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International Agreement Report

Numerical Analysis of Mixing Factors in the RPV of VVER-440 Reactor Using the TRACE Code

Prepared by:
P. Heralecky, M. Blaha

TES Ltd
Prazska 597
674 01 Trebic, Czech Republic

A. Calvo, NRC Project Manager

Office of Nuclear Regulatory Research
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ABSTRACT

Experimental investigations of coolant mixing under steady state conditions at the Dukovany (Czech Republic) VVER-440 NPP were performed. The main goal of these experiments was to evaluate the mixing factors under normal operations condition. An extensive TRACE input deck of VVER-440/213 reactor was developed in frame of R&D project 1H-PK/61 in the TES Company. The TRACE input deck of VVER-440/213 reactor includes the reactor pressure vessel, the core and all important RPV internals. This paper contains some post-test analyses of the NPP Dukovany experiments using TRACE code V4.160 in order to generate background data for the forthcoming standardization procedure. There was performed a RPV nodalisation study to analyze influence of division of RPV into theta-parts on the calculated mixing factor. The purpose of performed TRACE analyses is to assess the capability of the TRACE code and the developed input deck to solve coolant mixing problems in VVER-440 type of reactors.

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ABBREVIATIONS

CFD	Computational Fluid Dynamics
CRA	Control Rod Assembly
ECCS	Emergency Core Cooling System
ECI	Exterior Communication Interface
FA	Fuel Assembly
ITF	Integral Effect Test Facility
LOCA	Loss of Coolant Accident
MCP	Main Coolant Pump
MSIV	Main Steam Isolation Valve
MSLB	Main Steamline Break
NC	Natural Circulation
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
OECD	Organization for Economic Co-operation and Development
PKL	Experimental Facility in Finland
PWR	Pressurized Water Reactor
RCP	Reactor Coolant Pump
RCS	Reactor Cooling System
ROCOM	Experimental Facility in Germany
RPV	Reactor Pressure Vessel
RD	Research and Development
SETF	Separate Effect Test Facility
SG	Steam Generator
SPND	Self Powered Neutron Detector
TC	Thermo Couple
TH	Thermal Hydraulic
TR	Thermo Resistor
UP	Upper Plenum
VVER	Russian Pressurized Water Type Reactor

1. INTRODUCTION

Coolant mixing inside the reactor pressure vessel is an important phenomenon for wide range of NPP including normal operation as well as accidental conditions. The mixing phenomena, associated flow patterns and temperature distribution during a normal plant operation are interesting especially from an economical operation point of view. Other processes are dependent on coolant mixing under accident conditions – for example boron dilution, structural integrity, asymmetrical reactor cooldown, etc. Solution of these problems was rather problematic using 1-D system codes such as RELAP5 up to now. Thus the computational fluid dynamics (CFD) codes have had to be frequently used despite of some limitations that especially come from huge input decks and a long calculation time. There is also CFD codes limitation in case of coolant phase changes (evaporation, condensation).

The TRACE code is able to solve mixing problems avoiding above mentioned CFD limitations. TES Company intends to use the TRACE code for performing safety or licensing analyses in the Czech Republic for VVER type of reactors including e.g. analysis associated to coolant mixing phenomena. The extensive TRACE V4.160 input deck of VVER 440/213 reactor was developed in frame of R&D project 1H-PK/61 in TES Company in order to realise this intention. The Czech regulatory body SÚJB requires every code to undergo a standardisation procedure prior the application in safety or licensing analyses. The standardisation procedure consists of a representative set of comparative (validation) analyses that covers the extent of standardisation.

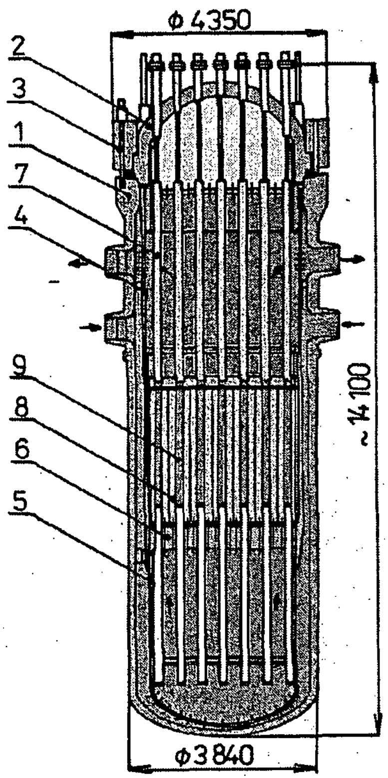
Experimental investigation of coolant mixing under steady state conditions at the Dukovany (Czech Republic) VVER-440 NPP was performed in years 1987 and 1997. Mixing factors (i.e. the effect of each single primary loop on the core inlet condition) for normal operation were measured in frame of these experiments. Some comparative post test analyses of these experiments were performed at TES Company using the TRACE code V4.160 in order to generate background data for the forthcoming standardization procedure.

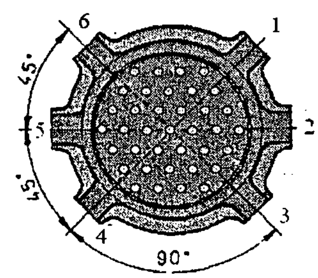
2. PLANT DESCRIPTION

Czech Dukovany NPP consists of four 6-loop units equipped with VVER440/213 reactors. VVER-440/213 is a light water-cooled and light water moderated pressurised thermal reactor of the Soviet design that was firstly commercially introduced in 1980s. Over 50 units with model 213 reactors are presently in operation or in final stage of construction mainly in Czech Republic, Finland, Hungary, Russia, Slovakia and Ukraine (Ref 9). The model 213 unit is a second generation of VVER-440 design. The first design version of VVER-440s, known as model 230, has been in operation since the early 1970s

2.1 <u>The reactor pressure vessel</u>

The reactor system is composed of the reactor pressure vessel (RPV) with the reactor internals (see the Figure 1). The reactor internals include the core barrel, the flow distribution structure, fuel assemblies and control assemblies. The total water volume inside the RPV is 94 m^3. The RPV has 6 inlet and 6 outlet nozzles of the inner diameter 0.496 m. The outlet nozzles are located at the higher elevation than the inlet nozzles. The inlet and outlet nozzles are at the same elevation. Three of the nozzles make an angle of 45 degrees, then after 90 degrees there are three other nozzles. The cold legs are connected to the top of the downcomer, and the hot legs to the upper plenum. The RPV head is bolted on to complete the vessel pressure boundary and to support and locate the control rod drives.





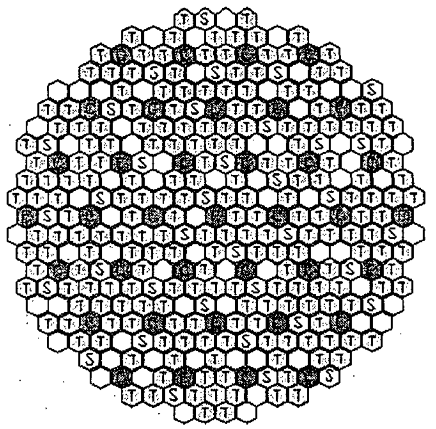
Key:
1 – reactor pressure vessel
2 – reactor pressure vessel head
3 – bolt
4 – core barrel
5 – bottom of core barrel
6 – lower core support plate
7 – block of control assembly guide tubes
8 – fuel assembly
9 – control rod assembly

Colour scheme:
BLUE – downcomer and lower plenum
ORANGE – core (fuel assemblies)
GREEN – core (control rods)
RED – upper plenum
YELLOW – reactor upper head

Figure 1: Scheme of the VVER-440/213 Reactor

2.2 The core

The core consists of 349 shrouded hexagonal assemblies arranged in a triangular lattice. The fuel is low enriched UO2. Criticality is controlled by the boric acid concentration and by the position of control rod banks. The active core height is 242 cm, the average core diameter is 308 cm. There are two types of assemblies in the core of VVER-440 reactor. There are 312 fuel assemblies (FA) and 37 movable control rod assemblies. The bottom portion of the control rod assembly contains fuel and is in tandem with the upper portion containing boron steel control material. There is the rack and pinion drive mechanisms used to move the control rods. Control rods are sorted into 6 groups. In a VVER-440 reactor, 210 assemblies are equipped with outlet temperature measurements, 36 assemblies with self powered neutron detectors (SPND's) – see the Figure 2. The flow rate through fuel assemblies is adjusted by means of throttling orifices, installed in the support plate of the core barrel.



Key:
C – control rods (green colour)
T – thermocouples (yellow colour)
S – self powered neutron detectors

Figure 2: Scheme of the Core of VVER-440/213 Reactor

2.3 The reactor coolant system

Reactor coolant system (RCS) consists of six main circulation loops. Each RCS loop includes a horizontal steam generator (SG), a main circulating pump (MCP) and isolation valves both in the hot and cold legs. The hydraulic diameter of hot/cold legs is 0.496 m and the total volume of primary coolant inside RCS (except the reactor and pressurizer) is 119 m^3. Large volume of primary coolant, isolation valves and horizontal SG's are considerable features of VVER-440 design compare to Western PWR's. All the coolant loops have common flow paths through the reactor vessel, but are otherwise independent in operation. Operation with a loop out of service is possible, due to the use of primary coolant system isolation valves. However, it is not recommended because of asymmetrical distribution of flow in individual loops. In order to reduce primary coolant elevations the hot leg includes an U-shaped section. This feature provides loop seal effects during a LOCA accident. Also there is a cold loop seal between the SG outlet and a main circulating pump, which may contribute to the reactor level during LOCA conditions. The pressurizer, which maintains overall system pressure and compensates for changes in the volume of the primary coolant, is connected by two pipelines with the hot leg in one of the loops. The pressurizer is equipped with a relief valve and two safety relief valves. During normal operation the pressurizer maintains RCS pressure within the prescribed limits using pressurizer sprays and heaters.

2.4 The main operational parameters

Some of the main operational parameters of the VVER-440/213 model under normal operational conditions are provided in the table below:

Table 1: VVER-440/213 Main Operational Parameters during Normal Operation

Reactor thermal power	1375 MW_t
Reactor coolant pressure	12.26 MPa
Average coolant temperature at reactor inlet	267 ± 2 °C
Average coolant temperature increase	31.0 °C
Cold loop flow	6 x 6858.2 m^3/h
Flow through the reactor	41137 m^3/h
Core bypass	8.5 %
Fuel assembly channel flow	312 x 113.36 m^3/h
Control rod assembly channel flow	37 x 150.83 m^3/h
Steam pressure in the steam generator	4.71 MPa

3. THE TRACE CODE

The TRACE (TRAC/RELAP Advanced Computational Engine) code is a component-oriented reactor systems analysis code designed to analyse light water reactor transients up to the point of significant fuel damage. The TRACE code is a finite-volume two-fluid compressible flow code with one, two and three dimensional flow geometry. The TRACE code can model heat structures and control systems that interact with component models and the fluid solution. The TRACE code can be directly coupled with the 3 D reactor kinetics code PARCS or with the other TRACE jobs and other codes (CFD, CONTAIN ...) through its exterior communications interface (ECI). TRACE uses what is commonly known as a 6-equation model for two-phase flow (mass equation, equation of motion and energy equation for each phase). Additional equations can be solved for non condensable gas, dissolved boron, control systems and reactor power. There are five additional closure relationships for field equations: equations of state, wall drag, interfacial drag, wall heat transfer and interfacial heat transfer. These constitutive models are semi empirical equations. There are two numerical methods available in TRACE: semi-implicit method and the stability enhancing two-step (SETS) method. All TRACE calculations presented in frame of this report were performed using TRACE V4.160 code.

3.1 Mixing phenomena modelling in the TRACE code

Modelling mixing phenomena requires 3-D computational environment. A 3-D Cartesian and/or cylindrical geometry flow calculation can be simulated within the reactor vessel or other reactor components where 3-D phenomena take place. All 3-D components can be modelled via VESSEL component. All basic equations for the 3-D VESSEL component are solved in the same form as the 1-D component. The vector form of the motion equation separates into three orthogonal coordinate velocity-component motion equations. The VESSEL nodalisation therefore becomes a collection of cells - see the Figure 3 (Ref 14), which are defined by their bottom and top faces (based on the level they occupy), their inner and outer faces (based on the ring they occupy) and by their two azimuth faces (based on the rotational location they occupy). All the field equations in the 3-D VESSEL component can have additional source terms to allow one or more 1-D component junctions to be connected to a mesh-cell interface anywhere in the 3-D VESSEL component.

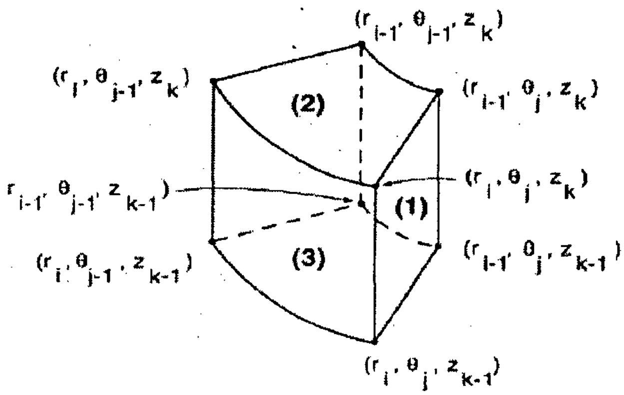


Figure 3: Single Cell of VESSEL Component in a Cylindrical Geometry

The 3-D implementation of the field equations in the TRACE code has two primary limitations (Ref 14). There is no model for turbulent diffusion and shear between fluid cells. This makes TRACE unsuitable for modelling circulation patterns in large open regions. The second limitation is related to the large computational volumes used in models of reactor vessels. Flow turns from the cold leg into the downcomer and normally from the downcomer to the lower plenum within a single volume. This yields an irrecoverable pressure loss within the calculation that is the same as can be obtained from a simple back of the envelop calculation for a sharp right angle turn. In fact the streamlines curve, and the pressure distribution is such that the actual pressure loss will be less than the right angle limit. The boron dilution problem is often analysed in frame of mixing phenomena. The set of field equations in the TRACE code can be further extended if a user chooses to follow the boron concentration in the system (Ref 13). An additional mass conservation equation can be activated to follow the concentration of boric acid, moving with the liquid. Total content of boric acid is assumed to be small enough that its mass is not used in the liquid momentum equation and it does not contribute to the thermodynamic or other physical properties of the liquid. Boron tracking capabilities are extended through the use of a model for solubility of boric acid, and a simple inventory of boric acid plated out in each cell in the system. Another solute could be modelled through a user option to replace the default solubility curve.

3.2 The TRACE code assessment

Confidence in the computational tools (codes) and establishment of their validity for a given application depends on assessment. TRACE, like other two-fluid codes, is composed of numerous models and correlations. When applied to full scale nuclear power plant conditions, many of these models and correlations can be applied outside of their original database. By assessing the code against thermal-hydraulic tests, it is possible to show that the code and its constituent model packages can be extended to conditions beyond those for which many of the individual correlations were originally intended (Ref 15). The assessment process however, can also indicate potential deficiencies in the code. There are following four sources of data for code assessment (Ref 18):

- "Fundamental" experiments
- Separate effect test facilities (SETF)
- Integral test facilities (ITF)
- Real plant data

3.2.1 Code assessment with real plant data

The assessment of PWR safety codes is mainly performed on the basis of experimental data coming from scaled-down integral or separate test facilities. Besides the demonstration of the code capability in reproducing an experiment performed in a test facility, the code should be checked also in performing NPP calculation (Ref 18). Generally, there is a need to evaluate code performance in actual plant conditions as the final step of the independent code assessment. Using real plant data in process of code assessment brings a lot of advantages as well as disadvantages. The main benefit of application of the real plant data in frame of the code assessment is the real scale of the tests and true geometry. Test facilities are frequently scaled down models of the actual p"wer plant. The scaling can increase the uncertainty of the results of the test facility relative to the reactor performance. However the measurement error is certainly higher in the real reactor. The plant data mostly concern only conditions under fairly mild transients (operational transients and start-up and commissioning tests). Multidimensional effects, especially with respect to flow splitting and flow merging process (e.g. connection of the main coolant pipe to the pressure vessel) exist also in relatively small scale integral test facilities (Ref 18). Although there were performed extensive mixing tests at ROCOM (Ref 1) and PKL (Ref 4) facilities, using the real plant data seems to be substantiated in this case. Real plant data are also often used as reference base in case by OECD/NEA benchmark problems which deals with mixing phenomena or spatial problems, such as VVER1000 Coolant Benchmark V1000CT (Ref19) or PWR MSLB Benchmark (Ref 20).

3.2.2 VVER typical features related to code assessment

This paper deals with the mixing phenomena inside the reactor pressure vessel of VVER 440/213 reactor. The TRACE code validation process is mainly based on the data from experimental facilities or real NPP's of Western PWR type. VVER reactors are in many aspects similar to Western PWR's (see the description of the VVER design in the Chapter 2). Therefore a lot of experimental data measured on PWR's or PWR test facilities is valuable also for VVER research. On the other hand, the VVER design has several specific features. From the hardware point of view the main differences between VVER-440 and PWR relating to the mixing phenomena are the following (Ref 10):

- Six loops of primary circuit equipped with loop seals in hot legs
- Shrouded fuel assemblies with hexagonal fuel rod arrangement
- Lower plenum volume larger and different internal structures
- ECCS injection points
- Two isolation valves in each main loop

The first three bullets only are relevant to the analysed phenomena of the RPV coolant mixing. There are 50 operating of VVER type (Ref 9). It is a meaningful number compare to 216 operating PWR reactors (Ref 9). Therefore corresponding attention should be given to code validation for VVER type of reactors. According to the (Ref 10) there is a phenomena of boron mixing and transport for VVER's, which needs special consideration compare to typical PWR's. The differences are not principal, but the mixing degree strongly depends on in-vessel geometry, which is different for VVER design compare to typical PWR design. This paper deals with modelling of coolant mixing during normal plant operation. This is the first step to code assessment for the whole mixing phenomena for the VVER type of reactors.

4. MIXING FACTORS

Generally the mixing factor represents the effect of each single primary loop on the reactor core inlet condition. It is essential to know mixing factors distribution, because the mixing factors determine the temperature and boron concentration at the core inlet. Energy of the coolant at the each fuel assembly inlet is given by energy of the coolant coming from cold primary loops (Ref 16):

$$g_k \cdot H(T_k) = \sum_{n=1}^{6} A_{nk} \cdot G_n \cdot H(T_{1n}) \qquad (1)$$

With
g_k ..... Mass flow through the k-th fuel assembly
$H(T_k)$ ..... Enthalpy of primary coolant at temperature T_k
T_k ..... Temperature at the k-th fuel assembly inlet
A_{nk} ..... Factor representing energy transmitted from n-th loop to k-th assembly
G_n ..... Mass flow through the n-th primary loop
T_{1n} ..... Temperature at the n-th primary loop outlet

There is practically no heat transfer to the coolant in the downcomer and lower plenum at nearly nominal temperatures in VVER-440 reactor. Thus coolant temperature at the core inlet does not depend on core power or core power distribution: If relative differences of the cold loop coolant temperature are small enough, it is acceptable to substitute coolant enthalpy by coolant temperature. The temperature at the inlet of the k-th fuel assembly (k = 1 – 312) is then given by:

$$T_k \cong \sum_{n=1}^{6} A_{nk} \cdot \frac{G_n}{g_k} \cdot T_{1n} = \sum_{n=1}^{6} B_{nk} \cdot T_{1n} \qquad (2)$$

Where B_{nk} is the mixing factor of the n-th primary loop to the k-th fuel assembly. The mixing factor thus represents the weight of a particular loop to the coolant parameters at the inlet of a particular fuel assembly. Mixing factors related to all 6 primary loops then have to satisfy:

$$\sum_{n=1}^{6} B_{nk} = 1 \qquad (3)$$

4.1 Measurements at NPP Dukovany

There were performed some experimental investigations of coolant mixing in the VVER 440/213 reactor under steady state conditions at the 1st unit of NPP Dukovany in 1997 (Ref 17) and at the 4th unit of NPP Dukovany in 1987 (Ref 22). Mixing factors under zero power operation were evaluated in frame of these experiments. There is no temperature instrumentation at the core inlet of VVER-440/213 reactor, therefore temperature at the outlet of particular fuel assemblies was measured and analysed by thermocouples (TC) of standard in-core instrumentation (see the VVER-440 core description in the Chapter 2.2). Thermo resistors (TR) were used to measure coolant temperature in the cold primary loops. Mixing factors were measured under zero power conditions in order to eliminate a spatial core power distribution and heat up through the core power. Thus the zero power reactor mode makes core inlet temperatures possible to substitute by core outlet temperatures. The main steam valves of steam generators were closed except of steam generator on the investigated primary loop. Thus significant deformation of the core inlet as well as the outlet temperature field was induced by the temperature change (a drop by several degrees of Celsius) of a particular cold primary loop. Relative temperature difference between investigated cold loop and the others was set up at about 2°C, so the above mentioned condition for substituting coolant enthalpy by temperature was satisfied. Influence of each of 6 primary loops was separately investigated. Six matrices of mixing factors were calculated as a result, one for each primary loop. There is a layout of Dukovany experiment at the 1st unit of NPP Dukovany in 1997 on the next Figure 4, when the 1-st cold loop had been subcooled. The field of calculated mixing factors relevant to the 1-st loop is demonstrated.

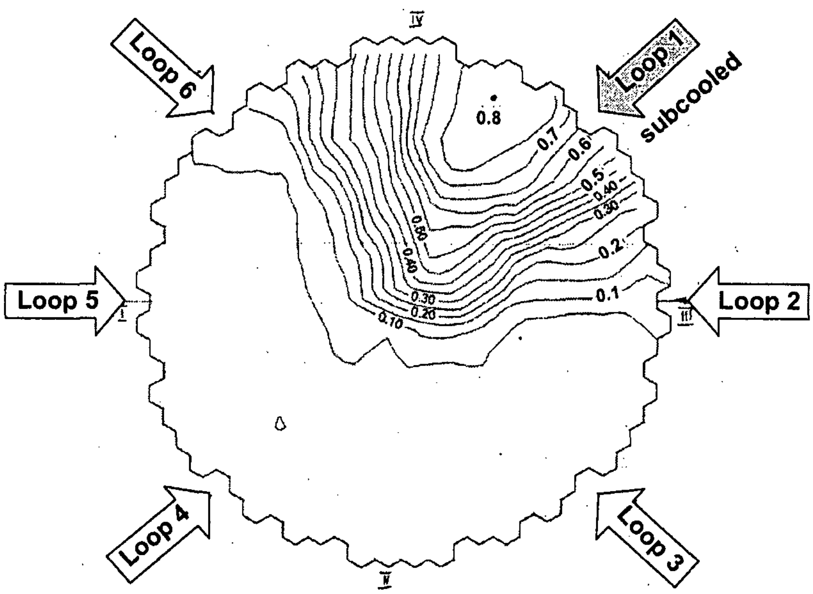


Figure 4: Measured Mixing factors of the 1-st Loop at the Dukovany NPP Unit 1

The fields of calculated mixing factors relevant to the all of investigated loops at Dukovany NPP are for both experimental tests demonstrated in the Appendix A. The measured mixing factor field corresponds to the typical VVER-440 geometry. The effect of every loop approximately covers the sector of 120 degrees adjacent to the investigated loop. The maximal values of measured mixing factors do not exceed 0.8 in any case. The fields of mixing factors for all the loops are not symmetrical. The symmetry was found only for central loops 2 and 5. This is first of all due to reactor inlet nozzles layout and also due to design of VVER-440 reactor internals. As you can see at the Figure A_1 in the Appendix A, the inlet nozzles of Loops 1 2 3 and Loops 4 5 6 form an angle 45 degrees each other. Loops1 6 and Loops 3 4 form make an angle 120 degrees, so there is larger clear area in the downcomer annulus related to the Loops 1,3,4,6. Thus coolant flowing from inlet nozzles of Loops 1 3 4 and 6 is deflected azimuthally towards the empty sectors. Generally we can say that there is a relatively poor mixing between the coolants of neighbouring loops. There were performed similar measurements of mixing factors at NPP Paks (Hungary), Rovno (Ukraine) and Loviisa (Finland) equipped with reactors VVER-440. The main results of these measurements indicated good mutual accordance to Dukovany NPP experiments except the Loviisa experiment, where noticeable azimuthal swirling was found. There is demonstrated comparison of measured mixing factors relevant to Loop1 from tests which were performed at the 1-st Unit of Dukovany NPP (Ref 17), 4-th Unit of Dukovany NPP (Ref 22), Paks NPP (Ref 1) and Loviisa NPP (Ref 1) on the next Figure 5. The conformity of results from other loops is consistent.

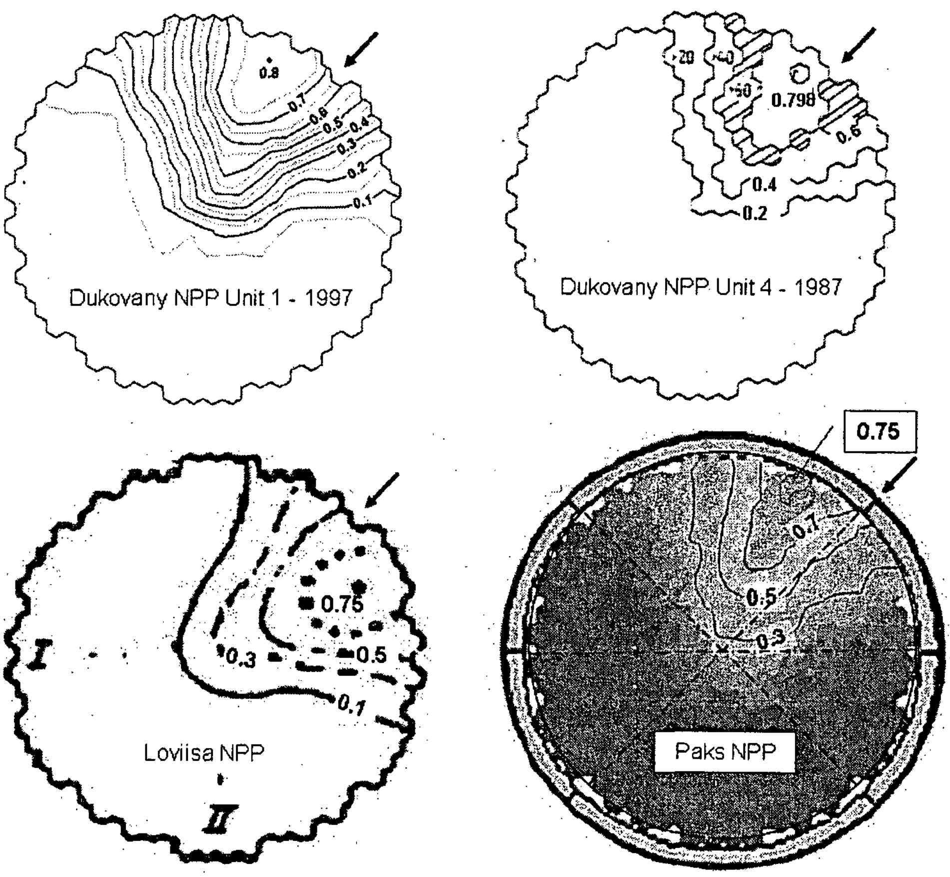


Figure 5: Comparison of Mixing Factors Related to the Loop1 at Different VVER-440 Type Plants

4.2 Measurement uncertainty

According to the equations in the Chapter 4, there are two following key parameters, which measurement uncertainty is crucial to assess the absolute error of the calculated mixing factor matrix: fuel assemblies outlet temperature measurement and cold loop temperature measurement. In a VVER-440 reactor, 210 fuel assemblies (FA) are equipped with outlet temperature measurements (thermocouples layout see the Figure 2). These temperatures are fundamental information in on-line core monitoring. Using them the radial distribution of the thermal neutron flux, the radial distribution of the heat power, mass flow of the fuel assemblies and by-pass mass flows are calculated. These temperatures play a significant role in the power limitation of the reactor too. Thermocouples TCHA 2076 at FA outlet are of Cr-Al type with the guaranteed measurement range 0-400°C and the declared overall measurement channel accuracy is 1.00% (Ref 21). There were performed detailed analysis of FA outlet temperature measurement channel accuracy in (Ref 22) and rather better accuracy was calculated to ±2.2 K, which is at about 0.85%. The real fuel outlet temperature measurement accuracy is better also due to TC calibration. There was performed calibration of in-core and loop thermocouples before the above described experiment at NPP Dukovany in order to minimise measurement uncertainty. The calibration is usually performed during especial isothermal modes at several temperature levels against accurate thermo resistors in primary loops. Such calibration is usually performed every year after refuelling and the average value of the mean root squared deviation of corrections for TC in reactor and TR in loops is at about 0.6°C (Ref 17). There are two thermo-couples and one thermo resistor in each cold and hot leg of VVER 1000. Thermoresistors (TR) TSP-8053 were used to measure coolant temperature in the cold primary loop during above described tests at Dukovany NPP. According to (Ref 22) the overall accuracy of loop temperature measurement (based on TR) is ±0.9°C, which is at about 0.35%. Then combined error of calculated mixing coefficients is at about 4.7% based on measurement channel accuracy from (Ref 22). A consistent error of the mixing coefficients was evaluated to about 3% in frame of similar tests which were performed at the Paks NPP (Ref 1). Above calculated value of combined error is valid for test which consists of 1 set of measurement in a definite time only. There were performed several sets of measurement for each test configuration under different coolant temperature. Thus over predicted matrix of linear equations had to be solved using least square method for each test configuration. This approach leads to reducing the resultant value of the calculated mixing factor accuracy. It was confirmed in (Ref 22), where the estimation of the least square method applied in such tests was performed. The values of the mean root squared deviation of differences between measured and finally calculated mixing factors varied from 0 to 0.15 with the most represented value 0.01-0.03 (occurrence at 117 fuel assemblies from 210). Such low values prove a good accuracy of mixing factors which was measured in frame of experimental tests at Dukovany NPP.

5. INPUT MODEL DESCRIPTION

Two extensive TRACE input decks of VVER-440/213 reactor was developed in TES Company in frame of R&D project 1H-PK/61. The aim of this project was to research of spatial thermo-hydraulic processes in VVER-440/213 reactors, especially in areas of upper plenum and reactor upper head. Both TRACE models deviate particularly from theta discrimination of reactor. Both models include all important reactor pressure vessel (RPV) internals. The 3-rd Unit of Dukovany NPP (Czech Republic) was chosen as reference plant. The basic hydraulics of these TRACE models was validated against plant data and reference data from Dukovany NPP plant database.

5.1 <u>8-Theta TRACE model</u>

The original 8-Theta TRACE model of VVER 440/213 reactor consists of 2400 3-D cells. The VESSEL component consists of 32 axial layers, 8 azimuthal theta sectors and 6 radial rings (see the Nodalisation scheme on the Figure B_1 in the Appendix B). The reactor core consists of 12 axial levels, 4 radial rings and 8 theta sectors. A spatial core power distribution was implemented using measured plant data. Control rods (HRK) channels in the core and guiding tubes of control rods were separately modelled as 24 PIPE components consisting of 480 volumes.

5.2 <u>16-Theta TRACE model</u>

The original 8-Theta TRACE input deck of VVER 440/213 reactor was modified in order to evaluate the influence of VESSEL component "Theta-mesh" density on the calculated mixing factors. The modified 16-Theta TRACE input deck consists of 4580 3-D cells. The modified VESSEL component consists of 32 axial layers, 16 azimuthal sectors and 6 radial rings (see the Nodalisation scheme on the Figure C_1 in the Appendix C). The reactor core consists of 12 axial levels, 4 radial rings and 8 (eventually 16) theta sectors. The comparison of the core radial and theta discrimination of both TRACE models and comparison of relative location of THETA sectors to the reactor inlet nozzles is shown at the next Figure 6. The outer diameter of the core represents inner wall of the core barrel.

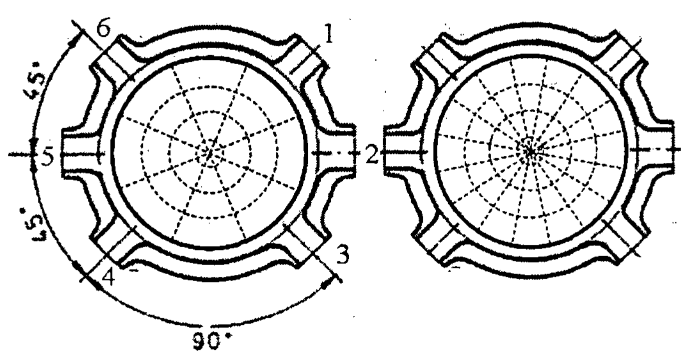


Figure 6: Comparison of the VVER-440/213 Reactor Core Theta and Radial Discretisation

5.3 Validation of the TRACE models basic thermo-hydraulics

The basic hydraulics of these TRACE models was validated against plant data and reference data from Dukovany NPP plant database (Ref 11) and data from measurement performed at reference 3-rd Unit of NPP Dukovany (Ref 23). For both TRACE models, the standard initial conditions representing normal operation conditions were implemented:

Table 2: TRACE Input Deck Initial Conditions Under Normal Operation Mode

Parameter	Unit	TRACE model [24]		Ref. data
		8-Theta	16-Theta	
Pressure at reactor outlet nozzles	MPa	12.5		12.26 (Ref 11)
Temperature at reactor inlet nozzles	°C	266.9		267 ± 2 (Ref 11)
Flow rate in one loop	m^3/h	6858.2		(6 713÷7087) ±160 (Ref 23)
Core power	MW_t	1375		1375 (Ref 11)

The comparison of basic reactor hydraulic parameters for both TRACE models to the plant reference data is presented in the next table.

Table 3: TRACE Model Basic Thermo-Hydraulics Under Normal Operation Mode

Parameter	Unit	TRACE model [24]		Ref. data (Ref 11)
		8-Theta	16-Theta	
Average coolant temp. increase	°C	30.1	30.1	31.0
Fuel assembly channel flow	kg/s	24.1	24.1	24.40
Control rod assembly channel flow	kg/s	33.4	33.4	32.46
Core bypass	%	8.9	8.9	8.5
Reactor inlet pressure drop	MPa	0.0810	0.0811	0.0811
Core pressure drop	MPa	0.2009	0.2018	0.2015
Reactor outlet pressure drop	MPa	0.0265	0.0261	0.0266

6. RESULTS

Several comparative steady-state calculations of two NPP Dukovany experiments at the 1st unit of NPP Dukovany in 1997 and at the 4th unit of NPP Dukovany in 1987 were performed using the TRACE V4.160 input decks. The fields of calculated mixing factors relevant to the all of investigated loops at Dukovany NPP are presented in the Appendix A. An investigated loop was subcoolled by 5°C in a comparison with another loops and the temperature at the fuel assemblies inlet nozzles was subsequently measured. Then the mixing factor representing the weight of a particular single loop was analysed using calculated data. There is presented the method of calculation of mixing factor related to the investigated Loop1. Based on equations (1), (2) and (3) in the Chapter 4 and regarding particular test configuration described on the Figure 4.1_1 the equation of mixing coefficients relating to k t-h fuel assembly and to the investigated Loop1 is given by:

$$B_{1k} = \frac{T_k - T_{Loop2\div6}}{T_{Loop1} - T_{Loop2\div6}} \qquad (4)$$

Where T_{Loop1} ..... temperature of investigated cold leg loop 1

$T_{Loop2\div6}$ ..... temperatures of non-investigated cold leg loops 2÷6

Mixing factors related to other loops were calculated by the same way. Thus six matrices of mixing factors (each for one loop) were realised. The comparison of mixing factors calculated from TRACE post-test calculation to the Dukovany NPP experimentally measured data is presented bellow.

6.1 Experiment at the 1-st unit of NPP Dukovany

The analysed experimental test of coolant mixing in the VVER 440/213 reactor under steady state conditions was performed at the 1st unit of NPP Dukovany in 1997 (Ref 17). Three factors were compared in order to evaluate influence of theta discretisation of TRACE VESSEL component on mixing phenomena inside the downcomer and lower plenum of VVER-440/213 reactor

- shape of affected area related to a given loop
- maximal values of mixing factors related to a given loop
- relative deviation of measured and calculated data to a given segment

There are presented results related to loop 1, 2 and 3 only. The results of other three loops 4, 5 and 6 are almost the same due to the plane of symmetry of the VVER 440/213 reactor which cuts the reactor vessel between loops 1-6 and 3-4.

6.1.1 8-ThetaTRACE model results

The 8-Theta VESSEL component consists of 8 azimuthal sectors THETA. Each of sectors is forming an angle 45 degrees – see Figure 6. This is a relatively rough discretisation compare to measured fields of mixing factors, which covers the sector at about 120 degrees adjacent to the investigated loop. Despite the fact that there is less then three theta segments covering the sector related to one loop, the calculation of mixing factors using 8 Theta model was performed in order to investigate the lowest level of theta discretisation. The results of calculation using 8-Theta model are documented on the Figure 7.

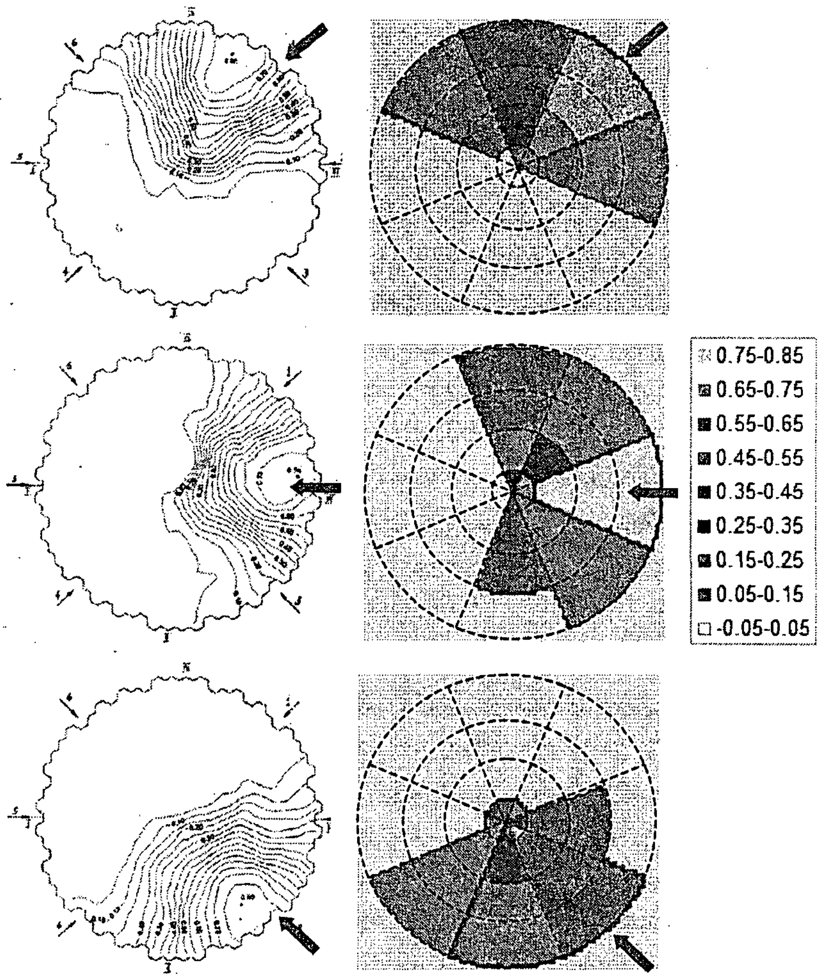


Figure 7: Shape of Affected Area of Mixing Factors (8-Theta model)

There are also Tables D_1-6 and Figure D_1 in the Appendix D which contains the summary of measured (maximal, minimal and averaged values) and TRACE calculated data. The red arrow indicates the location of a subcoolled loop, for which mixing factor was calculated. The TRACE calculated mixing factor fields correspond to the typical VVER-440 geometry (symmetry) analogous to the measured mixing factors. The effect of every loop covers the sector around 180 degrees (measured sector covers 120 degrees) which is (the same way as measured sector) adjacent to the investigated loop – see the Figure 7. There is a significant symmetry of calculated sector related to the middle Loop 2 the same way as for measured data.

The maximal values of TRACE calculated mixing factors related to the all investigated loops are highlighted in the Tables D_1-6 in the Appendix D and concentrated in the next Table 4.

Table 4: Maximal Values of of Measured and Calculated Mixing Factors (8-Theta Model)

Loop No	1	2	3	4	5	6
measured data	0.800	0.740	0.800	0.710	0.740	0.790
8-Theta TRACE model	0.711	0.793	0.640	0.655	0.793	0.711
DIFF [%]	-11	7	-20	-8	7	-10

The comparison of maximal values might be rather confusing due to the relative sharp peaks of measured maximal values, therefore experimentally measured values of mixing factors were averaged over segments related to TRACE Theta-Radial segments. The reason of weighting of the calculated deviation is to depress the significance of accuracy of the near zero values. The tables containing relative deviation of measured and calculated data weighted by average value of measured mixing factors related to investigated loop are presented in the Appendix D. Graphical presentation for loops 1, 2, 3 was done on Figure 8. As we can see from Tables D_1-6 there are relatively high values of weighted deviation depending on evaluated particular theta sector and radial ring. The maximal values of weighted deviations varies from -26% to +42% for a given loop. Generally we can say that the highest values of weighted deviation occurred at theta sectors related to the investigated loop or at theta sector adjoining to the empty sector between loops 1-6 and 3-4. This result corresponds to the azimuthal deflection of the coolant streams in the downcomer described in the Chapter 4.1.

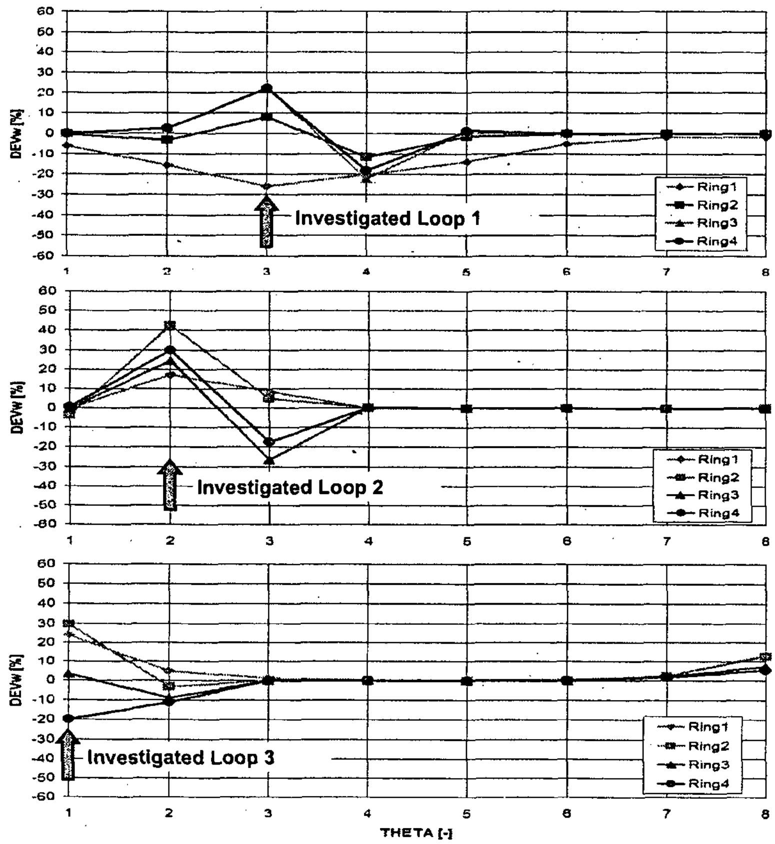


Figure 8: Weighted Relative Deviation of Measured and Calc. Mixing Factors (8-Theta Model)

6.1.2 16-ThetaTRACE model results

The 16-Theta VESSEL component consists of 16 azimuthal sectors THETA. Each of sector is forming an angle 22.5 degrees – see the Figure 6. Thus there are six theta segments covering the 120 degree sector related to one loop. The results of calculation using 16 Theta TRACE model are documented on the Figure 9 and in detail the results are presented in the tables and figures in the Appendix E. The red arrow indicates the location of a subcoolled loop, for which mixing factor was calculated. The effect of every loop covers the sector around 157.5 degrees (measured sector covers 120 degrees) which is adjacent to the investigated loop. The covered sector is due to the finer theta discretisation rather narrower compare to 8-Theta model results (180 degrees). The symmetry of calculated sector related to the middle Loop 2 occurred by the same way as for measured data and 8-Theta model data. There is a significant symmetry of calculated sector related to the middle Loop 2 the same way as for measured data.

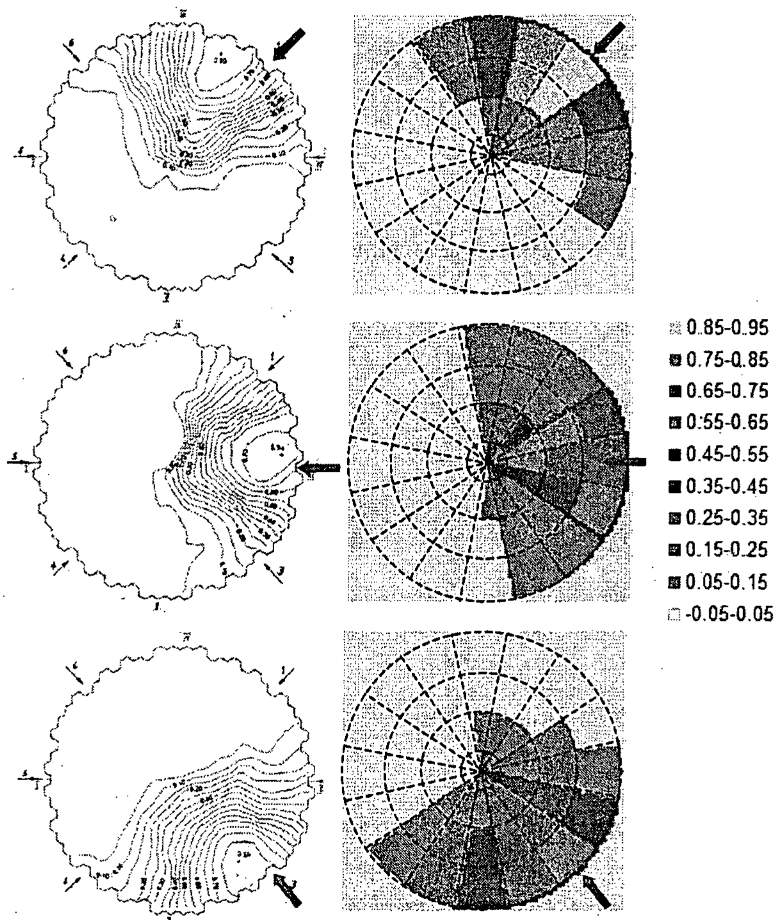


Figure 9: Shape of Affected Area of Mixing Factors (16-Theta model)

The maximal values of TRACE calculated mixing factors related to the all investigated loops are highlighted in the Tables E-1-6 in the Appendix E and concentrated in the next Table 5.

Table 5: Maximal Values of of Measured and Calculated Mixing Factors (16-Theta Model)

Loop No	1	2	3	4	5	6
measured data	0.800	0.740	0.800	0.710	0.740	0.790
16-Theta TRACE model	0.906	0.726	0.716	0.716	0.726	0.907
DIFF [%]	13	-2	-11	1	-2	15

The tables containing relative deviation of measured and calculated data weighted by average value of measured mixing factors related to investigated loop are also presented in the Appendix E. Graphical presentation for loops 1, 2, 3 was done on Figure 10. As we can see from Tables E-1-6 there are relatively high values of weighted deviation depending on evaluated particular theta sector and radial ring. The maximal values of weighted deviations varies from -31% to +53% for a given loop. The localisation of the maximal values is more accurate in case of 16-Theta model (see highlighted values in the Tables E-1-6).

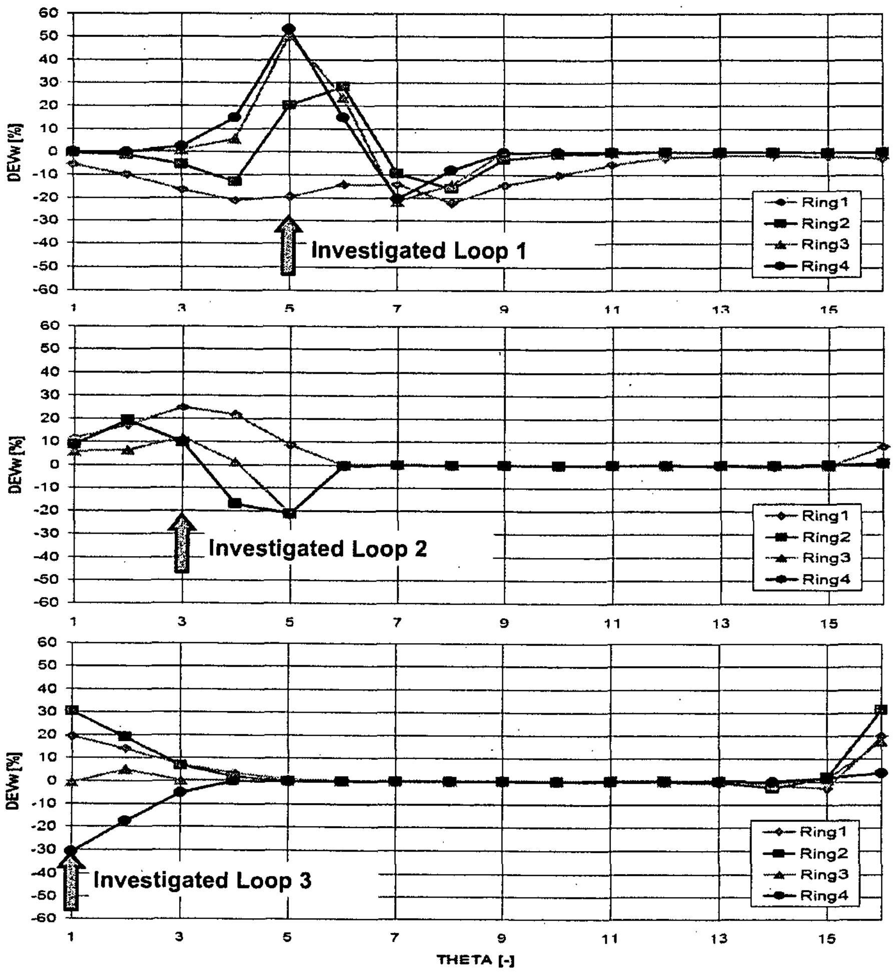


Figure 10: Weighted Relative Deviation of Measured and Calc. Mixing Factors (16-Theta Model)

6.1.3 Résumé of the TRACE VESSEL component nodalisation study

There were three key factors compared in order to evaluate influence of theta discretisation of TRACE VESSEL component on mixing phenomena inside the downcomer and lower plenum of VVER-440/213 reactor:

- shape of affected area related to a given loop
- maximal values of mixing factors related to a given loop
- relative deviation of measured and calculated data to a given theta-radial segment

Based on measured data, the effect of every loop approximately covers the sector of 120 degrees adjacent to the investigated loop. Based on 8-Theta model data, the effect of every loop covers the sector around 180 degrees which is adjacent to the investigated loop. Based on 16 Theta model data, the effect of every loop covers the sector around 157.5 degrees which is also adjacent to the investigated loop. The covered sector is due to the finer theta discretisation of the 16-Theta model rather narrower compare to 8-Theta model results. Thus 16-Theta model gives better results in this case, as it was anticipated.

The maximum values of measured and calculated were then investigated. The relative differences of maximal values of measured and calculated mixing factors are compared in the next Table 6 for both 8 Theta TRACE model as well as for 16 Theta model.

Table 6: The Differences of Maximal Values of Measured and Calculated Mixing Factors

	DIFF [%]					
Loop No	1	2	3	4	5	6
8-Theta TRACE model	-11	7	-20	-8	7	-10
16-Theta TRACE model	13	-2	-11	1	-2	15

The relative differences of maximal values of mixing factors differ loop by loop, when comparing the 8-Theta to the 16-Theta model data, though the absolute values are comparable each other. No dependency related to the theta discretisation has been discovered.

The comparison of maximal values are rather confusing due to the relative sharp peaks of measured maximal values, therefore experimentally measured values of mixing factors were averaged over segments related to TRACE Theta-Radial segments. Then relative deviations of calculated mixing factors vs. measured ones were investigated. These relative deviations were weighted by average value of measured mixing factors related to investigated loop in order to depress the significance of accuracy of the near-zero values. The comparison of a relative deviation of mixing factors calculated by both TRACE models to experimentally measured values is presented on the next Figure 11 which gives us a good visualisation of nodalisation study result. Based on 8 Theta model data, the maximal values of weighted deviations varies from -26% to +42% for a given loop. Based on 16 Theta model data, the maximal values of weighted deviations varies from -31% to +53% for a given loop, which is wider range compare to the 8-Theta model data. On the other hand the localisation of the maximal values is more accurate in case of 16 Theta model (see highlighted values in the Tables E-1-6 in the Appendix E). Generally we can say that using 16-Theta model with finer theta discretisation did not contribute to significantly better results. This could be (e.g.) a consequence of the following factors. The first factor is the location of peak (maximum) of a measured mixing factor against given sector boundaries that are worse in case of the 16-Theta model. This should be taken into account if a new TRACE input deck will be designed. The second factor is a smaller cross-sectional area of the 16-Theta model sectors. Thus the weight of any extreme value on average value in a particular sector is bigger in comparison with the 8-Theta model.

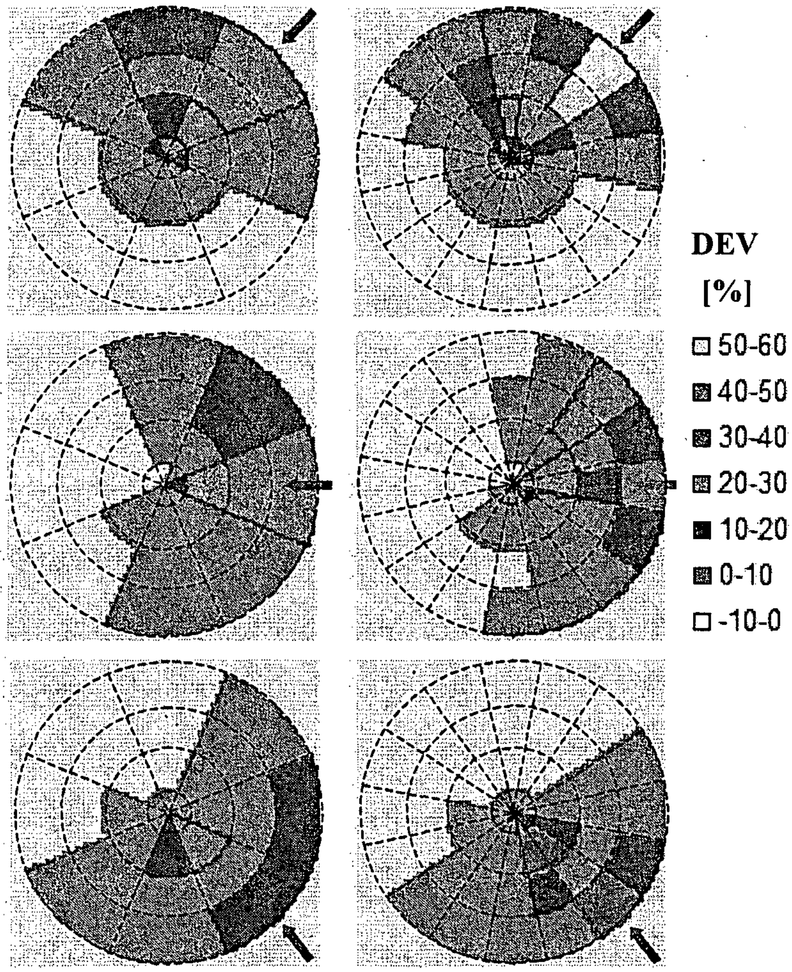


Figure 11: Comparison of a Calculated Relative Deviation of Mixing Factors (8 vs. 16-Theta)

6.2 Experiment at the 4-th unit of NPP Dukovany

The analysed experimental test of coolant mixing in the VVER 440/213 reactor under steady state conditions was performed at the 4-th unit of NPP Dukovany in 1987 (Ref 22). The fields of calculated mixing factors relevant to the all of investigated loops at Dukovany NPP are presented in the Appendix A. The maximal values and relative deviations of measured and calculated data were analysed in order to verify previous results.

6.2.1 8-ThetaTRACE model results

The results of comparative calculation of experimental test on 4-th Unit of NPP Dukovany confirmed results of previous calculations based on data from 1-st Unit test. The maximal values of TRACE calculated mixing factors related to the all investigated loops are presented in the next Table 7.

Table 7: Maximal Values of of Measured and Calculated Mixing Factors (8-Theta Model)

Loop No	1	2	3	4	5	6
measured data	0.798	0.788	0.795	0.786	0.781	0.772
8-Theta TRACE model	0.711	0.793	0.64	0.655	0.793	0.711
DIFF [%]	-11	1	-19	-17	2	-8

Graphs of weighted deviations of calculated and measured mixing factors for all investigated loops are presented in the Appendix F. The maximal value of weighted deviations varies from -46% to +35% for a given loop.

6.2.2 16-ThetaTRACE model results

The results of comparative calculation of experimental test on 4-th Unit of NPP Dukovany confirmed results of previous calculations based on data from 1-st Unit test. The maximal values of TRACE calculated mixing factors related to the all investigated loops are presented in the next Table 8.

Table 8: Maximal Values of of Measured and Calculated Mixing Factors (16-Theta Model)

Loop No	1	2	3	4	5	6
measured data	0.798	0.788	0.795	0.786	0.781	0.772
16-Theta TRACE model	0.906	0.726	0.716	0.716	0.726	0.907
DIFF [%]	14	-8	-10	-9	-7	17

Graphs of weighted deviations of calculated and measured mixing factors for all investigated loops are presented in the Appendix G. The maximal value of weighted deviations varies from -48% to +51% for a given loop.

7. RUN STATISTICS

The transients were calculated on personal computer with AMD Athlon X2 4200+ processor 2.2 GHz under Microsoft Windows XP Professional, Service Pack 2. The run statistics is shown in Table 9 and Table 10. The calculations run substantially slower than real time.

Table 9: Run statistics (8-Theta Model)

Number of components	335
Number of time steps	79 775
Transient time	1000 s
CPU time	29 747 s
CPU time / Transient time	29.7

Table 10: Run statistics (16-Theta Model)

Number of components	476
Number of time steps	120 887
Transient time	1000 s
CPU time	134 695 s
CPU time / Transient time	134.7

8. CONCLUSIONS

The new TRACE input decks of VVER-440/213 reactor were introduced in this paper. Mixing factors at the core inlet were defined and experiments under normal operation conditions at the 1-st unit of NPP Dukovany in 1997 and at the 4-th Unit of NPP Dukovany in 1987 were described. The measured mixing factors at the inlet of VVER-440 reactor were presented as results of these tests.

TRACE post-test calculations of VVER-440/213 mixing factors were presented in this paper. Calculated mixing factors were compared to measured ones at NPP Dukovany in order to investigate applicability of the TRACE code and the developed TRACE input decks to solve coolant mixing problems in VVER-440/213 type of reactors. Then the VESSEL component nodalisation study was performed to analyse the influence of theta discretisation on calculated mixing factors. It was showed that the calculated results indicate good agreement with the measured data first of all from qualitative point of view. The evaluation of calculated results from quantitative point of view was not so satisfactory. There are relatively high deviations between measured and calculated mixing factors even using fine 16-Theta discretisation of the VESSEL component. Though applicability of the TRACE code and the developed TRACE input decks were demonstrated to solve the coolant mixing phenomena in VVER 440/213 type of reactors. Moreover there was presented attainable accuracy of such calculations using the TRACE code.

The performed TRACE nodalisation study indicated that THETA division of VESSEL component had low influence on calculated mixing factors accuracy. It was stated, that finer THETA division gives better results in case of shape (outer boundaries) of mixing factors fields but not in a case of average mixing factor values in a given sectors. An exception was found in sectors containing peak or extreme value of measured mixing factors. It was recommended to carefully prepare a design of TRACE input deck of a VESSEL component.

Although a lot of work had been done in frame of this project, further investigation is necessary to asses the TRACE code application for mixing phenomena of VVER-440 (and other) reactors.

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APPENDIX A

MEASURED MIXING FACTORS AT THE DUKOVANY NPP

INTRODUCTION

In this appendix, the results of experimental investigations of coolant mixing in the VVER 440/213 reactor under steady state conditions at the 1-st Unit of NPP Dukovany in 1997 and at the 4-th Unit of NPP in 1987 Dukovany are presented. The fields of measured mixing factors relevant to the all of investigated loops at Dukovany NPP are shown.

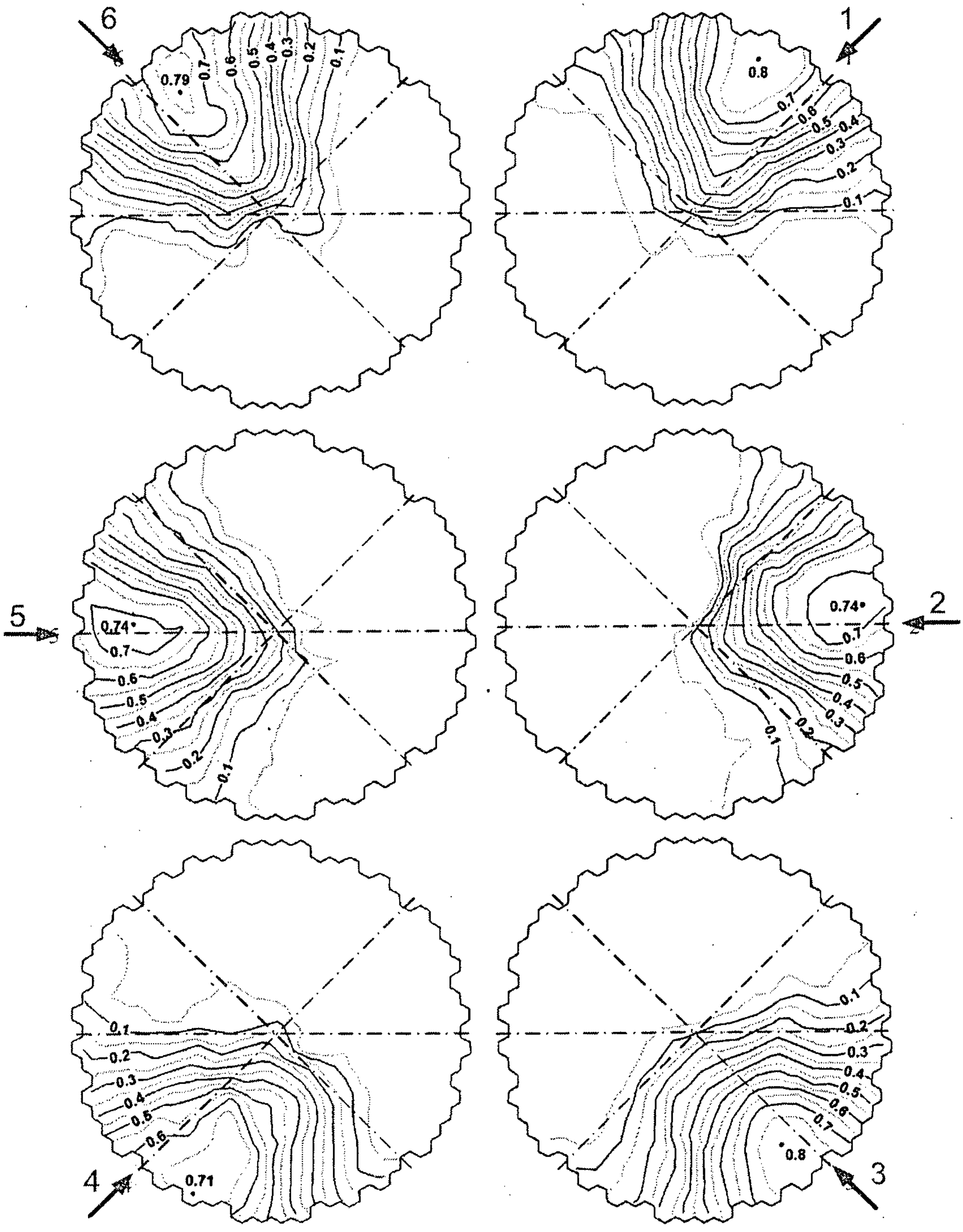

Figure A-1 Measured Mixing Factors at the 1-st Unit of Dukovany NPP 1997 (Ref 17)

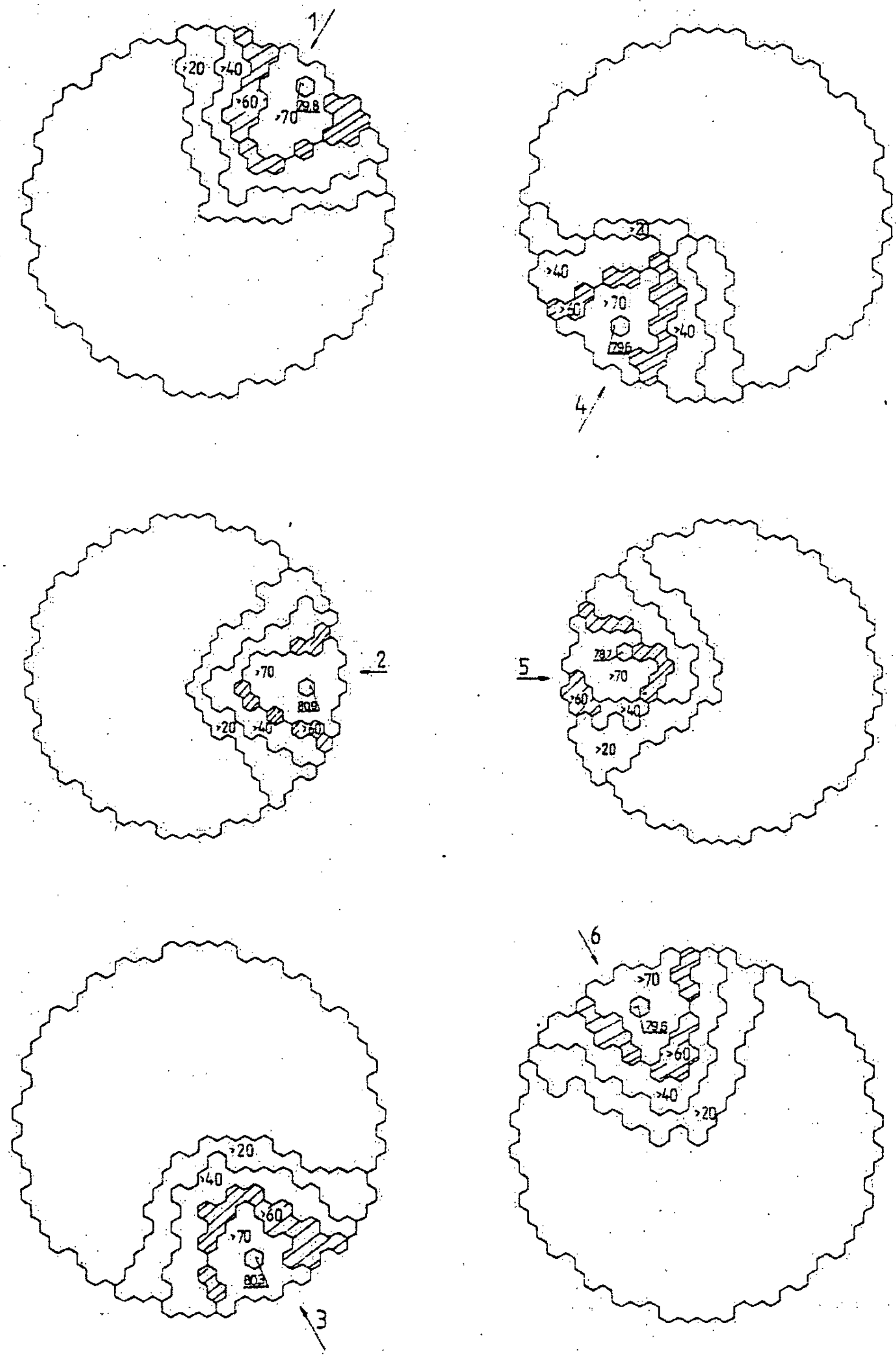

Figure A-2 Measured Mixing Factors at the 4-thUnit of Dukovany NPP 1987 (Ref 22)

APPENDIX B

NODALISATION OF THE 8-THETA VESSEL COMPONENT OF VVER-440/213 REACTOR

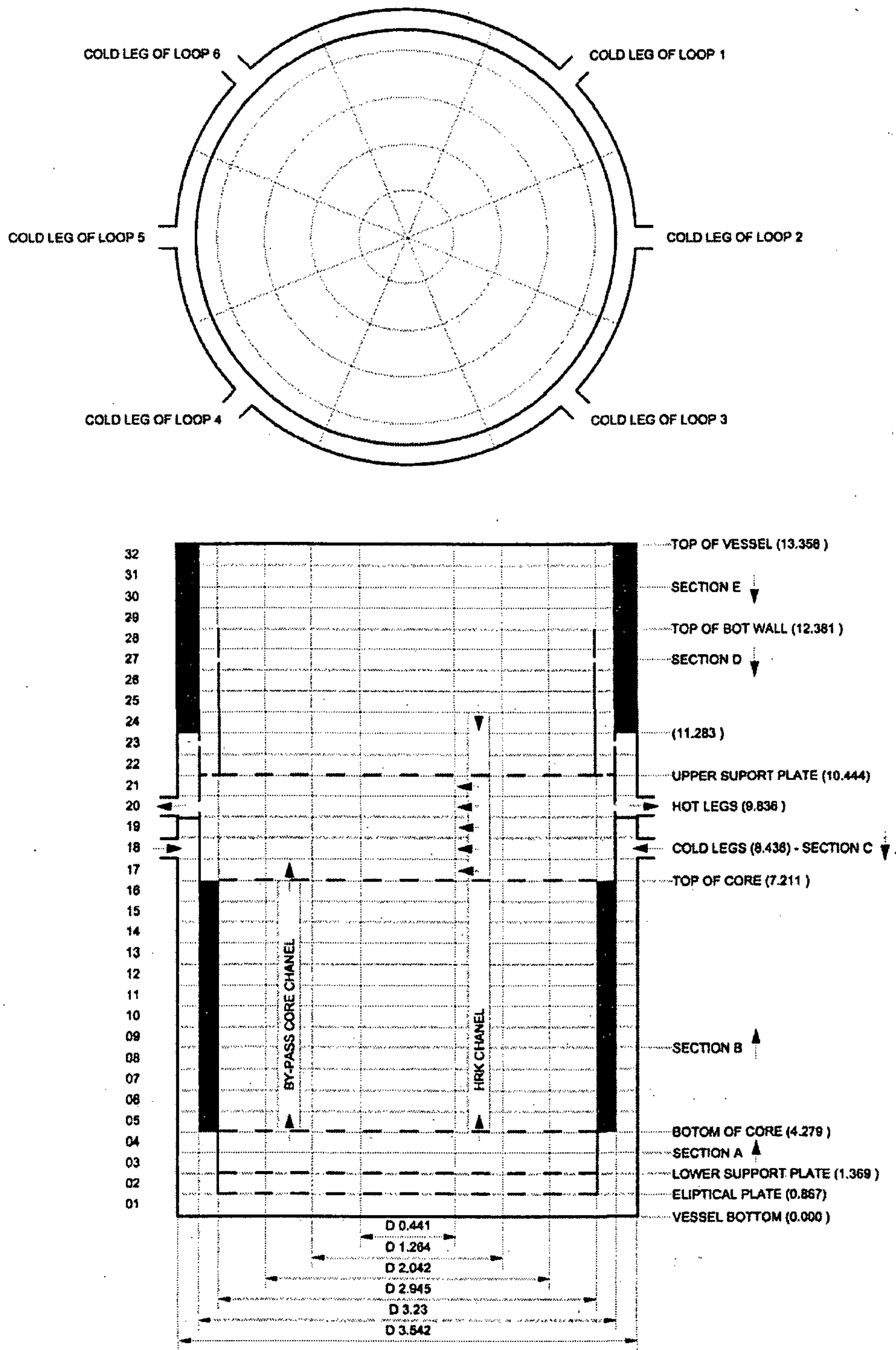

Figure B-1 Nodalisation of the 8-Theta VESSEL Component of VVER-440/213 Reactor

APPENDIX C

NODALISATION OF THE 16-THETA VESSEL COMPONENT OF VVER-440/213 REACTOR

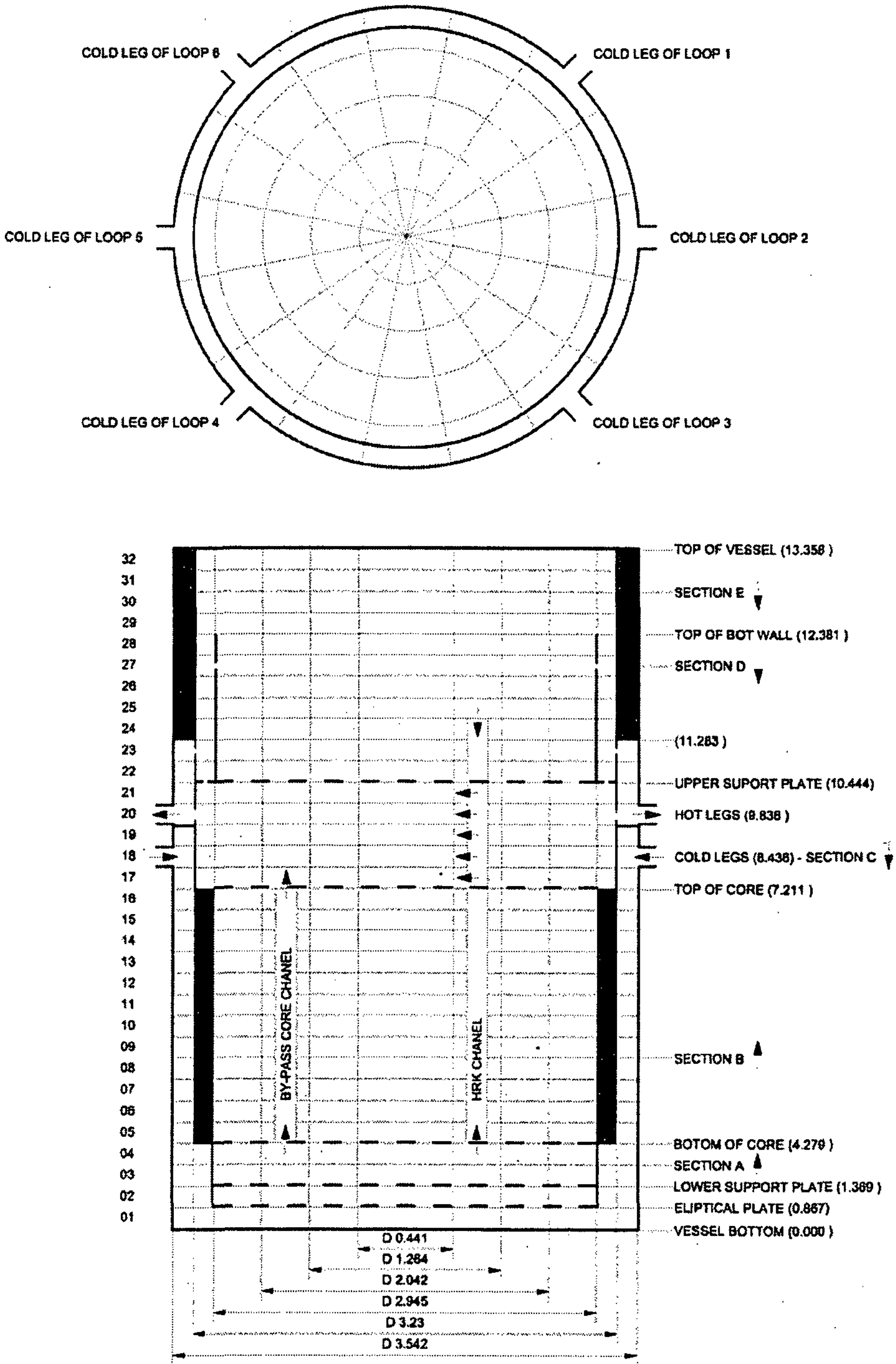

Figure C-1 Nodalisation of the 16-Theta VESSEL Component of VVER-440/213 Reactor

APPENDIX D

COMPARISON OF MEASURED AND CALCULATED MIXING FACTORS 1-ST UNIT OF NPP DUKOVANY 1997 (8-THETA MODEL)

INTRODUCTION

In this appendix, there are demonstrated Tables D-1÷6 and Figure D-1 which contains the summary of measured (maximal, minimal and averaged values) and calculated data using 8-Theta TRACE VESSEL input deck. The measured data came from experimental investigations of coolant mixing in the VVER-440/213 reactor under steady-state conditions at the 1-st unit of NPP Dukovany in 1997. The Tables D-1÷6 contain relative deviation of measured and calculated data weighted by average value of measured mixing factors related to investigated loop. The Figure D-1 contain 6 graphs (each for given investigated loop) of weighted relative deviation of measured an calculated mixing factors. The X-axis represents modelled Theta sectors. There are numbers of radial rings as independent parameter in these graphs.

Table D-1 Comparison of Measured an Calculated (8-Theta model) Mixing Factors for Loop1

LOOP1	RING 1					RING 2				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	8-Theta model		max value	min value	avg value	8-Theta model	
THETA1 (adj. to Loop3)	0.200	0.100	0.147	0.007	-6	0.150	0.050	0.036	0.007	0
THETA2 (adj. to Loop2)	0.300	0.250	0.264	0.068	-15	0.400	0.100	0.183	0.126	-3
THETA3 (adj. to Loop1)	0.400	0.300	0.356	0.113	-26	0.600	0.400	0.460	0.518	8
THETA4 (betw. Loop1-6)	0.400	0.200	0.319	0.107	-20	0.650	0.100	0.409	0.314	-12
THETA5 (adj. to Loop6)	0.000	0.000	0.226	0.021	-14	0.000	0.000	0.123	0.080	-2
THETA6 (adj. to Loop5)	0.200	0.150	0.138	0.014	-5	0.100	0.050	0.035	0.019	0
THETA7 (adj. to Loop4)	0.100	0.100	0.079	0.007	-2	0.050	0.050	0.017	0.007	0
THETA8 (betw. Loop3-4)	0.100	0.100	0.082	0.007	-2	0.050	0.050	0.008	0.007	0

LOOP1	RING 3					RING 4				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	8-Theta model		max value	min value	avg value	8-Theta model	
THETA1 (adj. to Loop3)	0.000	0.000	0.000	0.008	0	0.000	0.000	0.000	0.018	0
THETA2 (adj. to Loop2)	0.250	0.050	0.084	0.187	3	0.250	0.050	0.076	0.186	2
THETA3 (adj. to Loop1)	0.750	0.300	0.556	0.690	22	0.800	0.300	0.585	0.711	22
THETA4 (betw. Loop1-6)	0.750	0.050	0.525	0.385	-22	0.750	0.050	0.532	0.418	-18
THETA5 (adj. to Loop6)	0.000	0.000	0.070	0.121	1	0.000	0.000	0.060	0.121	1
THETA6 (adj. to Loop5)	0.000	0.000	0.000	0.030	0	0.000	0.000	0.000	0.026	0
THETA7 (adj. to Loop4)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.008	0
THETA8 (betw. Loop3-4)	0.000	0.000	0.000	0.006	0	0.000	0.000	0.000	0.006	0

Table D-2 Comparison of Measured an Calculated (8-Theta model) Mixing Factors for Loop2

LOOP2	RING 1					RING 2				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max. value	min. value	avg value	8-Theta model		max. value	min. value	avg value	8-Theta model	
THETA1 (adj. to Loop3)	0.250	0.250	0.165	0.156	0	0.350	0.100	0.212	0.158	-3
THETA2 (adj. to Loop2)	0.250	0.200	0.192	0.485	17	0.600	0.300	0.436	0.755	42
THETA3 (adj. to Loop1)	0.250	0.050	0.060	0.517	8	0.500	0.050	0.270	0.328	5
THETA4 (betw. Loop1-6)	0.000	0.000	0.000	0.256	0	0.150	0.050	0.008	0.168	0
THETA5 (adj. to Loop6)	0.000	0.000	0.000	0.014	0	0.000	0.000	0.000	0.018	0
THETA6 (adj. to Loop5)	0.000	0.000	0.000	0.015	0	0.000	0.000	0.000	0.010	0
THETA7 (adj. to Loop4)	0.050	0.050	0.037	0.021	0	0.050	0.050	0.002	0.020	0
THETA8 (betw. Loop3-4)	0.150	0.100	0.081	0.086	0	0.100	0.050	0.032	0.074	0
LOOP2	RING 3					RING 4				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max. value	min. value	avg value	8-Theta model		max. value	min. value	avg value	8-Theta model	
THETA1 (adj. to Loop3)	0.500	0.050	0.173	0.167	0	0.500	0.100	0.198	0.210	1
THETA2 (adj. to Loop2)	0.700	0.450	0.625	0.753	24	0.740	0.500	0.641	0.793	30
THETA3 (adj. to Loop1)	0.650	0.100	0.397	0.178	-26	0.650	0.100	0.333	0.161	-17
THETA4 (betw. Loop1-6)	0.150	0.050	0.013	0.117	0	0.100	0.050	0.007	0.089	0
THETA5 (adj. to Loop6)	0.000	0.000	0.000	0.027	0	0.000	0.000	0.000	0.026	0
THETA6 (adj. to Loop5)	0.000	0.000	0.000	0.011	0	0.000	0.000	0.000	0.010	0
THETA7 (adj. to Loop4)	0.000	0.000	0.000	0.021	0	0.000	0.000	0.000	0.021	0
THETA8 (betw. Loop3-4)	0.050	0.050	0.006	0.057	0	0.050	0.050	0.011	0.047	0

Table D-3 Comparison of Measured an Calculated (8-Theta model) Mixing Factors for Loop3

LOOP3	RING 1					RING 2				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	8-Theta model		max value	min value	avg value	8-Theta model	
THETA1 (adj. to Loop3)	0.200	0.150	0.163	0.655	24	0.550	0.250	0.373	0.641	30
THETA2 (adj. to Loop2)	0.150	0.100	0.091	0.269	5	0.400	0.100	0.167	0.099	-3
THETA3 (adj. to Loop1)	0.050	0.050	0.018	0.224	1	0.050	0.050	0.006	0.045	0
THETA4 (betw. Loop1-6)	0.000	0.000	0.002	0.127	0	0.000	0.000	0.000	0.047	0
THETA5 (adj. to Loop6)	0.000	0.000	0.003	0.087	0	0.000	0.000	0.000	0.021	0
THETA6 (adj. to Loop5)	0.050	0.050	0.034	0.101	1	0.050	0.050	0.005	0.039	0
THETA7 (adj. to Loop4)	0.100	0.100	0.089	0.185	3	0.250	0.050	0.093	0.184	3
THETA8 (betw. Loop3-4)	0.200	0.150	0.152	0.450	13	0.500	0.250	0.306	0.446	13
LOOP3	RING 3					RING 4				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	8-Theta model		max value	min value	avg value	8-Theta model	
THETA1 (adj. to Loop3)	0.750	0.450	0.623	0.640	3	0.800	0.500	0.691	0.595	-20
THETA2 (adj. to Loop2)	0.450	0.050	0.204	0.053	-9	0.500	0.050	0.208	0.026	-11
THETA3 (adj. to Loop1)	0.050	0.050	0.004	0.012	0	0.050	0.050	0.003	0.007	0
THETA4 (betw. Loop1-6)	0.000	0.000	0.000	0.022	0	0.000	0.000	0.000	0.010	0
THETA5 (adj. to Loop6)	0.000	0.000	0.000	0.009	0	0.000	0.000	0.000	0.007	0
THETA6 (adj. to Loop5)	0.000	0.000	0.000	0.020	0	0.000	0.000	0.000	0.010	0
THETA7 (adj. to Loop4)	0.150	0.050	0.052	0.184	2	0.150	0.050	0.045	0.182	2
THETA8 (betw. Loop3-4)	0.700	0.200	0.395	0.457	7	0.700	0.200	0.417	0.462	6

Table D-4 Comparison of Measured an Calculated (8-Theta model) Mixing Factors for Loop4

LOOP4	RING 1					RING 2				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max. value	min. value	avg value	8-Theta model		max. value	min. value	avg value	8-Theta model	
THETA1 (adj. to Loop3)	0.150	0.050	0.104	0.185	3	0.350	0.050	0.147	0.184	2
THETA2 (adj. to Loop2)	0.100	0.050	0.053	0.101	1	0.050	0.050	0.001	0.039	0
THETA3 (adj. to Loop1)	0.100	0.050	0.042	0.087	1	0.000	0.000	0.000	0.021	0
THETA4 (betw. Loop1-6)	0.050	0.050	0.053	0.127	1	0.050	0.050	0.001	0.047	0
THETA5 (adj. to Loop6)	0.000	0.000	0.055	0.224	3	0.000	0.000	0.023	0.045	0
THETA6 (adj. to Loop5)	0.150	0.100	0.088	0.269	5	0.250	0.050	0.091	0.099	0
THETA7 (adj. to Loop4)	0.250	0.150	0.176	0.655	28	0.600	0.200	0.324	0.641	34
THETA8 (betw. Loop3-4)	0.250	0.200	0.188	0.450	16	0.550	0.250	0.387	0.446	8

LOOP4	RING 3					RING 4				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max. value	min. value	avg value	8-Theta model		max. value	min. value	avg value	8-Theta model	
THETA1 (adj. to Loop3)	0.350	0.050	0.100	0.184	3	0.200	0.050	0.040	0.182	2
THETA2 (adj. to Loop2)	0.000	0.000	0.000	0.020	0	0.000	0.000	0.000	0.010	0
THETA3 (adj. to Loop1)	0.000	0.000	0.000	0.009	0	0.000	0.000	0.000	0.007	0
THETA4 (betw. Loop1-6)	0.000	0.000	0.000	0.022	0	0.050	0.050	0.000	0.010	0
THETA5 (adj. to Loop6)	0.000	0.000	0.000	0.012	0	0.000	0.000	0.008	0.007	0
THETA6 (adj. to Loop5)	0.300	0.050	0.090	0.053	-1	0.300	0.050	0.123	0.026	-4
THETA7 (adj. to Loop4)	0.650	0.300	0.495	0.640	23	0.710	0.350	0.540	0.595	10
THETA8 (betw. Loop3-4)	0.650	0.300	0.476	0.457	-3	0.650	0.200	0.463	0.462	0

Table D-5 Comparison of Measured an Calculated (8-Theta model) Mixing Factors for Loop5

LOOP5	RING 1					RING 2				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	8-Theta model		max value	min value	avg value	8-Theta model	
THETA1 (adj. to Loop3)	0.200	0.050	0.113	0.021	-3	0.150	0.050	0.022	0.020	0
THETA2 (adj. to Loop2)	0.100	0.050	0.065	0.015	-1	0.050	0.050	0.004	0.010	0
THETA3 (adj. to Loop1)	0.100	0.050	0.036	0.014	0	0.000	0.000	0.000	0.018	0
THETA4 (betw. Loop1-6)	0.200	0.050	0.075	0.256	4	0.450	0.050	0.023	0.168	1
THETA5 (adj. to Loop6)	0.000	0.000	0.179	0.517	19	0.000	0.000	0.216	0.328	8
THETA6 (adj. to Loop5)	0.350	0.200	0.280	0.485	18	0.650	0.400	0.494	0.755	40
THETA7 (adj. to Loop4)	0.350	0.250	0.285	0.156	-11	0.550	0.200	0.355	0.158	-22
THETA8 (betw. Loop3-4)	0.250	0.200	0.209	0.086	-8	0.250	0.050	0.114	0.074	-1
LOOP5	RING 3					RING 4				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	8-Theta model		max value	min value	avg value	8-Theta model	
THETA1 (adj. to Loop3)	0.000	0.000	0.000	0.021	0	0.000	0.000	0.000	0.021	0
THETA2 (adj. to Loop2)	0.000	0.000	0.000	0.011	0	0.000	0.000	0.000	0.010	0
THETA3 (adj. to Loop1)	0.000	0.000	0.000	0.027	0	0.000	0.000	0.000	0.026	0
THETA4 (betw. Loop1-6)	0.450	0.050	0.000	0.117	0	0.500	0.050	0.000	0.089	0
THETA5 (adj. to Loop6)	0.000	0.000	0.193	0.178	-1	0.000	0.000	0.197	0.161	-2
THETA6 (adj. to Loop5)	0.700	0.500	0.628	0.753	25	0.740	0.500	0.631	0.793	32
THETA7 (adj. to Loop4)	0.600	0.150	0.328	0.167	-17	0.550	0.150	0.300	0.210	-9
THETA8 (betw. Loop3-4)	0.100	0.050	0.034	0.057	0	0.100	0.050	0.023	0.047	0

Table D-6 Comparison of Measured an Calculated (8-Theta model) Mixing Factors for Loop6

LOOP6	RING 1					RING 2				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	8-Theta model		max value	min value	avg value	8-Theta model	
THETA1 (adj. to Loop3)	0.150	0.100	0.094	0.007	-2	0.100	0.050	0.022	0.007	0
THETA2 (adj. to Loop2)	0.200	0.150	0.150	0.014	-6	0.150	0.050	0.045	0.019	0
THETA3 (adj. to Loop1)	0.300	0.200	0.217	0.021	-13	0.300	0.050	0.115	0.080	-1
THETA4 (betw. Loop1-6)	0.450	0.250	0.307	0.107	-18	0.650	0.250	0.406	0.314	-11
THETA5 (adj. to Loop6)	0.000	0.000	0.316	0.113	-19	0.000	0.000	0.523	0.518	-1
THETA6 (adj. to Loop5)	0.300	0.150	0.209	0.068	-9	0.450	0.100	0.237	0.126	-8
THETA7 (adj. to Loop4)	0.150	0.050	0.057	0.007	-1	0.200	0.050	0.048	0.007	-1
THETA8 (betw. Loop3-4)	0.100	0.050	0.032	0.007	0	0.000	0.000	0.000	0.007	0

LOOP6	RING 3					RING 4				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	8-Theta model		max value	min value	avg value	8-Theta model	
THETA1 (adj. to Loop3)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.008	0
THETA2 (adj. to Loop2)	0.000	0.000	0.000	0.030	0	0.000	0.000	0.000	0.026	0
THETA3 (adj. to Loop1)	0.150	0.050	0.020	0.121	1	0.100	0.050	0.007	0.121	0
THETA4 (betw. Loop1-6)	0.750	0.150	0.375	0.385	1	0.790	0.100	0.366	0.418	6
THETA5 (adj. to Loop6)	0.000	0.000	0.630	0.690	11	0.000	0.000	0.633	0.711	15
THETA6 (adj. to Loop5)	0.450	0.050	0.159	0.187	1	0.400	0.050	0.132	0.186	2
THETA7 (adj. to Loop4)	0.050	0.050	0.000	0.008	0	0.050	0.050	0.002	0.018	0
THETA8 (betw. Loop3-4)	0.000	0.000	0.000	0.006	0	0.000	0.000	0.000	0.006	0

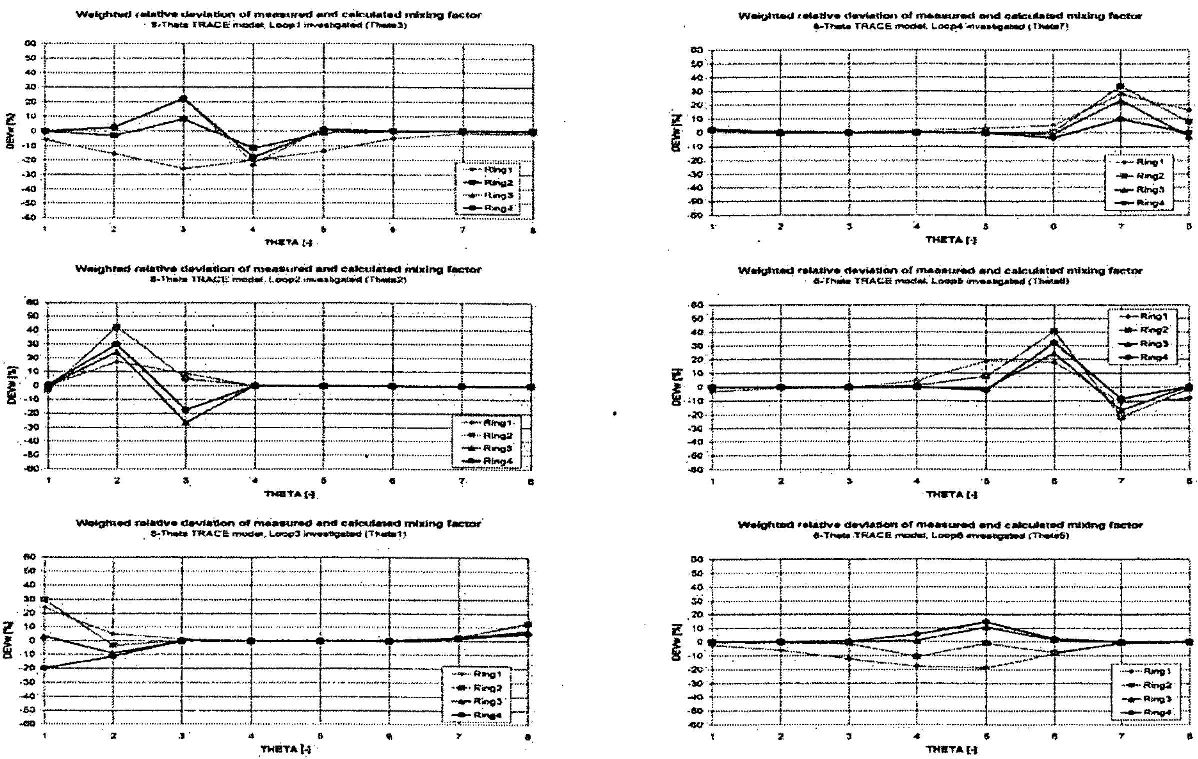

Figure D-1 Comparison of Weighted Relative Deviation of Measured and Calculated (8-Theta model) Mixing Factors

APPENDIX E

COMPARISON OF MEASURED AND CALCULATED MIXING FACTORS 1-ST UNIT OF NPP DUKOVANY 1997 (16-THETA MODEL)

INTRODUCTION

In this appendix, there are demonstrated Tables E-1÷6 and Figure E-1 which contains the summary of measured (maximal, minimal and averaged values) and calculated data using 16-Theta TRACE VESSEL input deck. The measured data came from experimental investigations of coolant mixing in the VVER-440/213 reactor under steady-state conditions at the 1-st unit of NPP Dukovany in 1997. The Tables D-1÷6 contain relative deviation of measured and calculated data weighted by average value of measured mixing factors related to investigated loop. The Figure E-1 contains 6 graphs (each for given investigated loop) of weighted relative deviation of measured a calculated mixing factors. The X-axis represents modelled Theta sectors. There are numbers of radial rings as independent parameter in these graphs.

Table E-1 Comparison of Measured an Calculated (16-Theta model) Mixing Factors for Loop1

LOOP1	RING 1					RING 2				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max. value	min. value	avg value	16-Theta model		max. value	min. value	avg value	16-Theta model	
THETA1 (adj. to Loop3)	0.150	0.150	0.145	0.020	-5	0.100	0.050	0.036	0.011	0
THETA4 (betw. Loop3-2)	0.250	0.200	0.196	0.029	-10	0.200	0.050	0.073	0.021	-1
THETA3 (adj. to Loop2)	0.300	0.300	0.264	0.056	-16	0.350	0.100	0.176	0.076	-5
THETA4 (betw. Loop2-1)	0.350	0.350	0.324	0.107	-21	0.400	0.250	0.331	0.200	-13
THETA5 (adj. to Loop1)	0.400	0.300	0.361	0.181	-19	0.550	0.450	0.472	0.616	20
THETA4 (betw. Loop1-6)	0.400	0.350	0.361	0.230	-14	0.650	0.450	0.522	0.705	29
THETA7 (betw. Loop1-6)	0.350	0.350	0.315	0.166	-14	0.550	0.350	0.412	0.336	-9
THETA8 (betw. Loop1-6)	0.300	0.250	0.276	0.008	-22	0.350	0.150	0.249	0.035	-16
THETA9 (adj. to Loop6)	0.250	0.250	0.223	0.008	-14	0.200	0.100	0.110	0.012	-3
THETA10 (betw. Loop6-5)	0.200	0.200	0.184	0.007	-10	0.150	0.100	0.059	0.007	-1
THETA11 (adj. to Loop5)	0.200	0.150	0.138	0.007	-5	0.100	0.050	0.034	0.007	0
THETA12 (betw. Loop5-4)	0.100	0.100	0.095	0.007	-2	0.050	0.050	0.023	0.007	0
THETA13 (adj. to Loop4)	0.000	0.000	0.077	0.007	-2	0.050	0.050	0.021	0.007	0
THETA14 (betw. Loop4-3)	0.000	0.000	0.074	0.007	-2	0.050	0.050	0.002	0.006	0
THETA15 (betw. Loop4-3)	0.100	0.100	0.080	0.010	-2	0.050	0.050	0.009	0.007	0
THETA16 (betw. Loop4-3)	0.200	0.100	0.105	0.015	-3	0.000	0.000	0.014	0.008	0

Table E-1 Comparison of Measured an Calculated (16-Theta model) Mixing Factors for Loop1 (continued)

LOOP1	RING 3					RING 4				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max. value	min. value	avg value	16-Theta model		max. value	min. value	avg value	16-Theta model	
THETA1 (adj. to Loop3)	0.000	0.000	0.000	0.011	0	0.000	0.000	0.000	0.022	0
THETA4 (betw. Loop3-2)	0.000	0.000	0.000	0.024	0	0.000	0.000	0.000	0.064	0
THETA3 (adj. to Loop2)	0.150	0.050	0.069	0.110	1	0.150	0.050	0.059	0.195	2
THETA4 (betw. Loop2-1)	0.450	0.200	0.273	0.343	6	0.500	0.150	0.273	0.457	15
THETA5 (adj. to Loop1)	0.700	0.450	0.585	0.872	50	0.750	0.500	0.619	0.906	53
THETA4 (betw. Loop1-6)	0.750	0.650	0.713	0.824	24	0.800	0.750	0.764	0.830	15
THETA7 (betw. Loop1-6)	0.700	0.400	0.533	0.397	-22	0.700	0.350	0.543	0.417	-21
THETA8 (betw. Loop1-6)	0.400	0.150	0.253	0.069	-14	0.400	0.150	0.218	0.098	-8
THETA9 (adj. to Loop6)	0.150	0.050	0.043	0.022	0	0.100	0.050	0.046	0.034	0
THETA10 (betw. Loop6-5)	0.050	0.050	0.002	0.008	0	0.000	0.000	0.000	0.012	0
THETA11 (adj. to Loop5)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.008	0
THETA12 (betw. Loop5-4)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.007	0
THETA13 (adj. to Loop4)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.007	0
THETA14 (betw. Loop4-3)	0.000	0.000	0.000	0.006	0	0.000	0.000	0.000	0.006	0
THETA15 (betw. Loop4-3)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.006	0
THETA16 (betw. Loop4-3)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.007	0

Table E-2 Comparison of Measured an Calculated (16-Theta model) Mixing Factors for Loop 2

LOOP2	RING 1					RING 2				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	16-Theta model		max value	min value	avg value	16-Theta model	
THETA1 (adj. to Loop3)	0.250	0.250	0.163	0.399	12	0.250	0.100	0.174	0.343	9
THETA4 (betw. Loop3-2)	0.200	0.200	0.197	0.486	17	0.650	0.300	0.442	0.586	19
THETA3 (adj. to Loop2)	0.250	0.250	0.197	0.608	25	0.700	0.650	0.678	0.726	10
THETA4 (betw. Loop2-1)	0.250	0.100	0.152	0.623	22	0.700	0.500	0.624	0.535	-17
THETA5 (adj. to Loop1)	0.100	0.050	0.055	0.575	9	0.500	0.250	0.309	0.084	-21
THETA4 (betw. Loop1-6)	0.000	0.000	0.000	0.549	0	0.250	0.050	0.079	0.065	0
THETA7 (betw. Loop1-6)	0.000	0.000	0.000	0.389	0	0.050	0.050	0.000	0.086	0
THETA8 (betw. Loop1-6)	0.000	0.000	0.000	0.008	0	0.000	0.000	0.000	0.021	0
THETA9 (adj. to Loop6)	0.000	0.000	0.000	0.008	0	0.000	0.000	0.000	0.011	0
THETA10 (betw. Loop6-5)	0.000	0.000	0.000	0.008	0	0.000	0.000	0.000	0.007	0
THETA11 (adj. to Loop5)	0.000	0.000	0.000	0.008	0	0.000	0.000	0.000	0.007	0
THETA12 (betw. Loop5-4)	0.050	0.050	0.006	0.008	0	0.000	0.000	0.000	0.007	0
THETA13 (adj. to Loop4)	0.000	0.000	0.043	0.009	0	0.000	0.000	0.000	0.009	0
THETA14 (betw. Loop4-3)	0.100	0.050	0.050	0.010	-1	0.000	0.000	0.000	0.013	0
THETA15 (betw. Loop4-3)	0.100	0.100	0.083	0.062	-1	0.000	0.000	0.003	0.039	0
THETA16 (betw. Loop4-3)	0.150	0.150	0.123	0.343	8	0.050	0.050	0.052	0.124	1

Table E-2 Comparison of Measured an Calculated (16-Theta model) Mixing Factors for Loop 2 (continued)

LOOP2	RING 3					RING 4				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	16-Theta model		max value	min value	avg value	16-Theta model	
THETA1 (adj. to Loop3)	0.250	0.100	0.142	0.276	6	0.300	0.150	0.174	0.343	9
THETA4 (betw. Loop3-2)	0.650	0.300	0.446	0.494	6	0.650	0.300	0.442	0.586	19
THETA3 (adj. to Loop2)	0.700	0.650	0.659	0.719	12	0.740	0.600	0.678	0.726	10
THETA4 (betw. Loop2-1)	0.700	0.500	0.609	0.616	1	0.700	0.500	0.624	0.535	-17
THETA5 (adj. to Loop1)	0.500	0.250	0.339	0.133	-21	0.500	0.200	0.309	0.084	-21
THETA4 (betw. Loop1-6)	0.250	0.050	0.094	0.095	0	0.200	0.050	0.079	0.065	0
THETA7 (betw. Loop1-6)	0.050	0.050	0.005	0.115	0	0.000	0.000	0.000	0.086	0
THETA8 (betw. Loop1-6)	0.000	0.000	0.000	0.017	0	0.000	0.000	0.000	0.021	0
THETA9 (adj. to Loop6)	0.000	0.000	0.000	0.009	0	0.000	0.000	0.000	0.011	0
THETA10 (betw. Loop6-5)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.007	0
THETA11 (adj. to Loop5)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.007	0
THETA12 (betw. Loop5-4)	0.000	0.000	0.000	0.008	0	0.000	0.000	0.000	0.007	0
THETA13 (adj. to Loop4)	0.000	0.000	0.000	0.010	0	0.000	0.000	0.000	0.009	0
THETA14 (betw. Loop4-3)	0.000	0.000	0.000	0.014	0	0.000	0.000	0.000	0.013	0
THETA15 (betw. Loop4-3)	0.000	0.000	0.000	0.043	0	0.050	0.050	0.003	0.039	0
THETA16 (betw. Loop4-3)	0.050	0.050	0.036	0.139	1	0.100	0.050	0.052	0.124	1

Table E-3 Comparison of Measured an Calculated (16-Theta model) Mixing Factors for Loop3

LOOP3	RING 1 measured data			RING 1 TRACE	RING 1	RING 2 measured data			RING 2 TRACE	RING 2
	max value	min value	avg value	16-Theta model	DEVw (%)	max value	min value	avg value	16-Theta model	DEVw (%)
THETA1 (adj. to Loop3)	0.200	0.200	0.168	0.557	19	0.550	0.250	0.386	0.651	30
THETA4 (betw. Loop3-2)	0.000	0.000	0.137	0.479	14	0.450	0.200	0.299	0.515	19
THETA3 (adj. to Loop2)	0.150	0.100	0.094	0.352	7	0.300	0.100	0.168	0.304	7
THETA4 (betw. Loop2-1)	0.100	0.100	0.049	0.289	3	0.100	0.050	0.044	0.191	2
THETA5 (adj. to Loop1)	0.050	0.050	0.010	0.258	1	0.000	0.000	0.000	0.091	0
THETA4 (betw. Loop1-6)	0.000	0.000	0.003	0.245	0	0.000	0.000	0.000	0.061	0
THETA7 (betw. Loop1-6)	0.000	0.000	0.002	0.218	0	0.000	0.000	0.000	0.077	0
THETA8 (betw. Loop1-6)	0.000	0.000	0.002	0.033	0	0.000	0.000	0.000	0.013	0
THETA9 (adj. to Loop6)	0.000	0.000	0.003	0.023	0	0.000	0.000	0.000	0.011	0
THETA10 (betw. Loop6-5)	0.000	0.000	0.007	0.025	0	0.000	0.000	0.000	0.017	0
THETA11 (adj. to Loop5)	0.050	0.050	0.039	0.029	0	0.050	0.050	0.003	0.025	0
THETA12 (betw. Loop5-4)	0.100	0.100	0.056	0.039	0	0.050	0.050	0.021	0.046	0
THETA13 (adj. to Loop4)	0.100	0.100	0.093	0.053	-1	0.150	0.050	0.087	0.079	0
THETA14 (betw. Loop4-3)	0.150	0.150	0.116	0.070	-2	0.300	0.150	0.202	0.152	-3
THETA15 (betw. Loop4-3)	0.200	0.200	0.155	0.090	-3	0.450	0.250	0.307	0.330	2
THETA16 (betw. Loop4-3)	0.150	0.150	0.170	0.570	20	0.500	0.250	0.384	0.661	32

Table E-3 Comparison of Measured an Calculated (16-Theta model) Mixing Factors for Loop3 (continued)

LOOP3	RING 3					RING 4				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	16-Theta model		max value	min value	avg value	16-Theta model	
THETA1 (adj. to Loop3)	0.750	0.550	0.664	0.659	-1	0.800	0.650	0.736	0.594	-31
THETA4 (betw. Loop3-2)	0.650	0.300	0.437	0.475	5	0.650	0.350	0.481	0.357	-18
THETA3 (adj. to Loop2)	0.350	0.100	0.192	0.194	0	0.350	0.100	0.192	0.102	-5
THETA4 (betw. Loop2-1)	0.150	0.050	0.045	0.067	0	0.100	0.050	0.032	0.027	0
THETA5 (adj. to Loop1)	0.000	0.000	0.000	0.021	0	0.000	0.000	0.000	0.011	0
THETA4 (betw. Loop1-6)	0.000	0.000	0.000	0.021	0	0.000	0.000	0.000	0.012	0
THETA7 (betw. Loop1-6)	0.000	0.000	0.000	0.034	0	0.000	0.000	0.000	0.018	0
THETA8 (betw. Loop1-6)	0.000	0.000	0.000	0.009	0	0.000	0.000	0.000	0.008	0
THETA9 (adj. to Loop6)	0.000	0.000	0.000	0.008	0	0.000	0.000	0.000	0.007	0
THETA10 (betw. Loop6-5)	0.000	0.000	0.000	0.009	0	0.000	0.000	0.000	0.007	0
THETA11 (adj. to Loop5)	0.000	0.000	0.000	0.015	0	0.000	0.000	0.000	0.010	0
THETA12 (betw. Loop5-4)	0.000	0.000	0.000	0.034	0	0.000	0.000	0.000	0.022	0
THETA13 (adj. to Loop4)	0.100	0.050	0.037	0.073	0	0.100	0.050	0.033	0.058	0
THETA14 (betw. Loop4-3)	0.300	0.150	0.178	0.159	-1	0.250	0.100	0.155	0.155	0
THETA15 (betw. Loop4-3)	0.550	0.300	0.396	0.405	1	0.600	0.300	0.416	0.431	2
THETA16 (betw. Loop4-3)	0.750	0.550	0.612	0.708	17	0.750	0.600	0.698	0.716	4

Table E-4 Comparison of Measured an Calculated (16-Theta model) Mixing Factors for Loop4

LOOP4	RING 1					RING 2				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max. value	min. value	avg value	16-Theta model		max. value	min. value	avg. value	16-Theta model	
THETA1 (adj. to Loop3)	0.150	0.100	0.099	0.053	-1	0.250	0.050	0.141	0.079	-3
THETA4 (betw. Loop3-2)	0.050	0.050	0.064	0.039	-1	0.100	0.050	0.022	0.046	0
THETA3 (adj. to Loop2)	0.050	0.050	0.054	0.029	0	0.000	0.000	0.000	0.025	0
THETA4 (betw. Loop2-1)	0.100	0.050	0.042	0.025	0	0.000	0.000	0.000	0.017	0
THETA5 (adj. to Loop1)	0.000	0.000	0.041	0.023	0	0.000	0.000	0.000	0.011	0
THETA4 (betw. Loop1-6)	0.100	0.050	0.049	0.033	0	0.000	0.000	0.000	0.013	0
THETA7 (betw. Loop1-6)	0.050	0.050	0.054	0.218	3	0.050	0.050	0.001	0.077	0
THETA8 (betw. Loop1-6)	0.000	0.000	0.054	0.245	3	0.050	0.050	0.004	0.061	0
THETA9 (adj. to Loop6)	0.000	0.000	0.055	0.258	4	0.050	0.050	0.026	0.091	1
THETA10 (betw. Loop6-5)	0.000	0.000	0.060	0.289	4	0.050	0.050	0.041	0.191	2
THETA11 (adj. to Loop5)	0.100	0.100	0.089	0.352	8	0.150	0.100	0.077	0.304	6
THETA12 (betw. Loop5-4)	0.150	0.150	0.132	0.479	15	0.300	0.150	0.191	0.515	20
THETA13 (adj. to Loop4)	0.200	0.200	0.177	0.557	22	0.550	0.250	0.332	0.651	35
THETA14 (betw. Loop4-3)	0.250	0.200	0.203	0.570	24	0.600	0.300	0.414	0.661	34
THETA15 (betw. Loop4-3)	0.000	0.000	0.192	0.090	-6	0.500	0.300	0.398	0.330	-9
THETA16 (betw. Loop4-3)	0.000	0.000	0.156	0.070	-4	0.400	0.200	0.301	0.152	-15

Table E-4 Comparison of Measured an Calculated (16-Theta model) Mixing Factors for Loop4 (continued)

LOOP4	RING 3					RING 4				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	16-Theta model		max value	min value	avg value	16-Theta model	
THETA1 (adj. to Loop3)	0.250	0.050	0.085	0.073	0	0.100	0.050	0.020	0.058	0
THETA4 (betw. Loop3-2)	0.050	0.050	0.004	0.034	0	0.000	0.000	0.000	0.022	0
THETA3 (adj. to Loop2)	0.000	0.000	0.000	0.015	0	0.000	0.000	0.000	0.010	0
THETA4 (betw. Loop2-1)	0.000	0.000	0.000	0.009	0	0.000	0.000	0.000	0.007	0
THETA5 (adj. to Loop1)	0.000	0.000	0.000	0.008	0	0.000	0.000	0.000	0.007	0
THETA4 (betw. Loop1-6)	0.000	0.000	0.000	0.009	0	0.000	0.000	0.000	0.008	0
THETA7 (betw. Loop1-6)	0.000	0.000	0.000	0.034	0	0.000	0.000	0.000	0.018	0
THETA8 (betw. Loop1-6)	0.000	0.000	0.000	0.021	0	0.000	0.000	0.000	0.012	0
THETA9 (adj. to Loop6)	0.000	0.000	0.000	0.021	0	0.000	0.000	0.000	0.011	0
THETA10 (betw. Loop6-5)	0.000	0.000	0.000	0.067	0	0.050	0.050	0.030	0.027	0
THETA11 (adj. to Loop5)	0.200	0.050	0.074	0.194	3	0.200	0.050	0.107	0.102	0
THETA12 (betw. Loop5-4)	0.450	0.200	0.278	0.475	18	0.500	0.250	0.317	0.357	4
THETA13 (adj. to Loop4)	0.600	0.400	0.504	0.659	26	0.650	0.500	0.563	0.594	6
THETA14 (betw. Loop4-3)	0.650	0.600	0.626	0.708	17	0.710	0.600	0.665	0.716	11
THETA15 (betw. Loop4-3)	0.650	0.400	0.477	0.405	-11	0.650	0.350	0.470	0.431	-6
THETA16 (betw. Loop4-3)	0.400	0.150	0.273	0.159	-10	0.350	0.100	0.180	0.155	-1

Table E-5 Comparison of Measured an Calculated (16-Theta model) Mixing Factors for Loop5

LOOP5	RING 1					RING 2				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	16-Theta model		max value	min value	avg value	16-Theta model	
THETA1 (adj. to Loop3)	0.150	0.150	0.114	0.009	-4	0.100	0.050	0.022	0.010	0
THETA4 (betw. Loop3-2)	0.150	0.050	0.075	0.008	-2	0.050	0.050	0.000	0.008	0
THETA3 (adj. to Loop2)	0.000	0.000	0.064	0.008	-1	0.050	0.050	0.007	0.008	0
THETA4 (betw. Loop2-1)	0.050	0.050	0.054	0.008	-1	0.000	0.000	0.001	0.007	0
THETA5 (adj. to Lcop1)	0.100	0.050	0.031	0.008	0	0.000	0.000	0.000	0.008	0
THETA4 (betw. Loop1-6)	0.150	0.150	0.039	0.008	0	0.000	0.000	0.000	0.010	0
THETA7 (betw. Loop1-6)	0.050	0.050	0.074	0.389	7	0.050	0.050	0.016	0.187	1
THETA8 (betw. Loop1-6)	0.150	0.150	0.125	0.549	17	0.150	0.050	0.086	0.224	4
THETA9 (adj. to Loop6)	0.200	0.200	0.175	0.575	22	0.350	0.200	0.209	0.360	10
THETA10 (betw. Loop6-5)	0.250	0.250	0.239	0.623	29	0.450	0.300	0.375	0.631	30
THETA11 (adj. to Loop5)	0.350	0.200	0.284	0.608	29	0.650	0.400	0.523	0.635	18
THETA12 (betw. Loop5-4)	0.000	0.000	0.299	0.486	18	0.600	0.450	0.496	0.443	-8
THETA13 (adj. to Loop4)	0.350	0.300	0.287	0.399	10	0.500	0.250	0.356	0.276	-9
THETA14 (betw. Loop4-3)	0.300	0.250	0.252	0.342	7	0.300	0.150	0.201	0.196	0
THETA15 (betw. Loop4-3)	0.250	0.200	0.212	0.062	-10	0.250	0.100	0.111	0.051	-2
THETA16 (betw. Loop4-3)	0.200	0.150	0.159	0.010	-7	0.150	0.050	0.052	0.014	-1

Table E-5 Comparison of Measured an Calculated (16-Theta model) Mixing Factors for Loop5 (continued)

LOOP5	RING 3					RING 4				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	16-Theta model		max value	min value	avg value	16-Theta model	
THETA1 (adj. to Loop3)	0.000	0.000	0.000	0.010	0	0.000	0.000	0.000	0.009	0
THETA4 (betw. Loop3-2)	0.000	0.000	0.000	0.008	0	0.000	0.000	0.000	0.007	0
THETA3 (adj. to Loop2)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.007	0
THETA4 (betw. Loop2-1)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.007	0
THETA5 (adj. to Loop1)	0.000	0.000	0.000	0.009	0	0.000	0.000	0.000	0.011	0
THETA4 (betw. Loop1-6)	0.000	0.000	0.000	0.017	0	0.000	0.000	0.000	0.021	0
THETA7 (betw. Loop1-6)	0.000	0.000	0.000	0.115	0	0.000	0.000	0.000	0.086	0
THETA8 (betw. Loop1-6)	0.100	0.050	0.021	0.095	0	0.100	0.050	0.021	0.065	0
THETA9 (adj. to Loop6)	0.350	0.100	0.182	0.133	-3	0.300	0.100	0.175	0.084	-5
THETA10 (betw. Loop6-5)	0.600	0.300	0.452	0.616	23	0.650	0.300	0.469	0.535	10
THETA11 (adj. to Loop5)	0.700	0.650	0.673	0.719	10	0.740	0.650	0.676	0.726	10
THETA12 (betw. Loop5-4)	0.700	0.500	0.574	0.494	-15	0.700	0.450	0.537	0.586	8
THETA13 (adj. to Loop4)	0.500	0.250	0.324	0.276	-5	0.450	0.200	0.281	0.343	5
THETA14 (betw. Loop4-3)	0.200	0.100	0.114	0.139	1	0.200	0.100	0.108	0.124	1
THETA15 (betw. Loop4-3)	0.050	0.050	0.027	0.043	0	0.050	0.050	0.012	0.039	0
THETA16 (betw. Loop4-3)	0.000	0.000	0.000	0.014	0	0.000	0.000	0.000	0.013	0

Table E-6 Comparison of Measured an Calculated (16-Theta model) Mixing Factors for Loop6

LOOP6	RING 1					RING 2				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min value	avg value	16-Theta model		max value	min value	avg value	16-Theta model	
THETA1 (adj. to Loop3)	0.000	0.000	0.099	0.007	-3	0.100	0.050	0.024	0.007	0
THETA4 (betw. Loop3-2)	0.150	0.150	0.118	0.007	-4	0.100	0.050	0.041	0.007	0
THETA3 (adj. to Loop2)	0.200	0.200	0.150	0.007	-6	0.150	0.050	0.043	0.007	0
THETA4 (betw. Loop2-1)	0.000	0.000	0.178	0.007	-9	0.150	0.050	0.055	0.007	-1
THETA5 (adj. to Loop1)	0.250	0.200	0.215	0.008	-13	0.250	0.050	0.101	0.012	-3
THETA4 (betw. Loop1-6)	0.350	0.200	0.262	0.009	-20	0.350	0.100	0.242	0.037	-15
THETA7 (betw. Loop1-6)	0.400	0.350	0.310	0.107	-19	0.500	0.350	0.411	0.329	-10
THETA8 (betw. Loop1-6)	0.450	0.300	0.334	0.251	-8	0.650	0.500	0.536	0.689	24
THETA9 (adj. to Loop6)	0.350	0.350	0.320	0.205	-11	0.650	0.450	0.542	0.617	12
THETA10 (betw. Loop6-5)	0.000	0.000	0.278	0.117	-13	0.500	0.350	0.409	0.200	-25
THETA11 (adj. to Loop5)	0.300	0.200	0.210	0.063	-9	0.350	0.150	0.223	0.075	-10
THETA12 (betw. Loop5-4)	0.200	0.100	0.129	0.034	-4	0.250	0.100	0.119	0.020	-3
THETA13 (adj. to Loop4)	0.100	0.050	0.052	0.024	0	0.100	0.050	0.043	0.011	0
THETA14 (betw. Loop4-3)	0.100	0.050	0.016	0.018	0	0.050	0.050	0.004	0.009	0
THETA15 (betw. Loop4-3)	0.050	0.050	0.030	0.010	0	0.000	0.000	0.000	0.007	0
THETA16 (betw. Loop4-3)	0.100	0.100	0.065	0.007	-1	0.050	0.050	0.001	0.006	0

Table E-6 Comparison of Measured an Calculated (16-Theta model) Mixing Factors for Loop6 (continued)

LOOP6	RING 3					RING 4				
	measured data			TRACE	DEVw (%)	measured data			TRACE	DEVw (%)
	max value	min. value	avg value	16-Theta model		max value	min. value	avg value	16-Theta model	
THETA1 (adj. to Loop3)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.007	0
THETA4 (betw. Loop3-2)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.007	0
THETA3 (adj. to Loop2)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.008	0
THETA4 (betw. Loop2-1)	0.000	0.000	0.000	0.008	0	0.000	0.000	0.000	0.012	0
THETA5 (adj. to Loop1)	0.050	0.050	0.006	0.023	0	0.000	0.000	0.000	0.035	0
THETA4 (betw. Loop1-6)	0.250	0.050	0.113	0.072	-1	0.200	0.050	0.080	0.101	1
THETA7 (betw. Loop1-6)	0.550	0.250	0.377	0.396	2	0.600	0.200	0.364	0.417	6
THETA8 (betw. Loop1-6)	0.700	0.600	0.631	0.823	36	0.750	0.550	0.654	0.833	34
THETA9 (adj. to Loop6)	0.750	0.550	0.670	0.872	40	0.790	0.550	0.678	0.907	46
THETA10 (betw. Loop6-5)	0.650	0.300	0.421	0.342	-10	0.600	0.200	0.393	0.455	7
THETA11 (adj. to Loop5)	0.250	0.050	0.139	0.109	-1	0.250	0.050	0.112	0.194	3
THETA12 (betw. Loop5-4)	0.100	0.050	0.014	0.023	0	0.050	0.050	0.012	0.064	0
THETA13 (adj. to Loop4)	0.000	0.000	0.000	0.011	0	0.000	0.000	0.000	0.022	0
THETA14 (betw. Loop4-3)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.007	0
THETA15 (betw. Loop4-3)	0.000	0.000	0.000	0.007	0	0.000	0.000	0.000	0.006	0
THETA16 (betw. Loop4-3)	0.000	0.000	0.000	0.006	0	0.000	0.000	0.000	0.006	0

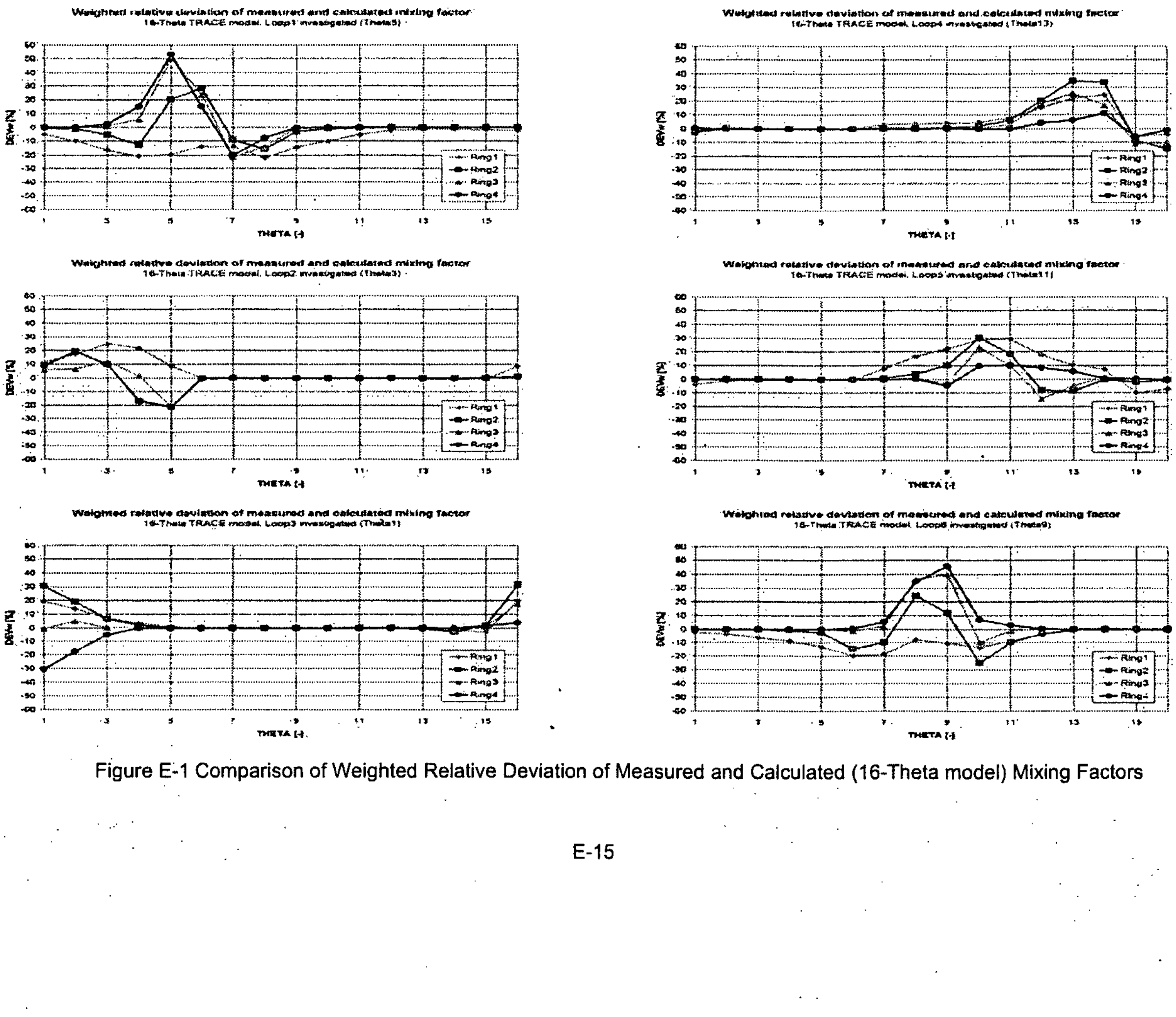

Figure E-1 Comparison of Weighted Relative Deviation of Measured and Calculated (16-Theta model) Mixing Factors

APPENDIX F

COMPARISON OF MEASURED AND CALCULATED MIXING FACTORS 4-TH UNIT OF NPP DUKOVANY 1987 (8-THETA MODEL)

INTRODUCTION

In this appendix, there is demonstrated Figure F-1 which contains the summary of measured and calculated data using 8-Theta TRACE VESSEL input deck. The measured data came from experimental investigations of coolant mixing in the VVER-440/213 reactor under steady-state conditions at the 4-th unit of NPP Dukovany in 1987. The Figure F-1 contains 6 graphs (each for given investigated loop) of weighted relative deviation of measured a calculated mixing factors. The X-axis represents modelled Theta sectors. There are numbers of radial rings as independent parameter in these graphs.

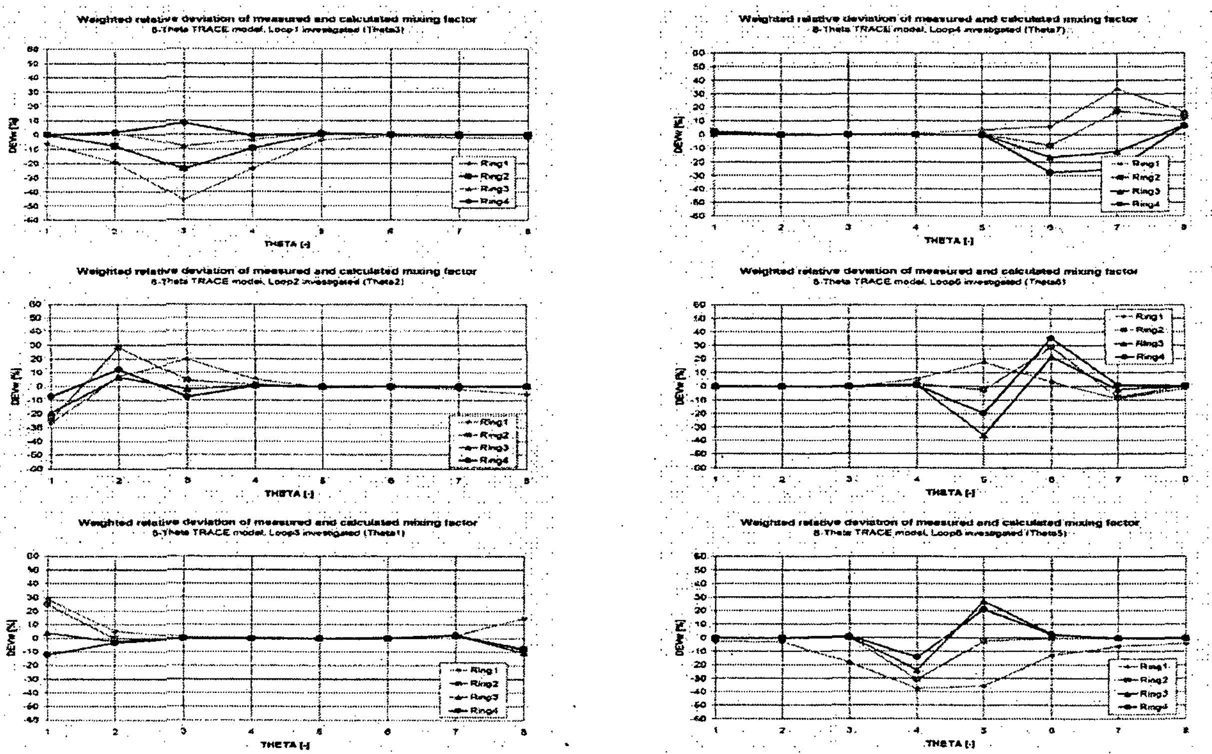

Figure F-1 Comparison of Weighted Relative Deviation of Measured and Calculated (8-Theta model) Mixing Factors

APPENDIX G

COMPARISON OF MEASURED AND CALCULATED MIXING FACTORS 4-TH UNIT OF NPP DUKOVANY 1987 (16-THETA MODEL)

INTRODUCTION

In this appendix, there is demonstrated Figure G-1 which contains the summary of measured and calculated data using 16-Theta TRACE VESSEL input deck. The measured data came from experimental investigations of coolant mixing in the VVER-440/213 reactor under steady-state conditions at the 4-th unit of NPP Dukovany in 1987. The Figure G-1 contains 6 graphs (each for given investigated loop) of weighted relative deviation of measured a calculated mixing factors. The X-axis represents modelled Theta sectors. There are numbers of radial rings as independent parameter in these graphs.

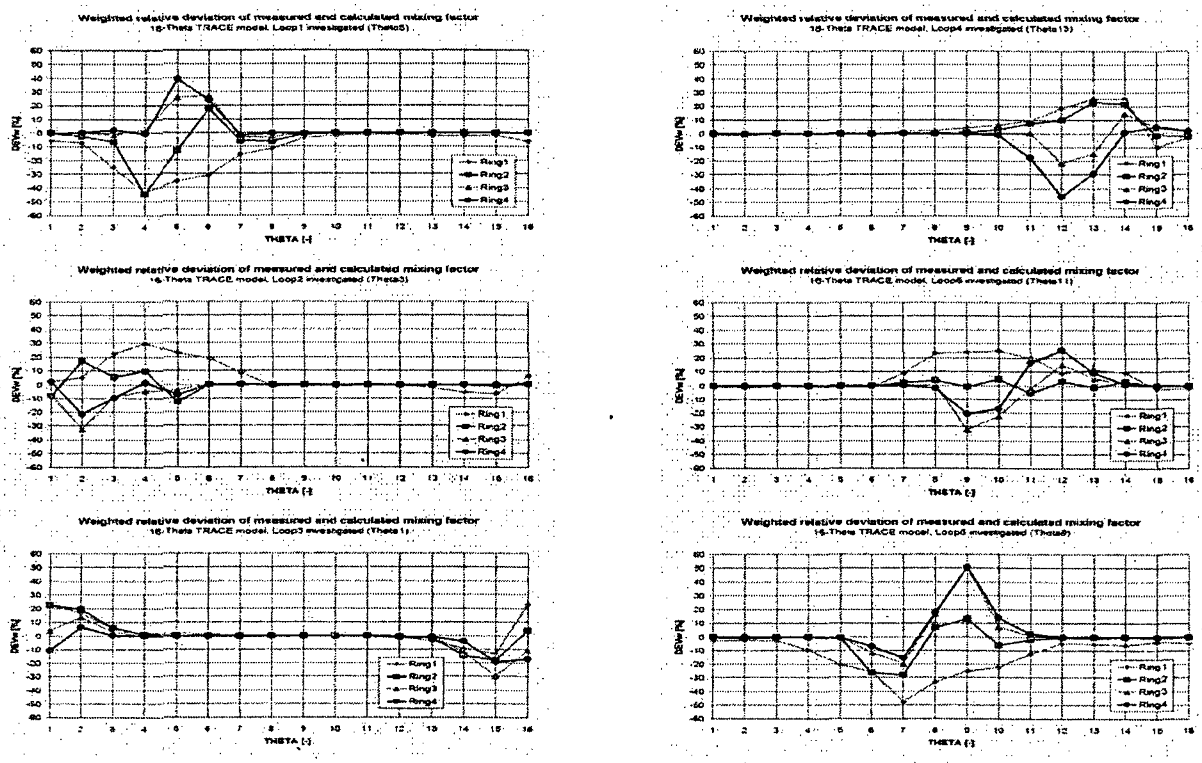

Figure G-1 Comparison of Weighted Relative Deviation of Measured and Calculated (16-Theta model) Mixing Factors

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11. ABSTRACT *(200 words or less)*
Experimental investigations of coolant mixing under steady state conditions at the Dukovany (Czech Republic) VVER-440 NPP were performed. The main goal of these experiments was to evaluate the mixing factors under normal operations condition. An extensive TRACE input deck of VVER-440/213 reactor was developed in frame of R&D project 1H-PK/61 in the TES Company. The TRACE input deck of VVER-440/213 reactor includes the reactor pressure vessel, the core and all important RPV internals. This paper contains some post-test analyses of the NPP Dukovany experiments using TRACE code V4.160 in order to generate background data for the forthcoming standardization procedure. There was performed a RPV nodalisation study to analyze influence of division of RPV into theta-parts on the calculated mixing factor. The purpose of performed TRACE analyses is to assess the capability of the TRACE code and the developed input deck to solve coolant mixing problems in VVER-440 type of reactors.

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