Development of Effective Algorithm for Coupled Thermal-Hydraulics – Neutron-Kinetics Analysis of Reactivity Transient

Licentiate Thesis
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This thesis is dedicated to my husband...
Abstract

Analyses of nuclear reactor safety have increasingly required coupling of full three dimensional neutron kinetics (NK) core models with system transient thermal-hydraulics (TH) codes. To produce results within a reasonable computing time, the coupled codes use different spatial description of the reactor core. The TH code uses few, typically 5 to 20 TH channels, which represent the core. The NK code uses explicit node for each fuel assembly. Therefore, a spatial mapping of coarse grid TH and fine grid NK domain is necessary. However, improper mappings may result in loss of valuable information, thus causing inaccurate prediction of safety parameters.

The purpose of this thesis is to study the sensitivity of spatial coupling (channel refinement and spatial mapping) and develop recommendations for NK-TH mapping in simulation of safety transients – Control Rod Drop, Turbine Trip, Feedwater Transient combined with stability performance (minimum pump speed of recirculation pumps).

The research methodology consists of spatial coupling convergence study, as increasing number of TH channels and different mapping approach the reference case. The reference case consists of one TH channel per one fuel assembly. The comparison of results has been done under steady-state and transient conditions. Obtained results and conclusions are presented in this licentiate thesis.

**Keywords:** Light Water Reactor, BWR, RELAP5, PARCS, Coupling TH/NK, Mapping, Spatial Refinement, Turbine Trip, Feedwater Transient, Control Rod Drop, Reactor Stability.
Acknowledgment

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A special thanks to my husband, Jyrki, who at the same time was the sharpest judge of my work and the biggest supporter. Thank you for all your love and patience!

Many thanks to my workmates: Tita, Sean, Francesco, Thanh and Andrei, for the never-ending talks and pleasant time. It was nice to work with all of you!

I wish to thank NORTHNET Road Map-2 for the financial support.

Dziękuję również moim rodzicom za niekończące się wsparcie i wiarę!

Once again thank you!
Jeszcze raz dziękuję Wam!
List of Papers and Publications


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Chapter 1

Introduction

1.1 Objectives

This investigation is a part of work in NORTHNET Roadmap 2 (Primary System Thermal-Hydraulics). The area of focus is effectiveness and accuracy of TH/NK (Thermal-Hydraulics/Neutron-Kinetics) coupling methods.

The main objective of this research is to develop and validate a methodology for the coupled TH/NK analysis, which enables to achieve higher accuracy and computational efficiency in predicting the safety importance of transients and accidents. It is important to establish an effective treatment of core thermal-hydraulics with small number of representative channels while using full 3D neutron-kinetics solution.

Additionally, the project examines the tools, qualifies the methods and selected models of coupled codes system for the analysis of BWR (Boiling Water Reactor) reactivity transients, including core stability at operating conditions. The evaluation of capability and limitations of existing coupled TH/NK will allow for improving multi-dimensional TH/NK coupling and developing recommendations for effective TH/NK coupled treatment.
1.2 Background

Current computational tools allow for coupling of full three dimensional core models with system transient codes, which gives advantage of understanding interaction between reactor core behavior and plant dynamics. The TH/NK coupling provides new capabilities for understanding a NPP (Nuclear Power Plant) as a whole system including proper neutronic feedbacks. This field of study has also unresolved issues, such as different spatial description of the reactor core between TH and NK model. The TH code (e.g. RELAP5) uses few, typically 5 to 20 TH, channels, which represent the core. The NK code (e.g. PARCS) uses explicit node for each fuel assembly. Therefore a mapping between TH and NK is necessary.

BWR core has a large number of fuel assemblies (about 700). The one channel per assembly coupling of TH and NK model of such core requires significant computational resources. Thus, there is a great interest in mapping optimization, reducing number of TH channel, while still maintaining desired accuracy.

The mapping entails loss of important information in both directions TH↔NK, as described in Figure 1. The increase of number of the TH channels leads to loss of computational efficiency and in case of reactivity transients, these limitations can become significant.
Figure 1: Loss of information due to incorrect mapping

1.3 Literature review

The problem of mapping has been discussed for many years by many researchers; however none of them has provided a sufficient algorithm for mapping. The most important conclusions are summarized below.

1.3.1 "PWR REA sensitivity analysis using TRAC-PF1/NEM". - N. Todorova, K. Ivanov, 2001

In the paper [1] authors performed sensitivity studies on spatial mesh overlays for PWR Rod Ejection Accident (REA). It was presented that
REA simulation shows sensitivity to spatial coupling. Based on the results authors concluded that TH feedback is non-linear therefore can not be separated in REA analysis.

1.3.2 "Investigation of spatial coupling aspects for coupled code application in PWR safety analysis" - N. Todorova, K. Ivanov, 2002

The authors of the paper [2] performed research on the sensitivity of coupled TH/NK system code’s results to the spatial mesh, which was used for PWR transient analysis. To analyze the effect of spatial nodding authors developed three different models in cylindrical geometry (2 models) and Cartesian geometry (1 model), and compared the results for different conditions (BOC – beginning of cycle, EOC – end of cycle for conditions HZP – hot zero power and HFP – hot full power). It was pointed out that in the case of REA (TMI-1 REA Benchmark) simulations show sensitivity to the spatial coupling, especially in the radial plane. Authors demonstrated that in case of asymmetric transients, geometric refinement has large influence on local parameters and control rod worth – NK mesh refinement impacts the local predictions in the same way as the TH refinement impacts global predictions. Because the local and global predictions are also sensitive to the TH refinement, the proper radial, axial nodding and mapping (spatial mesh overlays) schemes have to be developed for a given reactor and given transient.

1.3.3 ”Using the OECD/NRC PWR MSLB benchmark to study current numerical and computational issues of coupled calculations”, K. Ivanov, N. Todorova, E. Sartori, 2003

In the following paper [3] authors performed comparative analysis of PWR Main Steam Line Break (MSLB) with the 3D core TH models. It was discovered that the source of local parameter deviation is geometry approximation of the core TH. Authors present one example in which the reference data had a visible power peak at the position of the stuck control
rod, but the results obtained from simulations (18-channel model) didn’t show power peak. Due to incorrect mapping the power peak was not found in obtained results. It was concluded that the power peak was averaged with surrounding assemblies.

1.3.4 "OECD/NRC BWR Turbine Trip Transient Benchmark as a Basis for Comprehensive Qualification and Studying Best-Estimate Coupled Codes", K. Ivanov, A. Olson, E. Sartori, 2004

The article [4] focuses on OECD/NRC BWR coupled code benchmark. Authors mentioned that number of TH channels and spatial mapping is important modeling issue and it was found to be reason for differences obtained from participant results.

1.3.5 Neutronics/Thermal-Hydraulics Coupling in LWR Technology: State-of-the-art Report (REAC-SOAR), OECD, NEA; 2004, CRISSUE-S – WP2

In the report [5] authors pointed out that a number of different rules must be respected during mapping. It was recommended to group the channels in such a way that different neutronics and thermal-hydraulics information are conserved. The examples of possible groupings were introduced, such as: the relative power, coolant flow, void distribution, type of bundle throttling (orificing), type of fuel (enrichment), etc. Authors recommended keeping core symmetry during mapping and concluded that the usual approach is to group fuel assemblies taking into consideration initial steady-state power level (this method is known as “power flattering” mapping). Authors found that incorrect mapping was a reason for smoothing of the power distribution and small number of channels causes overestimation of local parameters. In case of BWR stability analysis, especially in the case of regional instability, a different approach was proposed. Authors recommend taking into consideration the neutron flux fundamental and first azimuthal mode obtained from steady-state calculation. It was pointed out that the spatial coupling effect created by
the void feedback is important in the regional instability events – the first azimuthal flux mode is deformed. In the regional instability mapping the hot bundles location and higher mode power shape must be properly grouped. One can find information about the significant number of hot bundles – the hot bundles should be isolated as individuals regions and surrounded by regions that have a bigger flow area. The report provides many recommendations and tips, which will be taken into consideration during this investigation.

1.3.6 "Assessment study of the coupled code RELAP5/PARCS against the Peach Bottom BWR turbine trip test", A. Salah, G. Galassi, F. D’Auria, B. Kočar, 2005

The article [6] describes the studies of coupled code RELAP5/PARCS behavior against the Peach Bottom BWR turbine trip test. The authors during their investigation assume that 77 heated channels are enough sufficient to represent the 764 fuel assemblies. The assemblies are grouped together according the relative power, coolant flow area, bundle type and inlet throttling.

1.3.7 "Coupled 3D neutronic and thermal-hydraulic codes applied to control rod ejection accident in PWR”, M. de Carvalho Junior, Osvaldo, 2005

The thesis [7] is devoted to 3D analysis of core behavior during a fast REA in a PWR. Author concludes that choosing mapping for a given transient is very difficult and a lot of requirements must be fulfilled. One requirement is to map similar neutronic assemblies into one TH channel, taking into consideration their design and other important characteristics such as coolant flow, void distribution, orificing, etc. During fast control rod ejection transient the author used 241 neutronic assemblies, which are grouped into 19 TH channels. The geometry grouping with separation of one channel (where control rod is ejected) was applied. The steady-state calculation showed good consistency between the simulated and reference power distribution, which proves that the applied mapping was well chosen.
1.3.8 “Challenges in coupled thermal–hydraulics and neutronics simulations for LWR safety analysis”, K. Ivanov, M. Avramova, 2007

The article [8] describes the coupled phenomena and challenges on both global (assembly-wise) and local (pin-wise) levels. The authors divided spatial coupling methods into two categories: fixed and flexible. The fixed coupling represents one channel per fuel assembly coupling of TH and NK model while flexible coupling is defined by mapping schemes. Authors again pointed out that mapping is challenging task and detailed mapping gives better results in case of coupled calculations.

1.3.9 ”Validation of coupled thermal-hydraulic and neutronics codes in international co-operation”, K. Ivanov, E. Sartori, E. Royer, S. Langenbuch, K. Velkov, 2007

The paper [9] focuses on OECD/NRC PWR MSLB (Main Steam Line Break) benchmark, which is based on real plant design and operational data for the TMI-1 NPP. The problem of the MSLB Benchmark was also mentioned in the paper [3]. The most important purpose of this benchmark was to identify the capability of coupled system codes for analyzing complex behavior. During this benchmark some discrepancies in the obtained results were found (e.g. the core averaged radial distributions, local axial distributions, and maximum nodal Doppler temperature). The authors found that the reason for discrepancies was different spatial coupling schemes: from very detailed spatial mesh overlays (one neutronic node per thermal-hydraulic channel) to coarser mesh overlays (18-channel model). Deviations of up to 15% in radial power distribution were observed due to the different thermal-hydraulic and heat structure nodalization and spatial mapping of TH channels to NK assemblies.

In the same paper one can find information about the BWR TT (Turbine Trip) benchmark, which gave an opportunity to study the impact of different TH and NK models on code predictions and to identify key
parameters for modeling of a TT transient. The results provided by participants allowed evaluations of key parameters and sensitivity studies (performed by CEA Saclay and PSU). The main sensitivity study object was the number of TH channels and spatial mapping schemes. The sensitivity studies showed that 33 channels mapping, which was used for TT benchmark was good enough to provide global core behavior, but detailed information about the local power distribution needed higher number of channels. In addition, the 33 channels were not able to give good accuracy for regional events such as out-of-phase oscillation. The BWR TT benchmark provided valuable information about consequences of insufficient number of TH channels and about the sensitivity studies. One should be very careful while performing coupled TH/NK analysis, as the mapping algorithm and the number of TH channels have a large impact on the results. This is why sensitivity studies are always needed.

1.4 Literature review summary

Based on practical experience and observations, several people (K. Ivanov, N. Todorova, M. Avramova) raised a problem of mapping in a number of publications. They proposed different kinds of possible mapping strategies and pointed out the key parameters, which should be taken into consideration during mapping.

The improper mapping was found as reason for many discrepancies between the simulation and reference cases. Despite many needs, a good mapping methodology has not yet been developed.

It was also concluded that the type of transient determines the mapping scheme. However it is not clear what kind of mapping approach one should apply for different transients.

The low number of publication shows that the area of coupling TH/NK codes is still not fully explored – this is why this investigation is devoted to mapping issues. All mentioned authors’ experience and suggestions will be taken into account in this project.
1.5 Thesis overview

The presented work includes following tasks:

- Examination of the TH/NK coupling in RELAP5/PARCS, with particular focus on effectiveness and accuracy of methods used to group the core’s fuel assemblies for thermal-hydraulic treatment in a full-core 3D NK model in both steady-state and selected transients.
- Development of requirements and recommendations for coupled calculations for a set of selected transients.
- Application of TH/NK code to the reactor transient scenario of safety significance.
- Review NK and TH in terms of loss of the significant information due to coupling TH/NK channels.

In the Chapter 2 adopted TH and NK codes and models are presented and described. Additionally coupling process between TH and NK is explained.

Mapping definition and types of mapping are described in Chapter 3. In addition problem of core inlet orificing during process of spatial refinement is explained and adopted solution is presented.

Chapter 4 presents the results of steady-state from both models and in Chapter 5 simulation results from selected transient are provided. Postulated transient scenarios are described as well.

Chapter 6 collects the set of the requirements and recommendations, which should be taken into consideration while designing the input deck for new transient code analysis with coupled TH/NK.

Chapter 7 presents plan of future work, which has to be done to fully cover mapping area and Chapter 8 concludes contents of this thesis.
Chapter 2

Adopted codes and models

2.1 Thermal-Hydraulic code and model

2.1.1 Code description

This investigation involves application of U.S. NRC code, namely RELAP5. RELAP5 is the light water reactor (LWR) transient analysis code, which is used for rulemaking licensing audit calculations and evaluation of operator guidelines [10].

RELAP5/MOD3.3 is a highly generic code that, in addition to calculating the behavior of a reactor coolant system during a transient, can be used for simulation of a wide variety of hydraulic and thermal transients in both nuclear and nonnuclear systems involving mixtures of steam, water, noncondensable, and solute. More detailed information can be found in RELAP5 manual [10].

RELAP5 was chosen for this investigation because it is commonly used by the industry for nuclear power transient investigations and by regulatory body (e.g. Swedish Radiation Safety Authority) for verification of power uprate simulations.
2.1.2 Model description

The model employed in the investigation is a detailed representation of a typical Boiling Water Reactor (BWR). It has been modeled in the RELAP5 input by using code built-in components. The model is fully one dimensional (1D). In this project, two TH models: Model I and Model II. In both models, the number of TH channels varies from 5 to 700 channels. The 700 TH channel model corresponds to the reference case – one channel per one fuel assembly coupling. Because of transient complexity, additional refinements were done in Model II: multiple feedwater systems, downcomers, recirculation pumps, and core together with the lower plenum were divided into four zones together. This is needed for transient scenarios with strongly asymmetric conditions e.g., feedwater transient.

Both models use fine refinement of the fuel bundle channels and heat structure, each channel was divided into 27 volumes - 25 equidistant axial volumes with a node size of 0.1484 m and 2 unheated ends. The fine nodalization is needed to get correct feedback from the neutronic code PARCS (nodalization used in PARCS is consistent with TH nodalization). Using the same nodalization in both codes, one eliminates the error, which may come from incorrect scaling of NK fuel bundles.

The TH Model I is presented in the Figures 2 – 3, and its safety systems are presented in the Figure 4.

Figures 5-7 present TH Model II. Taking into consideration conclusions from the reference [11] it is assumed that feedwater mixing in the lower plenum is insufficient (recirculation pumps are not perfect mixers). To model variation of the feedwater temperature at the inlet to the core, four different core zones were separated (small mixing is assumed).

Both models include also safety systems e.g., Auxiliary feedwater system, however during the transients they are usually assumed not to operate.
The Table 1 includes description of the TH component number series and the Table 2 includes description of the components used in both input decks (Model I and Model II).
Figure 2: RELAP5 BWR nodalisation (Model I)
Figure 3: RELAP5 BWR steam lines nodalisation (Model I)
Figure 4: RELAP5 BWR safety injection systems nodalisation (Model I)
Figure 5: RELAP5 BWR nodalization (Model II)
Figure 6: RELAP5 BWR steam lines nodalisation (Model II)
Figure 7: RELAP5 BWR safety injection systems nodalisation (Model II)
<table>
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<tr>
<th>Reserved Number Series</th>
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<th>Used Number Series</th>
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<td>701-707, 711-717, 721-727, 731-737, 741-747</td>
</tr>
<tr>
<td>751-799</td>
<td>Steam Lines/Turbines</td>
<td>760-775</td>
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</table>
| 800-900                | Reactor Vessel (without core):  
  - Below core (801-850)  
  - Junction to the core (830-839)  
  - Above core (850-900)  
  - Junction from the core (850-859) | 800-805, 810-815, 820-829, 830-839, 850-859, 870-871, 875, 880-881, 885-886, 900 |
| 901-920                | Feedwater Systems           | 901-904, 911-914 |
| 921-999                | Safety Systems:  
  - Drains systems: (921-930)  
  - Pressure control & relief system: | 921-924, 935-939 |
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<td>707,717,727,</td>
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Table 2: Component description and numbers
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<td>880</td>
<td>Sepa</td>
<td>separatr</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>881</td>
<td>Updc</td>
<td>annulus</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>885</td>
<td>Dryr</td>
<td>snglvol</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>886</td>
<td>Junction from dryr to sdome</td>
<td>sngljun</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>900</td>
<td>sdome</td>
<td>snglvol</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>901-920</td>
<td>902,904,912, 914</td>
<td>feedwater system 1, 2, 3 and 4</td>
<td>tmdpvot</td>
<td>1</td>
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<tr>
<td>901,903,911, 913</td>
<td>Junction from feedwater system 1, 2, 3, 4 Downc1, 2, 3, 4</td>
<td>tmdpjot</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>921-999</td>
<td>921-924</td>
<td>The drain system 1a, 1b, 2a, 2b.</td>
<td>valve</td>
<td>-</td>
</tr>
<tr>
<td>Page</td>
<td>Description</td>
<td>Type</td>
<td>Value</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>991-994</td>
<td>The drain system 1a, 1b, 2a, 2b.</td>
<td>tmdpvol</td>
<td>1</td>
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</tr>
<tr>
<td>935-939</td>
<td>Pressure Control and Relief system (1-5)</td>
<td>valve</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>995-999</td>
<td>Pressure Control and Relief system (1-5)</td>
<td>tmdpvol</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>941,943,945, 947</td>
<td>system 327, aux. feed water system Injection to core zones 1-4</td>
<td>tmdpjun</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>951</td>
<td>system 327, aux. feed water system Injection to bypass</td>
<td>tmdpjun</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>942,944,946, 948</td>
<td>system 327, aux. feed water system (core)</td>
<td>tmdpvol</td>
<td>1</td>
<td></td>
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<tr>
<td>952</td>
<td>system 327, aux. feed water system (bypass)</td>
<td>tmdpvol</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>961,963,965, 967</td>
<td>system 323, ECC system, Injection to core zones 1-4</td>
<td>tmdpjun</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>971</td>
<td>system 323, ECC system, Injection to bypass</td>
<td>tmdpjun</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>962,964,966, 968</td>
<td>system 323, ECC system, (core)</td>
<td>tmdpvol</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>972</td>
<td>system 323, ECC system, (bypass)</td>
<td>tmdpvol</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>981,983,985, 987</td>
<td>system 323, low pressure coolant injection system, Injection into downc1,2,3,4</td>
<td>tmdpjun</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
2.1.3 RELAP5 code limitations

2.1.3.1 RELAP5 memory limits
Due to existing two inherent limits (the total number of words entered in input deck and insufficient space for system tables) in RELAP5 – new version of RELAP5 had to be created. Therefore, for purpose of this work with the help of RELAP5 developers [12] new RELAP5 executable with new larger capacity was created.

2.1.3.2 RELAP5 inputs generation
Due to the need of several inputs with different number of channels special MATLAB program was created, which generates requested number of channels and related heat structures.

2.2 Neutronics code and model

2.2.1 Code description
This project includes also neutronics code – PARCS. PARCS [13] is a 3D core neutronics simulator developed a Purdue University for the U.S. NRC. PARCS solves steady-state and time-dependent multi-group neutron diffusion and SP3 transport equations for LWR, VVER and PBMR reactors. PARCS performs eigenvalue, transient, adjoint and depletion calculation.
2.2.2 Model description

The neutronics model includes 700 assemblies with a standard library of BWR cross-sections. Depending on the transient two cycle burnups were used - beginning or middle of the cycle. All of the transients are performed for the reactor at full power (109 %). The neutronics axial nodalization is the same as at the TH channel axial nodalization. The localization of control rod groups is presented in the Figure 8.

![Figure 8: Illustration of Control Rods location](image)

2.2.3 PARCS code limitations

For Control Rod Drop Accident PARCS source code was modified. It was assumed that during the SCRAM all the control rods are inserted with exception of dropped one. Original version of PARCS has default SCRAM option where all of the control rods are inserted. The PARCS source code was modified [14].
2.3 Coupling process

2.3.1 General description

The RELAP5/PARCS [15] code system simulates BWR with a 3D-neutronics model coupled to the 1D RELAP5 thermal hydraulics. The coupling makes use of an internal integration scheme – the system solution and core TH is obtained by RELAP5 and only spatial kinetic solution is obtained by PARCS. PARCS updates the cross-sections by using TH parameters predicted by RELAP5 and RELAP5 solves the heat conduction by using thermal power calculated by PARCS. The temporal coupling is explicit. The passing of variables goes according the mapping with the help of general interface (GI). A GI and PARCS are executed as separate processes that communicate to each other via the message-passing protocol in the Parallel Virtual Machine (PVM). The process of coupling is presented in the Figure 9.

The neutronic node structure is different from the T/H node structure. The difference is reconciled by a mapping scheme. The mapping of different T/H nodes has to be specified for all the neutronic nodes in a file called MAPTAB.
2.3.2 Coupling limitations

To make the mapping process easier, a special MATLAB program was created. Using as an input mapping matrix, program generates MAPTAB file, which includes all the mapping information and is used by PARCS for correct communication between NK assemblies and TH channels.

2.4 Other tools

2.4.1 DRARMAX Toolbox

The DRARMAX Toolbox [16] is used for evaluating the Decay Ratio and the Natural Frequency. The Decay Ratio (DR) is a measure of the stability of the system and it is calculated as a ratio of the amplitude of two consecutive oscillations. A system whose response indicates a DR higher than unity is unstable because oscillations increase in amplitude. If DR is equal unity, system will stay in a constant oscillation regime. The DR below unity indicates capability of the system for damping oscillations.

The Decay Ratio in DRARMAX Toolbox is calculated by using two approaches:

- Decay Ratio of the Autocorrelation Function (ACF),
- Decay Ratio of the Impulse Response Function (IRF).

Both approaches are described in the Toolbox manual [16]. In this investigation Decay Ratio was evaluated by ACF method.

One has to mention uncertainties connected with this Toolbox, e.g. DRARMAX calculates a lot of decay ratios using different methods. If obtained Decay Ratios are different from each other it might indicate problem with the signal or problem with the Toolbox.

DRARMAX Toolbox works in MATLAB environment.
2.4.2 MATLAB

MATLAB program [17], which is developed by MathWorks, is a high-level language use for calculations and data processing and visualization. MATLAB R2006a was used in this investigation.

2.4.3 APTPLOT

AptPlot [18] is a WYSIWYG 2D plotting tool, which allows for plots creation from numerical data and performing data analysis. It was used for visualization results from RELAP5 calculations.
Chapter 3

Mapping

3.1 Mapping definition

The mapping can be described as a spatial grouping of neutronic nodes with TH channels. Since in this investigation is assumed that axial TH nodes are the same as axial NK nodes, mapping has more narrow definition. The mapping is defined only in radial direction, when more then one NK fuel assembly is grouped into one TH channel. The process of mapping is illustrated in the Figure 10. In the figure it is visible that two fuel bundles, B and D are grouped into one TH channel (202).
3.2 Types of mapping

In this investigation many types of mapping are taken into consideration – from the most popular like geometry or exposure through less often used like control rod group or neutron flux fundamental and first azimuthal mode mapping. The possibility of mixing different types of mapping is also taken into account. Some types of mapping (e.g. power) need steady-state calculations before groups can be created. The possible TH/NK mappings, which were mentioned by others are:

- Geometry – the fuel bundles are grouped together according their geometry e.g. inlet orifices.
- Thermal-Hydraulic – the cluster of channels represents similar thermal-hydraulic characteristics e.g. void fraction.
- Exposure – channel grouping according to burnup.
- Power – grouping according peaking factors - neutron flux fundamental mode (need of steady-state calculations).
- Higher flux mode – grouping according to first azimuthal and higher harmonic modes (need of steady-state eigenvalues calculations).
- Control Rod Pattern – the fuel bundles are grouped taking into consideration control rods pattern.
- Mixed – combination of few different approaches (e.g. clustering).

The following figures present examples of the spatial coupling, which were used in this investigation. The Figure 11 presents example of grouping according core inlet orificing (Geometry mapping). Exposure mapping is presented in the Figure 12 where the fuel bundles are grouped according to burnup. The Figure 13 illustrates grouping according peaking factors - neutron flux fundamental mode (need of steady-state calculations). Grouping according to first azimuthal and higher harmonic modes (need of steady-state eigenvalues calculations) is presented in the Figure 14. The Figure 15 presents grouping of fuel bundles while taking into consideration control rod pattern. Illustration example presents grouping of 2 fuel bundles lying on diagonal of a Control Rod blade; only bundles, which are located around the same control rod are grouped together. The Figure 16
shows the combination (mixed mapping) of few different approaches: geometry (fuel assembly localization) and exposure (inside each small area is additional division according exposure).

Figure 11: Geometry mapping

Figure 12: Exposure mapping
Figure 13: Power mapping

Figure 14: Higher flux mode mapping
Figure 15: Control Rod pattern mapping

Figure 16: Mixed mapping
The Tables 3 and 4 present types of mapping used in this investigation for Model I and Model II, respectively. There exists a limitation in mapping used for Model II. Due to need of core zones separation each TH channel group can be only in one core zone. The core zones are presented in the Figure 17.

Figure 17: The core zones used in Model II

<table>
<thead>
<tr>
<th>Number of TH channels</th>
<th>Kind of mappings</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Geometry, Exposure, Power</td>
</tr>
<tr>
<td>20</td>
<td>Geometry, Exposure, Power</td>
</tr>
<tr>
<td>50</td>
<td>Geometry, Exposure, Power</td>
</tr>
<tr>
<td>70</td>
<td>Geometry, Exposure, Power</td>
</tr>
<tr>
<td>175</td>
<td>Control Rods Grouping</td>
</tr>
<tr>
<td>176</td>
<td>First mode combined with exposure grouping</td>
</tr>
<tr>
<td>192</td>
<td>Geometrical combined with exposure grouping</td>
</tr>
<tr>
<td>350</td>
<td>Control Rod Grouping</td>
</tr>
<tr>
<td>700</td>
<td>One to One grouping - Reference Case</td>
</tr>
<tr>
<td>Number of TH channels</td>
<td>Kind of mappings</td>
</tr>
<tr>
<td>-----------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>4</td>
<td>Geometry</td>
</tr>
<tr>
<td>20</td>
<td>Geometry, Exposure, Power</td>
</tr>
<tr>
<td>50</td>
<td>Geometry, Exposure, Power</td>
</tr>
<tr>
<td>70</td>
<td>Geometry, Exposure, Power</td>
</tr>
<tr>
<td>108</td>
<td>First mode combined with Exposure grouping</td>
</tr>
<tr>
<td>204</td>
<td>Control Rods Grouping</td>
</tr>
<tr>
<td>192</td>
<td>Geometrical combined with exposure grouping</td>
</tr>
<tr>
<td>350</td>
<td>Control Rod Grouping</td>
</tr>
<tr>
<td>700</td>
<td>One to One grouping - Reference Case</td>
</tr>
</tbody>
</table>

### 3.3 Mapping and clustering

To perform spatial coupling another approach can be used – clustering, which is a well-known method of unsupervised learning. The clustering [19] is very useful in many scientific areas e.g. pattern-analysis, decision-making, machine-learning and data mining. It is always used in case of large data bases, where objects are described by more than one feature. The clustering can be defined as a process of grouping the objects into groups according some common feature. Therefore, cluster is a collection of objects that show similar features. The example of clustering process is presented in the Figure 18. The picture presents a one group of objects, which were grouped in to two clusters according their radius.

For our purposes one can imagine the fuel assembly as a point in many-dimensional space. Each dimension represents different set of features e.g. burnup, peaking factor, orificing, void fraction, mode, position in the core, etc. Clustering algorithm during the grouping process takes into consideration all of the features at once.
There exists many divisions of clustering algorithms but the most known are hierarchical and partitional clustering. Almost all of them can be used for grouping of TH channels however the hierarchical methods were chosen in this investigation. The hierarchical method is slower than partitional but gives bigger flexibility and allows for using any similarity or dissimilarity measure. It is not needed to define preliminary number of class (however this option will not be used since we know desired number of groups); it is also important that the input data do not need special feature extraction. Another feature of hierarchical clustering is multi-level hierarchy, where clusters at one level are joined as clusters at the next higher level and creating so called cluster tree (dendrogram) – see Figure 19.
Only clustering functions, which are included in MATLAB Statistical Toolbox are used, however there exists many free or shareware clustering software available in internet.

The following figures (Figure 20-21) show examples of mapping, which were made by hierarchical clustering algorithm. The example I (Figure 20) presents mapping of 200 TH channels with mixed technique - 1st mode and exposure. Similarly, example II (Figure 21) shows mapping of 174 TH channels according to following features: 1st mode, exposure and control rods position. Since at this point there was no need to explore capabilities of all the available clustering options, both examples presented here were made by CLUSTERDATA function, which is very fast (it replaces three different functions: PDIST, LINKAGE, CLUSTER) because most of the parameters and options are default.

![Figure 20: Mapping made with help of clustering – example I](image-url)
There exist also clustering evaluation algorithms, which allow for verification if the tree represents significant similarity groupings.
3.4 Inlet orificing and mapping

The inlet orificing for the 700 channels model is presented in the Figure 22. There are three zones in the core in three different inlet $K_{\text{loss}}$ (140, 95 and 60). The reason of this is to get proper flow distribution in the hot channels area.

One of the many challenging tasks is bundle $K_{\text{loss}}$ and its treatment during spatial refinement. The problem appears when two (or more) different channels with different $K_{\text{loss}}$ are grouped together. The problem is to find $K_{\text{loss}}$ that should be implemented to the new channel to get the same total mass flow.

Figure 22: Distribution of inlet $K_{\text{loss}}$ for 700 TH channel model
During the grouping it is recommended (if possible) to have “separation” of channels with different $K_{\text{loss}}$. If the separation is not possible, then for the grouping of channels with different $K_{\text{loss}}$ the “weighted mean” was developed which is expressed by Equation 1.

$$\bar{K}_{\text{loss}} = n \cdot \frac{\sum_{i=1}^{n} \bar{m}_{i}^2 K_{\text{loss}i}}{\left(\sum_{i=1}^{n} \bar{m}_{i}\right)^2} = n \cdot \frac{m_1^2 K_{\text{loss}1} + m_2^2 K_{\text{loss}2} + \ldots + m_n^2 K_{\text{loss}n}}{(m_1 + m_2 + \ldots + m_n)^2}$$

Eq. 1

where:

$\bar{K}_{\text{loss}}$ - New $K_{\text{loss}}$ applied to grouped TH channel.

$m$ - Mass flow in the channel $i$.

$K_{\text{loss}}$ - $K_{\text{loss}}$ at the inlet to the channel $i$.

$n$ - Number of grouping channels.

$i$ - Current channel number; $i=1...n$

The Eq. 1 was derived from numerical experiment. The main idea was to run two cases. The case number one includes two fuel bundles with two different $K_{\text{loss}}$ and different power peaking factors. The case number two includes only one pipe with the area being sum of the bundles’ area from case one. The main task was to find a mass flow, which is the sum of mass flows from the “case one” bundles only by choosing appropriate $K_{\text{loss}}$ inlet. Bundles model is presented in the Figure 23 and results are shown in Table 5. The numerical experiment was run also with higher number of channels – see Table 6 (Three - channels) and Table 7 (Five channels).

Since we have one channel per one fuel assembly model (reference model), we have also the mass flow distribution. Therefore, usage of Eq. 1 while refining the scheme is possible.
Figure 23: $K_{loss}$ numerical experiment models.

Table 5: $K_{loss}$ results from numerical experiment – part 1

<table>
<thead>
<tr>
<th>No.</th>
<th>Description of the conditions</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$m_1$</td>
<td>$K_{loss1}$</td>
</tr>
<tr>
<td>1-1</td>
<td>$P_i=7.25e6$ [Pa], $T_i=551.75$ [K], $P_o=6.9e6$ [Pa], Pow.=4.89e6 [W], Pow. Ratio: 1.0:1.0, Pow. Prof: inlet-peak.</td>
<td>13.03</td>
<td>50</td>
</tr>
<tr>
<td>1-2</td>
<td></td>
<td>13.29</td>
<td>50</td>
</tr>
<tr>
<td>1-3</td>
<td></td>
<td>13.29</td>
<td>50</td>
</tr>
<tr>
<td>1-4</td>
<td></td>
<td>9.94</td>
<td>100</td>
</tr>
<tr>
<td>2-1</td>
<td>$P_i=7.25e6$ [Pa], $T_i=551.75$ [K], $P_o=6.9e6$ [Pa], Pow. Ratio: 1.1:0.9, Pow. Prof: inlet-peak.</td>
<td>9.88</td>
<td>100</td>
</tr>
<tr>
<td>2-2</td>
<td></td>
<td>8.53</td>
<td>140</td>
</tr>
<tr>
<td>2-3</td>
<td></td>
<td>8.53</td>
<td>140</td>
</tr>
</tbody>
</table>
Table 6: $K_{\text{loss}}$ results from numerical experiment – part 2

<table>
<thead>
<tr>
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<th>Case 1</th>
<th>Case 2</th>
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<tr>
<td></td>
<td></td>
<td>$\dot{m}_1$</td>
<td>$K_{\text{loss}1}$</td>
</tr>
<tr>
<td>5-1</td>
<td>$P_i=7.25\text{e}6$ [Pa], $T_i=551.75$ [K], $P_o=6.9\text{e}6$ [Pa], Pow.$=4.89\text{e}6$ [W], Pow. Ratio: 0.7:1.3, Pow. Prof: inlet-peak.</td>
<td>5.71</td>
<td>140</td>
</tr>
<tr>
<td>5-2</td>
<td></td>
<td>5.54</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 7: $K_{\text{loss}}$ results from numerical experiment – part 3

<table>
<thead>
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<th>Description of the conditions</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\dot{m}_1/\dot{m}_2/\dot{m}_3/\dot{m}_4/\dot{m}_5$</td>
<td>$K_{\text{loss}1}/.../K_{\text{loss}5}$</td>
</tr>
<tr>
<td>6-1</td>
<td>$P_i=7.25\text{e}6$ [Pa], $T_i=551.75$ [K], $P_o=6.9\text{e}6$ [Pa], Pow.$=4.89\text{e}6$[W], Pow. Ratio: 1.0:1.0:1.0:1.0:1.0, Pow. Prof: inlet-peak.</td>
<td>3.32/5.32/3.32/4.06/5.32</td>
<td>150/50/150/95/50</td>
</tr>
</tbody>
</table>
Chapter 4

Steady-State calculation

The following parameters are important for steady-state results comparison:

- K-eff [-],
- Inlet and outlet quality [%],
- Core outlet temperature [K],
- Steam dome pressure [MPa],
- Inlet mass flow through the pumps [kg/s],
- Maximum power peaking factor: radial, axial.

4.1 Model I – steady-state results

Table 8 contains the selected average steady-state (SS) results. As can be observed, the integral average values are similar and not dependent on the type of mapping and number of TH channels. This gives a consistent basis for transient comparison.

Looking more into detail results e.g. radial and axial peaking factors, one can find differences. The radial peaking factor (see Figure 24), rapidly converges, both neutronically and thermal-hydraulically, as the number of channel reaches 700. For the number of TH channels higher than 70, the uncertainty in the radial peaking factor is about 2%, regardless of the spatial mapping method used. For low number of channels, the radial peaking factor is conservative. Similar behavior can be seen for axial peaking factor (Figure 25). This confirms observation from other authors that the incorrect mapping leads to parameters overestimation.
Table 8: Comparison of SS results (Model I)

<table>
<thead>
<tr>
<th>Number of channels</th>
<th>Kind of grouping</th>
<th>K-eff [-]</th>
<th>Inlet and Outlet quality [%]</th>
<th>Core outlet temperature [K]</th>
<th>Steam dome pressure [MPa]</th>
<th>Recirculation flow [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Geometry</td>
<td>0.98877</td>
<td>-4.88/15.37</td>
<td>558</td>
<td>7.087</td>
<td>11354</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>0.98365</td>
<td>-4.81/15.11</td>
<td>558</td>
<td>7.087</td>
<td>11352</td>
</tr>
<tr>
<td></td>
<td>Exposure</td>
<td>0.98624</td>
<td>-4.86/15.32</td>
<td>558</td>
<td>7.087</td>
<td>11397</td>
</tr>
<tr>
<td>20</td>
<td>Geometry</td>
<td>0.98709</td>
<td>-4.89/15.40</td>
<td>558</td>
<td>7.087</td>
<td>11333</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>0.98318</td>
<td>-4.89/15.38</td>
<td>558</td>
<td>7.087</td>
<td>11348</td>
</tr>
<tr>
<td></td>
<td>Exposure</td>
<td>0.98363</td>
<td>-4.87/15.37</td>
<td>558</td>
<td>7.087</td>
<td>11361</td>
</tr>
<tr>
<td>50</td>
<td>Geometry</td>
<td>0.98516</td>
<td>-4.92/15.42</td>
<td>558</td>
<td>7.087</td>
<td>11320</td>
</tr>
<tr>
<td></td>
<td>Power</td>
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<td>-4.89/15.39</td>
<td>558</td>
<td>7.087</td>
<td>11335</td>
</tr>
<tr>
<td></td>
<td>Exposure</td>
<td>0.98296</td>
<td>-4.88/15.38</td>
<td>558</td>
<td>7.087</td>
<td>11350</td>
</tr>
<tr>
<td>70</td>
<td>Geometry</td>
<td>0.98581</td>
<td>-4.89/15.40</td>
<td>558</td>
<td>7.087</td>
<td>11336</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>0.98233</td>
<td>-4.89/15.40</td>
<td>558</td>
<td>7.087</td>
<td>11333</td>
</tr>
<tr>
<td></td>
<td>Exposure</td>
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<td>-4.88/15.39</td>
<td>558</td>
<td>7.087</td>
<td>11346</td>
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<tr>
<td>175</td>
<td>Control Rods</td>
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<td>-4.89/15.41</td>
<td>558</td>
<td>7.087</td>
<td>11324</td>
</tr>
<tr>
<td>176</td>
<td>1st Mode + Exposure</td>
<td>0.98196</td>
<td>-4.89/15.40</td>
<td>558</td>
<td>7.087</td>
<td>11333</td>
</tr>
<tr>
<td>192</td>
<td>Exposure + Geometry</td>
<td>0.98237</td>
<td>-4.89/15.41</td>
<td>558</td>
<td>7.087</td>
<td>11332</td>
</tr>
<tr>
<td>350</td>
<td>½ Control Rods</td>
<td>0.98251</td>
<td>-4.89/15.42</td>
<td>558</td>
<td>7.087</td>
<td>11321</td>
</tr>
<tr>
<td>700</td>
<td>Reference</td>
<td>0.98213</td>
<td>-4.94/15.54</td>
<td>558</td>
<td>7.087</td>
<td>11227</td>
</tr>
</tbody>
</table>
Figure 24: Maximum radial power peaking factor (SS, Model I)

Figure 25: Maximum axial power peaking factor (SS, Model I)
4.2 Model II – steady-state results

In Table 9 shows selected average steady-state results obtained from Model II. Similar to Model I results, the integral average values are similar and not dependent on the type of mapping and number of TH channels. The biggest variation in the steady-state average results is only 2%. Therefore a consistent basis for transient comparison can be assumed.

Also similar to earlier model, detail results e.g. radial and axial peaking factors are slightly different. The radial peaking factor (see Figure 26), rapidly converges, both neutronically and thermal-hydraulically, as the number of channel reaches 700. For the number of TH channels higher than 70, the uncertainty in the radial peaking factor is about 2.5%, regardless of the spatial mapping method used (except for 108 TH channels model with mapping according 1\textsuperscript{st} mode and exposure). For low number of channels, the radial peaking factor is conservative. Similar behavior can be seen for axial peaking factor (Figure 27). This confirms observation found in Model I and mentioned by other.
Table 9: Comparison of SS results (Model II)

<table>
<thead>
<tr>
<th>Number of channels</th>
<th>Kind of grouping</th>
<th>K-eff [-]</th>
<th>Inlet and Outlet quality [%]</th>
<th>Core outlet temperature [K]</th>
<th>Steam dome pressure [MPa]</th>
<th>Recirculation flow [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Geometry</td>
<td>0.99868</td>
<td>-4.80/14.86</td>
<td>558</td>
<td>7.045</td>
<td>11732</td>
</tr>
<tr>
<td>20</td>
<td>Geometry</td>
<td>0.98989</td>
<td>-4.87/15.05</td>
<td>558</td>
<td>7.045</td>
<td>11571</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>0.98664</td>
<td>-4.85/15.02</td>
<td>558</td>
<td>7.045</td>
<td>11596</td>
</tr>
<tr>
<td></td>
<td>Exposure</td>
<td>0.98761</td>
<td>-4.84/14.98</td>
<td>558</td>
<td>7.045</td>
<td>11634</td>
</tr>
<tr>
<td>50</td>
<td>Geometry</td>
<td>0.98977</td>
<td>-4.86/15.04</td>
<td>558</td>
<td>7.045</td>
<td>11578</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>0.98553</td>
<td>-4.86/15.05</td>
<td>558</td>
<td>7.045</td>
<td>11574</td>
</tr>
<tr>
<td></td>
<td>Exposure</td>
<td>0.98667</td>
<td>-4.85/15.02</td>
<td>558</td>
<td>7.045</td>
<td>11602</td>
</tr>
<tr>
<td>70</td>
<td>Geometry</td>
<td>0.98894</td>
<td>-4.87/15.06</td>
<td>558</td>
<td>7.045</td>
<td>11564</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>0.98519</td>
<td>-4.87/15.05</td>
<td>558</td>
<td>7.045</td>
<td>11571</td>
</tr>
<tr>
<td></td>
<td>Exposure</td>
<td>0.98580</td>
<td>-4.85/15.03</td>
<td>558</td>
<td>7.045</td>
<td>11592</td>
</tr>
<tr>
<td>108</td>
<td>1st Mode + Exposure</td>
<td>0.98676</td>
<td>-4.86/15.03</td>
<td>558</td>
<td>7.045</td>
<td>11594</td>
</tr>
<tr>
<td>192</td>
<td>Exposure + Geometry</td>
<td>0.98527</td>
<td>-4.86/15.06</td>
<td>558</td>
<td>7.045</td>
<td>11569</td>
</tr>
<tr>
<td>204</td>
<td>Control Rods</td>
<td>0.98744</td>
<td>-4.87/15.07</td>
<td>558</td>
<td>7.045</td>
<td>11560</td>
</tr>
<tr>
<td>350</td>
<td>½ Control Rods</td>
<td>0.98562</td>
<td>-4.87/15.07</td>
<td>558</td>
<td>7.045</td>
<td>11560</td>
</tr>
<tr>
<td>700</td>
<td>Reference</td>
<td>0.98357</td>
<td>-4.89/15.12</td>
<td>558</td>
<td>7.045</td>
<td>11514</td>
</tr>
</tbody>
</table>
Figure 26: Maximum radial power peaking factor (SS, Model II)

Figure 27: Maximum axial power peaking factor (SS, Model II)
Chapter 5

Transient calculations

RELAP5/PARCS has an ability to accurately evaluate reactivity feedback for localized spatial change, asymmetric flow conditions and over a wide range of operating conditions. But in many cases obtained results may not be accurate enough due to mapping, which causes incorrect parameter averaging. To check the transient sensitivity for a mapping approach, the following transients were simulated:

- Control Rods Perturbation (Model I),
- Local perturbation: Control Rod Drop Accident (Model I),
- Global perturbation: Turbine Trip (Model I),
- Regional perturbation: Feedwater Transient (Model II),

Model I and II and the reason for differences are described in Chapter 2.

5.1 Control Rods Perturbation Transient (CRP)

5.1.1 Introduction

The purpose of this transient is to check Decay Ratio dependency on the TH/NK mapping. The system is perturbed by quick movement of control rods (CR are moved during 1 second – Table 10) groups 1, 2, 3, 4 and 5. Figure 28 presents the location of each control rod bank, which was used for reactor perturbing (highlighted in a colored square – one color, one CR group).
Figure 28: Groups of Control Rods involved in the CRP transient

Table 10: Control Rod movement during CRP transient

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Control Rods Position [steps]¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>0.5</td>
<td>90</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
</tr>
</tbody>
</table>

5.1.2 Results comparison

To compute the Decay Ratio (DR) and Frequency DRARMAX toolbox [16] was used. The results for various coupling strategies are shown in Figure 29 and 30 for the Decay Ratio (DR) and Frequency (FR), respectively.

¹ Control Rods Position: 100 – fully withdrawn, 0 – fully in.
As can be seen on Figure 29, the DR slowly converge to the reference (a certain trend is visible) and it is sensitive to number of TH channels. For the low number of channels, one can obtain the error up to 25% but the error is always conservative, i.e. the predicted DR is always higher than the reference DR. The correct frequency (see Figure 30) can not be captured with any mapping, but the mean error is very small, 3% to 7%, depending on the mapping strategy.

The geometry-based discretization appears to have the fastest convergence for the DR, but the worst for the FR.

The exposure and power groupings show potential for inducing or sustaining oscillations. Inversely, the geometry grouping shows potential for damping oscillations.

No spatial coupling scheme considered in the present study is found adequate in predicting accurately the FR, even with 2-to-1 mapping (350-channel model).

---

**Figure 29: Decay Ratio - CRP transient.**
Figure 30: Frequency - CRP transient.
5.2 Control Rod Drop Accident (CRDA)

5.2.1 Introduction

The CRDA is a reactivity event, which is localized to the position of the dropped control rod and the surrounding fuel assemblies. It is assumed that during one and half second, one control rod drops from initial fully-inserted position, causing reactivity increase (see Table 11). The transient was calculated for full power reactor. In the Figure 31 is presented location of the dropped control rod.

![Location of Control Rod drop](image)

**Figure 31: Location of Control Rod drop**
Table 11: Control Rod movement during CRDA

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Control Rod Position [steps]²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>9.0</td>
</tr>
<tr>
<td>5.0</td>
<td>9.0</td>
</tr>
<tr>
<td>6.5</td>
<td>100</td>
</tr>
</tbody>
</table>

5.2.2 Results comparison

The parameters, which are important for this transient, are:

- Maximum power peak,
- Fuel enthalpy rise [J/g].

The maximum fuel enthalpy [20] limit is 970 [J/g] for fresh fuel. This limit is a safety criterion for RIA (Reactivity Insertion Accident) fragmentation. The enthalpy rise is found to be important for mechanical pellet-cladding interaction.

The Figures 32-33 present obtained results. Maximum power peak (Figure 32) quickly converges to the reference and for the number of channels higher than 50 the uncertainty is very small, about 2%. Below 50 TH channels the results are always conservative.

In case of fuel enthalpy rise (Figure 33) results are not as unequivocal. For the low number of TH channels the enthalpy rise can be underestimated by as much as 50%, and this is strongly dependent on the mapping approach. In case of power grouping the enthalpy rise quickly converges to the reference value. Other types of mapping, like geometry and exposure, show non-monotonic convergence.

Another important observation is that in case of control rod mapping (175 TH channels) the obtained maximum power peak is close to the reference but the enthalpy rise is underestimated by 50%. That means that the type

² Control Rods Position: 100 – fully withdrawn, 0 – fully in.
of mapping should not only be dependent on the transient scenario, but also on the search variable.

Figure 32: Maximum power peak during CRDA

Figure 33: Maximum enthalpy rise during CRDA
5.3 Turbine Trip Transient (TT)

5.3.1 Introduction

The Turbine Trip (TT) transient without bypass in a BWR is a global perturbation with pressurization event in which the coupling TH and NK is very important.

The TT transient scenario, which is used in this investigation is complex and belongs to the group of Anticipated Transient Without Scram (ATWS). In time zero, it is assumed sudden closure of all four turbine valves. Turbine bypass valves are assumed not to open. The closure of all four steam line valves increases pressure in the steam dome, which causes core void to collapse. The collapse of void results in positive reactivity insertion into the core – power increases and reaches the SCRAM line. Because it is also assumed malfunction of SCRAM hydraulic drive mechanism, the shut down of the reactor is achieved with screw drive mechanism, which takes 250 s to fully insert all CR. The pressure control and pressure relief valves are assumed to operate – these are responsible for power fluctuation visible in the Figure 34.

5.3.2 Results comparison

The obtained results were compared and no large differences have been found in the average behavior between the cases with small number of TH channel and the reference case. The Figure 34 presents the power evolution during the transient for two selected cases, one with 5 TH channels and the reference case (700 channels). The difference appears in small time shift and power peak magnitude, but the general plant response is recreated and it is not dependent on the number of TH channels or mapping strategy.
Figure 34: Power fluctuation during TT transient

However, one can find differences while scrutinizing local behavior: e.g. power increase due to collapse of void fraction and positive reactivity insertion, which is shown in the Figure 35.

In summary, the global perturbation transient is very well predicted even with small number of TH channels. The predicted global parameters do not strongly depend on mapping strategy: the largest overprediction (conservative) for the reactor’s peak power is 12%.
Figure 35: Maximum power peak during TT transient
5.4 Feedwater Transient (FT)

5.4.1 Introduction

The Feedwater Transient (FT) can be a regional perturbation. The significant decrease of feedwater temperature due to loss of high pressure pre-heaters is assumed (during 50 s temperature drops about 80°C). Cold water entering the core decreases void fraction, causing positive reactivity insertion. Due to positive reactivity reactor power increases reaching the SCRAM line (120% power). The malfunction of the SCRAM system is assumed – no control rods insertion is performed, only flow reduction of the core recirculation pump is executed (from about 11000 to about 4000 kg/s which is minimum pump speed). The recirculation flow reduction increases the void in the core causing power to decrease. Gradually, with the slow power increase and low flow reactor goes into unstable area (reactor power about 50% and 30% flow).

It is assumed beginning of the cycle (fresh fuel) and 109% power level when FT occurs.

Different Feedwater Transient scenarios are assumed:

- Scenario I: cold water enters from 1 feedwater pump giving fully unsymmetrical conditions,
- Scenario II: cold water enters from 4 feedwater pumps.
5.4.2 Results and comparison

5.4.2.1 Scenario I results

Figure 36 presents average power cross-section from 4 up to 700 TH channels. As it can be observed due to low feedwater temperature, core power increases but power increase does not hit the SCRAM line and new steady-state with new higher power level is reached. The Figure 37a shows the power radial distribution before occurrence of transient and Figure 37b presents asymmetrical change of radial power profile, which is caused by cold water entering from one quadrant of the core.

![Figure 36: Average power during FT – Scenario I](image)
The correct behaviour is reproduced by all types of mapping. Results obtained in this scenario do not depend on number of TH channels and mapping type but it is recommended that number of TH channels is more than four.

5.4.2.2 Scenario II results

Figure 38 presents core power from 4 up to 700 TH channels. Due to low feedwater temperature, core power increases and hits the SCRAM line. The recirculation pump flow is reduced and reactor goes into unstable area. From the power curve it is easy to distinguish onset of limit cycle, which is very different for each mapping type. One can observe also different kinds of limit cycle - regular or chaotic oscillations. Some mapping types show large power peak which reaches high level SCRAM line.

Figure 39 presents mass flow rate of a few TH channels (reference model – 700 TH channels, location of the channels is presented in the Figure 40) – where mass flow out-of-phase oscillations were observed. Out-of-phase oscillations of the mass flow induce small excitation of power higher mode but it is dominated by in-phase mode. Small out-of-phase oscillations were observed in each model.
Figure 38: Average power during FT – Scenario II

Figure 39: Mass flow rate oscillations during FT – Scenario II
This transient scenario is strongly dependent on mapping type causing (different power increase ramp, different time of instability onset, different development of limit cycle). The Table 12 collects results comparison for each mapping case. As can be seen, only few mapping managed to reproduce reference results with this transient scenario. Despite of small discrepancies, combined mapping of 1st mode and exposure (108 TH channels), and also ½ control rods mapping (350 TH channels) return good results. Power mapping type is not recommended for this transient – it results in incorrect prediction even with large number of TH channels. For most computationally efficient solution with small number of TH channels, geometry or exposure mapping is advised.
<table>
<thead>
<tr>
<th>Number of channels</th>
<th>Kind of grouping</th>
<th>SCRAM time [s]</th>
<th>Onset of instability</th>
<th>Evolution of instability</th>
<th>Additional power peak during limit cycle</th>
<th>Correct results prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Geometry</td>
<td>53</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Failed</td>
</tr>
<tr>
<td>20</td>
<td>Geometry</td>
<td>64</td>
<td>195</td>
<td>Regular</td>
<td>No</td>
<td>Partly</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>69</td>
<td>208</td>
<td>Chaotic</td>
<td>Yes (219 s)</td>
<td>Failed</td>
</tr>
<tr>
<td></td>
<td>Exposure</td>
<td>68</td>
<td>206</td>
<td>Regular</td>
<td>No</td>
<td>Partly</td>
</tr>
<tr>
<td>50</td>
<td>Geometry</td>
<td>62</td>
<td>179</td>
<td>Regular</td>
<td>Yes (184 s)</td>
<td>Failed</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>69</td>
<td>180</td>
<td>Chaotic</td>
<td>Yes (184 s)</td>
<td>Failed</td>
</tr>
<tr>
<td></td>
<td>Exposure</td>
<td>67</td>
<td>160</td>
<td>Chaotic</td>
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</tr>
<tr>
<td>70</td>
<td>Geometry</td>
<td>62</td>
<td>169</td>
<td>Chaotic</td>
<td>No</td>
<td>Partly</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>69</td>
<td>182</td>
<td>Chaotic</td>
<td>Yes (184 s)</td>
<td>Failed</td>
</tr>
<tr>
<td></td>
<td>Exposure</td>
<td>70</td>
<td>192</td>
<td>Chaotic</td>
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<td>Failed</td>
</tr>
<tr>
<td>108</td>
<td>1st Mode +</td>
<td>66</td>
<td>174</td>
<td>Regular</td>
<td>No</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td>Exposure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>192</td>
<td>Exposure +</td>
<td>68</td>
<td>170</td>
<td>Chaotic</td>
<td>No</td>
<td>Partly</td>
</tr>
<tr>
<td></td>
<td>Geometry</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>204</td>
<td>Control Rods</td>
<td>64</td>
<td>180</td>
<td>Chaotic</td>
<td>Yes (219 s)</td>
<td>Failed</td>
</tr>
<tr>
<td>350</td>
<td>½ Control Rods</td>
<td>66</td>
<td>175</td>
<td>Regular</td>
<td>No</td>
<td>OK</td>
</tr>
<tr>
<td>700</td>
<td>Reference</td>
<td>70</td>
<td>174</td>
<td>Regular</td>
<td>No</td>
<td>Reference</td>
</tr>
</tbody>
</table>
Chapter 6

Requirements and recommendations

6.1 General rules and recommendations

Based on the experience collected during this investigation, the general rules for the designing transient analysis can be defined:

1. Always be aware of the limitations connected with TH/NK coupling.
2. The analysed transient has to be well understood in relation to physics and sequences of events before correct mapping model can be chosen.
3. The selection of suitable mapping scheme should not be only dependent on kind of transient but also on the investigated variable, accuracy of secondary results sometimes have to be compromised since they are not the purpose of the analysis.
4. The number of TH channels should be kept as small as possible since it has the biggest impact on computational time. In most of the analysis small number of TH channels (around 20) is enough to return satisfying results, but sometimes full 700 TH channels model has to be used to get accurate results.

6.2 Steady-state recommendations

Taking into consideration steady-state results comparison, there are no special requirements, which have to be fulfilled. Almost all the mapping type returned average results similar to the reference case (obtained results deviation can be considered as negligible). Also, small number of TH
channels does not decrease significantly results quality. The recommended number of TH channels more than 4.

If one is interested in a certain steady-state variable e.g. distribution of the void fraction or radial power distribution, one has to choose mapping, which is appropriate for this kind of investigation. Engineering judgment is sufficient to make a selection.

### 6.3 Transient recommendations

In case of choosing the correct mapping scheme for specific transient, engineering judgment might not be enough. In this investigation local, regional and global perturbation of the core were investigated. The transient selection was done in a way that covers wide range of transients and gathered knowledge may be used for many other types transient.

#### 6.3.1 Local perturbation

The sensitivity of local perturbation on type of mapping and number of TH channels was investigated using Control Rod Drop Accident. The following observations were made:

1. **Number of TH channels is less important than type of mapping.**
2. **High number of TH channels does not guarantee better results.**
3. **The lowest recommended number of TH channels is 20.**
4. **Power mapping is the recommended for small number of TH channels.** For higher number of TH channels exposure mapping combined with geometry or \(1^{st}\) neutron flux mode can be applied.
5. **To avoid unnecessary averaging, channel where accident happens should be separated.**
6.3.1 Regional perturbation

The Feedwater Transient was an example of regional perturbation. Two different scenarios were calculated. The scenario I where the level of regional perturbation is “small”, all observations are in good agreement with the observations for global perturbation. However for scenario II following recommendations can be done:

1. While choosing type of mapping one should take into consideration that regional core zones in the model should be “separated” (see description of Model II – Chapter 2).
2. This transient scenario is strongly dependent on mapping type; type of mapping affects the power increase ramp, SCRAM time, instability onset time, kind of limit cycle, etc...
3. High number of TH channels does not guarantee the quality of results; however, minimum recommended number of TH channels is 100.
4. Only combined mappings can be recommended for this kind of transient e.g. 1st power mode combined with exposure.
5. If one does not want to use not combined kind of mapping, then geometry mapping is recommended. Power mapping should not be used at all.

6.3.2 Global perturbation

The global perturbation was investigated with the Turbine Trip transient. The following observations were made:

1. The number of TH channels and type of mapping do not have big impact on average plant behaviour – general plant response is always recreated.\(^3\)
2. The difference appears while scrutinizing local behaviour – choice of mapping should be performed according searched local variable.

\(^3\) Observation does not concern models with number of TH channels less than 5.
6.3.3 Core stability at operating conditions

Core stability was also investigated at operating conditions. To calculate DR and frequency, control rods were used to perturb reactor. The following observations were made:

1. Only one channel per one assembly model is recommended to capture correct DR and frequency.
2. Using low number of TH channels one can obtain 25% error in DR, however calculated DR is always conservative. An error connected with frequency varies from 3 to 7% depending on mapping strategy.
3. The exposure and power mapping show potential for inducing or sustaining oscillations while geometry mapping has damping potential.

The observations are applicable only to DR at operating conditions. Additional studies on DR under low flow conditions need to be performed in the future.
Chapter 7

Summary

This thesis presents the development of an effective algorithm for a problem of spatial coupling, which appears while coupling TH and NK codes. The topic of spatial coupling was found to be a problem by many researchers who were dealing with nuclear reactor simulations. The previous key findings from literature (Chapter 1) were pointed out and taken into consideration in this investigation. The obtained results were compared with the previous author’s findings and agreement between them was found.

During this investigation many unexpected issues and problems appeared. At the beginning of this investigation one RELAP5 input model (Model I) was used. This was due to two reasons: RELAP5 inherent memory limitations and simple transient cases. But for some postulated transients Model I was not able to provide satisfactory solution. Therefore, to fulfill increasing transient complexity, new RELAP5 input model deck (Model II) was created. RELAP5 memory limitation issue was resolved also. All the applied changes and solutions were described in Chapter 2.

The Chapter 3 was devoted to mapping issues. Mapping definition was formed and all possible mapping strategies mentioned by other researchers were described and illustrated. Since similarity has been found between types of mapping, not all of the possible mappings were taken into consideration in this investigation, e.g. mapping according void fraction. For a purpose of this investigation, channel inlet orificing grouping process was adopted and described in the same Chapter.

The steady-state results obtained from both plant models and all the investigated cases were presented in Chapter 4. Both models achieved
converged steady-state. The obtained small results deviation -about 2%, was assumed to be negligible. Therefore, solid basis for further transient analysis was found.

The Chapter 5 was devoted to transient analysis. In this investigation local, regional and global perturbation of the core were investigated. The transient selection was done in such a way that it covers a wide range of transients and gathered knowledge may be used for other types of transients. As a representative of local perturbation, Control Rod Drop Accident was chosen. The specially prepared Feedwater Transient was investigated as a regional perturbation and a Turbine Trip was an example of global one. All the obtained results are described and illustrated in the same Chapter.

The conclusions and recommendations were gathered in Chapter 6. Those recommendations were the purpose of this investigation and they should be taken into consideration while designing new coupled TH/NK models and choosing mapping strategy for a new transient analysis.
Chapter 8

Future work

Among the topics that will be investigated in the future are:

- Application and further development of automatic mapping methods like clustering which was described in this thesis, Chapter 3.
- Validation of 700 channel model with the real transient, which occurred in the past, e.g. Forsmark 3 1994 “Pancake core”; comparison the reference case and verification of the recommendations gathered in this investigation.
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