ANALYSIS OF EXERCISES 1 AND 2 OF THE OECD/NRC BWR TURBINE TRIP (TT) BENCHMARK BY THE COUPLED CODE SYSTEM ATHLET-QUABOX/CUBBOX

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ABSTRACT

The OECD/NRC BWR turbine trip (TT) benchmark [1] has been calculated by the coupled thermal-hydraulic neutronics system code ATHLET - QUABOX/CUBBOX [2,3] developed by GRS. The results obtained for the plant transient of Exercise 1 with specified integral power time history are presented. In addition, the core boundary problem of Exercise 2 with specified initial and time-dependent core boundary conditions is investigated. The results are presented, and the physical phenomena determining the BWR pressure transient are discussed. The sensitivity of results on variations of the initial steady state conditions and of parameters of the two-phase flow model is studied. A comparison is also performed between the reactor core model with 33 thermal-hydraulic channels (THC) as specified and a reactor core model with 764 THC using a 1:1 mapping scheme.

1. INTRODUCTION

The BWR turbine trip (TT) transient has been defined within the OECD Benchmark activities to validate the coupled thermal-hydraulic system codes with integrated 3D reactor core models for BWR conditions. The reference plant is Peach Bottom 2, where experiments were performed to study such transients at reduced initial power. Thus, the benchmark problem is intended to compare results from different coupled codes with measured plant data. Coupled codes have been developed to perform realistic analysis of accident conditions, which are determined by a strong coupling between neutronics of the core and the thermal-hydraulics of the primary circuit. The BWR TT transient is determined by a fast pressure increase leading to the reduction of average void content in the reactor core, which causes a very fast power transient due to the positive reactivity insertion. Therefore this transient is of particular interest for code validation.

The Benchmark specification proposes three steps for the plant transient analysis and for the detailed code comparison. Exercise 1 addresses the overall plant response during the turbine trip transient using a specified time-function of integral power for all codes. The purpose of this step is to initialise the system models eliminating all neutronics and reactivity feedback effects. In Exercise 2, the reactor core behaviour is separately analysed by applying specified initial conditions and time-functions as boundary conditions for the 3D reactor core models. These specified boundary conditions are: the pressure at core inlet and outlet, and the coolant temperature and mass flow rate for 33 thermal-hydraulic channels (THC) at the core inlet. In the final step, the full simulation capability with integrated 3D reactor core model in the thermal-hydraulic system code will be applied for the analysis to compare calculated results with measured plant transient data. This paper presents the available results for Exercises 1 and 2 obtained by the coupled code ATHLET-QUABOX/CUBBOX [2,3,4] together with the experiences gained during the model development.

2. DESCRIPTION OF THE ATHLET PLANT MODEL

The specification of the BWR TT Benchmark refers to the Peach Bottom 2 nuclear power plant, a BWR with jet pumps and two external recirculation loops. The ATHLET model of the coolant flow in the reactor vessel consists of a lower plenum, a core region with a single thermal-hydraulic channel with two fuel rod types corresponding to 7x7 and 8x8 fuel assemblies and a bypass channel, an upper plenum, stand pipes, a separator and a steam dome. The downward flow path is modelled by an upper down comer section, where the feed water is supplied, the jet pumps and a lower down comer section with the diffusors. Two symmetric recirculation loops are described. The model configuration of ATHLET for the reactor vessel is shown in Fig.1. The flow path of the generated steam to the turbine is modelled by the main steam line pipes with the turbine stop valve (TSV) and the connected bypass line with the turbine bypass valve (TBV). As the transient is initiated by a sudden closure of the turbine stop valve leading to pressure wave oscillations on the steam line, the steam line system should be modelled in detail. The total length of the main steam line is 133 m. The bypass line of 74.8 m length is connected to the steam line 9 m before the TSV. The arrangement of the main steam line system in the ATHLET nodalization is shown in Fig.2. The ATHLET thermal-hydraulic model describes this transient by the 5-equation flow model.

Initializing the ATHLET model, attention was paid to obtain the main system parameters of the total reactor power, the total coolant mass flow rate in the primary circuit, and the core inlet temperature, and also a good agreement for the overall pressure distribution of the initial steady state corresponding to the plant conditions. Typical values of local pressure in the vessel were given by the benchmark team. In Table 1 those values are compared with the values of the ATHLET model, which were obtained by suitably adjusting the flow resistance along the primary circuit. A comparison of other main parameters of the initial plant conditions is given in Table 2.

Table 1. Comparison of initial steady state pressure values

Nr.	Location	Pressure from specification [bar]	Pressure from ATHLET [bar]
1	Steam dome	67.98	68.01
2	Upper core plate	68.34	68.37
3	Top of active core	n.a.	68.49
4	Bottom of active core	n.a.	69.01
5	Lower plenum	69.72	69.73
5-2	Total pressure drop	1.38	1.36
4-3	Core pressure drop	n.a	0.52

Table 2. Comparison of other main parameters of the initial steady state

PARAMETER	Specification (mainly Table 5.2.1)	ATHLET
Initial total reactor power MW, 61.65 % rated	2030	2030
Total mass flow rate, [kg/s]	10445	10348
Core mass flow rate, [kg/s]	9603.2	9492
Core bypass mass flow rate, [kg/s]	841.8	856.7
Core inlet temperature, [°C]	274.7	274.7
Core average exit quality and average or exit void fraction	X_H=0.097 α_M=0.304	X_G=0.079 α_E=0.645

3. THE BWR TURBINE TRIP TRANSIENT RESULTS OBTAINED BY ATHLET

The turbine trip transient is determined by the following sequence of events. The transient begins at t=0 s with the sudden turbine stop valve closure, the valve is fully closed after 0.096 s. For steam release the bypass valve begins opening at 0.060 s, reaching the final fully open position at 0.846 s. The function of relative flow area versus time is specified. In Exercise 1 the time function of the total reactor power is predefined. The sudden closure of the turbine stop valve causes a reduction of the steam flow, which results in a pressure increase. In addition, it initiates a pressure wave travelling along the steam line which is superposed to the pressure increase. The pressure increase in the reactor core is the result of the superposition of the two flow paths through the standpipes above the core and through the down comer and the lower plenum. Subsequently, further pressure oscillations are observed in the reactor vessel and in the steam line. The pressure increase is limited by the steam release through the bypass valve. In the ATHLET calculations the total mass flow rate through the bypass valve and the flow resistance at the inlet of the main steam line from the reactor vessel were identified as important parameters for the overall plant behaviour.

The flow characteristic of the bypass valve is determined by the time-function of the open flow area, which is defined by the specification, and in addition by the relation of the flow resistance to the flow area. The ATHLET model for the bypass valve was chosen such that during the valve opening critical flow conditions are always established. The flow area of the fully open valve was defined to yield an asymptotic steam mass flow rate of 600 kg/s. This value gives good agreement for the time-function of the pressure in the steam dome or reactor core outlet, for which measured data are available.

In studies of different variants for modelling the steam line, it was observed that the flow resistance at the inlet of the main steam line from the reactor vessel strongly affects the amplitude of the pressure oscillations. If a very high resistance value is chosen, the oscillations are strongly damped; on the other hand, if a low value is chosen, the oscillations are nearly without damping. Finally, an intermediate value of the flow resistance approximately corresponding to geometrical data was chosen for the ATHLET benchmark results, which show oscillations as seen in the measurements.

The results obtained by the ATHLET model are shown in the following figures. Fig. 3 shows the time-function which is specified for Exercise 1 of the benchmark for the total reactor power. The pressure increase in the core and the steam dome obtained by the ATHLET calculation is shown in Fig. 4. This figure includes the time-functions of the available RETRAN results and the measurement. The comparison confirms an overall good agreement of the time evolution. The following figures present the time-functions of mass flow at different locations of the plant. Fig. 5 shows the mass flow at core inlet and core outlet and an intermediate location. At the beginning of the transient, the mass flow increases at core inlet and decreases at core outlet leading to an increased total mass in the core corresponding to the decrease of the average void content. Fig. 6 shows the mass flow through the stand pipes to the steam dome above the core and the mass flow at the diffuser outlet to the lower plenum and the core inlet. Fig. 7 presents the mass flow in the steam line at different locations. At the outlet the mass flow is reduced rapidly due to the closure of the TSV. The mass flow at the inlet shows strong oscillations. The amplitude of the mass flow oscillation is getting smaller along the steam line to the TSV. Fig. 8 shows the mass flow in the bypass line at different locations. During valve opening always critical flow is reached. The fully open flow area is adjusted to get an asymptotic mass flow of about 600 kg/s. These figures give an overview on the ATHLET results by presenting the main parameters of the BWR TT transient.

4. ANALYSIS OF EXERCISE 2, THE CORE BOUNDARY PROBLEM

The objective of Exercise 2 of the BWR TT benchmark is to analyse separately the reactor core behaviour for specified initial and time-dependent boundary conditions. The specification defines the core loading and a model of the reactor core coolant flow with 33 thermal-hydraulic coolant channels. For the reactor core initial values and time-dependent function tables for the pressure at core inlet and outlet as well as for each channel the coolant temperature and coolant mass flow rate at core inlet are given.

The reactor core problem is solved by the 3D neutron kinetics code QUABOX/CUBBOX including a feedback model describing coolant flow and fuel rods by ATHLET components. According to the specification, the thermal-hydraulic model consists of 33 pipe components, each with a fill component modelling inlet conditions and with a time-dependent volume modelling the upper plenum. The model represents the coolant flow by parallel flow channels without cross-flow. A fuel rod model, solving the heat-conduction equations with 5 radial zones for the fuel pellet, a gap heat resistance and a single zone for the cladding, is attached to each THC. Three types of THCs are defined corresponding to 7x7 respectively 8x8 fuel assemblies with and without flow restriction. The values of flow area, fuel rod diameter and flow resistances are determined according to the specification. Each THC and the corresponding fuel rod is mapped to a group of fuel assemblies of the core loading as specified. The ATHLET model uses the time-function tables for the boundary conditions of the pressure at the core outlet and the coolant temperature and the mass flow rate at the core inlet. As the pressure cannot be independently specified at the core outlet and inlet together with the mass flow rate at the core inlet, the pressure time-function at core inlet is substituted by meeting the total pressure difference in the steady state initialisation.

The 3D neutron kinetics code QUABOX/CUBBOX [5] solves the neutron diffusion equations with two prompt neutron energy groups and six precursor groups of delayed neutrons by a coarse mesh method based on flux expansion using high-order local polynomials. Each fuel assembly of the BWR core, totally 764, is represented by a single node in the XY-plane. The core loading of the fuel assemblies and the position of control rods correspond to the specification. In axial direction, the active core region is described by 24 nodes with one additional node for each of the top and bottom reflector. The nuclear cross-sections are calculated from the specified tables dependent on fuel temperature and coolant density. The effect of the fuel assembly bypass flow is considered using an

effective coolant density correction when calculating nuclear data. The effect of the Xenon concentration on the cross-sections is taken into account as specified. No ADF corrections are considered, in consistency with the solution method based on local neutron flux expansion.
In screening calculations for the BWR pressure transient, it was observed that variations of the core initial boundary conditions and also of some parameters of the two-phase flow model strongly affected the results. This applies to the initial steady state of the reactor core, like the k_{eff}-value, the averaged axial core power distribution and the axial power peaking factor, as well as the transient evolution, like the maximum value of power and the corresponding time-point. The phenomena of the induced pressure transient are the following: The pressure increase causes a collapse of steam bubbles, leading to a reduction of the average void content in the reactor core, and consequently to a fast power increase due to the positive reactivity insertion. The power increase is limited by the generation of void in the coolant during the power transient and/or by the scram activation which initiates control rod insertion movement at 0.75 s. Thus, the fast power transient caused by the positive reactivity insertion is sensitive to the average void content as well as the axial void distribution in the reactor core, and their relative changes during the pressure increase after the sudden closure of the turbine stop valve. In fact, the change of average void content and its axial distribution determine the effective positive reactivity insertion during the transient.
Therefore, it is expedient to study the sensitivity in detail. The results of this study are summarised in Table 3, which describes the relations between variations of input and model parameters on the left side and their consequences on the main characteristics of the result on the right side.

Table 3. Qualitative summary of the performed sensitivity study (explanation see in text)

Case	P_{out}	ΔP_c	T_{in}	G_{in}	Sub-cooling	Void Gener. Rate	ρ_{cor}	K_{eff}	Aver. Void	F_z	Integ. Power Peak	Max before 0.75 s
1	↓							↓	↑	↓	↑	NO
2		↓						↑	↓	–	↑	NO
3			↑					↓	↑	↓	↑	NO
4				↓				↓	↑	↓	↓	NO
5					↓			↑	↓	↓	↑	NO
6						↑		↓	↑	↓	↑	YES
7							↑	↑	–	–	↓	NO

The parameters studied are: P_{out} – the core outlet pressure; ΔP_{core} – the active core pressure loss; T_{in} – the core inlet temperature and G_{in} – the core inlet mass flow rate without bypass flow. In addition, parameters of the two-phase flow model and the bypass density correction are included. In the

variation of the subcooling model the standard relation between wall heat transfer and direct heat deposition in the bulk of flow is changed. The variation of void generation rate affects the thermal non-equilibrium conditions between steam and liquid phase. Starting from a reference set of input parameter values, the Table 3 describes the relative changes of independent variations. An arrow up indicates an increase of the value, contrary, an arrow down indicates a decrease, e.g. in line 4: a decrease of mass flow rate at core inlet leads to a higher average void content, consequently to a lower k_{eff}-value, and also to a lower axial power peaking factor in the steady state condition, and to a lower maximum power peak during the transient. The range of applied variations of initial conditions is: ΔP_{core} = 0.6,1.2 [bar]; $P_{out}= P_{spec}$, P_{spec} -1.2 [bar]; $T_{in}= T_{in}$ + 2 [K], T_{in} - 2 [K]; G_{in}= 9600, 9200 [kg/s]. The main objective of these variations is to study the effect of different subcooling conditions and different average void content in the core on the results obtained for the axial power density distribution in the initial state and the maximum power and its time-point during the transient.
The effect of using different numbers of THCs and fuel rods with mappings to the fuel assemblies of the core loading was also studied. The standard analysis of the BWR TT transient was performed using the 33 THC mapping scheme of the specification. For a comparison a detailed 1:1 modelling is applied, representing each fuel assembly by a THC, totally a number of 764 THC is used. The result of the k_{eff}-value for the initial steady state is 1.00188 with 33 THC and 0.99982 with 764 THC. Fig. 9 shows the transient relative fission power history for both cases compared to the measurement. The maximum of fission power reached by both calculations agrees very well, but the maximum is higher than in the measurement. The benchmark defines particular fuel assembly locations for a detailed comparison. In Fig. 10 and Fig. 11 is shown the axial power distribution of the initial steady state condition in fuel assembly #75, fully controlled, and in fuel assembly #367, uncontrolled, but with partially inserted control rods in the neighbourhood. The power shape in fuel assembly #75 is shifted to the upper core region when the 1:1 mapping scheme is used. In general, the overall power shapes for both calculations agree quite well.

5. SUMMARY

The presentation describes the results of the coupled system code ATHLET - QUABOX/CUBBOX for Exercises 1 and 2 of the BWR TT benchmark. The ATHLET model developed for the Peach Bottom 2 NPP with jet pumps and two external recirculation loops is able to represent the overall plant behaviour. The calculated pressure transient in the steam line and the reactor vessel caused by the sudden closure of the turbine stop valve agrees quite well with the available experimental data. The analysis of the reactor core boundary problem with specified initial and time-dependent boundary conditions revealed a strong sensitivity of the initial core characteristics and the power peak during the transient on the core initial boundary conditions and parameters of the two-phase flow model. A study was performed to determine the sensitivity of the main characteristic parameters of the results. In addition, a refined core model was applied using a 1:1 mapping of fuel assemblies to the THC. The comparison of results confirms good agreement for the integral power of the transient, but it shows relevant changes for the average axial and local power shapes and other local parameters. The experience gained will be applied for the calculation of the full plant transient problem as defined for Exercise 3 of the benchmark.

6. ACKNOWLEDGMENT

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7. REFERENCES

1. J. Solis, K. Ivanov, B. Sarikaya, A. Olson, K. Hunt, Boiling Water Reactor Turbine Trip (TT) Benchmark, **Volume 1**: Final Specifications, *NEA/NSC/DOC(2001) 1*.
2. G. Lerchl, H. Austregesilo, ATHLET Mod 1.2 Cycle A, *User's Manual, March 1998, GRS-P-1/VOL.1, Rev.1*.
3. S. Langenbuch, H. Austregesilo, P. Fomitchenko, U. Rohde, K. Velkov, Interface Requirements to Couple Thermal-Hydraulics Codes to 3D Neutronic Codes. *OECD/CSNI Workshop on Transient Thermal-Hydraulic and Neutronic Codes Requirements*, Annapolis, Md., U.S.A., November 5-8, 1996.
4. S.Langenbuch, K.-D.Schmidt, K.Velkov, The Coupled Code System ATHLET-QUABOX/CUBBOX – Model Features and Results for the Core Transients of the OECD PWR MSLB-Benchmark, *M&C*, September 1999, Madrid, Spain.
5. 5. S. Langenbuch, W. Maurer, W. Werner, Coarse Mesh Flux Expansion Method for the Analysis of Space-Time Effects in Large LWR Cores, *Nuclear Science and Engineering*, **63**, 437-456, 1977.

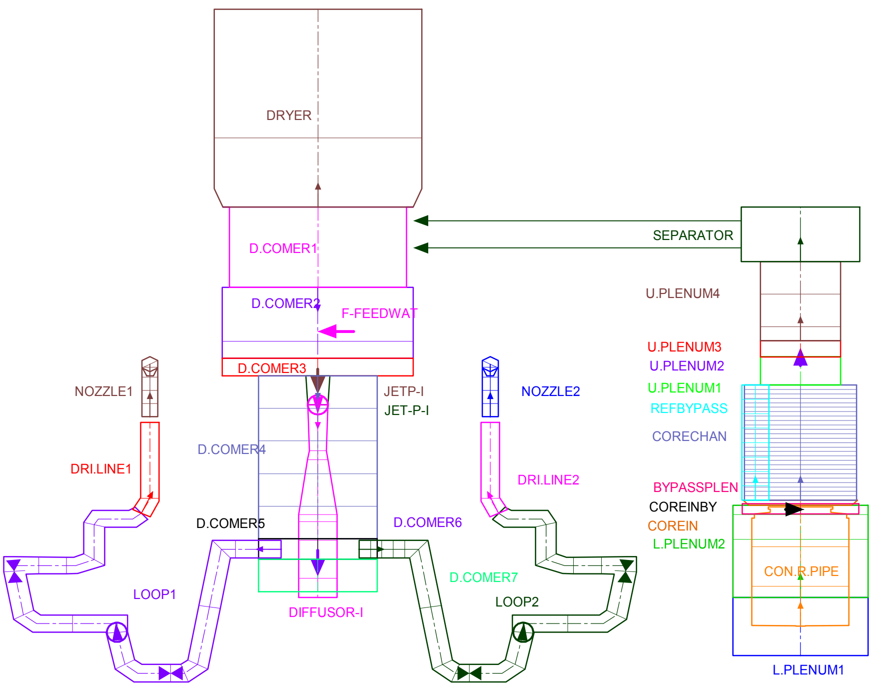

Figure 1. ATHLET nodalization of the reactor vessel and the recirculation loops

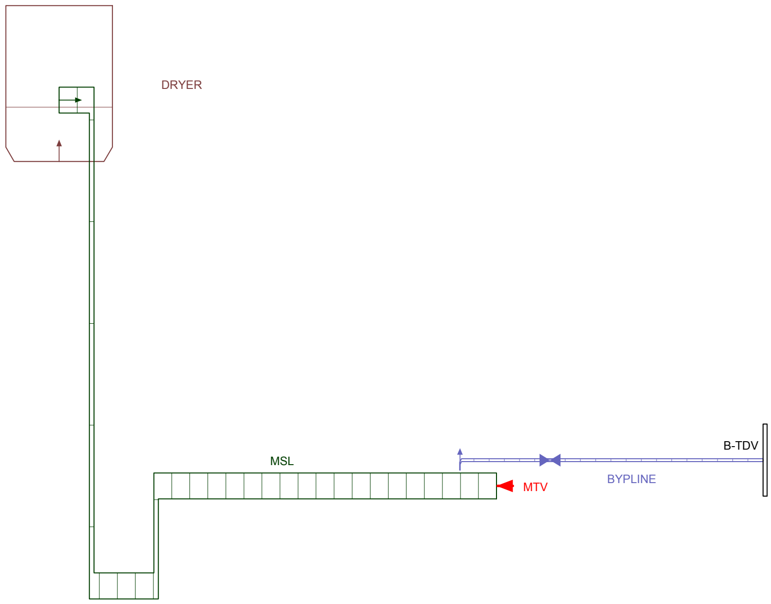

Figure 2. ATHLET nodalization of the steam line and the bypass line

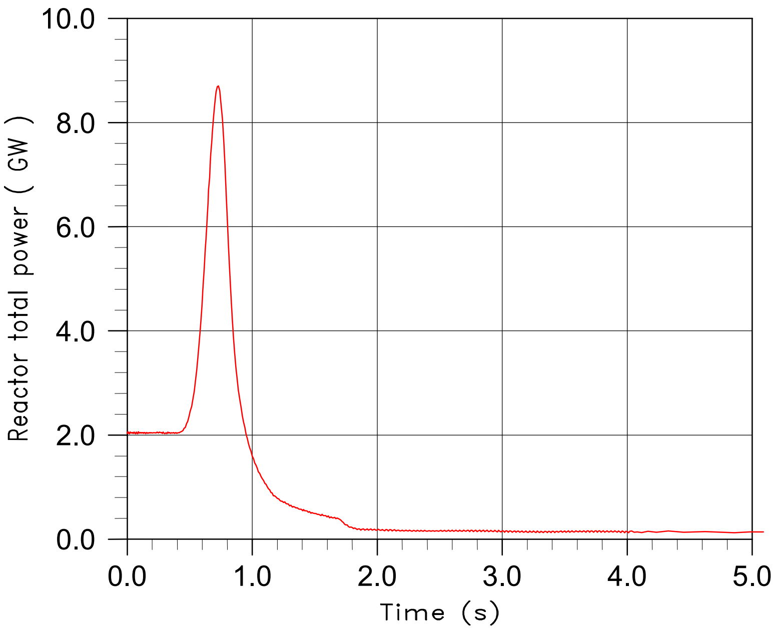

Figure 3. Total reactor power specified in the Benchmark for Exercise 1

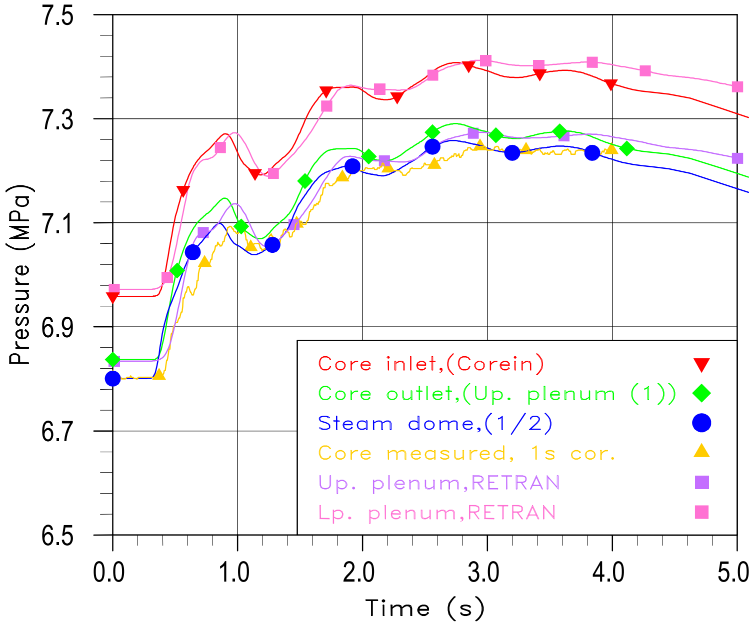

Figure 4. Comparison of pressure time-functions calculated by ATHLET and RETRAN with measured data

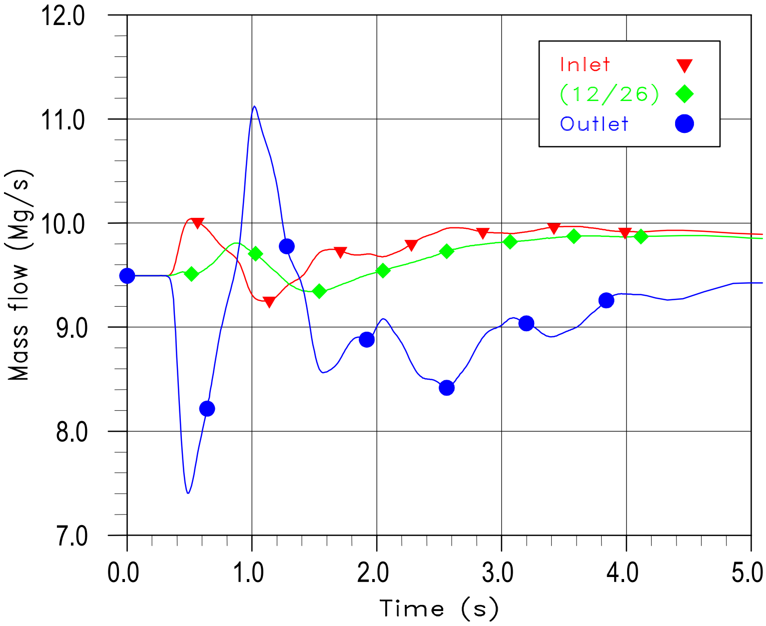

Figure 5. Mass flow rate in the reactor core at inlet, at outlet and at an intermediate location

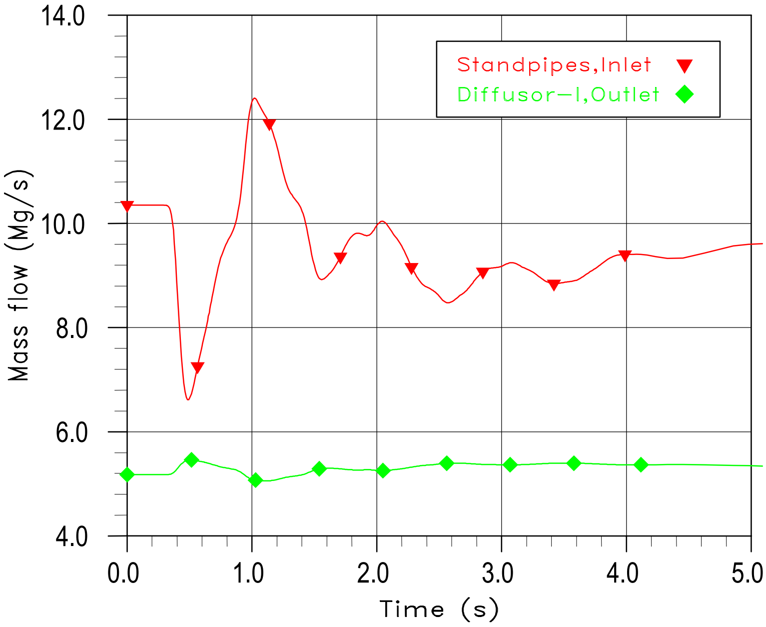

Figure 6. Mass flow rate in the standpipes above the core and the diffuser outlet

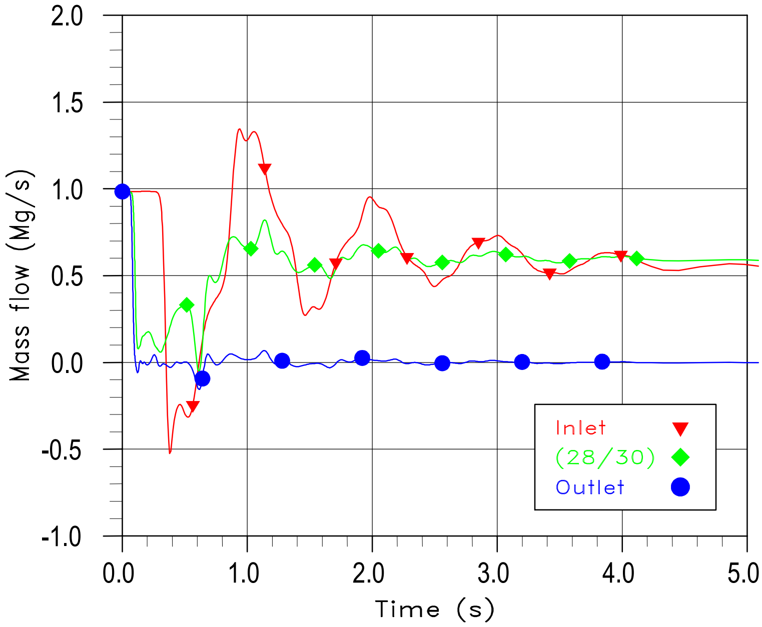

Figure 7. Mass flow rate in the steam line at the inlet from the reactor vessel, at the outlet to the turbine and at the connection to the bypass line

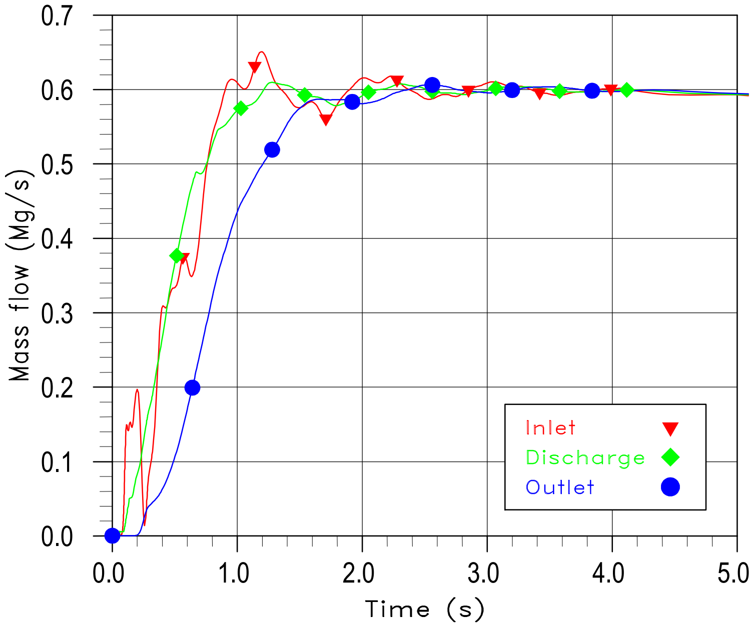

Figure 8. Mass flow rate in the bypass line at the inlet from the steam line, at the outlet and the discharge flow

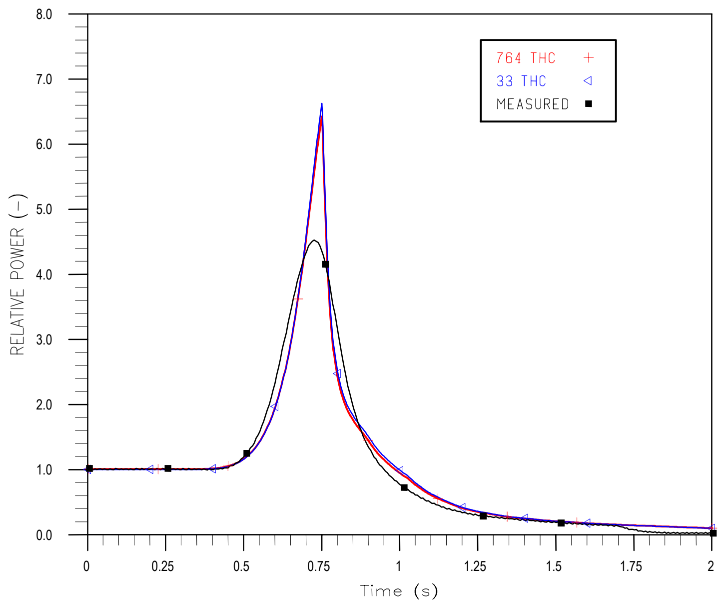

Figure 9. Relative power histories for Exercise 2 calculated by ATHLET-QUABOX/CUBBOX using 33 THC and 764 THC compared to measured data

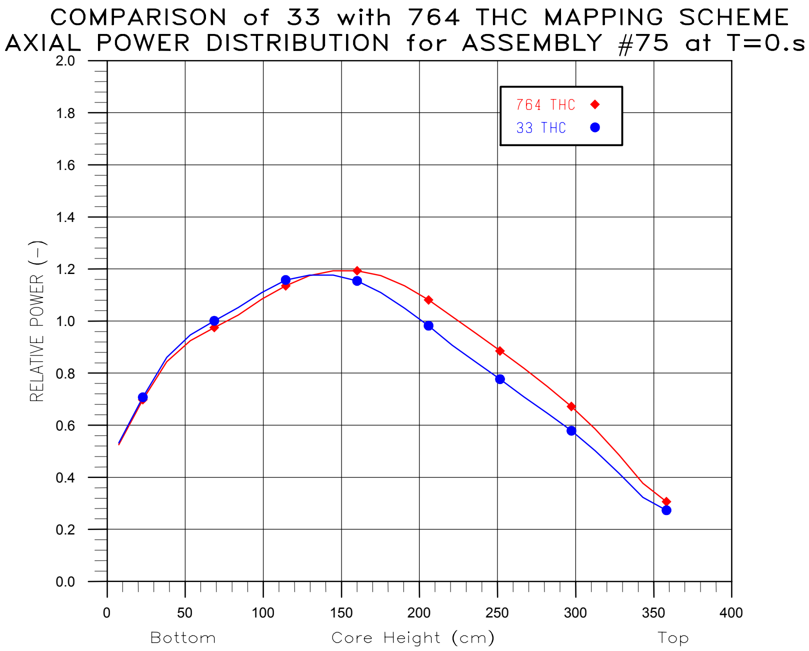

Figure 10. Comparison of axial power distributions in the initial steady state for fuel assembly #75 using 33 THC and 764 THC in the ATHLET-QUABOX/CUBBOX calculations

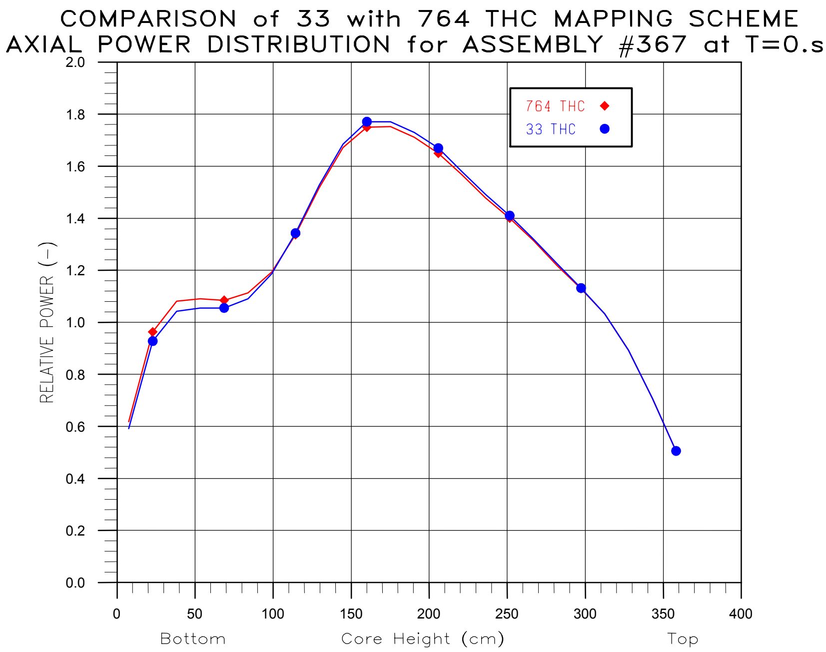

Figure 11. Comparison of axial power distributions in the initial steady state for fuel assembly #367 using 33 THC and 764 THC in the ATHLET-QUABOX/CUBBOX calculations