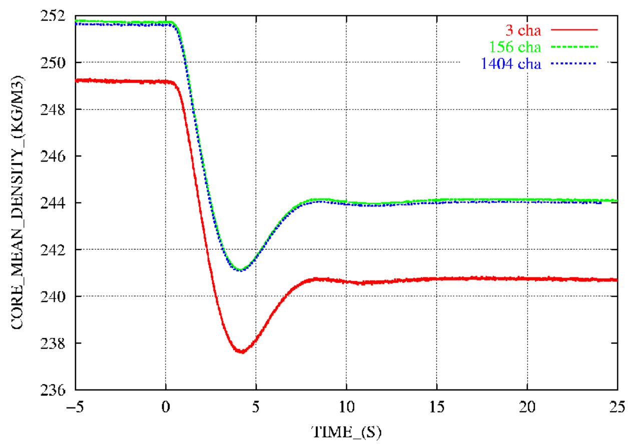

Figure 12. Core peaking factor of HPLWR core in CRE transient with 3, 156 and 1404 flow channel models.

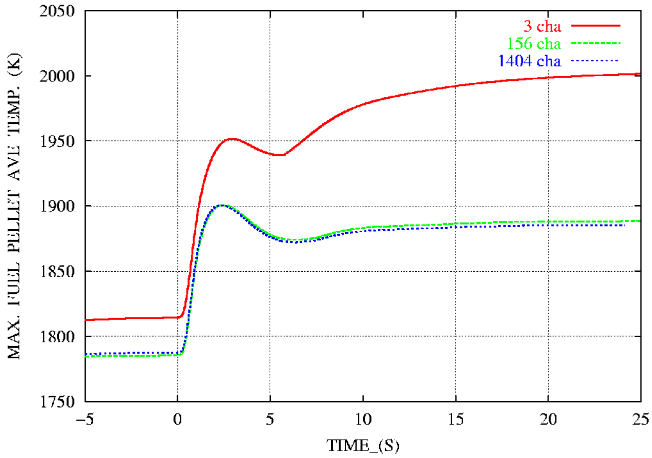

Figure 13. Maximum of fuel pellet average temperature of HPLWR core in CRE transient with 3, 156 and 1404 flow channel models.

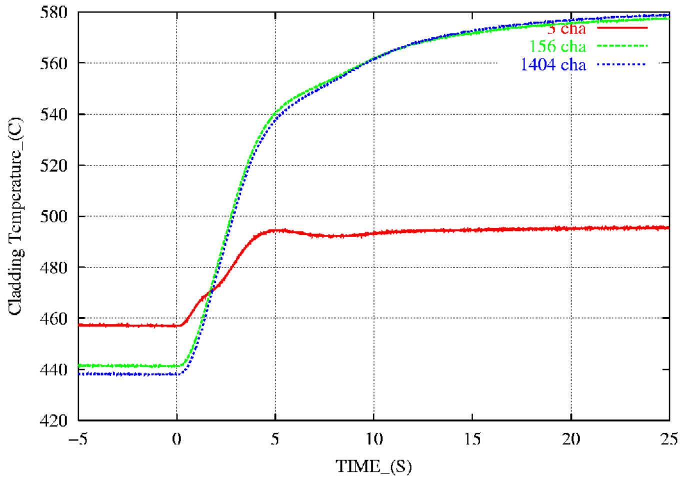

Figure 14. Maximum cladding temperature at the position of one ejected rod in HPLWR core in CRE transient with 3, 156 and 1404 flow channel models.

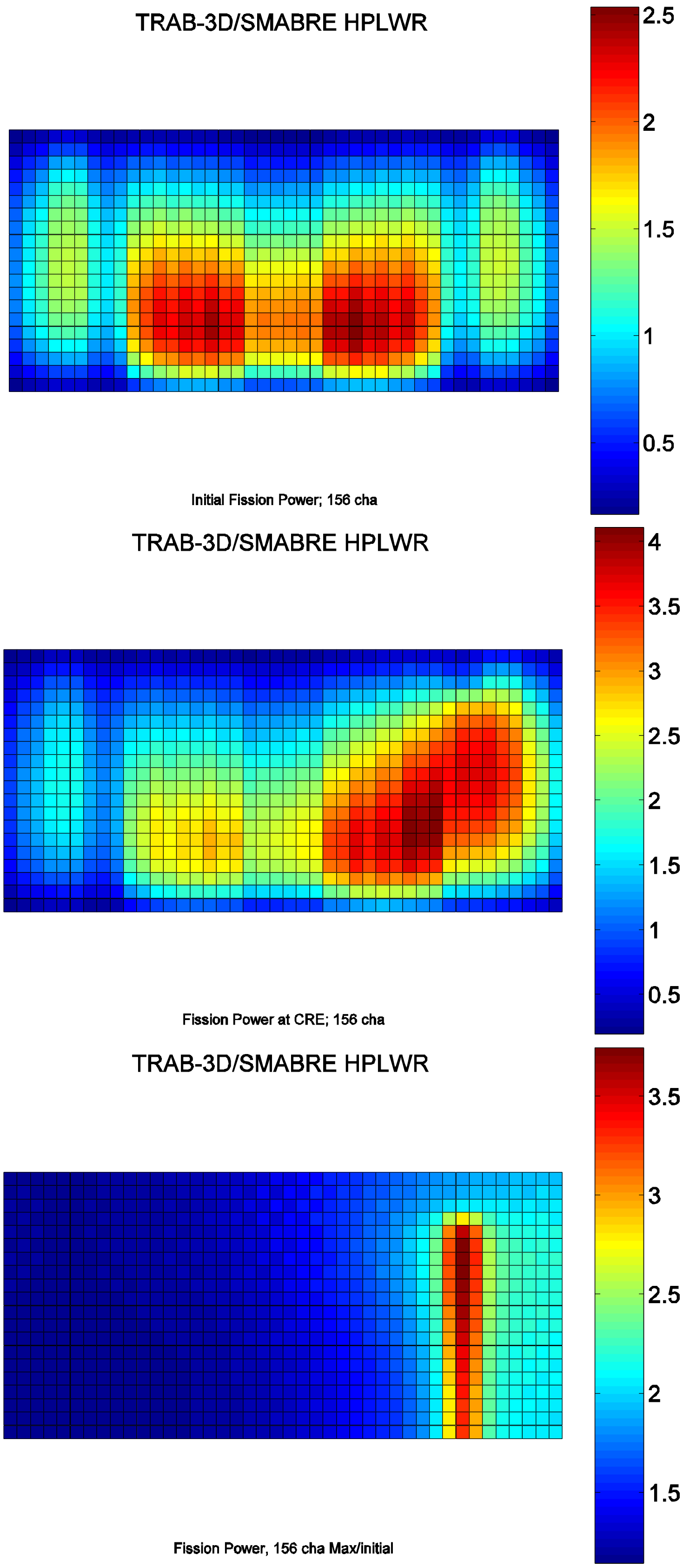

Figure 15. Initial axial fission power profile (a), axial power profile at maximum power (b) and relation between maximum and initial power profiles (c) with 156 channels horizontally in the ejected control rod line.

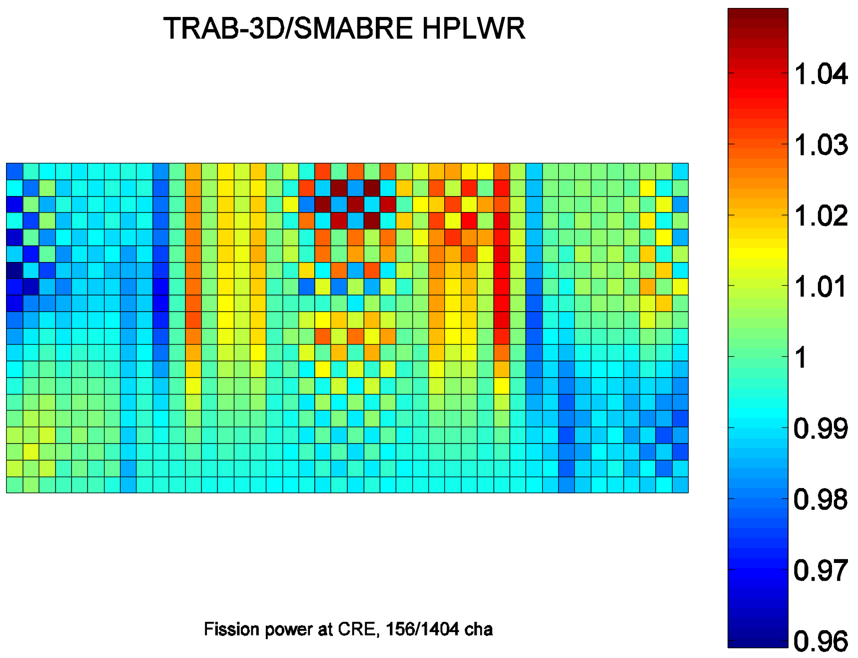

Figure 16. Relation of axial power profiles at maximum power with 156 and 1404 channels horizontally in the ejected control rod line.

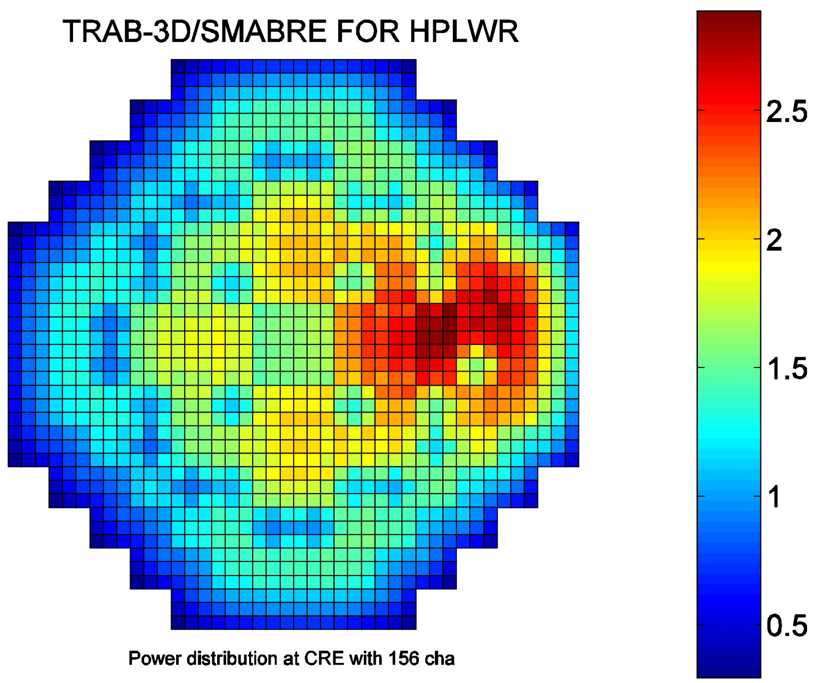

Figure 17. Radial fission power profile at time of maximum power in CRE with 156 channels.

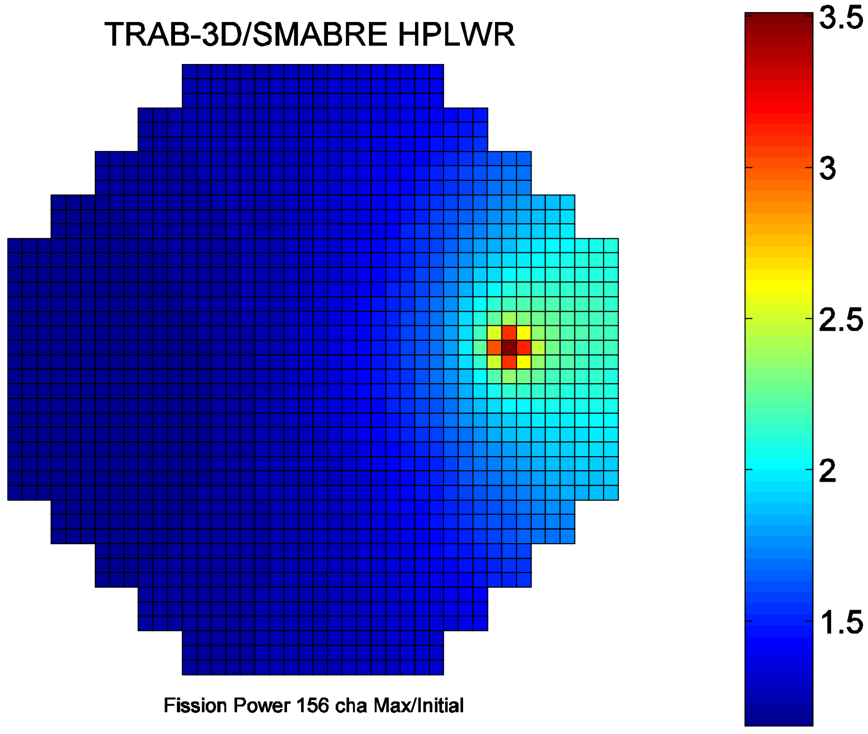

Figure 18. Relation of radial fission power profiles at time of maximum to initial power in CRE with 156 channels.

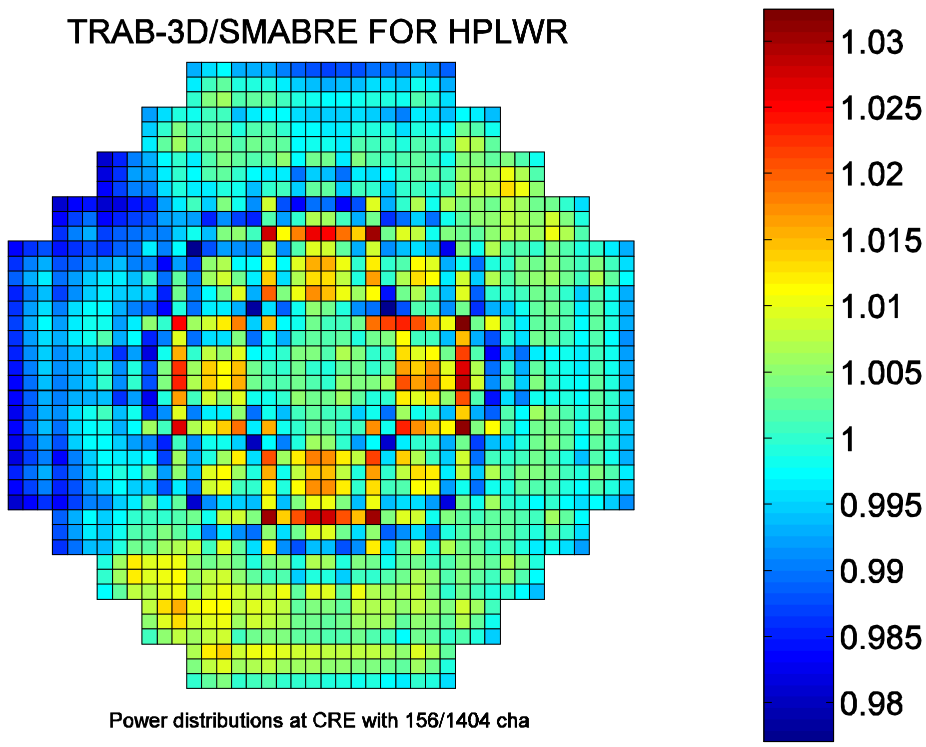

Figure 19. Relation of radial fission power profiles at time of maximum power in CRE with 156 and 1404 channels.

6 Further plans

The new coupling method has been developed and originally tested for BWR and now for PWR cores. After several modifications performed now for PWR, the circuit model of SMABRE will be checked against existing TRAB-models and supplemented where necessary for BWR dynamics applications. At same time the newest extension to the code, deviation of number of fluid channels and fuel assemblies could be checked for modern BWR fuel with internal water channels in assemblies. The BWR case is one of the validation cases. Utilizing the latest extensions also the heavy reflector may be modeled with a small effort and tested in the EPR model. The internal coupling of TRAB-3D/SMABRE will then get its final reporting and the manuals will be updated.

Internal coupling of the codes enables not only the calculation of reversed flows in core, which has been realized in the HPLWR application, but also cross flows in the core. Here, the porous media model PORFLO, developed also in the TRICOT project, could be coupled for the thermal hydraulics in the core. PORFLO includes the momentum equation solution in all flow directions and creates as good a solution as possible in the field of 3-D thermal hydraulics for the reactor dynamic codes. The possibility of describing flow 3-dimensionally in the core necessitates a new approach to the hot channel calculations.

7 Summary

The modeling of thermal hydraulics in the reactor dynamics computer code TRAB-3D is being improved by coupling it internally to the SMABRE code. The present research is a continuation of the work started already in a previous SAFIR project. Main advantages of the internal type of coupling are the possibilities to handle coolant flow reversals in core flow channels as well as modeling of cross flows in a open reactor core like EPR.

In the internally coupled code TRAB-3D performs the neutronics calculation, SMABRE will take care of the hydraulics calculation of the whole cooling circuit including the reactor core, and the heat transfer calculation may be carried out by either code by the user's choice. In the test case for coupling, the plant model, consisting of the whole primary loop of a PWR and the secondary loop from the feedwater tank to the turbine valves has been used.

Identification of differences causing deviating results in code versions and study of new options have been continued. The main new extension to the code, option for a different number of flow channels and fuel assemblies, has been programmed. In this context also accounting for feed backs from channels without fuel assemblies could be applied in TRAB-3D/SMABRE.

As test cases a pump seizure transient has been calculated for an EPR type reactor and control rod ejections for the high pressure light water reactor, HPLWR. The simultaneous development and testing with both the EPR and the HPLWR model have generated a useful cross-checking possibility and application for internal coupling, even though a peculiar oscillation behavior needed some efforts. After some new validation cases and checking the earlier modeled BWR features, internal coupling will be ready for final reporting and updating of the manuals.

References

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