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Thermal-Hydraulic Model of the Helium-Cooled Pebble Bed Test Blanket Module for ITER FEAT

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Abstract

Within the European fusion programme several test blanket modules (TBMs) are under development to be tested in the International Thermonuclear Experimental Reactor (ITER). The TBM prepared by Forschungszentrum Karlsruhe GmbH represents the helium-cooled pebble bed blanket (HCPB) considered as a viable concept for future fusion reactors. A safety assessment has to demonstrate that the HCPB TBM with its own cooling system does not impede the safe operation of ITER under normal and accidental conditions. For conducting the highly transient accident sequences of the loss of coolant type, a RELAP model has been developed for the HCPB TBM system. The present report describes in detail the modelling for both the TBM proper as a network of numerous parallel and serial flow channels, and the external cooling circuit with circulator, heat exchanger, heater, piping system, etc. According to the RELAP/MOD3.2 manual breakdown, for each component the characteristics are defined in separate sections, i.e., hydrodynamics, heat structures, material properties, and power sources. While the results of the safety study are documented in a different report, this work includes selected results of the steady state behaviour of the system in terms of gross parameters, hydrodynamic quantities, and temperature distributions in coolant and heat structures. Lessons learned from code application and appropriate further model extensions are outlined. Detailed data and program listings are given in three appendices.

Thermohydraulisches Modell des Helium-Cooled Pebble Bed Test Blanket Moduls für ITER-FEAT

Zusammenfassung

Im Rahmen des Europäischen Fusionsprogrammes werden derzeit verschiedene Test Blanket Module (TBM) entwickelt, die in ITER, dem „International Thermonuclear Experimental Reactor", erprobt werden sollen. Das vom Forschungszentrum Karlsruhe GmbH vorbereitete TBM spiegelt ein mit Helium gekühltes Feststoff-Blanket (engl. helium-cooled pebble bed blanket, HCPB) wider, das als ein mögliches Konzept für künftige Fusionsreaktoren angesehen wird. Eine Sicherheitsbetrachtung soll zeigen, daß das Testmodul mit seinem Kühlkreislauf den sicheren Betrieb der ITER-Anlage unter Normalbedingungen und bei Störfällen nicht beeinträchtigt. Für die Analyse dieser schnell ablaufenden Störfälle, z. B. bei plötzlichem Kühlmittelverlust, wurde ein Modell des HCPB TBM für den Rechencode RELAP erstellt. Im vorliegenden Bericht ist diese Modellierung für das TBM selbst mit seinem Netzwerk vieler parallel- und in Reihe geschalteter Komponenten sowie für den externen Kühlkreislauf mit Gebläse, Wärmetauscher, Heizer, Rohrleitungssystem etc. im Detail beschrieben. Entsprechend der Gliederung im RELAP/MOD3.2 Handbuch werden die Eigenschaften der Komponenten in Unterkapiteln definiert, also bezüglich Hydrodynamik, wämeführender Strukturen, Werkstoffeigenschaften und Wärmequellen. Während Ergebnisse aus der Sicherheitsanalyse in einem getrennten Bericht dokumentiert sind, enthält die vorliegende Arbeit einige Ergebnisse zum stationären Systemverhalten in Bezug auf integrale Parameter, hydrodynamische Größen und Temperaturverteilungen im Kühlmittel und in Wärmestrukturen. Einige Erfahrungen aus der Anwendung des Codesystems sowie zweckmäßige Ergänzungen zum erstellten Modell werden angesprochen. Ein detaillierter Datenteil und Programm-Auflistungen befinden sich in drei Anhängen.

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1 Introduction

It is one of the missions of the International Thermonuclear Experimental Reactor (ITER) to act as test bed for various breeder blanket test modules to explore their potential for a demonstration reactor. The purpose of the tests is to demonstrate tritium breeding and recovery as well as extraction of high grade heat suitable for generation of electricity. These ITER Test Blanket Modules (TBMs) are developed by the participating ITER Parties. Forschungszentrum Karlsruhe GmbH is pursuing the development of the helium-cooled pebble bed (HCPB) blanket type within the EU Home Team.

For integration in ITER the TBM has to assure a number of features. These are to provide adequate shielding, accommodate surface and nuclear heating, handle static and dynamic loads, support vacuum requirements, conform to safety criteria, have minimal impact on operational availability, and to conform to remote handling criteria. In terms of safety, the operation of the TBM should have as low as possible impact on the safe operation of ITER during postulated accidents. This has to be demonstrated in a safety assessment. The present work is to document the thermal-hydraulic model of the TBM subsystem to be used in the safety analysis [1].

The test objectives call for a series of TBMs of different designs and missions [2]. With respect to safety issues the one devoted to plant integration (PI) functions, the so-called PI-TBM, represents the enveloping case in terms of loads, duration, fluence and tritium production. Hence, the modelling of the HCPB type series of TBMs is at this stage restricted to the PI-TBM. It employs alternating layers of ceramic breeder material and beryllium, both in form of small pebbles. These pebble beds are separated by steel plates with integral cooling channels to remove the heat. Many of the geometric parameters adopted here are still subject of optimisation. The configuration analysed in this report corresponds to the status as of June 2001 as documented in [2].

The TBM system design including its cooling subsystem and other ancillary subsystems are described in the following chapter 2. In the main part, chapter 3, the RELAP/MOD3.2 TBM system model developed specifically for studying a series of postulated accidents in the frame of the safety assessment is described. This model is tailored for use of the one-dimensional thermal-hydraulic code RELAP, focussing at first on the hydrodynamic aspects of the system in section 3.3, followed by a detailed description of the heat structures in section 3.4 and specifying finally the material data in 3.5 and power sources in section 3.6. A few key results of the a steady state analysis will be outlined in chapter 4 as typical examples. Chapter 5 will finally point to specific experience gained in this application. Summary and conclusions are drawn in chapter 6.

Three appendices are mainly intended to complete the documentation in case the model has to be extended or updated in the course of further TBM development. Appendix A is a collection of major input data in tabular form. A typical RELAP input deck for steady state analysis is printed in Appendix B for the reader familiar with the RELAP convention. A RELAP output data set at a certain time step, a so-called major edit, is reproduced in Appendix C for illustration and, if needed, to look up further details of the steady state analysis.

2 System description

A detailed description of the HCPB TBM system can be found in the design description document [2] prepared for ITER. The system consists of several subsystems, i.e.,

- a set of TBMs installed and tested in ITER one at a time
- helium cooling system (HCS)
- tritium extraction system (TES)
- coolant purification system (CPS)
- Tritium measurement system (TMS)
- Neutronics measurement system (NMS)

The HCS, TES and CPS are designed to be used more or less for all types of TBMs, whereas the TMS and NMS are supposed to be operated during specific tests only, that is in combination with the neutronics and tritium production (NT) TBM. Thus, these two subsystems will be ignored in this report, since it focuses on the plant integration (PI) TBM.

The system description presented in this Chapter 2 will be limited to the extent as needed in this context. Details of performance analyses in the fields of nuclear, thermal-hydraulics, thermomechanics and tritium management can also be obtained from [2]. The following sections address the main design features of the HCPB TBM itself used for plant integration tests, the helium cooling system, and the hydraulic link to the tritium extraction system. A summary of power generation taken from [2] is added in section 2.4. Figure 1 on page 56 gives an idea of the arrangement of the TBM, HCS, CPS and TES in ITER FEAT.

2.1 HCPB Test Blanket Module (TBM)

The HCPB TBM represents a poloidal section of a DEMO blanket segment. An isometric representation when viewing from the back illustrating its principal design is depicted in Figure 2. It consists essentially of horizontal layers of breeder and beryllium pebble beds, separated by cooling plates and stiffening plates. The whole stack is encapsulated by a strong box. At one side the box faces the plasma and thus constitutes the FW, which is plated with 2 mm beryllium. The top and bottom of the box are covered by end caps with integral cooling channels. They are designed to withstand an internal pressure of approximately 2 MPa. The whole structure including the internal plates are cooled by a forced helium flow at a pressure of 8 MPa. Helium is fed from the rear side via manifolds, at first through the FW box and end caps, and subsequently through the cooling plates and stiffening plates in the breeding zone. A more detailed flow scheme will be presented in section 3.3.1, TBM hydrodynamic model on page 11. The pebble beds are purged (but not cooled) by a separate forced flow of low-pressure helium provided by the tritium extraction subsystem (TES). A description of the TBM and its testing strategy in ITER FEAT is given in [2].

The overall dimensions of the TBM are determined by the support frame of the ITER horizontal port, which is supposed to accommodate both the HCPB TBM in the upper half and a similar test module developed by the Japanese group in the lower half. The frame opening for one module has a size of 0.78 m high by 1.31 m wide, leaving an overall space for the TBM of 1.27 m x 0.74 m x 0.8[1] m in toroidal, poloidal and radial direction, respectively. Figure 3 shows the upper half of the ITER support frame with the TBM installed. One can see the main cooling pipes for helium inlet and outlet, and the four support studs, all designed for remote assembly and disassembly. Also indicated are the locations of two burst

[1] 0.8 m is the current radial depth assumed. This may be subject to changes as already indicated in the more recent drawing, Figure 3.

disks integrated in the back plate to prevent the TBM box from over-pressurisation in case of an internal leak.

The main part of the PI TBM is occupied by the pebble beds, constituting the breeding zone (BZ). A typical unit cell of the BZ is depicted in Figure 4. It shows one set of layers within the poloidal pitch, p, consisting of half a stiffening plate, beryllium pebble bed, cooling plate, ceramic breeder pebble bed, cooling plate, beryllium pebble bed and half a stiffening plate. The stiffening plates are attached to the first wall (FW) for mechanical reasons, while the pair of cooling plates is closed in the front region to form a sealed canister for the breeder pebbles.

In this report a pitch of 0.122 m and a radial depth of the pebble beds of L=0.5 m has been assumed. Other layer dimensions are indicated in the schematic poloidal-radial cross section in Figure 4. Further details on void fraction, cooling channel dimensions, materials will be explained in the respective subsections of chapter 3, describing the RELAP model.

2.2 Helium cooling system (HCS)

2.2.1 Overall arrangement

The cooling system includes the primary helium heat transport loop with all components and the secondary water heat removal loop, the latter being part of the ITER tokamak cooling water system (TCWS) with given operating conditions. The HCS is housed in the TCWS vault approximately 70 m away from the TBM (Figure 1). Hence, the pipe routing has to run essentially 18 m horizontally, 14 m vertically and again 60 m horizontally, plus 10 m between components. Including the U-bends for thermal expansion this results in a total length of roughly 100 m for the hot leg and cold leg each. The space allocated for the HCS components, including the glove box that will house the coolant purification system, measures 16 m^2 on floor, 5 m high.

2.2.2 Operating conditions

The HCS is designed for a series of TBMs as already mentioned, requiring different operating conditions according to the testing goals. The most demanding, and hence enveloping operating conditions, are set by the PI-TBM and the NT-TBM. We further have to distinguish between the nominal conditions with moderate surface heat flux of 0.1 MW/m^2 and extreme operating conditions, the latter setting the design requirements for the HCS. Table 1 summarises the extreme operating conditions for the PI-TBM and NT-TBM and it can be seen that the largest difference between both is in the helium inlet and outlet temperature level. But this has no impact on the RELAP model of the HCS described in sections 3.3.2, 3.3.3 and 3.4.2, 3.4.3, other than the need for choosing the respective input parameters.

2.2.3 Flow diagram

Main components of the primary HCS are, besides the TBM, a heat exchanger (HX), circulator, electrical heater, dust filter, control valves and pipework. A bypass to the HX with control valve and electrical heater is mainly intended to heat the system at start-up or for conditioning purposes, and to control the flow through the HX during pulsed power operation (see section 2.2.4). The secondary cooling loop is regarded to the extent as to specify the boundary conditions for the HX, that is a given constant water flow (which can be tripped to zero) of constant inlet and outlet temperature. A flow diagram is shown in Figure 5. The main loop is directly connected to the CPS via small diameter pipes, branching off a continuous small bypass flow of about 0.1% of the main flow[2]. The pressure control unit, connected to

[2] The PCS with its connections to the main loop has been neglected in the RELAP model so far because of its presumably small helium inventory.

the main loop by a surge line and safety valves, consists of a set of tanks for helium storage, dumping and pressure control. In the context of this report the pressure control unit is simply simulated by a pressuriser tank and a trip valve in the surge line that can be either fully open or closed, depending on the main system pressure (section 3.3.3.5). The TES has usually no hydraulic connection to the main loop, except in special accidental situations as explained in section 2.3. Attached volumes for instrumentation piping and transducers are ignored at this stage.

Table 1: Extreme operating conditions of the HCS for PI-TBM and NT-TBM

	Unit	PI-TBM	NT-TBM
Inner port dimensions (width x height)	m x m	1.31 x 0.78	
Projected area of module facing the plasma	m x m	1.27 x 0.74	
Surface heat flux	MW/m^2	0.25	0.25
Neutron wall loading	MW/m^2	0.78	0.78
Total heat to be removed	MW	0.93	0.92
Primary coolant		helium	helium
Temperature at module in/out	°C	250/500	100/300
Pressure	MPa	8	8
Number of circuits		1	1
Mass flow rate	kg/s	0.72	0.88
Secondary coolant		water	water
Temperature at heat exchanger in/out	°C	35/75	35/75
Pressure	MPa	<1	<1
Number of circuits		1	1
Mass flow rate	kg/s	5.6	5.5

2.2.4 Components of the HCS

A description of the components mentioned in the preceding subsection and their function are outlined in [2]. We repeat below a few technical data relevant for the RELAP model. Listed are estimated pressure losses and helium inventories in piping and components in Table 2[3], and main component dimensions and material masses in Table 3. Details will also be given in the pertaining sections of chapter 3 RELAP model.

[3] The pressure losses and inventories resulting from RELAP analysis may deviate slightly from the estimated values given in the table as shown in section 4.2.

Table 2: Pressure loss and helium inventory in HCS components (PI-TBM extreme conditions)

Component	Pressure loss [Pa]	Volume [m^3]	Mass [kg]
Hot leg pipework	113000	0.365	1.79
Cold leg pipework	70300	0.374	2.59
Main pipe elbows	28600	incl. in pipes	incl. in pipes
Bypass to heat exchanger	4300	0.014	0.07
Valves	27600	0.001	0.004
Heat exchanger	1000	0.006	0.35
Circulator	-	0.025	0.18
Electrical heater	bypassed	0.026	0.13
Dust filter	5000	0.2	0.98
Buffer tank	-	0.133	2.77
Test module	14000	0.09	0.54
TOTALS	259000	1.26	9.4

Table 3: Main dimensions and mass of HCS components

Component	Diameter (m)	Wall thickn. (m)	Length (m)	Mass (kg)
Helium/water heat exchanger shell	0.3	0.012	2.2	441
Circulator, vertical shaft (first guess)	0.4	0.025	0.5	170
Electrical heater	0.22	0.015	2.2	250
Dust filter (without shield)	0.34	0.02	2.5	800
Main pipework (including bypass)	0.0825	0.0071	210	2650
Pressuriser	0.3	0.015	2.4	228
Test Module	-	-	-	2000
Total mass of components listed				6539

2.3 Tritium extraction system (TES)

The function of the TES is to remove the tritium produced in the TBM pebble beds and control the gas composition of the low pressure purge flow. The mass flow rate determining the capacity of the system has been chosen to result in a velocity of the purge gas in the beds typical for a power reactor. Thus, main design data for the TES are a helium (plus small fraction of hydrogen isotopes) mass flow rate of 0.6 g/s at a system pressure of between 0.09 and 0.12 MPa and a gas temperature varying between –196°C in the adsorber beds and 450°C at the exit of the TBM. The system components are encapsulated in a glove box that is located in the tritium building. A detailed description is presented in [2].

In case of a coolant leak inside the TBM the TES would be subject to high pressure helium. In order to avoid over-pressurisation a system of valves will be installed in the pipes connecting the TBM with the TES as illustrated in Figure 6. The pressure reducing valve will limit the downstream pressure to 0.2 MPa, and the check valve in the purge gas feed line (TES to TBM) will prevent back streaming. The fast isolation valves are an additional active measure, to which, however, no credit is given in safety assessment. For the purpose of TBM safety considerations it is appropriate to regard the TES as a single volume connected to the TBM via two pipes and the pressure reducing valve and check valve according to Figure 6. An example case of application is shown in [1]. The following data are assumed:

- Total free volume of TES: 4 m^3
- Mean operating pressure of TES: 0.1 MPa
- Inner diameter and length of each pipe: 0.025 m and 90 m, respectively
- Pressure reducing valve: fully open if $p \leq 0.2$ MPa and fully closed if $p > 0.2$ MPa (p = pressure before valve)
- Location of valves: in TES box.

2.4 Power generation

2.4.1 Nuclear power generation in TBM at nominal fusion power

The nuclear power in the TBM has been calculated by the neutronics group [2]. The calculation was performed for normal operation at 500 MW of fusion power for both the PI-TBM and the NT-TBM. Both modules exhibit large differences in breeder and beryllium pebble bed thickness, but the power generation is very similar. It differs by less than 2% in the total power, 6.2% in the breeder and 11.4% in the beryllium power. Table A-1 in Appendix A shows the results taken from [2] for individual regions and elements in the PI-TBM and NT-TBM. The fractions of total nuclear power in the different regions FW/BZ/structure relate as 0.13/0.66/0.21.

The underlying geometrical model for the neutronics analysis is shown in Figure 7. The individual parts and zones (like the BZ, GC, MM, SM) are considered as homogeneous bodies with material compositions as listed in Table A-2 in Appendix A. For instance, in the breeding zone of the PI-TBM we have volume fractions of 8.2 % ferritic martensitic steel, 45.8 % beryllium, 9.5 % Li_4SiO_4 (OSI) and 36.5 % void (filled with helium). The other parts are more or less composed of steel and void. The same composition has also been used in establishing the RELAP model with some detailed adaptations discussed in Chapter 3.

2.4.2 Decay power

Activation and decay power after shutdown have been calculated for the NT-TBM only [2], using the same geometrical model as described in section 2.4.1. Continuous irradiation over 0.536 years at full fusion power (500 MW) was assumed. With a neutron wall loading of 0.78 MW/m^2 at the TBM first wall, this results in a total first wall fluence of 0.4036 MWa/m^2. At the envisaged ITER operation scenario this fluence would actually be achieved over a 20 years period at an average availability of 2.68%. The continuous full power operation assumption is thus conservative in terms of activation and decay heat. Because of this large conservatism and the fact that the power generated in both types of TBMs is similar as was shown in section 2.4.1, the decay power data for the NT-TBM (Table A-3) were also used for the PI-TBM with minor adjustments as will be documented in section 3.6.2.

2.4.3 Surface heat flux at the TBM

A uniform surface heat flux of 0.25 MW/m^2 is assumed at the TBM first wall during burn times. With a projected plasma facing surface of 1.27 m x 0.74 m this results in a surface heat load of 0.235 MW.

2.4.4 Other power sources and sinks in the system

A further power source in the cooling loop is introduces by the electrical heater. It is needed for baking the test module and for heating the whole system to operating temperature after maintenance and repair periods. The heater will also be needed for the NT-TBM for tritium release experiments at 500°C. The projected electrical power is 140 kW and it is at this stage assumes to be operated in the fully on or off mode.

The thermal power produced by the circulator amounts to between 15 and 25 kW, depending on the operational regime. It is automatically calculated by the RELAP code from mass flow rate and pumping head.

Heat sinks in the primary cooling circuit are found in the heat exchanger and in thermal losses through component walls. The heat transferred from the primary to the secondary side is modelled in RELAP and will be described in sections 3.3.3.1 and 3.4.3.1. The heat losses passing the thermal insulation from the cooling circuit (piping and components, but excluding the TBM proper) have been calculated in [2] as 24 kW for the PI-TBM. For short term transients to be addressed with this model the losses have been ignored.

3 RELAP5/MOD3.2 TBM system model

3.1 Scope of RELAP code and model architecture

The computer code RELAP5/MOD3.2 [3] has been developed for thermal-hydraulic transient simulation of light water reactor coolant systems. The code simulates the behaviour of the reactor coolant system during severe accidents like large and small break loss of coolant accidents, operational transients, loss of off-site power, loss of feed water, or loss of flow accidents. RELAP5 is a highly generic code that can be used for simulation of a wide variety of hydraulic and thermal transients in both nuclear and non-nuclear systems using a fluid that may be a mixture of steam, water, non-condensable gases, and a non-volatile solute (e.g. boron). In the present analysis, helium is the only component used as non-condensable gas in the primary cooling loop with the other three components set to zero.

The hydrodynamic model is a one-dimensional, transient, non-homogeneous, non-equilibrium model for flow of a two-phase water mixture. The basic field equations consist of two-phase continuity equations, two-phase momentum equations, and two-phase energy equations. The system model is solved numerically using a semi-implicit or nearly implicit finite-difference technique, depending on the user's choice. So-called heat structures provided in RELAP5 permit calculation of the heat transferred across solid boundaries of hydrodynamic components, e.g. heat transfer across steam generator tubes or heat transfer from pipe and vessel walls. Heat structures are assumed to be represented by one-dimensional heat conduction in rectangular, cylindrical, or spherical geometry. Surface multipliers are used to convert the unit surface of the one-dimensional calculation to the actual surface of the heat structure. Temperature-dependent thermal conductivities and volumetric heat capacities are provided in tabular or functional form either from built-in or user-supplied data.

The HCPB TBM cooling system has been modelled by RELAP5/MOD3.2 components. The model includes primary and secondary side pipework, heat exchanger, helium circulator, pressure control system, valves, dust filter and electrical heater. It is based on the TBM cooling circuit layout described in [2] and on the spatial arrangement of the TBM in ITER as shown in Figure 1. The nodalisation scheme of the cooling loop as used for simulating loss of coolant accidents (LOCAs) is shown in Figure 8. Detailed nodalisation of the TBM is given in Figure 9. A description of the model components is provided below.

According to the structure of the RELAP manual, the model description is given in two groups. At first the hydrodynamic features are specified in section 3.3 for the TBM, piping and components, and then in section 3.4 the heat structures are described in the same order. The material data and power sources are collected in sections 3.5 and 3.6. A complete input deck for a steady state RELAP run is attached in Appendix B for the reader who is familiar with the RELAP terminology. But let us begin with a few remarks on the organisation of a RELAP problem, for instance in case of a loss of coolant accident simulation.

3.2 Job control

RELAP5 provides for four problem types, i.e., NEW, RESTART, PLOT and STRIP. The first two are concerned with simulating hydrodynamic systems. NEW starts a simulation from input data describing the entire system (Appendix B) and RESTART restarts a previously executed NEW or RESTART problem. PLOT and STRIP are output type runs using the restart-plot file written by NEW or RESTART problems. NEW and RESTART problems require an additional option to be selected, that is steady state (STDY-ST) or transient (TRANSNT). PLOT has not been used here. STRIP writes selected information from a restart-plot file onto a new file. The new file consists of records containing time and the user-selected variables in the order selected by the user. These variables can be visualised by the plot program XMGR (see 8.1 of [3]).

In the following we explain a few entries used in the input deck for the steady state calculation (Appendix B). For details the reader should refer to the respective sections of the code manual [3].

The problem is initialised by a call for a new steady state run (card 100). This option uses the transient hydrodynamic, kinetic, and control system algorithms and a modified heat structure thermal algorithm to converge to a steady state. A testing scheme is used to check if steady state has been achieved (7.1.2 in [3]). An input check has been requested (card 101). The non-condensable gas specified is helium (card 110). It is in this case the only fluid in the primary circuit, which is expressed later on at several places specifying the fluid composition, and setting the water content to zero.

Input data for time step control consist of one or more cards containing a time limit, minimum time step, requested (maximum) time step, control option, minor edit plot/frequency, major edit frequency, and restart frequency. The information on the first card is used until the problem time exceeds the card limit; then the next card is used, and so on (8.2 in [3]). The time limit[4] is set to 1 s. The minimum time step has been set to 10^{-9} s and the maximum time step to 0.002 s. The fourth variable on time step control cards allows the user to select several options (8.2 in [3]). Here we entered this variable as 15011 with the last two digits specifying the nearly implicit advancement scheme using time step control; the heat conduction and hydrodynamics use the same time step, and the heat conduction/transfer and hydrodynamics are advanced separately. For details please refer to A3.2 in [3].

Cards 301 to 399 specify minor edit requests. They are optional and if present, minor edits (selected variables) are printed for specified time steps, and the order is given by the card number. The variable request code pair consists of a variable code and a parameter as defined in A4 of [3]. As example, we requested in the input deck in Appendix B the mass flow rate on card 319 (mflowj 1801000) in pipe component 18 (digits 18) at its first internal junction (digits 01); on card 326 the pump velocity (pmpvel 2) of the circulator, component 2, etc. Furthermore, cards 2080xxxx are entered for those variables that are not automatically written to the restart-plot file and are thus unavailable for plotting, unless they are requested here (A4.9 in [3]). The user can specify in the field xxxx of the card 2080xxxx that between 1 and 9999 of these variables be written to the restart-plot file. For example, we requested, among others, the mesh point temperature (httemp 22200302) in heat structure number 22 with geometry number 2, of card type 0, card number 03 within the card type, at radial mesh point 02. The reader may refer to the code manual in order to understand the complicated construction of the variable, which even changes with the component type.

The last group of input provided in this section consists of variable trips. They are entered with cards 401 through 599 (A5.3 of [3]) and are used here generally in the steady state run only to define the state of the component during this phase. The comment cards preceded by asterisks (*) in the input deck explain the supposed trip condition. Here we have foreseen a pump trip (card 501), power ramp-down initiation (card 502), pressuriser open/closed condition (card 504), secondary water flow (card 509), control valve in HX line open/closed (card 510) and control valve in bypass line open/closed (card 511). As mentioned, the parameters on the trip cards are set as to keep the conditions unchanged during the steady state run, but may be modified and supplemented in subsequent transient restart runs in order to become effective.

3.3 Hydrodynamics of TBM, piping and components

To briefly explain the modelling philosophy of the RELAP5 code we quote a paragraph from section 1.3 of [3] concerning the hydrodynamic model.

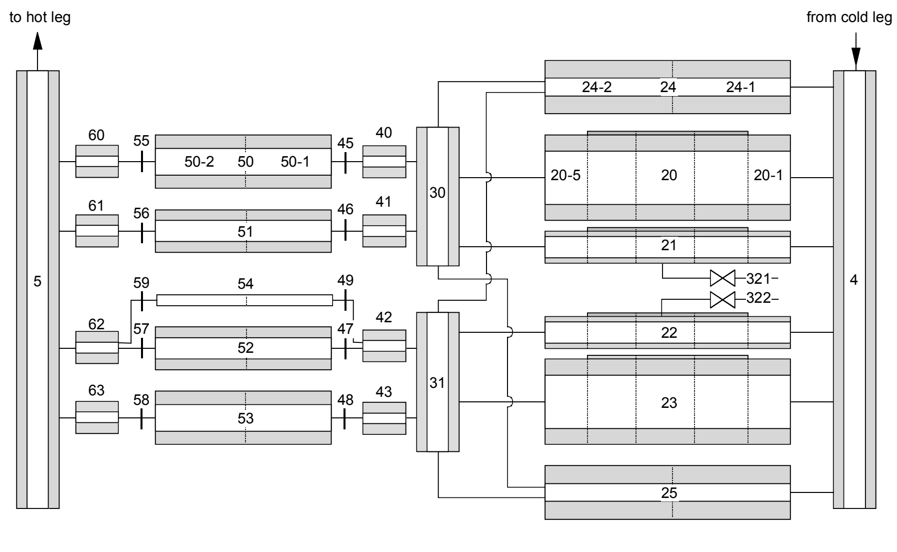
[4] It is not quite clear to the author what the time limit does in a steady state run, since the calculation is terminated by a testing scheme that checks if steady state has been achieved.

"The hydrodynamic model and associated numerical scheme are based on the use of fluid control volumes and junctions to represent the spatial character of the flow. The control volumes can be viewed as stream tubes having inlet and outlet junctions. The control volume has a direction associated with it that is positive from the inlet to the outlet. Velocities are located at the junctions and are associated with mass and energy flow between control volumes. Control volumes are connected in series, using junctions to represent a flow path. All internal flow paths, such as recirculation flows, must be explicitly modelled in this way since only single liquid and vapor velocities are represented at a junction. ... For flow in pipes, there is little confusion with respect to nodalisation. ... Branches and tees require more guidance."

In this case the model for the TBM system is essentially composed of branches (mainly for manifolds in the TBM proper), pipes, and single volumes. Pipes are also used to model the heat exchanger and the electrical heater. There are also a few special components, like valves and the circulator.

3.3.1 TBM hydrodynamic model

The PI-TBM design has been described in section 2.1 on page 3. There are numerous channels, branches, sub-channels, bends, transitions, orifices etc. Hence, for the RELAP analysis the components must be strongly simplified, and groups of channels or sub-channels have to be lumped together to give manageable numbers of components. For example, the complex breeding zone (BZ) will be divided into four components only. Likewise the first wall including their side walls will be represented by four components. These models should be equivalent to the real components in terms of mass, mass distribution, power generation and hydraulic performance to the largest extent possible. The envisaged RELAP nodalisation of the PI-TBM was already shown in Figure 9 on page 61. A description of the RELAP components is given in the following subsections with reference to the component numbers as indicated in the sketch below.



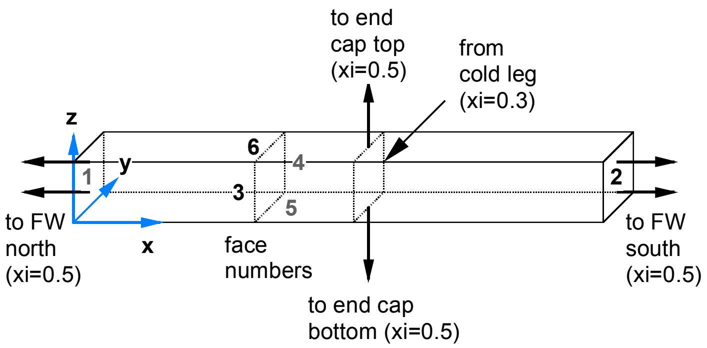
TBM component numbers (and examples for component-volume numbers)

3.3.1.1 Main inlet manifold (component 4)

The inlet manifold is modelled as a branch. It is assumed to consist of the lower half of the TBM back plate structure, consisting of BP1, BP2, MC/top and MC/bot. (see Figure 7 on page 60). The upper half is reserved for the outlet manifold. The outer dimensions are in x,y,z direction (toroidal, radial, poloidal) 1.218 m x 0.105 m x 0.37 m, and the steel and helium fractions are 60.4 and 39.6 %, respectively.[5] There is one main flow channel of

[5] These are the mean fractions when averaging over the components BP1, BP2, MM and MC.

square cross section 0.06 m x 0.06 m, 1.218 m long, to distribute the coolant coming from the cold leg to the FW in two main branches, one going to the south side wall and the other one to the north side wall. Two further groups of transition channels branching off from the main manifold are foreseen to supply the two end caps. These transition channels are not separately modelled. Their flow resistance is considered to be small compared to that of the sub-channels in the end caps. All junctions are provided with energy loss coefficients, ξ, for forward and reverse flow according to [4] as indicated in the sketch below. The wall roughness is assumed as $2x10^{-5}$ m.



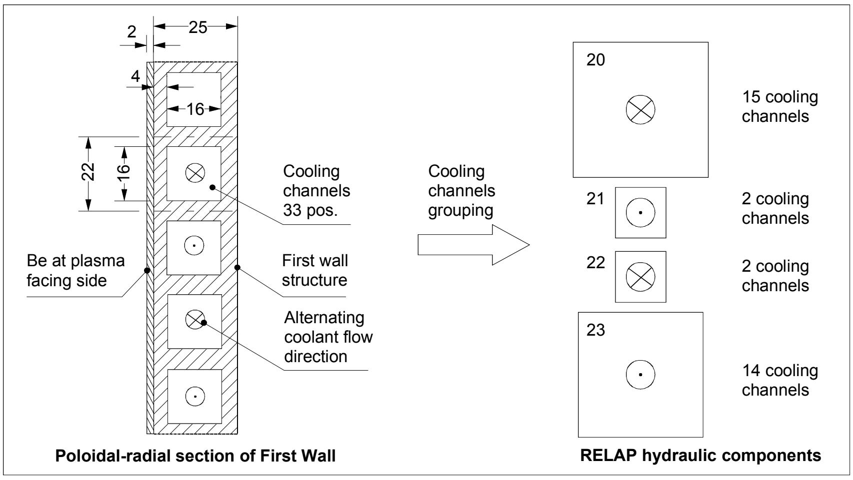
Main inlet manifold hydraulic representation

3.3.1.2 First wall (components 20 through 23)

The first wall (FW) forms a symmetric U-shaped structure of outer dimensions 1.268 m x 0.645 m x 0.74 m (toroidal x radial x poloidal). The coolant is supposed to flow in series, at first through the FW (with a parallel stream flowing through the end caps) and afterwards through the breeding zone (BZ). The flow in the FW is split into two branches of almost equal size, creating counter-flow in adjacent channels. Hence, there is one branch entering the south side wall and exiting the north side wall, and a second branch is flowing in opposite direction.

In the RELAP model the FW is divided into four pipe components, two large ones with 15 and 14 channels, and two small ones with 2 channels each, making a total of 33 cooling channels (see sketch below). The flow cross sectional areas of the lumped components has been enlarged according to the number of flow channels they represent, whereas the hydraulic diameter has been maintained as 0.016 m. The small components (No. 21 and 22) serve to simulate a FW failure after a severe disruption, where a total of four channels is assumed to fail as a double-ended pipe break. Therefore, these two components have an extra cross flow junction connected to valves 321 and 322, which are normally closed but will be opened for special transient cases.

The four FW components in turn are divided in flow direction into five volumes each, two of them representing the side walls and three volumes forming the front wall (see also section 3.4.1.2 on page 24. The five successive volumes have lengths of 0.615, 0.423, 0.422, 0.423, 0.615 m. The front wall sections are covered by a 2 mm thick beryllium protection layer. The profile of the FW steel structure is shown in the drawing below. It results in a steel volume fraction of 0.55 in the side walls and 0.458 in the front wall. Densities used for ferritic-martensitic (FM) steel and beryllium are 7700 and 1850 kg/m^3, respectively.



3.3.1.3 End caps (components 24 and 25)

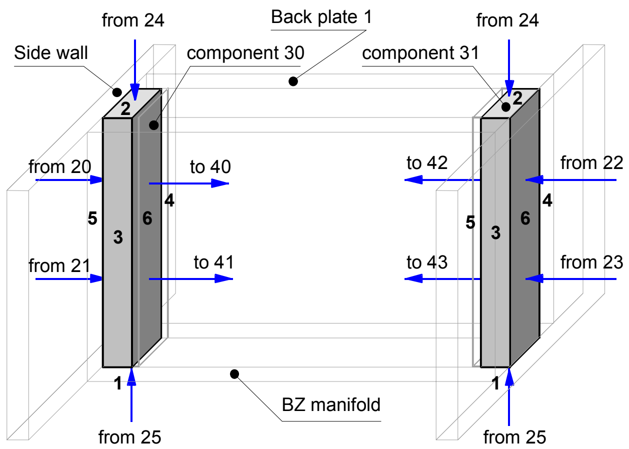
In order to cope with inadvertent overpressure in the TBM box in case of an internal coolant leak, the breeding zone is encapsulated by massive end caps. The current design allows a thickness of 0.075 m for each cap. The steel volume fraction is expected to be 0.88. The radial and toroidal dimensions are 0.51 m x 1.218 m. They are equipped with an array of internal U-shaped cooling channels running back and forth in radial direction (compare sketch in section 3.4.1.3 on page 26). The set of channels is connected to the main inlet manifold and to both intermediate manifolds as shown in the flow diagram Figure 9. We assume 14 cooling channels per cap with cross sectional areas of 0.009 x 0.009 m for the top cap and 0.01 x 0.01 m for the bottom cap.[6] The channel length is 2 x 0.501 m.

Each end cap is considered as one RELAP component with all channels being lumped together to a single coolant channel (summed cross sectional area but real hydraulic diameter). They consist of two successive volumes. The only internal junction between the volumes is modelled as a U-bend with forward and reverse flow energy loss coefficient of 0.4. Channel wall roughness is 5×10^{-6} m.

3.3.1.4 Intermediate manifolds (components 30 and 31)

One intermediate manifold is arranged at each side of the module (north component 30 and south component 31) to collect the coolant coming from FW channels (components 20 to 23) and from end caps (components 24 and 25), and to distribute the flow to the breeding zone inlet manifolds that supply the cooling and stiffening plates (components 40 to 43). Intermediate manifolds are modelled as rectangular ducts (RELAP branches with six junctions) located at both ends of the purge gas collection chamber as shown in the sketch below. Their flow cross section in a radial-toroidal plane is 0.08 m x 0.04 m and their walls separating them from the purge gas collection chamber are 0.01 m thick (see also section 3.4.1.4).

[6] Channel dimensions have been adjusted as to obtain the same outlet temperature at the caps as in the first wall. Please note that the bottom cap has slightly higher power than the top cap (Table A-1).

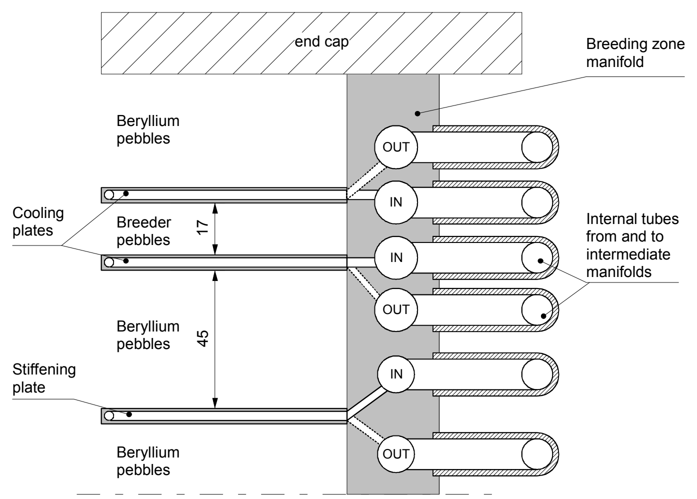


Detail of intermediate manifolds (schematic)
face numbers and flow junctions

3.3.1.5 Breeding zone inlet manifolds (components 40 through 43)

The breeding zone (BZ) is divided into two vertical halves (north side and south side), each half being cooled from one intermediate manifold. Therefore the breeding zone inlet manifolds are split in the same way. As a current approach, all the inlet and outlet manifolds together are considered as a continuous plate with an equivalent thickness of 30 mm and a steel volume fraction of 0.6 (see sketch below). This accounts for both the manifold structures and the internal piping associated with it. There are two types of inlet manifolds, one group with channel inner diameter of 0.014 m serving the cooling plates, and the other one with channel inner diameter of 0.012 m that serve the stiffening plates. Channels may be tapered in order to account for velocity variations along their length. The length is 0.609 m, i.e. half of the breeding zone toroidal width.

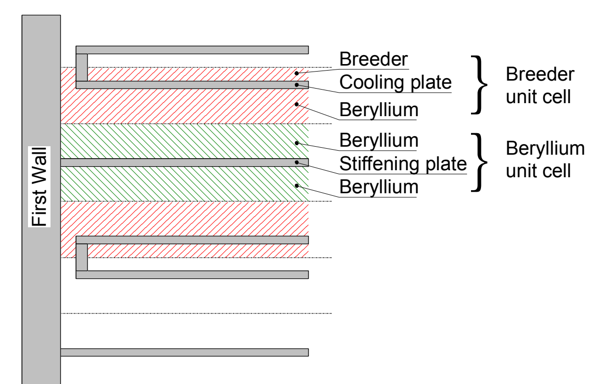
For the RELAP model, in each half of the BZ the inlet manifolds are lumped together to form two sets of channels, one supplying the 10 cooling plate (CP) halves and one set for the four stiffening plate (SP) halves. The space in between these channels is used for the corresponding outlet manifolds as shown in the sketch. Thus we obtain cross sectional areas of $10 \times 0.014^2 \times \pi / 4 = 0.001539\ m^2$ for the inlet manifolds that feed the two halves of CPs (components 41 and 42) and $4 \times 0.012^2 \times \pi / 4 = 0.000452\ m^2$ for the inlet manifolds that feed the two halves of SPs (components 40 and 43). The hydraulic diameters are taken as their real average values, 0.014 m and 0.012 m, respectively. A wall roughness of 5×10^{-6} m has been used.



BZ inlet/outlet manifolding schematic (radial-poloidal cut)

3.3.1.6 Breeding zone (components 50 through 53)

The current breeding zone design consists of five breeder layers encapsulated by the U-shaped pairs of cooling plates and surrounded by relatively thick beryllium layers. The beryllium layers are partially cooled by four stiffening plates. The unit cell width between the centre lines of two stiffening plates amounts to 0.122 m as follows from the schematic diagram in Figure 4 on page 58. For the RELAP model a division of the BZ in such unit cells is not appropriate, since the cell boundaries would be in the middle of stiffening plates and thus cut through flow channels. Therefore, the division chosen here is oriented at the centre lines of pebble layers, where the temperature gradient in poloidal direction is supposed to be small. So we define two types of unit cells, one representing breeder plus cooling plate plus part of the beryllium (termed as breeder unit cell), and another one representing the rest of beryllium plus stiffening plate (beryllium unit cell). These cells have then thickness of 0.05 m and 0.072 m, respectively (see sketch below)[7].



Breeding zone unit cell definition (radial-poloidal cut)

Having defined the unit cells, we can lump several cells together to a RELAP component. The choice made here is to split the whole BZ vertically into two halves (north and south) and to group within each half the four beryllium unit cells to one component (beryllium component) and the 10 breeder unit cells to another component (breeder component), in the same way as was done with the BZ inlet manifolds in section 3.3.1.5. Cooling channels in SPs and CPs are assumed to have cross sections of 0.003 m x 0.003 m with a pitch of 0.005 m. This allows to accommodate in the four SP halves 4 times 60 channels per beryllium component (of which one third will be blind) and in the 10 CP halves 10 times 60 hair pin channels per breeder component. Thus the flow cross sectional areas in these components result as 0.00144 m^2 and 0.0054 m^2, respectively, but the hydraulic diameters are derived for a single channel, i.e., 0.003 m. The material fractions by volume will then result as given in Table 4.

Table 4: Material fractions in RELAP components representing the breeding zone

	Material fractions by volume			
Component (Number)	FM-steel	Beryllium	Breeder	Void
North half beryllium cells (50)	0.0640	0.5670	0.0	0.3690
North half breeder cells (51)	0.0821	0.4119	0.1373	0.3687
South half breeder cells (52)	0.0821	0.4119	0.1373	0.3687
South half beryllium cells (53)	0.0640	0.5670	0.0	0.3690

The length of the hair pin channels is 2 times 0.4 m. The breeding zone components are therefore divided into two successive volumes, volume 1 representing the part of the flow path from back to front and volume 2 the path from front to back. The only internal junction

[7] The excess thickness of the beryllium layers at top and bottom is evenly distributed to the breeder unit cells.

between the volumes is modelled as a U-bend with forward and reverse flow energy loss coefficient of 0.4. The wall roughness is set as 5×10^{-6} m.

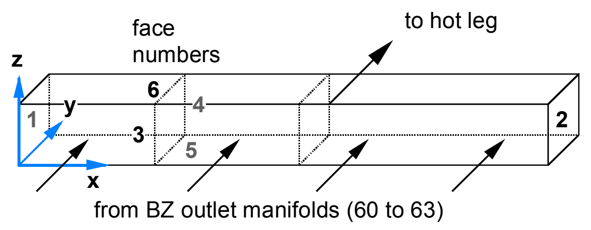
It should be mentioned that an additional single channel of a cooling plate is foreseen in the RELAP flow scheme (component 54 in the diagram in section 3.3.1) in order to simulate an internal leak from a CP channel break into the pebble bed. It has negligible bypass flow to the BZ and is considered to have no mass.

3.3.1.7 Breeding zone outlet manifolds (components 60 through 63)

The breeding zone outlet manifolds are grouped in the same way as described for the inlet manifolds. In each half of the BZ (north and south) the outlet manifolds are lumped together to form two groups, one for the cooling plates and one group for the stiffening plates. The outlet manifolds are assumed to have channel diameters of 0.014 m for the cooling plates and 0.012 m for the stiffening plates. Their length is 0.609 m. For hydraulic parameters and schematic diagram please refer to section 3.3.1.5 on page 14.

3.3.1.8 Main outlet manifold (component 5)

The outlet manifold is modelled as a branch. It is assumed to consist of the upper half of the TBM back plate structure, made up of BP1, BP2, MC/top and MC/bot. (see Figure 7). The lower half is reserved for the inlet manifold. The outer dimensions are in x,y,z direction (in m) 1.218 x 0.105 x 0.37, and the steel and helium fractions are 60.4 and 39.6 %, respectively.[8] There is one main flow channel of square cross section 0.06 x 0.06 m, 1.218 m long, to collect the coolant coming from the BZ outlet manifolds. Junctions are arranged as cross flow junctions. One further cross flow junction is connected to the hot leg (see schematic diagram below). The energy loss coefficients, ξ, for all junctions are set as zero for flow into the branch and 0.5 for outward flow according to [4]. The wall roughness is assumed as 2×10^{-5}m.



Main outlet manifold hydraulic representation

3.3.2 Piping hydrodynamic model

The architecture of the pipework of the helium cooling system is determined by the space allocation given by the ITER Team as indicated in Figure 1. The piping system will be discussed here in three subsections, covering (i) the cold leg between the circulator and the TBM, (ii) the hot leg leading from the TBM to the dust filter, and (iii) the relatively short pipe sections that interconnect the HCS components. All together the piping has a total length of about 199 m (92 m for the cold leg, 93 m for the hot leg, and 14 m between components). An outer diameter of 0.0825 m and a wall thickness of 0.0071 m have been chosen for all pipes, except for short sections terminating at the TBM, which have enlarged outer diameter of 0.1398 m and 0.0127 m wall thickness for maintenance purposes [2]. Pipes have generally been modelled as RELAP pipe components consisting of several volumes. Junctions between volumes have been placed at all pipe bends, and in addition in straight sections such that volumes would be no longer than about 5 to 7 m. There are a few pipe sections that are modelled as branch components. Details are outlined in the following subsections

[8] These are the mean fractions when averaging over the components BP1, BP2, MM and MC.

3.3.2.1 Cold leg architecture (component 3)

A schematic perspective view of the cold leg (and hot leg) architecture is shown in the diagram below. The cold leg is divided into 25 volumes with volume 1 connected to circulator outlet and volume 25 to TBM inlet nozzle. The total length results to 92.1 m and the elevation change between termination points is 10.6 m. There are 19 elbows. Internal junctions indicated by a cross are assumed to be either smooth in straight sections with energy loss coefficient of zero, or as bends with energy loss coefficient of 0.2. A wall roughness of $5x10^{-5}$ m has been used throughout. Volume lengths and co-ordinates of junctions are listed in Table A-4 in Appendix A. Pipe dimensions are given in Table 5.

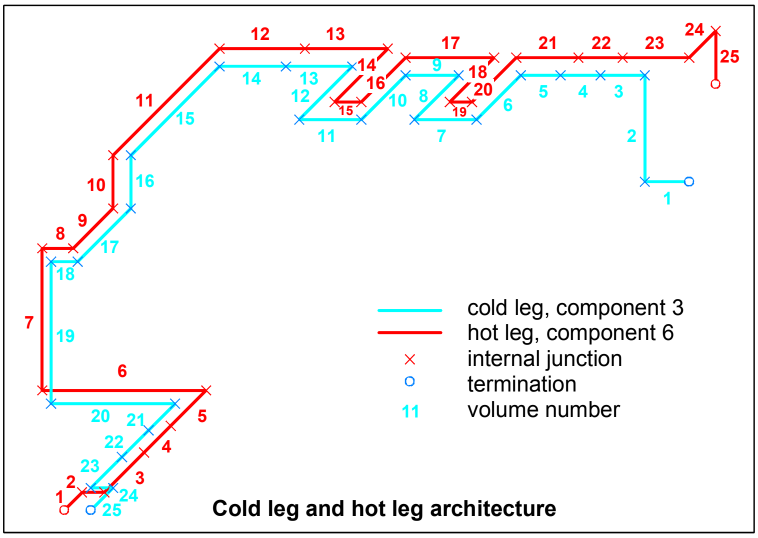


Table 5: Pipe dimensions of cold leg

Pipe volumes	ID (m)	OD (m)	Wall (m)	Area (m^2)	Roughness (m)
1 to 21	0.0683	0.0825	0.0071	0.003664	5.00E-05
22 to 25	0.1144	0.1398	0.0127	0.010279	5.00E-05

3.3.2.2 Hot leg architecture (component 6)

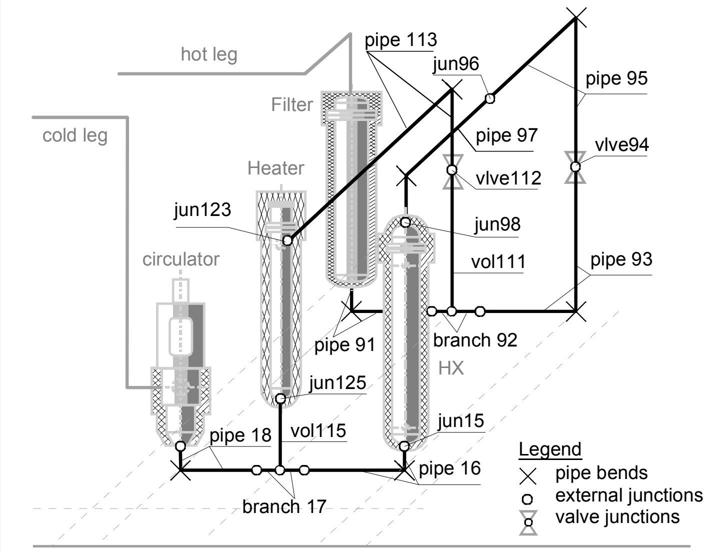
A schematic perspective view of the hot leg architecture is shown in the diagram above. The hot leg is divided into 25 volumes with volume 1 connected to the TBM outlet, and volume 25 to the filter. The total length results to 92.8 m and the elevation change between termination points is 12.5 m. There are 19 elbows. Internal junctions indicated by a cross are assumed to be either smooth in straight sections with energy loss coefficient of zero, or as bends with energy loss coefficient of 0.2. A wall roughness of $5x10^{-5}$ m has been used throughout. Volume lengths and co-ordinates of junctions are listed in Table A-5 in Appendix A. Pipe dimensions are given in Table 6.

Table 6: Pipe dimensions of hot leg

Pipe volumes	ID (m)	OD (m)	Wall (m)	Area (m^2)	Roughness (m)
1 to 4	0.1144	0.1398	0.0127	0.010279	5.00E-05
5 to 25	0.0683	0.0825	0.0071	0.003664	5.00E-05

3.3.2.3 *Piping between HCS components*

The pipe routing between components is shown in the isometric view below. It involves mainly pipes with bends (pipes 16, 18, 91, 93, 95, 97, 113), two straight pipes (volumes 111 and 115) and two branch components (branches 17 and 92). The total length results to 14.2 m. Volume lengths and co-ordinates of junctions are listed in Table A-6 in Appendix A. There are 7 elbows as internal junctions indicated by a cross. Energy loss coefficients assigned to junctions are tabulated in Table A-7 in Appendix A. A wall roughness of $5x10^{-5}$ m has been used throughout. Pipe diameters are OD=0.0825 m, ID=0.0683 m.



Pipe routing between components

3.3.3 HCS components hydrodynamic models

Components of the helium cooling system include heat exchanger, circulator, dust filter, electrical heater, pressuriser and several valves. Most of them are shown in the isometric view above. Their layout has been described in [2]. For the circulator and valves special RELAP components are provided to define their characteristics, whereas the rest is modelled as standard components (pipes, branches, single volumes) consisting of one or a few volumes only.

3.3.3.1 *Heat exchanger and secondary water loop*

The helium/water heat exchanger (HX) was modelled as a counter-flow heat exchanger employing straight tubes. The primary helium flows downward inside the tubes and the secondary water flows upward outside the tubes. The helium flow path is represented by pipe component (10) on the primary side and the water flow path by pipe component (102) on the secondary side (see Figure 8 on page 61). Primary and secondary side are connected via two-sided RELAP heat structures as will be described in section 3.4.3.1. A simplified representation of the secondary water loop is used for mass flow rate control.

3.3.3.1.1 Primary side (component 10)

The nominal inlet/outlet temperatures of the helium are 500/250 °C for the PI-TBM at a mass flow rate of 0.72 kg/s. The HX consists of two end domes with inside diameters of 0.276 m, and of 96 straight tubes with lengths of 1.2 m and inside/outside diameters of 14/18 mm. The overall height of the HX is 2.2 m. Pipe component (10) is divided into 7 volumes. Volumes 1 and 7 represent the end domes with flow areas of 0.05983 m^2 and lengths of 0.5 m, volumes 2 to 6 represent the 96 tubes lumped together to single volumes with flow areas of 0.01478 m^2 and lengths of 0.24 m. The hydraulic diameter of the volumes was set to the real tubes inside diameter of 0.014 m. A surface roughness of $5x10^{-5}$ m was applied to the HX walls.

3.3.3.1.2 Secondary side (component 102)

The nominal inlet/outlet temperatures of the cooling water are 35/75 °C at a mass flow rate of about 5 kg/s. The water pressure is 1 MPa. Pipe component (102) is divided into 5 volumes with flow areas of 0.0354 m^2 and lengths of 0.24 m. The flow area results from the shell cross sectional area, which has a diameter of 0.276 m, minus the area occupied by the 96 tubes. For computation of frictional pressure losses a surface roughness of $5x10^{-5}$ m was applied. The hydraulic diameter of the volumes was set to the real tube outside diameter of 18 mm.

3.3.3.1.3 Secondary water loop representation (components 100 through 104)

The secondary loop is modelled as an infinitely large mass source (vol100) and mass sink (vol104) at both ends of the open loop as indicated in the flow diagram Figure 8. This is achieved by defining them as time-dependent volume components with constant water content of, for instance, 100 m^3 at a pressure of 1 MPa and temperatures of 35 °C and 75 °C for vol100 and vol104, respectively. The water reservoirs are connected to the secondary side HX component, pipe 102, via junctions 101 and 103, which have a cross sectional area equal to that of pipe 102, i.e., 0.0354 m^2 with energy loss coefficients set to zero. There is a time-dependent junction (jun211) in the feed line to control the mass flow rate. It is set to the projected mass flow rate of about[9] 5 kg/s, which can be tripped at a specified time (trip number 509) and then ramped-down to zero within one second.

3.3.3.2 Circulator (component 2)

The helium circulator is identified by a RELAP pump component (2) in Figure 8 on page 61. The hydrodynamic model consists of one volume and two associated junctions (suction junction and discharge junction). Interaction of the circulator and the fluid is described by characteristic curves relating the circulator head and torque to the volumetric flow and angular velocity. Characteristic curves for the type of helium circulator planned for the TBM cooling loops are not yet available. Instead, they have been used as derived in [5] from characteristic curves of the helium circulators developed for the German Thorium High Temperature Reactor. Hence, in this work the circulator model described in detail in [5] has been adopted completely with minor adjustments at input data related to the pump description card (No. 0020302) in the input deck (Appendix B, section B-3.3.3.2, circulator). The adjustment of the data was performed by trial and error and refers to ratio of initial pump velocity to rated pump velocity, rated head, rated torque, and friction torque coefficient.

The physical arrangement of the circulator is shown in the isometric view of the HCS components in section 3.3.2.3 on page 18. The circulator volume geometry is assumed to have a length of 0.6 m and a volume of 0.005 m^3. Material masses will be presented in section 3.4.3.2.

3.3.3.3 Dust filter (component 8)

A filter unit is installed in the hot leg of the main loop (Figure 8), accumulating residual dust and particles from fabrication as well as erosion particles. An array of small-diameter filter tubes (or plates) is assumed to form a removable filter cartridge of 0.3 m diameter[10] and 2.1 m length. An alternative design of the filter insert could have cylindrical form with radial flow as indicated in the sketch of section 3.4.3.3. Anyway, the helium volume of the 2.5 m long filter shell is approximately 0.12 m^3. The pressure loss is expected to be less than 5000 Pa at the extreme PI-TBM operating conditions.

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[9] This number was changed several times and is currently set in the input deck as 10.5 kg/s.
[10] This dimension has been changed in a recent layout to 0.35 m [2].

The filter is modelled as a branch consisting of a single volume and two junctions. The volume flow area is set equal to 0.0507 m^2, i.e., 72% of the cross sectional area of the filter shell, the length is 2.5 m. A hydraulic diameter of 0.002 m has been assumed. The wall roughness is 10^{-5} m. The energy loss coefficients of the junctions at the end domes for forward and reverse flow are set to, respectively, 0 and 0.5 at the inlet (top), and 0.5 and 0 at the outlet (bottom) junction according to [4], p. 236. Material masses are discussed in section 3.4.3.3.

3.3.3.4 Electrical heater (component 114)

This component is needed for baking the test module and for heating the whole cooling subsystem to operating temperatures after maintenance or repair periods. The heater will be positioned in a bypass to the HX (see Figure 8). It has an electrical power of 140 kW. The main dimensions of the helium volume in the heater are 0.1907 m diameter times 1.8 m height[11], approximately 19 % of which being occupied by the heating rods. This yields a helium volume of 0.0415 m^3. The estimated pressure loss is small, ≈500 Pa. The overall dimensions are assumed to be 0.34 m diameter (at flanges) times 2.2 m height, including the end dome foreseen for electrical terminals (see also sketch in section 3.4.3.4 on page 35). The flow through the heater can vary between zero and full flow depending on the position of the control valves 94 and 112.

The heater is modelled as a pipe component consisting of two volumes of 0.9 m length each. The volume flow area is set equal to 0.02306 m^2. This results from the inner shell cross sectional area minus the space taken by 35 hairpin heating rods of 0.001 m diameter. A hydraulic diameter of 0.03296 m has been evaluated by taking four times the flow area divided by the wetted perimeter. The wall roughness is 5×10^{-5} m. The energy loss coefficients of the junctions at the end domes for forward and reverse flow are set to, respectively, 0 and 0.5 at the inlet (junction 123 at the top), and 0.5 and 0 at the outlet (junction 125 at bottom). The initial mass flow rate is set to zero, assuming that valve 112 is closed, unless it will be tripped to open position. Material masses are discussed in section 3.4.3.4.

3.3.3.5 Pressuriser and surge line valve (components 7 and 76)

The pressuriser is supposed to be connected to the hot leg, upstream of the filter, via the surge line valve 76 as indicated in the nodalisation diagram in Figure 8. It is considered as a helium reservoir and has to compensate for the loop pressure if the set point "pressure low" is reached. As it discharges to the loop it will be recharged from some reservoir else. A volume of approximately 10 % of the loop volume is chosen, that is about 0.13 m^3, and a maximum operating pressure of 14 MPa.

For simplification of the system pressure control procedure by means of an assembly of regulators, tanks and compressors, the pressuriser has been modelled here in two ways. First, for normal operation in steady state conditions, it is considered as an infinitely large helium reservoir that is kept at 7.9 MPa and 500 °C. The surge line valve is then open. In this situation fluid can flow back and forth in the steady state RELAP run, until the system pressure balances at thermal equilibrium. Second, for transient analysis, in particular for loss of coolant accidents, the pressuriser is redefined with its real volume and its nominal pressure and temperature of 14 MPa and 50 °C. The surge line valve is then initially closed and trips to the open position at specified times.

So, for the first situation described above the pressuriser is modelled as a time-dependent volume with an arbitrary (but large enough) flow area of 1 m^2 and a length of 25 m. Although the valve is then closed, its junction area is set to the minimum area of adjoining volumes, i.e., to the area of the hot leg (0.003664 m^2). For the second situation, transient restart runs,

[11] The overall dimensions have been reduced somewhat in the recent layout [2].

the pressuriser is specified as single volume with inner diameter of 0.26 m, flow area of 0.05309 m^2 and length of 2.8 m[12]. The trip valve has been assigned a flow area of 0.0005067 m^2 (1 inch diameter) and an energy loss coefficient for forward and reverse flow of 7. Pressures and temperatures are set as discussed in the paragraph above. There is no heat structure defined for these components.

3.3.3.6 Flow control valves (components 94 and 112)

To keep the helium temperature at the TBM inlet at a specified constant value (e.g., 250 °C) during pulsed operation a temperature control system is envisaged for the HCS. The control system will be realised by partition of the helium flow to the HX and a bypass to the HX, while the helium circulator operates at nominal speed. If the TBM inlet temperature falls below the set point, a certain amount of the helium will be diverted from the HX to the bypass until the reference value is reached. During ITER burn times, practically all of the helium will flow through the HX.

RELAP provides the possibility of simulating control systems, and an example of temperature control at the HX outlet has been modelled in previous studies [5]. For the objectives of the present work to study a spectrum of highly transient accident scenarios it was sufficient to simplify the model. Thus, the two control valves 94 and 112 upstream of the HX and in the bypass (see Figure 8 and section 3.3.2.3 on page 18) were modelled as trip valves with either fully open or closed position. This of course does not allow to precisely adjust the inlet temperature at the TBM to the desired value, which instead was achieved by trimming the secondary water flow by trial and error. The following quantities were specified for the two trip valves.

Table 7: Flow control valve specification

	HX valve 94	Bypass valve 112
Flow area (m^2)	0.003664	0.003364
Energy loss coefficient	1.0	7.0
Trip number	510 (generally open)	511 (generally closed)

3.3.4 Additional components for transient analysis

As a postulated accident a break inside the TBM may occur. This would allow primary helium to enter the purge gas collection chamber and, thereby, to penetrate the pebble beds. The result would be pressurisation of the blanket box and of the tritium extraction subsystem (TES). To prevent overpressure in the blanket box, one or two burst disks are foreseen that vent into the VV at a specified box pressure. Pressurisation of the TES will be prevented by fast isolation valves and by an additional pressure regulator in the purge gas return line (TBM to TES) and by a check valve in the purge gas feed line (TES to TBM) as already indicated in Figure 6. Upon rupture of the burst disk(s) the helium coolant discharges into the VV.

The additional components needed to simulate such process are shown in Figure 10 on page 62. They include the purge gas chamber in the TBM (202) connected via the break opening (201) to the main outlet manifold (5). Leaving the purge gas chamber there are three branches, one leading to the VV (320), another one to the TES (208) and the third connection going to the pebble beds (205). Also shown are the components in the connecting lines simulating the flow resistors (throttle 203, junction 204, pipe 206 and burst disk 209). The following quantities have been specified for these additional components.

[12] Most recent projected dimensions of the pressuriser are 0.27 m ID and 2.4 m length [2].

Table 8: Specification of additional components for transient analysis

Component No. and type		Flow area (m^2)	Hydr. Dia (m)	Length (m)	Volume (m^3)	Rough-ness (m)	Energy loss coeff.	Trip No.
201	trip valve	0.00359					0/0	530
202	branch	0.04248		1.218		$2x10^{-5}$	0.5/0.5	
203	pipe	0.002356	0.01	0.6		$1x10^{-6}$		
204	single junction	0.002356					0.5/0.5	
205	single volume	0.1267	0.001		0.0998	$1x10^{-6}$		
206	pipe	0.0004909	0.025	100		$5x10^{-6}$		
207	trip valve	0.0002454					$7.0/10^6$	531
208	single volume	1.0	1.0		4.0	$1x10^{-5}$		
209	trip valve	0.00785					0/0	532
320	single volume	36	6.91		1350	0		

3.4 Heat structures of TBM, piping and components

Heat structures represent the selected, solid portion of the thermal-hydrodynamic system. Being solid, there is no flow, but the total system response depends on heat transferred between the structure and the fluid, and the temperature distributions in the structure are often important requirements of the simulation. System components simulated by heat structures include, e.g., fuel rods (or heater rods), pipe walls, pressure vessels, and heat exchanger tubing. The modelling capabilities of RELAP allow for only one-dimensional calculation of heat conduction in simple geometry like rectangular plates, cylindrical shells, or spherical shells. Hence, the complicated shape of the TBM was modelled by equivalent rectangular and cylindrical heat structures.

According to RELAP conventions each heat structure has two sides, denoted as left side and right side, at which boundary conditions have to be specified by the user. If only one of the two boundaries communicates energy with a hydrodynamic volume, usually the left side of the heat structure is associated with the fluid volume. In this case, a convective boundary condition with heat transfer coefficients obtained from RELAP5/MOD3.1 Heat Transfer Package 1 (HTP1) or with user-supplied heat transfer coefficients is used at the left side. At the right side either an insulated boundary condition, a temperature boundary condition, or a heat flux boundary condition is used. When both boundaries communicate energy with different hydrodynamic volumes, convective boundary conditions are used at both the left and the right side of the heat structure.

In this work heat structures are formulated for practically all components of the primary helium cooling system as shown in Figure 8, in particular for the sub-components of the TBM proper (Figure 9), which experience significant temperature changes during transient processes. No heat structures were defined for the pressuriser and for the components of the secondary cooling water loop, as well as for the additional components used in loss of coolant analyses. In the following subsections we explain the heat structures in the same order as used for the hydrodynamics part.

3.4.1 TBM heat structures

The heat structures established for the TBM sub-components correspond to the breakdown described in section 3.3.1 on page 11 for the hydrodynamic components.

3.4.1.1 Main inlet manifold heat structure (component 4)

The inlet manifold being hydraulically modelled as a branch is made up of the lower half of the TBM back plate structure, consisting of BP1, BP2, MC/top and MC/bot (see Figure 7). The outer dimensions are 1.218 m x 0.105 m x 0.37 m, and the steel and helium fractions are 60.4 and 39.6 %, respectively. The flow channel has a square cross section of 0.06 m x 0.06 m (compare section 3.3.1.1). This structure has been modelled as a cylindrical heat structure assigned to the only volume of component 4 with the following dimensions and properties:

- Heat structure length l = 1.218 m
- Inner equivalent diameter d = 0.0764 m
- Outer equivalent diameter D = 0.189 m
- 3 mesh points at r = 0.0382, 0.06635, and 0.0945 m
- Left/right boundary condition HTP1/adiabatic
- Material properties MANET (assumed to be the same as for EUROFER)

l is identical to the component length. *d* is derived from maintaining the same heated perimeter as the square channel ($d = 4 \cdot 0.06 / \pi$), and *D* is the equivalent outer diameter leading to the same structural material volume, i.e.,

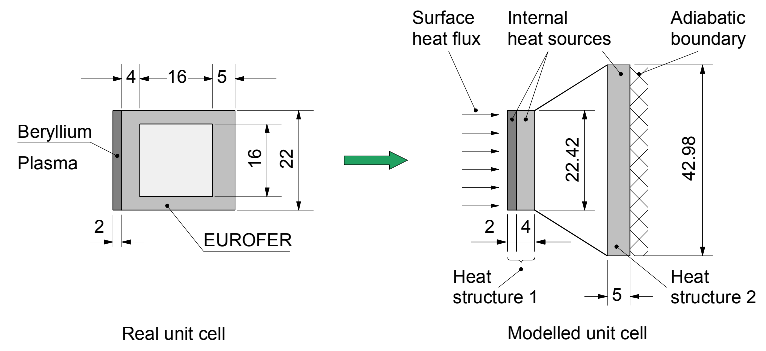
$$D = \sqrt{\left(\frac{4 \cdot 0.105 \cdot 0.37 \cdot 0.604}{\pi} + 0.0764^2 \right)}$$

The heat structure has three radial mesh points evenly distributed across the wall at radii, *r*, from the axis as shown above, that is at both surfaces and at wall centre.

3.4.1.2 First wall heat structures (components 20 through 23)

The structure of the blanket box, of which the plasma facing part constitutes the FW, was modelled by rectangular heat structures in such a way that the heat flux in radial direction in the FW area was simulated properly. The thickness of the heat structures in radial direction and the total volumes and masses equal the actual wall thickness and the actual volumes and masses (except for the small corrections as mentioned below). Actual and modelled cross section of a FW unit cell are shown in the sketch below. The model consists of two heat structures.

Heat structure 1 (HS1) models the part of the FW between the plasma and the coolant. It consists of a 2 mm beryllium layer and a 4 mm EUROFER layer. The poloidal height of the modelled unit cell is taken as the height of the actual unit cell, corrected for the discontinuities at the TBM edges, i.e., TBM height divided by the number of cooling channels (=0.74 m / 33). At one side of the heat structure a convective boundary condition is used where the heat transfer coefficient is obtained from RELAP5/MOD3.1 Heat Transfer Package 1. The sink temperature is the temperature of the helium in the hydrodynamic volume of the pipe component that is connected to HS1. At the other side of the heat structure the surface heat flux from the plasma is used as boundary condition. To account for the volumetric power generation, internal heat sources are applied to the heat structure as explained in section 3.6.1.2.2. Definition of the surface heat load is given in section 3.6.3.



Modelling of first wall with RELAP heat structures (dimensions in mm)

Heat structure 2 (HS2) shown in the display above models the remainder structure of the FW, that is the 5 mm thick rear plate plus the ribs between the cooling channels. It constitutes an enlarged 5 mm EUROFER layer with an equivalent poloidal width of w = 42.98 mm. Similar to heat structure 1, a convective boundary condition is used at the side in contact with the flowing helium (left boundary in RELAP terminology). At the other side an adiabatic boundary condition is used. This means, that heat exchange between the first wall and the breeding zone is ignored. An internal heat source is assigned to heat structure 2 to account for the volumetric power generation.

The total FW box comprising 33 coolant channels is divided into 4 components (No. 20 through 23), each one consisting of 5 hydrodynamic volumes as explained in section 3.3.1.2. The heat structures pertaining to each volume are depicted in the schematic diagram below. In order to assign the equivalent heat structure width to each volume of a given component, we have to multiply the HS poloidal width of the unit cell by the number of channels pertaining to that component. For example, component 20 has 15 channels and the equivalent poloidal width of all HS1 is thus 15 x 0.02242 m = 0.3363 m, and that of all HS2 is 15 x 0.04298 m = 0.6447 m. Furthermore, the RELAP code requires as input the HS-length, the heat transfer area, and the heat transfer hydraulic diameter (i.e., the heated equivalent diameter). These quantities and their definition are given for all components, volumes, and heat structures for the whole first wall box in Table A-8 of Appendix A. The volume of the heat structures is computed by the code from the heat transfer area times the heat structure thickness.

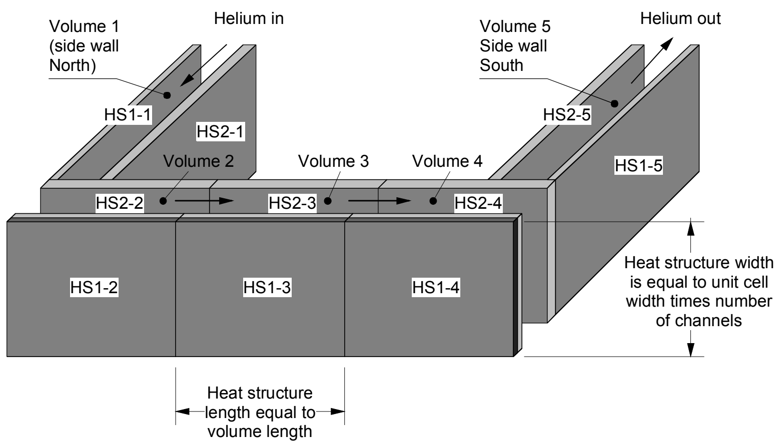
Additional input for heat structures needed by the RELAP code is the number and location of radial mesh points, measured from the middle of the hydrodynamic channels. The number of radial mesh points must be >1 and should be kept as small as acceptable in order to save computing time. In this application all structures HS1 facing the plasma (i.e., attached to volumes 2 through 4) are given 3 mesh points, all the other heat structures of the FW box have 2 mesh points only. The number and position of mesh points are summarised in Table 9.

Table 9: Number and position of mesh points in FW heat structures

Heat structure short name [13]	Number of mesh points	Radial position from centre of flow channel (m)		
		1^{st} MP	2^{nd} MP	3^{rd} MP
HS1-1, HS1-5	2	0.008	0.012	-
HS1-2, HS1-3, HS1-4	3	0.008	0.012	0.014
HS2-1, HS2-2, HS2-3, HS2-4, HS2-5	2	0.008	0.013	-

Please note that the HS1 at the side walls (volumes 1 and 5 of each FW component) is not plated with the 2 mm beryllium layer and has thus a thickness of 4 mm only.

[13] HS1 and HS2 denote heat structure 1 and 2, respectively, last digit denote the pertaining volume number.

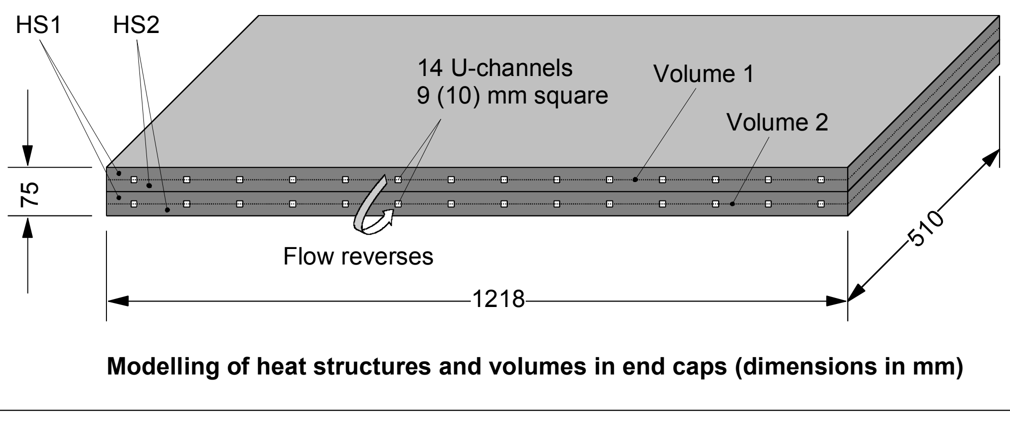


Schematic of Heat Structures (HS) and Volumes pertaining to First Wall component

3.4.1.3 End caps heat structures (components 24 and 25)

The end cap plate is modelled as two volumes, volume 1 is the upper half with flow from the back to the front, and volume 2 is the lower half with reverse flow direction. To each of the volumes two heat structures are assigned, HS1 and HS2 as indicated in the sketch below. All heat structures of the top cap are identical. Likewise the heat structures pertaining to the bottom cap are identical, but differ slightly from those in the top cap because of different channel size. Heat structures are modelled in rectangular geometry and their input data are compiled in Table A-9 of Appendix A. The equivalent HS thickness has been defined as one quarter of the cap's thickness times the steel volume fraction. The equivalent flow channel width has been defined as the total flow cross sectional area divided by the cap's toroidal length. The heat transfer hydraulic diameter (i.e., the heated equivalent diameter) for one HS has been defined as four times the total flow cross sectional area (which serves two HSs) divided by one half of the wetted perimeter. More definitions needed as input are given in the footing to Table A-9.

For all heat structures a convective boundary condition is used at the side in contact with the flowing helium (left boundary) and adiabatic boundary condition is specified at the right side. This means, that there is no heat flux across the surface of the caps (except the heat carried by the fluid) and no recuperative heat transport between volume 1 and volume 2 occurs.



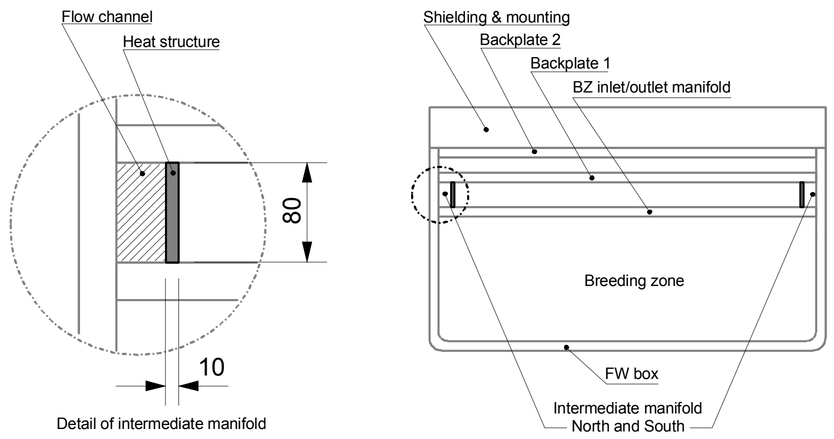
Modelling of heat structures and volumes in end caps (dimensions in mm)

3.4.1.4 Intermediate manifolds heat structures (components 30 and 31)

The hydraulic part of the intermediate manifolds has been described in section 3.3.1.4. The only heat structure that communicates energy with the hydrodynamic volume is assumed to be the wall with cross section 0.01 m x 0.08 m between the fluid and the purge gas collection chamber at both sides of the TBM (see sketch below). The remaining structures which surround the flow channels have been, or will be, considered in other components, like for instance as part of the FW or of the BZ inlet/outlet manifolds. This simplification is acceptable, since the amount of heat exchange between the fluid and the structure is small in this region.

Hence, the outer dimensions of the heat structure are 0.01 m x 0.08 m x 0.59 m with a steel fraction of 100 %. Heat structures attached to components 30 and 31 are identical. They are modelled in rectangular geometry with the following dimensions and properties:

- Heat structure length (TBM height minus end caps) 0.59 m
- Heat transfer area (0.08 m x 0.59 m) 0.0472 m^2
- Left boundary co-ordinate (half of flow channel width) 0.02 m
- Heat transfer hydraulic diameter[14] 0.16 m
- Number of mesh points 2 at r = 0.02, 0.03 m
- Left/right boundary condition HTP1/adiabatic
- Material properties EUROFER (data for MANET)



Intermediate manifolds heat structures (radial-toroidal cut through TBM)

3.4.1.5 Breeding zone inlet manifolds heat structures (components 40 through 43)

The breeding zone (BZ) is divided vertically into two halves (located at north side and south side of the TBM), each half being cooled from one intermediate manifold. Therefore the breeding zone inlet (and outlet) manifolds are split accordingly. All the inlet and outlet manifolds together are considered as a uniform plate 1.218 m wide by 0.59 m high, with an equivalent thickness of 0.03 m and a steel volume fraction of 0.6. This accounts for both the manifold structures and the internal piping associated with it (see sketch in section 3.3.1.5). There are two types of inlet manifolds, one group with channel inner diameter of 0.014 m serving the cooling plates (CP), and the other one with channel inner diameter of 0.012 m that serves the stiffening plates (SP). Their length is 0.5 x 1.218 m = 0.609 m.

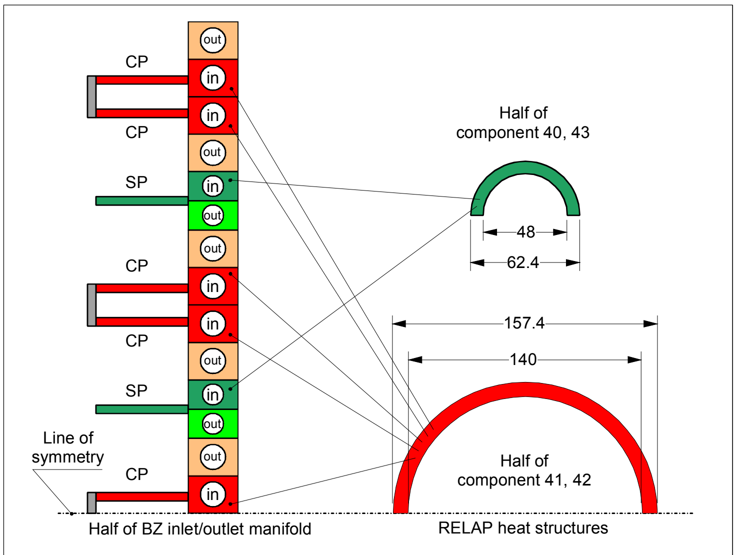
[14] equals 4 times flow area divided by heated perimeter = 4 x 0.04 x 0.08 / 0.08 = 0.16 m.

For the RELAP model, in each half of the BZ the inlet manifolds are divided into two groups, one supplying the 10 CPs and the other group supplying the four SPs. The remaining space between the inlet manifolds is used for the corresponding outlet manifolds as shown in the sketch below. Thus the four groups of inlet manifolds existing in both BZ halves are lumped together to form four RELAP components, i.e., No. 40 through 43. They are modelled in cylindrical geometry. Their flow area, wetted perimeter, heated perimeter and equivalent inner/outer diameter are shown in Table A-10 in Appendix A. The table shows also further input data needed in RELAP, like the left boundary co-ordinate, the number of mesh points chosen as 3, and the mesh interval radial width.

For all BZ inlet manifold heat structures a convective boundary condition is applied at the inside in contact with the flowing helium (left boundary) and adiabatic boundary condition is specified at the outside (right boundary).

Note: The inner equivalent diameter of the heat structures (line 7 in Table A-10) is determined by conserving the heated perimeter rather than the cross sectional area. It is different from the heat transfer hydraulic diameter (i.e., heated equivalent diameter) given in line 18 of the table. The inner equivalent diameter is only used to determine the outer equivalent diameter, which then results from structural mass conservation, and for the left boundary co-ordinate.

Note: The poloidal height of a single manifold (line 8 in Table A-10) has been chosen such that the CP manifolds are 30 % larger than the SP manifolds, and that the sum of all inlet manifolds gives half the poloidal height of the manifold plate (0.5 x 0.59 m = 0.295 m), the other half being reserved for the outlet manifolds.



Modelling of breeding zone inlet heat structures (radial - poloidal cut)

3.4.1.6 Breeding zone heat structures (components 50 through 53)

The breeding zone (BZ) consists of five breeder layers encapsulated by pairs of cooling plates and surrounded by beryllium layers as was explained in section 3.3.1.6 on page 15. The beryllium layers are cooled by both, stiffening plates and cooling plates. For the RELAP heat structure model a definition of the unit cells in poloidal direction is chosen in the same way as was done for the hydrodynamic modelling, i.e., such, that the temperature gradient in poloidal direction is supposed to be approximately zero. This enables to apply adiabatic boundary conditions at one side of the heat structures. So we define two types of unit cells, one representing breeder plus cooling plate plus part of the beryllium (denoted as breeder unit cell), and another one representing the rest of beryllium plus stiffening plate (beryllium unit cell, compare sketch in section 3.3.1.6 and sketch below).

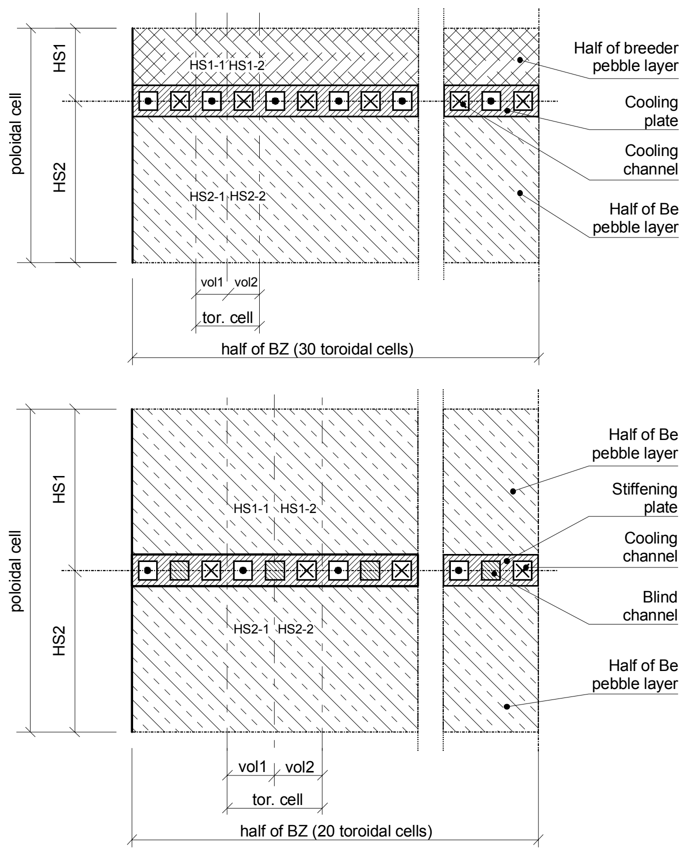
The poloidal unit cells are then transformed to two rectangular heat structures, HS1 and HS2 as indicated in the sketch. For instance in the breeder component 51 (in north half of BZ), HS1 comprises one quarter of a breeder pebble layer (because half of the BZ toroidal width and half of a layer poloidal thickness) plus one quarter of a cooling plate, multiplied by 10 because there are 10 such poloidal unit cells in the BZ. HS2 on the other hand comprises one quarter of a beryllium pebble layer plus one quarter of a cooling plate, multiplied by 10. The same applies to breeder component 52 (in south half of BZ). Similarly, in the beryllium components 50 (north) and 53 (south) each, HS1 comprises one quarter of a beryllium pebble bed plus one quarter of a stiffening plate, multiplied by 4 since there are four such poloidal unit cells in the BZ. HS2 here is identical to HS1 because of symmetry of the beryllium components.

The hydraulic components were divided into two volumes, vol. 1 for the channel sections with forward flow from back to front, and vol. 2 for the channel sections with reverse flow direction. Consequently, the heat structures have also been split into two parts along the flow path, each part being attached to one hydrodynamic volume. We indicate this by writing HS1-1, HS1-2, HS2-1, HS2-2 and read respectively: part of heat structure 1 pertaining to volume 1, part of heat structure 1 pertaining to volume 2, etc. Since the cooling channels in cooling plates are not identical to the ones in stiffening plates as shown in the sketch below, the division of volumes is little different for heat structures in breeder components compared to those in beryllium components. This has some influence on the heat transfer area and on the heat transfer hydraulic diameter as is shown in Table A-11 in Appendix A.

The thickness of material layers in heat structures HS1 and HS2 is derived from the poloidal unit cells with minor corrections, aiming at conserving the mass composition (and hence the generated power) in the BZ as follows: (details are listed in Table A-11 in Appendix A)

- Beryllium layer thickness of HS2 in breeder components has been slightly enlarged to account for the two bounding layers at top and bottom of the BZ, which are thicker than one half of the regular Be layers (see Figure 4).
- Steel thickness of cooling plates and stiffening plates has been replaced in HS1 and HS2 by an equivalent thickness to account for cooling channels and blind channels.

Finally the radial mesh points and boundary conditions have to be defined. For all heat structures of BZ components four radial mesh points have been chosen, one at each boundary of the heat structures, one at the steel/breeder or steel/beryllium interface, and one in the middle of the breeder or beryllium half-layers. A convective boundary condition is applied at the side in contact with the flowing helium (left boundary) and adiabatic boundary condition is specified at the outside (right boundary), where temperature gradients are negligible as already mentioned.



Breeder (top) and Beryllium (bottom) heat structure model (toroidal - poloidal cut)

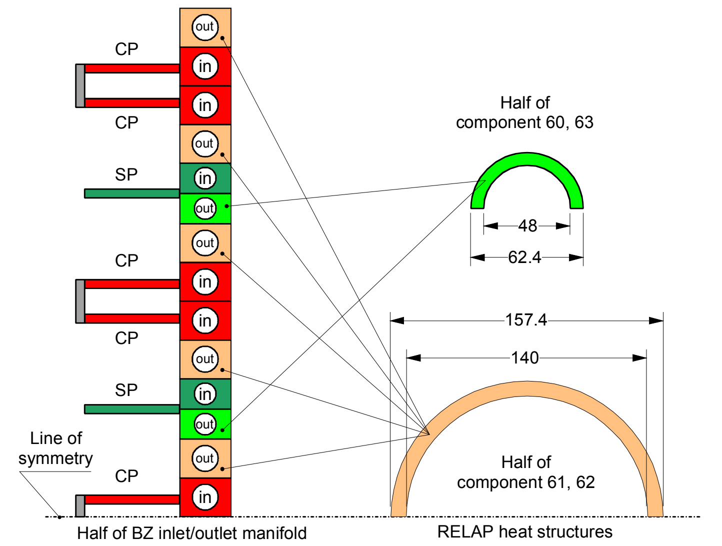
The design of heat structures in the breeding zone leads to a potential RELAP output of 64 temperature values per time step, namely for 4 components times 2 HSs per component times 2 volumes per HS times 4 mesh points across the HS thickness. The position of mesh points in flow direction can be regarded to lie at the end of the hydrodynamic volume.

<u>**Note:**</u> It is evident that this rough model of the breeding zone can only account for a gross power balance in the TBM and give an idea of heat transfer coefficients and of poloidal temperature profiles in BZ layers at distinct point and for radially averaged power densities. It certainly cannot reflect recuperative heat exchange between the two legs of the U-shaped cooling channels nor the actual radial power and temperature profile in the breeding zone.

3.4.1.7 Breeding zone outlet manifolds heat structures (components 60 through 63)

The breeding zone (BZ) outlet manifolds are identical in their dimensions to the BZ inlet manifolds (section 3.4.1.5). For the RELAP model, in each half of the BZ the outlet manifolds are divided into two groups, one collecting the coolant from the 10 CPs and the other group collecting the coolant from the four SPs. The remaining space between the outlet manifolds is used for the corresponding inlet manifolds as shown in the sketch below. Thus the four groups of inlet manifolds existing in both BZ halves are lumped together to form four RELAP components, i.e., No. 60 through 63. They are modelled in cylindrical geometry. Their flow area, cylinder height, wetted perimeter, heated perimeter and equivalent inner/outer diameter are shown in Table A-12 in Appendix A. The table shows also further input data needed in RELAP, like the left boundary co-ordinate, the number of mesh points chosen as 3, and the mesh interval radial width. Please refer to the notes added in section 3.4.1.5 on page 27.

For all BZ manifold outlet heat structures a convective boundary condition is applied at the inside in contact with the flowing helium (left boundary) and adiabatic boundary condition is specified at the outside (right boundary).



Modelling of breeding zone outlet heat structures (radial - poloidal cut)

3.4.1.8 Main outlet manifold heat structure (component 5)

The outlet manifold, being hydraulically modelled as a branch in the same way as the main inlet manifold (section 3.4.1.1), is made up of the upper half of the TBM back plate structure, consisting of BP1, BP2, MC/top and MC/bot (see Figure 7). The outer dimensions are 1.218 m x 0.105 m x 0.37 m, and the steel and helium fractions are 60.4 and 39.6 %, respectively. The flow channel has a square cross section of 0.06 m x 0.06 m (compare section 3.3.1.8). This structure has been modelled as a cylindrical heat structure assigned to the only volume of component 5 with the following dimensions and properties:

- Heat structure length — *l* = 1.218 m
- Inner equivalent diameter — *d* = 0.0764 m
- Outer equivalent diameter — *D* = 0.189 m
- 3 mesh points at — *r* = 0.0382, 0.06635, and 0.0945 m
- Left/right boundary condition — HTP1/adiabatic
- Material properties — MANET (assumed to be the same as for EUROFER)

l is identical to the component length. *d* is derived from maintaining the same heated perimeter as the square channel ($d = 4 \cdot 0.06 / \pi$), and *D* is the equivalent outer diameter leading to the same structural material volume, i.e.,

$$D = \sqrt{\left(\frac{4 \cdot 0.105 \cdot 0.37 \cdot 0.604}{\pi} + 0.0764^2 \right)}$$

The heat structure has three radial mesh points evenly distributed across the wall at radii, *r*, from the axis as shown above, that is at both surfaces and at wall centre.

3.4.2 Piping heat structures

The architecture of the pipework has been presented in the hydrodynamic model, section 3.3.2. All pipe sections (hydrodynamic volumes) are modelled as cylindrical heat structures with two radial mesh points located at the inner and outer tube wall. A convective boundary condition is applied at the inside in contact with the flowing coolant (left boundary) and adiabatic boundary condition is specified at the outside (right boundary). This implies that an effective thermal insulation is provided at the whole piping system. Material properties of stainless steel are used throughout. No internal heat source is applied. Hence, distinction of heat structures assigned to the cold leg, hot leg and piping between HCS components refers only to their dimensions as indicated in the following subsections.

3.4.2.1 Cold leg heat structures (component 3)

The component consists of 25 heat structures corresponding to the hydrodynamic volumes specified in section 3.3.2.1. There is a change in pipe diameter between heat structure 21 and 22. Pipe cross sectional dimensions are presented in Table 5 on page 17 and heat structure lengths (equal to volume lengths) are listed in Table A-4 in Appendix A.

3.4.2.2 Hot leg heat structures (component 6)

The component consists of 25 heat structures corresponding to the hydrodynamic volumes specified in section 3.3.2.2. There is a change in pipe diameter between heat structure 4 and 5. Pipe cross sectional dimensions are presented in Table 6 on page 17 and heat structure lengths (equal to volume lengths) are listed in Table A-5 in Appendix A.

3.4.2.3 Piping between HCS components heat structures

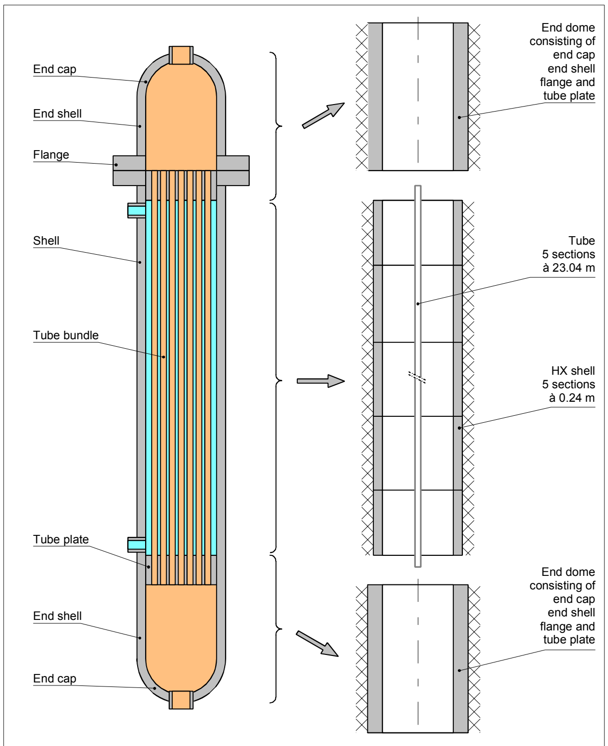
The pipe routing between components is shown in the isometric view in section 3.3.2.3 on page 18. It involves mainly pipes with bends (pipes 16, 18, 91, 93, 95, 97, 113) consisting of two volumes each, two straight pipes (volumes 111 and 115) and two branch components (branches 17 and 92). Cross sectional dimensions are all equal to the main part of the cold and hot leg (ID/OD=0.0683/0.0825). Heat structure lengths (equal to volume lengths) are listed in the right hand part of Table A-6 in Appendix A.

3.4.3 HCS components heat structures

Components of the helium cooling system include heat exchanger, circulator, dust filter, electrical heater, pressuriser and several valves as illustrated in the isometric view in section 3.3.2.3 on page 18. Heat structures have been defined for the heat exchanger, circulator, dust filter and electrical heater only. They are modelled in cylindrical geometry with two radial mesh points located at the inner and outer surface of the equivalent cylinder. A convective boundary condition is generally applied at the inside in contact with the fluid (left boundary) and adiabatic boundary condition is specified at the outside (right boundary). This implies that an effective thermal insulation is provided at the surface. No internal heat sources are specified, except in the heater rod bundle. Specifics are described in the following subsections.

3.4.3.1 Heat exchanger heat structures (components 10 and 102)

The helium/water heat exchanger (HX) was modelled as a counter-flow HX employing straight tubes. The primary coolant (helium) flows downward inside the tubes and the secondary coolant (water) flows upward outside the tubes. Primary and secondary sides are thermally communicating via the tube bundle, which is represented by two-sided RELAP5 heat structures. The primary side of the HX, hydraulically modelled by pipe component 10 (section 3.3.3.1) consists of the two end domes and the tube bundle. The secondary side, hydraulically modelled by pipe component 102, is enclosed by the tube bundle and the HX shell. As structural material INCOLOY 800 is assumed for the tubes and stainless steel 316 L for the remainder of the HX. Below is an exploded view of the heat structure modelling, the characteristic data are given in Table A-13 in Appendix A. The rationale is described in the following paragraphs.



Heat exchanger heat structures modelling

The solid structure of the end domes are assumed to consist of the 0.35 m long end shells, of the tube plates, flanges, and end caps, making up a steel volume of 0.027 m^3. These parts are lumped together to give two equal cylindrical heat structures with the actual material mass and a representative inside diameter, leading to inside/outside diameters of 0.276/0.3325 m at a lengths of 0.5 m. They are attached to volumes 1 and 7 of pipe component 10.

The structure of the 96 HX tubes is lumped together to a series of 5 cylindrical heat structures. Their left side is connected to component 10 and the right side to component 102. At both sides convective boundary conditions are used, where the heat transfer coefficient is obtained from RELAP5/MOD3.1 Heat Transfer Package 1. The heated equivalent diameter relevant for computing the heat transfer coefficient, is set to the real tube dimensions, i.e., to 0.014 m at the left boundary and 0.018 m at the right boundary. The length of each heat structure is 23.04 m (96 x 1.2 m / 5).

On the secondary side the only heat structure considered is the 1.2 m long HX shell, which is modelled by a series 5 cylindrical heat structures attached to volumes 1 to 5 of component 102 with lengths of 0.24 m. As inside/outside diameters the actual shell dimensions of 0.276 m/0.3 m are used. The heat transfer hydraulic diameter is obtained from evaluating 4x(flow area)/(heated perimeter), where as heated perimeter the inner perimeter of the HX shell is taken.

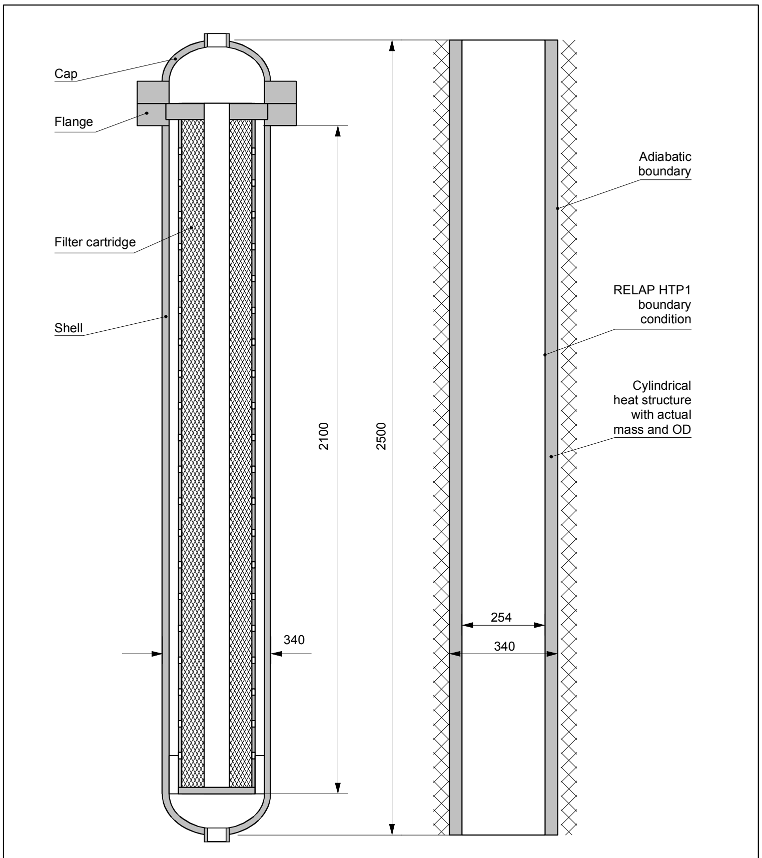
3.4.3.2 Circulator heat structure (component 2)

The housing and internals of the circulator that communicate heat with the fluid is modelled as cylindrical heat structure of 0.25 m length with inside/outside diameters of 0.45/0.59 m. This results in a material volume of 0.0286 m^3 and a mass of 228 kg. A convective boundary condition has been specified at the left side and an adiabatic condition at the right side. The heat transfer hydraulic diameter is set by the code equal to the hydraulic diameter of the hydrodynamic volume, i.e., 0.0683 m. Two radial mesh points are chosen for this heat structure. As structural material austenitic stainless steel 316 L is used.

3.4.3.3 Dust filter heat structure (component 8)

The filter design is not yet established. It is open whether there will be a column of packed filter material, like it was assumed in the hydrodynamic model in section 3.3.3.3, or a cylindrical filter cartridge with essentially radial flow through the filter bed (see sketch below). Hence, the heat transfer conditions between the fluid and the different parts of the filter structure are unclear. Therefore the approach taken here is simply to simulate the total filter mass by a single cylindrical heat structure of the same overall length and outer diameter as indicated in the sketch. This implies that in the calculation the same heat transfer coefficient will be used at all fluid/structure interfaces.

From a first filter layout proposed in [2] a total mass of the filter unit of 800 kg has been estimated, 65 % of which being in the outer shell and 35 % in the filter cartridge. This mass is lumped together to a cylinder of inner/outer diameter of 0.254/0.34 m and 2.5 m length. The heat structure with two radial mesh points is attached to the only hydrodynamic volume representing the filter, component 8. A convective heat transfer condition is specified at the inside (left boundary) and adiabatic condition at the outside (right boundary). The heat transfer hydraulic diameter is set by the code equal to the hydraulic diameter of the hydrodynamic volume, i.e., 0.002 m as assumed in section 3.3.3.3. The material is austenitic stainless steel 316 L.



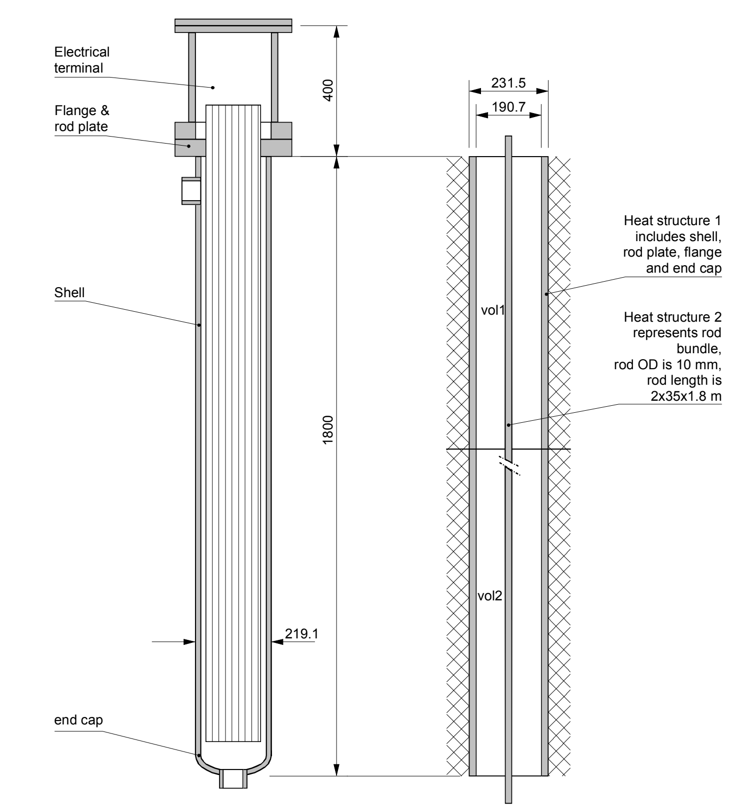
Dust filter heat structure modelling (dimensions in mm)

3.4.3.4 Electrical heater heat structure (component 114)

The structure of the electrical heater that communicates heat with the fluid is essentially the part from the flange downward, whereas the dome for the electrical terminals is supposed to be thermally isolated from that section. Thus, we define two heat structures to represent the heater, HS1 for the outer confinement and HS2 for the hairpin type heater rods.

HS1 is modelled in cylindrical geometry consisting of the shell, tube plate, flange and bottom cap with a total mass of 194 kg. Choosing the actual length (1.8 m) and inner diameter (0.1907 m) of the shell as representative dimensions, the outer diameter of HS1 results as 0.2315 m (see sketch below). HS1 is divided into two equal sections of 0.9 m length, each one being attached to one of the hydrodynamic volumes defined in section 3.3.3.4. At the inner surface (left boundary) convective heat transfer is computed from RELAP Heat Transfer Package 1, with the heat transfer hydraulic diameter set equal to the hydraulic diameter. It is calculated from 4 x (flow area)/(wetted perimeter) and is 0.03296 m. At the outside (right boundary) adiabatic conditions are specified. Two radial mesh points are chosen for HS1. The material is 316L.

HS2 is modelled in cylindrical geometry too, consisting of the 35 heater rods with 0.01 m diameter and 3.6 m length. The actual rod diameter has been retained as characteristic dimension, hence the total heat structure length is obtained from 35 x 3.6 m = 126 m. HS2 is divided into two equal sections of 63 m length, each one being attached to one of the hydrodynamic volumes of component 114. At the rod surface (right boundary) convective heat transfer is computed from HTP1 as above. At the centre of the rod (left boundary) adiabatic conditions are specified. Two radial mesh points are chosen for HS2. The material is also assumed to be 316L, ignoring that there will be different materials inside the cladding. A heat source can be defined for the rod bundle as a whole as described in section 3.6.4.



Electrical heater heat structures modelling

3.5 Heat structure thermal property data

The material data are entered with cards of the type 201mmmnn, where the sub-field mmm is the composition identification (ID) number. Besides this, the code needs the thermal conductivity and the volumetric heat capacity, which is $\rho \cdot C_p$, where ρ is the density and C_p is specific heat capacity. These quantities need to be entered as function of temperature, either in form of tables or as equations. Both types have been used here. Tables A-14 and A-15 in Appendix A show the data used in this analysis for the six material compositions involved. They are identified in Table 10 below together with the references, from where the conductivity and heat capacity data were adopted. All data have been taken as used in [5]. The end-point temperatures must bracket the expected temperatures during the transient, otherwise the calculation will be terminated. This is the reason for defining property values to temperature levels far beyond melting points, which then have no physical meaning. Data are plotted in Figure 11.

Table 10: Heat structure materials overview

Material name	Application	ID-Number	Reference
AISI 316L	piping and components	50	[6]
INCOLOY 800	HX tubes	100	[7]
MANET (EUROFER)	TBM structure	150	[8]
Be pebbles	Layers in breeding zone	200	[5]
Be dense	FW protection layer	210	[5]
Li_4SiO_4	Layers in breeding zone	250	[5]

3.6 Heat sources

There are four types of heat sources to be specified in this model as explained in section 2.4 on page 7. These are listed below and will be described in the subsections that follow.

- Neutron power generated in TBM components (heat structures) during normal operation
- Power ramp-down and decay power generation in TBM components after shutdown
- Surface heat load to plasma facing first wall heat structures
- Electrical power supplied to the electrical heater.

3.6.1 Neutron power in TBM components

The basis for assigning power sources to individual components and heat structures of the TBM is the breakdown of power generation in the PI-TBM from nuclear analysis presented in [2] and reproduced in Table A-1 in Appendix A. Hence, the total power of 0.696 MW (or 0.68376 MW when scaled down to 2 mm beryllium layer, see section 3.6.1.2.2) generated in the TBM during normal operation has to be partitioned to the heat structures defined in the present RELAP model. Unfortunately, RELAP heat structures and elements of the neutronics model are not congruent. Generally more than one RELAP heat structure belong to a given element. On the other hand, in some cases more than one element are combined to one or more RELAP heat structures. Hence, the procedure of power source division has to be explained for each heat structure. In any case the resulting power in a heat structure, P_{HS}, will be computed as

$$P_{HS} = m_{HS} \cdot P_{NE}$$

where m_{HS} is an internal source multiplier entered on heat structure cards ending with digits 701 for each heat structure, and P_{NE} is the power value entered in a general table data format for each element (or a group of elements) containing that heat structure.

3.6.1.1 Main inlet manifold power source

The main inlet and outlet manifolds together are structurally and in terms of heat sources assumed to be represented by the following elements of the neutronics model (sections 3.3.1.1, 3.4.1.1 and Figure 7). Power values are taken from Table A-1 in Appendix A.

- Back plate 1 (BP1) with a power of 4860 W
- Back plate 2 (BP2) with a power of 3220 W
- Main manifolds (MM) with a power of 413 W
- Shielding and mounting equipment (SM) with a power of 1310 W
- Manifold cover (MC/bottom) with a power of 193 W
- Manifold cover (MC/top) with a power of 151 W

Altogether, this gives a power of 10147 W. This value is used in the general table No. 4 as the power produced in the main inlet plus outlet manifold. Since the inlet manifold is considered as the bottom half of this group of elements, the source multiplier for the main inlet manifold is 0.50207, which results from [0.5 x (4860+3220+413+1310) + 193] / 10147.

3.6.1.2 First wall heat sources

In the RELAP model we distinguish between the side walls (without beryllium plating) and the front wall of the first wall.

3.6.1.2.1 Side walls heat sources

The total power generated in the side walls, which is entered in the general table data No. 201, amounts to 15400 W (Table A-1). This has to be split into two side walls per TBM, four hydrodynamic volumes per side wall (in proportion of their poloidal height) and two heat structures per volume (in proportion of their material fractions). So the source multipliers result from the product of 0.5 x (proportion of height) x (proportion of material), see Table 11 below.

Table 11: Source multiplier for heat structures in side walls of first wall

Component No.	Volume No.	Heat Structure	No. of Channels	Proportion of height	Proportion of material	Source multiplier
20	1 & 5	HS1	15	0.4545	0.2945	0.06692
20	1 & 5	HS2	15	0.4545	0.7055	0.16035
21	1 & 5	HS1	2	0.0606	0.2945	0.00892
21	1 & 5	HS2	2	0.0606	0.7055	0.02138
22	1 & 5	HS1	2	0.0606	0.2945	0.00892
22	1 & 5	HS2	2	0.0606	0.7055	0.02138
23	1 & 5	HS1	14	0.4242	0.2945	0.06246
23	1 & 5	HS2	14	0.4242	0.7055	0.14966

Here the proportion of height has been evaluated from number of channels in component divided by total number of channels in TBM.

The proportion of material in HS1 and HS2 is obtained (see sketch in section 3.4.1.2)

for HS1 from 4 x 22.42 / (4 x 22.42 + 5 x 42.98)

and for HS2 from 5 x 42.98 / (4 x 22.42 + 5 x 42.98).

3.6.1.2.2 Front wall heat sources

The total power generated in the steel of the front wall amounts to 69800 W (Table A-1). This can be split in proportion of the steel contained in both sets of heat structures in the front wall, HS1 and HS2, in the same way as was done for the side walls above, i.e., 0.2945 x 69800 W = 20556 W for all HS1 heat structures and 0.7055 x 69800 W = 49244 W for all HS2 heat structures.

Further, there is a power produced in the 2 mm beryllium layer amounting to 8160 W[15]. This is also part of HS1 as shown in the sketch of section 3.4.1.2 and has to be added to the power produced in the steel of HS1. So we get the power for the set of all HS1 of 20556 W + 8160 W = 28714 W and for the set of all HS2 of 49246 W, i.e., a total power to the front wall of 77960 W to be entered in the general table No. 202.

The total heat source in the front wall has then to be split into: two sets of heat structures HS1 and HS2 (in proportion of their power), four components (in proportion of their poloidal height) and three hydrodynamic volumes per component (in proportion of their toroidal lengths). So the source multipliers for the 24 front wall heat structures result from the product of these three proportions as evaluated in Table 12 below.

[15] This is 40 % of 20400 W given in Table A-1 for a 5 mm thick beryllium layer.

Table 12: Source multiplier for heat structures in the front wall of first wall

Compo-nent	Volume No.	Heat structure	No. Of channels	Proportion of HS power	Proportion of height	Proportion of length	Source multiplier
20	2	HS1	15	0.3683	0.4545	0.3336	0.0558
20	2	HS2	15	0.6317	0.4545	0.3336	0.0958
20	3	HS1	15	0.3683	0.4545	0.3328	0.0557
20	3	HS2	15	0.6317	0.4545	0.3328	0.0956
20	4	HS1	15	0.3683	0.4545	0.3336	0.0558
20	4	HS2	15	0.6317	0.4545	0.3336	0.0958
21	2	HS1	2	0.3683	0.0606	0.3336	0.0074
21	2	HS2	2	0.6317	0.0606	0.3336	0.0128
21	3	HS1	2	0.3683	0.0606	0.3328	0.0074
21	3	HS2	2	0.6317	0.0606	0.3328	0.0127
21	4	HS1	2	0.3683	0.0606	0.3336	0.0074
21	4	HS2	2	0.6317	0.0606	0.3336	0.0128
22	2	HS1	2	0.3683	0.0606	0.3336	0.0074
22	2	HS2	2	0.6317	0.0606	0.3336	0.0128
22	3	HS1	2	0.3683	0.0606	0.3328	0.0074
22	3	HS2	2	0.6317	0.0606	0.3328	0.0127
22	4	HS1	2	0.3683	0.0606	0.3336	0.0074
22	4	HS2	2	0.6317	0.0606	0.3336	0.0128
23	2	HS1	14	0.3683	0.4242	0.3336	0.0521
23	2	HS2	14	0.6317	0.4242	0.3336	0.0894
23	3	HS1	14	0.3683	0.4242	0.3328	0.0520
23	3	HS2	14	0.6317	0.4242	0.3328	0.0892
23	4	HS1	14	0.3683	0.4242	0.3336	0.0521
23	4	HS2	14	0.6317	0.4242	0.3336	0.0894

The proportion of heat structure power follows with numbers discussed above for HS1 from 28714/77960 and for HS2 from 49246/77960. The proportion of height has been evaluated from number of channels in component divided by total number of channels in TBM. The proportion of length results from volume lengths of 0.423, 0.422, 0.423 m for volumes 2, 3, 4 respectively, divided by the front wall length of 1.268 m.

There is one more factor to be discussed with HS1, the heat structure source distribution data (radial), since HS1 is composed of two materials with different heat density. This can be accounted for by applying a relative value to each radial mesh on heat structure input cards ending 301 through 399. By entering different values for the various mesh intervals, a characteristic shape of power curve can be described. The relative values can be scaled by any factor without changing the result. In our case we have two meshes in HS1, mesh 1 for the steel and mesh 2 for the beryllium. The power in mesh 1 relates to the power in mesh 2 as 20556/8160 (see numbers above) or 1/0.397. Thus we apply a factor of 1 to mesh 1 and 0.397 to mesh 2 on cards 301 for all HS1 of the front wall.

3.6.1.3 End caps power sources

The heat source in the end caps has been evaluated as 50400 W for the top cap (component 24) and 65400 W for the bottom cap (component 25), see Table A-1. These values are entered into general tables No. 24 and No. 25, respectively and have to be split within each end cap according to the heat structure definition given in section 3.4.1.3 into: two hydrodynamic volumes per component (in proportion of their lengths) and two heat structures per volume (in proportion of their material fractions). The source multipliers for the 4 heat structures per end cap result from the product of these two proportions as shown in Table 13 below.

Table 13: Source multiplier for heat structures in end caps

Component	Volume No.	Heat structure	Proportion of material	Proportion of length	Source multiplier
24 & 25	1	HS1	0.5	0.5	0.25
		HS2	0.5	0.5	0.25
	2	HS1	0.5	0.5	0.25
		HS2	0.5	0.5	0.25

3.6.1.4 Intermediate manifolds power sources

The intermediate manifolds, components 30 and 31, are considered as hydrodynamic branches, each one consisting of a single volume (section 3.3.1.4). One heat structure with a material volume 472 cm^3 is attached to each branch (section 3.4.1.4). The power generated in these heat structures is not explicitly given in Table A-1 and is therefore estimated to be about 150 W per component (as part of the 1630 W produced in the purge gas chamber, GC). This value is entered into the general table No. 30. Since there is only one heat structure per component, the source multiplier is 1.

3.6.1.5 Breeding zone inlet manifolds power sources

The total power assigned to breeding zone inlet/outlet manifolds is the power generated in the elements BM (breeding zone inlet/outlet manifold) plus GC (purge gas chamber) minus the fraction of GC already consumed in the intermediate manifolds in section 3.6.1.4. This leads with the values from Table A-10 to the total power to breeding zone inlet/outlet manifolds of 4910 W +1630 W - 300 W = 6240 W. This value is entered into the general table No. 40 and has to be distributed according to the heat structure design described in section 3.4.1.5 to: two equal sets of breeding zone manifolds (inlet and outlet), and four components per set (e.g. inlet manifolds components 40 through 43, in proportion of their steel fraction relative to the total steel in inlet manifolds). The source multipliers for the 4 heat structures of the breeding zone inlet manifolds result from the product of these two proportions as shown in Table 14 below and must sum up to 0.5, the other half being reserved for the outlet manifolds.

Table 14: Source multiplier for heat structures of breeding zone inlet manifolds

Component No.	Volume No.	Heat structure	Factor for sharing between inlet and outlet	Proportion of steel in components	Source multiplier
40 to SPs	1	HS1	0.5	0.1180	0.0590
41 to CPs	1	HS1	0.5	0.3820	0.1910
42 to CPs	1	HS1	0.5	0.3820	0.1910
43 to SPs	1	HS1	0.5	0.1180	0.0590

The proportion of steel in the components relative to the total steel in the inlet manifolds (5th column) has been derived from the cross sectional areas of inlet plates evaluated in Table A-10, line 12, in Appendix A.

3.6.1.6 Breeding zone power sources

The total power in the breeding zone (BZ) has been evaluated to 457900 W (Table A-1). This is composed of 205000 W (44.77 %) being generated in the breeder, 210000 W (45.86 %) in the beryllium pebbles, and 42900 W (9.37 %) in the steel (cooling and stiffening plates). These values are mean values, averaged over the whole BZ. They are used for distributing the power to: four BZ components (50 through 53), two hydrodynamic volumes per component and two heat structures per volume, irrespective of any power profile actually existing in radial direction, and to some extent also in poloidal direction. Using the total power as input to the general table No. 50, the source multipliers for each of the 16 heat structures defined in section 3.4.1.6 have been evaluated according to their compositional volume fractions and mean power densities. For example, the source multiplier, $m_{HS1-1-50}$, for heat structure 1 attached to volume 1 of component 50 (HS1-1-50) is the fraction of the power produced in that heat structure, $P_{HS1-1-50}$, divided by the total power in the BZ. The numerator of that fraction is evaluated from

$$P_{HS1-1-50} = p_{St} \cdot V_{St,HS1-1-50} + p_{Be} \cdot V_{Be,HS1-1-50} + p_{Br} \cdot V_{Br,HS1-1-50}$$

where p with indices are average power densities in steel, beryllium, and breeder, respectively, and V with indices are the absolute volumes of steel, beryllium, and breeder contained in HS1-1-50. The definition of heat structures depicted in the drawing in section 3.4.1.6 on page 28 shows that one of the three terms in the above equation is always zero, because there is only either steel and beryllium or steel and breeder in a heat structure. The computation of the equation and of the source multiplier for all of the 16 heat structures has been performed in a separate table. The results are given Table 15.

Table 15: Source multiplier and distribution factor for heat structures of BZ

Component No.	Volume No.	Heat structure	Source multiplier	Source distribution factors meshes 1 / 2 / 3
50 (North half of Beryllium cells)	1	HS1	0.0271	1 / 3.5447 / 3.5447
		HS2	0.0271	1 / 3.5447 / 3.5447
	2	HS1	0.0271	1 / 3.5447 / 3.5447
		HS2	0.0271	1 / 3.5447 / 3.5447
51 (North half of breeder cells)	1	HS1	0.1203	1 / 6.69 / 6.69
		HS2	0.0756	1 / 4.0174 / 4.0174
	2	HS1	0.1203	1 / 6.69 / 6.69
		HS2	0.0756	1 / 4.0174 / 4.0174
52 (South half of breeder cells)	1	HS1	0.1203	1 / 6.69 / 6.69
		HS2	0.0756	1 / 4.0174 / 4.0174
	2	HS1	0.1203	1 / 6.69 / 6.69
		HS2	0.0756	1 / 4.0174 / 4.0174
53 (South half of Beryllium cells)	1	HS1	0.0271	1 / 3.5447 / 3.5447
		HS2	0.0271	1 / 3.5447 / 3.5447
	2	HS1	0.0271	1 / 3.5447 / 3.5447
		HS2	0.0271	1 / 3.5447 / 3.5447

Four radial mesh points have been chosen for all heat structures of BZ components, one at each boundary of the heat structures, one at the steel/breeder or steel/beryllium interface, and one in the middle of the breeder or beryllium half-layers. To account for the different power densities in dissimilar materials of a heat structure, a relative value for each radial mesh is applied as already explained in section 3.6.1.2.2 on page 38. Here we have three meshes, one for the steel layer and two for the beryllium or breeder pebble layer, respectively. Thus we apply source distribution factors of 1 to the steel mesh, 0.5x(power in beryllium)/(power in steel) to each of the two beryllium meshes and 0.5x(power in breeder)/(power in steel) to each of the two breeder meshes. These factors are also given in Table 15 for the three meshes of each heat structure and are entered on cards 301 in the input deck.

3.6.1.7 Breeding zone outlet manifolds power sources

As discussed in section 3.6.1.5 the total power assigned to breeding zone inlet/outlet manifolds amounts to 6240 W, which is entered into the general table No. 40 and has to be distributed according to the heat structure design described in section 3.4.1.7 to: two equal sets of breeding zone manifolds (inlet and outlet), and four components per set (e.g. outlet manifolds components 60 through 63, in proportion of their steel fraction relative to the total steel in outlet manifolds). The source multipliers for the 4 heat structures of the breeding zone outlet manifolds result from the product of these two proportions as shown in Table 16 below and must sum up to 0.5, the other half being reserved for the inlet manifolds. The source multipliers are the same for inlet and outlet manifolds.

Table 16: Source multiplier for heat structures of breeding zone outlet manifolds

Component No.	Volume No.	Heat structure	Factor for sharing between inlet and outlet	Proportion of steel in components	Source multiplier
60 from SPs	1	HS1	0.5	0.1180	0.0590
61 from CPs	1	HS1	0.5	0.3820	0.1910
62 from CPs	1	HS1	0.5	0.3820	0.1910
63 from SPs	1	HS1	0.5	0.1180	0.0590

3.6.1.8 Main outlet manifold power source

Power source to the main outlet manifold is determined in the same way as for the inlet manifold in section 3.6.1.1. The source multiplier for the main outlet manifold is thus 0.49793, which results from [0.5 x (4860+3220+413+1310) + 151] / 10147 and is applied to the power value in the general table No. 40.

3.6.2 Power ramp-down and decay power generation in TBM components

In principle, the procedure developed in section 3.6.1 would have to be conducted for a reasonable number of time steps, for which the power is provided from nuclear analysis, as for instance listed in Table A-3 in Appendix A. This however, would be very troublesome, especially for heat structures composed of more than one material, and is not appropriate at this stage. Instead, a simplified way is taken here: The averaged decay power ratio (ratio of decay power in the total TBM to the power in normal operation in the total TBM) is applied to all components (and heat structures) equally, irrespective of their material composition and location. This enables to extend the general power input tables referred to in the last sub-sections by scaling the first power entry (valid for normal operation) with an assumed power ramp-down profile followed by the averaged decay power history for selected time steps after shutdown. Table 17 shows the power history used in this analysis for several time steps.

Table 17: General power input table for heat structures for various time steps

Heat structures in components	Table No.	Power (W) at time (s) after beginning of shutdown					
		0	0.5	1	1.3	2	61
Main inlet/outlet manifold	4	10147	5175	229.3	202.9	188.7	147.1
Side walls of first wall	201	15400	7854	348	308	286.4	223.3
Front wall of first wall	202	77960	39760	1762	1559	1450	1130
End cap top	24	50400	25704	1139	1008	937.4	730.8
End cap bottom	25	65400	33354	1478	1308	1216	948.3
Intermediate manifolds	30	150	76.5	3.4	3.0	2.8	2.2
BZ inlet/outlet manifolds	40	6240	3182	141	124.8	116.1	90.5
Breeding zone	50	457900	233529	10349	9158	8517	6640
Power factor $P(t)/P_0$		1	0.51	0.0226	0.02	0.0186	0.0145

<u>Notes to Table 17:</u>

- The power history between 0 and 1 s has been introduced to simulate a linear power ramp-down within one second from full power to decay heat power (usually calculated for an abrupt shutdown at t=0). This is a frequent assumption in safety analyses.

- As a consequence of the above measure the decay power calculated in the nuclear analysis starts in our time scale at t=1 s.
- The power factor $P(t)/P_0$ given in the last line for times between 1 s and 61 s is taken from Table A-3 in Appendix A, which was produced for the NT-TBM. No such data are available for the PI-TBM but are expected to be similar.
- The power values at t=1.3 s have been interpolated by the author.
- Further sets of power values for times up to 30 days are included in the input deck in Appendix B, section B-3.6.2.

3.6.3 Surface heat load to plasma facing first wall heat structures

A uniform heat flux of 250000 W/m^2 is applied to the plasma facing side of the front wall. This value is entered (as negative value, because it flows inward) into a general table No. 41 named "htrnrate" in the input deck Appendix B (section B-3.6.3). The heat structures exposed to the surface heat flux are all HS1s attached to volumes 2 through 4 of components 20 through 23. In order to calculate the heat load, the code needs as input the surface area of each heat structure, which is tabulated Table 18. Surface areas are entered in the input deck on heat structure cards ending with 601 through 603 in this case.

Table 18: Surface area of plasma facing first wall heat structures

Compo-nent	Volume No.	Heat structure	No. of channels	HS1 length (m)	HS1 height (m)	Surface area (m^2)
20	2	HS1	15	0.423	0.3364	0.14228
	3	HS1	15	0.422	0.3364	0.14195
	4	HS1	15	0.423	0.3364	0.14228
21	2	HS1	2	0.423	0.0448	0.01897
	3	HS1	2	0.422	0.0448	0.01893
	4	HS1	2	0.423	0.0448	0.01897
22	2	HS1	2	0.423	0.0448	0.01897
	3	HS1	2	0.422	0.0448	0.01893
	4	HS1	2	0.423	0.0448	0.01897
23	2	HS1	14	0.423	0.3139	0.13280
	3	HS1	14	0.422	0.3139	0.13248
	4	HS1	14	0.423	0.3139	0.13280

3.6.4 Power supplied to the electrical heater

A power value can be applied to heat structure 2 of this component. It was defined in section 3.4.3.4 and consists of two axial sections, which represent the heater rod bundle. The total power of the heater in watts has to be entered on card 11141301 in word 1 (section B-3.4.3.4 in Appendix B). Upon a trip the power is shut off following a given time history specified in the general power table No. 114 in section B-3.6.4.1 in Appendix B.

At present, the power is set equal to zero, and the shut off history (if the initial power is not zero) is an exponential decay to 1 % within 10 s.[16]

[16] This part of the program has not yet been tested.

4 Results of steady state analysis

The purpose of developing the RELAP model for the HCPB system was mainly to use it in transient safety analysis. This has been successfully performed and the results of several highly transient loss of coolant scenarios are documented in [1]. As a starting point for the transient process thermal equilibrium has to be simulated for typical operational conditions in terms of hydrodynamics, temperatures and heat loads. This steady state analysis is described in the following sub-sections with reference to the PI-TBM under extreme operating conditions outlined in Table 1 on page 5. The aim is to demonstrate that the model works as expected, and to give information on thermal-hydraulic effects in the complex network of flow channels present in the TBM.

In a first subsection several computed gross quantities like power, flow rates, inlet/outlet temperatures, coolant inventory, and secondary coolant conditions will be compared with predicted and projected data. In section 4.2 key hydrodynamic quantities for the cooling circuit and for the TBM are presented, i.e., pressure loss in components, flow rate distribution in the system, helium velocities at distinct points, and calculated heat transfer coefficients. Section 4.3 compares the coolant temperature distribution in the TBM with projected data and with results obtained from refined and localised thermal-hydraulic analyses. Finally, in section 4.4 typical heat structure temperatures are reported, knowing that in this respect the model is too coarse as to simulate the complex heat flux pattern in the TBM. Detailed results are given in the computer output listing reproduced in Appendix C, although difficult to interpret for the reader not familiar with the RELAP nomenclature.

4.1 Gross quantities

The sum of internal heat source, calculated to be 0.68373 MW, agrees excellently with the total nuclear power in the TBM (0.68376 MW), which has been distributed to the individual RELAP components (section 3.6.1). This demonstrates that the geometrical model of heat structures in the sum is correct.

The circulator flow rate balances at a value of 0.7065 kg/s. This falls short by 1.5 % relative to the projected mass flow rate of 0.717 kg/s. It is to be noted that the circulator flow rate adjusts itself according to the pump characteristics specified (section 3.3.3.2) and the actual flow resistance in the system.

The computed circulator head (pressure increase) results as 0.2393 MPa. Design estimates of the total pressure drop in the whole TBM system documented in [2] revealed a value of 0.259 MPa, i.e., 8.2 % higher. Contributions of individual components are discussed in section 4.2.

The inlet/outlet temperature at the TBM turned out to be 255.5/505.4 °C. It is 5.5 K higher than the design values. The temperature rise is correct. The deviation in temperature level results from the fact that the present model dispenses with the temperature control mechanism (see section 3.3.3.6). Instead, the target temperature has been approached by adjusting the secondary water flow in the heat exchanger.

The computed helium inventory in the system amounts to 6.94 kg. The estimated helium inventory in the system design study [2] is 6.63 kg (4.5 % smaller) when excluding the pressuriser tank. (Note: It is not clear why the code obviously, too, ignores the inventory in the pressuriser, although the surge line is open.)

The water flow rate at the secondary side of the HX is an input value and was set to 10.5 kg instead to the reference value, which is 5.6 kg. This was deliberately done to adjust the temperature level on the primary side as mentioned earlier.

4.2 Key hydrodynamic quantities

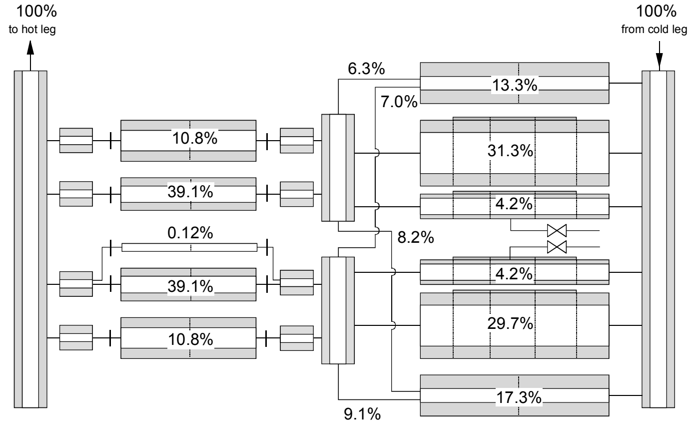
A breakdown of the pressure loss in the circuit components is given in Table 19. The TBM contributes with only 8.1 %. The value for the dust filter is not representative because the filter insert has not been modelled properly.

Table 19: Pressure loss in circuit components

Component	Pressure loss (Pa)	% of total
Cold leg (pipe 3)	69430	29.1
TBM	19360	8.1
Hot leg (pipe 6)	115180	48.2
Dust filter	9300	3.9
Pipes between filter and HX	17410	7.3
Heat exchanger	320	0.1
Pipes between HX and circulator	7890	3.3

Typical helium velocities are 26 m/s in the main part of the cold leg, 39 m/s in the hot leg and 6.5 to 9.8 m/s in the HX.

The mass flow rate distribution in the TBM is shown in the diagram below. The end caps, being supplied in parallel to the first wall, take 30.6 % of the total flow rate, with 69.4 % remaining for the first wall. The ratio in the top to bottom end cap of 13.3 / 17.3 = 0.77 matches the power ratio in both caps (5.04 / 6.54) as was envisaged by adjusting the flow resistance in the channels. The four first wall components share the flow rates according to the number of channels they represent, namely 2.1 % per first wall channel. In the breeding zone 21.7 % of the total TBM mass flow rate is taken by the four stiffening plates and 78.3 % by the ten cooling plates. Overall the flow distribution in the different parallel first wall and breeding zone components is very symmetric and is not impeded by the small asymmetry occurring in the end caps.



Helium flow rate distribution in TBM RELAP components (in % of total flow rate)

Typical flow velocities are 8 to 10 m/s in first wall channels, 12.5 to 13.2 m/s in end caps and 10 m/s in stiffening and cooling plates. The breeding zone inlet and outlet manifolds have rather high velocities up to 30 and 36 m/s, respectively (as printed for junctions 45 through 48 for the inlet and junctions 55 through 58 for the outlet in Appendix C).

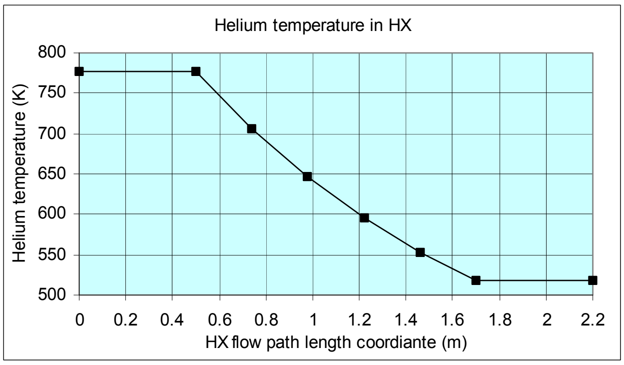
The heat transfer coefficient (HTC) computed by the heat transfer package 1 of the code amounts to between 900 and 1060 W/(m^{2}K) in first wall channels, 1400 W/(m^{2}K) in stiffening plates and 1250 W/(m^{2}K) in cooling plates. These numbers are rather low and do not account for any enhancement by means of artificial wall roughness.

4.3 Coolant temperature distribution

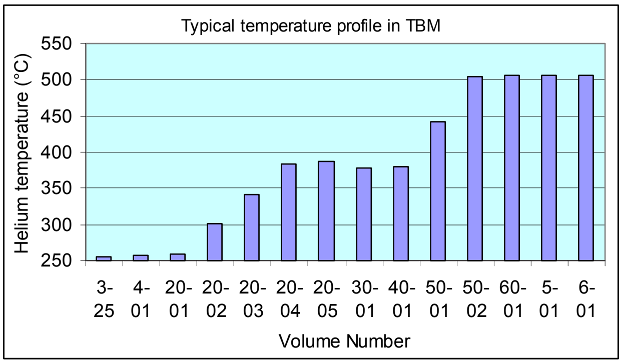
Fluid temperature is computed by RELAP as a single value for each volume of a component. In the cold and hot leg of the circuit the temperature distribution within the 25 volumes is very uniform showing variations within 528.68 $\pm$ 0.094 K in the cold leg and 778.2 $\pm$ 0.33 K in the hot leg.

The temperature rise in the circulator amounts to 11.6 K. It is larger than the predicted value of 6.7 K for adiabatic compression. The difference is attributed to the extra friction torque applied in the RELAP calculation in order to control the pump coast down behaviour.

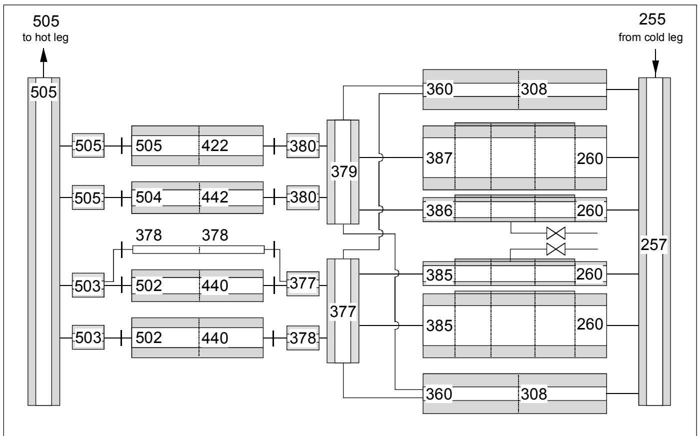
The temperature evolution in the HX is shown in the diagram below. It comes down from 777.3 K (504.1 °C) in the inlet dome to 517.4 K (244.2 °C) in the outlet dome and follows almost a logarithmic trend along the tube bundle. The temperature gradient at the bundle inlet is twice the one at the outlet, i.e., 297 K/m vs. 150 K/M. The HX is not yet optimised.



A typical coolant temperature profile in a selected flow path of the TBM is plotted in the diagram below. The path starts from the last volume of the cold leg (3-25), proceeds through the main inlet manifold (4-01), the first wall (20-01 through 20-05, first ramp), intermediate manifold (30-01), BZ inlet manifold (40-01), stiffening plates of BZ (50-01 and 50-02, second ramp), BZ outlet manifold (60-01), main outlet manifold (5-01). It ends at the first volume of the hot leg (6-01). Half of the total temperature rise occurs in the first wall and half of it in the breeding zone. The heating in the various manifolds is very small.



A more complete picture is given in the helium temperature mapping that follows for the TBM components with component numbers indicated in the diagram in section 3.3.1 on page 11. Given the inlet/outlet temperatures of 255/505 °C the coolant exits the first wall components (20 through 23) at 386±1 °C. In the end caps (24 and 25) the helium is heated to 360 °C, which leads to a mixing temperature of 378±1 °C in the intermediate manifolds (30 and 31). Further heating to 504±1.5 °C occurs in the breeding zone (50 through 53). It is to be noted that the temperature rise in the stiffening plates (50 and 53) is well balanced with the rise in the cooling plates (51 and 52). The single dummy channel (54) sees no heating because it has no heat structure attached to it (compare section 3.3.1.6). The small asymmetry in breeding zone outlet temperature between the north half (50 and 51) and the south half (52 and 53) of the TBM is tolerable. It is caused by the geometric asymmetry in the first wall and end cap components as outlined in sections 3.3.1.2 and 3.3.1.3, respectively. As a whole the steady state temperatures match well with results from one-dimensional calculations performed in [9] using text book equations.



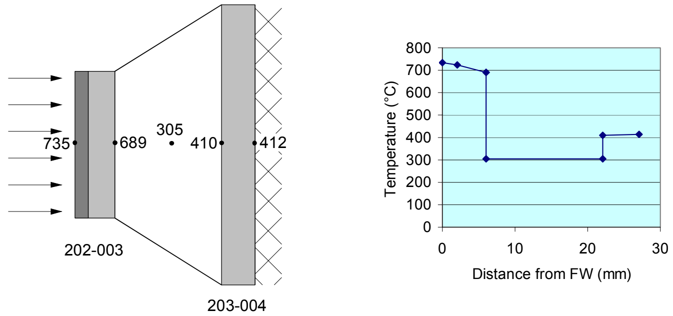
Helium temperature mapping in TBM RELAP components (rounded to full °C)

4.4 Typical heat structure temperatures

The output listing reproduced in Appendix C for a given time step lists, among other variables, the surface temperature for each heat structure (compare section “heat structure output” beginning on page C-5). The heat structure numbering scheme is complicated and the reader may refer to the code manual. Here we will discuss a few examples of surface temperatures, keeping in mind the one-dimensional nature of the code and the coarse nodalisation already mentioned.

Surface temperatures at the left and right side (corresponding to inner and outer surface) pertaining to volumes of the cold and hot leg pipes (structure numbers 30-001 through 31-004 and 60-001 through 61-004) are always equal, indicating that the system is at equilibrium and there is no heat flux across heat structure boundaries. This is also confirmed by the very small heat flux explicitly given in the sixth column of the output listing. Wall temperatures are practically equal to coolant temperatures.

An example for the radial temperature distribution in the first wall is shown in the following sketch. It represents volume 4 of component 20 in a poloidal-radial cut and is thus the location of highest temperature in the corner of the TBM. So the peak surface temperature is 735 °C and the temperature difference in the front plate is 46 °C. Due to the small heat transfer coefficient (HTC) of 920 W/(m^2K) the difference to the coolant temperature is 384 °C. It follows that by increasing the HTC by a factor of two by means of artificial roughness the surface temperature can be brought down in this model to about 545 °C. This is close to the value of 530 °C obtained from refined finite element analysis reported in Table 2.2-1 of [2]. In the back plate of the first wall the code calculates a mean temperature of 411 °C with an adiabatic boundary condition at the interface to the breeding zone.

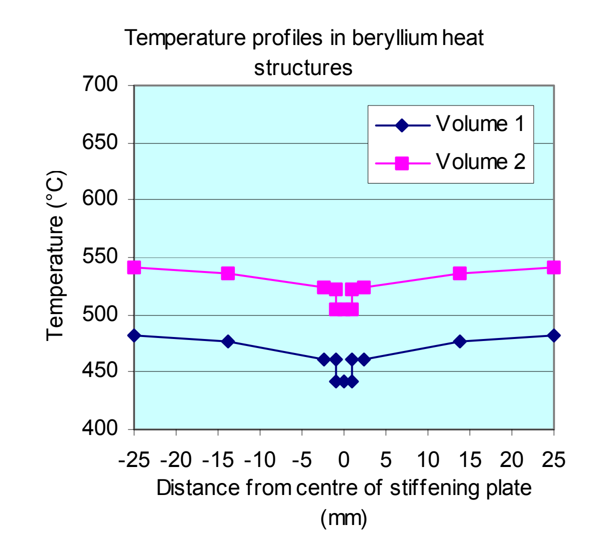


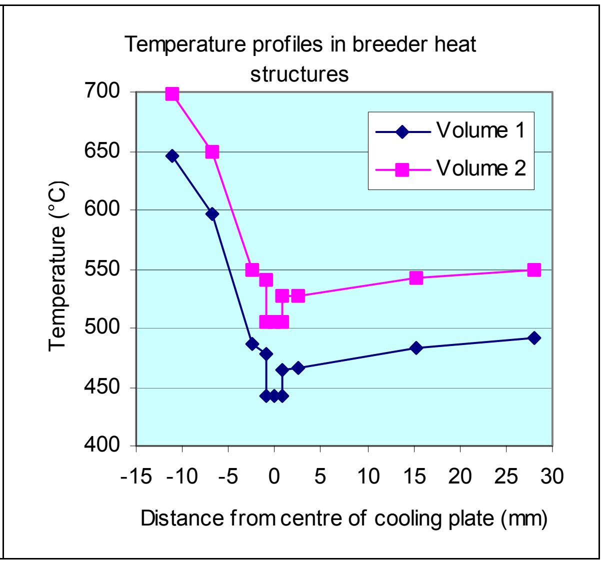
Temperature distribution (°C) in first wall heat structures
(component 20, vol. No. 4)

In the breeding zone we have defined two types of unit cells illustrated in section 3.3.1.6, one consisting of beryllium and stiffening plate, and the second one consisting of breeder, cooling plate and beryllium. Accordingly, the related sets of heat structures have been established as depicted in the drawing in section 3.4.1.6 denoted as beryllium heat structures and breeder heat structures. Poloidal temperature profiles of these sets of heat structures (including their coolant channel) are plotted in the diagrams below. Curves denoted “Volume 1” and “Volume 2” indicate the hydrodynamic volume they belong to, along the flow path from the back to the front and reverse, respectively.

The profile in the beryllium heat structures (left frame) is symmetric with peak beryllium temperatures of 541 °C and a stiffening plate temperature of 524 °C. The temperature difference in the beryllium layer is thus only 17 °C if the volume average power density (over the whole beryllium inventory in the TBM) is present. Likewise the ΔT between stiffening plate and coolant is only 18 °C.

The profile in the breeder heat structures (right frame) is asymmetric with peak breeder temperature of 698 °C and an average cooling plate temperature of 545 °C. The temperature difference in the breeder layer is thus about 150 °C if the volume average power density (over the whole breeder inventory in the TBM) is present. The profile in the beryllium layer resembles the one discussed above with the beryllium heat structures. The ΔT between cooling plate and coolant is 36 °C at the breeder side and 23 °C at the beryllium side.



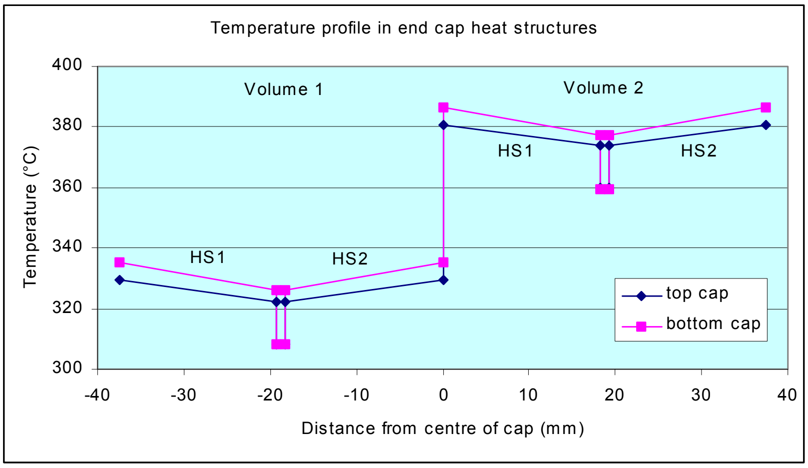


In general, peak beryllium and breeder temperatures fall short in this model compared to refined calculations reported in [2] for reasons already addressed.

Note: Temperatures at intermediate mesh points in heat structures (besides the left and right surface) are printed on request only and are not included in the output listing in Appendix C. Request has to be made in the input deck on cards 301 through 399.

Finally we look at the end cap heat structures defined in section 3.4.1.3. The poloidal temperature profile through the thickness of the plate with cooling channels shows the difference in the temperature level between volume 1 (left half of the curves below) and volume 2 (right half), caused by the heating up of the coolant along its path. The step between these two halves is artificial and is caused by the adiabatic boundary condition assumed in the heat structure model. In reality it will smooth out, driven by conduction.

The peak structure temperature becomes 381 °C in the top cap and 386 °C in the bottom cap, if the volume average power density (over the whole end cap) is applied. This will change significantly when a real power profile and recuperative heat exchange between heat structures will be considered in detailed analyses. Please note that the maximum power density in the end cap near the first wall is about 5 times higher than the average power density [2], driving the ΔT between the peak structure temperature and the coolant from now 26 °C to the order of 130 °C, which might still be acceptable.



5 Lessons learned from applying the model

Compared to former work performed in [5] the model has been refined, especially reflecting the new TBM design and the more realistic pipe routing in the ITER building. Hence, the number of components in the RELAP model and the number of heat structures has been increased substantially, leading to longer computing times. Steady state condition is reached after about 10 minutes of cpu.

The transient analysis was performed in a series of restart runs to get experience with time control. The minimum time step was set to 10^{-9} s and the problem time was successively increased, starting from 10^{-6} s up to 1s in increments of a factor of 10. Unexpectedly, the cpu time increased with progressing problem time, although the process became more smooth. It can temporarily go up as high as 5000 seconds of cpu per second of problem time. This however is attributed to the strongly transient nature of the loss of coolant process rather than to the increased number of heat structures used.

In general it can be stated that the model works as expected, both in steady state and transient analyses. The results from steady state analysis agreed with predictions as demonstrated in section 4. The transient studies documented in [1] delivered reasonable and traceable evolutions of the blow-down processes. Yet it turned out that for the highly transient processes alone the model could have been designed more efficient by omitting many of the heat structures as well as the decay power history. On the other hand, for slow transients like pulsed operation sequences and warm-up procedures the level of detailing is adequate.

It is appropriate to define those components, which are used in special transient cases only, in the restart input deck, rather than in the steady state input file. For instance, in order to model the break of the FW, a cross flow junction was introduced in volume 3 of the first wall components 21 and 22 and connected via trip valves to the pressure vessel. The valves were tripped open at restart, t=0. These additions were input in the restart file.

For the present purpose it could be afforded to dispense with exact flow control of the circulator and temperature control in the heat exchanger as explained in sections 3.3.3.2 and 3.3.3.6, respectively. This would not be adequate for studying slow transients like pulsed operation sequences or warming-up trends. For those studies the model should be extended using valuable hints given in [5].

In loss of coolant problems interruptions occurred repeatedly at around 2.7 s problem time with error message “segmentation fault”. At that time the temperature in the pressuriser had dropped to about 100 K, which seems to be the reason for the interruption. The problem was by-passed by closing the pressuriser valve prior to that condition. The same problem had also be observed in earlier studies like in [5].

There was a problem with modelling a double-ended pipe break in loss of coolant analysis. Several attempts to simulate a double-ended break in the cold leg (component 3) failed with the error message “singular matrix”, which points to numerical instabilities. In fact, flow velocity in the break opening reached unrealistic values of the order 10^5 m/s. The model variations tried included: (a) introduction of two cross flow junctions to volume 1 with direct connection to the vault, (b) ditto with volume 15, (c) connection of volume 15 by a single junction to the vault, and (d) changing the minimum time step from 10^{-9} s to 10^{-12} s as well as the junction control flag. All measures did not help. A major pipe break of the size of the main pipe (but no double-ended pipe break) was finally achieved by introducing a single cross flow junction to volume 15 and connecting that junction via a trip valve to the vault in the ITER building.

The strip procedure provided by the RELAP code system to condense the output was successfully exercised. Numerous examples for parameter vs. time plots are given in the safety report [1] and in internal notes. The plot program XMGR referred to in [3] and the user-oriented package SPEAKEASY [11] were useful tools to process the output.

At runtime with an input deck (e.g., tbm7.i or tbm7.rst.i in case of restart) the code produces two files, one output file (tbm7.o or tbm7.rst.o) and one restart file (tbm7.r or tbm7.rst.r). The latter contains process information for successive restart runs. This file has to be deleted (or renamed) before starting the next run with the same input file name, unless the next run is intended to be a successive restart run, for which the restart number (advancement number) has to be entered in the input file, card 103 (compare section B-4.2 in Appendix B).

6 Summary and conclusions

Various types of test blanket modules (TMB) are currently developed in order to be tested in the International Thermonuclear Experimental Reactor (ITER). One of these is the helium-cooled pebble bed (HCPB) blanket being pursued by Forschungszentrum Karlsruhe GmbH. For integration in ITER the HCPB TBM has to assure a number of features. Among them, a safety assessment has to demonstrate that the TBM during postulated accidents does not impede the safe operation of ITER. The safety assessment required to develop an integrated model of the TBM system, capable of studying a variety of highly transient accident sequences. This thermal-hydraulic model written for the RELAP/MOD3.2 version is detailed in the present report.

The report has the following structure. After an introduction, the TBM system design including its cooling subsystem and other ancillary subsystems are briefly described in chapter 2. In chapter 3 the RELAP TBM system model is presented in detail. The description covers in four sections the hydrodynamic aspects, the definition of heat structures, material properties, and power sources. Key results of the steady state analysis are outlined in chapter 4. Chapter 5 points out specific experience gained in this application. Three appendices are mainly intended to complete the documentation in case the model has to be extended or updated in the course of further TBM development. Appendix A is a collection of major input data in tabular form. A typical RELAP input deck for steady state analysis is reproduced in Appendix B for the reader familiar with the RELAP convention. An output data set at a certain time step, a so-called major edit, allows to look up further details of the steady state analysis.

The test objectives in ITER call for a series of TBMs of different designs. The one devoted to plant integration (PI) functions, the so-called PI-TBM, represents the enveloping case in terms of safety. Hence, the modelling is at this stage restricted to the PI-TBM. It employs alternating layers of ceramic breeder material and beryllium in form of small pebbles, separated by steel plates with integral cooling channels (Figure 2). The TBM has its own single-loop helium cooling system. Its components are located in the ITER building, approximately 100 m away from the TBM. The cooling system is designed to remove about 1 MW of heat from the TBM at inlet/outlet temperatures of typically 250/500 °C and 8 MPa system pressure. The helium inventory is of the order of 10 kg. The configuration analysed in this report corresponds to the design status as of June 2001.

The RELAP model includes the TBM proper, circulator, dust filter, helium/water heat exchanger, a pressuriser for pressure control, and the interconnecting piping (Figure 8). All components are modelled as heat structures to account for the thermal inertia of the system. The secondary cooling system is considered to the extent as to define the boundary conditions at the heat exchanger. The TBM itself is a network of interconnected RELAP components (Figure 9). In each of them several physical unit cells are lumped together in order to limit the number of components. For instance, the U-shaped FW structure, containing 33 cooling channels is divided into four components, two small ones and two large ones. The small components with two cooling channels each enable to simulate a FW break (section 3.3.1.2). Likewise the breeding zone is divided into four components which represent the pertaining steel, beryllium, breeder and coolant arrangement in a planar geometry with adapted thermal and hydraulic characteristics (section 3.3.1.6). Parallel to the FW there is a bypass flow to cool the end caps of the TBM box. The components are interconnected via a system of manifolds. Altogether, the model comprises 65 components equipped with 154 heat structures. The latter are defined in cylindrical geometry (typically for pipes, manifolds and circuit components) or in planar geometry (typically for FW and breeding zone components). Heat structures have between 2 and 4 mesh points.

The basis for assigning power sources to individual components and heat structures of the TBM is the breakdown of power generation in the PI-TBM from nuclear analysis (section 3.6). Since RELAP heat structures and elements of the neutronics model were not congruent, a conversion procedure had to be applied. The total power amounts to 0.684 MW during normal operation (section 3.6.1). An extra surface heat load of 0.25 MW/m^2 has been assumed to the FW (section 3.6.3). The decay power behaviour had to be taken from a slightly different TBM design. Thus, instead of using an individual decay power history for each heat structure, a common mean (averaged over the whole TBM) decay power vs. time profile has been applied to all TBM heat structures (section 3.6.2).

Application of the model delivered valuable results, in particular in the safety assessment of the PI-TBM. Reference [1] is a summary of various types of loss of coolant scenarios, reporting on transient hydrodynamic processes during the blowdown phase. In the present report however, results of the steady state analysis are described only to demonstrate that the model works properly (chapter 4). At first, several computed gross quantities like power, flow rates, inlet/outlet temperatures, coolant inventory, and secondary coolant conditions are compared with predicted data. The agreement is excellent or good. Furthermore, key hydrodynamic quantities for the cooling circuit and for the TBM are presented, i.e., pressure loss in components, flow rate distribution in the system, helium velocities at distinct points, and heat transfer coefficients. Also the coolant temperature distribution in the TBM and in the circuit is evaluated. Again, the computed results compare well with predictions and give more detailed information on the flow pattern in the complex network of the TBM. Finally, typical heat structure temperatures are interpreted. However, they are considered as trend indicators only because of the one-dimensional nature of the code and the coarse nodalisation.

Tailoring a RELAP model to a given system like the TBM requires some experience in handling the code. At the beginning the user should carefully specify the objectives the model has to fulfil. For instance, fast hydrodynamic processes require a different model than slow thermal evolutions. In this context it may be interesting to note that approximately 70 % of the effort has been put into the development of the TBM model itself, 30 % remaining for the cooling circuit. Hence, specific lessons learned from similar tasks can be helpful. Major lessons that came across during this exercise are outlined in chapter 5. They include statements about computing time, adequacy of the model for fast and slow transients, placement of component definitions in steady state or restart input file, simplifications made with respect to flow and temperature control, problems with helium temperatures below 100K occurring in the pressuriser, numerical instabilities for double-ended breaks of the main pipe, post processing tools, and job control.

A number of additive improvements to the model has been addressed in case the model should be upgraded for extended studies of slow thermal transients. They comprise (a) inclusion of coolant temperature control mechanism by making use of the heat exchanger bypass, (b) updating of heat exchanger layout, (c) consideration of thermal losses from circuit components, (d) refinement of circulator model with the capability of flow control.

In conclusion, the RELAP model developed for the PI-TBM system worked satisfactory for the main purpose it was designed for, i.e., to study various loss of coolant scenarios in the frame of safety assessment. It is also capable of investigating the thermal-hydraulic behaviour of the whole system, including the complex network of flow channels in the TBM during steady state operation, for a variety of prime parameters and load conditions. In order to investigate slow thermal-hydraulic processes a few upgrades would be appropriate.

7 References

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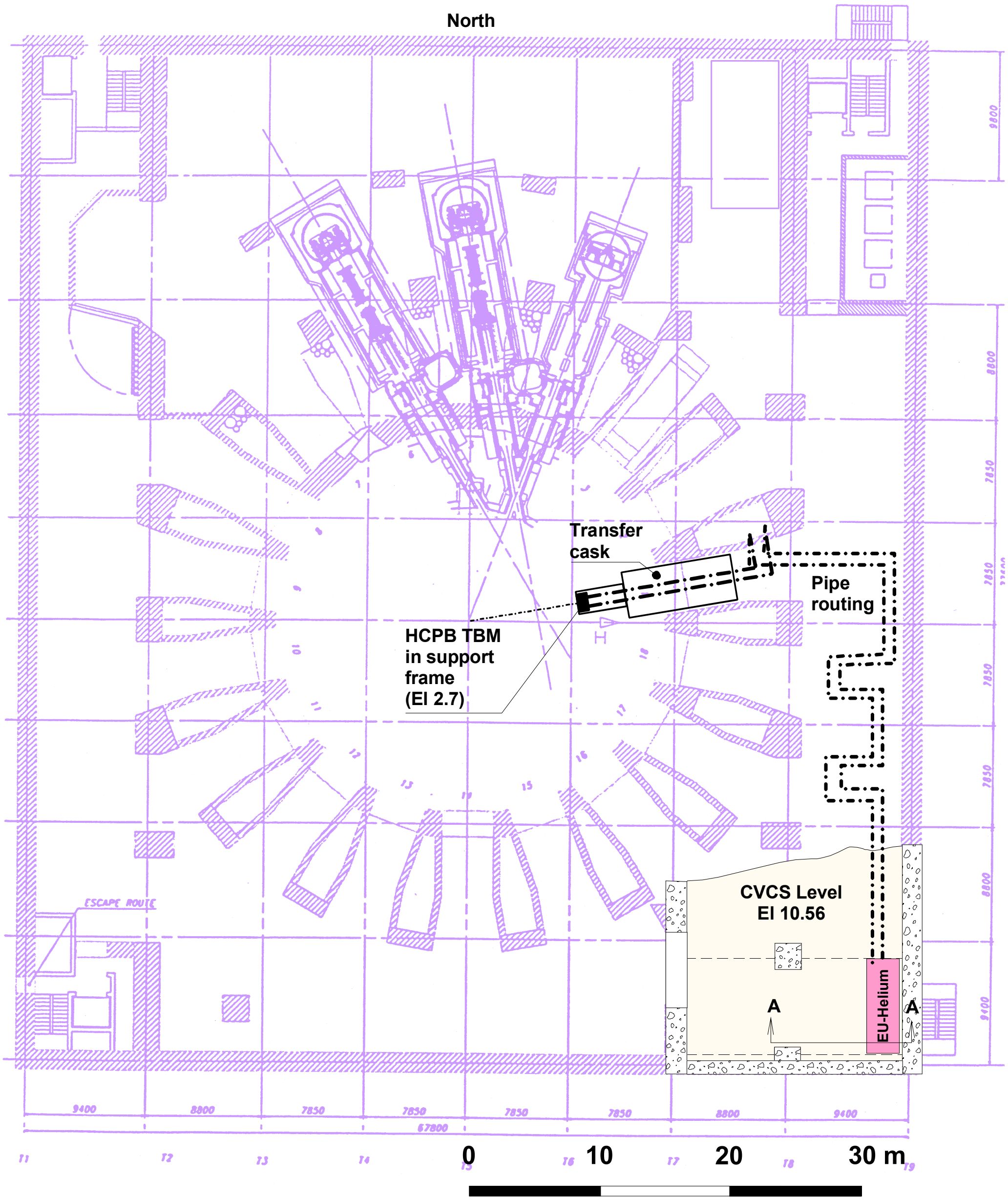


Figure 1: Location of TBM, HCS and PCS in ITER FEAT

HCS and PCS are in the “EU-Helium” compartment, TES is in the tritium building (not shown). Please note the different elevations of TBM (EL 2.7 m) and HCS, PCS (El. 10.56 m).

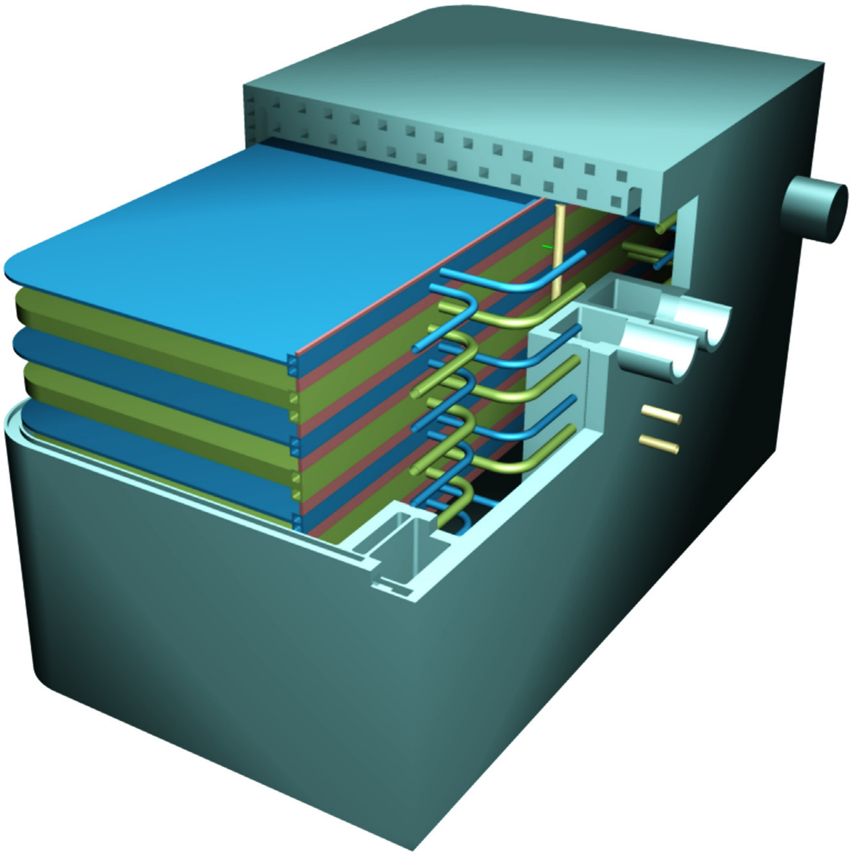


Figure 2: Isometric view of the PI-TBM

Shown is the stack of breeding zone layers with intermediate manifolds and piping (see sections 2.1 and 3.3.1.4). Main manifolding region is preliminary and not up to date. The mechanical attachment studs are not shown.

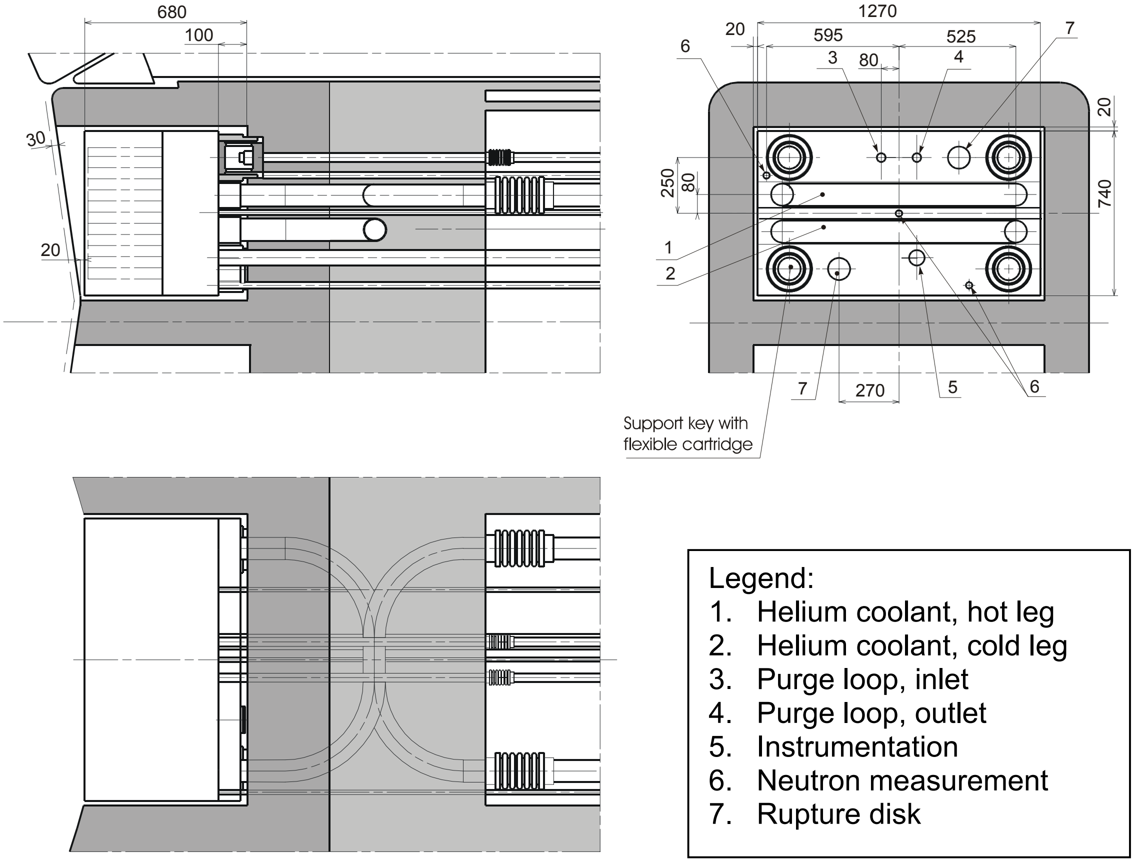


Figure 3: HCPB TBM integration in ITER support frame

Helium coolant pipes have enlarged diameter within the biological shield and also large curvature to allow remote access for welding and rewelding with standardised tools.

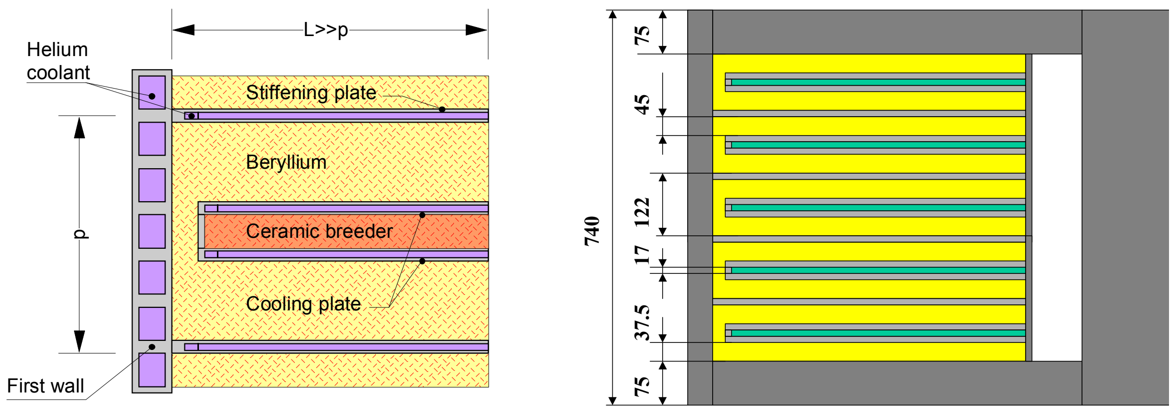


Figure 4: Breeding zone pebble bed arrangement

left: Regular unit cell of beryllium and ceramic pebble beds encapsulated by stiffening plates and cooling plates (see section 2.1). right: Dimensions of layers in regular unit cells and end cells in mm.

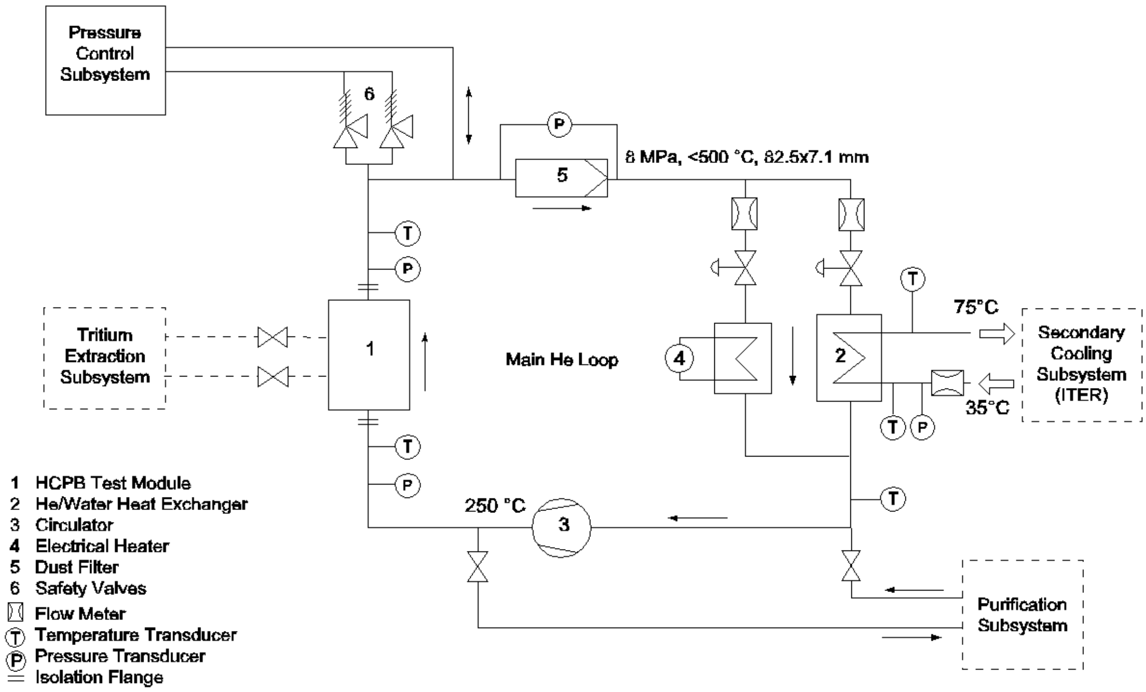
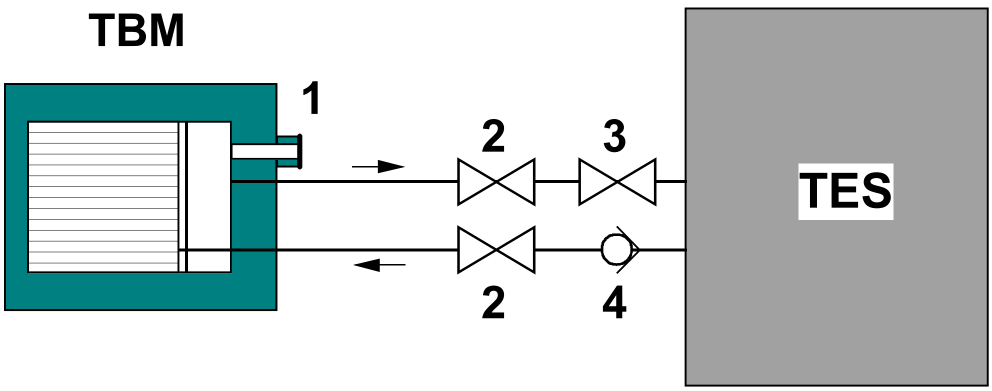


Figure 5: HCPB TBM helium cooing system flow diagram

Shown are the main loop (components[17] 1-5-2-3), bypass to HX with electrical heater (4), pressure control unit connected via valves (6) and ancillary subsystems (see section 2.2.3 on page 4).

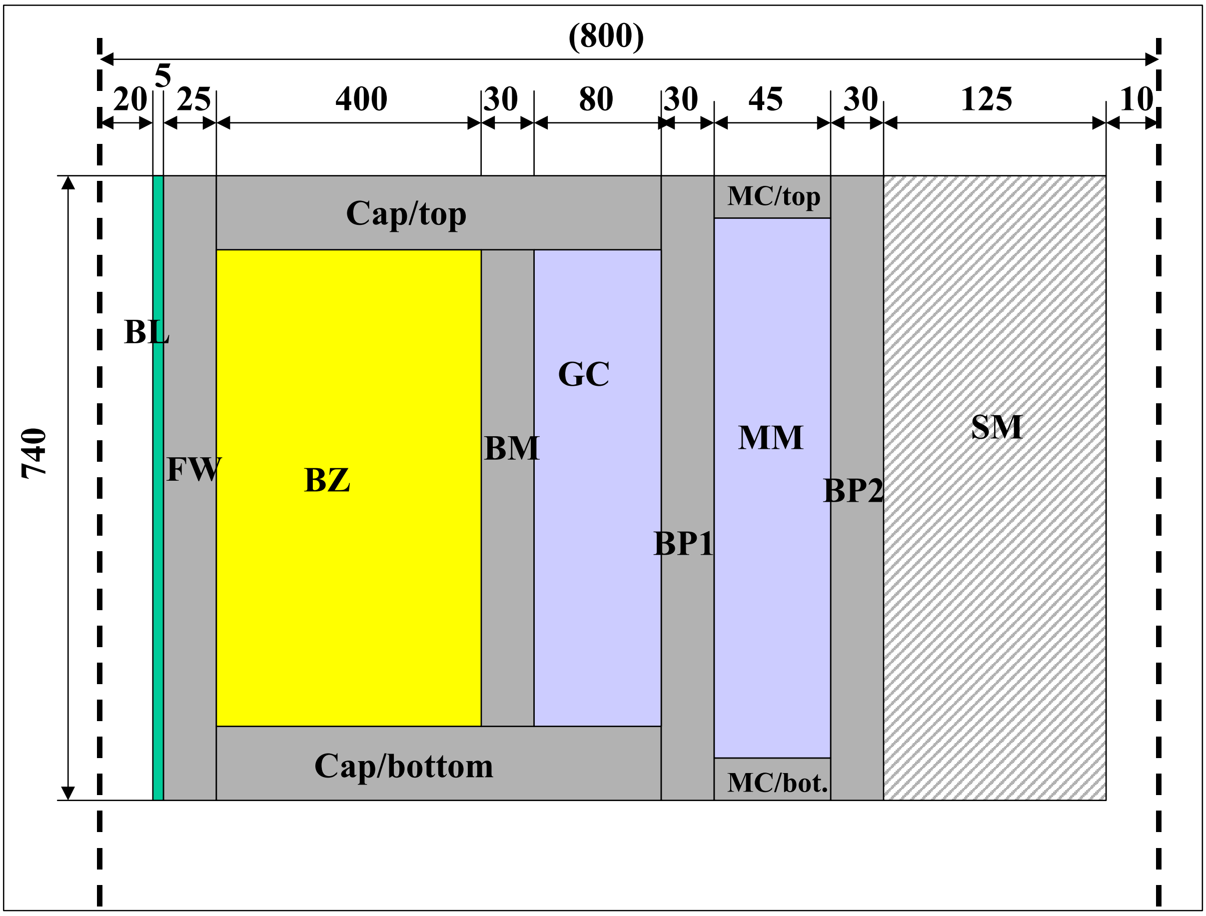


1 rupture disk
2 fast isolation valve
3 pressure reducing valve
4 check valve

Figure 6: Valve arrangement to protect the TES from pressurisation

The pressure reducing valve will limit the downstream pressure to 0.2 MPa in case of an in-TBM coolant leak.

[17] Component numbering in this drawing has nothing to do with numbers given to RELAP components.



Legend:

BL	Beryllium layer (protection)	BP1	Back plate 1 (intermediate manifold walls)
FW	First wall (with internal cooling channels)	MM	Main manifolds (inlet and outlet collectors)
BZ	Breeding zone (beryllium, breeder and steel)	MC	Manifold covers (top and bottom)
Cap	End caps (with internal cooling channels)	BP2	Back plate 2 (main support structure)
BM	Breeding zone inlet/outlet manifolds	SM	Shielding and mounting equipment
GC	Gas chamber (purge gas collector)		

Figure 7: Dimensional model of NT-TBM and PI-TBM in neutronics analysis

Shown is a radial-poloidal cut through the TBM. Elements and zones are considered as homogeneous bodies. Missing dimensions and material composition are listed in Appendix A, Table A-2 (see also description in section 2.4.1).

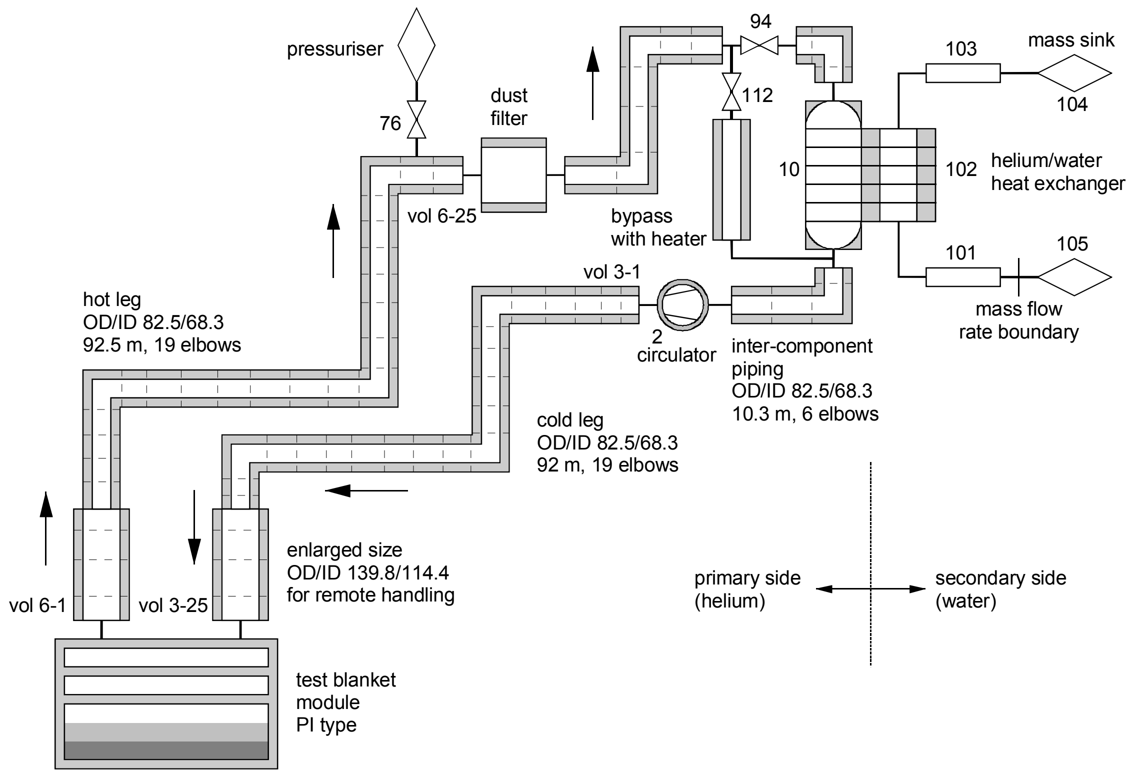


Figure 8: RELAP5/MOD3.2 nodalisation of HCPB TBM cooling system (schematic)

Components with gray borders indicate heat structures with internal heat capacity

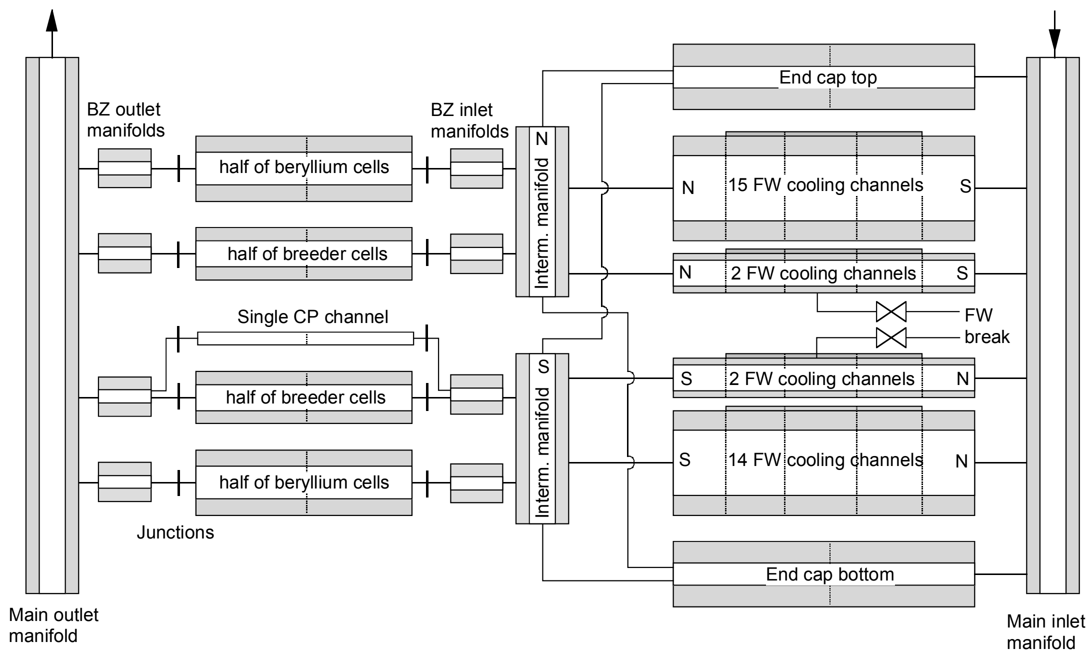


Figure 9: Detailed RELAP5/MOD3.2 nodalisation of the HCPB PI-TBM

Components with grey borders indicate heat structures with internal heat capacity. Dashed lines indicate subdivision of components into several RELAP volumes. N and S refer to North-South orientation in the plant.

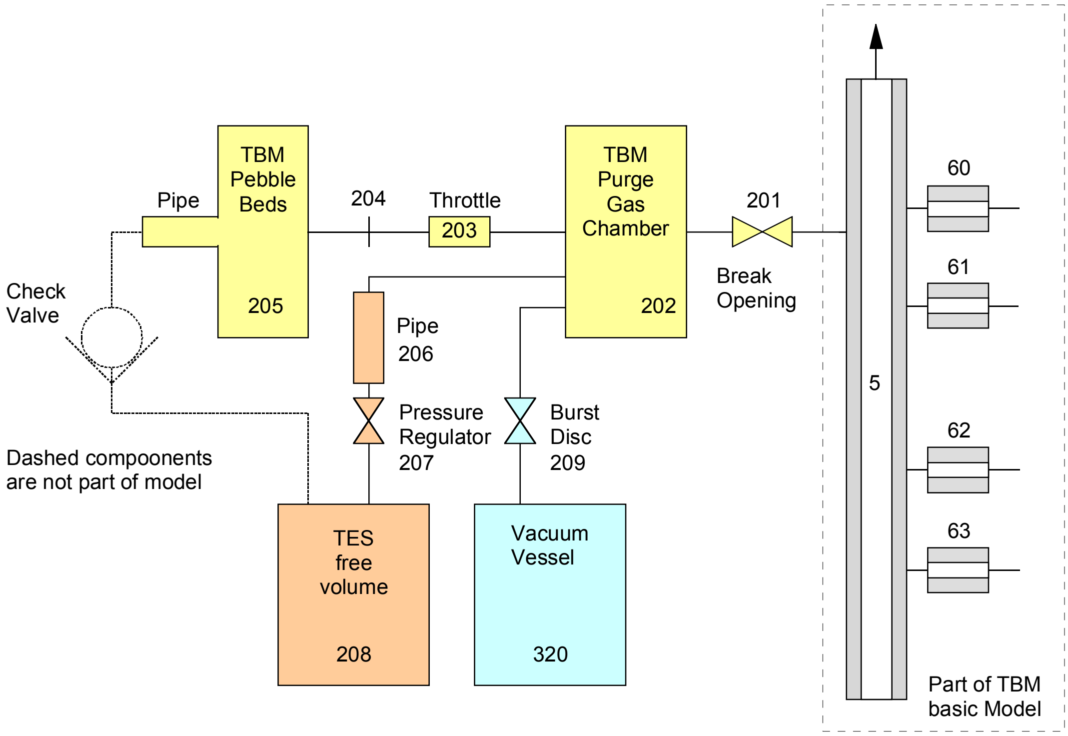
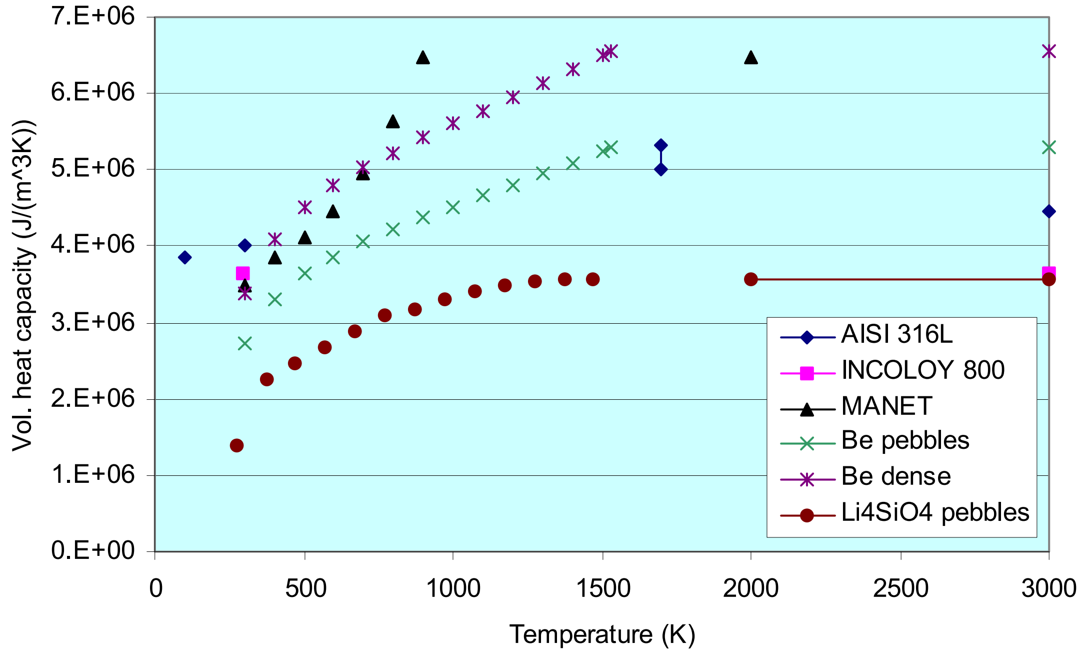


Figure 10: Flow diagram of additional components for loss of coolant analysis

For specification of components please refer to section 3.3.4 on page 21.



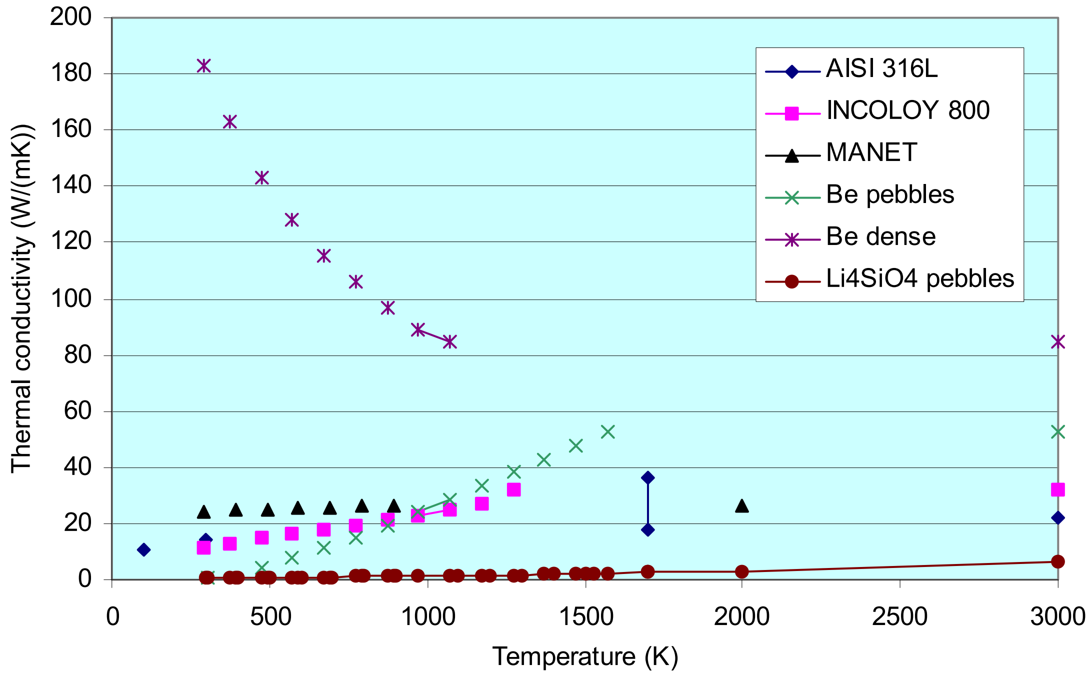


Figure 11: Heat structures thermal conductivity and volumetric heat capacity

For references please refer to section 3.5 on page 36. Values are listed in Appendix A, Tables A-14 and A-15.

APPENDIX A - COMPILATION OF INPUT DATA

This appendix contains full-page tables of input data and, where needed, their derivation, which are of interest to the model developer only. There are:

- basic data on power generation and TBM dimensions as used from references cited, Table A-1 to Table A-3
- Dimensions on pipe routing for cold leg, hot leg and piping between components, Table A-4 to Table A-6
- Energy loss coefficients of junctions, Table A-7
- Derivation of heat structure quantities of TBM components, Table A-8 through Table A-13
- Material properties vs. temperature, Tables A-14 and Table A-15.

List of Tables

Table A- 1: Power generation (MW) in the NT-TBM and PI-TBM from [2]

Region	Component	NT-TBM	PI-TBM
First Wall (FW)	Be protection	2.04E-02	2.04E-02
	Structure	6.95E-02	6.98E-02
	FW total	0.0899	0.0902
Breeding zone (BZ)	Breeder	0.193	0.205
	Be pebbles	0.184	0.21
	Cooling plates	7.45E-02	4.29E-02
	BZ total	0.452	0.458
TBM structure	BM	3.77E-03	4.91E-03
	GC	1.28E-03	1.63E-03
	BP1	4.20E-03	4.86E-03
	MM	3.65E-04	4.13E-04
	BP2	2.93E-03	3.22E-03
	SM	1.21E-03	1.31E-03
	Cap/top	5.17E-02	5.04E-02
	Cap/bottom	6.30E-02	6.54E-02
	MC/top	1.78E-04	1.51E-04
	MC/bottom	1.82E-04	1.93E-04
	Sidewalls	1.46E-02	1.54E-02
	Struckture Total	0.143	0.148
TBM total		0.684	0.696

Table A- 2: Dimensions, material composition, masses and volumes in the PI-TBM used in nuclear analysis

PI-TBM part sizes and material volume fractions, densities, masses and volumes											
Part or zone	Dimensions (m)			Number of	Material fraction by volume				Mix. Density	Mix. Mass	Volume
	toroidal	radial	Poloidal	Parts	FM-steel	Beryllium	OSI	Void	(kg/m3)	(kg)	(m3)
FW	1.268	0.025	0.740	1	0.550	0	0	0.450	4235.0	99.3	0.02346
BL	1.268	0.005	0.740	1	0.000	1	0	0.000	1850.0	8.7	0.00469
SW	0.025	0.615	0.740	2	0.550	0	0	0.450	4235.0	96.4	0.02276
CAP	1.218	0.510	0.075	2	0.880	0	0	0.120	6776.0	631.4	0.09318
BZ	1.218	0.400	0.590	1	0.082	0.458	0.095	0.365	1702.1	489.3	0.28745
BM	1.218	0.030	0.590	1	0.600	0	0	0.400	4620.0	99.6	0.02156
BP1	1.218	0.030	0.740	1	0.950	0	0	0.050	7315.0	197.8	0.02704
BP2	1.218	0.030	0.740	1	0.950	0	0	0.050	7315.0	197.8	0.02704
GAP	1.218	0.080	0.590	1	0.100	0	0	0.900	770.0	44.3	0.05749
MC	1.218	0.045	0.030	2	0.950	0	0	0.050	7315.0	24.1	0.00329
MM	1.218	0.045	0.680	1	0.072	0	0	0.928	554.4	20.7	0.03727
SM	1.268	0.125	0.740	1	0.100	0	0	0.900	770.0	90.3	0.11729
Module	1.268	0.770	0.740	1	0.303	0.189	0.0378	0.471	2767.5	1999.5	0.72251

For legend of parts and zones please refer to Figure 7.

Table A- 3: Nuclear power generation in the NT TBM (MW) during operation at 500 MW fusion power and after shutdown as a function of cooling time [10]

	Operation	Shutdown	1 s	1 min	10 min	1h	5 h	1 d	30 d
FW Be prot.	2.04E-02	2.80E-04	1.20E-04	2.21E-06	1.81E-06	1.40E-06	9.59E-07	5.03E-07	7.97E-08
FW Structure	6.95E-02	3.05E-03	3.05E-03	2.98E-03	2.75E-03	2.27E-03	1.08E-03	3.67E-04	1.50E-04
FW Total	8.99E-02	3.33E-03	3.17E-03	2.98E-03	2.75E-03	2.27E-03	1.08E-03	3.67E-04	1.50E-04
Li_4SiO_4 breeder	1.93E-01	9.71E-04	9.03E-04	3.14E-04	3.41E-05	1.03E-05	6.68E-06	4.15E-06	2.07E-06
Be pebbles	0.184	4.36E-03	1.87E-03	2.37E-05	1.99E-05	1.53E-05	1.03E-05	5.49E-06	6.98E-07
Cooling plates	7.45E-02	2.43E-03	2.43E-03	2.38E-03	2.20E-03	1.83E-03	9.12E-04	3.47E-04	1.70E-04
TBM structure									
BM	3.77E-03	9.51E-05	9.49E-05	9.29E-05	8.81E-05	7.74E-05	4.97E-05	2.72E-05	1.17E-05
GC	1.28E-03	3.41E-05	3.40E-05	3.33E-05	3.16E-05	2.80E-05	1.84E-05	1.04E-05	4.53E-06
BP1	4.20E-03	1.14E-04	1.13E-04	1.11E-04	1.06E-04	9.42E-05	6.41E-05	3.75E-05	1.65E-05
MM	3.65E-04	9.62E-06	9.60E-06	9.38E-06	8.96E-06	8.01E-06	5.52E-06	3.29E-06	1.48E-06
BP2	2.93E-03	8.74E-05	8.72E-05	8.51E-05	8.15E-05	7.35E-05	5.26E-05	3.22E-05	1.40E-05
SM	1.21E-03	3.76E-05	3.75E-05	3.65E-05	3.49E-05	3.16E-05	2.32E-05	1.46E-05	6.36E-06
Cap top	5.17E-02	1.60E-03	1.60E-03	1.56E-03	1.46E-03	1.25E-03	7.05E-04	3.35E-04	1.53E-04
Cap bottom	6.30E-02	1.91E-03	1.91E-03	1.86E-03	1.74E-03	1.48E-03	8.15E-04	3.73E-04	1.71E-04
MC top	1.78E-04	5.10E-06	5.08E-06	4.94E-06	4.72E-06	4.25E-06	3.02E-06	1.89E-06	8.88E-07
MC bottom	1.82E-04	5.63E-06	5.62E-06	5.47E-06	5.20E-06	4.65E-06	3.23E-06	2.00E-06	9.92E-07
Side walls	1.46E-02	4.58E-04	4.57E-04	4.47E-04	4.17E-04	3.57E-04	2.05E-04	9.83E-05	4.16E-05
Sub-total	1.43E-01	4.36E-03	4.35E-03	4.25E-03	3.98E-03	3.40E-03	1.94E-03	9.36E-04	4.22E-04
Total TBM	6.84E-01	1.55E-02	1.27E-02	9.95E-03	8.98E-03	7.53E-03	3.95E-03	1.66E-03	7.44E-04
$P_{decay}/P_{operation}$		2.26E-02	1.86E-02	1.45E-02	1.31E-02	1.10E-02	5.78E-03	2.42E-03	1.09E-03

Table A- 4: Cold leg pipe routing for the HCPB TBM cooling system

Junction		Co-ordinate from torus centre[1]			Pipe section[2] (volume)		
No.	type	x (m)	y (m)	z (m)	No.	length (m)	Angle (deg.)
from circ.	external	31.4	-26.5	11.6	1	0.700	0
1	elbow	31.4	-25.8	11.6	2	2.800	90
2	elbow	31.4	-25.8	14.4	3	5.000	0
3	smooth	31.4	-20.8	14.4	4	5.000	0
4	smooth	31.4	-15.8	14.4	5	4.000	0
5	elbow	31.4	-11.8	14.4	6	3.200	0
6	elbow	28.2	-11.8	14.4	7	2.200	0
7	elbow	28.2	-9.6	14.4	8	3.200	0
8	elbow	31.4	-9.6	14.4	9	3.200	0
9	elbow	31.4	-6.4	14.4	10	3.200	0
10	elbow	28.2	-6.4	14.4	11	2.200	0
11	elbow	28.2	-4.2	14.4	12	4.200	0
12	elbow	32.4	-4.2	14.4	13	5.400	0
13	smooth	32.4	1.2	14.4	14	5.000	0
14	elbow	32.4	6.2	14.4	15	7.000	0
15	elbow	25.4	6.2	14.4	16	7.200	-90
16	elbow	25.4	6.2	7.2	17	2.800	0
17	elbow	22.6	6.2	7.2	18	1.204	0
18	elbow	22.5	7.4	7.2	19	6.050	-90
19	elbow	22.5	7.4	1.15	20	3.178	0
20	elbow	23.2	4.3	1.15	21	4.851	0
21	D-change	18.4	3.6	1.15	22	4.455	0
22	smooth	14	2.9	1.15	23	4.554	0
23	elbow	9.5	2.2	1.15	24	1.031	0
24	elbow	9.7	1.2	1	25	0.510	0
to TBM	external	9.2	1.1	1			
Total length of cold leg						92.133	

[1] Junction co-ordinates x, y, z are measured from torus centre in south, east, and vertical direction, respectively.
[2] Pipe section (volume) with number i is located between the junction number i-1 and the junction i.

Table A- 5: Hot leg pipe routing for the HCPB TBM cooling system

Junction		Co-ordinate from torus centre			Pipe section[3] (volume)		
No.	type	x (m)	y (m)	z (m)	No.	length (m)	Angle (deg.)
from TBM	external	9.2	2.1	1	1	0.510	0
1	elbow	9.7	2.2	1	2	1.031	0
2	elbow	9.5	1.2	1.15	3	4.554	0
3	smooth	14	1.9	1.15	4	4.455	0
4	D-change	18.4	2.6	1.15	5	5.445	0
5	elbow	23.8	3.3	1.15	6	4.258	0
6	elbow	23.1	7.5	1.15	7	6.050	90
7	elbow	23.1	7.5	7.2	8	0.707	0
8	elbow	23.2	6.8	7.2	9	2.200	0
9	elbow	25.4	6.8	7.2	10	7.200	90
10	elbow	25.4	6.8	14.4	11	7.600	0
11	elbow	33	6.8	14.4	12	5.600	0
12	smooth	33	1.2	14.4	13	6.000	0
13	elbow	33	-4.8	14.4	14	4.200	0
14	elbow	28.8	-4.8	14.4	15	1.000	0
15	elbow	28.8	-5.8	14.4	16	3.200	0
16	elbow	32	-5.8	14.4	17	4.400	0
17	elbow	32	-10.2	14.4	18	3.200	0
18	elbow	28.8	-10.2	14.4	19	1.000	0
19	elbow	28.8	-11.2	14.4	20	3.200	0
20	elbow	32	-11.2	14.4	21	4.600	0
21	smooth	32	-15.8	14.4	22	5.000	0
22	smooth	32	-20.8	14.4	23	5.700	0
23	elbow	32	-26.5	14.4	24	0.800	0
24	elbow	32.8	-26.5	14.4	25	0.900	-90
to filter	external	32.8	-26.5	13.5			
Total length of hot leg						92.810	

[3] Pipe section (volume) with number i is located between the junction number i-1 and the junction i.

Table A- 6: Pipe routing between components of HCPB TBM cooling system

Junction		Junction co-ordinates			Component[4]		
Name	Location	x (m)	y (m)	z (m)	Name	Length (m)	Vert. angle (degrees)
jun15	HX, out	31.4	-28.8	11	pipe 16-1	0.30	-90
16-1	pipe 16	31.4	-28.8	10.7	pipe 16-2	0.90	0
17-1	branch 17	31.4	-27.9	10.7	branch 17	0.50	0
17-2	branch 17	31.4	-27.4	10.7	pipe 18-1	0.90	0
18-1	pipe 18	31.4	-26.5	10.7	pipe 18-2	0.30	90
2-1	circ., in	31.4	-26.5	11	circulator	0.60	90
2-2	circ., out	31.4	-26.5	11.6			
8-1	filter 8, in	32.8	-26.5	13.5	filter 8	2.50	-90
8-2	filter 8, out	32.8	-26.5	11	pipe 91-1	0.30	-90
91-1	pipe 91	32.8	-26.5	10.7	pipe 91-2	0.90	0
92-1	branch 92	32.8	-27.4	10.7	branch 92	0.50	0
92-2	branch 92	32.8	-27.9	10.7	pipe 93-1	0.90	0
93-1	pipe 93	32.8	-28.8	10.7	pipe 93-2	1.50	90
vlve94	valve 94	32.8	-28.8	12.2	pipe 95-1	1.50	90
95-1	pipe 95	32.8	-28.8	13.7	pipe 95-2	0.70	0
jun96	pipe 95/96	32.1	-28.8	13.7	pipe 97-1	0.70	0
97-1	pipe 97	31.4	-28.8	13.7	pipe 97-2	0.50	-90
jun98	HX, in	31.4	-28.8	13.2	HX 10	2.20	-90
jun15	HX, out	31.4	-28.8	11			
92-3	branch 92	32.8	-27.65	10.7	vol111	1.50	90
vlve112	valve 112	32.8	-27.65	12.2	pipe 113-1	0.60	90
113-1	pipe 113	32.8	-27.65	12.8	pipe 113-2	1.40	0
jun123	heater, in	31.4	-27.65	12.8	heater 114	1.80	-90
jun125	heater out	31.4	-27.65	11	vol115	0.30	-90
17-3	branch 17	31.4	-27.65	10.7			

[4] Component specified in a certain line i is located between the junction in line i and the junction in line i+1.

Table A- 7: Energy loss coefficients of junctions for forward and reverse flow

Junction No.	forward	reverse	Junction No.	forward	reverse
jun15	0.5	0	93-1	0.2	0.2
16-1	0.2	0.2	vlve94	1.0	1.0
17-1	0	0	95-1	0.2	0.2
17-2	0	0	jun96	0.5	0
17-3	0	0.5	97-1	0.2	0.7
18-1	0.2	0.2	jun98	0	0.5
91-1	0.2	0.2	vlve112	7.0	7.0
92-1	0	0	113-1	0.2	0.2
92-2	0	0	jun123	0	0.5
92-3	0.8	0.4	jun125	0.5	0

Table A- 8: First wall components heat structures – Geometrical parameters

Component No.	Volume No.	Heat Struct. Name	Channels Number of	HS-length (m)	ht-area (m^2)	ht-hydr. Dia (m)
20	1	1	15	0.615	0.2069	0.0457
		2	15	0.615	0.3965	0.0238
	2	1	15	0.423	0.1423	0.0457
		2	15	0.423	0.2727	0.0238
	3	1	15	0.422	0.1419	0.0457
		2	15	0.422	0.2721	0.0238
	4	1	15	0.423	0.1423	0.0457
		2	15	0.423	0.2727	0.0238
	5	1	15	0.615	0.2069	0.0457
		2	15	0.615	0.3965	0.0238
21	1	1	2	0.615	0.0276	0.0457
		2	2	0.615	0.0529	0.0238
	2	1	2	0.423	0.0190	0.0457
		2	2	0.423	0.0364	0.0238
	3	1	2	0.422	0.0189	0.0457
		2	2	0.422	0.0363	0.0238
	4	1	2	0.423	0.0190	0.0457
		2	2	0.423	0.0364	0.0238
	5	1	2	0.615	0.0276	0.0457
		2	2	0.615	0.0529	0.0238
22	1	1	2	0.615	0.0276	0.0457
		2	2	0.615	0.0529	0.0238
	2	1	2	0.423	0.0190	0.0457
		2	2	0.423	0.0364	0.0238
	3	1	2	0.422	0.0189	0.0457
		2	2	0.422	0.0363	0.0238
	4	1	2	0.423	0.0190	0.0457
		2	2	0.423	0.0364	0.0238
	5	1	2	0.615	0.0276	0.0457
		2	2	0.615	0.0529	0.0238
23	1	1	14	0.615	0.1931	0.0457
		2	14	0.615	0.3701	0.0238
	2	1	14	0.423	0.1328	0.0457
		2	14	0.423	0.2545	0.0238
	3	1	14	0.422	0.1325	0.0457
		2	14	0.422	0.2539	0.0238
	4	1	14	0.423	0.1328	0.0457
		2	14	0.423	0.2545	0.0238
	5	1	14	0.615	0.1931	0.0457
		2	14	0.615	0.3701	0.0238

Remarks: (compare sketches in section 3.4.1.2)

- HS-length is equal to the length of the pertaining hydrodynamic volume.
- ht-area is the heat transfer area of the HS, resulting from the product of number of channels times HS poloidal width in the unit cell (see drawing in section 3.4.1.2) times HS-length.
- ht-hydr. Dia is the heat transfer hydraulic diameter (i.e., the heated equivalent diameter), resulting from 4 times coolant channel cross section divided by HS poloidal width.

Table A- 9: End caps heat structures – geometrical parameters

Line No.	Parameter	Top end cap		Bottom end cap	
		Volume 1 and Volume 2		Volume 1 and Volume 2	
		HS1	HS2	HS1	HS2
1	steel plate thickness (cap total), m	0.075	0.075	0.075	0.075
2	steel plate toroidal length, m	1.218	1.218	1.218	1.218
3	steel plate radial depth, m	0.51	0.51	0.51	0.51
4	cooling channel toroidal width, m	0.009	0.009	0.01	0.01
5	cooling channel poloidal width, m	0.009	0.009	0.01	0.01
6	cooling channel toroidal pitch, m	0.087	0.087	0.087	0.087
7	total number of channels per plate	14	14	14	14
8	equivalent heat structure thickness steel, m	0.01828	0.01828	0.01818	0.01818
9	total flow cross section per component, m^2	0.001134	0.001134	0.0014	0.0014
10	equivalent flow channel width, m	0.0009310	0.0009310	0.001149	0.001149
11	HS left boundary co-ordinate, m (card 000)	4.6552E-04	4.6552E-04	5.7471E-04	5.7471E-04
12	number of radial mesh points (card 000)	3	3	3	3
13	mesh interval, first and second, m (card 101)	9.1422E-03	9.1422E-03	9.0876E-03	9.0876E-03
14	source value for mesh intervals (card 301)	1.0	1.0	1.0	1.0
15	left surface area of HS, m^2 (card 501)	0.62118	0.62118	0.62118	0.62118
16	right surface area of HS, m^2 (card 601)	0.62118	0.62118	0.62118	0.62118
17	power in steel of heat structure, W	read from power table 24			
18	internal source multiplier (card 701)	0.25	0.25	0.25	0.25
19	heat transfer hydraulic diameter, m (card 801)	0.018	0.018	0.02	0.02
20	Additional information				
21	total steel volume, m^3	0.01136	0.01136	0.01129	0.01129
22	total steel mass, kg	87.4563	87.4563	86.934	86.934
23	steel fraction in plate	0.9752		0.9693	

Definitions: (Numbers in brackets () refer to line No. in above table)
(1) through (7) are given input
(8) equivalent HS thickness = ¼ x { (1) – 2 x (7) x (4) x (5) / (2) }
(9) total flow cross section per component = (4) x (5) x (7)
(10) equivalent flow channel width = (9) / (2)
(11) HS left boundary co-ordinate = ½ x (10)
(13) mesh interval (first and second) = ½ x (8)
(15) left surface area of HS = (2) x (3)
(16) right surface area of HS = (2) x (3)
(19) heat transfer hydraulic diameter = 4 x (9) / { (7) x [(4) + (5)] }

Table A- 10: Breeding zone inlet manifolds heat structures

	HS assigned to component number	40	41	42	43
	Inlet manifolds to →	SPs (north)	CPs (north)	CPs (south)	SPs (south)
1	Number of inlet manifolds per BZ half	4	10	10	4
2	Assumed channel inner diameter, m	0.012	0.014	0.014	0.012
3	Channel flow area, m^2	0.0001131	0.0001539	0.0001539	0.0001131
4	RELAP component flow area, m^2	0.0004524	0.001539	0.001539	0.0004524
5	RELAP component wetted perimeter	0.1508	0.4398	0.4398	0.1508
6	RELAP component heated perimeter	0.1508	0.4398	0.4398	0.1508
7	RELAP component inner diameter, m	0.048	0.14	0.14	0.048
8	Poloidal height of single manifold, m	0.0174	0.02254	0.02254	0.0174
9	Poloidal height of all inlet manifolds, m	0.0696	0.2254	0.2254	0.0696
10	Manifold "plate" thickness, m	0.03	0.03	0.03	0.03
11	Assumed steel volume fraction	0.6	0.6	0.6	0.6
12	cross sectional area of inlet plates, m^2	0.001253	0.004057	0.004057	0.001253
13	RELAP component equiv. O.D., m	0.06244	0.1574	0.1574	0.06244
14	left boundary co-ordinate, m (card 000)	0.024	0.07	0.07	0.024
15	number of mesh points (card 000)	3	3	3	3
16	mesh interval, m (card 101)	0.003611	0.004343	0.004343	0.003611
17	Internal source multiplier (card 701)	0.05898	0.1910	0.1910	0.05898
18	heat transfer hydr. dia., m (card 801)	0.012	0.014	0.014	0.012
19	heat structure length, m	0.609	0.609	0.609	0.609

Definitions: (Numbers in brackets () refer to line No. in above table)
(1) and (2) are given by design
(3) channel flow area = $(2)^2 \times \pi / 4$
(4) RELAP component flow area = (1) x (3)
(5) RELAP component wetted perimeter = (1) x (2) x π
(6) RELAP component heated perimeter = (5)
(7) RELAP component inner diameter = (1) x (2)
(8) poloidal height of single manifold = assumed values
(9) poloidal height of all inlet manifolds in a component = (1) x (8)
(10) manifold plate thickness = given by design
(11) assumed steel volume fraction = estimated from design
(12) steel cross sectional area of inlet plates = (9) x (10) x (11)
(13) RELAP component equivalent diameter = $\{ 4 \times (12) / \pi - (7)^2 \}^{0.5}$
(14) left boundary co-ordinate = ½ x (7)
(15) number of mesh points = chosen values
(16) mesh interval = 0.25 x [(13) – (7)]
(17) see section 3.6.1.5
(18) heat transfer hydraulic diameter = 4 x (4) / (6)
(19) heat structure length = given by design

Table A- 11: Breeding zone heat structures

	Parameter	Breeder components 51 (north) & 52 (south)		Beryllium components 50 (north) & 53 (south)	
		Volumes 1 & 2		Volumes 1 & 2	
		HS1	HS2	HS1	HS2
1	steel plate thickness (CP or SP), m	0.005	0.005	0.005	0.005
2	steel plate toroidal width (half TBM), m	0.609	0.609	0.609	0.609
3	steel plate radial depth, m	0.4	0.4	0.4	0.4
4	channel toroidal width, m	0.003	0.003	0.003	0.003
5	channel poloidal width, m	0.003	0.003	0.003	0.003
6	channel toroidal pitch, m	0.005	0.005	0.005	0.005
7	total number of channels per plate	60	60	60	60
8	number of blind channels per plate	0	0	20	20
9	number of cooling channels per plate	60	60	40	40
10	equivalent steel thickness in HS, m	0.001613	0.001613	0.001613	0.001613
11	equivalent Be pebble bed thickness in HS, m	0	0.0255	0.0225	0.0225
12	equivalent breeder pebble bed thickness in HS, m	0.0085	0	0	0
13	channel cross sectional area per plate, m^2	0.00054	0.00054	0.00036	0.00036
14	number of plates per component	10	10	4	4
15	total flow cross section per component, m^2	0.0054	0.0054	0.00144	0.00144
16	equivalent flow channel width in component, m	0.001773	0.001773	0.001182	0.001182
17	HS left boundary co-ordinate, m	0.0008867	0.0008867	0.0005911	0.0005911
18	number of radial mesh points (card 000)	4	4	4	4
19	mesh interval, first, m (card 101)	0.001613	0.001613	0.001613	0.001613
20	mesh interval, second, m (card 101)	0.00425	0.01275	0.01125	0.01125
21	mesh interval, third, m (card 101)	0.00425	0.01275	0.01125	0.01125
22	left surface area of HS, m^2 (card 501)	1.218	1.218	0.4872	0.4872
23	heat transfer hydr. dia., m (card 801)	0.007094	0.007094	0.004729	0.004729

Definitions: (Numbers in brackets () refer to line No. in above table)
(1) through (9) are given by design
(10) equivalent steel thickness in HS = 0.5 x [(1) x (2) – 2 x (7) x (4) x (5)] / (2)
(11) equivalent Be pebble bed thickness in HS = 0.5 x 0.045 for beryllium components, and
= [8 x 0.5 x 0.045 + 2 x 0.0375] / 10 for HS2 of breeder components
(12) equivalent breeder pebble bed thickness = 0.5 x 0.017 for HS1 of breeder components
(13) channel cross sectional area per plate = (4) x (5) x (9)
(14) number of plates per component = given by design
(15) total flow cross section per component = (13) x (14)
(16) equivalent flow channel width in component = (13) / [0.5 x (2)]
(17) HS left boundary co-ordinate = 0.5 x (16)
(18) number of radial mesh points = chosen
(19) mesh interval, first = (10)
(20) and (21) mesh interval, second & third = 0.5 x (12) for HS1 of breeder components, and = 0.5 x (11) for HS2 of breeder components and for Be components
(22) left surface area of HS = 0.5 x (2) x (3) x (14)
(23) heat transfer hydraulic diameter = 4 x (13) / [0.5 x (2)]

Table A- 12: Breeding zone outlet manifolds heat structures

	HS assigned to component number	60	61	62	63
	Outlet manifolds from	SPs (north)	CPs (north)	CPs (south)	SPs (south)
1	Number of outlet manifolds per BZ half	4	10	10	4
2	Assumed channel inner diameter, m	0.012	0.014	0.014	0.012
3	Channel flow area, m^2	0.0001131	0.0001539	0.0001539	0.0001131
4	RELAP component flow area, m^2	0.0004524	0.001539	0.001539	0.0004524
5	RELAP component wetted perimeter	0.1508	0.4398	0.4398	0.1508
6	RELAP component heated perimeter	0.1508	0.4398	0.4398	0.1508
7	RELAP component inner diameter, m	0.048	0.14	0.14	0.048
8	Poloidal height of single manifold, m	0.0174	0.02254	0.02254	0.0174
9	Poloidal height of all inlet manifolds, m	0.0696	0.2254	0.2254	0.0696
10	Manifold "plate" thickness, m	0.03	0.03	0.03	0.03
11	Assumed steel volume fraction	0.6	0.6	0.6	0.6
12	cross sectional area of outlet plates, m^2	0.001253	0.004057	0.004057	0.001253
13	RELAP component equiv. O.D., m	0.06244	0.1574	0.1574	0.06244
14	left boundary co-ordinate, m (card 000)	0.024	0.07	0.07	0.024
15	number of mesh points (card 000)	3	3	3	3
16	mesh interval, m (card 101)	0.003611	0.004343	0.004343	0.003611
17	Internal source multiplier (card 701)	0.05898	0.1910	0.1910	0.05898
18	heat transfer hydr. dia., m (card 801)		0.014	0.014	0.012
19	heat structure length, m	0.609	0.609	0.609	0.609

Definitions: (Numbers in brackets () refer to line No. in above table)
(1) and (2) are given by design
(3) channel flow area = $(2)^2 \times \pi / 4$
(4) RELAP component flow area = (1) x (3)
(5) RELAP component wetted perimeter = (1) x (2) x π
(6) RELAP component heated perimeter = (5)
(7) RELAP component inner diameter = (1) x (2)
(8) poloidal height of single manifold = assumed values
(9) poloidal height of all outlet manifolds in a component = (1) x (8)
(10) manifold plate thickness = given by design
(11) assumed steel volume fraction = estimated from design
(12) steel cross sectional area of outlet plates = (9) x (10) x (11)
(13) RELAP component equivalent diameter = $\{ 4 \times (12) / \pi - (7)^2 \}^{0.5}$
(14) left boundary co-ordinate = ½ x (7)
(15) number of mesh points = chosen values
(16) mesh interval = 0.25 x [(13) – (7)]
(17) see section 3.6.1.7
(18) heat transfer hydraulic diameter = 4 x (4) / (6)
(19) heat structure length = given by design

Table A- 13: Heat exchanger heat structures

	Primary side		Secondary side
	End domes	Tube bundle	HX shell
HS attached to component - volumes	10-1 & 10-7	10-2 to 10-6	102-1 & 102-2
Number of HS of the same geometry	2	5	2
HS equivalent inner diameter, m	0.276	0.014	0.276
HS equivalent outer diameter, m	0.3325	0.018	0.3
HS length, m	0.5	23.04	0.24
Left heat transfer hydraulic diameter, m	0.276	0.014	0.1633
Right heat transfer hydraulic diameter, m	-	0.018	-
Left boundary condition	HTP1	HTP1	HTP1
Right boundary condition	adiabatic	HTP1	adiabatic
Number of radial mesh points	2	2	2
HS material	316 L	Incoloy 800	316 L

Table A- 14: Thermal conductivity of heat structure materials

Temperature (K) ↓	AISI 316L	INCOLOY 800	MANET	Be pebbles	Be dense	Li4SiO4
Material ID →	50	100	150	200	210	250
100	10.8					
293		11.5	24.21		183	
300	14					0.721
303				1.06		0.722
373		13			163	0.759
393			24.78			0.770
400						0.774
473		14.7		4.12	143	0.821
493			25.25			0.835
500						0.839
573		16.3		7.54	128	0.894
593			25.63			0.910
600						0.916
673		17.9		11.27	115	0.979
693			25.96			0.997
700						1.004
773		19.5		15.29	106	1.075
793			26.24			1.095
800						1.103
873		21.1		19.54	97	1.182
893			26.45			1.205
900						1.213
973		22.8		23.99	89	1.301
1073		24.7		28.61	85	1.431
1100						1.468
1173		27.1		33.34		1.572
1200						1.612
1273		31.9		38.16		1.725
1300						1.768
1373				43.02		1.889
1400						1.935
1473				47.88		2.064
1500						2.113
1530						2.169
1573				52.71		2.251
1700	36					2.504
1701	18					2.506
2000			26.45			3.175
3000	22.2	31.9		52.71	85	6.146
4000			26.45			

Note: Values for temperatures above 1700K have no physical meaning and are given for numerical reasons only.

Table A- 15: Volumetric heat capacity of heat structure materials

Temperature (K) ↓	AISI 316L	INCOLOY 800	MANET	Be pebbles	Be dense	Li4SiO4
Material ID →	50	100	150	200	210	250
100	3.85E+06					
273						1.40E+06
293		3.65E+06				
300	4.02E+06		3.49E+06	2.73E+06	3.38E+06	
373						2.25E+06
400			3.85E+06	3.31E+06	4.10E+06	
473						2.46E+06
500			4.13E+06	3.64E+06	4.50E+06	
573						2.67E+06
600			4.47E+06	3.87E+06	4.79E+06	
673						2.88E+06
700			4.96E+06	4.05E+06	5.02E+06	
773						3.09E+06
800			5.64E+06	4.22E+06	5.23E+06	
873						3.17E+06
900			6.46E+06	4.37E+06	5.42E+06	
973						3.30E+06
1000				4.52E+06	5.60E+06	
1073						3.41E+06
1100				4.66E+06	5.78E+06	
1173						3.49E+06
1200				4.81E+06	5.96E+06	
1273						3.53E+06
1300				4.95E+06	6.14E+06	
1373						3.56E+06
1400				5.10E+06	6.32E+06	
1473						3.58E+06
1500				5.24E+06	6.50E+06	
1530				5.29E+06	6.55E+06	
1700	5.00E+06					
1701	5.31E+06					
2000			6.46E+06			3.58E+06
3000	4.46E+06	3.65E+06		5.29E+06	6.55E+06	3.58E+06
4000			6.46E+06			

Note: Values for temperatures above 1700K have no physical meaning and are given for numerical reasons only.

APPENDIX B – RELAP Input Deck

B-1 Introduction

A complete input deck prepared for safety analysis of the HCPB TBM system is presented in this Appendix B. It includes in section B-3 the RELAP5/MOD3.2 input deck for the steady state calculation and in section B-4 an example for a transient run. For easy cross referencing with the model description given in the main part of the report, the input list provides headings, which in section B-3 correspond to the breakdown used in the model description.

For details of input cards please refer to the RELAP5/MOD3 code manual, Volume II: User's guide and input requirements, in particular to sections A1 through A6 related to various control cards, section A7 concerning hydrodynamic components, and section A8 dealing with heat structures. The manual sections A10 and A11 cover heat structure thermal property data and general table data information, respectively. The plot request input data defined in A13 and the strip request data description in A15 are of interest in connection with the transient calculation input file.

All lines of the input list beginning with a asterisk (*) are comment cards and are ignored by the code during run time.

B-2 Contents of Appendix B

B-3 RELAP5 Input Deck

B-3.1 Prologue and key data

```
=tbm1
**- This file is based on tbm7.
**- Changes to tbm7.i refer to pump speed control,
**- friction factor for vlve94 for HX flow control,
**- pressuriser junction (vlve76) relocation
**- additional components are defined in the
transient
**- restart file.
**---------------------- KEY DATA ----------------------------
**- Difference in altitude TBM - HX = - 10.95 m
**- T(1/2) circulator  =  2 s (tbd s)
**- Surface heat flux to first wall = 25 MW/m2
**- T(TBM, in) = 250 C, T(TBM, out)=500 C
**- Rev. 4 cooling system
**- PI-TBM extreme operating conditions
**- 33 FW- cooling channels
**- 5 breeder layers, 4 stiffening plates
**- Total mass flow rate in system = 0.72 kg/s
**- Component and heat structure numbering
**- see Component-Numbers.xls
```

B-3.2 Job control

```
100  new  stdy-st
*101  inp-chk
110  helium
**- time step and minor and major edit control
201    1. 1.0-9  0.002  15011  500   500 10000
202    5. 1.0-9  0.010  15011  100   500 10000
203  600. 1.0-9  0.015  15011  500 10000 10000
**- additional minor edit requests
319  mflowj 18010000
326  pmpvel  2
327  pmphead 2
328  pmptrq  2
330  httemp 20200302
332  cntrlvar 10
20800011 httemp 22200302
20800015 httemp 23200302
20800034 httemp 20200102
20800035 httemp 20200202
20800036 httemp 20200302
20501000 pdiff1 sum 1. 0.0 1
20501001 0.0 1.0 p  6250000 -1.0 p  91010000
**----------------------- TRIPS -------------------------
*** pump keeps running in steady state
501  time  0  ge  null  0  10000.0  l
*** TBM power generation history
502  time  0  ge  null  0  10000.0  l
*** Pressuriser is open if p>1MPa
504 p 10010000 gt null  0   1.0+6   l
*** secondary side water flow control on
509  time 0   gt null   0  10000.0  n  -1.0
*** Valve in HX line remains open
510 time 0 ge null 0 0.0   l
*** Bypass closed for p>10 Pa
511  p  10010000  lt null  0  10.  l
```

B-3.3 Hydrodynamics of TBM, piping and components

B-3.3.1 TBM hydrodynamics

B-3.3.1.1 Main inlet manifold

```
0040000  manif4 branch
0040001 7 0
**-dimensions
0040101 0.0036 1.218  0. 180. 0. 0. 2.0-5 0.06
0011000
0040200 104 8.0+6 523.15 0.0
**-junctions to and from manifold
**-energy loss coefficients from Eck p. 234 and 237
0041101 003250002 004010004 0.0 0.3 0.3
0000100
0041201 0.0 0.0 0.0
0042101 004010002 020010001 0.0 0.5 0.5
0000100
0042201 0.0 0.0 0.0
0043101 004010002 021010001 0.0 0.5 0.5
0000100
0043201 0.0 0.0 0.0
0044101 004010001 022010001 0.0 0.5 0.5
0000100
0044201 0.0 0.0 0.0
0045101 004010001 023010001 0.0 0.5 0.5
0000100
0045201 0.0 0.0 0.0
0046101 004010006 024010001 0.0 0.5 0.5
0000100
0046201 0.0 0.0 0.0
0047101 004010005 025010001 0.0 0.5 0.5
0000100
0047201 0.0 0.0 0.0
```

B-3.3.1.2 First wall

```
**--------------------- 4 FW components    --------------
**-component 20, 15 FW channels
0200000  pipe20 pipe
0200001  5
0200101  0.003840  5
0200301  0.615 1 0.423 2 0.422 3 0.423 4 0.614 5
0200401  0.0 5
0200501  90. 1 0. 4 270. 5
0200601  0. 5
0200801  5.0-6 0.016 1 5.0-4 0.016 4 5.0-6 0.016 5
0201001  0011000 5
0201201  104 8.0+6 523.15 0.0 0.0 0.0 5
0201300  1
**- junction loss coefficient in FW corners
0200901  0.2 0.2 1 0.0 0.0 3 0.02 0.02 4
0201101  0001000 4
0201301  0.2431 0.2431 0.0 4
**-component 21, 2 FW channels
0210000  pipe21 pipe
0210001  5
0210101  0.000512 5
0210301  0.615 1 0.423 2 0.422 3 0.423 4 0.614 5
0210401  0.0 5
0210501  90. 1 0. 4 270. 5
0210601  0. 5
0210801  5.0-6 0.016 1 5.0-4 0.016 4 5.0-6 0.016 5
0211001  0011000 5
0211201  104 8.0+6 523.15 0.0 0.0 0.0 5
0211300  1
**- junction loss coefficient in FW corners
0210901  0.2 0.2 1 0.0 0.0 3 0.02 0.02 4
0211101  0001000 4
0211301  0.0324 0.0324 0.0 4
```

```
**-component 22, 2 FW channels
0220000  pipe22 pipe
0220001  5
0220101  0.000512 5
0220301  0.615 1 0.423 2 0.422 3 0.423 4 0.614 5
0220401  0.0 5
0220501  90. 1 0. 4 270. 5
0220601  0. 5
0220801  5.0-6 0.016 1 5.0-4 0.016 4 5.0-6 0.016 5
0221001  0011000 5
0221201  104 8.0+6 523.15 0.0 0.0 0.0 5
0221300  1
**- junction loss coefficient in FW corners
0220901  0.2 0.2 1 0.0 0.0 3 0.02 0.02 4
0221101  0001000 4
0221301  0.0324 0.0324 0.0 4
**-component 23, 14 FW channels
0230000  pipe23 pipe
0230001  5
0230101  0.003584 5
0230301  0.615 1 0.423 2 0.422 3 0.423 4 0.614 5
0230401  0.0 5
0230501  90. 1 0. 4 270. 5
0230601  0. 5
0230801  5.0-6 0.016 1 5.0-4 0.016 4 5.0-6 0.016 5
0231001  0011000 5
0231201  104 8.0+6 523.15 0.0 0.0 0.0 5
0231300  1
**- junction loss coefficient in FW corners
0230901  0.2 0.2 1 0.0 0.0 3 0.02 0.02 4
0231101  0001000 4
0231301  0.2269 0.2269 0.0 4
```

B-3.3.1.3 End caps

```
**-component 24, end cap top
0240000  pipe24 pipe
0240001  2
0240101  0.001134 2
0240301  0.501 2
0240401  0.0 2
0240501  90. 1 270. 2
0240601  0. 2
0240801  5.0-6 0.009 2
0240901  0.4 0.4 1
0241001  0011000 2
0241101  0001000 1
0241201  104 8.0+6 523.15 0.0 0.0 0.0 2
0241300  1
0241301  0.0793 0.0793 0.0 1
**-component 25, end cap bottom
0250000  pipe25 pipe
0250001  2
0250101  0.0014 2
0250301  0.501 2
0250401  0.0 2
0250501  90. 1 270. 2
0250601  0. 2
0250801  5.0-6 0.01 2
0250901  0.4 0.4 1
0251001  0011000 2
0251101  0001000 1
0251201  104 8.0+6 523.15 0.0 0.0 0.0 2
0251300  1
0251301  0.1028 0.1028 0.0 1
```

B-3.3.1.4 Intermediate manifolds

```
**-component 30, manifold north
0300000  manif30 branch
0300001 6 0
**-dimensions
0300101 0.0032 0.59 0. 0. 0. 0. 2.0-5 0.053
0011000
0300200 104 8.0+6 647. 0.0
**-junctions to and from manifold
**-energy loss coefficients from Eck p. 236 and 237
0301101 020050002 030010006 0.0 0.0 0.5
0000100
0301201 0.0 0.0 0.0
0302101 021050002 030010006 0.0 0.0 0.5
0000100
0302201 0.0 0.0 0.0
0303101 024020002 030010002 0.0 0.0 0.5
0000100
0303201 0.0 0.0 0.0
0304101 025020002 030010001 0.0 0.0 0.5
0000100
0304201 0.0 0.0 0.0
0305101 030010005 040010001 0.0 0.5 0.0
0000100
0305201 0.0 0.0 0.0
0306101 030010005 041010001 0.0 0.5 0.0
0000100
0306201 0.0 0.0 0.0
**-component 31, manifold south
0310000  manif31 branch
0310001 6 0
**-dimensions
0310101 0.0032 0.59 0. 0. 0. 0. 2.0-5 0.053
0011000
0310200 104 8.0+6 647. 0.0
**-junctions to and from manifold
**-energy loss coefficients from Eck p. 236 and 237
0311101 022050002 031010005 0.0 0.0 0.5
0000100
0311201 0.0 0.0 0.0
0312101 023050002 031010005 0.0 0.0 0.5
0000100
0312201 0.0 0.0 0.0
0313101 024020002 031010002 0.0 0.0 0.5
0000100
0313201 0.0 0.0 0.0
0314101 025020002 031010001 0.0 0.0 0.5
0000100
0314201 0.0 0.0 0.0
0315101 031010006 042010001 0.0 0.5 0.0
0000100
0315201 0.0 0.0 0.0
0316101 031010006 043010001 0.0 0.5 0.0
0000100
0316201 0.0 0.0 0.0
```

B-3.3.1.5 Breeding zone inlet manifolds

```
**.component 40 nanifold north to beryllium -----------
---
0400000  vol40 snglvol
0400101  4.52-4 0.609 0.0 180. 0.0 0.0 5.0-6 0.012
0011000
0400200  104 8.0+6 647. 0.0
**-junction 40 - 50
0450000  jun45 sngljun
0450101  040010002 050010001 0.0 0.5 0.0
0001100
0450201  0 0.0 0.0 0.0
**-component 41 nanifold north to breeder -------------
---
0410000  vol41 snglvol
0410101  1.539-3 0.609 0.0 180. 0.0 0.0 5.0-6 0.014
0011000
```

0410200 104 8.0+6 647. 0.0
**-junction 41 - 51
0460000 jun46 sngljun
0460101 041010002 051010001 0.0 0.5 0.0
0001100
0460201 0 0.0 0.0 0.0
**.component 42 nanifold south to breeder -------
0420000 vol42 snglvol
0420101 1.539-3 0.609 0.0 0. 0.0 0.0 5.0-6 0.014
0011000
0420200 104 8.0+6 647. 0.0
**-junction 42 - 52
0470000 jun47 sngljun
0470101 042010002 052010001 0.0 0.5 0.0
0001100
0470201 0 0.0 0.0 0.0
**.component 43 nanifold south to beryllium   ----
0430000 vol43 snglvol
0430101 4.52-4 0.609 0.0 0. 0.0 0.0 5.0-6 0.012
0011000
0430200 104 8.0+6 647. 0.0
**-junction 43 - 53
0480000 jun48 sngljun
0480101 043010002 053010001 0.0 0.5 0.0
0001100
0480201 0 0.0 0.0 0.0
**-junction 42 - 54
0490000 jun49 sngljun
0490101 042010002 054010001 0.0 0.5 0.0
0001100
0490201 0 0.0 0.0 0.0

B-3.3.1.6 Breeding zone

**----------- component 50, beryllium north --------------
--
0500000 pipe50 pipe
0500001 2
0500101 0.00144 2
0500301 0.4 2
0500401 0.0 2
0500501 90. 1 270. 2
0500601 0. 2
0500801 5.0-6 0.003 2
0501001 0011000 2
0501201 104 8.0+6 709.15 0.0 0.0 0.0 2
0501300 1
**- junction loss coefficient in channel return bends
0500901 0.4 0.4 1
0501101 0001000 1
0501301 0.0776 0.0776 0.0 1
**----------- component 51, breeder north ---------------

0510000 pipe51 pipe
0510001 2
0510101 0.0054 2
0510301 0.4 2
0510401 0.0 2
0510501 90. 1 270. 2
0510601 0. 2
0510801 5.0-6 0.003 2
0511001 0011000 2
0511201 104 8.0+6 709.15 0.0 0.0 0.0 2
0511300 1
**- junction loss coefficient in channel return bends
0510901 0.4 0.4 1
0511101 0001000 1
0511301 0.2809 0.2809 0.0 1
**----------- component 52, breeder south ---------------

0520000 pipe52 pipe
0520001 2
0520101 0.0054 2
0520301 0.4 2
0520401 0.0 2
0520501 90. 1 270. 2
0520601 0. 2
0520801 5.0-6 0.003 2
0521001 0011000 2
0521201 104 8.0+6 709.15 0.0 0.0 0.0 2
0521300 1
**- junction loss coefficient in channel return bends
0520901 0.4 0.4 1
0521101 0001000 1
0521301 0.2809 0.2809 0.0 1
**----------- component 53, beryllium south -------------

0530000 pipe53 pipe
0530001 2
0530101 0.00144 2
0530301 0.4 2
0530401 0.0 2
0530501 90. 1 270. 2
0530601 0. 2
0530801 5.0-6 0.003 2
0531001 0011000 2
0531201 104 8.0+6 709.15 0.0 0.0 0.0 2
0531300 1
**- junction loss coefficient in channel return bends
0530901 0.4 0.4 1
0531101 0001000 1
0531301 0.0776 0.0776 0.0 1
**------EXTRA component 54, breeder south, for SAFETY--------
0540000 pipe54 pipe
0540001 2
0540101 9.0-6 2
0540301 0.4 2
0540401 0.0 2
0540501 90. 1 270. 2
0540601 0. 2
0540801 5.0-6 0.003 2
0541001 0011000 2
0541201 104 8.0+6 709.15 0.0 0.0 0.0 2
0541300 1
**- junction loss coefficient in channel return bends
0540901 0.4 0.4 1
0541101 0001000 1
0541301 3.0-4 3.0-4 0.0 1

B-3.3.1.7 Breeding zone outlet manifolds

**.component 60 nanifold north from beryllium --------

0600000 vol60 snglvol
0600101 4.52-4 0.609 0.0 180. 0.0 0.0 5.0-6 0.012
0011000
0600200 104 8.0+6 771.86 0.0
**-junction 50 - 60
0550000 jun55 sngljun
0550101 050020002 060010001 0.0 0.0 0.5
0001100
0550201 0 0.0 0.0 0.0
**.component 61 nanifold north from breeder --------

0610000 vol61 snglvol
0610101 1.539-3 0.609 0.0 180. 0.0 0.0 5.0-6 0.014
0011000
0610200 104 8.0+6 770.96 0.0
**-junction 51 - 61

0560000 jun56 sngljun
0560101 051020002 061010001 0.0 0.0 0.5
0001100
0560201 0 0.0 0.0 0.0
**.component 62 nanifold south from breeder ---------

0620000 vol62 snglvol
0620101 1.539-3 0.609 0.0 0. 0.0 0.0 5.0-6 0.014
0011000
0620200 104 8.0+6 770.96 0.0
**-junction 52 - 62
0570000 jun57 sngljun
0570101 052020002 062010001 0.0 0.0 0.5
0001100
0570201 0 0.0 0.0 0.0
**.component 63 nanifold south from beryllium -------

0630000 vol63 snglvol
0630101 4.52-4 0.609 0.0 0. 0.0 0.0 5.0-6 0.012
0011000
0630200 104 8.0+6 771.86 0.0
**-junction 53 - 63
0580000 jun58 sngljun
0580101 053020002 063010001 0.0 0.0 0.5
0001100
0580201 0 0.0 0.0 0.0
**-junction 54 - 62
0590000 jun59 sngljun
0590101 054020002 062010001 0.0 0.0 0.5
0001100
0590201 0 0.0 0.0 0.0

B-3.3.1.8 Main outlet manifold

0050000 manif5 branch
0050001 5
**-dimensions
0050101 0.0036 1.218 0. 180. 0. 0. 2.0-5 0.06
0011000
0050200 104 8.0+6 771. 0.0
**-junctions to and from manifold
**-energy loss coefficients from Eck p. 236 and 237
0051101 060010002 005010003 0.0 0.0 0.5
0000100
0051201 0.0 0.0 0.0
0052101 061010002 005010003 0.0 0.0 0.5
0000100
0052201 0.0 0.0 0.0
0053101 062010002 005010003 0.0 0.0 0.5
0000100
0053201 0.0 0.0 0.0
0054101 063010002 005010003 0.0 0.0 0.5
0000100
0054201 0.0 0.0 0.0
0055101 005010004 006010001 0.0 0.5 0.0
0000100
0055201 0.0 0.0 0.0

B-3.3.2 Piping hydrodynamics

B-3.3.2.1 Cold leg architecture

0030000 pipe3 pipe
0030001 25
0030101 0.003664 21
0030102 0.01028   25
0030301 0.7 1 2.8 2   5.0 4   4.0 5   3.2 6   2.2
7
0030302 3.2 10 2.2 11 4.2 12   5.4 13   5.0 14
0030303 7.0 15 7.2 16 2.8 17   1.204 18 6.05
19
0030304 3.178 20 4.851 21 4.455   22 4.554 23
0030305 1.031 24 0.51   25
0030501 0. 25
0030601 0. 1   90. 2 0.   15   -90. 16
0030602 0. 18   -90. 19   0.   25
0030801 5.0-5 0.0683 21
0030802 5.0-5 0.1144 25
0030901 0.2 0.2 2 0. 0. 4 0.2 0.2   12
0030902 0. 0. 13 0.2 0.2 20 0. 0. 22   0.2 0.2 24
0031001 0011000 25
0031101 20 24
0031201 104 78.5+5 523. 0.0 0.0 0.0 25
0031300 1
0031301 0. 0.717 0. 24

B-3.3.2.2 Hot leg architecture

0060000 pipe6 pipe
0060001 25
0060101 0.01028 4
0060102 0.003664   25
0060301 0.51 1   1.031   2   4.554 3   4.455 4
5.445   5
0060302 4.258 6   6.05 7   0.707 8   2.2 9   7.2
10
0060303 7.6 11   5.6 12   6.0 13   4.2 14   1.0 15
0060304 3.2 16   4.4 17   3.2 18   1.0 19   3.2 20
0060305 4.6 21   5.0 22   5.7 23   0.8 24   0.9 25
0060501 0. 25
0060601 0. 6   90. 7 0.   9   90. 10
0060602 0. 24   -90. 25
0060801 5.0-5 0.1144   4
0060802 5.0-5 0.0683 25
0060901 0.2 0.2 2 0. 0. 4 0.2 0.2   11
0060902 0. 0. 12 0.2 0.2 20 0. 0. 22   0.2 0.2 24
0061001 0011000 25
0061101 20 24
0061201 104 78.5+5 773. 0.0 0.0 0.0 25
0061300 1
0061301 0. 0.717 0. 24

B-3.3.2.3 Piping between HCS components

**-pipe 16
0160000 pipe16 pipe
0160001 2
0160101 0.003664 2
0160301 0.3 1 0.9 2
0160501 0.   1 90. 2
0160601 -90. 1 0. 2
0160801 5.0-5 0.0683 2
0160901 0.2 0.2 1
0161001 0011000 2
0161101 20 1
0161201 104 78.5+5 523. 0.0 0.0 0.0 2
0161300 1
0161301 0. 0.717 0. 1
**- branch 17
0170000 branch17 branch
0170001 3 1
0170101 0.003664 0.5 0.0 90. 0. 0. 5.-5 0.0683
11000
0170200 104 78.5+5 523. 0.0
**-energy loss coefficients from Eck p. 236
0171101 016020002 017010001 0.0 0.0 0.0 120
0172101 017010002 018010001 0.0 0.0 0.0 120
0173101 115010002 017010003 0.0 0.0 0.5 120
0171201 0. 0.717 0.
0172201 0. 0.717 0.
0173201 0. 0.717 0.

```
**-pipe 18
0180000  pipe18 pipe
0180001  2
0180101  0.003664  2
0180301  0.9  1  0.3  2
0180501  90.  1  0.   2
0180601  0.   1  90.  2
0180801  5.0-5  0.0683  2
0180901  0.2  0.2  1
0181001  0011000  2
0181101  20  1
0181201  104  87.5+5  523.  0.0  0.0  0.0  2
0181300  1
0181301  0.  0.717  0.  1
**-pipe dust filter - bypass branch
0910000  pipe91  pipe
0910001  2
0910101  0.003664  2
0910301  0.3  1   0.9  2
0910501  0.  1   270.  2
0910601  -90.  1   0.  2
0910801  5.0-5   0.0683  2
0910901  0.2  0.2  1
0911001  11000   2
0911101  0  1
0911201  104  78.5+5  773.  0.0  0.0  0.0  2
0911300  1
0911301  0.  0.717  0.  1
**- branch to bypass
0920000  branch92 branch
0920001  3 1
0920101  0.003664  0.5 0.0  270.  0.  0.  5.-5
0.0683  11000
0920200  104  78.5+5  773.  0.0
**-energy loss coefficients from Eck p. 234
0921101  091020002 092010001  0.0  0.0  0.0  120
0922101  092010002 093010001  0.0  0.0  0.0  120
0923101  092010003 111010001  0.0  0.8  0.4  120
0921201  0.  0.717  0.
0922201  0.  0.717  0.
0923201  0.  0.0  0.
**-pipe bypass branch to valve 94
0930000  pipe93  pipe
0930001  2
0930101  0.003664  2
0930301  0.9  1   1.5  2
0930501  270.  1   0.  2
0930601  0.  1   90.  2
0930801  5.0-5   0.0683  2
0930901  0.2  0.2  1
0931001  11000   2
0931101  0  1
0931201  104  78.5+5  773.  0.0  00  0.0  2
0931300  1
0931301  0.  0.717  0.  1
**-pipe between valve 94 and HX
0950000  pipe95  pipe
0950001  2
0950101  0.003664  2
0950301  1.5  1   0.7  2
0950501  0.  1   270.  2
0950601  90.  1  0.  2
0950801  5.0-5   0.0683  2
0950901  0.2  0.2  1
0951001  11000   2
0951101  0  1
0951201  104  78.5+5  773.  0.0  0.0  0.0  2
0951300  1
0951301  0.  0.717  0.  1
**-junction between pipes 95 and 97
0960000  jun96 sngljun
0960101  095020002 097010001 0.0 0.5 0.0
0001100
0960201  0 0.0 0.0 0.0
**- pipe 97
0970000  pipe97  pipe
0970001  2
0970101  0.003664  2
0970301  0.7  1   0.5   2
0970501  270.  1   0.  2
0970601  0.  1  -90.  2
0970801  5.0-5   0.0683  2
0970901  0.2  0.7  1
0971001  11000   2
0971101  0  1
0971201  104  78.5+5  773.  0.0  0.0  0.0  2
0971300  1
0971301  0.  0.717  0.  1
**-junction between pipes 97 and HX
0980000  jun98 sngljun
0980101  097020002 010010001 0.0 0.0 0.5
0001100
0980201  0 0.0 0.0 0.0
**-junction between pipes HX and cold leg, pipe 16
0150000  jun15 sngljun
0150101  010070002 016010001 0.0 0.5 0.0
0001100
0150201  0 0.0 0.0 0.0
**-pipe branch 92 to valve 112
1110000  vol111  snglvol
1110101  0.003664  1.5  0.0  0.0  90.  1.5  5.0-5
0.0683  11000
1110200  104   78.5+5   773.  0.0
**-pipe 113 between valve 112 and heater
1130000  pipe113  pipe
1130001  2
1130101  0.003664  2
1130301  0.6  1   1.4  2
1130501  0.  1   90.  2
1130601  90.  1  0.  2
1130801  5.0-5   0.0683  2
1130901  0.2  0.2  1
1131001  11000   2
1131101  0  1
1131201  104  78.5+5  773.  0.0  0.0  0.0  2
1131300  1
1131301  0.  0.0  0.  1
**- Junction 113 - 114
1230000  jun123 sngljun
1230101  113020002 114010001 0.0  0.  0.5   0
1230201  1   0.   0.   0.
**-pipe heater to branch 17
1150000  vol115  snglvol
1150101  0.003664  0.3  0.0  0.0  -90.  -0.3  5.0-5
0.0683  11000
1150200  104   78.5+5   773.  0.0
```

B-3.3.3 HCS components hydrodynamics

B-3.3.3.1 HX and secondary water loop

```
**- HX primary side
0100000  pipe10 pipe
0100001  7
0100101  0.05983   1
0100102  0.01478  6
```

```
0100103  0.05983   7
0100301  0.5 1  0.24 6  0.5 7
0100601  -90. 7
0100801  5.0-5 0.014 7
0101001  0  7
0101101  0  6
0101201  104 78.50+5 773. 0.0 0.0 0.0 1
0101202  104 78.50+5 713. 0.0 0.0 0.0 2
0101203  104 78.50+5 660. 0.0 0.0 0.0 3
0101204  104 78.50+5 610. 0.0 0.0 0.0 4
0101205  104 78.50+5 570. 0.0 0.0 0.0 5
0101206  104 78.50+5 540. 0.0 0.0 0.0 6
0101207  104 78.50+5 523. 0.0 0.0 0.0 7
0101300  1
0101301  0. 0.717 0. 6
**- HX secondary side
**- tmdpvol hx-inlet water side
1000000  vol100  tmdpvol
1000101  0.0354 0.0 100. 180. 0. 0. 0. 0. 0
1000200  103
1000201  0.0 10.0+5  308.15
**- tmdpjun hx inlet water side
2110000  jun211 tmdpjun
2110101  100000000 101000000 0.
2110200  1    509
2110201  0.0  10.5  0.  0.
2110202  1.0  0.0  0.  0.
**- volumen hx inlet water side
1010000  hx101 branch
1010001  1 1
1010101  0.0354 5.0 0. 180. 0. 0. 0. 0. 00010
1010200  103 10.0+5 308.15
1011101  101010000 102000000 0. 0. 0. 0
1011201  12.0  0. 0.
**- Pipe HX secondary side
1020000  pipe102 pipe
1020001  5
1020101  0.0354 5
1020301  0.24 5
1020501  0.0 5
1020601  90. 5
1020801  5.0-5 0.018 5
**- pressure loss coefficient
1021001  0  5
1021101  0  4
1021201  103 10.0+5 320.5 0.0 0.0 0.0 5
1021300  0
1021301  0. 0. 0. 4
**- volume hx outlet water side
1030000  hx103 branch
1030001  1 1
1030101  0.0354 5.0 0. 0. 0. 0. 0. 0. 00010
1030200  103 10.0+5 348.15
1031101  102010000 103000000 0. 0. 0. 0
1031201  12.0  0. 0.
**- tmdpvol hx outlet water side
1040000  vol104  tmdpvol
1040101  0.0354 0.0 100. 0. 0. 0. 0. 0. 0
1040200  103
1040201  0.0 10.0+5  348.15
**- Junction 103 - 104
1340000  jun134 sngljun
1340101  103010000 104000000 0.0 0. 0. 0
1340201  1 12.0 0. 0.
```

B-3.3.3.2 Circulator

```
0020000  gebl2  pump
0020101  0.0  0.6  0.005  0.0  90.   0.6   0
0020108  018020002  0. 0. 0.  20
0020109  003010001  0. 0. 0.  20
0020200  104 80.0+5 523.0 0.0
0020201  0  0. 0. 0.
0020202  0  0. 0. 0.
0020301  0 -1  -3  -1  -1  501  0
**- P = Mw = dp*Q/eta, n=6000 U/min (THTR) -->
w=2*pi*n = 628.3 rad/s
**- Te = 240 C, pe = (80-2.7/2) = 78.65 bar --> rho =
7.38 kg/m3
**- Design data: M = 0.72 kg/s, dp = 2.7 bar --> Q =
0.1 m3/s
**- H = dp/(rho*g) = 3730 m, P = Q*dp/eta = 35 kW
for eta = 0.75
**- --> M = P/w = 56 Nm
**- The following card 302 gives:
**- Rated pump velocity
**- Ratio of initial to rated pump velocity
**- Rated flow rate Q
**- Rated head
**- Rated torque
**- Moment of inertia
**- Rated density
**- Rated pump motor torque
**- Speed dependent friction torque coeficient
**- Constant friction rorque coefficient
0020302  628.3 0.86 0.25 3907.0 150.0 0.55 7.38
0.0 0.0  6.0  0.  0.
**- Pumping head, nominal operation, according to
reference curve from Juelich
**- HAN
0021100  1 1
0021101  0.0 1.172 0.074 1.168 0.148 1.166 0.222
1.164 0.296 1.162
0021102  0.370 1.160 0.445 1.155 0.518 1.154
0.592 1.145 0.666 1.134
0021103  0.740 1.114 0.815 1.088 0.888 1.057
0.963 1.020
**- HVN
0021200  1 2
0021201  0.675 0. 0.711 0.185 0.750 0.320 0.795
0.459 0.845 0.592
0021202  0.901 0.742 0.965 0.909
**- Pump head – energy dissipation (from curve in
RELAP manual)
**- These data are only used to avoid interruption in
case
**- of oscillations which could need data from this
**- regime during a RELAP run
**- HAD
0021300  1 3
0021301  -0.97 1.48 -0.92 1.47 -0.90 1.44 -0.82
1.32 -0.77 1.27
0021302  -0.60 1.34 -0.54 1.36 -0.51 1.36 -0.36
1.36 -0.22 1.31
0021303  -0.18 1.29
**- HVD
0021400  1 4
0021401  -0.97 1.48 -0.84 1.25 -0.60 0.97 -0.46
0.87 -0.38 0.84
0021402  -0.20 0.78 0.0 0.73
**- Torque, normal operation (from curve Juelich)
**- BAN
0021500  2 1
0021501  0.0 0.294 0.074 0.344 0.148 0.406 0.222
0.469 0.296 0.532
0021502  0.370 0.587 0.445 0.656 0.518 0.713
0.592 0.775 0.666 0.831
```

0021503 0.740 0.888 0.815 0.937 0.888 0.975
0.963 1.006
**- BVN
0021600 2 2
0021601 0.675 0.354 0.711 0.455 0.750 0.539
0.795 0.636 0.845 0.731
0021602 0.901 0.838 0.965 0.955
**- Torque - energy dissipation (from curve in
RELAP manual)
**- These data are only used to avoid interruption in
case
**- of oscillations which could need data from this
**- regime during a RELAP run
**- BAD
0021700 2 3
0021701 -0.94 0.80 -0.86 0.78 -0.74 0.73 -0.65
0.70 -0.58 0.51
0021702 -0.39 0.49 -0.22 0.49
**- BVD
0021800 2 4
0021801 -0.98 0.64 -0.80 0.49 -0.64 0.40 -0.48
0.44 -0.40 0.43
0021802 -0.32 0.43 -0.28 0.40 0.0 0.30

B-3.3.3.3 Dust filter

**-dust filter, upright 2.5m long
0080000 filter8 branch
0080001 2 1
0080101 0.0507 2.5 0.0 0.0 -90. -2.5 10.-5 0.002
11000
0080200 104 78.5+5 773. 0.0
**-energy loss coefficients from Eck p. 236
0081101 006250002 008010001 0.0 0.0 0.5 120
0082101 008010002 091010001 0.0 0.5 0.0 120
0081201 0. 0.717 0.
0082201 0. 0.717 0.

B-3.3.3.4 Electrical heater

**-heater 114, 1.8 m upright
1140000 pipe114 pipe
1140001 2
1140101 0.02306 2
1140301 0.9 2
1140501 0. 2
1140601 -90. 2
1140801 5.0-5 0.03296 2
1140901 0. 0. 1
1141001 11000 2
1141101 0 1
1141201 104 78.5+5 773. 0.0 0.0 0.0 2
1141300 1
1141301 0. 0.0 0. 1
**- Junction 114 - 115
1250000 jun125 sngljun
1250101 114020002 115010001 0.0 0.5 0. 0
1250201 1 0. 0. 0.

B-3.3.3.5 Pressuriser and surge line valve

**- pressuriser
0070000 vol7 tmdpvol
0070101 10. 25.0 0. 0.0 -90. -25. 0. 0. 0
0070200 104
0070201 0.0 7.9+6 773. 0.0
**- valve junction 7 - 97 (druckhalter)
0760000 vlve76 valve
0760101 7000000 006240004 0.0 7. 7. 0
0760201 0 0. 0. 0.
0760300 trpvlv
0760301 504

B-3.3.3.6 Flow control valves

**- valve 94 flow control through HX
0940000 vlve94 valve
0940101 093020002 095010001 0.003664 1. 1.
20
0940201 0 0. 0. 0.
0940300 trpvlv
0940301 510
**- valve 112 flow control through bypass
1120000 vlve112 valve
1120101 111010002 113010001 0.003664 7. 7.
20
1120201 0 0. 0. 0.
1120300 trpvlv
1120301 511

B-3.3.4 Additional components for transient analysis

See section B-4

B-3.4 Heat structures of TBM, piping and components

B-3.4.1 TBM heat structures

B-3.4.1.1 Main inlet manifold HS

**- component4
10040000 1 3 2 1 0.0382 0 0 128
10040100 0 2
10040101 0.02815 2
10040201 150 2
10040301 1. 2
10040400 0
**-initial temperature estimate
10040401 523. 3
10040501 004010000 0 1 1 1.218 1
10040601 0 0 0 1 1.218 1
**-power from general table to be specified with No.
4
10040701 4 0.50207 0. 0. 1
10040801 0.0 20.0 20.0 0.0 0.0 0.0 0.0 1.0 1

B-3.4.1.2 First wall heat structure

**-pipe 20, 15 FW cooling channels, top
**-heat structure 1, with surface heat load and
beryllium
**-side walls volumes 1 and 5 (here no surface load,
no Be)
10201000 2 2 1 1 8.-3 0 0 128
10201100 0 2
10201101 4.0-3 1
10201201 150 1
10201301 1. 1
**-initial temperature estimate
10201401 523. 2
10201501 020010000 000000 1 1 0.2069 1
10201502 020050000 000000 1 1 0.2069 2
10201601 0 0 0 1 0.2069 1
10201602 0 0 0 1 0.2069 2
10201701 201 0.06692 0. 0. 2
10201801 0.0457 20. 20. 0. 0. 0. 0. 1. 2
**-front wall sections, volumes 2, 3, 4
10202000 3 3 1 0 8.-3 0 0 128
10202100 0 2
10202101 4.0-3 1 2.0-3 2
10202201 150 1 210 2
10202301 1.0 1 0.397 2

```
**-initial temperature estimate
10202400  0
10202401  773. 3
10202501  020020000 000000 1 1 0.1423 1
10202502  020030000 000000 1 1 0.1419 2
10202503  020040000 000000 1 1 0.1423 3
10202601  0 0 2041 1 0.1423 1
10202602  0 0 2041 1 0.1419 2
10202603  0 0 2041 1 0.1423 3
10202701  202 0.0558 0. 0. 1
10202702  202 0.0557 0. 0. 2
10202703  202 0.0558 0. 0. 3
10202801  0.0457 20. 20. 0. 0. 0. 0. 1. 3
**-heat structure 2, inner FW plate and channel ribs
10203000  5 2 1 1 8.0-3 0 0 128
10203100  0 2
10203101  5.0-3 1
10203201  150 1
10203301  1. 1
**-initial temperature estimate
10203401  600. 2
10203501  020010000 000000 1 1 0.3965 1
10203502  020020000 000000 1 1 0.2727 2
10203503  020030000 000000 1 1 0.2721 3
10203504  020040000 000000 1 1 0.2727 4
10203505  020050000 000000 1 1 0.3965 5
10203601  0 0 0 1 0.3965 1
10203602  0 0 0 1 0.2727 2
10203603  0 0 0 1 0.2721 3
10203604  0 0 0 1 0.2727 4
10203605  0 0 0 1 0.3965 5
10203701  201 0.16035 0. 0. 1
10203702  202 0.0958 0. 0. 2
10203703  202 0.0956 0. 0. 3
10203704  202 0.0958 0. 0. 4
10203705  201 0.16035 0  0. 5
10203801  0.0238 20. 20. 0. 0. 0. 0. 1. 5
**-pipe 21, 2 FW cooling channels, central top
**-heat structure 1, with surface heat load and
beryllium
**-side walls volumes 1 and 5 (here no surface load,
no Be)
10211000  2 2 1 1 8.-3 0 0 128
10211100  0 2
10211101  4.0-3 1
10211201  150 1
10211301  1. 1
**-initial temperature estimate
10211401  523. 2
10211501  021010000 000000 1 1 0.0276 1
10211502  021050000 000000 1 1 0.0276 2
10211601  0 0 0 1 0.0276 1
10211602  0 0 0 1 0.0276 2
10211701  201 0.00892 0. 0. 2
10211801  0.0457 20. 20. 0. 0. 0. 0. 1. 2
**-front wall sections, volumes 2, 3, 4
10212000  3 3 1 0 8.-3 0 0 128
10212100  0 2
10212101  4.0-3 1 2.0-3 2
10212201  150 1 210 2
10212301  1.0 1 0.397 2
**-initial temperature estimate
10212400  0
10212401  773. 3
10212501  021020000 000000 1 1 0.0190 1
10212502  021030000 000000 1 1 0.0189 2
10212503  021040000 000000 1 1 0.0190 3
10212601  0 0 2041 1 0.0190 1
10212602  0 0 2041 1 0.0189 2
10212603  0 0 2041 1 0.0190 3
10212701  202 0.0074 0. 0. 1
10212702  202 0.0074 0. 0. 2
10212703  202 0.0074 0. 0. 3
10212801  0.0457 20. 20. 0. 0. 0. 0. 1. 3
**-heat structure 2, inner FW plate and channel ribs
10213000  5 2 1 1 8.0-3 0 0 128
10213100  0 2
10213101  5.0-3 1
10213201  150 1
10213301  1. 1
**-initial temperature estimate
10213401  600. 2
10213501  021010000 000000 1 1 0.0529 1
10213502  021020000 000000 1 1 0.0364 2
10213503  021030000 000000 1 1 0.0363 3
10213504  021040000 000000 1 1 0.0364 4
10213505  021050000 000000 1 1 0.0529 5
10213601  0 0 0 1 0.0529 1
10213602  0 0 0 1 0.0364 2
10213603  0 0 0 1 0.0363 3
10213604  0 0 0 1 0.0364 4
10213605  0 0 0 1 0.0529 5
10213701  201 0.02138 0. 0. 1
10213702  202 0.0128 0. 0. 2
10213703  202 0.0127 0. 0. 3
10213704  202 0.0128 0. 0. 4
10213705  201 0.02138 0  0. 5
10213801  0.0238 20. 20. 0. 0. 0. 0. 1. 5
**-pipe 22, 2 FW cooling channels, central bottom
**-heat structure 1, with surface heat load and
beryllium
**-side walls volumes 1 and 5 (here no surface load,
no Be)
10221000  2 2 1 1 8.-3 0 0 128
10221100  0 2
10221101  4.0-3 1
10221201  150 1
10221301  1. 1
**-initial temperature estimate
10221401  523. 2
10221501  022010000 000000 1 1 0.0276 1
10221502  022050000 000000 1 1 0.0276 2
10221601  0 0 0 1 0.0276 1
10221602  0 0 0 1 0.0276 2
10221701  201 0.00892 0. 0. 2
10221801  0.0457 20. 20. 0. 0. 0. 0. 1. 2
**-front wall sections, volumes 2, 3, 4
10222000  3 3 1 0 8.-3 0 0 128
10222100  0 2
10222101  4.0-3 1 2.0-3 2
10222201  150 1 210 2
10222301  1.0 1 0.397 2
**-initial temperature estimate
10222400  0
10222401  773. 3
10222501  022020000 000000 1 1 0.0190 1
10222502  022030000 000000 1 1 0.0189 2
10222503  022040000 000000 1 1 0.0190 3
10222601  0 0 2041 1 0.0190 1
10222602  0 0 2041 1 0.0189 2
10222603  0 0 2041 1 0.0190 3
10222701  202 0.0074 0. 0. 1
10222702  202 0.0074 0. 0. 2
10222703  202 0.0074 0. 0. 3
10222801  0.0457 20. 20. 0. 0. 0. 0. 1. 3
**-heat structure 2, inner FW plate and channel ribs
```

10223000 5 2 1 1 8.0-3 0 0 128
10223100 0 2
10223101 5.0-3 1
10223201 150 1
10223301 1. 1
**-initial temperature estimate
10223401 600. 2
10223501 022010000 000000 1 1 0.0529 1
10223502 022020000 000000 1 1 0.0364 2
10223503 022030000 000000 1 1 0.0363 3
10223504 022040000 000000 1 1 0.0364 4
10223505 022050000 000000 1 1 0.0529 5
10223601 0 0 0 1 0.0529 1
10223602 0 0 0 1 0.0364 2
10223603 0 0 0 1 0.0363 3
10223604 0 0 0 1 0.0364 4
10223605 0 0 0 1 0.0529 5
10223701 201 0.02138 0. 0. 1
10223702 202 0.0128 0. 0. 2
10223703 202 0.0127 0. 0. 3
10223704 202 0.0128 0. 0. 4
10223705 201 0.02138 0 0. 5
10223801 0.0238 20. 20. 0. 0. 0. 0. 1. 5
**-pipe 23, 14 FW cooling channels, bottom
**-heat structure 1, with surface heat load and beryllium
**-side walls volumes 1 and 5 (here no surface load, no Be)
10231000 2 2 1 1 8.-3 0 0 128
10231100 0 2
10231101 4.0-3 1
10231201 150 1
10231301 1. 1
**-initial temperature estimate
10231401 523. 2
10231501 023010000 000000 1 1 0.1931 1
10231502 023050000 000000 1 1 0.1931 2
10231601 0 0 0 1 0.1931 1
10231602 0 0 0 1 0.1931 2
10231701 201 0.06246 0. 0. 2
10231801 0.0457 20. 20. 0. 0. 0. 0. 1. 2
**-front wall sections, volumes 2, 3, 4
10232000 3 3 1 0 8.-3 0 0 128
10232100 0 2
10232101 4.0-3 1 2.0-3 2
10232201 150 1 210 2
10232301 1.0 1 0.397 2
**-initial temperature estimate
10232400 0
10232401 773. 3
10232501 023020000 000000 1 1 0.1328 1
10232502 023030000 000000 1 1 0.1325 2
10232503 023040000 000000 1 1 0.1328 3
10232601 0 0 2041 1 0.1328 1
10232602 0 0 2041 1 0.1325 2
10232603 0 0 2041 1 0.1328 3
10232701 202 0.0521 0. 0. 1
10232702 202 0.0520 0. 0. 2
10232703 202 0.0521 0. 0. 3
10232801 0.0457 20. 20. 0. 0. 0. 0. 1. 3
**-heat structure 2, inner FW plate and channel ribs
10233000 5 2 1 1 8.0-3 0 0 128
10233100 0 2
10233101 5.0-3 1
10233201 150 1
10233301 1. 1
**-initial temperature estimate
10233401 600. 2
10233501 023010000 000000 1 1 0.3701 1
10233502 023020000 000000 1 1 0.2545 2
10233503 023030000 000000 1 1 0.2539 3
10233504 023040000 000000 1 1 0.2545 4
10233505 023050000 000000 1 1 0.3701 5
10233601 0 0 0 1 0.3701 1
10233602 0 0 0 1 0.2545 2
10233603 0 0 0 1 0.2539 3
10233604 0 0 0 1 0.2545 4
10233605 0 0 0 1 0.3701 5
10233701 201 0.14966 0. 0. 1
10233702 202 0.0894 0. 0. 2
10233703 202 0.0892 0. 0. 3
10233704 202 0.0894 0. 0. 4
10233705 201 0.14966 0 0. 5
10233801 0.0238 20. 20. 0. 0. 0. 0. 1. 5

B-3.4.1.3 End caps heat structures

**- component 24, end cap top, two volumes
**-heat structure 1, 14 cooling channels 9x9 mm
10241000 2 3 1 1 4.6552-4 0 0 128
10241100 0 2
10241101 9.1422-3 2
10241201 150 2
10241301 1.0 2
**-initial temperature estimate
10241401 555. 3
10241501 024010000 000000 1 1 0.62118 1
10241502 024020000 000000 1 1 0.62118 2
10241601 0 0 0 1 0.62118 1
10241602 0 0 0 1 0.62118 2
10241701 24 0.25 0. 0. 2
10241801 0.018 20. 20. 0. 0. 0. 0. 1. 2
**- component 24, end cap top, two volumes
**-heat structure 2, 14 cooling channels 9x9 mm
10242000 2 3 1 1 4.6552-4 0 0 128
10242100 0 2
10242101 9.1422-3 2
10242201 150 2
10242301 1.0 2
**-initial temperature estimate
10242401 605. 3
10242501 024010000 000000 1 1 0.62118 1
10242502 024020000 000000 1 1 0.62118 2
10242601 0 0 0 1 0.62118 1
10242602 0 0 0 1 0.62118 2
10242701 24 0.25 0. 0. 2
10242801 0.018 20. 20. 0. 0. 0. 0. 1. 2
**- component 25, end cap bottom, two volumes
**-heat structure 1, 14 cooling channels 10x10 mm
10251000 2 3 1 1 5.7471-4 0 0 128
10251100 0 2
10251101 9.0876-3 2
10251201 150 2
10251301 1.0 2
**-initial temperature estimate
10251401 555. 3
10251501 025010000 000000 1 1 0.62118 1
10251502 025020000 000000 1 1 0.62118 2
10251601 0 0 0 1 0.62118 1
10251602 0 0 0 1 0.62118 2
10251701 25 0.25 0. 0. 2
10251801 0.02 20. 20. 0. 0. 0. 0. 1. 2
**- component 25, end cap bottom, two volumes
**-heat structure 2, 14 cooling channels 10x10 mm
10252000 2 3 1 1 5.7471-4 0 0 128
10252100 0 2
10252101 9.0876-3 2
10252201 150 2

10252301 1.0 2
**-initial temperature estimate
10252401 605. 3
10252501 025010000 000000 1 1 0.62118 1
10252502 025020000 000000 1 1 0.62118 2
10252601 0 0 0 1 0.62118 1
10252602 0 0 0 1 0.62118 2
10252701 25 0.25 0. 0. 2
10252801 0.02 20. 20. 0. 0. 0. 0. 1. 2

B-3.4.1.4 Intermediate manifolds HS

**- component30 (north)
10300000 1 2 1 1 0.02 0 0 128
10300100 0 2
10300101 0.01 1
10300201 150 1
10300301 1. 1
10300400 0
**-initial temperature estimate
10300401 523. 2
10300501 030010000 0 1 1 0.0472 1
10300601 0 0 0 1 0.0472 1
**-power from general table No. 30
10300701 30 1. 0. 0. 1
10300801 0.16 20.0 20.0 0.0 0.0 0.0 0.0 1.0 1
**- component31 (south)
10310000 1 2 1 1 0.02 0 0 128
10310100 0 2
10310101 0.01 1
10310201 150 1
10310301 1. 1
10310400 0
**-initial temperature estimate
10310401 523. 2
10310501 031010000 0 1 1 0.0472 1
10310601 0 0 0 1 0.0472 1
**-power from general table No. 30 (same as component 30)
10310701 30 1. 0. 0. 1
10310801 0.16 20.0 20.0 0.0 0.0 0.0 0.0 1.0 1

B-3.4.1.5 Breeding Zone inlet manifolds HS

**-.component 40 nanifold north to beryllium
10400000 1 3 2 1 0.024 0 0 128
10400100 0 2
10400101 0.00361 2
10400201 150 2
10400301 1. 2
10400400 0
**-initial temperature estimate
10400401 647.0 3
10400501 040010000 0 1 1 0.609 1
10400601 0 0 0 1 0.609 1
**-power from general table 40
10400701 40 0.0590 0. 0. 1
10400801 0.012 20.0 20.0 0.0 0.0 0.0 0.0 1.0 1
**-.component 41 nanifold north to breeder
10410000 1 3 2 1 0.07 0 0 128
10410100 0 2
10410101 0.004343 2
10410201 150 2
10410301 1. 2
10410400 0
**-initial temperature estimate
10410401 647.0 3
10410501 041010000 0 1 1 0.609 1
10410601 0 0 0 1 0.609 1
**-power from general table 40
10410701 40 0.1910 0. 0. 1
10410801 0.014 20.0 20.0 0.0 0.0 0.0 0.0 1.0 1
**-.component 42 nanifold south to breeder
10420000 1 3 2 1 0.07 0 0 128
10420100 0 2
10420101 0.004343 2
10420201 150 2
10420301 1. 2
10420400 0
**-initial temperature estimate
10420401 647.0 3
10420501 042010000 0 1 1 0.609 1
10420601 0 0 0 1 0.609 1
**-power from general table 40
10420701 40 0.1910 0. 0. 1
10420801 0.014 20.0 20.0 0.0 0.0 0.0 0.0 1.0 1
**- component 43 nanifold south to beryllium
10430000 1 3 2 1 0.024 0 0 128
10430100 0 2
10430101 0.00361 2
10430201 150 2
10430301 1. 2
10430400 0
**-initial temperature estimate
10430401 647.0 3
10430501 043010000 0 1 1 0.609 1
10430601 0 0 0 1 0.609 1
**-power from general table 40
10430701 40 0.0590 0. 0. 1
10430801 0.012 20.0 20.0 0.0 0.0 0.0 0.0 1.0 1

B-3.4.1.6 Breeding zone heat structures

**------------- component 50, beryllium north --------------
**-heat structure 1, steel and beryllium pebbles
10501000 2 4 1 1 5.9113-4 0 0 128
10501100 0 2
10501101 1.6133-3   1   1.125-2   3
10501201 150 1 200 3
10501301 1.   1 3.5447   3
**-initial temperature estimate
10501401 723.   4
10501501 050010000 000000 1 1 0.4872 1
10501502 050020000 000000 1 1 0.4872 2
10501601 0 0 0 1 0.4872 1
10501602 0 0 0 1 0.4872 2
10501701 50 2.7068-2   0. 0. 2
10501801 0.004729 20. 20. 0. 0. 0. 0. 1. 2
**-heat structure 2, steel and beryllium pebbles
10502000 2 4 1 1 5.9113-4 0 0 128
10502100 0 2
10502101 1.6133-3   1   1.125-2   3
10502201 150 1 200 3
10502301 1.   1 3.5447   3
**-initial temperature estimate
10502401 723.   4
10502501 050010000 000000 1 1 0.4872 1
10502502 050020000 000000 1 1 0.4872 2
10502601 0 0 0 1 0.4872 1
10502602 0 0 0 1 0.4872 2
10502701 50 2.7068-2   0. 0. 2
10502801 0.004729 20. 20. 0. 0. 0. 0. 1. 2
**------------- component 51, breeder north -----------------
**-heat structure 1, steel and breeder pebbles
10511000 2 4 1 1 8.867-4 0 0 128
10511100 0 2
10511101 1.6133-3   1   4.25-3   3
10511201 150 1 250 3

```
10511301  1.    1   6.69   3
**-initial temperature estimate
10511401  723.   4
10511501  051010000 000000 1 1 1.218 1
10511502  051020000 000000 1 1 1.218 2
10511601  0 0 0 1 1.218 1
10511602  0 0 0 1 1.218 2
10511701  50  12.029-2   0.  0. 2
10511801  0.007094 20. 20. 0. 0. 0. 0. 1. 2
**-heat structure 2, steel and beryllium pebbles
10512000  2 4 1 1 8.867-4 0 0 128
10512100  0 2
10512101  1.6133-3   1   1.275-2   3
10512201  150 1 200  3
10512301  1.    1   4.0174   3
**-initial temperature estimate
10512401  723.   4
10512501  051010000 000000 1 1 1.218 1
10512502  051020000 000000 1 1 1.218 2
10512601  0 0 0 1 1.218 1
10512602  0 0 0 1 1.218 2
10512701  50  7.558-2   0.  0. 2
10512801  0.007094 20. 20. 0. 0. 0. 0. 1. 2
**------------- component 52, breeder south -------------
----
**-heat structure 1, steel and breeder pebbles
10521000  2 4 1 1 8.867-4 0 0 128
10521100  0 2
10521101  1.6133-3   1   4.25-3   3
10521201  150 1 250  3
10521301  1.    1   6.69   3
**-initial temperature estimate
10521401  723.   4
10521501  052010000 000000 1 1 1.218 1
10521502  052020000 000000 1 1 1.218 2
10521601  0 0 0 1 1.218 1
10521602  0 0 0 1 1.218 2
10521701  50  12.029-2   0.  0. 2
10521801  0.007094 20. 20. 0. 0. 0. 0. 1. 2
**-heat structure 2, steel and beryllium pebbles
10522000  2 4 1 1 8.867-4 0 0 128
10522100  0 2
10522101  1.6133-3   1   1.275-2   3
10522201  150 1 200  3
10522301  1.    1   4.0174   3
**-initial temperature estimate
10522401  723.   4
10522501  052010000 000000 1 1 1.218 1
10522502  052020000 000000 1 1 1.218 2
10522601  0 0 0 1 1.218 1
10522602  0 0 0 1 1.218 2
10522701  50  7.558-2   0.  0. 2
10522801  0.007094 20. 20. 0. 0. 0. 0. 1. 2
**------------- component 53, beryllium south -----------
---
**-heat structure 1, steel and beryllium pebbles
10531000  2 4 1 1 5.9113-4 0 0 128
10531100  0 2
10531101  1.6133-3   1   1.125-2   3
10531201  150 1 200  3
10531301  1.    1 3.5447   3
**-initial temperature estimate
10531401  723.   4
10531501  053010000 000000 1 1 0.4872 1
10531502  053020000 000000 1 1 0.4872 2
10531601  0 0 0 1 0.4872 1
10531602  0 0 0 1 0.4872 2
10531701  50  2.7068-2   0.  0. 2
10531801  0.004729 20. 20. 0. 0. 0. 0. 1. 2
**-heat structure 2, steel and beryllium pebbles
10532000  2 4 1 1 5.9113-4 0 0 128
10532100  0 2
10532101  1.6133-3   1   1.125-2   3
10532201  150 1 200  3
10532301  1.    1 3.5447   3
**-initial temperature estimate
10532401  723.   4
10532501  053010000 000000 1 1 0.4872 1
10532502  053020000 000000 1 1 0.4872 2
10532601  0 0 0 1 0.4872 1
10532602  0 0 0 1 0.4872 2
10532701  50  2.7068-2   0.  0. 2
10532801  0.004729 20. 20. 0. 0. 0. 0. 1. 2
```

B-3.4.1.7 Breeding zone outlet manifolds HS

```
**-----------.component 60 nanifold north from
beryllium
10600000  1  3  2  1  0.024  0  0  128
10600100  0 2
10600101  0.00361 2
10600201  150 2
10600301  1. 2
10600400  0
**-initial temperature estimate
10600401  647.0  3
10600501  060010000 0 1 1 0.609 1
10600601  0 0 0 1 0.609 1
**-power from general table 40
10600701  40  0.0590  0. 0. 1
10600801  0.012 20.0 20.0 0.0 0.0 0.0 0.0 1.0 1
**-----------.component 61 nanifold north from
breeder
10610000  1  3  2  1  0.07  0  0  128
10610100  0 2
10610101  0.004343 2
10610201  150 2
10610301  1. 2
10610400  0
**-initial temperature estimate
10610401  647.0  3
10610501  061010000 0 1 1 0.609 1
10610601  0 0 0 1 0.609 1
**-power from general table 40
10610701  40  0.1910  0. 0. 1
10610801  0.014 20.0 20.0 0.0 0.0 0.0 0.0 1.0 1
**-----------.component 62 nanifold south from
breeder
10620000  1  3  2  1  0.07  0  0  128
10620100  0 2
10620101  0.004343 2
10620201  150 2
10620301  1. 2
10620400  0
**-initial temperature estimate
10620401  647.0  3
10620501  062010000 0 1 1 0.609 1
10620601  0 0 0 1 0.609 1
**-power from general table 40
10620701  40  0.1910  0. 0. 1
10620801  0.014 20.0 20.0 0.0 0.0 0.0 0.0 1.0 1
**-----------.component 63 nanifold south from
beryllium
10630000  1  3  2  1  0.024  0  0  128
10630100  0 2
10630101  0.00361 2
```

```
10630201  150 2
10630301  1. 2
10630400  0
**-initial temperature estimate
10630401  647.0  3
10630501  063010000 0 1 1 0.609 1
10630601  0 0 0 1 0.609 1
**-power from general table 40
10630701  40  0.0590  0. 0. 1
10630801  0.012 20.0 20.0 0.0 0.0 0.0 0.0 1.0 1
```

B-3.4.1.8 Main outlet manifold HS

```
**- component5
10050000  1  3  2  1  0.0382  0  0  128
10050100  0 2
10050101  0.02815 2
10050201  150 2
10050301  1. 2
10050400  0
**-initial temperature estimate
10050401  773. 3
10050501  005010000 0 1 1 1.218 1
10050601  0 0 0 1 1.218 1
**-power from general table to be specified with No.
4
10050701  4   0.49793  0. 0. 1
10050801  0.0 20.0 20.0 0.0 0.0 0.0 0.0 1.0 1
```

B-3.4.2 Piping heat structures

B-3.4.2.1 Cold leg heat structures

```
**- pipe 3
10030000  21  2  2  1  0.03415  0  0  128
10030100  0  2
10030101  7.1-3  1
10030201  50  1
10030301  0. 1
10030401  523. 1 523. 2
10030501  003010000  0  1  1 0.7    1
10030502  003020000  0  1  1 2.8    2
10030503  003030000  0  1  1 5.0    3
10030504  003040000  0  1  1 5.0    4
10030505  003050000  0  1  1 4.0    5
10030506  003060000  0  1  1 3.2    6
10030507  003070000  0  1  1 2.2    7
10030508  003080000  0  1  1 3.2    8
10030509  003090000  0  1  1 3.2    9
10030510  003100000  0  1  1 3.2    10
10030511  003110000  0  1  1 2.2    11
10030512  003120000  0  1  1 4.2    12
10030513  003130000  0  1  1 5.4    13
10030514  003140000  0  1  1 5.0    14
10030515  003150000  0  1  1 7.0    15
10030516  003160000  0  1  1 7.2    16
10030517  003170000  0  1  1 2.8    17
10030518  003180000  0  1  1 1.204   18
10030519  003190000  0  1  1 6.05    19
10030520  003200000  0  1  1 3.178   20
10030521  003210000  0  1  1 4.851   21
10030601       0  0  0  1   0.7    1
10030602       0  0  0  1   2.8    2
10030603       0  0  0  1   5.0    3
10030604       0  0  0  1   5.0    4
10030605       0  0  0  1   4.0    5
10030606       0  0  0  1   3.2    6
10030607       0  0  0  1   2.2    7
10030608       0  0  0  1   3.2    8
10030609       0  0  0  1   3.2    9
10030610       0  0  0  1   3.2    10
10030611       0  0  0  1   2.2    11
10030612       0  0  0  1   4.2    12
10030613       0  0  0  1   5.4    13
10030614       0  0  0  1   5.0    14
10030615       0  0  0  1   7.0    15
10030616       0  0  0  1   7.2    16
10030617       0  0  0  1   2.8    17
10030618       0  0  0  1   1.204    18
10030619       0  0  0  1   6.05     19
10030620       0  0  0  1   3.178    20
10030621       0  0  0  1   4.851    21
10030701  0    0.0    0.0   0.0    21
10030801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 21
**-pipe 3, enlarged section
10031000  4  2  2  1  0.0572  0  0  128
10031100  0  2
10031101  12.7-3  1
10031201  50  1
10031301  0. 1
10031401  523. 1 523. 2
10031501  003220000  0  1  1 4.455    1
10031502  003230000  0  1  1 4.554    2
10031503  003240000  0  1  1 1.031    3
10031504  003250000  0  1  1 0.510    4
10031601       0  0  0  1   4.455    1
10031602       0  0  0  1   4.554    2
10031603       0  0  0  1   1.031    3
10031604       0  0  0  1   0.510    4
10031701  0    0.0    0.0   0.0    4
10031801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0  4
```

B-3.4.2.2 Hot leg heat structures

```
**-pipe 6, enlarged section
10061000  4  2  2  1  0.0572  0  0  128
10061100  0  2
10061101  12.7-3  1
10061201  50  1
10061301  0. 1
10061401  773. 1 773. 2
10061501  006010000  0  1  1 0.510    1
10061502  006020000  0  1  1 1.031    2
10061503  006030000  0  1  1 4.554    3
10061504  006040000  0  1  1 4.455    4
10061601       0  0  0  1   0.510    1
10061602       0  0  0  1   1.031    2
10061603       0  0  0  1   4.554    3
10061604       0  0  0  1   4.455    4
10061701  0    0.0    0.0   0.0    4
10061801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0  4
**- pipe 6
10060000  21  2  2  1  0.03415  0  0  128
10060100  0  2
10060101  7.1-3  1
10060201  50  1
10060301  0. 1
10060401  773. 1 773. 2
10060501  006050000  0  1  1  5.445    1
10060502  006060000  0  1  1  4.258    2
10060503  006070000  0  1  1  6.050    3
10060504  006080000  0  1  1  0.707    4
10060505  006090000  0  1  1  2.2    5
10060506  006100000  0  1  1  7.2    6
10060507  006110000  0  1  1  7.6    7
10060508  006120000  0  1  1  5.6    8
10060509  006130000  0  1  1  6.0    9
10060510  006140000  0  1  1  4.2    10
10060511  006150000  0  1  1  1.0    11
10060512  006160000  0  1  1  3.2    12
10060513  006170000  0  1  1  4.4    13
```

```
10060514  006180000  0  1  1  3.2    14
10060515  006190000  0  1  1  1.0    15
10060516  006200000  0  1  1  3.2    16
10060517  006210000  0  1  1  4.6    17
10060518  006220000  0  1  1  5.0    18
10060519  006230000  0  1  1  5.7    19
10060520  006240000  0  1  1  0.8    20
10060521  006250000  0  1  1  0.9    21
10060601       0  0  0  1   5.445    1
10060602       0  0  0  1   4.258    2
10060603       0  0  0  1   6.050    3
10060604       0  0  0  1   0.707    4
10060605       0  0  0  1   2.2    5
10060606       0  0  0  1   7.2    6
10060607       0  0  0  1   7.6    7
10060608       0  0  0  1   5.6    8
10060609       0  0  0  1   6.0    9
10060610       0  0  0  1   4.2    10
10060611       0  0  0  1   1.0    11
10060612       0  0  0  1   3.2    12
10060613       0  0  0  1   4.4    13
10060614       0  0  0  1   3.2    14
10060615       0  0  0  1   1.0    15
10060616       0  0  0  1   3.2    16
10060617       0  0  0  1   4.6    17
10060618       0  0  0  1   5.0    18
10060619       0  0  0  1   5.7    19
10060620       0  0  0  1   0.8    20
10060621       0  0  0  1   0.9    21
10060701  0    0.0    0.0   0.0    21
10060801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 21
```

B-3.4.2.3 Piping between HCS components HS

```
**- pipe 16
10160000  2  2  2  1  0.03415  0  0  128
10160100  0  2
10160101  7.1-3  1
10160201  50  1
10160301  0. 1
10160401  513. 1 513. 2
10160501  016010000  0  1  1 0.3    1
10160502  016020000  0  1  1 0.9    2
10160601       0  0  0  1   0.3    1
10160602       0  0  0  1   0.9    2
10160701  0    0.0    0.0   0.0    2
10160801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 2
**- branch 17
10170000  1  2  2  1  0.03415  0  0  128
10170100  0  2
10170101  7.1-3  1
10170201  50  1
10170301  0. 1
10170401  513. 1  513.  2
10170501  017010000  0  1  1 0.5    1
10170601       0  0  0  1   0.5    1
10170701  0    0.0    0.0   0.0    1
10170801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 1
**- pipe 18
10180000  2  2  2  1  0.03415  0  0  128
10180100  0  2
10180101  7.1-3  1
10180201  50  1
10180301  0. 1
10180401  513. 1 513. 2
10180501  018010000  0  1  1 0.9    1
10180502  018020000  0  1  1 0.3    2
10180601       0  0  0  1   0.9    1
10180602       0  0  0  1   0.3    2
10180701  0    0.0    0.0   0.0    2
10180801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 2
**- pipe 91
10910000  2  2  2  1  0.03415  0  0  128
10910100  0  2
10910101  7.1-3  1
10910201  50  1
10910301  0. 1
10910401  773. 1 773. 2
10910501  091010000  0  1  1 0.3    1
10910502  091020000  0  1  1 0.9    2
10910601       0  0  0  1   0.3    1
10910602       0  0  0  1   0.9    2
10910701  0    0.0    0.0   0.0    2
10910801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 2
**- branch 92
10920000  1  2  2  1  0.03415  0  0  128
10920100  0  2
10920101  7.1-3  1
10920201  50  1
10920301  0. 1
10920401  773. 1  773.  2
10920501  092010000  0  1  1 0.5    1
10920601       0  0  0  1   0.5    1
10920701  0    0.0    0.0   0.0    1
10920801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 1
**- pipe 93
10930000  2  2  2  1  0.03415  0  0  128
10930100  0  2
10930101  7.1-3  1
10930201  50  1
10930301  0. 1
10930401  773. 1 773. 2
10930501  093010000  0  1  1 0.9    1
10930502  093020000  0  1  1 1.5    2
10930601       0  0  0  1   0.9    1
10930602       0  0  0  1   1.5    2
10930701  0    0.0    0.0   0.0    2
10930801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 2
**- pipe 95
10950000  2  2  2  1  0.03415  0  0  128
10950100  0  2
10950101  7.1-3  1
10950201  50  1
10950301  0. 1
10950401  773. 1 773. 2
10950501  095010000  0  1  1 1.5    1
10950502  095020000  0  1  1 0.70    2
10950601       0  0  0  1   1.5    1
10950602       0  0  0  1   0.70    2
10950701  0    0.0    0.0   0.0    2
10950801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 2
**- pipe 97
10970000  2  2  2  1  0.03415  0  0  128
10970100  0  2
10970101  7.1-3  1
10970201  50  1
10970301  0. 1
10970401  773. 1 773. 2
10970501  097010000  0  1  1 0.70    1
10970502  097020000  0  1  1 0.5    2
10970601       0  0  0  1   0.70    1
10970602       0  0  0  1   0.5    2
10970701  0    0.0    0.0   0.0    2
10970801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 2
**- pipe 111
11110000  1  2  2  1  0.03415  0  0  128
```

```
11110100  0  2
11110101  7.1-3  1
11110201  50  1
11110301  0. 1
11110401  773. 1 773. 2
11110501  111010000  0  1  1  1.5    1
11110601       0  0  0  1   1.5    1
11110701  0    0.0    0.0   0.0     1
11110801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 1
**- pipe 113
11130000  2  2  2  1  0.03415  0  0  128
11130100  0  2
11130101  7.1-3  1
11130201  50  1
11130301  0. 1
11130401  773. 1 773. 2
11130501  113010000  0  1  1 0.6    1
11130502  113020000  0  1  1 1.4    2
11130601       0  0  0  1   0.6    1
11130602       0  0  0  1   1.4    2
11130701  0    0.0    0.0   0.0     2
11130801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 2
**- pipe 115
11150000  1  2  2  1  0.03415  0  0  128
11150100  0  2
11150101  7.1-3  1
11150201  50  1
11150301  0. 1
11150401  773. 1 773. 2
11150501  115010000  0  1  1 0.3    1
11150601       0  0  0  1   0.3    1
11150701  0    0.0    0.0   0.0     1
11150801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 1
```

B-3.4.3 HCS components heat structures

B-3.4.3.1 Heat exchanger heat structures

```
**- pipe 10 (primary side)
10100000  5  2  2  1  7.0-3  0  0  128
10100100  0  2
10100101  2.-3  1
10100201  100  1
10100301  0. 1
10100400  -1
10100401  617. 334.
10100402  600. 330.
10100403  583. 326.
10100404  567. 321.
10100405  550. 317.
**- F=96*1.2/5=23.04
10100501   10020000   010000  1  1 23.04 5
10100601  102050000  -010000  1  1 23.04 5
10100701  0  0.0  0.0  0.0  5
10100801  0.014 20.0  20.0  0.0  0.0  0.0  0.0 1.0 5
10100901  0.018 20.0  20.0  0.0  0.0  0.0  0.0 1.0 5
**- Remaining structures
10101000  2  2  2  1  0.138  0  0  128
10101100  0  2
10101101  28.25-3  1
10101201  50  1
10101301  0. 1
10101400  -1
10101401  623. 623.
10101402  515. 515.
10101501   10010000  0  1  1 0.5 1
10101502   10070000  0  1  1 0.5 2
10101601         0  0  0  1 0.5 1
10101602         0  0  0  1 0.5 2
10101701  0  0.0  0.0  0.0  2
10101801  0.276 20.0  20.0  0.0  0.0  0.0  0.0 1.0 2
**- pipe 102 (secondary side)
11020000  5  2  2  1  0.138  0  0  128
11020100  0  2
11020101  0.012  1
11020201  50  1
11020301  0. 1
11020401  325.5 1 325.5 2
11020501  102010000  010000  1  1 0.24 5
11020601         0       0  0  1 0.24 5
11020701  0  0.0  0.0  0.0  5
11020801  0.1633 20.0  20.0  0.0  0.0  0.0  0.0 1.0 5
```

B-3.4.3.2 Circulator heat structures

```
10020000  1  2  2  1  0.225 0  0  128
10020100  0  2
10020101  0.07  1
10020201  50  1
10020301  0. 1
10020401  518. 1 518. 2
10020501  2010000  0  1  1 0.25 1
10020601       0  0  0  1 0.25 1
10020701  0  0.0  0.0  0.0  1
10020801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 1
```

B-3.4.3.3 Dust filter heat structure

```
10080000  1  2  2  1  0.127 0  0  128
10080100  0  2
10080101  0.043  1
10080201  50  1
10080301  0. 1
10080401  773. 1 773. 2
10080501  8010000  0  1  1 2.5 1
10080601       0  0  0  1 2.5 1
10080701  0  0.0  0.0  0.0  1
10080801  0.0 20.0  20.0  0.0  0.0  0.0  0.0 1.0 1
```

B-3.4.3.4 Electrical heater heat structures

```
**- heater 114, heat structure 1
11140000  2  2  2  1  0.09535  0  0  128
11140100  0  2
11140101  20.4-3  1
11140201  50  1
11140301  1.0  1
11140401  773. 1 773. 2
11140501  114010000  0  1  1  0.9    1
11140502  114020000  0  1  1  0.9    2
11140601       0  0  0  1   0.9    1
11140602       0  0  0  1   0.9    2
11140701  0    0.0    0.0   0.0     2
11140801  0.03296 20.0  20.0  0.0  0.0  0.0  0.0 1.0
2
**- heater rod bundle, heat structure 2
11141000  2  2  2  1  0.0  0  0  128
11141100  0  2
11141101  5.0-3  1
11141201  50  1
11141301  0. 1
11141401  773. 1 773. 2
11141501  0  0  0  1   63.0    1
11141502  0  0  0  1   63.0    2
11141601  114010000    0  1  1  63.0    1
11141602  114020000    0  1  1  63.0    2
11141701  114   0.5  0.0    0.0  2
11141901  0.03296 20.0 20.0  0.0  0.0  0.0  0.0  1.0
2
```

B-3.5 Heat structure thermal properties

B-3.5.1 AISI 316L

**- (Reference Komen/Koning: LOFA FW NET/ITER)
20105000 tbl/fctn 1 1
 * Thermal conductivity (W/mK)
20105001 100. 10.8 300. 14.0 1700. 36.0 1701. 18.0 3000. 22.2
**- Volumetric heat capacity (J/m3K)
20105051 100. 3.85+6 300. 4.02+6 1700. 5.0+6 1701. 5.31+6 3000. 4.46+6

B-3.5.2 INCOLOY 800

**- (REFERENCE Komen/Koning: LOCA SEAFP)
20110000 tbl/fctn 1 1
 * Thermal conductivity (W/mK)
20110001 293. 11.5 373. 13.0 473. 14.7 573. 16.3 673. 17.9
20110002 773. 19.5 873. 21.1 973. 22.8 1073. 24.7 1173. 27.1
20110003 1273. 31.9 3000. 31.9
**- Volumetric heat capacity (J/m3K)
20110051 293. 3.6524+6 3000. 3.6524+6
**- Extended material data

B-3.5.3 MANET

**- (Reference Kuechle) also used for EUROFER
20115000 tbl/fctn 1 1
 * Thermal conductivity (W/mK)
20115001 293.0 24.21 393.0 24.78 493.0 25.25 593.0 25.63
20115002 693.0 25.96 793.0 26.24 873.0 26.45 2000. 26.45
20115003 4000. 26.45
**- Volumetric heat capacity (J/m3K)
20115051 300.0 3493.0+3 400.0 3850.8+3 500.0 4128.1+3
20115052 600.0 4470.0+3 700.0 4963.5+3 800.0 5637.9+3
20115053 900.0 6464.8+3 2000. 6464.8+3 4000. 6464.8+3

B-3.5.4 Beryllium pebble bed

20120000 tbl/fctn 1 1
 * Thermal conductivity (W/mK)
20120001 303.0 1.06 473.0 4.12 573.0 7.54 673.0 11.27
20120002 773.0 15.29 873.0 19.54 973.0 23.99 1073.0 28.61
20120003 1173.0 33.34 1273.0 38.16 1373.0 43.02
20120004 1473.0 47.88 1573.0 52.71 3000. 52.71
**- Volumetric heat capacity (J/m3K)
20120051 300.0 2728.7+3 400.0 3307.4+3 500.0 3635.1+3 600.0 3866.0+3
20120052 700.0 4052.8+3 800.0 4217.7+3 900.0 4371.1+3 1000.0 4518.7+3
20120053 1100.0 4663.4+3 1200.0 4807.4+3 1300.0 4951.6+3
20120054 1400.0 5097.0+3 1500.0 5244.1+3 1530.0 5288.6+3
20120055 3000.0 5288.6+3

B-3.5.5 Beryllium (dense)

**- FW protection layer
20121000 tbl/fctn 1 1
 * Thermal conductivity (W/mK)
20121001 293. 183. 373. 163. 473. 143. 573. 128. 673. 115.
20121002 773. 106. 873. 97. 973. 89. 1073. 85. 3000. 85.
**- Volumetric heat capacity (J/m3K)
20121051 300.0 3381.4+3 400.0 4098.5+3 500.0 4504.6+3 600.0 4790.7+3
20121052 700.0 5022.2+3 800.0 5226.6+3 900.0 5416.7+3 1000.0 5599.6+3
20121053 1100.0 5778.9+3 1200.0 5957.3+3 1300.0 6136.0+3
20121054 1400.0 6316.2+3 1500.0 6498.5+3 1530.0 6553.6+3
20121055 3000.0 6553.6+3

B-3.5.6 Li4SiO4

20125000 tbl/fctn 2 1
 * Thermal conductivity of pebble bed (W/mK)
20125001 300. 3000. 0.708 4.51-4 5.66e-7 0. 0. 0. 273.15
**- Volumetric heat capacity of pebble bed (J/m3K)
20125051 273. 1400.6+3 373. 2249.9+3 473. 2458.5+3 573. 2667.1+3
20125052 673. 2875.7+3 773. 3091.8+3 873. 3166.3+3 973. 3300.4+3
20125053 1073. 3412.1+3 1173. 3486.6+3 1273. 3531.3+3 1373. 3561.1+3
20125054 1473. 3576.0+3 2000. 3576.0+3 3000. 3576.0+3

B-3.6 Power sources

B-3.6.1 Neutron power to TBM

**----- see Decay heat power ot TBM

B-3.6.2 Decay heat power to TBM

**----- General power table input
**----- Neutron power ramp-down to 0 within 1 s --

B-3.6.2.1 Main inlet manifold heat sources

**------- MAIN INLET AND OUTLET MANIFOLD
20200400 power 502 1.0 1.0
20200401 0.0 10147. 0.5 5175. 1. 229.3 1.3 202.9
20200402 2.0 188.7 6.0 172.5 11.0 162.4 61.0 147.1
20200403 121. 142.1 601. 132.9 3601. 111.6 18001. 58.6
20200404 86401. 24.6 2592001. 11.1

B-3.6.2.2 First wall heat sources

**-component 20, 15 FW channels
20220100 power 502 1.0 1.0
20220101 0.0 15.4+3 0.5 7854. 1.0 384.0 1.3 308.0
20220102 2.0 286.4 6.0 261.8 11.0 246.4 61.0 223.3
20220103 121. 215.6 601. 201.7 3601. 169.4 18001. 89.0
20220104 86401. 37.3 2592001. 16.8
20220200 power 502 1.0 1.0
20220201 0.0 77.96+3 0.5 69.76+3 1.0 1.762+3 1.3 1.559+3
20220202 2.0 1.45+3 6.0 1.325+3 11.0 1.247+3 61.0 1.13+3

20220203 121. 1.09+3 601. 1.021+3 3601. 857.6 18001. 450.6
20220204 86401. 188.7 2592001. 85.0

B-3.6.2.3 End caps heat sources

**--------------------END CAP TOP -----------------
20202400 power 502 1.0 1.0
20202401 0.0 5.04+4 0.5 25704. 1.0 1139.0 1.3 1008.0
20202402 2.0 937.4 6.0 856.8 11.0 806.4 61.0 730.8
20202403 121. 705.6 601. 660.2 3601. 554.4 18001. 291.3
20202404 86401. 122.0 2592001. 54.9
**----------------END CAP BOTTOM ---------------
20202500 power 502 1.0 1.0
20202501 0.0 6.54+4 0.5 33354. 1.0 1478. 1.3 1308.
20202502 2.0 1216.4 6.0 1111.8 11.0 1046.4 61.0 948.3
20202503 121. 915.6 601. 856.7 3601. 719.4 18001. 378.0
20202504 86401. 158.3 2592001. 71.3

B-3.6.2.4 Intermediate manifolds heat sources

20203000 power 502 1.0 1.0
20203001 0.0 150.0 0.5 76.5 1.0 3.4 1.3 3.0 2.0 2.8 6.0 2.6
20203002 11.0 2.4 61. 2.2 121. 2.1 601. 2.0 3601. 1.7
20203003 18001. 0.9 86401. 0.4 2592001. 0.2

B-3.6.2.5 BZ inlet manifolds heat sources

**---------------BZ INLET AND OUTLET MANIFOLDS
20204000 power 502 1.0 1.0
20204001 0.0 6240.0 0.5 3182.0 1.0 141.0 1.3 124.8 2.0 116.1
20204002 6.0 106.1 11.0 99.8 61. 90.5 121. 87.4 601. 81.7
20204003 3601. 68.6 18001. 36.1 86401. 15.1 2592001. 6.8

B-3.6.2.6 Breeding zone heat sources

**----------------------BREEDING ZONE --------------
20205000 power 502 1.0 1.0
20205001 0.0 4.579+5 0.5 233529. 1.0 10348.5 1.3 9158.
20205002 2.0 8516.9 6.0 7784.3 11.0 7326.4 61.0 6639.6
20205003 121. 6410.6 601. 5998.5 3601. 5036.9
20205004 18001. 2646.7 86401. 1108.1 2592001. 499.1

B-3.6.2.7 Breeding zone outlet manifolds heat sources

see breeding zone inlet manifolds heat sources

B-3.6.2.8 Main outlet manifold heat sources

see main inlet manifolds heat sources

B-3.6.3 Surface heat flux to FW

**-------------SURFACE HEAT FLUX TO FIRST WALL
20204100 htrnrate 502 1.0 1.0
20204101 0.0 -25.0+4 0.05 0.0

B-3.6.4 Other heat sources

B-3.6.4.1 Electrical heater

**-----------70 ELECTRICAL HEATER RODS -----
20211400 power 502 1.0 1.0
20211401 0.0 1.0
20211402 0.05 0.5 1.0 0.1 10.0 1.0-2 100.0 0.0
. end

B-4 Restart input deck for transient internal leak analysis

(file \case2a5\tbm1.rst.i, edited)

B-4.1 Prologue

=tbm1 transient
**-For first transient restart only.
**- This file is generated from tbm7 restart file.
**- changes refer to: addition of components
**- for internal leak, revision of trips, revision
**- of minor edit request
* IN-TBM LEAK, case1c

B-4.2 Job control

100 restart transnt
101 *inp-chk
103 6420
**----------- TIME STEP CONTROL -----------------
201 1.0-5 1.0-9 1.0-6 15011 1 10 10
202 1.0-4 1.0-9 1.0-5 15011 1 10 10
203 1.0-3 1.0-9 1.0-4 15011 1 10 10
204 3.0-3 1.0-9 1.0-4 15011 1 10 10
205 1.0-2 1.0-9 1.0-3 15011 1 10 10
206 3.0-2 1.0-9 1.0-3 15011 1 10 10
207 1.0-1 1.0-9 1.0-2 15011 1 10 10
208 1.0 1.0-9 1.0-1 15011 1 10 10
209 3.0 1.0-9 1.0-1 15011 1 10 10
*207 1.0 1.0-9 1.0-1 15011 1 10 10
*207 2.0 1.0-9 1.0-1 15011 1 10 10
*208 10.0 1.0-9 5.0-1 15011 1 10 10
*209 40.0 1.0-9 1.0 15011 1 10 10
*210 100. 1.0-9 10. 15011 1 10 10
**------------------------------- TRIPS -----------------------
* Shutdown occurs at t=td (time of rupture disc response)
*** No pump trip until td+1s
501 time 0 ge null 0 1.0 l -1.0
*** no power trip until td
502 time 0 gt null 0 0.01 l
*** Pressuriser opens if p<7.2 MPa
504 p 10010000 lt null 0 72.+5 l
*** Secondary side water flow control off
509 time 0 ge null 0 1.0 l -1.0
*** Valve in HX line remains open
510 time 0 ge null 0 0.0 l 0.0
*** Bypass closed for p>10 Pa
511 p 10010000 lt null 0 10. l
*** break opening opens at time zero
530 time 0 ge null 0 0.0 l
*** pressure regulator closes at p>2e5 Pa
531 p 206020000 lt null 0 2.0+5 n
*** burst disc opens at p>1e6 Pa
532 p 202010000 gt null 0 1.0+6 l
*** termination if temp <150K
534 tempg 7010000 lt null 0 150. l
*** termination of computation if trip 534 true

```
600  534
```

B-4.3 Hydrodynamics of additional components

```
**--------New definition of pressuriser --- --------------
0070000 vol7 delete
0070000 vol7 snglvol
0070101 5.309-2  2.8  0.  0. -90.  -2.8  5.0-5  0.  0
0070200 104  140.+5  323.0  0.0
* no pressuriser heat structure considered
**- valve junction 7 - 624  (pressuriser to hot leg)
0760000  vlve76  valve
0760101  7000000  006240004 5.067-4   7. 7. 0
0760201  0 0. 0. 0.
0760300  trpvlv
0760301  504
**----------INTERNAL LEAK SIMULATION ---------
**--------------- break opening (valve 201) ---------------
2010000 vlve201 valve
2010101 005010006 202010003  3.59-3  0.0  0.0
120
2010201 0  0.  0.  0.
2010300 trpvlv
2010301 530
**-------------- TBM purge gas chamber 202  -----------
2020000  manif202 branch
2020001 2
2020101 0.04248 1.218 0. 180. 0. 0. 2.0-5 0.0634
0011000
2020200 104 1.0+5  773. 0.0
**-junctions to and from purge gas chamber
**-energy loss coefficients from Eck p. 236 and 237
2021101 202010004 203010001 0.0 0.5 0.5
0000100
2021201 0.0 0.0 0.0
2022101 202010003 206010001 0.0 0.5 0.5
0000100
2022201 0.0 0.0 0.0
**- two additional junctions are input to valves
**------------throttle 203  to pebble beds  ----------------
2030000  pipe203 pipe
2030001  1
2030101  0.002356   1
2030301  0.6  1
2030501  0.  1
2030601  0.  1
2030801  1.0-6  0.01   1
2031001  0011000  1
2031201  104  1.0+5  773.  0.0  0.0  0.0  1
**-----  junction 204 between throttle and pebbles ----
-
2040000  jun204 sngljun
2040101  203010002 205010001   0.0  0.5 0.5
1100
2040201  0 0.0 0.0 0.0
**------- pebble bed void volume plus pipe 205--------
2050000  vol205 snglvol
2050101 0.1267 0. 0.0998 0. 0.0 0. 1.0-6 1.0-3
11000
2050200  104   1.0+5  773.0  0.0
**------------ pipe 206  to pressure regulator ------------
2060000  pipe206 pipe
2060001  2
2060101  4.909-4   2
2060301  50.  2
2060501  0.  2
2060601  0.  2
2060801  5.0-6  0.025  2
2061001  0011000   2
2061101  0001120  1
2061201  104  1.0+5  773.  0.0  0.0  0.0  2
2061301  0.0  0.0  0.0  1
**--------------- pressure regulator 207 --------------------
2070000 vlve207 valve
2070101 206020002 208010001 2.54-4 7.0 1.+6
120
2070201 0  0.  0.  0.
2070300 trpvlv
2070301 531
**-------------- free volume of TES 208 ------------------
2080000  vol208 snglvol
2080101  1.0  0.0  4.0  0.0  0.0  0.0  1.0-5  1.0
0011001
2080200  104   1.0+5  323.0  0.0
**--------------------- burst disc 209 ------------------------
2090000 vlve209 valve
2090101 202010003  320010001 0.00785  0.  0.
120
2090201 0  0.  0.  0.
2090300 trpvlv
2090301 532
**-----------  vacuum vessel 320 ---------------------------
3200000  vol320 snglvol
3200101  36.0  0.0  1350.  90. 0.0  0.0  0.0 6.91
0011010
3200200  104   1.0  443.0  0.0
```

B-4.4 Minor edit request

```
310 p 3010000
311 p 3250000
312 p 6250000
313 p 6010000
314 p 91010000
315 p 202010000
316 p 203010000
317 p 205010000
318 p 206010000
319 p 206020000
320 p 208010000
321 p 320010000
330 mflowj 201000000
331 mflowj 204000000
332 mflowj 206010000
333 mflowj 207000000
334 mflowj 209000000
335 mflowj 18010000
336 mflowj 3010000
337 mflowj 6240000
338 mflowj 91010000
339 mflowj 76000000
350 velgj 201000000
351 velgj 204000000
352 velgj 206010000
353 velgj 207000000
354 velgj 209000000
355 velgj 18010000
356 velgj 3010000
357 velgj 6240000
358 velgj 91010000
359 velgj 76000000
370 tempg 3010000
371 tempg 3250000
372 tempg 6010000
373 tempg 6250000
375 tempg 202010000
376 tempg 203010000
```

377 tempg 205010000
378 tempg 206010000
379 tempg 206020000
380 tempg 208010000
381 tempg 320010000
382 pmpvel 002
385 httemp 50100101
386 httemp 50100201
387 httemp 50100104
388 httemp 50100204
389 httemp 51100101
390 httemp 51100201
391 httemp 51100104
392 httemp 51100204
393 httemp 51200104
394 httemp 51200204
395 httemp 20200303
396 httemp 20200302
397 httemp 20200301
398 httemp 20300401
399 httemp 20300402
. end

Appendix C - Example of output listing, steady state run

Major edit of RELAP/MOD3.2 test run, REVISION 2 of 18.09.01

Job control statistics and trips

```
0MAJOR EDIT !!!time=    89.8250     sec
0 attempted adv: tot.=   7147   edit=   5655   min.dt=   1.500000E-02 sec   last dt=   1.500000E-02 sec   ms.red=   1.095952E-04 kg
   repeated adv: tot.=    231   edit=      0   max.dt=   1.500000E-02 sec   crnt.dt=   7.601166E-03 sec   tot.ms=    399.398     kg
 successful adv: tot.=   6916   edit=   5655   avg.dt=   1.500000E-02 sec   err.est=   2.264382E-10       m.ratn=   2.744007E-07
  requested adv: tot.=   6555   edit=   5655   req.dt=   1.500000E-02 sec       cpu=    733.740     sec     time=    89.8250     sec
0Trip number, trip time (sec)
     501  -1.000000         502  -1.000000         504  0.0000000E+00     509  -1.000000         510  0.0000000E+00
     511  -1.000000
```

Hydrodynamics - quantities related to volumes

```
0System  1    *none*  mass=    6.9391      kg    mass error=  1.56524E-06 kg    err.est.=  2.26438E-10
0   Vol.no.  pressure      voidf         voidg         voidgo        tempf        tempg       sat. temp.        uf            ug          volume
               (pa)                                                   (k)          (k)          (k)          (j/kg)        (j/kg)          flag
 gebl2    pump
   rpm =   540.34     (rad/sec)     head =  2.39334E+05 (pa)          torque =  -78.471       (n-m)
   octant = 1                                                     mtr.torque =   78.471       (n-m)
   2-010000  7.98489E+06  0.00000E+00   1.0000       1.0000       525.657      525.657      525.657      1.65125E+06  1.65125E+06  11010
 pipe3    pipe
   3-010000  8.10221E+06  0.00000E+00   1.0000       1.0000       528.760      528.760      528.760      1.66092E+06  1.66092E+06  11000
   3-020000  8.10027E+06  0.00000E+00   1.0000       1.0000       528.766      528.766      528.766      1.66094E+06  1.66094E+06  11000
   3-030000  8.09665E+06  0.00000E+00   1.0000       1.0000       528.772      528.772      528.772      1.66096E+06  1.66096E+06  11000
   3-040000  8.09278E+06  0.00000E+00   1.0000       1.0000       528.772      528.772      528.772      1.66096E+06  1.66096E+06  11000
   3-050000  8.08930E+06  0.00000E+00   1.0000       1.0000       528.762      528.762      528.762      1.66093E+06  1.66093E+06  11000
   3-060000  8.08600E+06  0.00000E+00   1.0000       1.0000       528.740      528.740      528.740      1.66086E+06  1.66086E+06  11000
   3-070000  8.08341E+06  0.00000E+00   1.0000       1.0000       528.717      528.717      528.717      1.66079E+06  1.66079E+06  11000
   3-080000  8.08081E+06  0.00000E+00   1.0000       1.0000       528.713      528.713      528.713      1.66078E+06  1.66078E+06  11000
   3-090000  8.07782E+06  0.00000E+00   1.0000       1.0000       528.700      528.700      528.700      1.66073E+06  1.66073E+06  11000
   3-100000  8.07483E+06  0.00000E+00   1.0000       1.0000       528.686      528.686      528.686      1.66069E+06  1.66069E+06  11000
   3-110000  8.07223E+06  0.00000E+00   1.0000       1.0000       528.663      528.663      528.663      1.66062E+06  1.66062E+06  11000
   3-120000  8.06924E+06  0.00000E+00   1.0000       1.0000       528.670      528.670      528.670      1.66064E+06  1.66064E+06  11000
   3-130000  8.06501E+06  0.00000E+00   1.0000       1.0000       528.668      528.668      528.668      1.66064E+06  1.66064E+06  11000
   3-140000  8.06097E+06  0.00000E+00   1.0000       1.0000       528.664      528.664      528.664      1.66062E+06  1.66062E+06  11000
   3-150000  8.05580E+06  0.00000E+00   1.0000       1.0000       528.671      528.671      528.671      1.66064E+06  1.66064E+06  11000
   3-160000  8.05003E+06  0.00000E+00   1.0000       1.0000       528.666      528.666      528.666      1.66063E+06  1.66063E+06  11000
   3-170000  8.04589E+06  0.00000E+00   1.0000       1.0000       528.614      528.614      528.614      1.66047E+06  1.66047E+06  11000
   3-180000  8.04383E+06  0.00000E+00   1.0000       1.0000       528.584      528.584      528.584      1.66037E+06  1.66037E+06  11000
   3-190000  8.04071E+06  0.00000E+00   1.0000       1.0000       528.626      528.626      528.626      1.66050E+06  1.66050E+06  11000
   3-200000  8.03683E+06  0.00000E+00   1.0000       1.0000       528.589      528.589      528.589      1.66039E+06  1.66039E+06  11000
   3-210000  8.03319E+06  0.00000E+00   1.0000       1.0000       528.592      528.592      528.592      1.66040E+06  1.66040E+06  11000
   3-220000  8.03338E+06  0.00000E+00   1.0000       1.0000       528.603      528.603      528.603      1.66043E+06  1.66043E+06  11000
   3-230000  8.03312E+06  0.00000E+00   1.0000       1.0000       528.603      528.603      528.603      1.66043E+06  1.66043E+06  11000
   3-240000  8.03289E+06  0.00000E+00   1.0000       1.0000       528.598      528.598      528.598      1.66042E+06  1.66042E+06  11000
   3-250000  8.03278E+06  0.00000E+00   1.0000       1.0000       528.596      528.596      528.596      1.66041E+06  1.66041E+06  11000
 manif4   branch
   4-010000  8.03229E+06  0.00000E+00   1.0000       1.0000       529.972      529.972      529.972      1.66470E+06  1.66470E+06  11000
 manif5   branch
   5-010000  8.01587E+06  0.00000E+00   1.0000       1.0000       778.621      778.621      778.621      2.43980E+06  2.43980E+06  11000
 pipe6    pipe
   6-010000  8.01342E+06  0.00000E+00   1.0000       1.0000       778.528      778.528      778.528      2.43951E+06  2.43951E+06  11000
   6-020000  8.01326E+06  0.00000E+00   1.0000       1.0000       778.525      778.525      778.525      2.43950E+06  2.43950E+06  11000
   6-030000  8.01291E+06  0.00000E+00   1.0000       1.0000       778.526      778.526      778.526      2.43950E+06  2.43950E+06  11000
   6-040000  8.01251E+06  0.00000E+00   1.0000       1.0000       778.525      778.525      778.525      2.43950E+06  2.43950E+06  11000
   6-050000  8.00581E+06  0.00000E+00   1.0000       1.0000       778.514      778.514      778.514      2.43946E+06  2.43946E+06  11000
   6-060000  7.99933E+06  0.00000E+00   1.0000       1.0000       778.457      778.457      778.457      2.43929E+06  2.43929E+06  11000
   6-070000  7.99233E+06  0.00000E+00   1.0000       1.0000       778.463      778.463      778.463      2.43930E+06  2.43930E+06  11000
   6-080000  7.98743E+06  0.00000E+00   1.0000       1.0000       778.305      778.305      778.305      2.43881E+06  2.43881E+06  11000
   6-090000  7.98495E+06  0.00000E+00   1.0000       1.0000       778.310      778.310      778.310      2.43883E+06  2.43883E+06  11000
   6-100000  7.97845E+06  0.00000E+00   1.0000       1.0000       778.388      778.388      778.388      2.43907E+06  2.43907E+06  11000
   6-110000  7.96874E+06  0.00000E+00   1.0000       1.0000       778.361      778.361      778.361      2.43899E+06  2.43899E+06  11000
   6-120000  7.96015E+06  0.00000E+00   1.0000       1.0000       778.284      778.284      778.284      2.43875E+06  2.43875E+06  11000
   6-130000  7.95325E+06  0.00000E+00   1.0000       1.0000       778.293      778.293      778.293      2.43877E+06  2.43877E+06  11000
   6-140000  7.94643E+06  0.00000E+00   1.0000       1.0000       778.221      778.221      778.221      2.43855E+06  2.43855E+06  11000
   6-150000  7.94257E+06  0.00000E+00   1.0000       1.0000       778.117      778.117      778.117      2.43822E+06  2.43822E+06  11000
   6-160000  7.93931E+06  0.00000E+00   1.0000       1.0000       778.138      778.138      778.138      2.43829E+06  2.43829E+06  11000
   6-170000  7.93403E+06  0.00000E+00   1.0000       1.0000       778.136      778.136      778.136      2.43828E+06  2.43828E+06  11000
   6-180000  7.92874E+06  0.00000E+00   1.0000       1.0000       778.078      778.078      778.078      2.43810E+06  2.43810E+06  11000
   6-190000  7.92547E+06  0.00000E+00   1.0000       1.0000       777.996      777.996      777.996      2.43785E+06  2.43785E+06  11000
   6-200000  7.92220E+06  0.00000E+00   1.0000       1.0000       778.018      778.018      778.018      2.43792E+06  2.43792E+06  11000
   6-210000  7.91679E+06  0.00000E+00   1.0000       1.0000       778.020      778.020      778.020      2.43792E+06  2.43792E+06  11000
   6-220000  7.91105E+06  0.00000E+00   1.0000       1.0000       778.029      778.029      778.029      2.43795E+06  2.43795E+06  11000
   6-230000  7.90465E+06  0.00000E+00   1.0000       1.0000       778.045      778.045      778.045      2.43800E+06  2.43800E+06  11000
   6-240000  7.90000E+06  0.00000E+00   1.0000       1.0000       777.900      777.900      777.900      2.43755E+06  2.43755E+06  11000
   6-250000  7.89824E+06  0.00000E+00   1.0000       1.0000       777.873      777.873      777.873      2.43746E+06  2.43746E+06  11000
 vol7     tmdpvol
   7-010000  7.90000E+06  0.00000E+00   1.0000       1.0000       773.000      773.000      773.000      2.42227E+06  2.42227E+06  11000
filter8  branch
   8-010000  7.89723E+06  0.00000E+00   1.0000       1.0000       777.914      777.914      777.914      2.43759E+06  2.43759E+06  11000
 pipe10   pipe
  10-010000  7.87168E+06  0.00000E+00   1.0000       1.0000       777.260      777.260      777.260      2.43555E+06  2.43555E+06  00000
  10-020000  7.87139E+06  0.00000E+00   1.0000       1.0000       705.919      705.919      705.919      2.21315E+06  2.21315E+06  00000
  10-030000  7.87130E+06  0.00000E+00   1.0000       1.0000       646.205      646.205      646.205      2.02700E+06  2.02700E+06  00000
  10-040000  7.87122E+06  0.00000E+00   1.0000       1.0000       595.948      595.948      595.948      1.87034E+06  1.87034E+06  00000
  10-050000  7.87115E+06  0.00000E+00   1.0000       1.0000       553.446      553.446      553.446      1.73786E+06  1.73786E+06  00000
  10-060000  7.87108E+06  0.00000E+00   1.0000       1.0000       517.348      517.348      517.348      1.62535E+06  1.62535E+06  00000
  10-070000  7.87121E+06  0.00000E+00   1.0000       1.0000       517.351      517.351      517.351      1.62536E+06  1.62536E+06  00000
 pipe16   pipe
  16-010000  7.86636E+06  0.00000E+00   1.0000       1.0000       517.230      517.230      517.230      1.62499E+06  1.62499E+06  11000
  16-020000  7.86540E+06  0.00000E+00   1.0000       1.0000       517.223      517.223      517.223      1.62496E+06  1.62496E+06  11000
 branch17 branch
  17-010000  7.86485E+06  0.00000E+00   1.0000       1.0000       517.219      517.219      517.219      1.62495E+06  1.62495E+06  11000
 pipe18   pipe
  18-010000  7.86431E+06  0.00000E+00   1.0000       1.0000       517.223      517.223      517.223      1.62496E+06  1.62496E+06  11000
  18-020000  7.86332E+06  0.00000E+00   1.0000       1.0000       517.203      517.203      517.203      1.62490E+06  1.62490E+06  11000
```

0 Vol.no.	pressure (pa)	voidf	voidg	voidgo	tempf (k)	tempg (k)	sat. temp. (k)	uf (j/kg)	ug (j/kg)	volume flag
pipe20 pipe										
20-010000	8.03175E+06	0.00000E+00	1.0000	1.0000	533.015	533.015	533.015	1.67418E+06	1.67418E+06	11000
20-020000	8.03140E+06	0.00000E+00	1.0000	1.0000	574.319	574.319	574.319	1.80292E+06	1.80292E+06	11000
20-030000	8.03100E+06	0.00000E+00	1.0000	1.0000	615.515	615.515	615.515	1.93133E+06	1.93133E+06	11000
20-040000	8.03058E+06	0.00000E+00	1.0000	1.0000	656.816	656.816	656.816	2.06008E+06	2.06008E+06	11000
20-050000	8.03019E+06	0.00000E+00	1.0000	1.0000	659.863	659.863	659.863	2.06958E+06	2.06958E+06	11000
pipe21 pipe										
21-010000	8.03177E+06	0.00000E+00	1.0000	1.0000	532.997	532.997	532.997	1.67413E+06	1.67413E+06	11000
21-020000	8.03141E+06	0.00000E+00	1.0000	1.0000	574.101	574.101	574.101	1.80224E+06	1.80224E+06	11000
21-030000	8.03101E+06	0.00000E+00	1.0000	1.0000	614.990	614.990	614.990	1.92970E+06	1.92970E+06	11000
21-040000	8.03058E+06	0.00000E+00	1.0000	1.0000	656.091	656.091	656.091	2.05781E+06	2.05781E+06	11000
21-050000	8.03019E+06	0.00000E+00	1.0000	1.0000	659.120	659.120	659.120	2.06726E+06	2.06726E+06	11000
pipe22 pipe										
22-010000	8.03176E+06	0.00000E+00	1.0000	1.0000	532.966	532.966	532.966	1.67403E+06	1.67403E+06	11000
22-020000	8.03139E+06	0.00000E+00	1.0000	1.0000	573.651	573.651	573.651	1.80084E+06	1.80084E+06	11000
22-030000	8.03098E+06	0.00000E+00	1.0000	1.0000	614.123	614.123	614.123	1.92699E+06	1.92699E+06	11000
22-040000	8.03055E+06	0.00000E+00	1.0000	1.0000	654.805	654.805	654.805	2.05381E+06	2.05381E+06	11000
22-050000	8.03015E+06	0.00000E+00	1.0000	1.0000	657.804	657.804	657.804	2.06315E+06	2.06315E+06	11000
pipe23 pipe										
23-010000	8.03176E+06	0.00000E+00	1.0000	1.0000	532.967	532.967	532.967	1.67403E+06	1.67403E+06	11000
23-020000	8.03139E+06	0.00000E+00	1.0000	1.0000	573.612	573.612	573.612	1.80072E+06	1.80072E+06	11000
23-030000	8.03098E+06	0.00000E+00	1.0000	1.0000	614.166	614.166	614.166	1.92713E+06	1.92713E+06	11000
23-040000	8.03055E+06	0.00000E+00	1.0000	1.0000	654.809	654.809	654.809	2.05382E+06	2.05382E+06	11000
23-050000	8.03015E+06	0.00000E+00	1.0000	1.0000	657.808	657.808	657.808	2.06317E+06	2.06317E+06	11000
pipe24 pipe										
24-010000	8.03121E+06	0.00000E+00	1.0000	1.0000	581.536	581.536	581.536	1.82542E+06	1.82542E+06	11000
24-020000	8.03006E+06	0.00000E+00	1.0000	1.0000	633.088	633.088	633.088	1.98611E+06	1.98611E+06	11000
pipe25 pipe										
25-010000	8.03114E+06	0.00000E+00	1.0000	1.0000	581.367	581.367	581.367	1.82489E+06	1.82489E+06	11000
25-020000	8.02999E+06	0.00000E+00	1.0000	1.0000	632.752	632.752	632.752	1.98506E+06	1.98506E+06	11000
manif30 branch										
30-010000	8.03032E+06	0.00000E+00	1.0000	1.0000	652.064	652.064	652.064	2.04526E+06	2.04526E+06	11000
manif31 branch										
31-010000	8.03028E+06	0.00000E+00	1.0000	1.0000	649.853	649.853	649.853	2.03837E+06	2.03837E+06	11000
vol40 snglvol										
40-010000	8.02514E+06	0.00000E+00	1.0000	1.0000	652.925	652.925	652.925	2.04795E+06	2.04795E+06	11000
vol41 snglvol										
41-010000	8.02478E+06	0.00000E+00	1.0000	1.0000	652.808	652.808	652.808	2.04758E+06	2.04758E+06	11000
vol42 snglvol										
42-010000	8.02474E+06	0.00000E+00	1.0000	1.0000	650.595	650.595	650.595	2.04068E+06	2.04068E+06	11000
vol43 snglvol										
43-010000	8.02512E+06	0.00000E+00	1.0000	1.0000	650.714	650.714	650.714	2.04105E+06	2.04105E+06	11000
pipe50 pipe										
50-010000	8.02271E+06	0.00000E+00	1.0000	1.0000	715.346	715.346	715.346	2.24253E+06	2.24253E+06	11000
50-020000	8.02115E+06	0.00000E+00	1.0000	1.0000	777.796	777.796	777.796	2.43722E+06	2.43722E+06	11000
pipe51 pipe										
51-010000	8.02242E+06	0.00000E+00	1.0000	1.0000	715.211	715.211	715.211	2.24211E+06	2.24211E+06	11000
51-020000	8.02098E+06	0.00000E+00	1.0000	1.0000	777.642	777.642	777.642	2.43674E+06	2.43674E+06	11000
pipe52 pipe										
52-010000	8.02240E+06	0.00000E+00	1.0000	1.0000	713.051	713.051	713.051	2.23538E+06	2.23538E+06	11000
52-020000	8.02097E+06	0.00000E+00	1.0000	1.0000	775.535	775.535	775.535	2.43017E+06	2.43017E+06	11000
pipe53 pipe										
53-010000	8.02269E+06	0.00000E+00	1.0000	1.0000	713.109	713.109	713.109	2.23556E+06	2.23556E+06	11000
53-020000	8.02114E+06	0.00000E+00	1.0000	1.0000	775.532	775.532	775.532	2.43017E+06	2.43017E+06	11000
pipe54 pipe										
54-010000	8.02373E+06	0.00000E+00	1.0000	1.0000	650.685	650.685	650.685	2.04096E+06	2.04096E+06	11000
54-020000	8.01966E+06	0.00000E+00	1.0000	1.0000	650.675	650.675	650.675	2.04093E+06	2.04093E+06	11000
vol60 snglvol										
60-010000	8.01488E+06	0.00000E+00	1.0000	1.0000	778.627	778.627	778.627	2.43981E+06	2.43981E+06	11000
vol61 snglvol										
61-010000	8.01438E+06	0.00000E+00	1.0000	1.0000	778.352	778.352	778.352	2.43896E+06	2.43896E+06	11000
vol62 snglvol										
62-010000	8.01437E+06	0.00000E+00	1.0000	1.0000	775.865	775.865	775.865	2.43120E+06	2.43120E+06	11000
vol63 snglvol										
63-010000	8.01488E+06	0.00000E+00	1.0000	1.0000	776.363	776.363	776.363	2.43276E+06	2.43276E+06	11000
pipe91 pipe										
91-010000	7.88894E+06	0.00000E+00	1.0000	1.0000	777.601	777.601	777.601	2.43662E+06	2.43662E+06	11000
91-020000	7.88747E+06	0.00000E+00	1.0000	1.0000	777.586	777.586	777.586	2.43657E+06	2.43657E+06	11000
branch92 branch										
92-010000	7.88663E+06	0.00000E+00	1.0000	1.0000	777.576	777.576	777.576	2.43654E+06	2.43654E+06	11000
pipe93 pipe										
93-010000	7.88579E+06	0.00000E+00	1.0000	1.0000	777.585	777.585	777.585	2.43657E+06	2.43657E+06	11000
93-020000	7.88355E+06	0.00000E+00	1.0000	1.0000	777.568	777.568	777.568	2.43651E+06	2.43651E+06	11000
pipe95 pipe										
95-010000	7.87787E+06	0.00000E+00	1.0000	1.0000	777.415	777.415	777.415	2.43604E+06	2.43604E+06	11000
95-020000	7.87575E+06	0.00000E+00	1.0000	1.0000	777.364	777.364	777.364	2.43588E+06	2.43588E+06	11000
pipe97 pipe										
97-010000	7.87300E+06	0.00000E+00	1.0000	1.0000	777.289	777.289	777.289	2.43564E+06	2.43564E+06	11000
97-020000	7.87153E+06	0.00000E+00	1.0000	1.0000	777.254	777.254	777.254	2.43554E+06	2.43554E+06	11000
vol111 snglvol										
111-010000	7.88659E+06	0.00000E+00	1.0000	1.0000	774.386	774.386	774.386	2.42659E+06	2.42659E+06	11000
pipe113 pipe										
113-010000	7.86476E+06	0.00000E+00	1.0000	1.0000	773.487	773.487	773.487	2.42379E+06	2.42379E+06	11000
113-020000	7.86475E+06	0.00000E+00	1.0000	1.0000	773.447	773.447	773.447	2.42367E+06	2.42367E+06	11000
pipe114 pipe										
114-010000	7.86477E+06	0.00000E+00	1.0000	1.0000	773.522	773.522	773.522	2.42390E+06	2.42390E+06	11000
114-020000	7.86481E+06	0.00000E+00	1.0000	1.0000	769.983	769.983	769.983	2.41287E+06	2.41287E+06	11000

0System 2 *none* mass= 392.46 kg mass error= 1.08030E-04 kg err.est.= 1.48509E-11

0 Vol.no.	pressure (pa)	voidf	voidg	voidgo	tempf (k)	tempg (k)	sat. temp. (k)	uf (j/kg)	ug (j/kg)	volume flag
vol115 snglvol										
115-010000	7.86484E+06	0.00000E+00	1.0000	1.0000	641.580	641.580	641.580	2.01258E+06	2.01258E+06	11000
vol100 tmdpvol										
100-010000	1.00000E+06	1.0000	0.00000E+00	0.00000E+00	308.150	453.034	453.034	1.46445E+05	2.58187E+06	11000
hx101 branch										
101-010000	1.01177E+06	1.0000	0.00000E+00	0.00000E+00	308.150	453.543	453.543	1.46445E+05	2.58219E+06	00010
pipe102 pipe										
102-010000	1.01059E+06	1.0000	0.00000E+00	0.00000E+00	311.171	453.492	453.492	1.59060E+05	2.58216E+06	00000
102-020000	1.00823E+06	1.0000	0.00000E+00	0.00000E+00	314.728	453.391	453.391	1.73913E+05	2.58210E+06	00000
102-030000	1.00587E+06	1.0000	0.00000E+00	0.00000E+00	318.933	453.289	453.289	1.91476E+05	2.58203E+06	00000
102-040000	1.00352E+06	1.0000	0.00000E+00	0.00000E+00	323.927	453.187	453.187	2.12346E+05	2.58197E+06	00000
102-050000	1.00117E+06	1.0000	0.00000E+00	0.00000E+00	329.893	453.085	453.085	2.37277E+05	2.58191E+06	00000
hx103 branch										

103-010000	1.00000E+06	1.0000	0.00000E+00	0.00000E+00	329.970	453.034	453.034	2.37600E+05	2.58187E+06	00010
vol104 tmdpvol										
104-010000	1.00000E+06	1.0000	0.00000E+00	0.00000E+00	348.150	453.034	453.034	3.13689E+05	2.58187E+06	11000

Hydrodynamics - Quatities related to junctions

0System 1	*none*											
0 Jun.no.	from vol.	to vol.	liq.j.vel. (m/sec)	vap.j.vel. (m/sec)	mass flow (kg/sec)	jun.area (m2)	throat ratio	junction flags	flow regi	no. last	advs. edit	choked total
gebl2 pump												
2-010000	18-020002	2-010001	26.345	26.345	.70651	3.66400E-03	1.0000	000010	x	0	0	0
2-020000	2-010002	3-010001	26.368	26.368	.70651	3.66400E-03	1.0000	000010	x	0	0	0
pipe3 pipe												
3-010000	3-010002	3-020001	26.140	26.140	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-020000	3-020002	3-030001	26.146	26.146	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-030000	3-030002	3-040001	26.158	26.158	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-040000	3-040002	3-050001	26.171	26.171	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-050000	3-050002	3-060001	26.182	26.182	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-060000	3-060002	3-070001	26.191	26.191	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-070000	3-070002	3-080001	26.198	26.198	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-080000	3-080002	3-090001	26.207	26.207	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-090000	3-090002	3-100001	26.216	26.216	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-100000	3-100002	3-110001	26.225	26.225	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-110000	3-110002	3-120001	26.232	26.232	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-120000	3-120002	3-130001	26.242	26.242	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-130000	3-130002	3-140001	26.256	26.256	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-140000	3-140002	3-150001	26.269	26.269	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-150000	3-150002	3-160001	26.286	26.286	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-160000	3-160002	3-170001	26.305	26.305	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-170000	3-170002	3-180001	26.316	26.316	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-180000	3-180002	3-190001	26.321	26.321	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-190000	3-190002	3-200001	26.333	26.333	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-200000	3-200002	3-210001	26.344	26.344	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-210000	3-210002	3-220001	26.356	26.356	.70651	3.66400E-03	1.0000	000010	x	0	0	0
3-220000	3-220002	3-230001	9.3938	9.3938	.70651	1.02800E-02	1.0000	000010	x	0	0	0
3-230000	3-230002	3-240001	9.3942	9.3942	.70652	1.02800E-02	1.0000	000010	x	0	0	0
3-240000	3-240002	3-250001	9.3943	9.3943	.70652	1.02800E-02	1.0000	000010	x	0	0	0
manif4 branch												
4-010000	3-250002	-4-010004	26.826	26.826	.70652	3.60000E-03	1.0000	000101	mpr	0	0	0
4-020000	4-010002	20-010001	8.4101	8.4101	.22091	3.60000E-03	1.0000	000100	mpr	0	0	0
4-030000	4-010002	21-010001	7.9301	7.9301	2.96245E-02	5.12000E-04	1.0000	000100	mpr	0	0	0
4-040000	-4-010001	22-010001	8.0117	8.0117	2.99295E-02	5.12000E-04	1.0000	000100	mpr	0	0	0
4-050000	-4-010001	23-010001	8.0118	8.0118	.20951	3.58400E-03	1.0000	000100	mpr	0	0	0
4-060000	4-010006	24-010001	11.370	11.370	9.40764E-02	1.13400E-03	1.0000	000102	mpr	0	0	0
4-070000	-4-010005	25-010001	11.990	11.990	.12247	1.40000E-03	1.0000	000102	mpr	0	0	0
manif5 branch												
5-010000	60-010002	5-010003	34.112	34.112	7.64065E-02	4.52000E-04	1.0000	000101	mpr	0	0	0
5-020000	61-010002	5-010003	36.249	36.249	.27653	1.53900E-03	1.0000	000101	mpr	0	0	0
5-030000	62-010002	5-010003	36.213	36.213	.27714	1.53900E-03	1.0000	000101	mpr	0	0	0
5-040000	63-010002	5-010003	34.027	34.027	7.64387E-02	4.52000E-04	1.0000	000101	mpr	0	0	0
5-050000	5-010004	6-010001	39.599	39.599	.70652	3.60000E-03	1.0000	000102	mpr	0	0	0
pipe6 pipe												
6-010000	6-010002	6-020001	13.870	13.870	.70652	1.02800E-02	1.0000	000010	x	0	0	0
6-020000	6-020002	6-030001	13.870	13.870	.70652	1.02800E-02	1.0000	000010	x	0	0	0
6-030000	6-030002	6-040001	13.871	13.871	.70652	1.02800E-02	1.0000	000010	x	0	0	0
6-040000	6-040002	6-050001	38.918	38.918	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-050000	6-050002	6-060001	38.951	38.951	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-060000	6-060002	6-070001	38.979	38.979	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-070000	6-070002	6-080001	39.014	39.014	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-080000	6-080002	6-090001	39.030	39.030	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-090000	6-090002	6-100001	39.042	39.042	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-100000	6-100002	6-110001	39.078	39.078	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-110000	6-110002	6-120001	39.124	39.124	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-120000	6-120002	6-130001	39.163	39.163	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-130000	6-130002	6-140001	39.197	39.197	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-140000	6-140002	6-150001	39.227	39.227	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-150000	6-150002	6-160001	39.241	39.241	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-160000	6-160002	6-170001	39.258	39.258	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-170000	6-170002	6-180001	39.284	39.284	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-180000	6-180002	6-190001	39.307	39.307	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-190000	6-190002	6-200001	39.319	39.319	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-200000	6-200002	6-210001	39.337	39.337	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-210000	6-210002	6-220001	39.364	39.364	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-220000	6-220002	6-230001	39.393	39.393	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-230000	6-230002	6-240001	39.426	39.426	.70652	3.66400E-03	1.0000	000010	x	0	0	0
6-240000	6-240002	6-250001	39.440	39.440	.70650	3.66400E-03	1.0000	000010	x	0	0	0
filter8 branch												
8-010000	6-250002	8-010001	39.448	39.448	.70650	3.66400E-03	1.0000	000110	x	0	0	0
8-020000	8-010002	91-010001	39.455	39.455	.70651	3.66400E-03	1.0000	000110	x	0	0	0
pipe10 pipe												
10-010000	10-010002	10-020001	9.8045	9.8045	.70651	1.47800E-02	1.0000	000000	mpr	0	0	0
10-020000	10-020002	10-030001	8.9049	8.9049	.70651	1.47800E-02	1.0000	000000	mpr	0	0	0
10-030000	10-030002	10-040001	8.1517	8.1517	.70651	1.47800E-02	1.0000	000000	mpr	0	0	0
10-040000	10-040002	10-050001	7.5178	7.5178	.70651	1.47800E-02	1.0000	000000	mpr	0	0	0
10-050000	10-050002	10-060001	6.9817	6.9817	.70651	1.47800E-02	1.0000	000000	mpr	0	0	0
10-060000	10-060002	10-070001	6.5264	6.5264	.70651	1.47800E-02	1.0000	000000	mpr	0	0	0
jun15 sngljun												
15-000000	10-070002	16-010001	26.326	26.326	.70651	3.66400E-03	1.0000	001100	mpr	0	0	0
pipe16 pipe												
16-010000	16-010002	16-020001	26.336	26.336	.70651	3.66400E-03	1.0000	000010	x	0	0	0
branch17 branch												
17-010000	16-020002	17-010001	26.339	26.339	.70651	3.66400E-03	1.0000	000110	x	0	0	0
17-020000	17-010002	18-010001	26.341	26.341	.70651	3.66400E-03	1.0000	000110	x	0	0	0
17-030000	115-010002	17-010003	-2.46739E-08	-2.46739E-08	-6.61799E-10	3.66400E-03	1.0000	000111	x	0	0	0
pipe18 pipe												
18-010000	18-010002	18-020001	26.343	26.343	.70651	3.66400E-03	1.0000	000010	x	0	0	0
pipe20 pipe												
20-010000	20-010002	20-020001	7.9303	7.9303	.22091	3.84000E-03	1.0000	001000	mpr	0	0	0
20-020000	20-020002	20-030001	8.5452	8.5452	.22091	3.84000E-03	1.0000	001000	mpr	0	0	0
20-030000	20-030002	20-040001	9.1586	9.1586	.22091	3.84000E-03	1.0000	001000	mpr	0	0	0
20-040000	20-040002	20-050001	9.7737	9.7737	.22091	3.84000E-03	1.0000	001000	mpr	0	0	0
pipe21 pipe												
21-010000	21-010002	21-020001	7.9759	7.9759	2.96245E-02	5.12000E-04	1.0000	001000	mpr	0	0	0
21-020000	21-020002	21-030001	8.5914	8.5914	2.96245E-02	5.12000E-04	1.0000	001000	mpr	0	0	0
21-030000	21-030002	21-040001	9.2037	9.2037	2.96245E-02	5.12000E-04	1.0000	001000	mpr	0	0	0
21-040000	21-040002	21-050001	9.8193	9.8193	2.96245E-02	5.12000E-04	1.0000	001000	mpr	0	0	0

```
0   Jun.no.   from vol.    to vol.  liq.j.vel.   vap.j.vel.   mass flow    jun.area     throat        junction  flow no. advs. choked
                                    (m/sec)      (m/sec)      (kg/sec)     (m2)         ratio            flags  regi last edit  total
 pipe22   pipe
  22-010000   22-010002   22-020001   8.0575       8.0575       2.99295E-02  5.12000E-04  1.0000        001000   mpr  0       0       0
  22-020000   22-020002   22-030001   8.6730       8.6730       2.99295E-02  5.12000E-04  1.0000        001000   mpr  0       0       0
  22-030000   22-030002   22-040001   9.2854       9.2854       2.99295E-02  5.12000E-04  1.0000        001000   mpr  0       0       0
  22-040000   22-040002   22-050001   9.9010       9.9010       2.99295E-02  5.12000E-04  1.0000        001000   mpr  0       0       0
 pipe23   pipe
  23-010000   23-010002   23-020001   8.0576       8.0576        .20951      3.58400E-03  1.0000        001000   mpr  0       0       0
  23-020000   23-020002   23-030001   8.6725       8.6725        .20951      3.58400E-03  1.0000        001000   mpr  0       0       0
  23-030000   23-030002   23-040001   9.2861       9.2861        .20951      3.58400E-03  1.0000        001000   mpr  0       0       0
  23-040000   23-040002   23-050001   9.9012       9.9012        .20951      3.58400E-03  1.0000        001000   mpr  0       0       0
 pipe24   pipe
  24-010000   24-010002   24-020001   12.478       12.478       9.40764E-02  1.13400E-03  1.0000        001000   mpr  0       0       0
 pipe25   pipe
  25-010000   25-010002   25-020001   13.154       13.154        .12247      1.40000E-03  1.0000        001000   mpr  0       0       0
 manif30  branch
  30-010000   20-050002  -30-010006   11.783       11.783        .22091      3.20000E-03  1.0000        000101   mpr  0       0       0
  30-020000   21-050002  -30-010006   9.8652       9.8652       2.96245E-02  5.12000E-04  1.0000        000101   mpr  0       0       0
  30-030000   24-020002  -30-010002   6.4396       6.4396       4.45906E-02  1.13400E-03  1.0000        000100   mpr  0       0       0
  30-040000   25-020002   30-010001   6.7597       6.7597       5.78168E-02  1.40000E-03  1.0000        000100   mpr  0       0       0
  30-050000  -30-010005   40-010001   28.512       28.512       7.64065E-02  4.52000E-04  1.0000        000102   mpr  0       0       0
  30-060000  -30-010005   41-010001   30.307       30.307        .27653      1.53900E-03  1.0000        000102   mpr  0       0       0
 manif31  branch
  31-010000   22-050002   31-010005   9.9469       9.9469       2.99295E-02  5.12000E-04  1.0000        000101   mpr  0       0       0
  31-020000   23-050002   31-010005   11.141       11.141        .20951      3.20000E-03  1.0000        000101   mpr  0       0       0
  31-030000   24-020002  -31-010002   7.1465       7.1465       4.94858E-02  1.13400E-03  1.0000        000100   mpr  0       0       0
  31-040000   25-020002   31-010001   7.5591       7.5591       6.46543E-02  1.40000E-03  1.0000        000100   mpr  0       0       0
  31-050000   31-010006   42-010001   30.271       30.271        .27714      1.53900E-03  1.0000        000102   mpr  0       0       0
  31-060000   31-010006   43-010001   28.428       28.428       7.64386E-02  4.52000E-04  1.0000        000102   mpr  0       0       0
 jun45    sngljun
  45-000000   40-010002   50-010001   28.568       28.568       7.64065E-02  4.52000E-04  1.0000        001100   mpr  0       0       0
 jun46    sngljun
  46-000000   41-010002   51-010001   30.363       30.363        .27653      1.53900E-03  1.0000        001100   mpr  0       0       0
 jun47    sngljun
  47-000000   42-010002   52-010001   30.235       30.235        .27630      1.53900E-03  1.0000        001100   mpr  0       0       0
 jun48    sngljun
  48-000000   43-010002   53-010001   28.484       28.484       7.64386E-02  4.52000E-04  1.0000        001100   mpr  0       0       0
 jun49    sngljun
  49-000000   42-010002   54-010001   15.715       15.715       8.39858E-04  9.00000E-06  1.0000        001100   mpr  0       0       0
 pipe50   pipe
  50-010000   50-010002   50-020001   9.8276       9.8276       7.64065E-02  1.44000E-03  1.0000        001000   mpr  0       0       0
 pipe51   pipe
  51-010000   51-010002   51-020001   9.4834       9.4834        .27653      5.40000E-03  1.0000        001000   mpr  0       0       0
 pipe52   pipe
  52-010000   52-010002   52-020001   9.4468       9.4468        .27630      5.40000E-03  1.0000        001000   mpr  0       0       0
 pipe53   pipe
  53-010000   53-010002   53-020001   9.8010       9.8010       7.64386E-02  1.44000E-03  1.0000        001000   mpr  0       0       0
 pipe54   pipe
  54-010000   54-010002   54-020001   15.720       15.720       8.39858E-04  9.00000E-06  1.0000        001000   mpr  0       0       0
 jun55    sngljun
  55-000000   50-020002   60-010001   34.049       34.049       7.64065E-02  4.52000E-04  1.0000        001100   mpr  0       0       0
 jun56    sngljun
  56-000000   51-020002   61-010001   36.186       36.186        .27653      1.53900E-03  1.0000        001100   mpr  0       0       0
 jun57    sngljun
  57-000000   52-020002   62-010001   36.058       36.058        .27630      1.53900E-03  1.0000        001100   mpr  0       0       0
 jun58    sngljun
  58-000000   53-020002   63-010001   33.964       33.964       7.64386E-02  4.52000E-04  1.0000        001100   mpr  0       0       0
 jun59    sngljun
  59-000000   54-020002   62-010001   15.727       15.727       8.39858E-04  9.00000E-06  1.0000        001100   mpr  0       0       0
 vlve76   valve
  76-000000    7-010000   -6-240004 -1.19129E-03 -1.19129E-03 -2.13400E-05  3.66400E-03  1.0000        000001   mpr  0       0       0
 pipe91   pipe
  91-010000   91-010002   91-020001   39.480       39.480        .70651      3.66400E-03  1.0000        000000   mpr  0       0       0
 branch92 branch
  92-010000   91-020002   92-010001   39.487       39.487        .70651      3.66400E-03  1.0000        000110   x    0       0       0
  92-020000   92-010002   93-010001   39.491       39.491        .70651      3.66400E-03  1.0000        000110   x    0       0       0
  92-030000  -92-010003  111-010001 -7.83465E-10 -7.83466E-10 -1.40742E-11  3.66400E-03  1.0000        000112   x    0       0       0
 pipe93   pipe
  93-010000   93-010002   93-020001   39.495       39.495        .70651      3.66400E-03  1.0000        000000   mpr  0       0       0
 vlve94   valve
  94-000000   93-020002   95-010001   39.506       39.506        .70651      3.66400E-03  1.0000        000010   x    0       0       0
 pipe95   pipe
  95-010000   95-010002   95-020001   39.526       39.526        .70651      3.66400E-03  1.0000        000000   mpr  0       0       0
 jun96    sngljun
  96-000000   95-020002   97-010001   39.535       39.535        .70651      3.66400E-03  1.0000        001100   mpr  0       0       0
 pipe97   pipe
  97-010000   97-010002   97-020001   39.544       39.544        .70651      3.66400E-03  1.0000        000000   mpr  0       0       0
 jun98    sngljun
  98-000000   97-020002   10-010001   39.550       39.550        .70651      3.66400E-03  1.0000        001100   mpr  0       0       0
 vlve112  valve
 112-000000  111-010002  113-010001  0.00000E+00  0.00000E+00  0.00000E+00  3.66400E-03  0.00000E+00   000010   x    0       0       0
pipe113  pipe
 113-010000  113-010002  113-020001 -1.20647E-09 -1.20647E-09 -2.16392E-11  3.66400E-03  1.0000        000000   mpr  0       0       0
 pipe114  pipe
 114-010000  114-010002  114-020001 -2.36795E-09 -2.36795E-09 -2.68507E-10  2.30600E-02  1.0000        000000   mpr  0       0       0
 jun123   sngljun
 123-000000  113-020002  114-010001 -4.02164E-09 -4.02164E-09 -7.21255E-11  3.66400E-03  1.0000        000000   mpr  0       0       0
 jun125   sngljun
 125-000000  114-020002  115-010001 -2.50970E-08 -2.50970E-08 -5.42667E-10  3.66400E-03  1.0000        000000   mpr  0       0       0
0System  2     *none*
 hx101    branch
 101-010000  101-010002  102-010001   .29824       .29824       10.500      3.54000E-02  1.0000        000000   bby  0       0       0
pipe102  pipe
 102-010000  102-010002  102-020001   .29857       .37031       10.500      3.54000E-02  1.0000        000000   bby  0       0       0
 102-020000  102-020002  102-030001   .29898       .37084       10.500      3.54000E-02  1.0000        000000   bby  0       0       0
 102-030000  102-030002  102-040001   .29951       .37151       10.500      3.54000E-02  1.0000        000000   bby  0       0       0
 102-040000  102-040002  102-050001   .30018       .37237       10.500      3.54000E-02  1.0000        000000   bby  0       0       0
 hx103    branch 103-010000  102-050002  103-010001   .30105       .37349       10.500      3.54000E-02  1.0000        000000   bby
0      0       0
 jun134   sngljun
 134-000000  103-010002  104-010000   .30105       .30105       10.500      3.54000E-02  1.0000        000000   bby  0       0       0
 jun211   tmdpjun
 211-000000  100-010000  101-010001   .29824       .29824       10.500      3.54000E-02  1.0000        000000   bby  0       0       0
```

Heat structure quantities

```
1  RELAP5/3.1          Reactor Loss Of Coolant Analysis Program
  tbm1                                                                   18-Sep-01    00:08:18
0 HEAT STRUCTURE OUTPUT +++time=      89.8250     sec
```

str.no.	side	bdry.vol. number	surface temp. (k)	heat-trf. convection (watt)	heat-flux convection (watt/m2)	critical heat-flux (watt/m2)	CHF mul	ht mode	heat-trf. coef.conv (watt/m2-k)	int.-heat source (watt)	conv+rad -source (watt)	vol.ave. temp. (k)
20-001	left	2-010000	525.657	-3.53799E-03	-1.00105E-02	0.00000E+00	.00	29	1025.0	0.00000E+00	-3.53799E-03	525.66
	right	0-000000	525.657	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-001	left	3-010000	528.760	-1.45457E-02	-9.68422E-02	0.00000E+00	.00	29	2149.4	0.00000E+00	-1.45457E-02	528.76
	right	0-000000	528.760	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-002	left	3-020000	528.766	-5.84806E-02	-9.73383E-02	0.00000E+00	.00	29	2149.4	0.00000E+00	-5.84806E-02	528.77
	right	0-000000	528.766	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-003	left	3-030000	528.772	-.10538	-9.82258E-02	0.00000E+00	.00	29	2149.4	0.00000E+00	-.10538	528.77
	right	0-000000	528.772	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-004	left	3-040000	528.772	-.10634	-9.91143E-02	0.00000E+00	.00	29	2149.4	0.00000E+00	-.10634	528.77
	right	0-000000	528.772	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-005	left	3-050000	528.762	-8.56789E-02	-9.98259E-02	0.00000E+00	.00	29	2149.4	0.00000E+00	-8.56789E-02	528.76
	right	0-000000	528.761	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-006	left	3-060000	528.740	-6.89342E-02	-.10040	0.00000E+00	.00	29	2149.4	0.00000E+00	-6.89342E-02	528.74
	right	0-000000	528.740	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-007	left	3-070000	528.717	-4.75770E-02	-.10079	0.00000E+00	.00	29	2149.4	0.00000E+00	-4.75770E-02	528.72
	right	0-000000	528.716	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-008	left	3-080000	528.713	-6.95963E-02	-.10136	0.00000E+00	.00	29	2149.4	0.00000E+00	-6.95963E-02	528.71
	right	0-000000	528.713	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-009	left	3-090000	528.700	-6.99902E-02	-.10193	0.00000E+00	.00	29	2149.4	0.00000E+00	-6.99902E-02	528.70
	right	0-000000	528.700	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-010	left	3-100000	528.686	-7.03848E-02	-.10251	0.00000E+00	.00	29	2149.4	0.00000E+00	-7.03848E-02	528.69
	right	0-000000	528.686	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-011	left	3-110000	528.663	-4.85758E-02	-.10290	0.00000E+00	.00	29	2149.4	0.00000E+00	-4.85758E-02	528.66
	right	0-000000	528.663	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-012	left	3-120000	528.670	-9.34213E-02	-.10366	0.00000E+00	.00	29	2149.4	0.00000E+00	-9.34213E-02	528.67
	right	0-000000	528.670	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-013	left	3-130000	528.668	-.12125	-.10465	0.00000E+00	.00	29	2149.4	0.00000E+00	-.12125	528.67
	right	0-000000	528.668	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-014	left	3-140000	528.664	-.11325	-.10556	0.00000E+00	.00	29	2149.4	0.00000E+00	-.11325	528.66
	right	0-000000	528.664	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-015	left	3-150000	528.671	-.16050	-.10686	0.00000E+00	.00	29	2149.4	0.00000E+00	-.16050	528.67
	right	0-000000	528.671	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-016	left	3-160000	528.666	-.16717	-.10821	0.00000E+00	.00	29	2149.4	0.00000E+00	-.16717	528.67
	right	0-000000	528.666	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-017	left	3-170000	528.614	-6.53249E-02	-.10873	0.00000E+00	.00	29	2149.3	0.00000E+00	-6.53249E-02	528.61
	right	0-000000	528.614	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-018	left	3-180000	528.584	-2.81478E-02	-.10896	0.00000E+00	.00	29	2149.3	0.00000E+00	-2.81478E-02	528.58
	right	0-000000	528.584	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-019	left	3-190000	528.626	-.14295	-.11012	0.00000E+00	.00	29	2149.3	0.00000E+00	-.14295	528.63
	right	0-000000	528.626	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-020	left	3-200000	528.589	-7.55046E-02	-.11073	0.00000E+00	.00	29	2149.3	0.00000E+00	-7.55046E-02	528.59
	right	0-000000	528.588	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
30-021	left	3-210000	528.592	-.11624	-.11167	0.00000E+00	.00	29	2149.3	0.00000E+00	-.11624	528.59
	right	0-000000	528.592	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
31-001	left	3-220000	528.603	-.10246	-6.39948E-02	0.00000E+00	.00	29	849.32	0.00000E+00	-.10246	528.60
	right	0-000000	528.603	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
31-002	left	3-230000	528.603	-.10703	-6.53954E-02	0.00000E+00	.00	29	849.32	0.00000E+00	-.10703	528.60
	right	0-000000	528.603	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
31-003	left	3-240000	528.598	-2.43501E-02	-6.57152E-02	0.00000E+00	.00	29	849.32	0.00000E+00	-2.43501E-02	528.60
	right	0-000000	528.598	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
31-004	left	3-250000	528.596	-1.20743E-02	-6.58742E-02	0.00000E+00	.00	29	849.32	0.00000E+00	-1.20743E-02	528.60
	right	0-000000	528.596	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
40-001	left	4-010000	678.558	5094.5	17426.	0.00000E+00	.00	29	117.28	5094.5	-4.75936E-02	689.05
	right	0-000000	692.984	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
50-001	left	5-010000	961.158	5052.4	17283.	0.00000E+00	.00	29	94.680	5052.5	-8.48339E-02	971.36
	right	0-000000	975.187	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-001	left	6-050000	778.514	-.31340	-.26825	0.00000E+00	.00	29	2305.0	0.00000E+00	-.31340	778.51
	right	0-000000	778.514	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-002	left	6-060000	778.457	-.24659	-.26990	0.00000E+00	.00	29	2305.0	0.00000E+00	-.24659	778.46
	right	0-000000	778.457	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-003	left	6-070000	778.463	-.35348	-.27229	0.00000E+00	.00	29	2305.0	0.00000E+00	-.35348	778.46
	right	0-000000	778.463	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-004	left	6-080000	778.305	-4.13424E-02	-.27252	0.00000E+00	.00	29	2304.9	0.00000E+00	-4.13424E-02	778.30
	right	0-000000	778.305	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-005	left	6-090000	778.309	-.12906	-.27340	0.00000E+00	.00	29	2304.9	0.00000E+00	-.12906	778.31
	right	0-000000	778.309	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-006	left	6-100000	778.388	-.42686	-.27630	0.00000E+00	.00	29	2304.9	0.00000E+00	-.42686	778.39
	right	0-000000	778.388	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-007	left	6-110000	778.361	-.45556	-.27936	0.00000E+00	.00	29	2304.9	0.00000E+00	-.45556	778.36
	right	0-000000	778.361	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-008	left	6-120000	778.284	-.33837	-.28160	0.00000E+00	.00	29	2304.9	0.00000E+00	-.33837	778.28
	right	0-000000	778.284	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-009	left	6-130000	778.293	-.36569	-.28405	0.00000E+00	.00	29	2304.9	0.00000E+00	-.36569	778.29
	right	0-000000	778.293	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-010	left	6-140000	778.221	-.25751	-.28574	0.00000E+00	.00	29	2304.8	0.00000E+00	-.25751	778.22
	right	0-000000	778.221	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-011	left	6-150000	778.117	-6.13920E-02	-.28612	0.00000E+00	.00	29	2304.8	0.00000E+00	-6.13920E-02	778.12
	right	0-000000	778.117	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-012	left	6-160000	778.138	-.19736	-.28744	0.00000E+00	.00	29	2304.8	0.00000E+00	-.19736	778.14
	right	0-000000	778.138	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-013	left	6-170000	778.136	-.27308	-.28925	0.00000E+00	.00	29	2304.8	0.00000E+00	-.27308	778.14
	right	0-000000	778.136	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-014	left	6-180000	778.078	-.19950	-.29055	0.00000E+00	.00	29	2304.8	0.00000E+00	-.19950	778.08
	right	0-000000	778.078	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-015	left	6-190000	777.996	-6.24257E-02	-.29093	0.00000E+00	.00	29	2304.7	0.00000E+00	-6.24257E-02	778.00
	right	0-000000	777.996	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-016	left	6-200000	778.018	-.20068	-.29226	0.00000E+00	.00	29	2304.7	0.00000E+00	-.20068	778.02
	right	0-000000	778.018	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-017	left	6-210000	778.020	-.29035	-.29417	0.00000E+00	.00	29	2304.7	0.00000E+00	-.29035	778.02
	right	0-000000	778.020	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-018	left	6-220000	778.029	-.31783	-.29625	0.00000E+00	.00	29	2304.7	0.00000E+00	-.31783	778.03
	right	0-000000	778.029	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-019	left	6-230000	778.045	-.36524	-.29863	0.00000E+00	.00	29	2304.7	0.00000E+00	-.36524	778.04
	right	0-000000	778.045	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-020	left	6-240000	777.899	-5.13084E-02	-.29890	0.00000E+00	.00	29	2304.6	0.00000E+00	-5.13084E-02	777.90
	right	0-000000	777.899	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
60-021	left	6-250000	777.872	-5.77881E-02	-.29924	0.00000E+00	.00	29	2304.6	0.00000E+00	-5.77881E-02	777.87
	right	0-000000	777.872	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
61-001	left	6-010000	778.527	-2.64073E-02	-.14407	0.00000E+00	.00	29	910.83	0.00000E+00	-2.64073E-02	778.53

	right	0-000000	778.527	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			

str.no.	side	bdry.vol. number	surface temp. (k)	heat-trf. convection (watt)	heat-flux convection (watt/m2)	critical heat-flux (watt/m2)	CHF mul	ht mode	heat-trf. coef.conv (watt/m2-k)	int.-heat source (watt)	conv+rad -source (watt)	vol.ave. temp. (k)
61-002	left	6-020000	778.524	-5.35816E-02	-.14460	0.00000E+00	.00	29	910.83	0.00000E+00	-5.35816E-02	778.52
	right	0-000000	778.524	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
61-003	left	6-030000	778.526	-.24060	-.14701	0.00000E+00	.00	29	910.83	0.00000E+00	-.24060	778.53
	right	0-000000	778.526	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
61-004	left	6-040000	778.525	-.23920	-.14940	0.00000E+00	.00	29	910.83	0.00000E+00	-.23920	778.52
	right	0-000000	778.525	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
80-001	left	8-010000	777.913	-.10566	-5.29670E-02	0.00000E+00	.00	29	642.87	0.00000E+00	-.10566	777.91
	right	0-000000	777.913	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
100-001	left	10-020000	452.175	-2.61810E+05	-2.58360E+05	0.00000E+00	.00	29	1018.2	0.00000E+00	-.15795	435.11
	right	102-050000	420.048	2.61810E+05	2.00947E+05	0.00000E+00	.00	2	2228.9			
100-002	left	10-030000	430.343	-2.19155E+05	-2.16267E+05	0.00000E+00	.00	29	1001.9	0.00000E+00	-.12560	415.71
	right	102-040000	402.800	2.19155E+05	1.68208E+05	0.00000E+00	.00	2	2132.7			
100-003	left	10-040000	411.622	-1.84439E+05	-1.82009E+05	0.00000E+00	.00	29	987.43	0.00000E+00	-9.98958E-02	399.05
	right	102-030000	387.950	1.84439E+05	1.41563E+05	0.00000E+00	.00	2	2051.1			
100-004	left	10-050000	395.523	-1.55974E+05	-1.53919E+05	0.00000E+00	.00	29	974.64	0.00000E+00	-7.93131E-02	384.69
	right	102-020000	375.132	1.55974E+05	1.19714E+05	0.00000E+00	.00	2	1981.9			
100-005	left	10-060000	381.648	-1.32470E+05	-1.30724E+05	0.00000E+00	.00	29	963.33	0.00000E+00	-6.27071E-02	372.30
	right	102-010000	364.046	1.32470E+05	1.01675E+05	0.00000E+00	.00	2	1922.9			
101-001	left	10-010000	777.260	-3.46433E-02	-7.99081E-02	0.00000E+00	.00	29	186.58	0.00000E+00	-3.46433E-02	777.26
	right	0-000000	777.260	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
101-002	left	10-070000	517.351	-1.03467E-02	-2.38656E-02	0.00000E+00	.00	29	173.39	0.00000E+00	-1.03467E-02	517.35
	right	0-000000	517.351	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
160-001	left	16-010000	517.230	-6.10054E-03	-9.47712E-02	0.00000E+00	.00	29	2141.3	0.00000E+00	-6.10054E-03	517.23
	right	0-000000	517.230	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
160-002	left	16-020000	517.223	-1.83313E-02	-9.49248E-02	0.00000E+00	.00	29	2141.3	0.00000E+00	-1.83313E-02	517.22
	right	0-000000	517.223	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
170-001	left	17-010000	517.219	-1.01932E-02	-9.50100E-02	0.00000E+00	.00	29	2141.3	0.00000E+00	-1.01932E-02	517.22
	right	0-000000	517.219	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
180-001	left	18-010000	517.223	-1.83775E-02	-9.51641E-02	0.00000E+00	.00	29	2141.3	0.00000E+00	-1.83775E-02	517.22
	right	0-000000	517.223	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
180-002	left	18-020000	517.203	-6.12906E-03	-9.52143E-02	0.00000E+00	.00	29	2141.3	0.00000E+00	-6.12906E-03	517.20
	right	0-000000	517.203	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
201-001	left	20-010000	538.634	1030.5	4980.7	0.00000E+00	.00	29	886.33	1030.6	-6.12428E-02	538.83
	right	0-000000	539.026	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
201-002	left	20-050000	665.274	1030.5	4980.6	0.00000E+00	.00	29	920.56	1030.6	-8.25280E-02	665.47
	right	0-000000	665.659	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
202-001	left	20-020000	886.769	39925.	2.80566E+05	0.00000E+00	.00	29	897.96	4350.2	-.57125	914.68
	right	0-000000	932.734	-35575.	-2.50000E+05	0.00000E+00	.00	0	.00000E+00			
202-002	left	20-030000	924.177	39817.	2.80598E+05	0.00000E+00	.00	29	909.08	4342.4	-.58654	952.12
	right	0-000000	970.328	-35475.	-2.50000E+05	0.00000E+00	.00	0	.00000E+00			
202-003	left	20-040000	961.849	39925.	2.80566E+05	0.00000E+00	.00	29	919.79	4350.2	-.61129	989.81
	right	0-000000	1008.108	-35575.	-2.50000E+05	0.00000E+00	.00	0	.00000E+00			
203-001	left	20-010000	539.181	2469.3	6227.7	0.00000E+00	.00	29	1009.9	2469.4	-9.37022E-02	539.49
	right	0-000000	539.794	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
203-002	left	20-020000	601.088	7468.5	27387.	0.00000E+00	.00	29	1023.1	7468.6	-7.33986E-02	602.42
	right	0-000000	603.756	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
203-003	left	20-030000	641.959	7452.9	27390.	0.00000E+00	.00	29	1035.8	7453.0	-8.02902E-02	643.29
	right	0-000000	644.613	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
203-004	left	20-040000	682.949	7468.5	27387.	0.00000E+00	.00	29	1048.0	7468.6	-8.76944E-02	684.27
	right	0-000000	685.590	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
203-005	left	20-050000	665.801	2469.3	6227.7	0.00000E+00	.00	29	1048.9	2469.4	-.12624	666.10
	right	0-000000	666.403	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
211-001	left	21-010000	538.587	137.36	4976.8	0.00000E+00	.00	29	890.43	137.37	-8.16833E-03	538.78
	right	0-000000	538.978	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
211-002	left	21-050000	664.502	137.36	4976.7	0.00000E+00	.00	29	924.63	137.37	-1.09914E-02	664.69
	right	0-000000	664.887	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
212-001	left	21-020000	884.904	5326.8	2.80359E+05	0.00000E+00	.00	29	902.05	576.90	-7.62330E-02	912.80
	right	0-000000	930.841	-4750.0	-2.50000E+05	0.00000E+00	.00	0	.00000E+00			
212-002	left	21-030000	922.194	5301.8	2.80520E+05	0.00000E+00	.00	29	913.14	576.90	-7.80780E-02	950.13
	right	0-000000	968.327	-4725.0	-2.50000E+05	0.00000E+00	.00	0	.00000E+00			
212-003	left	21-040000	959.556	5326.8	2.80359E+05	0.00000E+00	.00	29	923.86	576.90	-8.14965E-02	987.50
	right	0-000000	1005.791	-4750.0	-2.50000E+05	0.00000E+00	.00	0	.00000E+00			
213-001	left	21-010000	539.132	329.24	6223.8	0.00000E+00	.00	29	1014.5	329.25	-1.24996E-02	539.44
	right	0-000000	539.744	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
213-002	left	21-020000	600.774	997.88	27414.	0.00000E+00	.00	29	1027.8	997.89	-9.79075E-03	602.11
	right	0-000000	603.445	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
213-003	left	21-030000	641.205	990.08	27275.	0.00000E+00	.00	29	1040.4	990.09	-1.06962E-02	642.53
	right	0-000000	643.849	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
213-004	left	21-040000	682.134	997.88	27414.	0.00000E+00	.00	29	1052.6	997.89	-1.16871E-02	683.46
	right	0-000000	684.778	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
213-005	left	21-050000	665.028	329.24	6223.7	0.00000E+00	.00	29	1053.5	329.25	-1.68155E-02	665.33
	right	0-000000	665.629	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
221-001	left	22-010000	538.510	137.36	4976.8	0.00000E+00	.00	29	897.74	137.37	-8.16591E-03	538.71
	right	0-000000	538.901	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
221-002	left	22-050000	663.144	137.36	4976.7	0.00000E+00	.00	29	931.90	137.37	-1.09567E-02	663.34
	right	0-000000	663.529	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
222-001	left	22-020000	881.961	5326.8	2.80359E+05	0.00000E+00	.00	29	909.34	576.90	-7.61185E-02	909.86
	right	0-000000	927.884	-4750.0	-2.50000E+05	0.00000E+00	.00	0	.00000E+00			
222-002	left	22-030000	918.897	5301.8	2.80520E+05	0.00000E+00	.00	29	920.42	576.90	-7.79579E-02	946.83
	right	0-000000	965.014	-4725.0	-2.50000E+05	0.00000E+00	.00	0	.00000E+00			
222-003	left	22-040000	955.902	5326.8	2.80359E+05	0.00000E+00	.00	29	931.13	576.90	-8.12403E-02	983.85
	right	0-000000	1002.127	-4750.0	-2.50000E+05	0.00000E+00	.00	0	.00000E+00			
223-001	left	22-010000	539.051	329.24	6223.8	0.00000E+00	.00	29	1022.9	329.25	-1.24961E-02	539.36
	right	0-000000	539.663	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
223-002	left	22-020000	600.110	997.88	27414.	0.00000E+00	.00	29	1036.1	997.89	-9.77570E-03	601.45
	right	0-000000	602.782	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
223-003	left	22-030000	640.131	990.08	27275.	0.00000E+00	.00	29	1048.7	990.09	-1.06706E-02	641.45
	right	0-000000	642.775	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
223-004	left	22-040000	680.646	997.88	27414.	0.00000E+00	.00	29	1060.9	997.89	-1.16503E-02	681.97
	right	0-000000	683.289	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
223-005	left	22-050000	663.665	329.24	6223.7	0.00000E+00	.00	29	1061.8	329.25	-1.67629E-02	663.97
	right	0-000000	664.267	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
231-001	left	23-010000	538.515	961.83	4981.0	0.00000E+00	.00	29	897.75	961.88	-5.71320E-02	538.71
	right	0-000000	538.907	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
231-002	left	23-050000	663.152	961.81	4980.9	0.00000E+00	.00	29	931.91	961.88	-7.66559E-02	663.34
	right	0-000000	663.537	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
232-001	left	23-020000	882.167	37261.	2.80581E+05	0.00000E+00	.00	29	909.34	4061.7	-.53200	910.08
	right	0-000000	928.112	-33200.	-2.50000E+05	0.00000E+00	.00	0	.00000E+00			
232-002	left	23-030000	919.012	37178.	2.80591E+05	0.00000E+00	.00	29	920.44	4053.9	-.54653	946.95
	right	0-000000	965.136	-33125.	-2.50000E+05	0.00000E+00	.00	0	.00000E+00			
232-003	left	23-040000	956.141	37261.	2.80581E+05	0.00000E+00	.00	29	931.13	4061.7	-.56785	984.10
	right	0-000000	1002.387	-33200.	-2.50000E+05	0.00000E+00	.00	0	.00000E+00			

str.no.	side	bdry.vol. number	surface temp. (k)	heat-trf. convection (watt)	heat-flux convection (watt/m2)	critical heat-flux (watt/m2)	CHF mul	ht mode	heat-trf. coef.conv (watt/m2-k)	int.-heat source (watt)	conv+rad -source (watt)	vol.ave. temp. (k)
233-001	left	23-010000	539.054	2304.7	6227.2	0.00000E+00	.00	29	1022.9	2304.8	-8.74258E-02	539.36
	right	0-000000	539.667	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
233-002	left	23-020000	600.044	6969.6	27385.	0.00000E+00	.00	29	1036.1	6969.6	-6.83400E-02	601.38
	right	0-000000	602.712	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
233-003	left	23-030000	640.282	6954.0	27389.	0.00000E+00	.00	29	1048.7	6954.0	-7.46499E-02	641.61
	right	0-000000	642.937	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
233-004	left	23-040000	680.622	6969.5	27385.	0.00000E+00	.00	29	1060.9	6969.6	-8.14516E-02	681.94
	right	0-000000	683.263	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
233-005	left	23-050000	663.672	2304.6	6227.1	0.00000E+00	.00	29	1061.8	2304.8	-.11727	663.97
	right	0-000000	664.274	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
241-001	left	24-010000	595.494	12600.	20284.	0.00000E+00	.00	29	1453.2	12600.	-.18299	600.01
	right	0-000000	602.723	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
241-002	left	24-020000	646.835	12600.	20284.	0.00000E+00	.00	29	1475.4	12600.	-.20629	651.32
	right	0-000000	654.017	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
242-001	left	24-010000	595.494	12600.	20284.	0.00000E+00	.00	29	1453.2	12600.	-.18299	600.01
	right	0-000000	602.723	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
242-002	left	24-020000	646.835	12600.	20284.	0.00000E+00	.00	29	1475.4	12600.	-.20629	651.32
	right	0-000000	654.017	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
251-001	left	25-010000	599.097	16350.	26321.	0.00000E+00	.00	29	1484.5	16350.	-.18400	604.92
	right	0-000000	608.417	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
251-002	left	25-020000	650.215	16350.	26321.	0.00000E+00	.00	29	1507.1	16350.	-.20629	656.00
	right	0-000000	659.474	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
252-001	left	25-010000	599.097	16350.	26321.	0.00000E+00	.00	29	1484.5	16350.	-.18400	604.92
	right	0-000000	608.417	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
252-002	left	25-020000	650.215	16350.	26321.	0.00000E+00	.00	29	1507.1	16350.	-.20629	656.00
	right	0-000000	659.474	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
300-001	left	30-010000	698.546	149.99	3177.8	0.00000E+00	.00	29	68.367	150.00	-7.93868E-03	698.85
	right	0-000000	699.158	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
310-001	left	31-010000	696.248	149.99	3177.8	0.00000E+00	.00	29	68.494	150.00	-7.89823E-03	696.55
	right	0-000000	696.860	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
400-001	left	40-010000	654.335	368.07	4007.9	0.00000E+00	.00	29	2843.5	368.16	-9.07043E-02	654.68
	right	0-000000	654.863	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
410-001	left	41-010000	654.345	1191.6	4448.9	0.00000E+00	.00	29	2895.1	1191.8	-.20399	654.81
	right	0-000000	655.076	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
420-001	left	42-010000	652.130	1191.6	4448.9	0.00000E+00	.00	29	2898.4	1191.8	-.20294	652.60
	right	0-000000	652.861	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
430-001	left	43-010000	652.124	368.07	4007.9	0.00000E+00	.00	29	2842.7	368.16	-9.02418E-02	652.47
	right	0-000000	652.653	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
501-001	left	50-010000	733.799	12394.	25439.	0.00000E+00	.00	29	1378.6	12394.	-.67271	746.90
	right	0-000000	755.148	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
501-002	left	50-020000	795.963	12394.	25438.	0.00000E+00	.00	29	1400.2	12394.	-.80890	807.29
	right	0-000000	814.320	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
502-001	left	50-010000	733.799	12394.	25439.	0.00000E+00	.00	29	1378.6	12394.	-.67271	746.90
	right	0-000000	755.148	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
502-002	left	50-020000	795.963	12394.	25438.	0.00000E+00	.00	29	1400.2	12394.	-.80890	807.29
	right	0-000000	814.320	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
511-001	left	51-010000	751.812	55079.	45221.	0.00000E+00	.00	29	1235.5	55081.	-1.4747	841.28
	right	0-000000	918.184	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
511-002	left	51-020000	813.676	55079.	45221.	0.00000E+00	.00	29	1255.0	55081.	-1.6815	898.44
	right	0-000000	971.301	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
512-001	left	51-010000	738.207	34606.	28413.	0.00000E+00	.00	29	1235.5	34608.	-1.6081	754.47
	right	0-000000	764.620	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
512-002	left	51-020000	800.282	34606.	28412.	0.00000E+00	.00	29	1255.0	34608.	-1.8731	814.36
	right	0-000000	823.031	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
521-001	left	52-010000	749.697	55079.	45221.	0.00000E+00	.00	29	1234.0	55081.	-1.4681	839.33
	right	0-000000	916.375	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
521-002	left	52-020000	811.611	55079.	45221.	0.00000E+00	.00	29	1253.5	55081.	-1.6746	896.53
	right	0-000000	969.522	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
522-001	left	52-010000	736.076	34606.	28413.	0.00000E+00	.00	29	1234.0	34608.	-1.5998	752.43
	right	0-000000	762.631	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
522-002	left	52-020000	798.201	34606.	28412.	0.00000E+00	.00	29	1253.5	34608.	-1.8641	812.35
	right	0-000000	821.058	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
531-001	left	53-010000	731.567	12394.	25439.	0.00000E+00	.00	29	1378.2	12394.	-.66899	744.74
	right	0-000000	753.039	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
531-002	left	53-020000	793.703	12394.	25438.	0.00000E+00	.00	29	1399.9	12394.	-.80457	805.09
	right	0-000000	812.156	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
532-001	left	53-010000	731.567	12394.	25439.	0.00000E+00	.00	29	1378.2	12394.	-.66899	744.74
	right	0-000000	753.039	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
532-002	left	53-020000	793.703	12394.	25438.	0.00000E+00	.00	29	1399.9	12394.	-.80457	805.09
	right	0-000000	812.156	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
600-001	left	60-010000	779.991	368.03	4007.5	0.00000E+00	.00	29	2937.6	368.16	-.12865	780.33
	right	0-000000	780.512	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
610-001	left	61-010000	779.839	1191.6	4448.6	0.00000E+00	.00	29	2990.8	1191.8	-.27116	780.30
	right	0-000000	780.559	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
620-001	left	62-010000	777.350	1191.6	4448.6	0.00000E+00	.00	29	2994.2	1191.8	-.26984	777.81
	right	0-000000	778.071	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
630-001	left	63-010000	777.728	368.03	4007.5	0.00000E+00	.00	29	2936.9	368.16	-.12807	778.07
	right	0-000000	778.249	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
910-001	left	91-010000	777.601	-2.00377E-02	-.31128	0.00000E+00	.00	29	2304.4	0.00000E+00	-2.00377E-02	777.60
	right	0-000000	777.601	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
910-002	left	91-020000	777.585	-6.01848E-02	-.31165	0.00000E+00	.00	29	2304.4	0.00000E+00	-6.01848E-02	777.59
	right	0-000000	777.585	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
920-001	left	92-010000	777.576	-3.34580E-02	-.31186	0.00000E+00	.00	29	2304.4	0.00000E+00	-3.34580E-02	777.58
	right	0-000000	777.576	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
930-001	left	93-010000	777.585	-6.02987E-02	-.31224	0.00000E+00	.00	29	2304.4	0.00000E+00	-6.02987E-02	777.59
	right	0-000000	777.585	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
930-002	left	93-020000	777.568	-.10070	-.31287	0.00000E+00	.00	29	2304.4	0.00000E+00	-.10070	777.57
	right	0-000000	777.568	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
950-001	left	95-010000	777.414	-.10088	-.31342	0.00000E+00	.00	29	2304.3	0.00000E+00	-.10088	777.41
	right	0-000000	777.414	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
950-002	left	95-020000	777.364	-4.71152E-02	-.31368	0.00000E+00	.00	29	2304.3	0.00000E+00	-4.71152E-02	777.36
	right	0-000000	777.364	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
970-001	left	97-010000	777.288	-4.71534E-02	-.31394	0.00000E+00	.00	29	2304.3	0.00000E+00	-4.71534E-02	777.29
	right	0-000000	777.288	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
970-002	left	97-020000	777.254	-3.37015E-02	-.31413	0.00000E+00	.00	29	2304.3	0.00000E+00	-3.37015E-02	777.25
	right	0-000000	777.254	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
1020-001	left	102-010000	311.171	-1.11791E-04	-5.37203E-04	0.00000E+00	.00	2	1237.1	0.00000E+00	-1.11791E-04	311.17
	right	0-000000	311.171	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
1020-002	left	102-020000	314.728	-2.57105E-04	-1.23549E-03	0.00000E+00	.00	2	1275.1	0.00000E+00	-2.57105E-04	314.73
	right	0-000000	314.728	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
1020-003	left	102-030000	318.933	-4.46030E-04	-2.14335E-03	0.00000E+00	.00	2	1319.6	0.00000E+00	-4.46030E-04	318.93
	right	0-000000	318.933	0.00000E+00	0.00000E+00	0.00000E+00	.00	0	.00000E+00			
1020-004	left	102-040000	323.927	-6.92062E-04	-3.32564E-03	0.00000E+00	.00	2	1372.1	0.00000E+00	-6.92062E-04	323.93

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         right   0-000000  323.927  0.00000E+00  0.00000E+00  0.00000E+00  .00   0      .00000E+00
 1020-005  left  102-050000  329.893 -1.01443E-03 -4.87476E-03  0.00000E+00  .00   2      1434.0       0.00000E+00 -1.01443E-03 329.89
         right   0-000000  329.893  0.00000E+00  0.00000E+00  0.00000E+00  .00   0      .00000E+00
  str.no. side   bdry.vol.  surface  heat-trf.    heat-flux    critical     CHF   ht   heat-trf.    int.-heat    conv+rad     vol.ave.
                  number    temp.    convection   convection   heat-flux    mul  mode  coef.conv    source       -source      temp.
                            (k)      (watt)       (watt/m2)    (watt/m2)              (watt/m2-    (watt)       (watt)       (k)
                                                                                        k)

 1110-001  left  111-010000  774.386  7.43904E-06  2.31129E-05  0.00000E+00  .00  29      18.764       0.00000E+00  7.43904E-06 774.39
         right   0-000000  774.386  0.00000E+00  0.00000E+00  0.00000E+00  .00   0      .00000E+00
 1130-001  left  113-010000  773.487 -1.08299E-05 -8.41208E-05  0.00000E+00  .00  29      18.749       0.00000E+00 -1.08299E-05 773.49
         right   0-000000  773.487  0.00000E+00  0.00000E+00  0.00000E+00  .00   0      .00000E+00
 1130-002  left  113-020000  773.447 -2.52766E-05 -8.41433E-05  0.00000E+00  .00  29      18.748       0.00000E+00 -2.52766E-05 773.45
         right   0-000000  773.447  0.00000E+00  0.00000E+00  0.00000E+00  .00   0      .00000E+00
 1140-001  left  114-010000  773.522 -1.44230E-05 -2.67493E-05  0.00000E+00  .00  29      38.853       0.00000E+00 -1.44230E-05 773.52
         right   0-000000  773.522  0.00000E+00  0.00000E+00  0.00000E+00  .00   0      .00000E+00
 1140-002  left  114-020000  769.983 -3.53671E-06 -6.55928E-06  0.00000E+00  .00  29      38.727       0.00000E+00 -3.53671E-06 769.98
         right   0-000000  769.983  0.00000E+00  0.00000E+00  0.00000E+00  .00   0      .00000E+00
 1141-001  left    0-000000  773.522  0.00000E+00  0.00000E+00  0.00000E+00  .00   0     0.00000E+00  0.00000E+00 -5.11990E-05 773.52
         right 114-010000  773.522 -5.11990E-05 -2.58685E-05  0.00000E+00  .00  29      38.853
 1141-002  left    0-000000  769.983  0.00000E+00  0.00000E+00  0.00000E+00  .00   0     0.00000E+00  0.00000E+00 -1.25542E-05 769.98
         right 114-020000  769.983 -1.25542E-05 -6.34303E-06  0.00000E+00  .00  29      38.727
 1150-001  left  115-010000  641.580  6.85238E-05  1.06451E-03  0.00000E+00  .00  29      16.423       0.00000E+00  6.85238E-05 641.58
         right   0-000000  641.580  0.00000E+00  0.00000E+00  0.00000E+00  .00   0      .00000E+00
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Miscellaneous output

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                                                                          SUM of int.-heat-source=    .68373E+06 (watt)
0                    Control variable edit; at time=     89.8250      sec
   10     pdiff1       sum          9298.59
0---Restart no.    7147 written, block no.     3---
1 time         mflowj        pmpvel        pmphead       pmptrq        httemp        cntrlvar
  (sec)        18010000        2             2             2            202003  2        10
               (kg/sec)      (rad/sec)      (pa)          (n-m)         (k)             pdiff1
                                                                                        sum
  0.000000E+00   .71700        540.34      2.44564E+05  -38.545       773.00       0.00000E+00
   1.00000       .70650        540.34      2.38561E+05  -78.339       996.79        9304.0
   2.00000       .70688        540.34      2.39380E+05  -78.498       998.96        9279.3
   3.00000       .70629        540.34      2.39461E+05  -78.473       1000.6        9285.3
   4.00000       .71138        540.34      2.40351E+05  -78.864       1002.1        9317.4
   5.00000       .71690        540.34      2.41504E+05  -79.341       1003.3        9335.0
   12.5000       .70557        540.34      2.39271E+05  -78.411       998.87        9285.3
   20.0000       .70811        540.34      2.39762E+05  -78.620       1001.6        9299.6
   27.5000       .70692        540.34      2.39468E+05  -78.513       1001.2        9297.4
   35.0000       .70698        540.34      2.39479E+05  -78.518       1001.8        9297.6
   42.5000       .70680        540.34      2.39420E+05  -78.499       1001.9        9298.2
   50.0000       .70671        540.34      2.39396E+05  -78.491       1002.0        9298.2
   57.5000       .70664        540.34      2.39374E+05  -78.484       1002.1        9298.4
   65.0000       .70659        540.34      2.39359E+05  -78.479       1002.2        9298.4
   72.5000       .70656        540.34      2.39349E+05  -78.476       1002.3        9298.5
   80.0000       .70653        540.34      2.39341E+05  -78.474       1002.3        9298.6
   87.5000       .70651        540.34      2.39335E+05  -78.472       1002.3        9298.6
   89.8250       .70651        540.34      2.39334E+05  -78.471       1002.3        9298.6
0Final time=    89.8250      sec    advancements attempted=   7147
0Transient has reached steady state.
```

Remarks to changes made during preparation of final report

Revision 1:

1. Small changes in heat structure surface area of HS1 in the front wall
2. Redefinition of heating rod heat structure
3. Adjustments in general power tables

Revision 2:

4. Redefinition of modelled FW unit cell (22.42 mm instead of 22 mm)
5. Reset of circulator data to tbm7 status