MOTEL facility modeling with TRACE code

Lappeenranta–Lahti University of Technology LUT
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ABSTRACT

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The purpose of this master's thesis is to develop a TRACE model of a small modular reactor Modular Test Loop (MOTEL) designed and built at Lappeenranta-Lahti University of Technology.
The MOTEL digital model has been implemented with a TRACE code to perform tests and simulation of normal operation, carrying out safety tests, implementing and conducting experiments for monitoring changes in equipment operation when the initial condition changes.
The master's thesis consists of reviewing small modular reactors, their types, reactors already implemented and under design. A description of the SMR technology. Descriptions of the MOTEL equipment, geometric and physical plant parameters. The architecture of the TRACE model and the description of the steam generator, core, pressurizer, operating systems as a part of the test equipment Part with the results of the simulation and their analysis.

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I would like to say thank you to all my family and friends, my mother, sister and my girlfriend, who supported me and motivated me throughout the whole study.

Many thanks to my mentors and teachers Juhani Vihavainen and Juhani Hyvärinen for guiding me, helping me to understand the nature of the processes that occur in the simulation and in the real installation. Thanks to Juhani Vihavainen I learned a TRACE and an APROS code, approaches and methods to simulate reactors. Thanks to your efforts it was possible to write this work!

ABBREVIATIONS

AIRIS	Advanced Reactors Information System
BWR	Boiling Water Reactor
CAREM	Central Argentina de Elementos Modulares (Central Argentina of Modular Elements)
GVF	Gas volume fraction
IAEA	International Atomic Energy Agency
INES	International Nuclear Events Scale
LUT	Lappeenranta- Lahti University of Technology
MOTEL	Modular Test Loop
NRS	Nuclear Regulatory Commission
OTSG	Once-through Steam Generator
PWR	Pressurized water reactor
RPV	Reactor Pressure Vessel
SG	Steam Generator
SMR	Small Modular Reactor
SNAP	Symbolic Nuclear Analysis Package
TRACE	TRAC/RELAP Advanced Computational Engine
VTT	VTT Technical Research Centre of Finland

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1 Introduction

In our modern and constantly evolving world, the need for energy production for technological development, the growing needs of the population, globalization, and urbanization is increasing every year. Analysts predict that global energy consumption will increase by approximately 50% between 2021 and 2050. The industrial and residential end-user sectors will be the key ones consuming electric power (EIA, 2021). Power plants based on traditional power sources (gas, coil, petroleum liquids) produce electricity with high CO2 and other greenhouse gas emissions mainly because of the aging infrastructure of power plants and dependence on fluctuating power prices. The growing demand in the electricity market makes us think about competitive, scalable, safe, reliable and environmentally friendly energy sources.

Nuclear power is a good example of low-carbon energy, capable of producing sufficient electricity efficiently. In 2021 Nuclear energy provides 10% of the world's electricity from 437 power reactors (World Nuclear Association, 2022). However, construction of new Nuclear Power Plants requires large capital expenses, difficulties arise in equipment production, maintenance of power grid infrastructure, moreover, it is almost impossible to locate NPPs close to the point of consumption what makes the development of compact reactors, which can be produced in modular form and which will be more reliable and safe, to be conceived. For these purposes, small modular reactors (SMRs) are of growing interest.

According to the IAEA classification, small modular reactors are advanced nuclear reactors that have power capacity up to 300 MW per unit (IAEA, 2020). These reactors are small in physical size compared to conventional nuclear power reactors, and their systems and components have a modular structure and can be assembled in a factory and transported as a unit to the point of installation and use. Small modular reactors can replace fossil fuel power stations with aging equipment.

Advantages of SMRs include the following:

- The ability to place small modular reactors in locations is not suitable for building large nuclear plants;
- Capital costs for the construction of this type of reactor are much lower, as SMRs prefabricated units can be manufactured and then installed on site;
- The modular structure provides versatility of elements for reactor assembly and subsequent replacement;
- Small modular reactors can be installed in an existing power system or remotely from the power system;
- Safety systems rely on passive systems, and low operating pressure and power provide the necessary safety features;
- Reduced nuclear fuel requirements for SMRs, which require less frequent refueling, every 3-7 years, compared to 1-2 years for conventional reactor plants.

Based on the versatility, affordability of construction and high safety of SMRs, they are now the most interesting to consider as energy sources satisfying current trends in green power generation that can compete with renewable sources of energy.

1.1 Typical integral PWR architecture and features

In 2020, there are 72 SMRs at various stages of development (IAEA IRIS, 2020). All SMR concepts can be classified into five main groups based on technology based on design, coolant, number of modules and fuel type, etc. Most of the concepts are based on light water reactor technology (LWR), they work with a similar type of fuel. There are also SMR concepts with liquid metal and gas cooled reactors, but there are not many of them.

One more parameter, according to which SMR can be classified, is a quantity of modules. There are multi-module, single-module and micromodule SMR concepts. The main difference between the installations is the need and purpose for which the SMR must be used.

Single-module plant is suitable for the replacement of small fossil fuel power plants, as well as for the generation of electricity in an autonomous distributed network. Multi-module plant is suitable for replacement of medium capacity plants, which provide a base load.

Micro-modular plants - units with capacity less than 10 MW (IAEA IRIS, 2019), can be used as units for autonomous power generation in remote areas from the main power zone, easy to transport.

There are two solutions for the design of the reactor's primary circuit concept: a loop arrangement and an integral arrangement. Because of the relatively small size of the SMR core, the integral reactor design can be applied.

1.1.1 Integral PWR architecture

The integral PWR design is a design in which all elements of the nuclear steam circuit, namely the nuclear reactor, steam generator, pressure compensator and main circulation pump and piping (in the case of forced circulation), are placed in one reactor vessel. In the case of an integral arrangement, the reactor vessel increases in size and contains more coolant compared to an externally looped reactor, and the thermal inertia of the system also increases.

Table 1 presents a comparison of prototype architecture and concepts of Land-based Water-cooled SMRs (IAEA ARIS, 2020).

Table 1.Comparison of SMR integral architecture. (IAEA AIRIS, 2020)

Name of SMR	CAREM	NuScale	ACP100
Reactor type	Integral PWR	Integral PWR	Integral PWR
Circulation type	Natural	Natural	Forced
Reactor vessel content	Core, Steam generators, Steam dome (self pressurized), primary coolant	Core, steam generator, pressurizer	Core, 16 once-through steam generators
Fuel type/ assembly array	UO_2 pellet/ hexagonal	UO_2 pellet/ 17x17 square	UO_2 pellet/ 17x17 square
Steam Generator	Mini-helical vertical SG of the one-through type	Helical coil SG	OTSG
Pressurizer (Steam dome)	Unheated self-pressurized steam dome	Heated pressurizer	Vertical, cylindrical, located outside RPV
Pumps	-	-	Canned motor pumps, installed nozzle to nozzle to RPV
Reactor vessel parameters:			
height	11	17.7	10
diameter	3.2	2.7	3.35

Based on the design concepts and SMRs prototypes at different stages of construction and licensing, it can be concluded that the typical integral structure of PWR for land-based water-cooled SMRs is a core, a steam generator and a pressurizer located inside the PRV. There is also PWR with natural circulation of the primary circuit and PWR with forced circulation. PWR with natural circulation do not need circulation pumps, the primary coolant is moved because the fluid density difference between the core (heat source) and the elevated heat sink. For PWR with forced circulation pumps are needed to move the primary coolant, in all cases the pumps are outside the PRV.

There are a number of advantages to the integral arrangement:

- The reliability and safety of the system has improved because less output power is developed, and the increased surface-to-volume ratio due to the smaller core dimensions increases the effectiveness of passive safety systems under both normal and abnormal operating conditions.

- The reduced radioactivity of the core allows the use of fewer shielding systems and reduced protective planning zones. This fact also reduces the probability of accidents associated with radioactive releases.
- Use of a large amount of water for passive reactor cooling systems ensures reactor cooling even in emergency situations. The high degree of use of passive cooling systems provides an opportunity to develop simplified designs and to optimize operation and maintenance.

1.2 System testing

In today's world there is no place for accidents at nuclear power facilities. This approach is confirmed by the growing requirements for safety at nuclear power plants. Growing requirements to safety of nuclear reactors and necessity in research of processes and physical phenomena occurring during operation of nuclear reactors promote development of technologies and development of computer programs that allow to consider physics of neutrons, material behavior, fluid mechanics and heat and mass exchange as well. Thus, computer code makes it possible to determine the behavior of coolant under emergency conditions and under normal operating conditions.

Testing of the system is necessary, because conducting experiments on a scaled-down experimental facility will not give a representative result and in the analysis of the plant it is necessary to consider the behavior not only of a separate part of the system, but the system as a whole for the safety analysis of all equipment. For objective reasons, safety testing of the system in a nuclear power plant is not possible, since experiments can lead to unfortunate consequences. Because of this, computer code and programs have been developed that consider physical phenomena to fully replicate the operation of equipment and systems in a nuclear power plant. Such codes make it possible to validate experiments on test equipment and to evaluate the operation of the entire plant systems. In order to verify and perform calculations of the selected plant design, many simulations and studies must be performed to meet international safety requirements, which are mainly formulated by the IAEA and, by extension, by local nuclear power regulatory agencies.

There are many programs for safety analysis and many approaches to the analysis. Such programs are used to check safety for processes occurring in reactor - neutron code; thermal-hydraulic code - used to determine mechanics of fluids, heat exchange between materials and elements of analyzed equipment; code for analysis of accidents of different severity degree - the purpose of such programs is to check nuclear power plant equipment for resistance to severe accidents beyond design parameters, it is simulation of accidents of 5, 6 and 7 levels according to INES scale.

In this master thesis, the focus of the work will be to develop a thermal-hydraulic code to verify the experiments performed at the Modular Test Loop (MOTEL) facility and to simulate equipment tests for major accidents that may occur for subsequent safety tests. Developing the code will focus on the equipment scale of the plant, i.e., needed to develop a code that considers the major components of the MOTEL reactor design. The model will include a core, a steam generator, a riser and a downcomer, a ressurizer, and an operating system.

For purpose of code, the development would use a TRACE (TRAC/RELAP Advanced Computational Engine) code developed by the United States Nuclear Regulatory Commission (U.S. NRC) via Symbolic Nuclear Analysis Package (SNAP) -model Editor to build the model and for safety analysis. The TRACE code is well suited for steady-state and transient neutron-thermal-hydraulic analysis for light water reactors. TRACE is currently a federated research platform that incorporates the capabilities of the four major NRC system codes (TRAC-P, TRAC-B, RELAP5, and RAMONA)

To validate the written TRACE model, it is necessary to verify the operation of the code by performing experiments on an experimental facility. If the resulting model describes the physical processes occurring on the test and real equipment with convincing accuracy, then it can be considered that this model can be used for security research in general.

In order to get a more accurate model of the MOTEL test equipment, in parallel with my code development with TRACE, MSc Virpi Kouhia are making a model of the MOTEL test facility with APROS code developed by Finnish companies VTT and Fortum. This approach of code comparison is called benchmarking, it is a part of the validation and verification process approved by IAEA (Verification and validation of software related to nuclear power plant instrumentation and control, 1999).

2 MOTEL facility general description

The MOTEL is designed as an integral modular reactor with a vertical cylindrical reactor vessel to study thermal-hydraulic phenomenon and nuclear reactor safety. The architecture of the modular reactor is based on the concepts of MASLWR (S. M. Modro ,2003) and NuScale (José N. Reyes Jr., 2012, 153-163). Inside the MOTEL reactor pressure vessel there is:

- An electrically heated core model;
- A helical coil steam generator;
- A pressurizer;
- A riser and downcomer p Natural circulation flow at operating conditions.

There is no containment, emergency core cooling, separate decay heat removal loops in this unit.

The MOTEL design is not finite and can be changed. Additional elements and equipment can be added to the design, as well as some components can be excluded if necessary. Such approach in design is made for convenience of research of dependence of design on efficiency, and also for understanding of behavior of integral PWR and for data reception for creation and check of the code of thermal hydraulic system and testing of system as a whole. Figure 1 shows a general view of the installation in the laboratory.

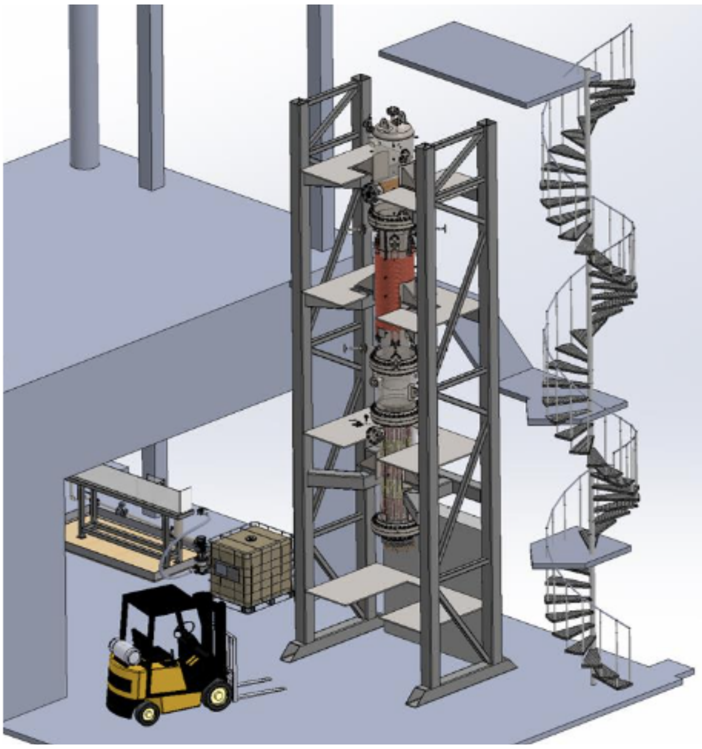


Figure 1. MOTEL test facility placed in the Nuclear Engineering Laboratory (Modular Test Loop (MOTEL) 2018, 9).

2.1 MOTEL design

MOTEL in the first modification is SMR, the primary circuit is inside the reactor vessel. Water movement for the primary circuit is carried out by natural circulation and pumps are not needed for water circulation (J. Hyvärinen, J.Telkkä, K.Tielinen, 2022).

The general view of the MOTEL and main dimensions of the MOTEL test facilities are shown in Figure 2.

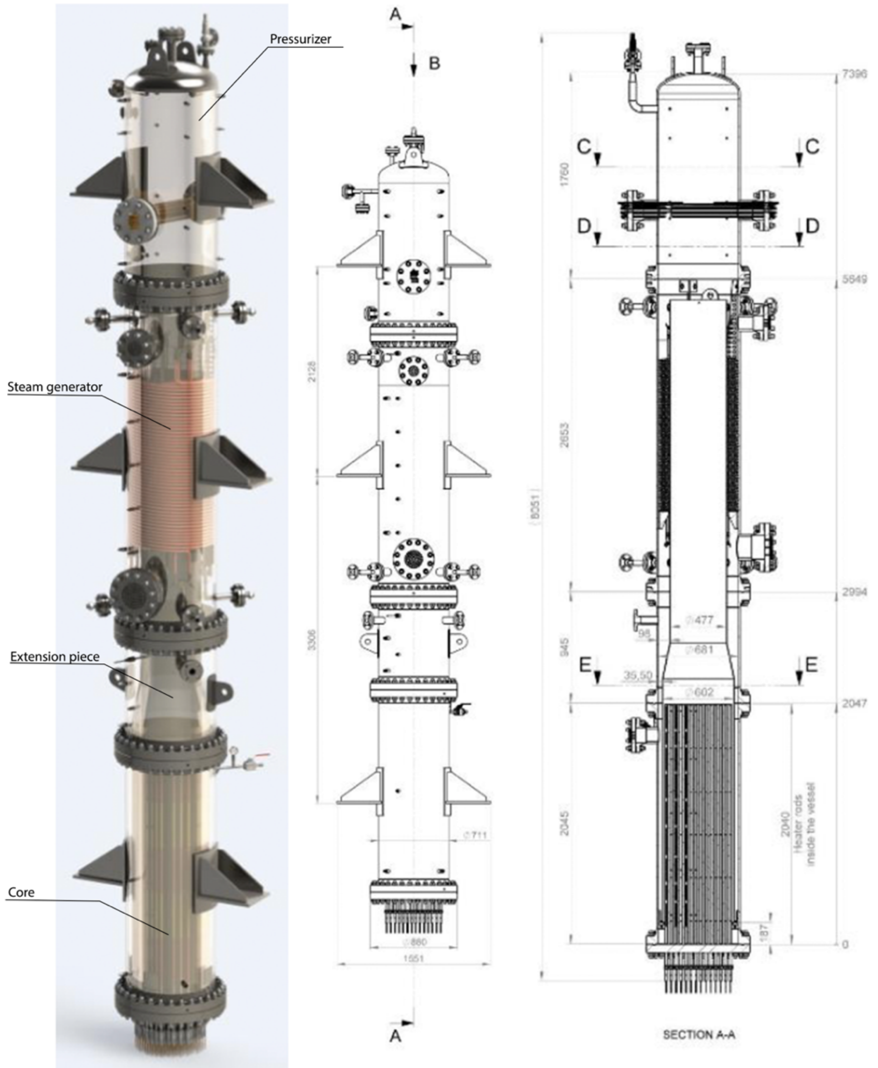


Figure 2. MOTEL test facility main view. Main view on the left, main dimensions and internal structures on the right (Modular Test Loop (MOTEL) 2018, 7).

Because of the failure to achieve 4 MPa in most cooling related accidents, the MOTEL was designed as an intermediate pressure facility with 4MPa design pressure and the ability to reach a temperature of 523 K (250ºC). The height of the MOTEL was reduced by 1:2 when compared to typical integral PWR. Main parameters and characteristics of MOTEL are presented in Table 2. (J. Hyvärinen, J.Telkkä, K.Tielinen, 2022)

Table 2. Main parameters of MOTEL test facility (J. Hyvärinen, J.Telkkä, K.Tielinen,2022,4).

Characteristic	MOTEL test facility
Reference system	Non – overall geometry similar to MASLWR and NuScale
Height scale (riser & downcomer pipelines, heat exchanger) (approximate)	1:2
Maximum pressure, reactor vessel	4 MPa
Maximum heating power	990 kW
Maximum temperature, reactor vessel	523 K (250 ºC)
Height of the vessel	7.4 m
Height of core	1.83 m
Height of the helical coil steam generator	1.311 m
Elevation difference from core midplane to steam generator midplane	3.23 m
Core outer diameter	0.602 m
Downcomer annulus gap (riser / core)	98 mm / 36 mm
Main material of the components	Stainless steel
Insulation material / thickness	Mineral wool / 120 mm

2.2 Core design

The Modular Test Loop core does not represent the actual reactor core, but a general representation of the NPP reactor bundle. The height of the core is based on the 1:2 approach of the standard PWR core size and is 1.83 m.

The core consists of 293 rods, and the rod dimensions and heated rod have been selected to satisfy thermal-hydraulic fidelity and mechanical practicality. The maximum power of heated rod is 7.5 kW. The core basic configuration is shown at Figure 3.

In order to meet the space requirements for heater rods and to reduce the pitch-to-diameter ratio (MOTEL's pitch-to-diameter ratio is 1.56) the following configuration and layout were adopted, dummy rods were staggered with heated rods. The core basic configuration is shown at Figure 3.

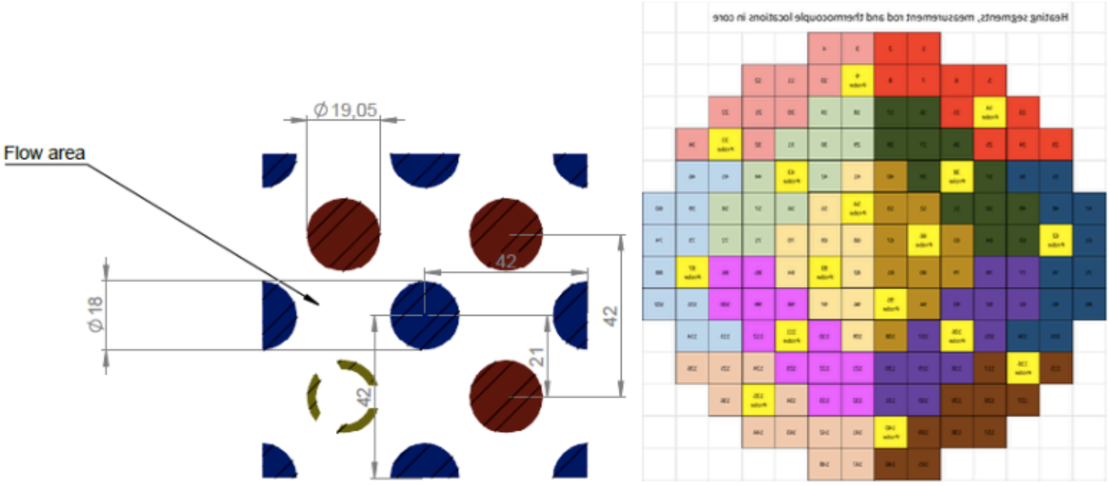


Figure 3. MOTEL core basic configuration on the left and core cross section on the right (J. Hyvärinen, J.Telkkä, K.Tielinen,2022, 5).

On the Figure 3 at the left side heated rods are red, dummies rods are blue and the instrument rods open. On the Figure 3 at the right-side division of the 132 rods divided into 12 power region (individually controllable segments) of 8 to 12 rods each is shown and instrument rods are yellow. At the Table 3 main parameters for MOTEL-SMR core design are shown.

Table 3.Main parameters of MOTEL core. .(J. Hyvärinen, J.Telkkä, K.Tielinen,2022,6)

Characteristic	MOTEL test facility
Hight of core	1.83 m
Core diameter	0.6 m
Electrically heated rods	132
Heated rod diameter	19.05 mm
Rod pitch	29.7 mm
Heated rod power profile	Chopped cosine, 5 steps
Rod power individual / total	7.5 / 990 kW
Independently controllable core heating segments	12
Dummy rods	145

Dummy rods diameter	18 mm
Instrument rods	16
Instrument rods diameter	18 mm
Largest achievable average heat flux	63 kW/m^2
Largest achievable average heat flux, relative to initial NuScale design	17%

2.3 Steam generator design

The MOTEL steam generator is a helical coil steam generator with four bundles of four heat exchange tubes each. The steam generator has four radial layers which point in opposite directions, two right-hand and two left-hand coils. Tube lengths range from 20 to 25.1 m, and the gap between tube layers is 7.5 mm, but due to specific thermocouple locations and necessary measurements, the gap varies as well.

Each tube coil layer is connected to a feedwater collector and each collector supplies water to all coils. The water flow is arranged as follows. The water is heated inside the reactor core and rises, passes the steam generator and flows down the extreme wall of the vessel through the annulus. As the colder water has a higher density and is pulled by gravity back down to the bottom, where it goes up again through the reactor core area. The water flows through the tube coil layer through the cold collector, passes through the heat exchanger, and is collected in the hot collector. Figure 4 shows a helical coil steam generator with internal structures at left side and real MOTEL SG facility photo at right side.

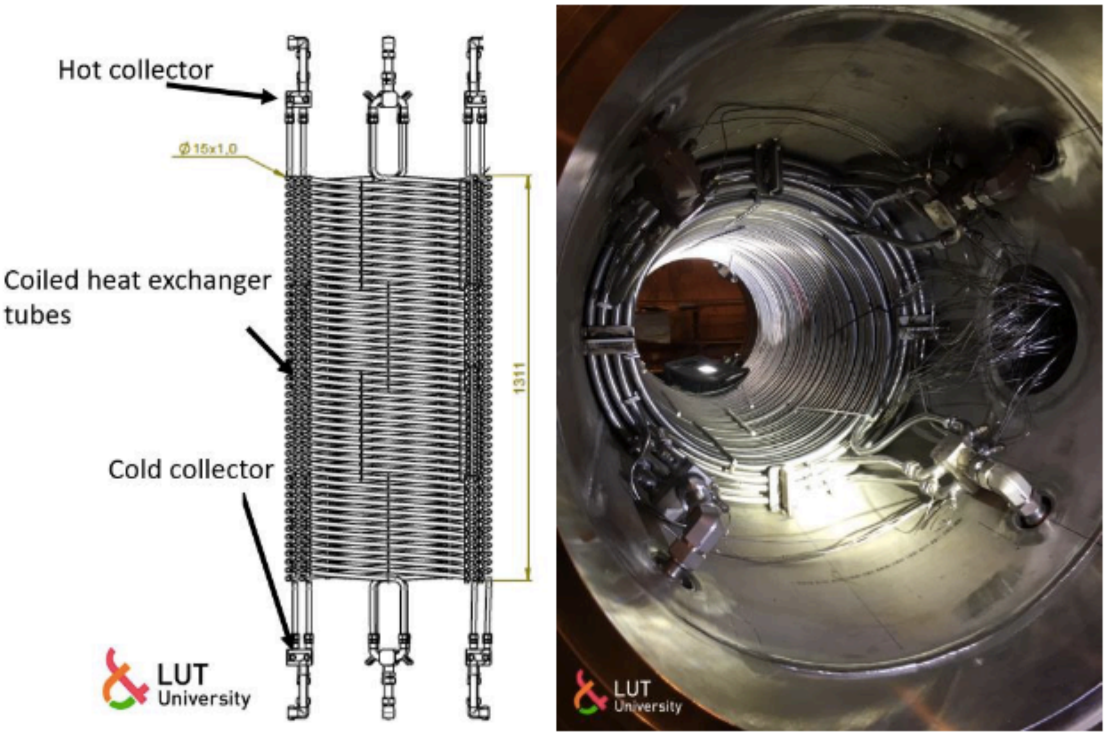


Figure 4. The helical coil steam generator model of MOTEL (J. Hyvärinen, J.Telkkä, K.Tielinen,2022,7)

At the Table 4 main parameters for MOTEL-SMR steam generator design are shown.

Table 4.Main parameters of MOTEL steam generator. (J. Hyvärinen, J.Telkkä, K.Tielinen,2022, 7).

Characteristic	MOTEL test facility
Hight of the helical coil steam generator	1.311 m
Total number of tubes / Number of layers	16 / 4
Tube outer diameter / wall thickness	15 mm / 1mm
Tube lengths, m	20.0, 21.7, 23.4, 25.1
Coil diameters, mm	515, 560, 605, 650
Total heat transfer area	17 m^2
Tube material	Stainless steel

MOTEL SG height based 1:2 approach and makes 1:2 of the MASLWR SG height. Natural circulation in the whole circuit is carried out due to the density difference between the riser and the downpipe. The height difference from the heat source to the heat sink in the MOTEL is about 3.2 m, which is 40% of the corresponding value in the MASLWR.

2.4 Pressurizer

The MOTEL pressurizer is located on the top of the RPV after the steam generator. The pressurizer has two 30kW heating power each. Figure 5 shows the main design of the pressurizer and on the Figure 6 the heaters inside the pressurizer. The top of the pressurizer has a 40-bar safety valve with a rupture disc and connection to the steam line.

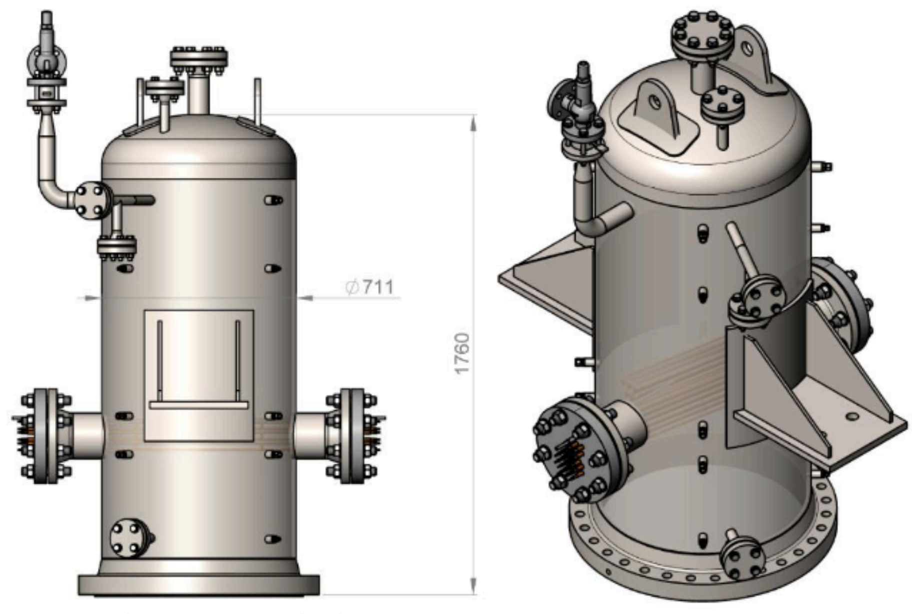


Figure 5. MOTEL Pressurizer main design (Modular Test Loop (MOTEL) 2018, 15).

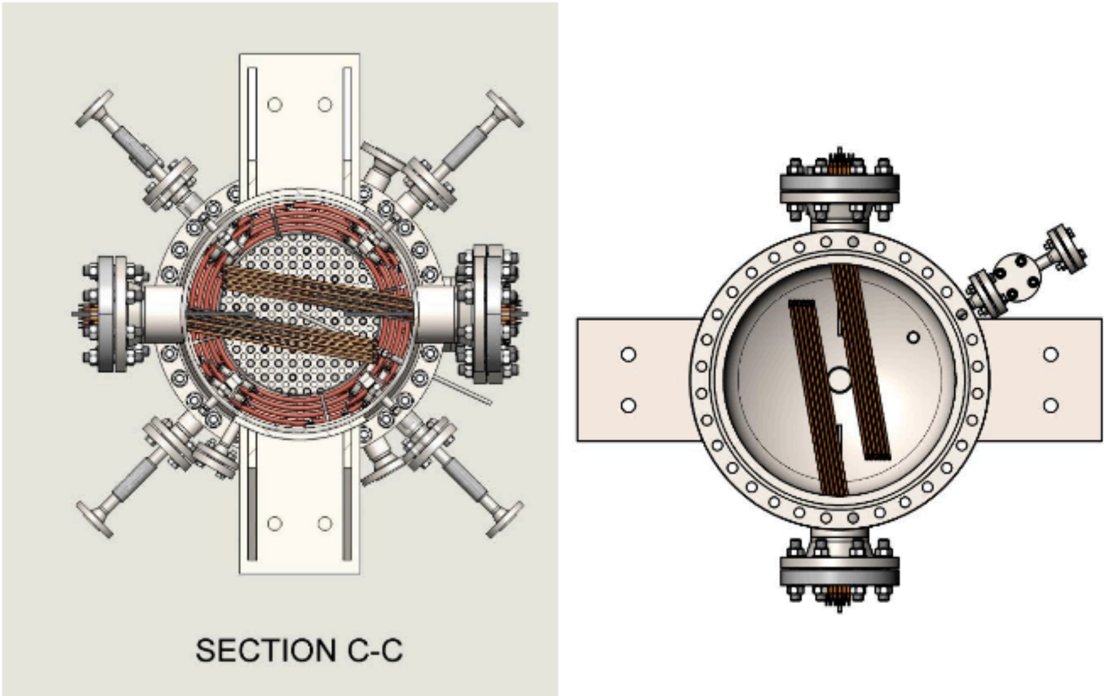


Figure 6. MOTEL Pressurizer heater view from above (Modular Test Loop (MOTEL) 2018, 15).

2.5 Operational systems

As operational systems in MOTEL there are two systems necessary to control the primary circuit inventory and chemistry control (make-up and let-down systems) and another to control the secondary inventory, feedwater system. Figure 7 shows the MOTEL primary feedwater system and chemistry control system.

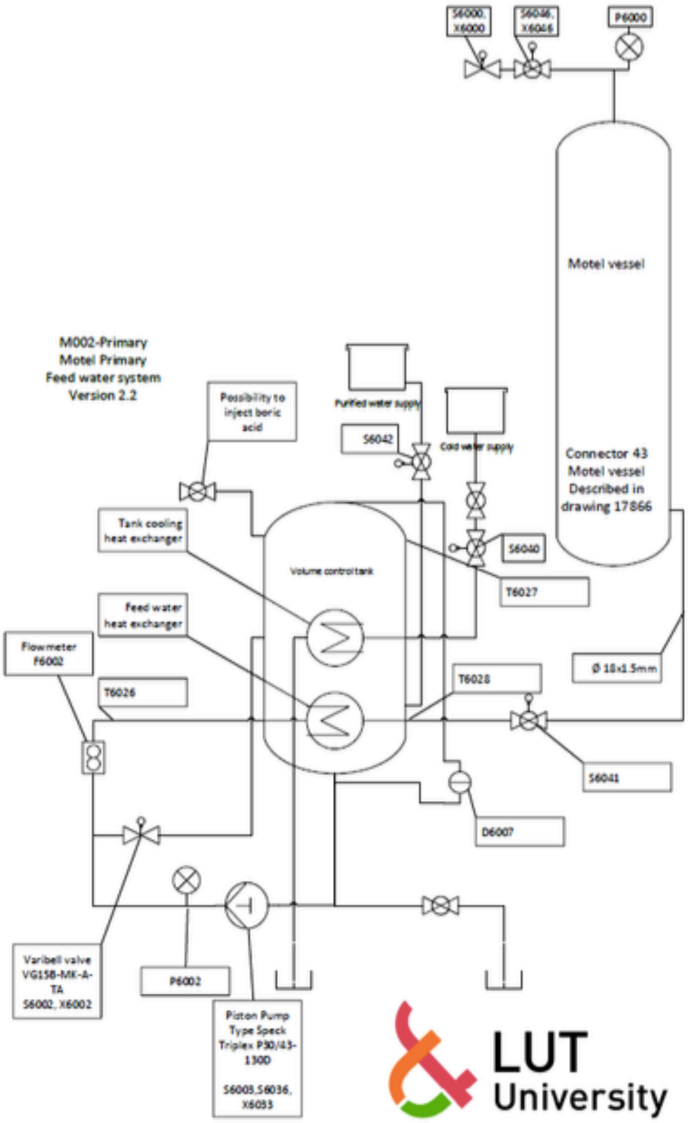


Figure 7. MOTEL Primary circuit inventory and chemistry control. (J. Hyvärinen, J.Telkkä, K.Tielinen,2022,11)

The Volume control tank, which is shown in Figure 7, is used both to store excess water from the primary portion of the pressure tank during the heating period and as a reservoir for additional water if the primary water level needs to be raised. Figure 8 shows the MOTEL feedwater system and steam relief.

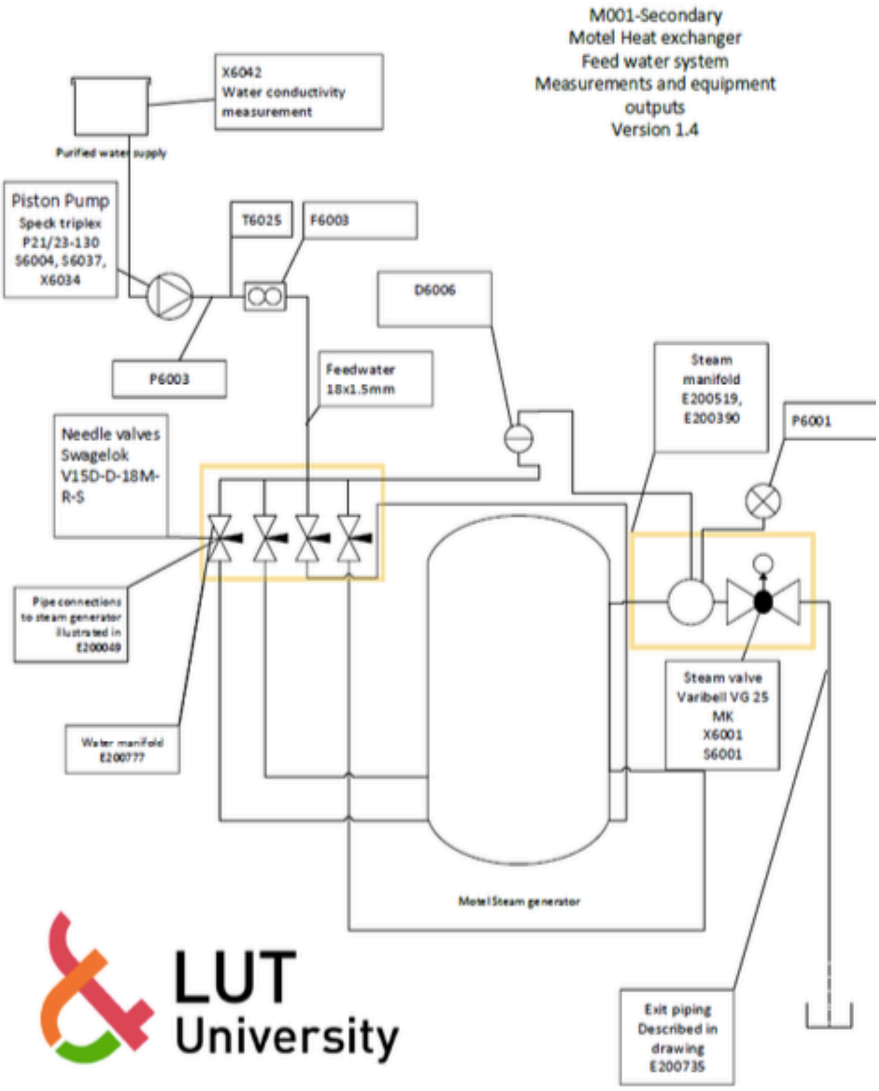


Figure 8. MOTEL Feedwater system and steam relief. (J. Hyvärinen, J.Telkkä, K.Tielinen,2022,12)

In the feedwater system, the feedwater stream enters the cold collectors where the water enters the steam generator tubes.

3 TRACE model setup

It was previously discussed what TRACE and the Symbolic Nuclear Analysis Package (SNAP) are used for: to build a model of a nuclear reactor and nuclear power plant, to check safety systems and simulate processes in the reactor and a plant as a whole.

In this thesis the United States Nuclear Regulatory Commission (U.S. NRC) Symbolic Nuclear Analysis Package (SNAP)-Model Editor is used. It was described in the first chapter, to simulate the MOTEL SMR created in the LUT.

The MOTEL test facility includes the following elements that need to be modelled with the TRACE code:

- A core
- A steam generator
- A riser and downcomer
- A pressurizer
- Operational systems

In the following, each element will be discussed and the way of modelling with the TRACE code will be described. The TRACE code includes elements for building a thermal-hydraulic model of power equipment. The Symbolic Nuclear Analysis Package (SNAP) includes a graphical programming language that can be used to build a model of a real MOTEL test facility. The graphical programming language used in this master's thesis uses prescribed graphical blocks to describe the geometry of the elements, heat and mass transfer parameters between the constituent elements of the model, heat-generating elements (Relap5/MOD3 code Manual, 1995).

3.1 Steam generator

Modelling of steam generator for MOTEL test facility is based on physical parameters of helical coil steam generator described in paragraph 2.3.

The difficulty in writing system code to describe the steam generator is that the steam generator consists of four groups of heat exchange tubes of different lengths, which contain four tubes in each group. Based on the approach of simplifying the geometry of the tubes, namely simplifying the helical shape to a "straight", inclined geometric shape. For the new shape of the tubes, we will consider the change in height from the connection point with the cold collector to the entry of the tubes into the hot collector, which is shown in Table 5.

As a result of research, the best structure was made of three types of steam generator schema. The main points of the best steam generator schema are to match the geometric parameters of the tubes, the structural compliance based on the test facility, as well as to obtain the pressure, mass flow, and temperature maintenance characteristics in accordance with the parameters adopted for the design of real equipment, as well as maintaining natural circulation and compliance with the heat exchange parameters.

Based on implementation of helical coil steam generator in real test facility MOTEL, steam generator tubes make up the heat exchange space in the downcomer part. The heat generated in the reactor core part is transferred to the coolant and flows through the riser part of the steam generator. Then the flow is directed to the downcomer and gives the accumulated heat to the steam generator tubes. To achieve this logic with TRACE code, hydraulic components-pipes and thermal elements- heat structures are used. In order to model the downcomer (included in primary circuit) pipes elements were used to model and describe the secondary circuit, namely steam generator tubes, manifolds (cold and hot) and steam generators tubes group collectors are also used pipes elements. To simulate the heat exchange between steam generator tubes and downcomer heat structures uses (Sensitivity analysis of the MASLWR helical coil steam generator using TRACE, 2011).

In order to model a helical coil steam generator, it is necessary to simplify the geometrical structure of steam generating tubes. With knowledge of the height and the length of each tube, it is possible to calculate the inclination angle (Esch, M., Hurtado, A., Knoche, D., Tietsch, W., 2010). Figure 9 shows simplification of the geometry of steam generator tubes for their subsequent modelling.

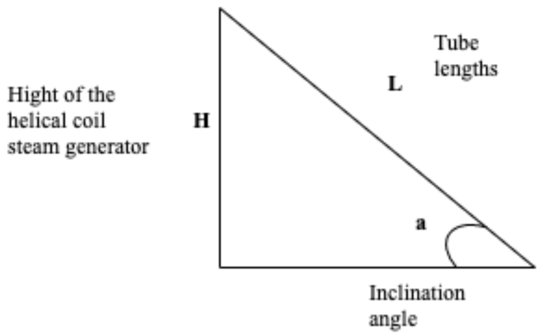


Figure 9. Steam generator helical tubes simplification.

The calculated inclination angle for each length group of steam generator tubes is shown in Table 5.

Table 5.SG simplifications characteristic.

Characteristic	Group1	Group 2	Group 3	Group 4
Hight of the helical coil steam generator, H	1.311 m			
Tube lengths, L, m	20.0	21.7	23.4	25.1
Coil diameters, mm	515	560	605	650
Inclination angle Θ, rad	0.066	0.060	0.056	0.052

As a structure for steam generator model a structure that considers geometric parameters of tubes, the presence of hot and cold group collectors, and hot and cold manifolds will be made. The final structure of the steam generator model includes:

- Four groups of tubes with four tubes of different lengths (20m, 21.7m, 23.4m, 25.1m) each, which are modeled separately;
- Cold and hot group collector (for each group of tubes);
- Cold and hot manifold (for all steam generator tubes);
- One point coolant supply to the cold collector;
- Check valves for each group of tubes

Figure 10 shown structured steam generator tubes schema.

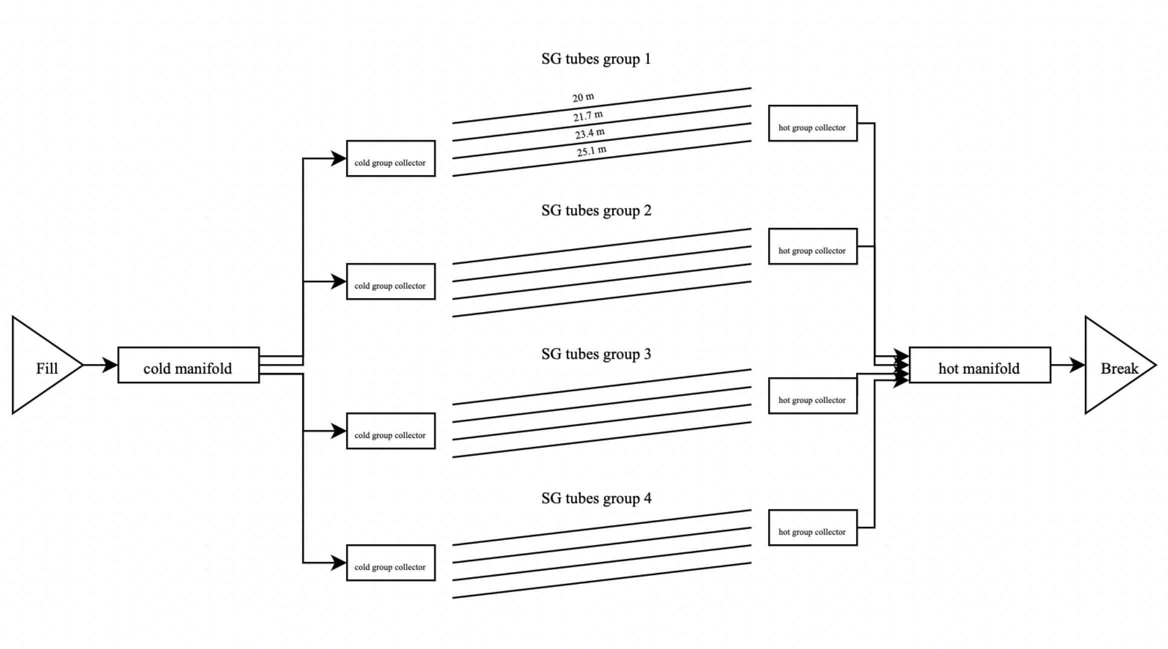


Figure 10. Steam generator tubes structured schema.

Based on schema shown below on Figure 10, TRACE model of steam generator tubes will be made. It is necessary to consider equal distribution of coolant between groups of steam generator tubes. By making experiments to determine the optimal structure of cold/hot manifold and cold/hot group collectors and peculiarities of modelling with TRACE code, a structure by which an equal distribution of coolant is achieved has been taken. Figure 11 shows the structural diagram of cold and hot manifold and cold/hot group collector.

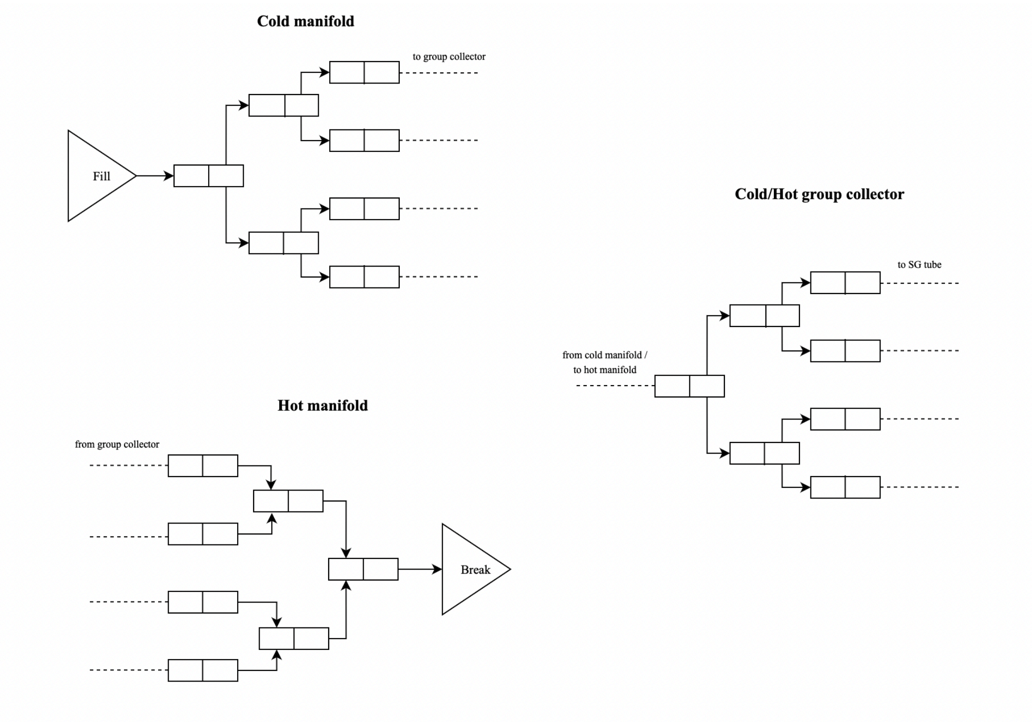


Figure 11. Cold and hot manifold and cold/hot group collectors structured schema.

All geometric parameters for cold and hot group collectors and cold/hot manifold are shown in Table 6. Each collector consists of 7 pipe elements, Table 6 shows the parameters for one pipe that makes up the collector.

Table 6. Manifolds and group collectors characteristics.

Characteristic	Hot /cold manifold	Hot /cold group collector
Length, m	0.0625	0.0625
Hydraulic diameter, m	0.015	0.013
Flow area, m^2	0.000176	0.000132
Volume, m^3	$1.1044 \cdot 10^{-5}$	$8.2956 \cdot 10^{-6}$
Number of cells	2	2

The created structural scheme should maintain the coolant flow by means of natural circulation, so no automatic control systems are provided. Figure 12 shows the TRACE model of the steam generator.

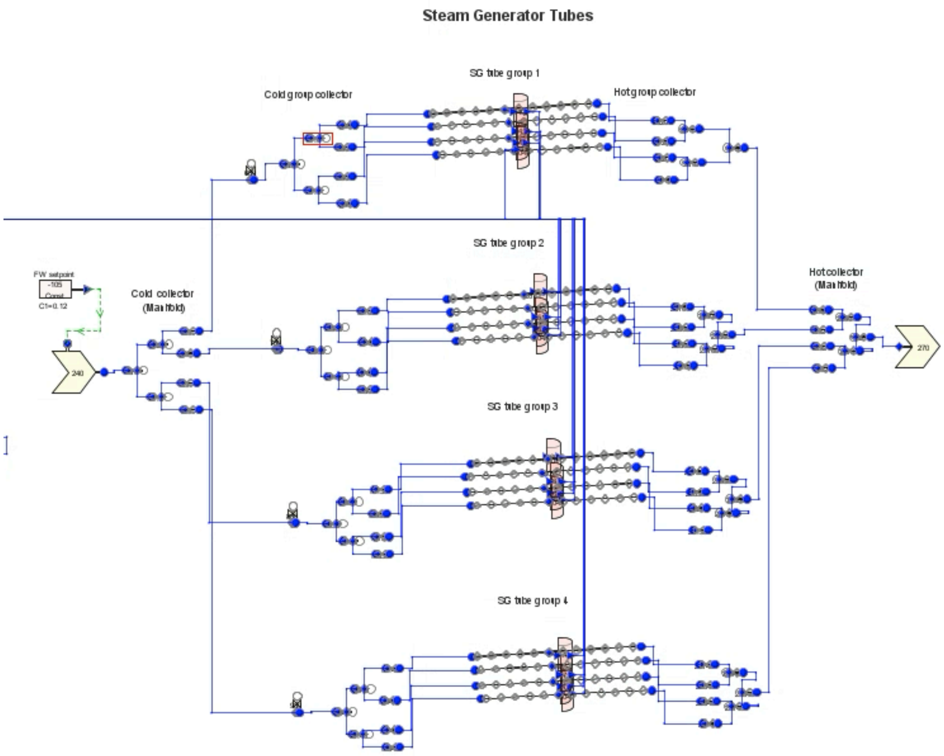


Figure 12. Steam generator tubes TRACE model.

Where pipe elements forms groups of tubes (elements 101-104, 201-204, 301-304, 401-404), group cold collector (elements 105-405) and group hot collector (elements 106, 206, 208, 406), elements 550-580 – check valves for group cold collectors. Element 120 – coolant supply (fill in) from secondary circuit , element 130 – break for coolant.

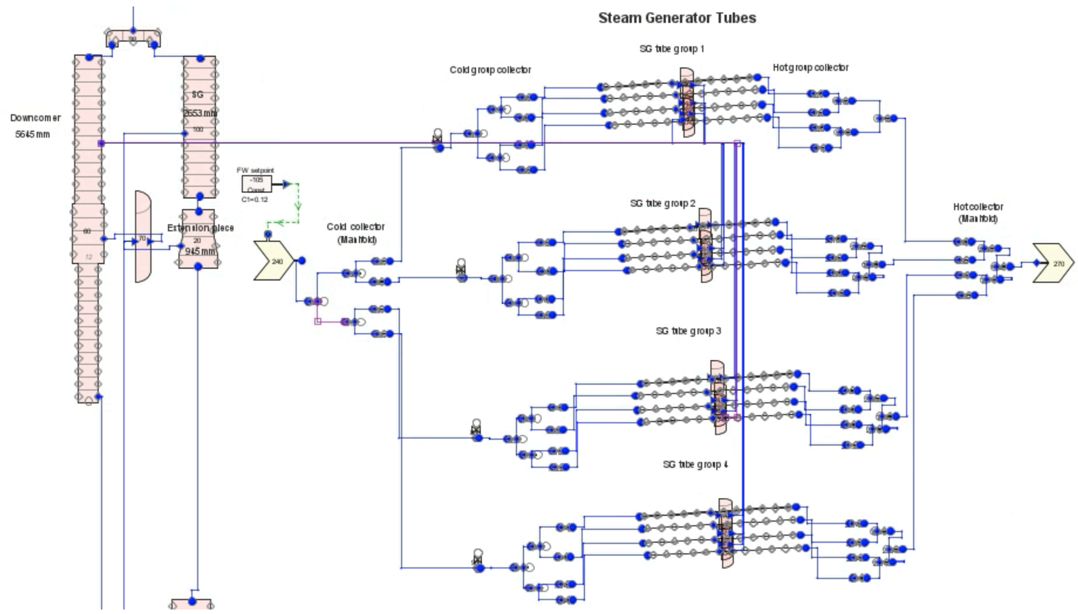


Figure 13. Steam generator TRACE model.

As it can be seen in Figure 13, the steam generator shell (element 100) is divided into 12 cells. For each cell, the flow area, length and hydraulic diameter are calculated and set. Steam generator shell is modelled as a pipe, inside which there is a riser pipe for coolant flow. The characteristics of the steam generator shell pipe cells are presented in Table 7.

Table 7.Steam generator TRACE modelled characteristics.

Characteristic	Value
Number of cells	12
Length of cell, m	0.22108
Volume, m^3	0.03950
Flow area, m^2	0.17870
Hydraulic diameter, m	0.4770

3.2 Riser and downcomer

To simulate the riser and downcomer, the architecture was adopted to separate these parts into two separate components, although in the real test facility the riser part is as if inside the downcomer part, as in Figure 14. In Figure 14 the downcomer part is highlighted in red, and the riser part is made up of flow free cavities as part of the core, extension piece and steam generator (core-highlighted green, extension piece- highlighted yellow and riser part in steam generator - highlighted blue)

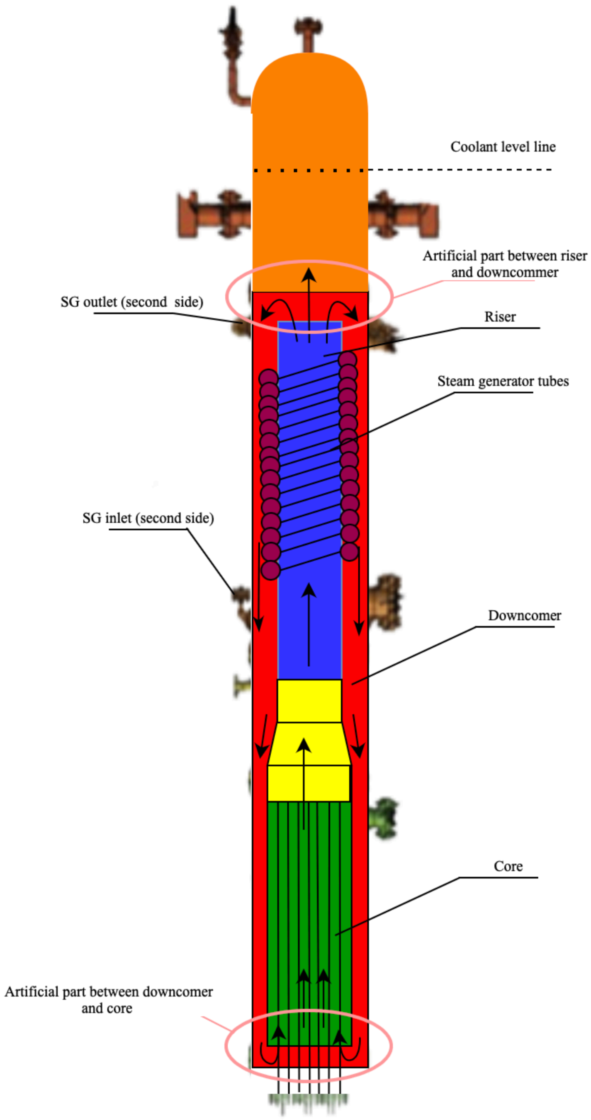


Figure 14. Riser and downcomer schema and coolant flow.

The riser and downcomer parts are made with the pipe element, these elements are modelled based on the physical parameters of the MOTEL test facility, basic characteristics shown in Table 8.

Table 8.Riser and downcomer characteristics.

Characteristic	Riser	Downcomer
Hight ,m	5.473	5.645
Diameters, m	515	560

In MOTEL test facility there is a connection part between downcomer and riser in upper part of steam generator. With this part the coolant flows from the riser to the downcomer, and it allows to keep the natural circulation of the coolant and to form a connection between the steam generator part and the pressurizer. In order to implement this part with TRACE code the structure of type pipe was created. Of course, this structure does not exist separately in the test facility, it is a part of the downcomer, but in the TRACE model it is impossible to implement this part of the downcomer without artificially creating a transition part as a separate structure in the form of pipe. Artificial parts between riser-downcomer-pressuriser and downcomer-core highlighted pink circles are shown on Figure 14. Figure 15 shows the artificial transition part between downcomer, riser and pressurizer created via TRACE code.

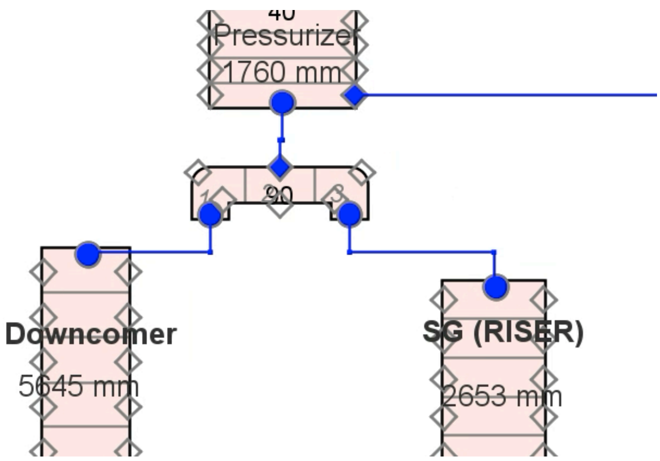


Figure 15. Connection part between riser, downcomer and pressurizer.

To connect the downcomer and core at the bottom of the vessel in a real test facility, a connection channel is used which allows the coolant to flow from the downcomer to core and thereby maintain natural circulation. In the TRACE model this also needs to be implemented. With the help of a single junction element, which like the pipe element can be used as a flow path between hydraulic components, but unlike the pipe element the single junction does not have a volume parameter and can easily be used as a single flow path (Relap5/MOD3 code Manual, 1995). With this element, the last cell in the downcomer connects to the first cell of the core and thus the coolant flows from downcomer to core. Figure 16 shows the implementation of the connection between downcomer and core using a single junction.

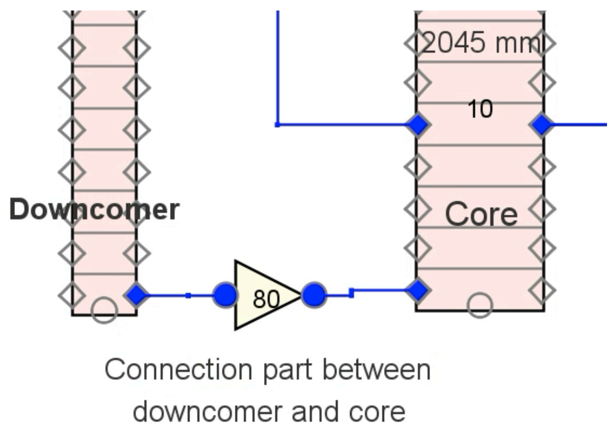


Figure 16. Connection part between downcomer and core.

The geometric parameters taken for modelling the connecting part between a riser, a downcomer and a pressurizer as well as the connecting part between downcomer and core are shown in Table 9.

Table 9. Connection parts characteristics.

Characteristic	
Connection part between riser, downcomer and pressurizer (pipe 90)	
Number of cells	3

Length ,m	0.603	
Hydraulic diameter, m	First edge	0.196
	Second edge	0.540
	Third edge	0.540
	Fourth edge	0.477
Flow area, m^2	First edge	0.13014
	Second edge	0.22902
	Third edge	0.22902
	Fourth edge	0.17870
Angle, rad	First edge	1.571
	Second edge	0
	Third edge	0
	Fourth edge	-1.571
Connection part between downcomer and core (single junction 80)		
Hydraulic diameter, m	0.2048	
Flow area, m^2	0.18	

To simulate these parts of the test equipment, it is necessary to consider the volume of the core part in which the coolant is heated and at natural circulation rises to the extension piece. Therefore, it will be taken into account when modelling the riser and downcomer part of the core.

3.2.1 Riser

As mentioned earlier, the riser is modelled in TRACE with the pipe element. For the convenience of modelling, the riser is not modelled separately but is considered in the modelling of the extension piece, the steam generator. For each part, the flow area and hydraulic diameter were calculated based on the geometric parameters of the test facility (Mascari, F., Vella, G., Woods, B.G., Welter, K., Pottorf, J., Young, E., Adorni, M., D'auria, F., 2011).

To take into account the flow of the coolant in the core part, it is necessary to calculate the volume of the core free for the flow of the coolant, i.e., to calculate the hydraulic diameter. The core hydraulic diameter is calculated by the formula (1):

$$D_h = \frac{A}{P} \tag{1}$$

where A is total flow area [m^2], P is length divided wetted perimeter [m].

Table 10 shows calculated values of flow area for fuel rods, dummy rods, probe rods and core-shell. Table 11 shows the hydraulic diameter calculations.

Table 10.Core flow area calculation.

Value	
Core shell total flow area, m^2	0.284631
Dummy rods total flow area, m^2	0.036898
Heater rods total flow area, m^2	0.037623
Probe rods total flow area, m^2	0.004560
Total area, m^2	0.205550

Table 11.Hydraulic diameter calculations.

Value	Diameter, m	Length/ wetted perimeter, m
Core shell	0.60200	1.89123
Dummy rods	0.01800	7.89984
Heater rods	0.01905	8.19955
Probe rods	0.01905	0.95755
Hydraulic diameter, m	0.04339	

Figure 17 shows the modulated TRACE code and SNAP visualization for riser.

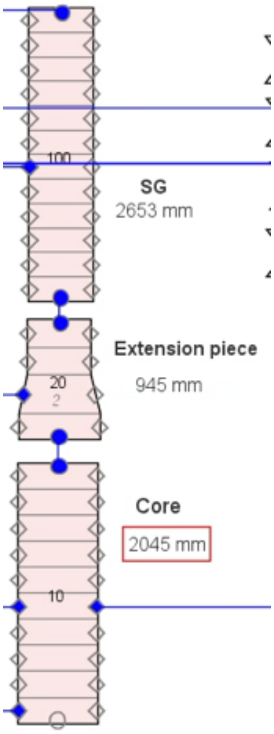


Figure 17. Modulated riser in TRACE.

3.2.2 Downcomer

For ease of construction of the downcomer model in this model the hydraulic component-pipe will be used as in the construction of the riser model. The geometric characteristics change with length and geometrically correspond to the components of the MOTEL test facility, namely core, extension part and steam generator.

The downcomer is divided into 26 cells. Since the downcomer is the surface for lowering the coolant back into the core part, the parameters flow area, volume, length and hydraulic diameter have to be calculated. The hydraulic diameter of annular pipe can be calculated using (2):

$$D_h = \frac{4 \cdot \pi \cdot (D_{out}^2 - D_{in}^2)}{4 \cdot \pi \cdot (D_{out} + D_{in})} \quad (2)$$

where D_{out} is outer diameter of pipe [m], D_{in} is inner diameter of pipe [m].

Table 12 shows the result of the parameter calculation for each group of cells.

Table 12.Downcomer TRACE modelled characteristics.

Characteristic	Value
Core downcomer	
Number of cells	10
Length of cell, m	0.2048
Volume, m^3	0.03675
Flow area, m^2	0.007199
Hydraulic diameter, m	0.071
Extension piece downcomer	
Number of cells	4
Length of cell, 1/2/3/4 cell, m	0.21/0.3/0.217/0.217
Volume, m^3	0.003769/0.0538/0.0389/0.0389
Flow area, 1/2/3/4 cell, m^2	0.003960/0.03017/0.03017/0.03017
Hydraulic diameter, 1/2/3/4 cell, m	0.071/0.179/0.179 /0. 179
Steam generator downcomer	
Number of cells	12
Length of cell, m	0.221
Volume, m^3	0.039188
Flow area, m^2	0.013014
Hydraulic diameter, m	0.196

Figure 18 shows the modulated TRACE code for downcomer.

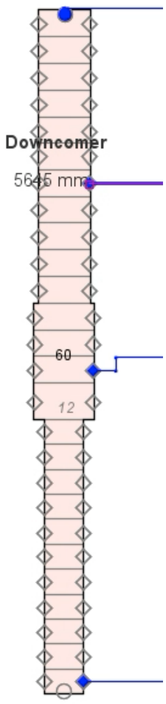


Figure 18. Modulated downcomer in TRACE.

3.3 Core

To model the core the hydraulic component -pipe will be used to build the core-shell, the thermal-heat structure to describe the thermal processes inside the core-shell and for heated rods, as well as the power component to simulate the power delivered from heated rods.

The core shell is connected to the extension piece and a heat structure 70 element is used to model the heat transfer between the downcomer pieces.

Table 13 shows the geometric parameters of the core-shell, considering the heated rods, dummy rods and probe rods inside.

Table 13. Core- shell TRACE modelled characteristics.

Characteristic	Value
Number of cells	10
Length of cell, m	0.2045
Volume, m^3	0.0422
Flow area, m^2	0.2055
Hydraulic diameter, m	0.0433

Based on the values of Table 3 in the core model, a heat structure was created, which considers the power generated by heated rods. Since the number of heated rods is 132, we will use the surface multiplier for modelling. Radial geometry is set based on the description of the test facility and is presented in Table 14.

Table 14.Heated rods radial geometry TRACE modelled characteristics.

Characteristic	Value
Material	Magnesium oxide (Material 13)
Inner radius, m	0
Outer radius, m	0.0088
Thickness, m	0.0088
Material	Stainless 304 (Material 6)
Inner radius, m	0.0088
Outer radius, m	0.0095
Thickness, m	0.0007

In order to simulate the power that each heated rod emits, a power component is created and connected to heat structure 260. In the real test facility power is emitted only when the heated rods are sufficiently heated. Taking this fact into account, in order to simulate we will set the power table inside power element . At the initial moment of time the power value is 0 and after 100 seconds the power reaches 250 kW for all heat rods. Figure 19 shows the modulated TRACE code for core.

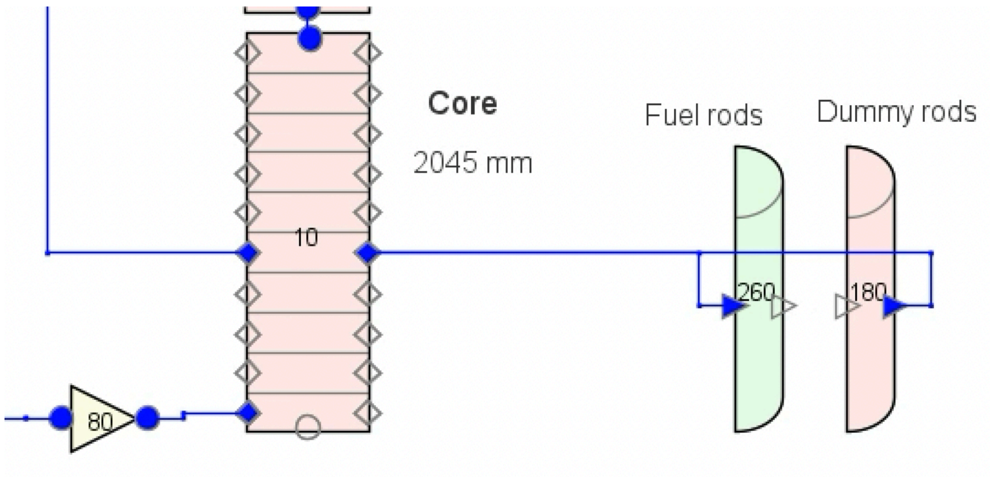


Figure 19. Modulated core in TRACE.

In order to simulate hydrodynamics and hydraulics correctly we have to consider friction against the walls. Also, in each subchannel it is necessary to maintain the pitch-to-diameter ratio approximately equal to 1.2-1.3 as in PWRs (J. Hyvärinen, J.Telkkä, K.Tielinen, 2022). It is physically impossible to maintain the pitch-to-diameter ratio of 1.2-1.3 because it is not possible to place the heated rods so close to each other (in the case of the MOTEL test facility). Therefore, it is necessary to use dummy rods to meet the pitch-to-diameter parameters. The number of dummy rods is 145. As in the case of modelling heated rods, we will create a heat structure with the parameters described in Table 3 and use the multiplication factor to realize 145 rods.

Thus, keeping the pitch-to-diameter ratio equal to 1.56 (J. Hyvärinen, J.Telkkä, K.Tielinen, 2022), hydrodynamics and hydraulics in each core subchannel are considered, as well as thermal interaction between heated rods and dummy rods is considered.

3.4 Pressurizer

To model the pressurizer with TRACE code we will use geometry simplification and use hydraulic component - pipe as the pressurizer shell and heat structure for describing heat transferring. The pressurizer height is 1760 mm, for modelling with TRACE code will divide the shell into 10 cells. The geometrical parameters of the pressurizer shell in the TRACE code are given in Table 14.

Table 15.Pressuriser- shell TRACE modelled characteristics.

Characteristic	Value
Number of cells	8
Length of cell, m	0.22
Volume, cell with / cell without heaters, m^3	0.08013/ 0.07991
Flow area, cell with / cell without heaters, m^2	0.3642/ 0.3632
Hydraulic diameter, cell with / cell without heaters, m	0.681 / 0.532

From the characteristics of the pressurizer test facility, it can be seen that the heaters are located at the height of 6232 mm (583 mm from the beginning of the pressurizer). Parameters of the heaters are presented in Table 16.

Table 16.Pressuriser heaters characteristics.

Characteristic	Value
Number of heaters	2
Heater power, kW	30
Number of rods in each heater	9
Rod diameter, mm	8.3
Rod length, m	1.16

The parameters of flow area, volume and hydraulic diameter presented in Table 15 have already taken into account the content of the heaters inside the pressurizer shell. The parameters of the allocated power for each heater are set using the power component for each heater. The pressurizer shell is connected to the steam generator shell and to the downcomer employing an adapter pipe 90.

In order for the variation of the heated rods parameter to correspond to the variable -pressure measured inside the pressurizer it was necessary to implement pressurizer heaters logic control. Based on pressure and using trip element (with ON (for)| | off logic) when the pressure inside the pressurizer changes, the power output of the heaters also changes. The Figure 20 shows the logical system of operation of pressurizer heaters.

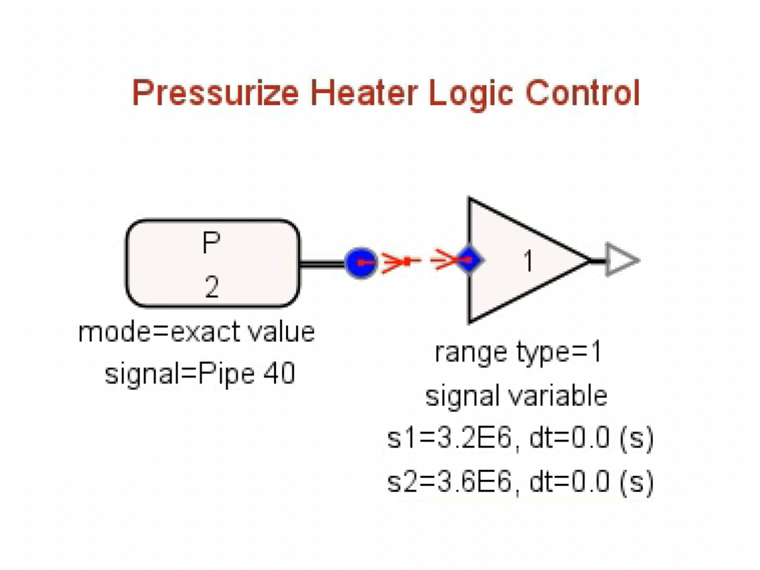


Figure 20. Pressurizer heater logic control system.

The level of coolant in the pressurizer, based on experimental data, is located at 6766 mm (1117 mm from the beginning of the pressurizer) the coolant level line is shown in Figure 14. Figure 21 shows the modulated TRACE code for pressurizer.

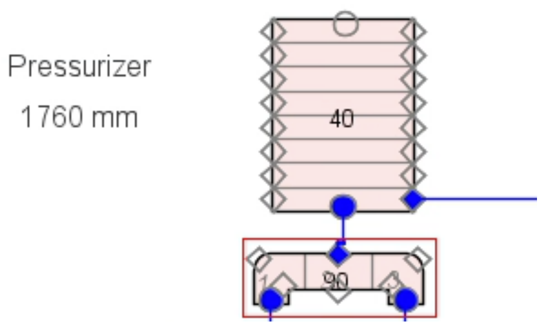


Figure 21. Modulated pressurizer in TRACE.

At pressurizer is needed to maintain water level equal 0.7 meters from bottom of pressurizer. For this purpose, is needed to set up gas volume fraction for initial conditions equal 0 for cells with water and equal 1 for cells without water.

In order to maintain the water level in the pressurizer, it is necessary to build a system that automatically changes the water level in the pressurizer based on measured parameter that will characterize conditions and behavior of pressurizer. In the MOTEL test facility, primary feed water system is used to maintain the water level in the system. As it was mentioned before, the focus of TRACE model building is on MOTEL vessel and main systems. Therefore, in pressurizer model will use PI-regulator with commanded value - Pi-controller constant (Set point for PRZ) and measured value- extracted pressure value from pressurizer for realization of water level maintenance in pressurizer (Pressurizer water level).

PI- controller parameters is: Gain [G]=200, Constant= 0.7, delta T= 100 s, time constant= 0.1 s. Figure 22 shown pressurizer and water level control system.

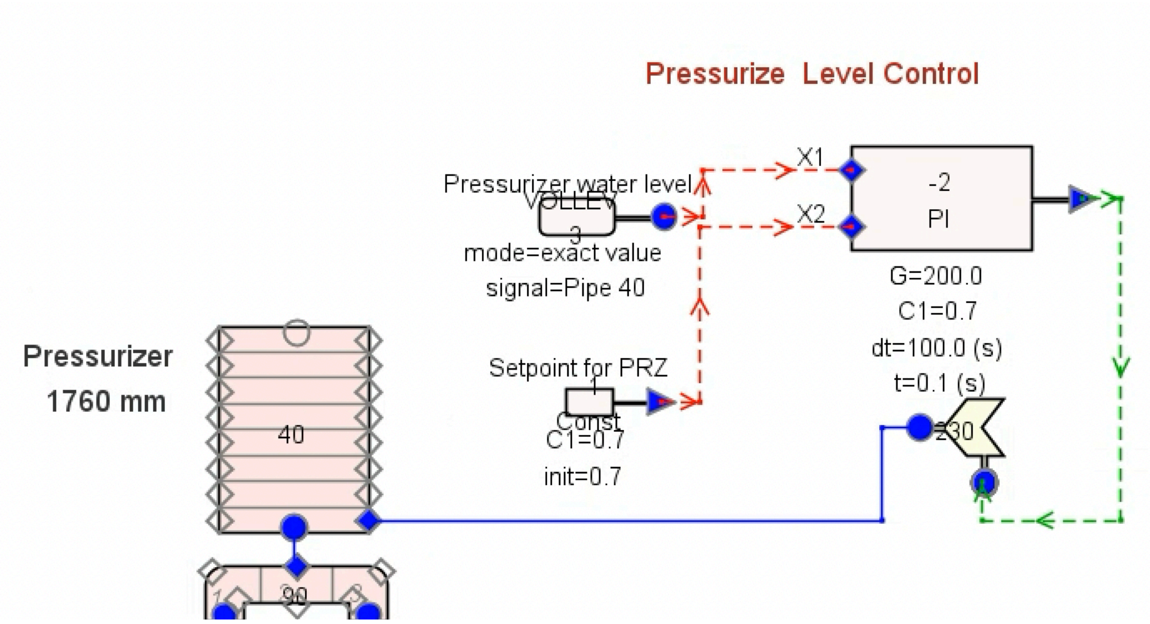


Figure 22. TRACE model and SNAP visualization of pressurizer and water control system.

In the result we get simplified model, with main functionality of primary feed water system realized as pressurizer water control system and pressurizer shall with heaters inside based on MOTEL project paper (J. Hyvärinen, J.Telkkä, K.Tielinen, 2022).

3.5 Operational systems

The Modular test loop was designed as a small modular reactor operating in natural circulation, with passive safety systems. This means that all control systems that are commonly used in systems with active safety systems are not used in MOTEL. Passive safety systems operate based on natural laws, without the involvement of plant operating personnel and without electricity.

3.5.1 Primary circuit inventory and chemistry control system

B MOTEL test facility has two operational systems: Primary circuit inventory and chemistry control (Primary feed water) system and feedwater system and steam relief (paragraph 2.5). In primary circuit inventory and chemistry control (Primary feed water) system the main function of the system is to store and prepare (heating or cooling) the expanded volume of feed water inside the MOTEL vessel, as well as to inject boric acid (if necessary) inside the system.

As stated earlier, the modelling focus is shifted to the development of the primary equipment model, as well as model simplification. Primary circuit inventory and chemistry control (primary feed water system) is implemented as the main function to be performed, namely maintaining the water level in the pressurizer. This system is described in paragraph 3.4. The other elements of this system such as the volume control tank, pumps and valves shown in Figure 7 have not been implemented in this master's thesis.

3.5.2 Feedwater system and steam relief system

As for the feedwater system and steam relief, the concept of simplifying the MOTEL test facility in the creation of the model also influenced the model being created. This system includes technical elements to regulate the feed water flow from purified water supply. It was important to consider the technical means of water distribution from water manifold to the cold collector, such as needle valves and pipe connections from water manifold to cold collector and next to steam generator.

The feedwater manifold with needle valves and connection from needle valve to cold collector of each group of steam generator tubes were considered in the steam generator modelling. Figure 20 shows the physical implementation of the feedwater manifold with needle valves as well as the cold/hot collector for each steam generator group of tubes.

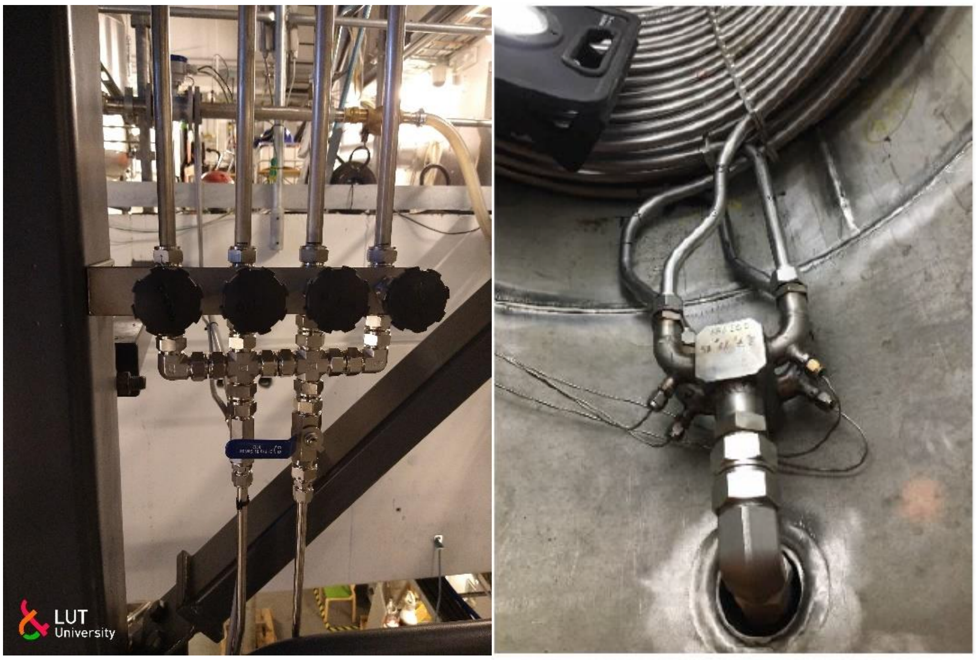


Figure 23. Feedwater manifold with needle valve (left) and steam generator group tubes hot/cold collector (right). (J. Hyvärinen, J.Telkkä, K.Tielinen, 2022, 12).

As a result, the implementation and model of this system consists of two parts feed water manifolds with needle valves and steam generator group tubes hot/cold collector. Figure 10 shows a structural diagram of the implementation of parts of the system without the rest of the technical equipment: piston pumps, purified water supply and measurement system. This operating system is a part of the model of steam generator described in paragraph 3.1.

4 Challenges at model setup

When modelling the MOTEL test facility, difficulties arose in modelling the reactor equipment due to the need to simplify the model and the ability to implement basic and necessary processes. Thus, during the development of models of individual parts of the reactor, the optimal design of each element was investigated. Also, problems with incompleteness and sufficiency of test equipment data occurred during modelling. Further the main difficulties encountered during modelling will be described.

4.1 Research of better steam generator model design

When building the steam generator model, both fully simplified models and models that most accurately describe behaviour and operation were investigated. The biggest challenge was to describe the steam generator tubes by means of system code. Thus, as discussed in paragraph 3.1, three steam generator tube models were created during code writing.

As a result of experiments on searching optimal architecture of steam generator model it was found out that simplification of steam generator tube model in part of replacement of group of four tubes by one tube using multiplication factor does not describe behaviour and structure of real steam generator tube structure. There were overflows between pipes and consequently coolant was heated and distributed unevenly, and as a result hydro-shocks and increase of pressure and temperature of coolant started to occur.

As mentioned earlier, distribution of coolant between groups of steam generator tubes and distribution between tubes within a group is also important for correct modelling. For correct distribution of coolant, the manifold and group collectors presented in Fig. 23 have been simplified and are shown in paragraph 3.1. As a result of the study of the optimal TRACE structure of the steam generator tube model, the structure described in paragraph 3.1 was applied.

4.2 Data insufficiency problem

When building the TRACE model, there were problems with insufficient input data. The main data for building the model were obtained from (SMR Integral PWR System Test Facility – Design and First Test Results, 2022) and (Modular Test Loop (MOTEL), Research Report, 2008) and from the design documentation.

To build the model, geometric dimensions of the test equipment, parameters characterizing all model elements, and functional characteristics of each element were required. It was possible to obtain from the sources the basic geometrical characteristics of the steam generator, core and pressurizer, as well as the parameters of heated and dummy rods. Problems with the data occurred when calculating hydraulic diameter, coolant flow parameters through the reactor, and mass flow rate in the secondary circuit and initial parameters of temperature, pressure and gas volume fraction value. The secondary circuit was modeled part with inlet and outlet (Fill and break elements) because of insufficient data, but the main reason was to simplify the model structure.

When constructing the steam generator tubes model, data on cold and hot collector and heat exchange parameters were lacking. In order to realize the model by mathematical way some parameters were calculated, the result of which did not cause inaccuracy of modeling. Lack of data should be taken into account in the subsequent modeling of the MOTEL test facility. For a more accurate implementation of the TRACE model, additional research and refinement of functional and geometric values may be necessary and data about initial parameters.

Some approximations were used in this model for lack of real measured values. When checking the influence of these parameters on the final result was evaluated as insignificant and satisfying the concept of modelling.

4.3 Inaccuracies in the simulation results

When validating the obtained simulation results, it was necessary to consider simplifications and incompleteness of data, which are described in paragraph 4.2.

When setting the simulation parameters, the parameters and phase of the coolant flow were not considered, the initial temperature of the coolant in the simulation was taken in the approximate operating range, the power table for power component 220 was formed based on the approximate value of the power to be investigated.

Also, when validating the real test facility, it is necessary to consider the actions of personnel and the operation of the equipment in sub anomalous modes of operation.

5 TRACE modelling results and analysis

As a result of TRACE simulation data on the changes in the values characterising the operation of equipment and maintaining the specified modes of operation were obtained. The initial conditions set for each component of the MOTEL equipment are shown in Table 17. The modelling considered equipment operation with a combined heated rod output of 250 kW, as discussed in paragraph 3.3. The mass flow in the secondary circuit is kept constant at 0.12 kg/s by the fill element.

Table 17. Initial conditions for modeling.

Part of facility	Pressure, MPa	Liquid temperature, K	Vapor temperature,K	Gas volume fraction
Riser (SG)	3.5	458.0	523.504	0
Downcomer	3.5	458.0	523.504	0
Core	3.5	458.0	523.504	0
Extension piece	3.5	458.0	523.504	0
Pressurizer	3.5	515.707	515.707	1-3 cell -0 4-8 cell -1
Secondary circuit (SG tubes, manifolds and group collectors)	1.0	300.0	453.0	0
Fill, Break	1.0	292.0	292.0	0

5.1 Modelling results

One of the features of the MOTEL is to maintain natural circulation. At the beginning it is necessary to check that the pressure is maintained within the set range in the primary circuit. As mentioned before in paragraph 3.4, the pressure must be between 3.2 MPa and 3.5 MPa. The upper limit of pressure regulation is stipulated in the technical documentation and when it is reached, the pressurizer heaters are switched off, thus regulating the pressure in the primary circuit. Figure 24 shows the change in pressure in the primary circuit.

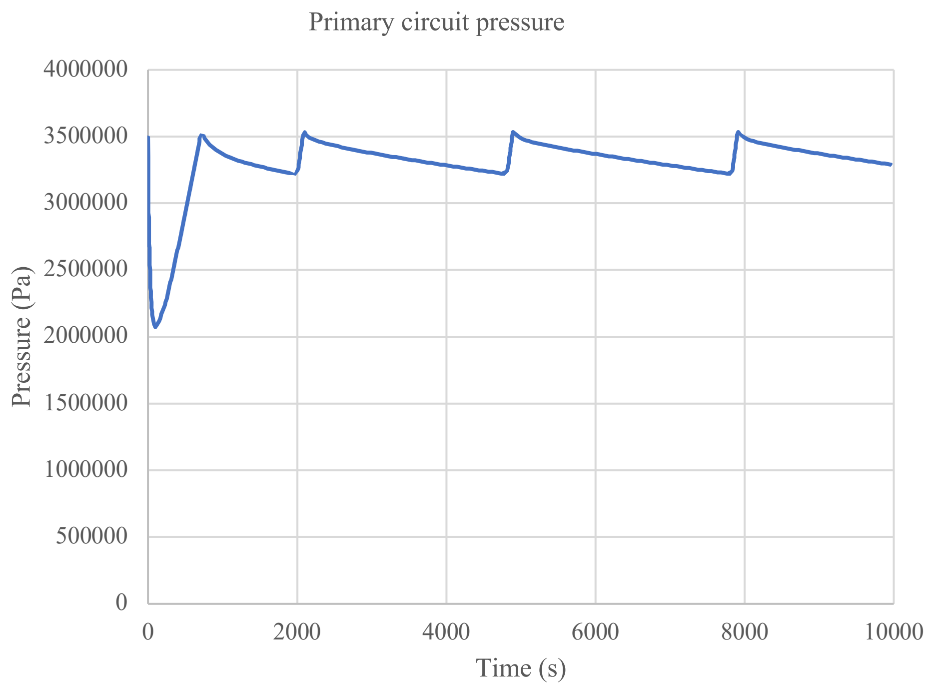


Figure 24. Primary circuit pressure.

The change in primary circuit coolant temperature changes from riser to downcomer after heat transfer to the steam generator pipes. The difference between the riser and downcomer steady-state temperatures must be monitored to estimate whether the natural circulation in the primary circuit has been accomplished. Using the TRACE model, a temperature difference of 10 C is obtained. Figure 25 shows a graph of the temperature change in the riser and downcomer.

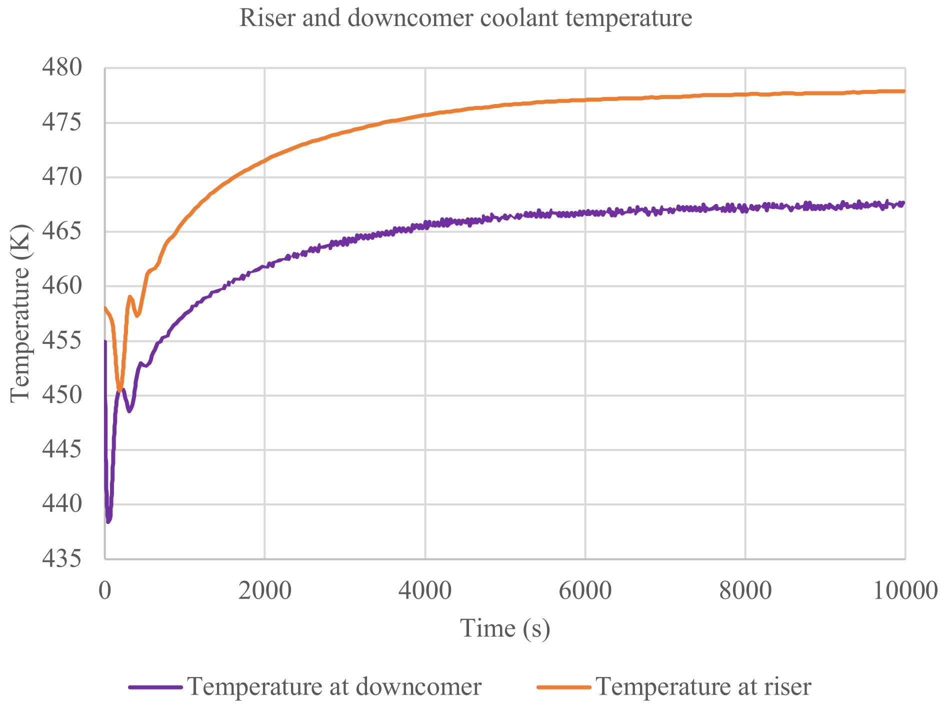


Figure 25. Riser and downcomer coolant temperature.

As can be seen from the temperature graphs in the downcomer, it can be said that the temperature has reached a steady state. The observed jumps and small changes in temperature are the cause of the two-phase flow and the maintenance of the natural circulation within the circuit.

Figure 26 shows the change in mass flow in the primary circuit. The graph shows that natural circulation in the primary circuit is maintained, as the change in mass flow occurs without large jumps, small mass flow fluctuations when reaching steady state (after 4000 seconds a mass flow value of 5.14 kg/s is observed) are due to the phase flow, which is quite characteristic of natural circulation.

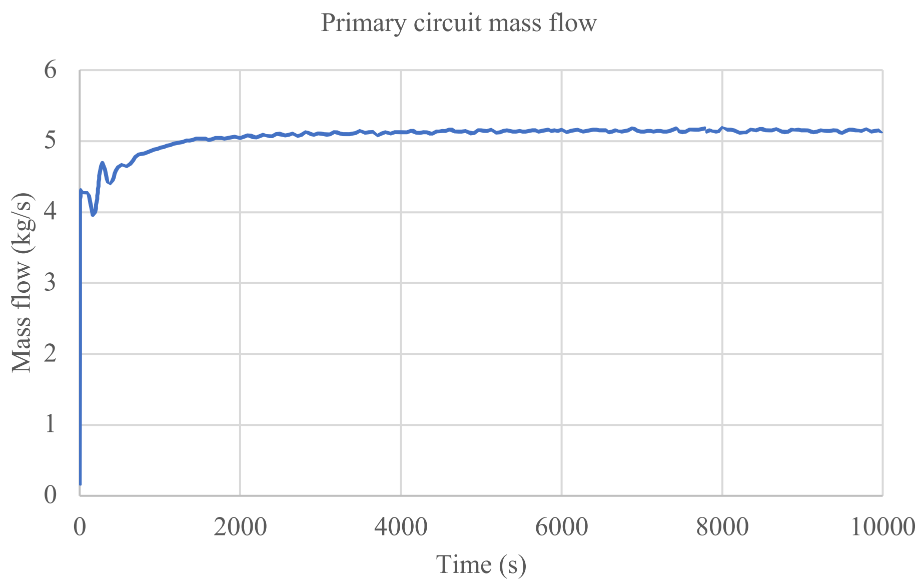
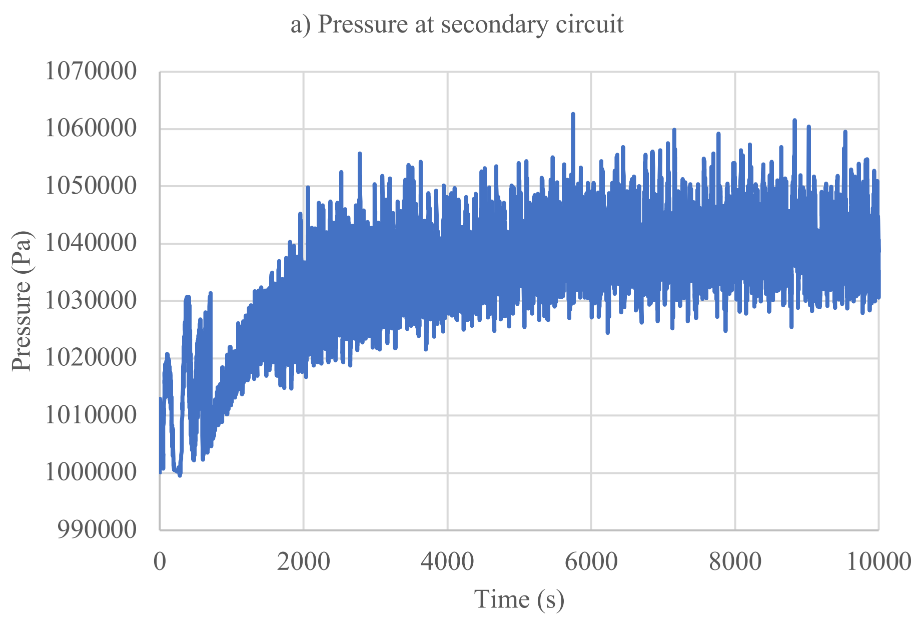


Figure 26. Primary circuit mass flow.

Table 17 presents the pressure and temperature parameters for the secondary circuit, but these values also change during the simulation. Figure 27 shows the pressure in the secondary circuit graph (a) and the coolant temperatures at the cold manifold inlet and at the hot manifold outlet.



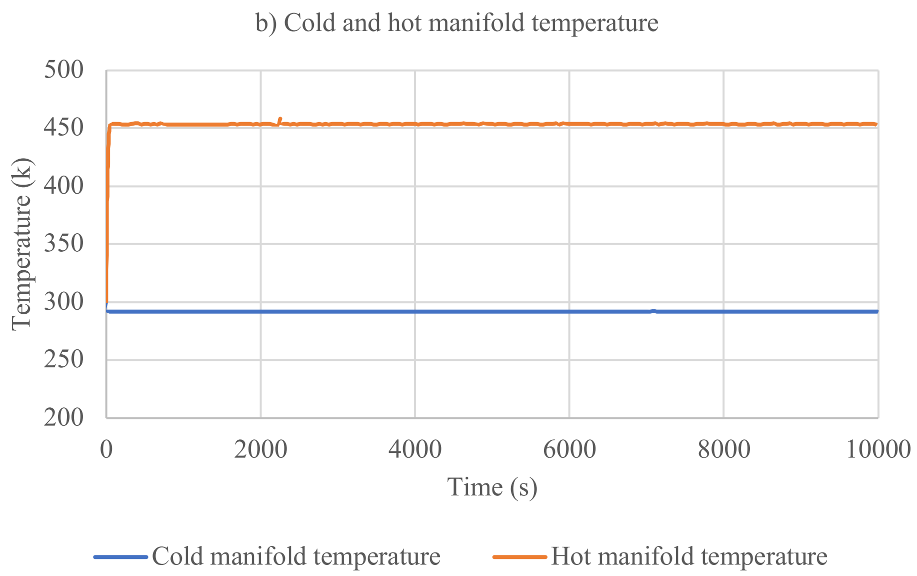


Figure 27. a) Secondary circuit pressure b) Cold and hot manifold temperature

As can be seen in Figure 27a the pressure in the secondary circuit comes to a steady state at 1.04 MPa, low and high pressure variations indicate a two-phase flow and coolant flow with some frequency, as well as uneven heating of the coolant in the steam generator tubes with swirling flow.

As discussed in paragraph 3.3, the steam generator tubes have a simplified geometry when developing the TRACE model. In the design of the steam generator tubes it was necessary to pay special attention to the equal distribution of the coolant over the steam generator tubes and to the implementation of the steam generation by the tubes. Further, two factors have to be checked: steam generation by means of gas volume fraction and coolant distribution by means of mass flow tracking.

Figure 28 shows the results of the simulation of the mass flow and the distribution of the coolant over the steam generator tube groups in the cold manifold. The figure shows 5 mass flow graphs in inlet pipe of manifold and in the output pipes of the manifold, which are connected to the check valve of each pipe group. The mass flow variation is fluctuating due to two-phase flow inside the tubes, in order to make the graphs visually readable it was necessary to integrate the mass flow and then divide by time (s) to get the correct mass flow value.

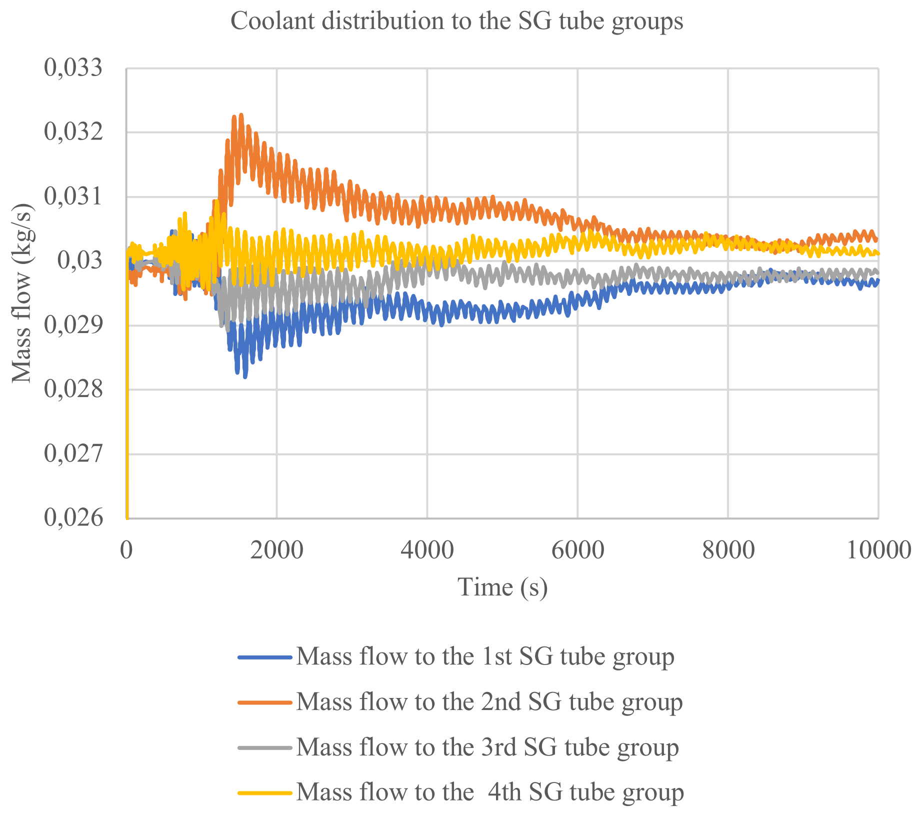


Figure 28. Distribution of the coolant from cold manifold to the steam generator tube groups.

Figure 29 illustrates the distribution of coolant over the steam generator tubes within each group. Since the distribution of coolant at the cold manifold outlet is equal for each pipe group, Figure 29 shows a graph of the change in mass flow, which will be the same for all steam generator pipe groups.

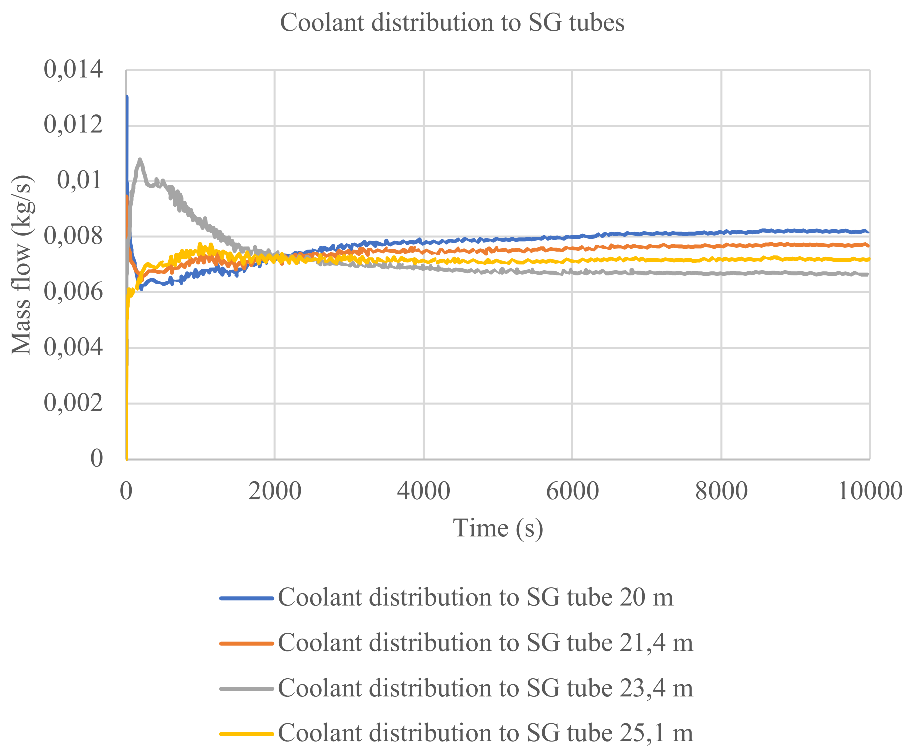
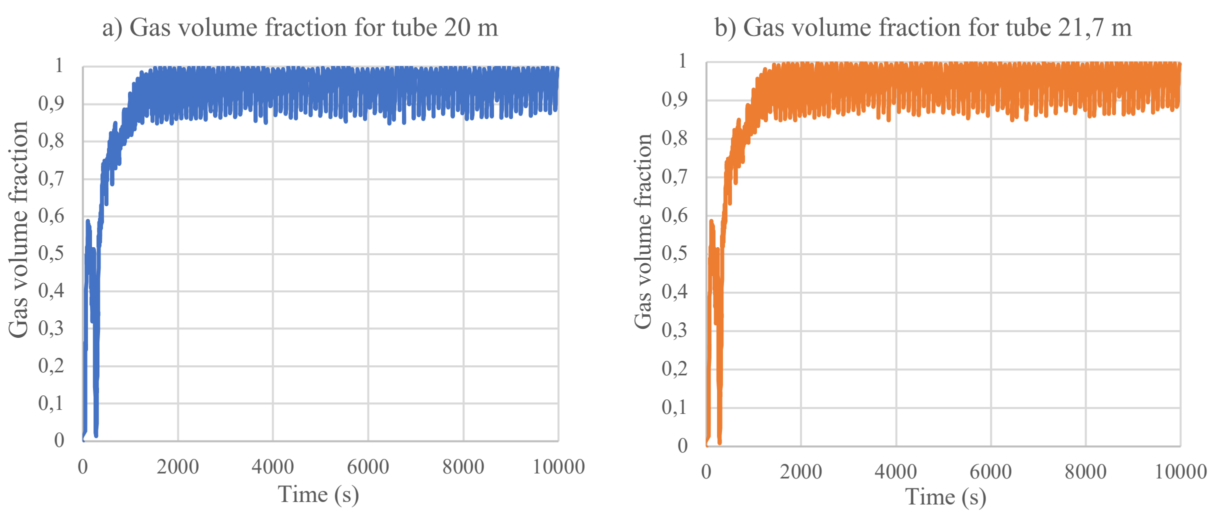


Figure 29. Coolant distribution to SG tube inside groups.

In order to assess the quality of steam generation, plot the change in gas volume fraction for each pipe length of the steam generator at the outlet of the pipe. Figure 30 shows the change in gas volume fraction for each pipe length.



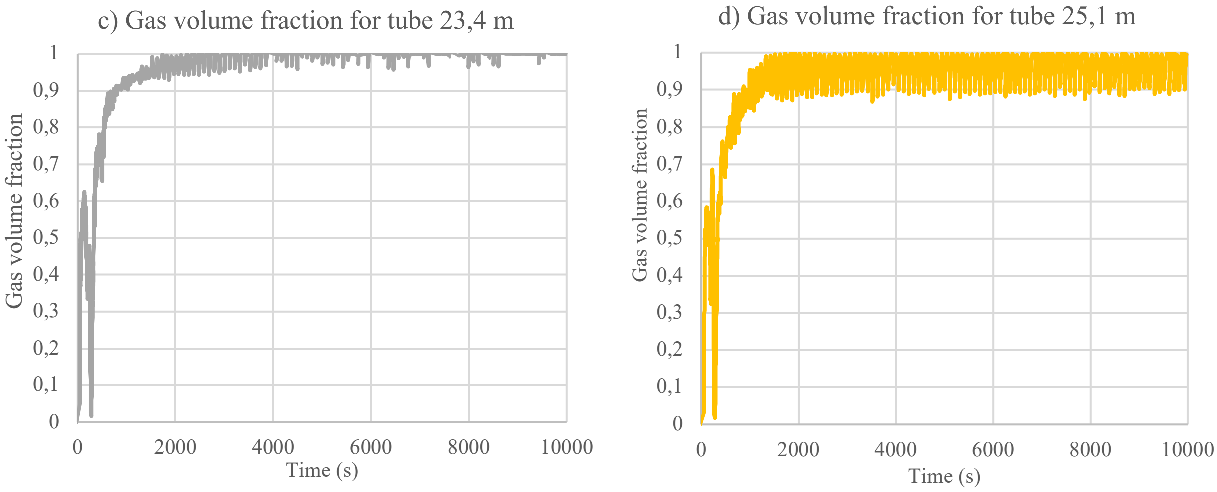


Figure 30. Gas volume fraction for a) tube length 20 m; b) tube length 21.4 m; c) tube length 23.4 m; d) tube length 25.1 m

The variation of gas volume fraction as a function of the length of the steam generating pipes has to be estimated. Figure 31 shows the distribution of gas volume fraction as a function of pipe length.

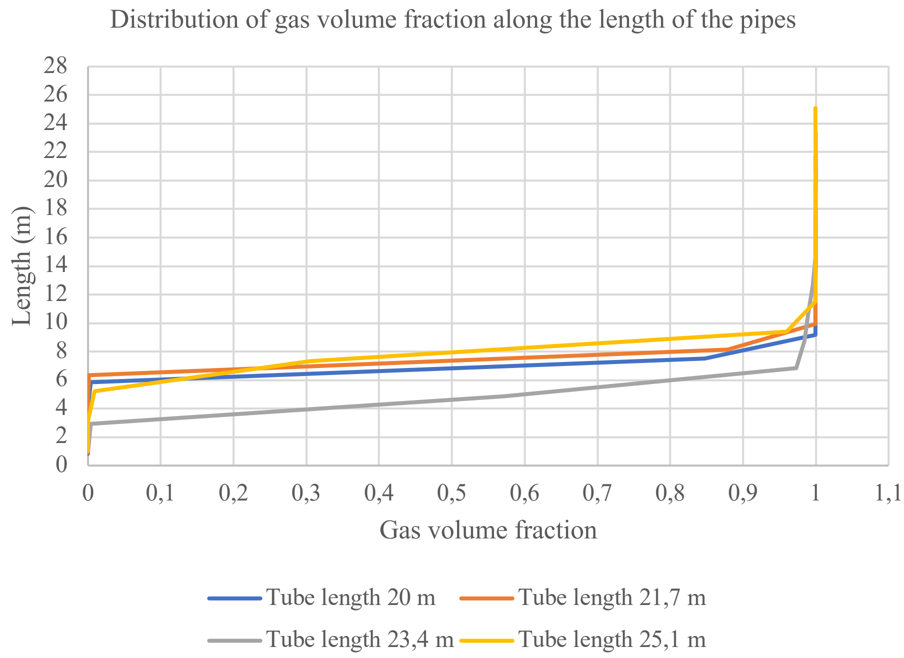


Figure 31. Distribution of gas volume fraction along the length of the SG pipes.

Figure 32 shows the change in gas volume fraction at the outlet of the hot manifold.

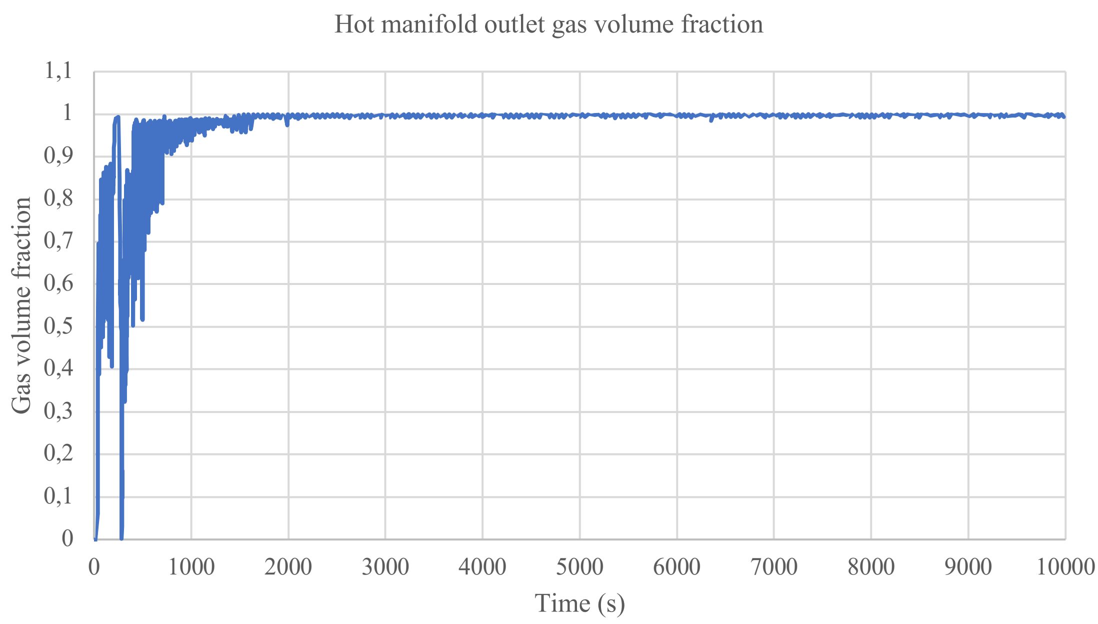


Figure 32. Hot manifold outlet gas volume fraction.

In order to estimate heat losses and the level of heat absorption by the steam generator tubes from the core, it is necessary to calculate the power balance of the system as a whole. To do this, subtract power absorbed by the steam generator tubes and heat losses emitted from the vessel from the power generated in the core. The calculation result is shown in Figure 33.

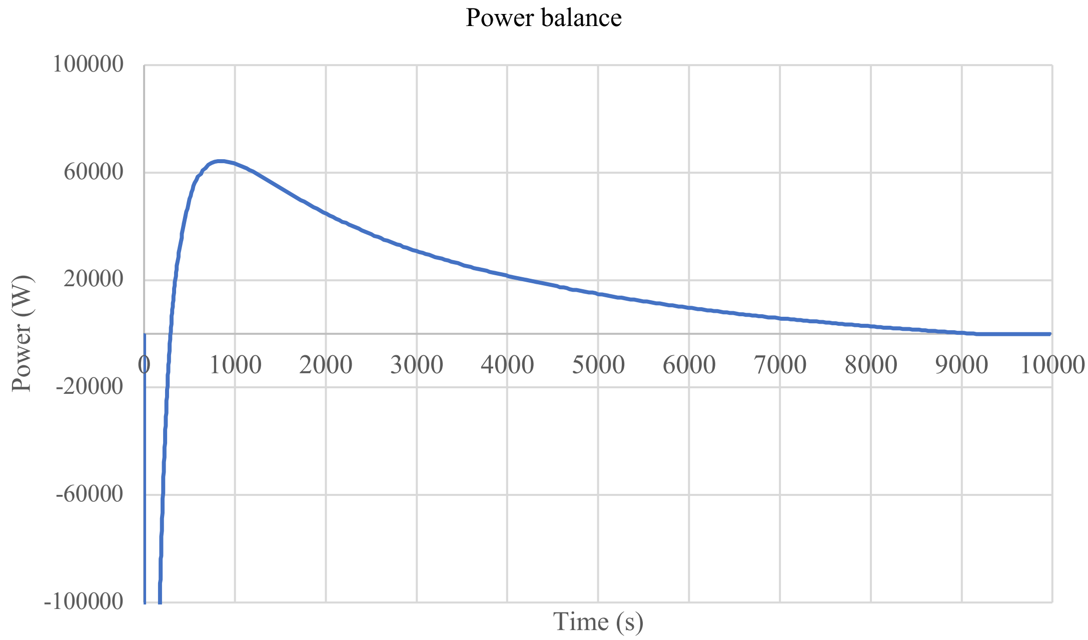


Figure 33. Power balance.

5.2 Results analysis

During the simulation the parameters of the simulated real test facility MOTEL were obtained. The simulation results, presented in paragraph 5.1, show realization of behaviour of basic equipment in terms of keeping natural circulation in steady state. This is indicated by pressure and temperature differential maintenance changes in the primary circuit presented in Figures 24 and 25, as well as mass flow presented in Figure 26. The pressure in the primary circuit is maintained in the set range according to technically defined values.

As mentioned above, during simulation of the steam generator, special attention was paid to operation of the steam generating pipes and equal distribution of coolant among the groups of pipes. The results shown in Figures 30 and 31 indicate the correct operation of the steam generating tubes and generally describe the behaviour of the actual equipment. In figure 28 it can be seen that the distribution of coolant between the tube groups is not exactly equal, but the mass flow indicating the coolant distribution varies from 0.0297 to 0.0304 kg/s, which is approximately equal. At an estimation of results of modelling of processes passing in pipes of the steam generator it is necessary to consider that uniform distribution of the heat-carrier between pipes is not reached as at modelling the secondary circuit the simplified structure with fill and break elements instead of realization of all circuit completely described in para. 2.5 was accepted. The pipes of the steam generator have different length, but they have identical difference of pressure between hot and cold tubes, that leads to the fact that the speed of flow in long tubes is less, than in short ones. No technical description of the experiments for checking the equal distribution of coolant between the tube groups has been carried out.

Figure 30 shows results of variation of gas volume fraction at the outlet of tubes of different length of steam generator. At steady state gas volume fraction value varies from 0.94 to 1. Fluctuations of this value are caused by two-phase flow of the coolant inside tubes and non-uniformity of the coolant heating in radial section of tubes. In Fig. 31 it is seen that steam generation with gas volume fraction of 0.94 -1 for 20 m and 21.7 m tubes starts at 10 m from the tube's beginning, and for 23.4 m and 25.1 m tubes from 11.5 m. This indicates that the heating of the tubes in the tube bundle is uniform when considering the horizontal cross-section. At the outlet of the hot manifold, the gas volume fraction varies from 0.98 to 0.998, as shown in Figure 32. Calculations and model results show that the steam generator model works as expected and the steam quality is quite good

The power balance shown in Figure 33 shows that the power generated by the core remains inside the vessel. Power change shows that when equipment comes to steady state, power absorbed by steam generator tubes and heat losses from vessel are balanced and come to equilibrium state. Heat loss through vessel walls in simulation is estimated as 3500W. This means that most of it remains inside the equipment system.

The simulation results obtained and presented above are similar to the results of real tests of the MOTEL plant. Experiments on the test facility were carried out within the framework of the study of maintaining natural circulation in the primary circuit with step change in the power of heated rods 90 kW, 250 kW, 500 kW at intervals of 1500 sec, 3500 sec, 5000 sec.

The results of the experiment and the results obtained in the simulations described in this paper are presented in Table 18.

Table 18. Experiment and model calculation results modeling.

Parameter	MOTEL experiment	TRACE model calculations
Downcomer mass flow (kg/s)	7.9	5.1
Inlet core temperature (°C)	181.45	195.16
Outlet core temperature (°C)	189.80	204.85
SG hot group collector temperature (°C)	180.72	180.21
Primary circuit pressure (MPa)	3.49 -3.5	3.2 -3.5
Secondary circuit pressure (MPa)	1.0	1.09
Fill, Break	1.0	292.0

As can be seen in Table 18, the mass flow, inlet, and outlet core temperature parameters are different when modeling with TRACE. As mentioned earlier, simplifications were used in the modelling to build the model. So in modeling of downcomer and riser we used a separate artificial element for connection of downcomer, riser and pressurizer, which in the real equipment is implemented by means of vessels and spaces passing into each other. Also, when building the TRACE model, the primary feedwater system was not built. These facts indicate the possibility of differences in parameters in the primary circuit. The downcomer mass flow differs by 2.8 kg/s and this is caused by the simplifications described above, because at the initial moment of modeling the primary circuit is filled with coolant and its change does not depend on the addition of coolant from the primary feedwater system. It is difficult to estimate the mass flow parameter in steady state from the experimental data, because the simulation was carried out for 3500 seconds and the mass flow parameter did not reach a constant value. In subsequent tests on the MOTEL facility, changes in downcomer mass flow should be monitored and clarified.

The difference in inlet and outlet core temperature is also caused by the simplifications when building the model in TRACE. To simulate the core, the pipe element was used, and to implement heated and dummy rods, the heat structure element was used. In the model the measurement rods have not been taken into account as well. This caused a change in heat transfer between rods and heat transfer between rods and coolant. Because of this the heating of the coolant in the core is more intensive and the coolant reaches a temperature of 195.16 °C instead of 181.45 °C in the experiment. ΔT of coolant heating in the core obtained in the experiment is 8.35 °C, and ΔT obtained in modeling by TRACE code is 9.69 °C, which satisfies parameters and allowable error.

The difference between the calculated temperature obtained by TRACE code calculations and the experimentally obtained primary circuit temperature lies in weak heat transfer between the steam generator tubes and the coolant in the downcomer. As it was stated in paragraph 3.1, the heat flux between the steam generator tubes and the coolant in the downcomer is made with the heat structure element and the boundary conditions for heat transfer from the coolant to the wall are also made with this element, and during heat transfer there is a heat resistance that counteracts the total and normal heat transfer. At further modification of the model it is worth to pay attention to heat transfer between steam generator pipes and coolant.

Due to the use of TRACE code to build the MOTEL model, the channels of coolant flowing in the core were not taken into account. The fact of channels was taken into account when calculating hydraulic diameter by subtracting all hydraulic surfaces in which the coolant cannot flow. Thus, calculation of coolant flow in the core and downcomer was simplified.

All simplifications made during construction of MOTEL model influence parameters received as a result of modeling, but intervals of parameters received correspond to confidence intervals described in documentation, and in part of modeling of steam generator correspond to experimental data when comparing temperatures reached in hot SG tubes group collector.

6 Conclusion

This master thesis describes a TRACE model of a small modular reactor Modular Test Loop (MOTEL) designed and built at Lappeenranta-Lahti University of Technology. The MOTEL digital model has been implemented with TRACE code to perform tests and simulation of normal operation, carrying out safety tests, implementing and conducting test modulation for monitoring changes in equipment operation when the initial condition changes. The following tasks were completed to realize the TRACE model of the MOTEL test facility:

- Reviewing the structure of the test equipment, the design documentation, and the models already implemented. Obtaining and studying the physical and geometrical parameters of the test equipment;
- Conducting parameter calculations and finding missing parameters needed for modelling;
- Finding the optimum structure and architecture for modeling the steam generator, steam generator tubes, core, pressurizer, the system of equal distribution of coolant over groups of steam generator tubes in the secondary circuit, as well as the structure of all equipment to maintain natural circulation in the primary circuit using TRACE code;
- Performing modelling and analyzing the resulting data for compliance with technical and project documentation.

The result of TRACE modelling is that the parameters obtained are in accordance with the technical parameters and the behavior of the real equipment. A test modulation was carried out to maintain natural circulation within the primary circuit and steam generation of a helical coil steam generator at 250 kW power for 10000 seconds. On the basis of the data, it can be said that steady state is reached after 5000 seconds. According to the results of the test modelling, the results were obtained mainly repeating the operation of the equipment and satisfying the purpose of the simulation.

The test simulation of the riser and downcomer part shows the presence and maintenance of natural circulation within the primary circuit, as indicated by the temperature difference between the riser and downcomer parts and the mass flow. TRACE simulations of the steam generator and steam generator tubes in particular show that the simulation satisfies expectations and falls within the confidence range of gas void fraction values, and the mass flow for each tube group corresponds to the manner of coolant distribution in a helical coil steam generator of similar type.

The coolant level control in the pressurizer is at 0.7 m from the beginning of the pressurizer throughout the simulation. The pressure in the pressurizer is regulated according to the power of the two heated rods in the pressurizer, the regulation is also performed according to the values specified in the technical documentation.

The simulation of the reactor core shows a satisfactory simulation of the heated rods and the heat exchange between the heated parts and the heat transfer medium. No boiling of the coolant occurs inside the reactor core and the reactor behaviour satisfies the technical documentation.

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