Standard Model of WWER-440 Fuel Rod for TRANSURANUS and its Application for RELAP5 Hot Channel Validation

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1. Introduction

The final aim of the work presented in this paper was in extension of the TRANSURANUS validation to code to code comparison against system thermohydraulics codes. The general approach and point of view was limited to safety (licensing) application of the codes, to the safety analysis method, used for development of Safety Analysis Report (SAR).

The RELAP5 was selected to be the representative of system codes for this project. The reasons for this selection were – the code is generally, internationally accepted for SAR application, and – there is large experience with the code application for SAR application in the VUJE Trnava. Additionally, there is a broad database available of already existing RELAP5 analyses for the whole scope of SAR, applicable for the project purposes.

For the same reasons, the WWER code specifics are considered within this part of the project (shrouded fuel assembly, WWER fuel geometry and characteristics).

The tasks which content and results are presented here were focussed:

- To study relevant safety aspects of methods, used for safety analysis within the SAR;
- To assess relevant capabilities of RELAP5 and TRANSURANUS codes;
- To develop corresponding models for the both codes and;
- To perform initial comparison of the both models and codes.

Within the first task of the project, model of typical fuel rod of WWER-440 was developed, based on available references and suggestions both published and discussed with ITU. Nodalization of the model was adjusted to the existing model for RELAP5 code for Bohunice V2 units (WWER-440/V213). The developed model describes standard, representative fuel rod for safety application. It contains suggested options for the TRANSURANUS algorithms for WWER application and description of typical fuel rod of the "profiled" fuel assembly, with maximum initial enrichment of 4%. The both slice and sectional version of axial nodalization was developed and checked. In axial direction, the fuel is divided onto ten slices, five radial nodes for fuel and three for cladding are defined. The model was in detail documented.

The existing model for RELAP5 code for Bohunice V2 units was checked and modified in hot channel part to allow transparent comparison with the TRANSURANUS code.

The project should contribute to TRANSURANUS code validation, as well as to quantification of level of induced conservatism of safety analysis methods (SAR scope), and to assess potential gain from introduction of the TRANSURANUS code into the safety analysis procedure.

2. Relevant Safety Criteria and General Approach

The leading principle of a SAR analysis is to provide assessment of relevant parameters in a bounding way, for scenarios and configurations, representing the most challenging conditions, expected within the scope of relevant operational states. This principle has to be fulfilled by appropriate (conservative enough) selection of models, boundary and initial conditions of the analysis.

Using system code, the conservative conditions (for unit safety and control systems and for primary and secondary circuits) are defined within the analyzed scenario. The relevant scope of parameters, providing interface between the overall unit behaviour and the most challenged fuel element (assembly) is identical for both application of the system code internal models as well as for potential application of separated, detailed code for fuel analysis. The appropriate selection of the interface between system analysis and fuel specifics safety analysis could influence largely confidence of predictions of the fuel margins.

The approach of the SAR analysis is defined and has to be adjusted to the demanded result. The primary aim of the safety analysis is to assess contribution of the analyzed scenario to the overall risk. It means generally to assess amount of leaked fission products (or number of leaked fuel rods). This task is for practical reasons transformed to the prove that derived acceptance criteria are fulfilled. The structure of the set of acceptance criteria varies between different countries, modified criteria are applied for different scenarios according given safety risk, the set of criteria develops in time. Nevertheless, it can be generalized for this purpose, that the following basic criteria (based on [5]) has to be checked within the standard SAR analysis:

- There shall be no melting of the fuel pellets, not even locally, e.g. melting point T-(2780-3·B)°C, where B [MWd/kgU] is burnup;
- Fuel melting shall not exceed defined fraction of fuel pellet (e.g. radially averaged fuel enthalpy does not exceed 963 J/g at any axial location);
- Fuel rod cladding temperature shall not exceed specified value (e.g. temperature of the fuel rod cladding does not exceed 1200°C;
- Total oxidation of the cladding shall not exceed defined level (e.g. total local oxidation of the cladding does not exceed 17% of the initial thickness before oxidation);
- Number of fuel rods with leakage (cladding failure) shall to be limited.

Evaluation of the above acceptance criteria should be done in representative way for specified spectrum of operational occurrences, possible operational states of the unit, within the time interval of several years. To cope with this, the term of "hot channel" is introduced in the SAR methodology. Hot channel model must ensure, that the relevant safety analysis describes the problem in a bounding, representative way, that there will be no worse conditions during unit operation and that during given time interval of unit operation the predicted minimum safety margins will not be violated. On the other side the introduced conservatism must be limited, adjusted to optimize uncertainty in prediction (analysis) and economical effects.

Table 1. Summary of interfaces for realistic case

	RELAP5	TRANSURANUS
Cladding conductivity		▨
Gap conductivity		▨
Fuel conductivity		▨
Heat-transfer coefficient cladding-coolant	▨	
Coolant temperature	▨	
Coolant pressure	▨	
Coolant mass flow rate	▨	

3. Development of WWER Fuel Rod (Hot Channel) Model

3.1. Model for TRANSURANUS Code

First version of the model was developed, based on available references and suggestions both pub-

Table 2. Heat-transfer coefficient cladding-coolant

Slice	1	2	3	4	5	6	7	8	9	10
HTC, [W/m^{2}K]	25987	26081	26266	26409	26663	27024	30862	37543	43297	45072

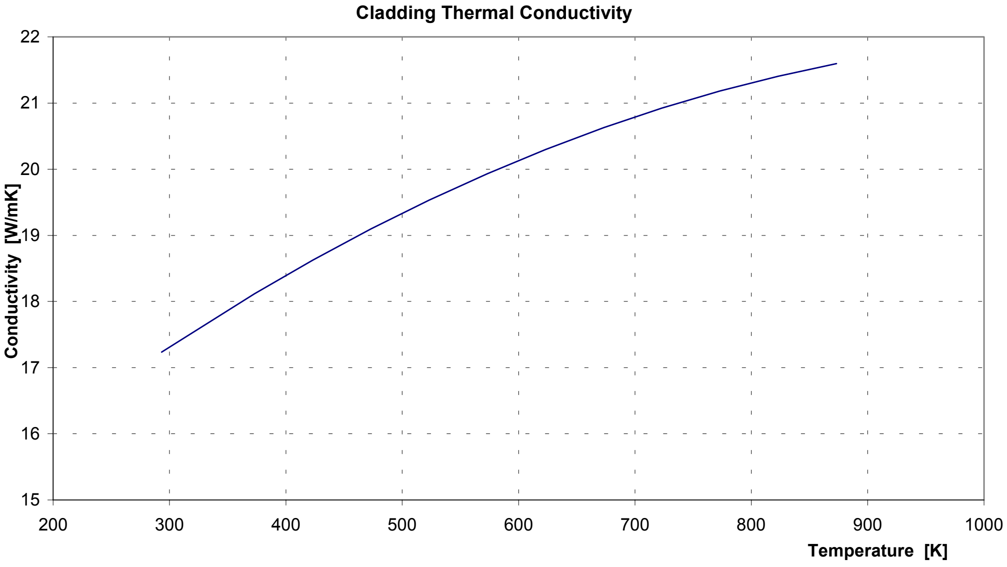

Figure 1. Cladding thermal conductivity

lished and discussed with TRANSURANUS code developers The typical fuel rod of WWER-440 was modelled. The only adjustment to safety analysis application was in selection of the hot rod as defined in safety analysis approach (geometry, maximum power, minimum coolant flow rate).

Nodalization of the model was adjusted to the existing model for RELAP5 code for Bohunice V2 units (WWER-440/V-213).

The model describes standard, representative fuel rod for safety application. It contains suggested options for the TRANSURANUS algorithms for WWER application and description of typical fuel rod of the radially profiled fuel assembly, with maximum initial enrichment of 4%. The both slice and sectional version of axial nodalization was developed and checked. In axial direction, the fuel is divided onto ten slices, five radial nodes for fuel and three for cladding are defined.

Step by step, individual phenomena were checked. Corresponding findings were evaluated and if found justified, corresponding modifications of the model were performed.

Table 3. Cladding conductivity

Temperature, [°C]	Thermal conductivity for cladding, [W/mK]
20	17.235172
100	18.119300
150	18.625925
200	19.097200
250	19.533125
300	19.933700
350	20.298925
400	20.628800
450	20.923325
500	21.182500
550	21.406325
600	21.594800

Table 4. Calculation of effective gap conductivity

Slice	1	2	3	4	5	6	7	8	9	10
Gap temperature, [°C] TRANSURANUS	355.4127	380.243	390.271	405.094	424.953	452.584	464.868	474.351	471.862	451.356
Gap conductance, [W/m^{2}K] from TRANSURANUS	4456	4819	4960	5203	5598	6387	6893	7449	7104	5965
Gap size RELAP, [mm]	0.0409	0.0409	0.0409	0.0409	0.0409	0.0409	0.0409	0.0409	0.0409	0.0409
Effective gap conductivity, [W/mK]	0.18225	0.197097	0.20286	0.21280	0.22895	0.26122	0.28192	0.30466	0.29055	0.24396

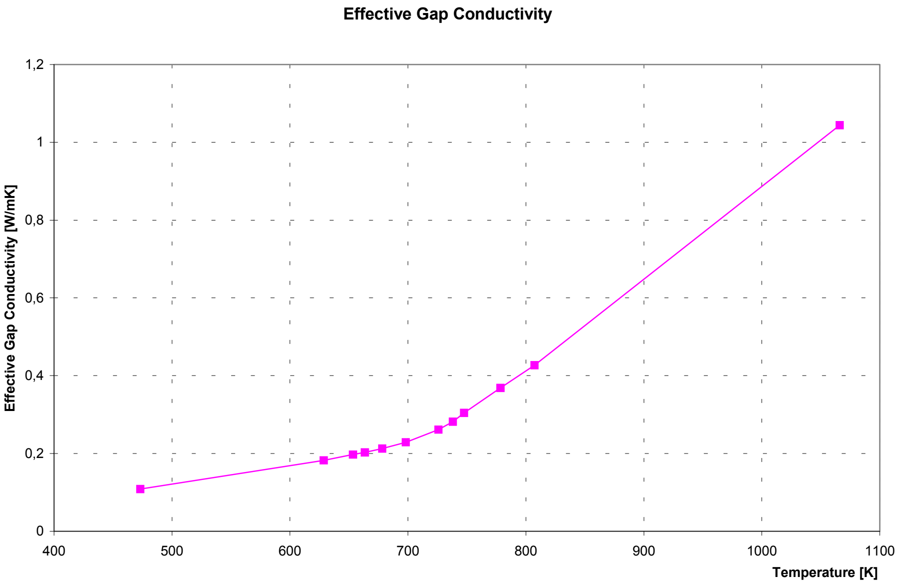

Figure 2. Effective gap conductivity

3.2. Model for RELAP5 Code

The existing integral model of Bohunice V2 NPP units (WWER-440/V-213) was selected for the project. The model is a well validated model, used extensively for both realistic (EOPs, operation support) and conservative (SAR) analyses of the relevant unit. The model was locked (not changed) in all parts with exception of the hot channel section and of selected auxiliary inputs, enabling adjustment of output information for purpose of comparison against TRANSURANUS.

As the TRANSURANUS model was developed to be as close to RELAP5 model as possible, the RELAP5 model modifications could be limited to:

- Fuel rod geometry, [m]. The fuel rod geometry data were taken from TRANSURANUS results as axially averaged values in the selected time of operational history;
- Cladding conductivity;
- Gap conductivity;
- Fuel conductivity.

The modifications did not affect other parts of the model, therefore, the validation status of the model was not changed.

4. Comparison of TRANSURANUS and RELAP5 Fuel Rod Models for Fresh Fuel

4.1. Definition of Boundary Condition for Comparison of TRANSURANUS and RELAP5

The basic case represents simple steady state scenario – operation of the fuel rod at nominal power, with power distribution close to the hot channel (the most loaded fuel rod) at normal operation. The TRANSURANUS scenario considers typical start up of the unit, starting from zero power level to nominal power during (postulated) 30 hours. For comparison against RELAP5, the outputs in 35 hours of operation were selected. By RELAP5 simulated scenario is also stabilized operation at nominal operation. Results were read from outputs in 250s of the simulation. In both models initial and boundary conditions were adjusted correspondingly.

For the RELAP5 model, the validated material properties of fuel, cladding and gap conductivity were used, taken from the TRANSURANUS code. On the other side, the heat transfer coefficient between cladding and coolant and some other interfacing parameters were taken from the RELAP5 analysis. Change of individual characteristic (parameter) taken from one code to be input to other affects mostly also values of others. Therefore, the tuning was necessary, done in several iterations. Resulting values, as set in the models, are described below. The interfaces are summarized in the Table 1.

Coolant temperature at the core inlet, taken from RELAP5 calculation is equal to temperature at the inlet of hot channel of the both codes. For the analyzed case, the value was:

541.892 K =268.748°C.

Coolant pressure at the hot channel inlet was also taken from relevant RELAP5 calculation, close to nominal value: 12.816 MPa^{abs}.

Coolant flow rate through the hot channel was taken also from RELAP5 calculation, representing approximately minimum value for the Bohunice V2 units: 0.175 kg/s = $6.3{\cdot}10^5$ g/h.

Table 5. Effective gap conductivity – set for RELAP5 calculation

Gap temperature, [°C]	Effective gap conductivity, [W/m·K]	Note
200.000	0.10840	Approximated
355.412	0.18225	TRANSURANUS
380.243	0.19709	TRANSURANUS
390.271	0.20286	TRANSURANUS
405.091	0.21280	TRANSURANUS
424.953	0.22895	TRANSURANUS
452.584	0.26122	TRANSURANUS
464.868	0.28192	TRANSURANUS
474.351	0.30466	TRANSURANUS
505.200	0.36870	Approximated
534.100	0.42720	Approximated
792.850	1.04400	Approximated

Table 6 Generated function of thermal conductivity

Temperature, [°C]	Thermal conductivity for fuel, [W/m·K]
407.86	4.734
501.82	4.265
600.42	3.862
702.33	3.521
813.51	3.211
920.87	2.961
987.03	2.826
1200.54	2.483
1303.91	2.361

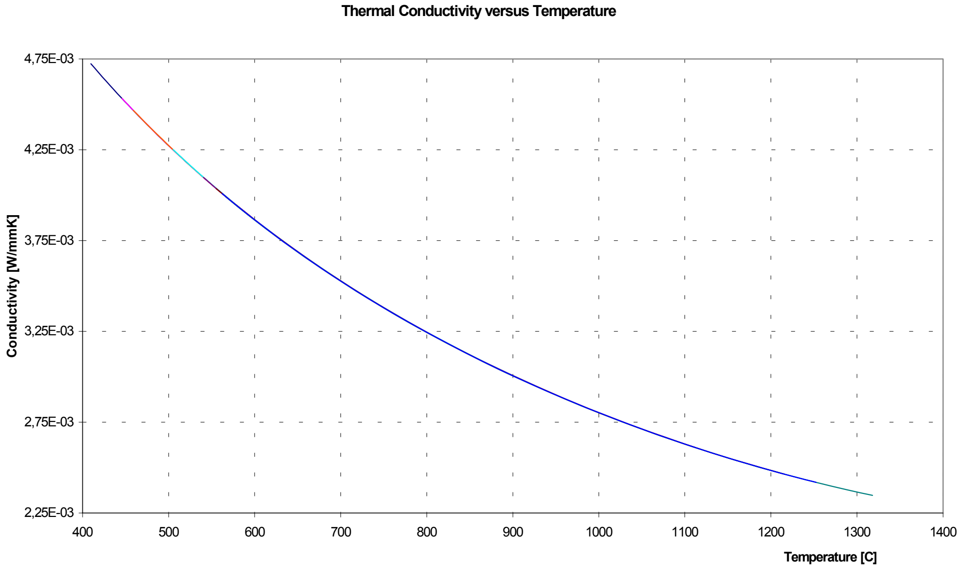

Figure 3. Function of thermal conductivity on temperature

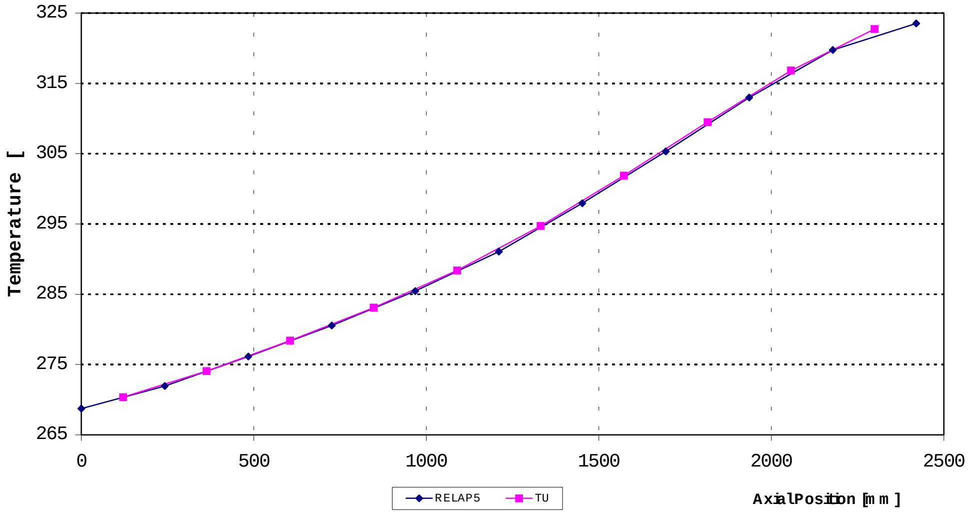

Figure 4. Coolant temperature

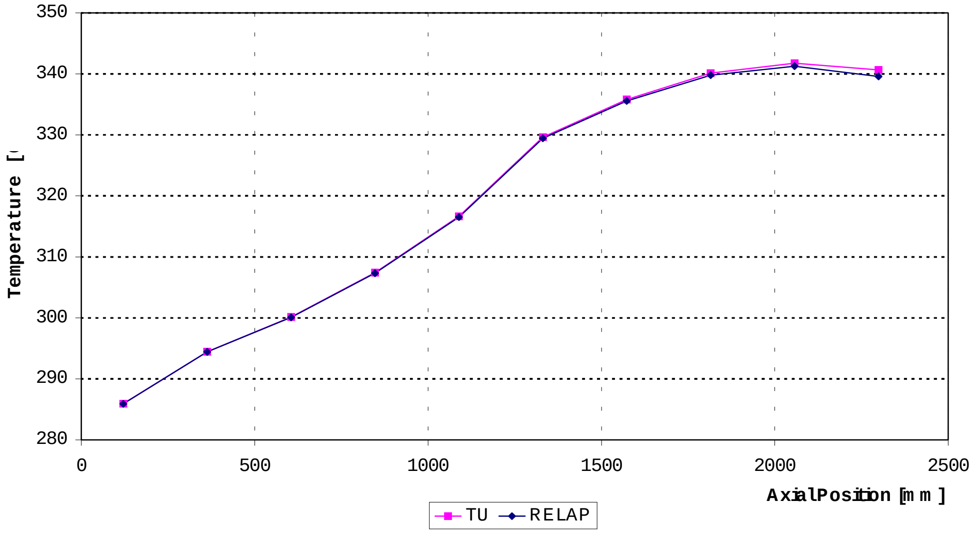

Figure 5. Outer cladding temperature

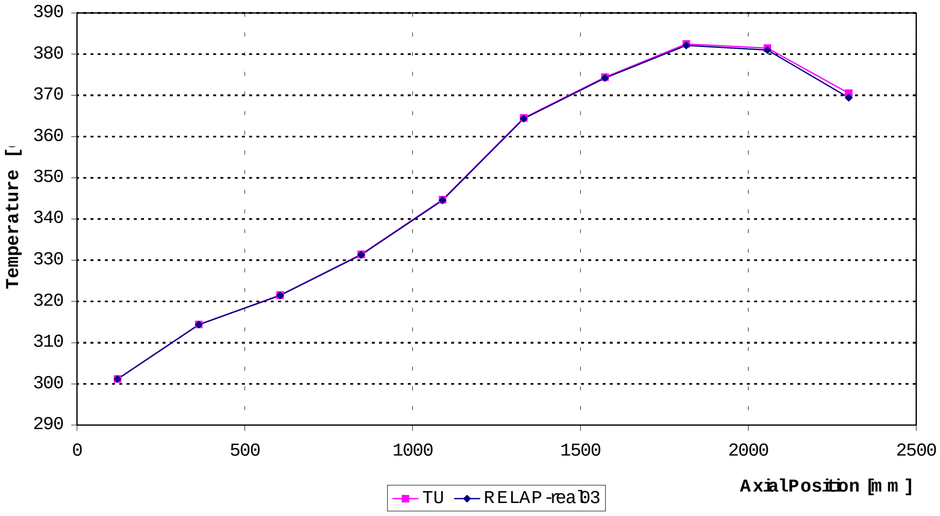

Figure 6. Inner cladding temperature

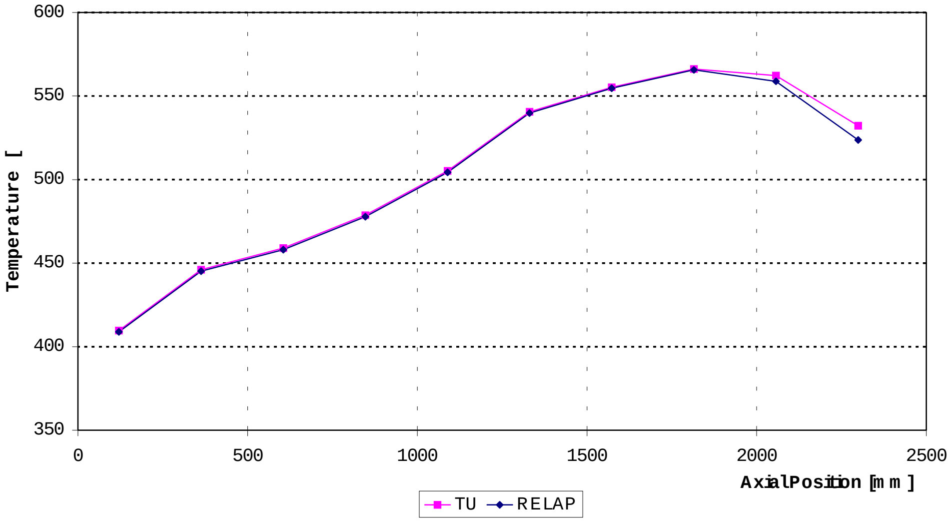

Figure 7. Outer fuel temperature

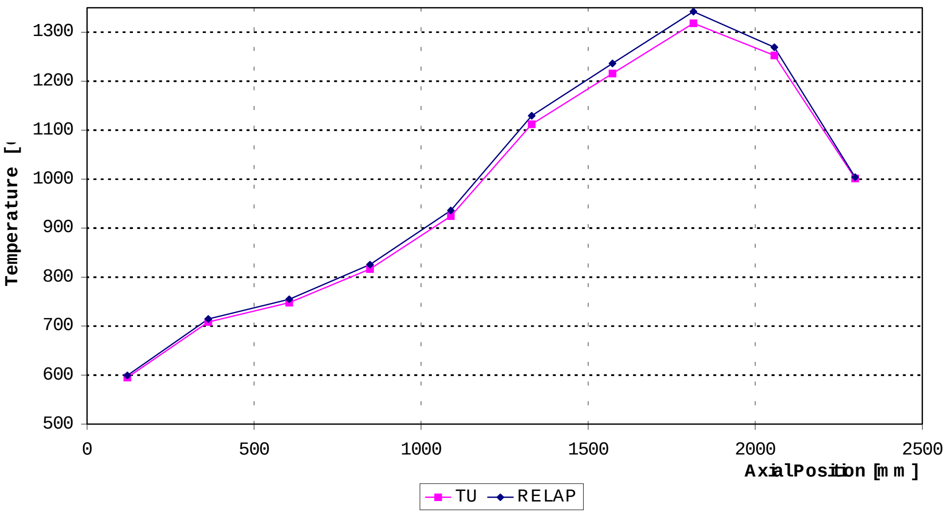

Figure 8. Central fuel temperature

Heat-Transfer Coefficient (HTC) Cladding-Coolant can be calculated by both codes internal algorithms. To ensure full compatibility, values of HTC Cladding-Coolant were taken from RELAP result and used explicitly in the TRANSURANUS model (relevant internal algorithms were not used). The values are presented in the Table 2.

Cladding conductivity has to be defined explicitly for the RELAP5 code. The values were calculated from equation, taken from TRANSURANUS source code, from subroutine LAMBDA. Applied values are presented in the Table 3. The cladding thermal conductivity is presented on Figure 1.

Gap conductivity has to be defined explicitly for the RELAP5 code as a function of temperature.

In used RELAP5 input model is assumed constant gap with (fuel-cladding) and than for the RELAP5 input file was used "effective gap conductivity" based on TRANSURANUS results. Effective gap conductivity was calculated form TRANSURANUS results as the product of the TRANSURANUS gap conductance (dependent on the axial co-ordinate) and a fixed gap width. Based on data in the Table 4 was defined effective gap conductivity as a function of temperature. Effective gap conductivity – set for RELAP5 calculation is presented in Table 5 and Figure 2.

Fuel conductivity as a function of fuel temperature was derived from the TRANSURANUS results. Corresponding values were taken from TRANSURANUS results. The diagrams of Temperature and Thermal Conductivity as a function of the radius were used in the function development. As the burn up of each radial node is close to zero, there are no differences in conductivity values and the curves are identical. It allows to generate one fuel conductivity function for all nodes. The values for the lowest temperature and the highest temperature were extrapolated. Resulting values, presented in Table 6 and Figure 3 were used in the RELAP5 model.

It should be noted here, that for cases with higher burn up, due to both radial and axial power profiles and dependence of conductivity on burn up, it will be necessary to develop different approach.

4.2. Results of Comparison

The results from comparison calculations of TRANSURANUS and RELAP are presented bellow in graphical forms. The results are in very good agreement, almost identical.

Results are shown in Figures 4 to 8.

5. Conclusion

The final aim of the work presented in this paper was in extension of the TRANSURANUS validation to code to code comparison against system thermohydraulics codes. The RELAP5 was selected to be the representative of system codes for this project because the code is generally, internationally accepted for SAR application, and – there is large experience with the code application for SAR in the VUJE Trnava.

The input model of WWER-440 fuel rod for TANSURANUS was developed. The existing model for RELAP5 code for WWER-440/V-213 Bohunice V2 units was checked and modified in hot channel part to allow transparent comparison with the TRANSURANUS code.

The results of steady state cases are in a very good agreement, almost identical. The results prove the algorithms of both TRANSURANUS and RELAP5 describe the relevant phenomena for fresh fuel in comparable credibility.

Results of the steady state cases are basis for the transient analysis.

References

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