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THE 3D CORE THERMOHYDRAULICS AND NEUTRONICS SOLUTION IN THE TRAB-SMABRE ACCIDENT AND TRANSIENT CODE

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ABSTRACT
The TRAB-SMABRE code is a result of code development efforts carried out at VTT Processes in Finland for calculating transient and accident behavior in Finnish LWR plants. The operating plants are two 770 MWe BWR units in Olkiluoto and two 500 MWe PWR units of VVER-440 type in Loviisa. In addition a new PWR plant of the 1600 MWe EPR type in under construction into Olkiluoto.
The TRAB core model, two group neutronics solution with nodal expansion method, has been initially developed as a transient 3D transient code for the BWR plant transients, and HEXTRAN code for the 3D VVER transients having the hexagonal fuel geometry.
The SMABRE thermohydraulic model is a drift flux based LOCA model. HEXTRAN and SMABRE were coupled in parallel for making the ATWS analyses in VVER plants possible and TRAB and SMABRE were coupled in parallel for calculating the transients in the PWR plants with the squared core array.
As the new step the TRAB core model was coupled internally with the SMABRE for making possible the BWR analyses with the flow reversal possible. and as an optional tool for the PWR plant analyses with the squared core array. The model predicts well the 3D core thermohydraulics with the encapsulated fuel, but not for the open PWR core.
There are plans to overcome this deficiency by using iterative solvers for the matrix inversion. Simulating 100 – 500 parallel core channels demands special iteration capabilities.
The experiences with the model prove proves that the internal coupling gives new possibilities for the core simulation.
The development of a complex neutronics-thermohydraulics code is in such a way sophisticated task that for the complete code validation the resources of several man-years would be necessary. But is this project a special benefit was taken from all validation cases carried out during past 20 years. No own plant specific validation data was collected. Instead the old code version before the new integration was considered as a reference. The codes were installed on a platform, but the codes could be run independently as well. And the results of standalone codes are expected exactly same. Especially in the neutronic part the small deviations cumulated together would lead easily into a unreliable code version. But by requiring the calculation results with the codes on the platform exactly same as standalone and reasonable similar results with the internally coupled code against the standalone code, the integrated code can be considered validated well enough.
The earlier results with the in parallel coupled code system may be repeated with the internally coupled code system as well.
The simulation of the BWR core was found as a large challenge for the integrated code system. In the first phase the behavior was validated against 3-dimensional core wide distributions. The PWR core without void fraction in the stationary state is more easier to be adjusted for the stationary state.
As the dynamic test case for the BWR plant a real plant transient including partial scram by control rod, partial steam flow reduction and reactor pump trip to the minimum speed was selected. This kind of transient includes most essential dynamic characteristics, the power peaking related to the pressure peaking, the effect of the control rods to the core power and effect of the pumps speed to the core flow and core power.
A nrether extensive set of PWR plant transient for the large PWR palnt with an open core has been carried out with the

inparalle coupled code version. These transients are repeated with the internally coupled code version as well.

1. INTRODUCTION

The main tools for analyses of reactor transients at VTT are presently the 3D reactor dynamics code HEXTRAN [1] for cores with a hexagonal fuel assembly geometry and TRAB-3D [2] for cores with a quadratic fuel assembly geometry. HEXTRAN has been applied to safety analyses of VVER-type reactors since early 1990's. TRAB-3D is the latest addition to the code system, and has been applied to BWR and PWR analyses in recent years.

TRAB-3D is a reactor dynamics code with three-dimensional neutronics coupled to core and circuit thermal hydraulics. The two-group neutron diffusion equations are solved by a nodal expansion method in x-y-z geometry within the reactor core, which is divided into homogenized nodes. A basic feature of the method is decoupling of the two-group equations into separate equations for two spatial modes and construction of group fluxes from characteristic solutions to these equations. The two solutions are called the fundamental or asymptotic mode, which has a fairly smooth behavior within a homogenized node, and the transient mode, which has a large and negative buckling in LWR reactors. The fundamental mode is approximated by a polynomial inside the homogenized node. The transient mode deviates significantly from zero only near material discontinuities, and is approximated by an exponential function on each nodal interface.

The nodal equations are solved with a two-level iteration scheme where only one unknown per node, the average of fundamental mode, is determined in inner iterations. The nodal flux shapes are improved in outer iterations by recalculation of the coupling coefficients. Cross sections are computed from polynomial fittings to fuel and coolant temperature, coolant density and soluble boron density

The code can be used for transient and accident analyses of boiling (BWR) and pressurized water (PWR) reactors. It includes the BWR circuit model containing one-dimensional descriptions for the main circulation system inside the reactor vessel including the steam dome with related systems, steam lines, recirculation pumps, incoming and outgoing flows and control and protection systems. The one-dimensional TRAB-1D code has been extensively used for the plant analyses of the Finnish TVO reactors of BWR type. The three-dimensional TRAB-3D has been validated against OECD LWR core transient benchmarks, and real plant transients for the Olkiluoto 1 plant, including pump trip, pressurization transient, instability incident and load rejection test including partial asymmetric scram. Validation of the code is summarized in [5]. TRAB-3D is now in production use for plant transient and accident analyses.

The system code SMABRE [3] models the thermohydraulics of light water reactors using a generalized nodalization scheme similarly with system codes. Originally the code has been developed for small break analyses of PWR and BWR plants. The code can handle two-phase flow in forced flow and stagnant situation, as well as the forced flow during the normal operation and natural circulation after the reactor coolant pump trip. Both codes have been entirely developed at VTT. The validation of SMABRE includes mainly calculations related to tests in integral facilities, which were often arranged as international standard problems by the OECD/CSNI. Validation cases of SMABRE are listed in e.g. [6]. As compared to large system codes, like the RELAP5, CATHARE, and the ATHLET, SMABRE has a limited simulation capability, but by concentrating on the most important modelling aspects around the LWR safety the code can be considered as a rather versatile analysis tool. In the combined products in simulators and integral code systems the analysis the transients and accidents have been possible, which are outside the applicability range of the traditional system codes.
For PWR applications the TRAB-3D and SMABRE codes have been coupled earlier by using the parallel coupling principle: the full core TRAB-3D hydraulics coupled to neutronics and heat transfer, and the coarse SMABRE core hydraulics with fewer channels are solved in parallel. The rest of the circulation system is solved with SMABRE.

VTT's dynamics codes have performed well in all the situations that they have originally been designed for. The most important limitation of the present code models is their inability to handle coolant flow reversal in the core channel, a phenomenon that can be encountered in e.g. BWR ATWS cases or VVER power excursions. To remove this limitation, the TRAB-3D neutronics and the SMABRE thermal hydraulics code have been coupled together using an internal coupling scheme. In the new concept TRAB-3D will perform only the neutronics calculation, SMABRE will take care of the hydraulics calculation of the whole cooling circuit including the reactor core, while the fuel pellet heat conduction and heat transfer on the cladding surface may be calculated by either code, by the user's choice.

2. NEUTRONIC-THERMOHYDRUALIC COUPLING PRINCIPLES

Three different modes for coupling dynamic core models and system codes are utilised worldwide, called external, internal and parallel coupling. With external coupling the whole core calculation is carried out by the dynamics code, and the system code is used for the rest of the circuit. This approach has not been applied at VTT.
The first realized coupling concept at VTT is parallel coupling, the principles of which are illustrated in Figure 1. In this mode the two coupled codes are running independently with minimum amount of data transfer between the modules. Thermal-hydraulics of the core is calculated with both codes in parallel, but rest of the circulation system is solved with SMABRE. The connection is carried out by data exchange once in a time-step for core inlet flow and outlet pressure into the TRAB direction and core power distribution into the SMABRE direction. The TRAB-3D / SMABRE parallel coupling was validated against the OECD benchmark calculation of main steam line break transient in the TMI-1 PWR plant [7]. However, the first application realised with the parallel coupling principle was for 1D neutronics in 1988 and for

hexagonal 3D neutronics in 1991 – 1992.

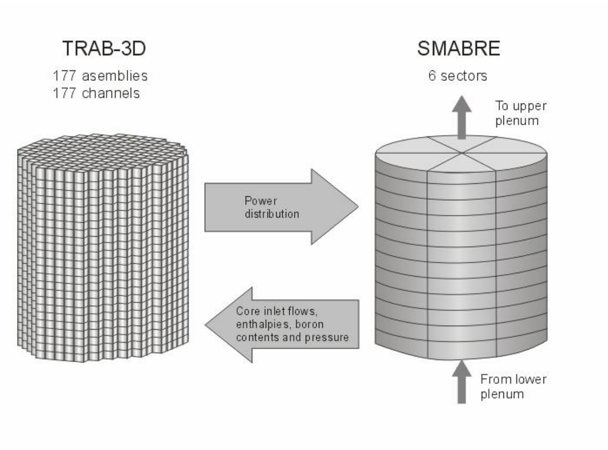

Figure 1. The parallel core coupling principle

In Figure 2 the internal coupling principle has been illustrated. Most of the parameters are transferred in the interface routines called from the main program level. Recalculation of the thermohydraulics is needed after each neutronic iteration. The entire internal coupling was realized on a platform, which allows running all of the code coupling modes, TRAB-3D alone, TRAB-3D coupled with SMABRE parallelly and TRAB-3D coupled with SMABRE internally. The stationary run with SMABRE is typically calculated in a separate run. The platform, however, includes the possibility for an independent SMABRE run, as well as starting the transient calculation with a SMABRE stationary phase from its own input and activating the neutronics in the beginning of the transient.
The principles of connecting the circuit model with the core model are also illustrated in Figure 2. The reactor vessel may be divided into sectors and radial rings for the non-symmetric flow calculation. In the core inlet several rings and sectors may exist, and each section is connected with a number of individual fuel and flow channels of the core. This allows taking into account some transverse features in the thermal hydraulics calculation at the core inlet.

TRAB-3D solves the core neutronics and SMABRE the thermal hydraulics in the reactor systems outside the core and in the core. The heat conduction equations in the fuel are solved in both codes in parallel, by using identical material properties for the fuel rod. For TRAB-3D coupling SMABRE delivers the surface heat flux rates. The parallel calculations help in analysing the calculation methods for the heat conduction. The fuel temperature feedback for the neutronics may optionally be selected based on either the TRAB-3D or SMABRE result.

3. REALIZATION OF THE COUPLING

The plant input used in the development and testing was the TRAB-3D input for the 500 fuel element Olkiluoto BWR core and the 242 node input of SMABRE, in which the core is described by four sectors and 25 axial nodes. The input has originally been developed for the BWR simulator applications. In the initialization phase the core nodalization is automatically expanded into 500 hydraulic channels, one for each fuel element, and after this expansion the thermal hydraulics nodalization contains 12642 nodes.

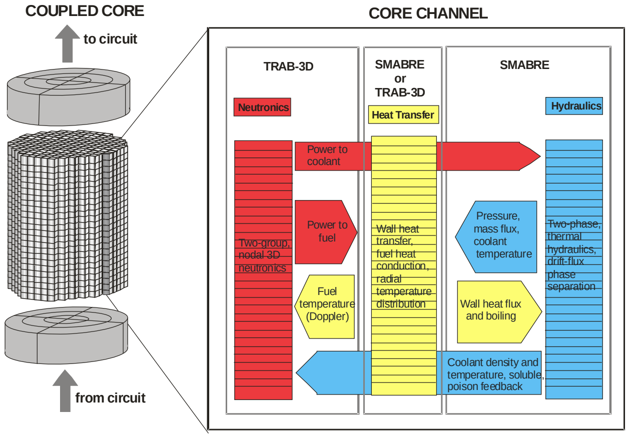

Figure 2. The internal core coupling and connection into radial and circumferential zones in the vessel

The TRAB features for describing PWR and BWR bundle geometry and fuel compositions have been maintained. Each bundle is related to an individual flow channel, flow channels may have axial subdivisions, and each fuel element may have an individual fuel rod composition. The SMABRE nodalization enables multidimensional subdivision in the lower and upper plenums through circumferential sectors and radial rings.
The modelling of controls systems as well as the methods for initiating disturbances through TRAB-3D are all included in the coupled code. All the plant controls included in SMABRE are also available, and the input and output signals for control and disturbance functions can be transferred from one code to another according to the user's needs. Some of the control system models are overlapping, but they may be used optionally and compared with respect to similarity.
In the original TRAB-3D the main iteration was carried out for neutronics and inside these external iterations TRAB-3D thermohydraulics was typically repeated ten times. In the internal coupling SMABRE is calculated only once after each neutronics iteration. The convergence of the iteration is determined by TRAB-3D, based on analysing the neutronics convergence. During each outer iteration the new neutron flux corresponding to the core void, coolant temperature and fuel temperature distribution is searched. The heat conduction equation is integrated with new heat transfer and power generation parameters during the iteration step, and as a consequence the core heat flux distribution is changed. In SMABRE the thermal hydraulics is solved by a matrix inversion. The present matrix inversion is based on Gaussian elimination. An iterative matrix inversion has been tested for future use, allowing the modelling of open core structure as well.
The detailed fuel element specific information, with different types of fuel loaded into the core, is included

through TRAB-3D input. Initially, the SMABRE input is defined for few radial zones and few circumferential sectors and the core inlet enthalpy into individual channels depends on this subdivision. In the initialization phase core division in few (typically 1 to 18) zones is divided according to the fuel assemblies defined in the TRAB-3D input, still in this phase with identical characteristics, as defined for the zones. The original TRAB-3D input may be used for SMABRE both in the independent and coupled calculation mode. The core may include different fuel element types, with different inlet orifice pressure loss coefficients, local flow area, heat transfer characteristics and local friction, but the original SMABRE input includes only the averaged element characteristics. After reading the TRAB-3D input the element specific information is updated into individual fuel elements, and the calculation is stabilized. After the first run the initialization part automatically calculates flow area and friction data for the original core zones in such a way that in the next run the need for the stabilization is reduced.
The phase separation in TRAB-3D is calculated by using the slip model, i.e. the velocity ratio between the steam velocity and liquid velocity, which is calculated by using separate slip correlations. The flow separation in SMABRE is based on the drift-flux model which allows the simulation of flow reversal in the core during the transient. For accurate thermal hydraulic comparisons an optional solution was created, where the TRAB-3D single-phase and two-phase frictions may be directly used with their original formulations: the slip correlation of TRAB-3D was rewritten into the drift-flux format. The evaporation rate for the subcooled boiling was included as an optional solution, too. The TRAB correlations are formulated as fuel specific. By simple options the user may select, if the original TRAB or existing SMABRE correlations are used for these purposes. The material properties in the fuel rod may be applied based on either the TRAB-3D formalism or SMABRE formalism.

Different versions of the fuel heat transfer calculations may be selected optionally. In one mode the fuel calculation is carried out totally by SMABRE, with the same radial meshing as in TRAB-3D and the Doppler feedback is directly transferred to neutronics. In another mode SMABRE calculates only the heat transfer on the fuel surface and it is transferred to TRAB, which results in a more simplified model than in the present TRAB-3D. The first mode gives better stability characteristics.

4. STEADY STATE TESTING RESULTS

The internally coupled steady state solution has been tested against both the production version of TRAB-3D and the fuel management code SIMULATE [8].
Compared against TRAB-3D the difference in the steady state bundle flow distribution calculated with the coupled code is from +3 to -4 % (TRAB-SMABRE/TRAB-3D, see figure 3), and against SIMULATE from +4 to -5 % (see Figure 5). This accuracy is quite satisfactory when comparing two different thermal hydraulics calculations.

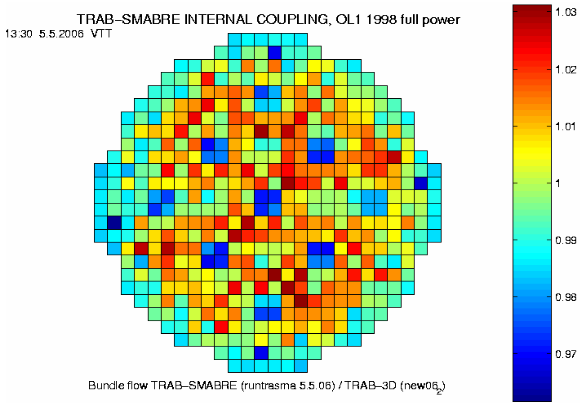

Figure 3. Deviation of the bundle flow distribution between the internally coupled TRAB-SMABRE and original TRAB-3D

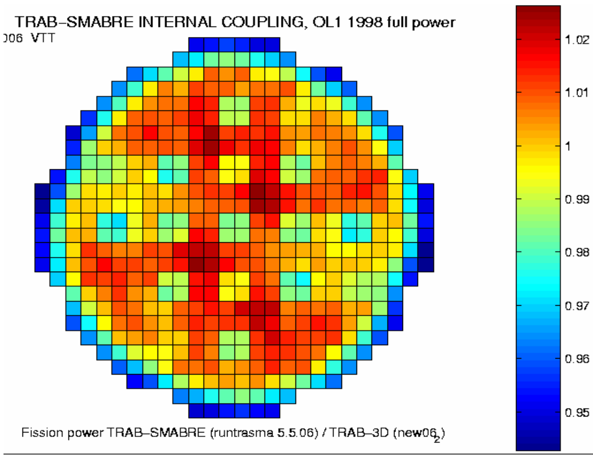

Figure 4. Deviation of the radial power distribution between the internally coupled TRAB-SMABRE and original TRAB-3D

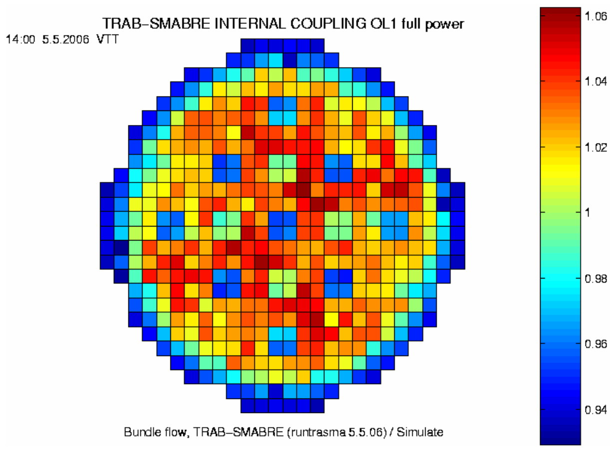

Figure 5. Deviation of the radial flow distribution between the internally coupled TRAB-SMABRE and SIMULATE

In the relative fission power distribution the difference in the results of the coupled code against TRAB-3D (TRAB-3D-SMABRE/TRAB-3D, see Figure 4) is of the order ± 2 %, except for the outermost circle of bundles where it is around 4-5 %.

fission power to the 75 % level, the reactor pump coastdown (a flow transient) to the minimum speed resulting with the 60 % reactor power, and a steam line flow disturbance with a 13 % steam line flow reduction during 0.6 seconds were

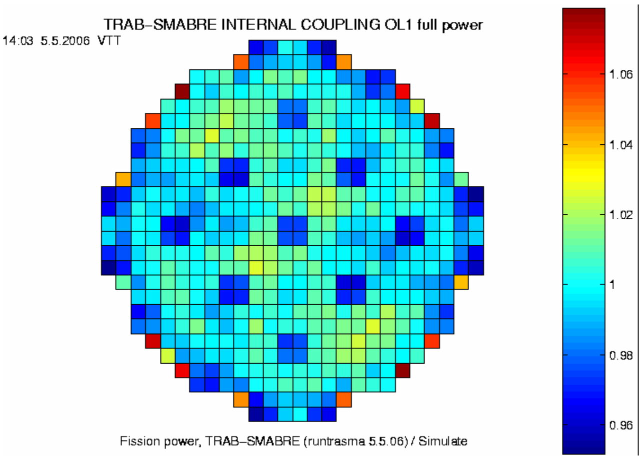

Figure 6. Deviation of the radial power distribution between the internally coupled TRAB-SMABRE and SIMULATE

Against SIMULATE the difference is also around ± 2 %, but in certain bundles in the outermost zone the difference is up to 8-12 % (see Figure 6). The same difference is found between TRAB-3D and SIMULATE, too, and probably derives from differences in core neutronic boundary conditions. The accuracy of the steady state calculation is thus quite good, and suitable for both PWR and BWR calculations.

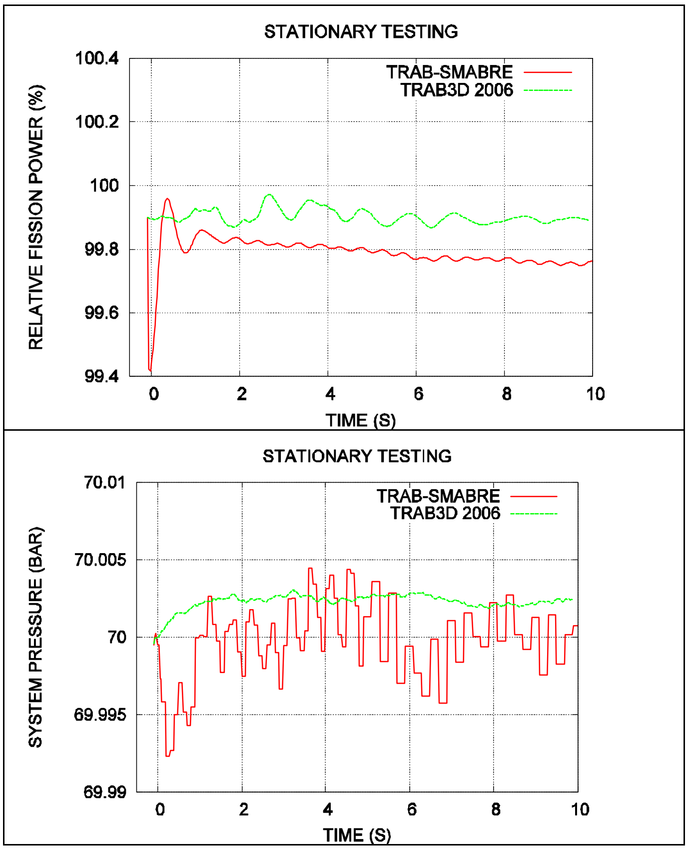

Figure 7. The results from the steady state performance

Three single parameter disturbances have been tested so far: the partial reactor scram (a reactivity transient) reducing the

5. DYNAMIC TESTING RESULTS

Dynamic testing of the coupled code is presently in progress, and some preliminary results will be shown here.
Dynamic testing was started by calculating a null transient in order to demonstrate a stable initial state. The pressure controllers of each code were included and tested against each other. This testing revealed further need to refine the initialization of the stand-alone SMABRE. Presently small disturbances still remain in the process of switching from SMABRE to the coupled code (see Figure 7.

Three single parameter disturbances have been tested so far: the partial reactor scram (a reactivity transient) reducing the fission power to the 75 % level comparison is shown in Figure 8.

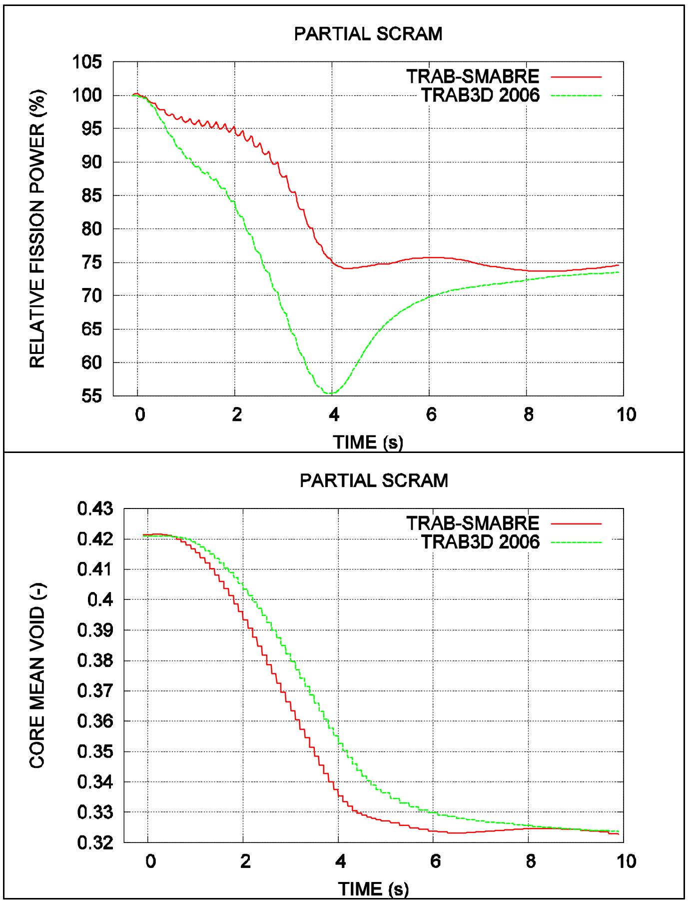

Figure 8. The results for the partial scram

The results for the reactor pump coastdown (a flow transient) to the minimum speed resulting with the 60 % reactor power are shown in Fig. 9

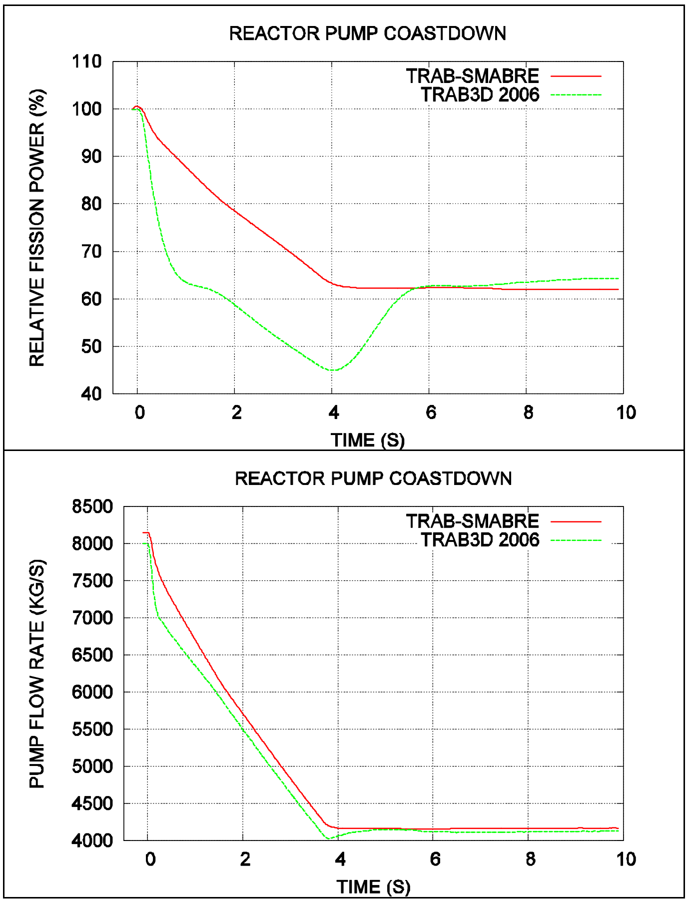

Figure 9. The results for the reactor pump coastdown

.The results for a steam line flow disturbance with a 13 % steam line flow reduction during 0.6 seconds are shown in Figure 10.

The dynamic tests include rapid thermal hydraulic phenomena and are challenging to the coupled code

The results of the two codes are qualitatively similar in the first two test cases, partial scram and pump coastdown. In both cases the response in fission power is slower in the coupled code than in the reference TRAB-3D. In the pump coastdown case both codes have used their own pump models and these have to be compared against each other.

In the steam line flow disturbance the results are again qualitatively similar in both codes, but the pressure response calculated by TRAB-SMABRE is 5 times the response by TRAB. Both codes have used their own models for the steam lines and steam dome, and the modelling needs to be compared in order to clarify the differences in their results.

For calculation of BWR transients the dynamics of the coupled code will need to be studied further and the circuit modelling as well as the dynamics calculation procedure supplemented where necessary.

All the tests have been carried out with a BWR test case so far, which has been more of a challenge to the code thermal hydraulics. On the other hand the test cases allowed identifying needs for remodelling and revealed code shortcomings and errors, which would have been difficult to notice with less challenging test cases. Next step with the coupled code will be testing of a PWR (EPR) model.

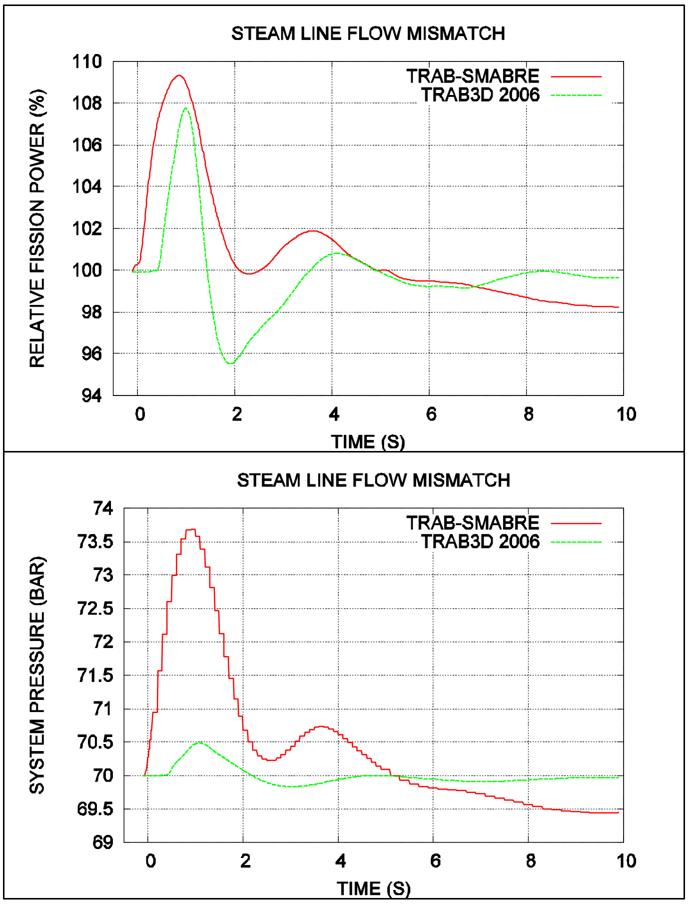

Figure 10. The results for the steam, line flow mismatch

All the tests have been carried out with a BWR test case so far, which has been more of a challenge to the code thermal hydraulics. On the other hand the test cases allowed identifying needs for remodelling and revealed code shortcomings and errors, which would have been difficult to

6. CONCLUSIONS

The three-dimensional TRAB-3D core dynamics code has been successfully coupled to the thermal hydraulics system code SMABRE, and a satisfactorily working steady state solution has been achieved. The coupling has been more laborious than could be foreseen, due to the inherently coupled nature of the physical processes and the different solution philosophies of the two codes.
The coupling has been carried out in a platform, which includes a lot of improvements into the user interface. This has allowed making detailed comparison between different code versions and coupling modes with a vastly reduced

need of manual intervention compared to earlier methods.
Accuracy of the steady state calculation with the coupled code is sufficient for BWR and PWR calculation.
Dynamic testing with single disturbances in a BWR test case shows qualitatively similar results with the coupled code and the TRAB-3D code, but further study is needed before BWR transients can be calculated. Calculation of PWR (EPR) is not expected to add any major problems to the ones already solved.
Besides solving the flow reversal limitation of the present dynamics models, a successful coupling will allow more realistic modelling of an open core. It will allow new options to couple the core model to other thermal hydraulic system codes, and enable further work to couple core neutronics to a thermal hydraulics porosity type model.

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