Accident Safety Analysis for Loss of Helium Coolant in Primary Helium Cooling System using the Code RELAP5.

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DEPARTMENT OF MECHANICAL ENGINEERING
AHMEDABAD-382481

MAY 2013

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Major Project

Submitted in partial fulfillment of the requirements

For the degree of

Master of Technology in Mechanical Engineering

(Thermal Engineering)

By

Madhuri Bhadauria

11MMET07

DEPARTMENT OF MECHANICAL ENGINEERING

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MAY 2013

Declaration

This is to certify that

(i) The thesis comprises my original work towards the degree of Master of Technology in Mechanical Engineering (THERMAL) at Nirma University and has not been submitted elsewhere for a degree.

(ii) Due acknowledgement has been made in the text to all other material used.

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Undertaking for Originality of the Work

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Certificate

This is to certify that the Major Project Report entitled **"Accident Safety Analysis for Loss of Helium Coolant in Primary Helium Cooling System using the Code RELAP5."** submitted by **Madhuri Bhadauria (11MMET07)** , towards the partial fulfillment of the requirements for the degree of **Master of Technology (Mechanical Engineering)** in the field of (**Thermal Engineering**) of Nirma University is the record of work carried out by her under our supervision and guidance. The work submitted has reached a level required for being accepted for examination. The results embodied in this major project, to the best of my knowledge, have not been submitted to any other University or Institution for award of any degree or diploma.

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Abstract

Test Blanket System (TBS) is the prototype of the proposed Indian DEMO fusion reactor to be tested in International Thermonuclear Experimental Reactor (ITER) in France. TBS consists of a tritium breeding blanket module made of Reduced Activation Ferritic Martensitic Steel (RAFMS), the Test Blanket Module (TBM) structure is cooled by high pressure helium gas. TBM consists of Lead Lithium (Pb-Li) liquid metal and Ceramic Breeder (CB) zones alternately arranged inside the box. Pb-Li liquid metal acts as neutron multiplier, tritium breeder and coolant for the CB zones which also produce tritium by nuclear reactions of neutrons with lithium. Low pressure helium gas is purged through the CB pebble beds to collect the tritium produced during reactor operation. TBS consists of a TBM and its ancillary systems viz. First Wall Helium Cooling System (FWHCS), Lead Lithium Liquid metal System (LLCS), Helium Purge System (HPS) which is a part of Tritium Extraction System (TES) and Lead Lithium Helium Cooling System (LLHCS). Safety licensing requires accident safety analysis of all these systems to be carried out to prove robustness of the design in case of various accident incident scenarios. A accident safety analysis of Primary Helium Cooling System (PHCS) is carried out in this project using the Reactor Excursion Leak Analysis Program (RELAP5). When loss of coolant accident (LOCA) happens the loss of helium coolant leads to the break of First wall channels causing the pressurization of vacuum vessel and evolution of temperature in TBM which remains with in the design limit of the ITER safety guidelines. Based on these results it was found that the present helium cooling system is designed with sufficient capability for the accident scenarios.

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Abbreviations

AEU .... Auxiliary Equipment Unit
CB .... Ceramic Breeder
CHWS .... Chilled Water System
EH .... Electric Heater
EU .... Europian Union
FMS .... Ferritic Martensitic Steel
FW .... First Wall
FWHCS .... First Wall Helium Cooling System
HCS .... Helium Cooling System
He .... Helium
HPS .... Helium Purge System
HRS .... Heat Rejection System
HTC .... Heat Transfer Coefficients
HX .... Heat Exchanger
ITER .... International Thermonuclear Experimental Reactor
LLCB .... Lead Lithium Ceramic Breeder
LLCS .... Lead Lithium Liquid metal System (LLCS)
LOCA .... Loss of Coolant Accident
MHD .... Magneto Hydrodynamics
Pb-Li .... Lead-Lithium
PC .... Port Cell
PCS .... Pressure Control System
PHCS .... Primary Helium Cooling System
RAFMS .... Reduced Activation Ferritic Martensitic Steel
RELAP5 .... Reactor Excursion Leak Analysis Program 5
SHCS .... Secondary Helium Cooling System
TBM .... Test Blanket Module
TBS .... Test Blanket System
TCWS .... Tokomak Cooling Water System

TES .... Tritium Extraction System

VV .... Vacuum Vessel

Nomenclature

A .... Area, m^2

d .... Diameter,m

d .... Diameter of bend

f_T .... Friction factor

h .... Heat Transfer Coefficient, $\frac{W}{m^2 * K}$

K .... Thermal Conductivity, $(W/(m * K))$

k .... Resistance coefficient

l .... Length, m

m .... Mass Flow Rate,Kg/sec

P .... Pressure, MPa

Q .... Heat Transfer, $(W/(m * K))$

r .... Radius of pipe

ρ .... Density, Kg/m^3

T .... Temperature, K

v .... Velocity, (m/sec)

Chapter 1

Introduction

1.1 About International Thermonuclear Experimental Reactor(ITER)

The International Thermonuclear Experimental Reactor(ITER) is an international nuclear fusion research and engineering project, which is currently building the world's largest and most advanced experimental Tokamak nuclear fusion reactor at the Cadarache facility in the south of France. The ITER project aims to make the long-awaited transition from experimental studies of plasma physics to full-scale electricity-producing fusion power plants. The project is funded and run by seven member entities the European Union (EU), India, Japan, China, Russia, South Korea and the United States. The EU, as host party for the ITER complex, is contributing 45% of the cost, with the other six parties contributing 9% each.

The ITER fusion reactor itself has been designed to produce 500 MW of output power for 50 MW of input power, or ten times the amount of energy put in. The machine is expected to demonstrate the principle of producing more energy from the fusion process than is used to initiate it, something that has not yet been achieved with previous fusion reactors. Construction of the facility began in 2007, and the first plasma is expected to be produced in 2019. When ITER becomes operational, it will become the largest magnetic confinement plasma physics experiment in use, surpassing the Joint European Torus. The first commercial demonstration fusion power plant, named DEMO, is proposed to follow on from the ITER project to bring fusion energy to the commercial market. One of the key missions of the International Thermonuclear Experimental Reactor (ITER) is to validate the design concepts of tritium breeding blankets relevant to a power-producing reactor like DEMO. ITER should demonstrate the feasibility of the breeding blanket concepts that would in future, lead to tritium self-sufficiency and high grade heat extraction, which are necessary goals for DEMO. Three ports are available in the ITER to test various blanket concepts through Test Blanket Modules (TBMs) from interested parties. India has proposed Lead-Lithium cooled Ceramic Breeder (LLCB) as the blanket concept for its DEMO considering its forte in liquid metal technologies and strong experience in diverse scientific areas relevant to blanket development. LLCB blanket concept is distinct from other concepts as it inherits the features of both solid and liquid type concepts. The LLCB blanket concept consists of lithium titanate as ceramic breeder (CB) material in the form of packed pebble beds and Pb-Li eutectic as multiplier, breeder, and coolant for the CB zones. The outer box however is cooled by helium.

ITER is a large-scale scientific experiment that aims to demonstrate that it is possible to produce commercial energy from fusion. The Q in the formula on the right symbolizes the ratio of fusion power to input power. Q greater than or equal to 10 represents the scientific goal of the ITER project: to deliver ten times the power it consumes. From 50 MW of input power, the ITER machine is designed to produce 500 MW of fusion powerthe first of all fusion experiments to produce net energy. During its operational lifetime, ITER will test key technologies necessary for the next step: the demonstration fusion power plant that will prove that it is possible to capture fusion energy for commercial use.

1.2 Nuclear Fusion

Nuclear fusion is a nuclear reaction in which two or more atomic nuclei join together, or "fuse", to form a single heavier nucleus. It is the reaction in which two atoms of hydrogen combine together, or fuse, to form an atom of helium. In the process some of the mass of the hydrogen is converted into energy. The easiest fusion reaction to

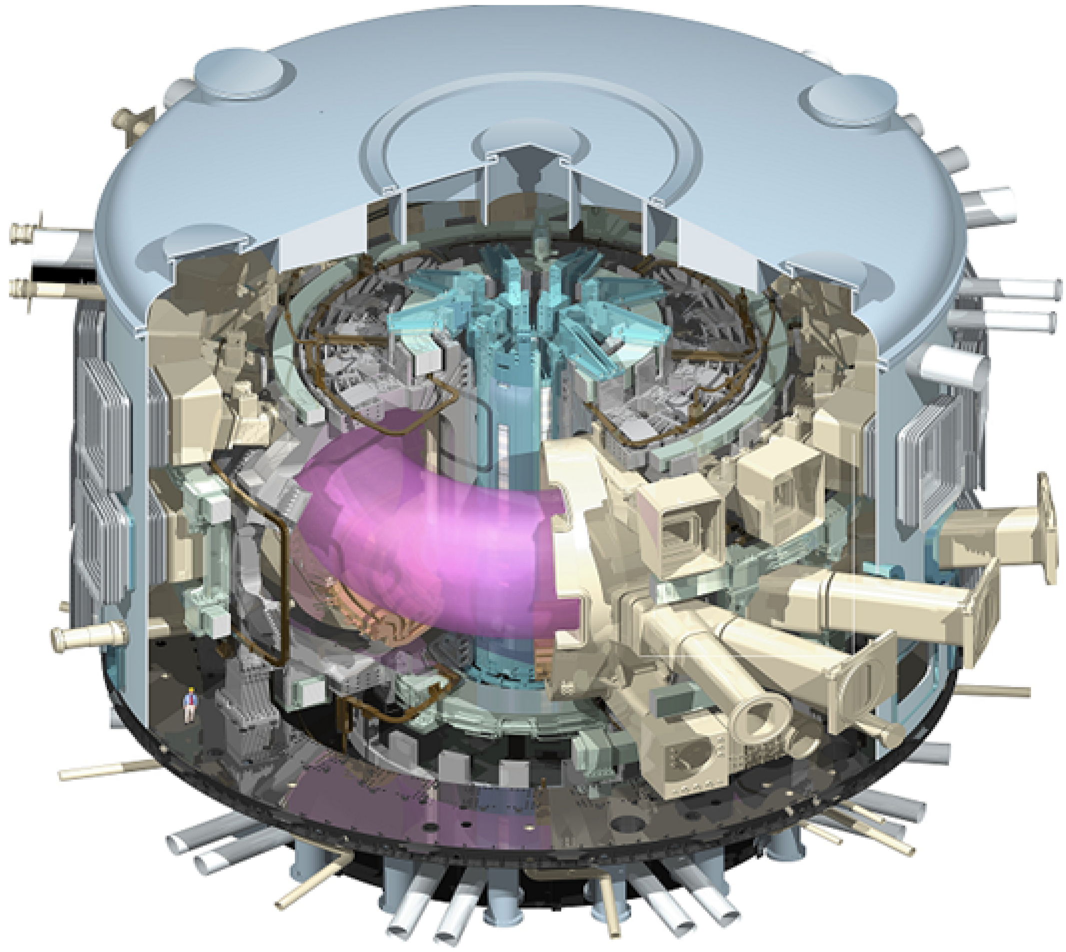

Figure 1.1: A detailed cutaway of the ITER Tokamak, with the hot plasma, in pink, in the centre[20]

make happen is combining deuterium (or heavy hydrogen) with tritium (or heavy-heavy hydrogen) to make helium and a neutron. Deuterium is plentifully available in ordinary water. Tritium can be produced by combining the fusion neutron with the abundant light metal lithium. Thus fusion has the potential to be an inexhaustible source of energy.

1.2.1 Nuclear Fusion Reaction

The reaction involved in the Nuclear fusion is given below:

$^2D +^3 T \rightarrow^4 He + n + 17.6MeV$

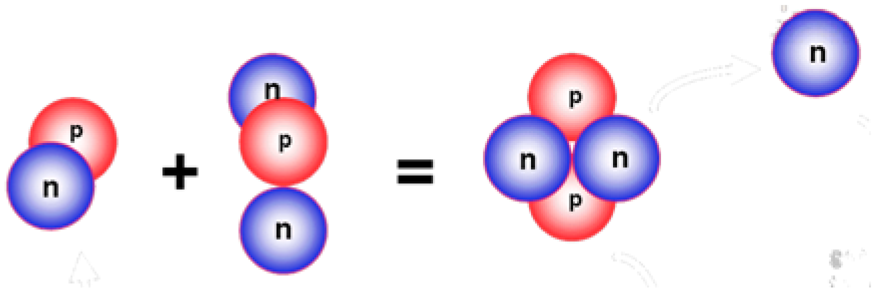

Figure 1.2: Deuterium and tritium reaction[14]

1.3 International Thermonuclear Experimental Reactor(ITER) Components

1.3.1 Vacuum Vessel

The vacuum vessel is a hermetically-sealed steel container inside the cryostat that houses the fusion reaction and acts as a first safety containment barrier. In its doughnut-shaped chamber, or torus, the plasma particles spiral around continuously without touching the walls.

The size of the vacuum vessel dictates the volume of the fusion plasma; the larger the vessel, the greater the amount of power that can be produced. The ITER vacuum vessel will be twice as large and sixteen times as heavy as any previous tokamak, with an internal diameter of 6 metres. It will measure a little over 19 metres across by 11 metres high, and weigh in excess of 5,000 tons. The vacuum vessel will have double steel walls, with passages for cooling water to circulate between them. The inner surfaces of the vessel will be covered with blanket modules that will provide shielding from the high-energy neutrons produced by the fusion reactions. Some of the blanket modules will also be used at later stages to test materials for tritium breeding concepts.

1.3.2 Magnets

The ITER magnet system comprises 18 superconducting toroidal field and 6 poloidal field coils, a central solenoid, and a set of correction coils that magnetically confine, shape and control the plasma inside the vacuum vessel. Additional coils will be implemented to mitigate Edge Localized Modes (ELMs), which are highly energetic outbursts near the plasma edge that, if left uncontrolled, cause the plasma to lose part of its energy. The power of the magnetic fields required to confine the plasma in the ITER vacuum vessel is extreme. For maximum efficiency and to limit energy consumption, ITER uses superconducting magnets that lose their resistance when cooled down to very low temperatures. The toroidal and poloidal field coils lie between the vacuum vessel and the cryostat, where they are cooled and shielded from the heat generating neutrons of the fusion reaction. The superconducting material for both the central solenoid and the toroidal field coils is designed to achieve operation at high magnetic field (13 Tesla), and is a special alloy made of niobium and tin (Nb_3Sn). The poloidal field coils and the correction coils use a different, niobium-titanium (NbTi) alloy. In order to achieve superconductivity, all coils are cooled with supercritical helium in the range of 4 Kelvin (-269^0C). Superconductivity offers an attractive ratio of power consumption to cost for the long plasma pulses envisaged for the ITER machine.

1.3.3 Blanket

The blanket covers the interior surfaces of the vacuum vessel, providing shielding to the vessel and the superconducting magnets from the heat and neutron fluxes of the fusion reaction. The neutrons are slowed down in the blanket where their kinetic energy is transformed into heat energy and collected by the coolants. In a fusion power plant, this energy will be used for electrical power production[2]. For purposes of maintenance on the interior of the vacuum vessel, the blanket wall is modular. It consists of 440 individual segments, each measuring 1x1.5 metres and weighing up to 4.6 tons. Each segment has a detachable first wall which directly faces the plasma and removes the plasma heat load, and a semi-permanent blanket shield dedicated to the neutron shielding. The ITER blanket is one of the most critical and technically challenging components in ITER: together with the divertor it directly faces the hot plasma. Because of its unique physical properties, beryllium has been chosen as the element to cover the first wall. The rest of the blanket shield will be made of high-strength copper and stainless steel. ITER project, test breeding modules will be used to test materials for tritium breeding concepts. A future fusion power plant producing large amounts of power will be required to breed all of its own tritium. ITER will test this essential concept of tritium self-sustainment.

1.3.4 Cryostat

The cryostat is a large, stainless steel structure surrounding the vacuum vessel and superconducting magnets, providing a super-cool, vacuum environment. It is made up of a single wall cylindrical construction, reinforced by horizontal and vertical ribs. The cryostat is 29.3 m tall and 28.6 m wide. The cryostat has many openings, some as large as four metres in diameter, which provide access to the vacuum vessel for cooling systems, magnet feeders, auxiliary heating, diagnostics, and the removal of blanket and divertor parts. Large bellows are used between the cryostat and the vacuum vessel to allow for thermal contraction and expansion in the structures. The cryostat is completely surrounded by a concrete layer known as the bioshield. Above the cryostat, the bioshield is two metres thick.

1.3.5 Power Supply

Electricity requirements for the ITER plant and facilities will range from 110 MW to up to 620 MW for peak periods of 30 seconds during plasma operation. Power will be provided through the 400 kV circuit that already supplies the nearby Cadarache site a one-kilometre extension will be enough to link the ITER plant into the network. ITER will have a steady state distribution system to supply the electricity needed to operate the entire plant, including offices and the operational facilities. The cooling water and cryogenic systems will together absorb about 80% of this supply. A second pulsed power system will be used during plasma operation to provide the superconducting magnet coils and the heating and current drive systems with the large amount of power that they need. Electricity from the 400 kV circuit will be transformed to an intermediate level (69 kV) via 3 step-down transformers.

1.3.6 Fuel Cycle

The fuels used in ITER will be processed in a closed cycle. The fusion reaction in the ITER Tokamak will be powered with deuterium and tritium, two isotopes of hydrogen. ITER is expected to be the first fusion machine fully designed for deuterium-tritium operation. Commissioning is planned in three phases: hydrogen operation, followed by deuterium operation, and finally full deuterium-tritium operation. As a first step to starting the fusion reaction, all air and any impurities must be evacuated from the vacuum vessel. The powerful magnets that will help to confine and control the plasma are then turned on and the low-density gaseous fuel is introduced into the vacuum vessel by a gas injection system. Once the fuel has been introduced into the vacuum chamber, an electrical current is applied to the system which causes the gas to break down electrically, become ionized, and form a plasma.

1.3.7 Cooling Water

ITER is equipped with a cooling water system to manage the heat generated during operation of the tokamak. The internal surfaces of the vacuum vessel (first wall blanket and divertor) must be cooled to approximately 240^0C only a few metres from the 150-million-degree plasma. Water is used to remove heat from the vacuum vessel and its components, and to cool auxiliary systems such as radio frequency heating and current drive systems, the chilled water system (CHWS), the cryogenic system, and the coil power supply and distribution system. The cooling water system incorporates multiple closed heat transfer loops plus an open-loop heat rejection system (HRS). Heat generated in the plasma during the deuterium-tritium reaction will be transferred through the tokamak cooling water system (TCWS) to the intermediate component cooling water system (CCWS), and to the HRS, which will reject the heat to the environment.

1.4 Lead Lithium Ceramic Breeder (LLCB) Test Blanket Module

Lead lithium ceramic breeder (LLCB) TBM is test blanket module located in equatorial port of vacuum vessel .

1.4.1 Function of Test Blanket Module (TBM)

Function of TBM are listed below:

- Tritium production (breeding) and extraction (purging).
- Transforming neutron power into heat and collection of the heat.
- Shielding of the Vacuum Vessel and Toroidal Field Coils.

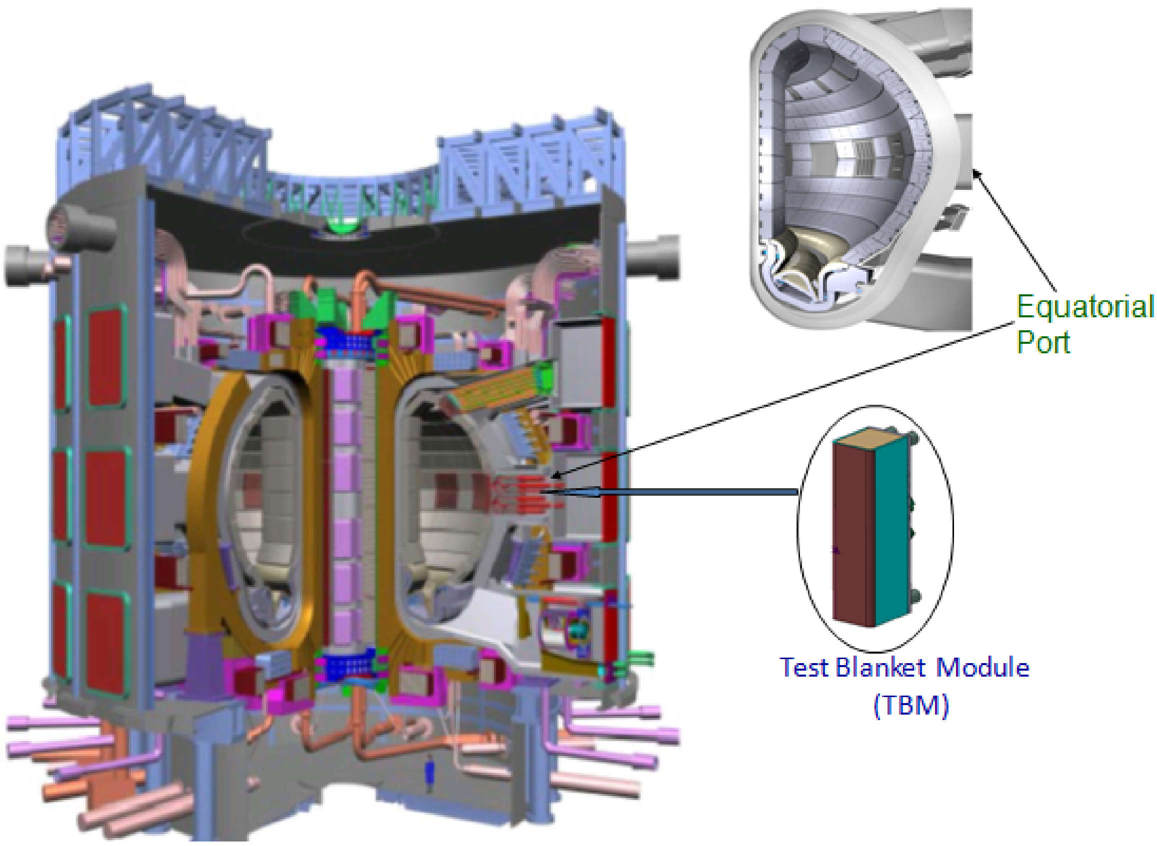

Figure 1.3: TBM in ITER [20].

1.5 Test Blanket Module Systems

TBM Systems (TBS) consist of three systems namely Helium Cooling System (HCS), Lead-lithium Cooling System (LLCS) and Helium Purge System (HPS)[3].

1.5.1 Helium Cooling System

Helium Cooling System (HCS) is divided in two loops Primary HCS and Secondary HCS. Primary HCS (PHCS) is meant for extracting heat from the TBM first wall. The TBM first wall along with other sides is cooled by high pressure helium, which rejects heat subsequently to water. Secondary Helium Cooling System (SHCS) removes heat from liquid metal system through liquid metal heat exchanger (LMHX) and heat is ultimately rejected in water.

1.5.2 Lead-Lithium Cooling System

LLCS is a closed loop system in which, the tritium enriched hot Pb-Li coming out of TBM is directly fed to the heat exchanger, for the removal of heat by using Helium coolant. To control the level and volumetric swelling/shrinkage in the loop, an expansion volume is provided in the sump tank of the stand-by pump. This way the two sump tanks work as complimentary to each other for pump sump and expansion tank, without having to provide any extra expansion tank. A gas space is provided in the top of the sump tank to protect the mechanical seal of the pump. This Pb-Li flow is pumped back to the TBM by maintaining the specified temperature at the entrance of TBM with the help of an electric heater.

1.5.3 Helium Purge System

The helium purge system is designed to extract the tritium produced in solid breeder as well as in liquid breeder (lead-lithium). Purge gas removes the tritium produced in the solid beds, carries it to tritium extraction system. The hot purge gas streams with tritium pass through recuperator to lose heat from incoming streams. Purge gas stream coming from detritiation unit and TBM after recuperation combine and a single line is taken from port cell to tritium building in port cell. Further the purge gas stream temperature is reduced using Helium-water heat exchanger.

1.6 Need for Safety Analysis

Safety analysis is part of the ITER Test Blanket Module (TBM) design process ensuring that the TBM does not adversely affect the safety of ITER. To get the licence for TBM as a whole with ITER, relevant safety analysis is required for each TBM system.

1.6.1 Safety Characteristics-The Basis of Safety Performance

Favorable safety performance and low environmental impact can generally be characterized in four areas:

- The impact of normal operation, including routine maintenance activities. The focus is to minimize releases to the environment of radioactive and other potentially hazardous substances, in gaseous, liquid, or aerosol form.
- The potential for accidents, initiated by a fault internal to the facility or by some external event. A strong safety design is required to minimize the frequency of plant failures that could initiate an accident sequence, and to eliminate or reduce the potential consequences of all off-normal situations.
- The well-being of personnel working at the facility, ensuring that exposure to radiation is as low as reasonably achievable, as well as minimizing other occupational hazards.
- Consideration of radioactive waste in solid form that may arise during the operation and in decommissioning at end of life, to ensure that the quantity and its level of activation and contamination is minimized, and ensuring that there is a safe and secure route for its long-term disposal.

The safety analyses performed in support of the licensing of ITER have sought to demonstrate that the design will give good performance in these four areas.

1.7 RELAP5

Reaction Excursion Leak Analysis Program (RELAP5) has been developed for the best estimate transient simulation for light water reactor coolant systems during postulated accidents. The code models the couple behaviour of reactor coolant systems and the core for loss of coolants accidents and operational transients. It is highly generic code and allows to simulate a wide range of hydraulic and thermal transients in both nuclear and non nuclear systems. The basic field equations contains two phase continuity equations,two phase momentum equations and two phase energy equations. The system is solved numerically using semi-implicit or nearly implicit finite difference methods.

The RELAP5 code has been used:

- To support basic research on two-phase thermal-hydraulics.
- To design small and large-scale thermal-hydraulic experimental facilities, research reactors, and commercial power plants.
- To assess the safety of nuclear plants.

RELAP5 was one of the most widely used versions of the software and is still used to support the regulation of commercial power plants in the United States, Europe, and Asia. RELAP5, which was initially released in the late 1980's, is the most advanced major version of the code and is still under active development in the United States by the U.S. Department of Energy and Nuclear Regulatory Commission (USNRC). RELAP5 is currently the latest publicly available version of the code. RELAP5 use multidimensional thermal-hydraulic, heat transfer, generic and special component, control systems, and other models to describe the behavior of complex fluid-filled systems under single and two-phase conditions. The hydrodynamic models track the flow of liquid, vapor, and non-condensable gases including air, hydrogen, helium and nitrogen. The heat transfer models describe 1D/2D heat conduction in system structures, connective and radiative heat transfer between the structures and the fluid. The generic component models include valves, separators, dryers, pumps, electric heaters, turbines, and accumulators. Control system models include arithmetic functions, integrating and differentiating functions, proportional-integral, lead, and lead-lag controllers, and trip logic. Special component models in RELAP5, developed for the analysis of nuclear reactors, include fuel element, control rod/blade, and other core structure models, debris bed models, and general models for porous structures.[10]

1.7.1 Capabilty of RELAP5 Code

The capability of the code is vast, it offers to model : Hydrodynamic components like pipes, valves, branches, seperators, pumps, multiple branches and junctions, bellows and others. Heat structures which involve conduction,convection and radiation. Heat sources from nuclear heat and thermal can be well modelled using this code. Reactor kinetics,point kinetics which are involved in nuclear reactions. Metal reactions, mainly metal steam reactions.[9]
There are four main steps involved while modelling the systems in RELAP5:

- Nodalization of the systems into volumes for computation.
- Tabulation of parameters for each components involved in modelling which are given as input to the code.
- Running the code for steady /transient state.
- Analysis and validation.

1.8 About Institute for Plasma Research (IPR)

In 1982 Government of India accepted a proposal to initiate studies on magnetically confined high temperature plasmas and resulted in establishment of the Plasma Physics Programme (PPP) supported by the Department of Science and Technology. Design and engineering of India's first Tokamak ADITYA started at the same time in independent campus in Bhat, Gandhinagar. The PPP evolved into the autonomous Institute for Plasma Research under the Department of Science and Technology in 1986. A full-fledged tokamak experiments started with the commissioning of ADITYA in 1989. A decision was taken in 1995 to build the second generation superconducting steady state tokamak SST-1 capable of 1000 second operation. Due to this, the institute grew rapidly and came under the Department of Atomic Energy. The industrial plasma activities were reorganized under the Facilitation Centre for Industrial Plasma Technologies (FCIPT) and moved to a separate campus in Gandhinagar in 1998.[20]

1.9 Objective of the Present Study

The objective of present study is to develop a thermal-hydraulic model of helium cooling system with a computational tool RELAP5 because Safety licensing requires accident safety analysis of all these systems to be carried out to prove robustness of the design in case of various accident/ incident scenarios. As a part of it, the accident safety analysis of Primary Helium Cooling System (PHCS) is proposed to be carried out using RELAP5.

Chapter 2

Literature Survey

Literature survey for the current dissertation work has been carried out in which Various research papers, web articles, theories have been studied relevant to the topic of work.

2.1 Test Blanket Module (TBM) and Associated Systems

Lead Lithium Ceramic Breeder LLCB TBM will be placed in half part of one of the equatorial port of ITER machine during the testing campaign, which will last for 10 years of operation. Figure 2.1 gives idea of the TBM placed in equatorial half port of TBM with ancillary systems and the confinement boundaries to be considered in the accident safety analysis. The major functions of TBM are demonstration of high-grade heat removal, tritium breeding and extraction, radiation shield from radiological safety point of view. While performing its functions in ITER machine the TBM must comply with the engineering safety norms of ITER. The objective of the present analysis is to identify and prove through the analyses of various PIEs that the design of LLCB TBM is in compliance with the ITER safety norms.[3]
The systems involved in the safety analyses are identified below with their functions in brief. The Test Blanket Module consists of the major components viz. First Wall (FW), top and bottom plates, back plate, PbLi zones, ceramic breeder zones,

manifolds for PbLi, helium coolant and purge helium gas. FW is made of RAFMS (Reduced Activation Ferritic Martinsitic Steel), designed for heat removal deposited in it from the heat flux of 0.3 MW/m^2 and a peak heat load of 0.5 MW/m^2 on 10% of its surface area. FW is U shaped covering plasma facing side and left and right sides of the module. Helium is used as coolant for the FW. Caps are the top and bottom plates of the module cooled by helium, which contains the manifolds of the purge gas helium. Back plate besides providing a major confinement barrier from rear side of the module, also contains manifolds for liquid metal (PbLi), coolant helium and purge helium gas. PbLi in the form of liquid metal is used as neutron multiplier, tritium breeder and coolant, removing heat deposited by neutrons and gamma rays in ceramic breeder zones as well as in the PbLi zones itself. Ceramic breeder zones sandwiched between two PbLi zones are used solemnly for tritium breeding. While the tritium produced in PbLi is extracted outside in the PbLi circulating loop, the tritium produced in solid ceramic breeder zones is removed by purging a low-pressure helium gas through the ceramic breeder zones. During the normal operation of ITER machine the radiations from the plasma deposits heat in all components of TBM, producing tritium in the liquid and solid breeder zones.

Besides the TBM the other systems involved in safety analyses are:

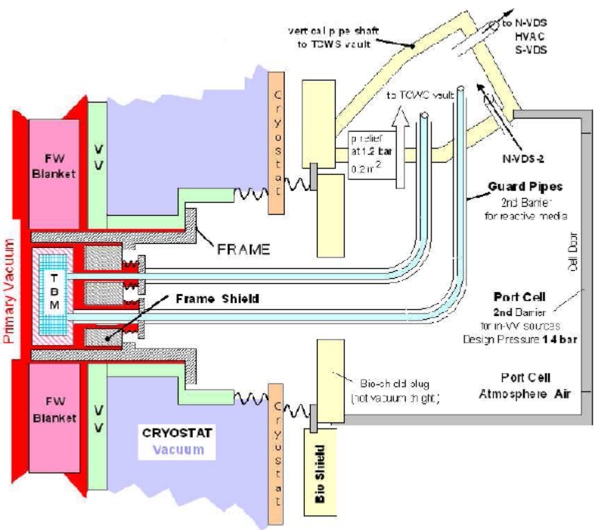

Figure 2.1: Schematic of TBM placed in ITER equatorial port and the ancillary systems[11] .

- Helium cooling system (HCS) circulates the coolant helium in TBM for heat removal from FW and Caps.
- PbLi loop circulates PbLi in the form of liquid metal through the TBM extracting heat from the bulk of TBM .
- Tritium extraction system is designed to extract the tritium from PbLi and the purge helium gas, which removes tritium from the ceramic breeder zones.
- Equatorial port is the place where the TBM is installed in the toroidal shaped ITER vacuum vessel (VV).
- Vacuum Vessel (VV) in the form of a torous is the first confinement barrier of the ITER machine.
- Port Cell is the area behind the TBM equatorial port in VV where all the ancillary equipments associated with TBM are located acts as second confinement barrier.
- TCWS (Tokamak Cooling Water System) is an area where the tritium extraction system is located, is an important confinement barrier.

Physical and functional barriers that protect against the spread and release of radioactive materials provide confinement. VV, port cell, TCWS vault are the important confinement barriers in the present analyses, pressurization of these barriers during the accident scenarios becomes an important safety issue.
Indian team TBM [17] this document comprises of design description of LLCB TBM and the associated systems.

2.2 Design description of LLCB TBM

The overall dimensions of the LLCB TBM are 1.66 m (pol)* 0.484 m (tor)*0.534 m (rad). Fig. 2.2 shows the different components of LLCB TBM includes the FW, top, bottom, and back plate and the ceramic breeder assembly inside the module. PbLi eutectic is flowing around all CB zones extracts heat from them as well as the heat generated within it as shown in Fig. 2.3 This figure shows the details of all five CB zones and the path of six PbLi channels around these CB zones. The PbLi flow velocity is moderate enough such that its self generated heat and the heat transferred from ceramic breeder bed is extracted effectively. Effectively there is no separate helium cooling in the interface RAFMS plates between the PbLi and ceramic breeder.[4]

The FW is designed to withstand the energetic particle fluxes and heat fluxes from

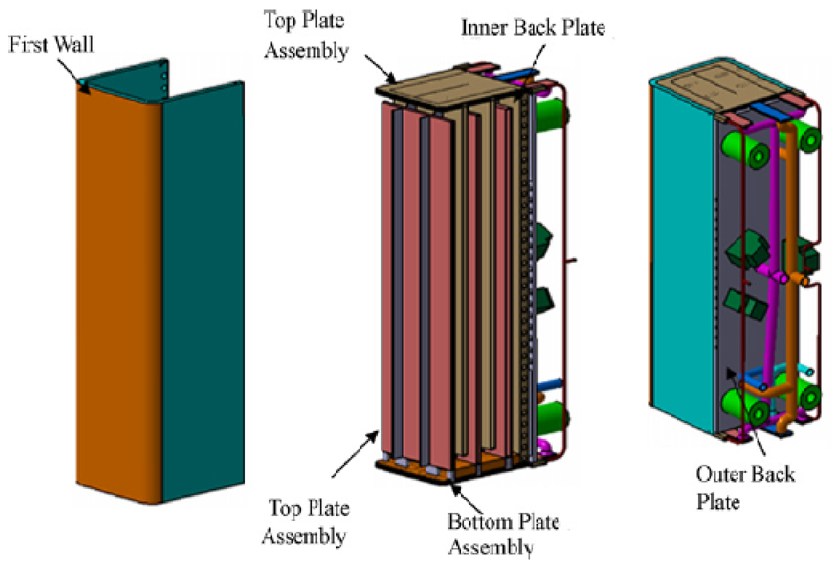

Figure 2.2: Different components of LLCB TBM.[11]

the plasma, high thermal and mechanical stresses and magnetic forces during plasma disruptions. The FW structure is actively cooled by helium gas flowing through the cooling channels which are running in radial−toroidal−radial direction and designed to withstand the He pressure of 8 MPa. The heat transfer coefficients (HTC) obtained form the correlations revealed that required cooling could be achieved by artificially roughened surface towards the plasma side wall of He cooling channel which helps to keep the RAFMS temperatures below the allowable limit.

In the paper by Paritosh Chaudhuri, et al[16] discusses concepts of tritium breeding blankets relevant to a power-producing reactor like DEMO. India has developed two breeding blanket concepts such as, lead lithium cooled ceramic breeder (LLCB) and helium cooled ceramic breeder (HCCB) for its DEMO. LLCB concept will be tested

Table I: LLCB TBM Parameters[5]

Structural material	IN-RAFMS
Breeder material	PbLi, Li_2TiO_3
Lithium enrichment	90% in PbLi 60% in Li_2TiO_3
Coolants Helium	PbLi
Helium temperature (inlet/outlet)	573/673 K
Helium gas pressure	8 MPa
PbLi temperature (inlet/outlet)	598/723 K
Purge gas for tritium extraction	Helium with 0.1% hydrogen at 0.12 MPa

in ITER where Li_2TiO_3 ceramic breeder (CB) in the form of packed pebble beds is used as a tritium breeding material and PbLi eutectic is used as multiplier, breeder, and coolant for the CB zones. A detail engineering design and analysis has been executed for the LLCB TBM to optimize the flow parameters for helium and PbLi circuits, to estimate the temperature distribution in the various breeding zones and to ensure the thermal design limits for structural material and temperature window in ceramic breeder for effective tritium extraction.

In the paper by G. Rampal,et al[6] latest design of the final TBM is presented. The most recent developments consist in geometrical optimisations and modifications needed to have a realistic manufacturing sequence, in defining the attachments to the port frame, and in assessing the integration of the testing instrumentation required for each mock-up. The status of studies on sub-components fabrication is presented. Preliminary proposals for the design of the initial TBM are also discussed.

In the paper by E. Rajendra Kumar, et al[5] will provide an overview of LLCB TBM Research and Development activities under progress in India.The LLCB TBM will be tested from the first phase of ITER operation (H-H phase) in one-half of an ITER port No.2. The Indian TBM Research and Development program is focused on the development of blanket materials and critical technologies: structural material (IN-RAFMS), breeding materials (PbLi, Li_2TiO_3), development of technologies for Lead-Lithium cooling system (LLCS), helium cooling system (HCS), tritium extraction system (TES) and TBM related fabrication technologies.

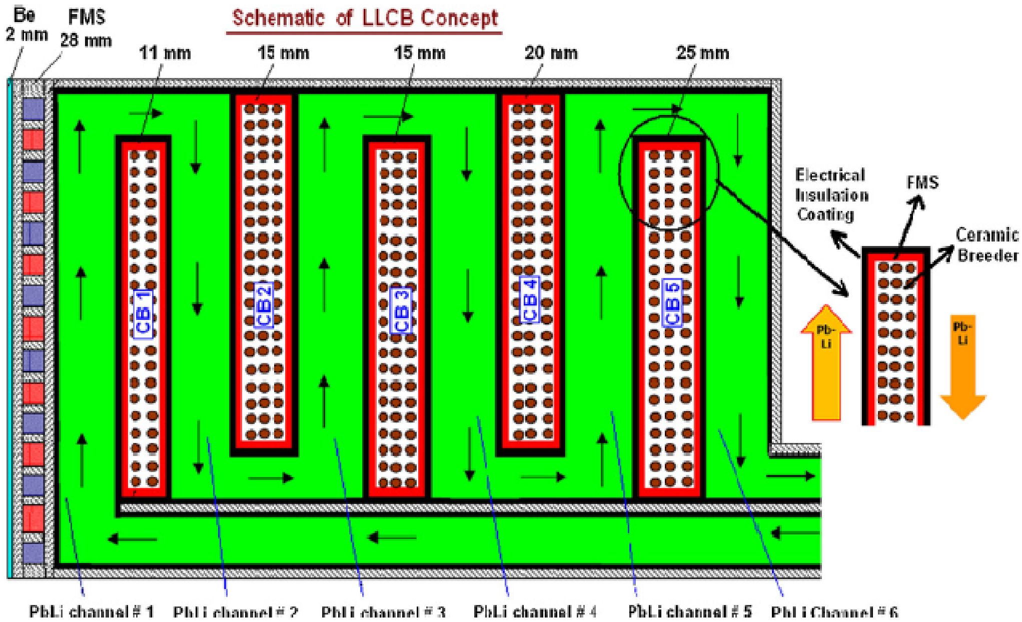

Figure 2.3: Schematic of inside view of LLCB TBM.[11]

2.2.1 TBM First wall

The FW assembly is designed to withstand the heat flux from the plasma and neutronics heat generation on the FW structure to maintain its temperature below the allowable limits. The typical dimensions of one DEMO blanket is 1.7 m (poloidal)*1.0 m(toroidal)*0.5 m (radial). The DEMO blanket consists of two modules resembles the two TBM dimensions are placed toroidally side-by-side as shown in Fig.2.4. shows the schematic of top-view of a module placed at outboard mid-plane. All thermalhydraulic calculations have been performed based on DEMO relevant neutronics heat load and surface heat flux from plasma on one such DEMO module as shown in Fig 2.4. The U-shaped FW structure as shown in Fig.2.4, is composed of a 28 mm thick RAFMS structure, having internal cooling channels of $20mm * 20mm$ cross section. The coolant channels are designed to allow multiple passes of helium coolant across the FW in order to maximize the heat removal. The number of helium passes has been optimized such that the maximum temperature in the RAFMS remains below the design limit of 500^0C. Based on the surface heat flux and neutronic heat generation on FW, thermalhydraulic analyses have been carried out for the normal and extreme conditions. Main parameters of FW structure are tabulated in Table II.

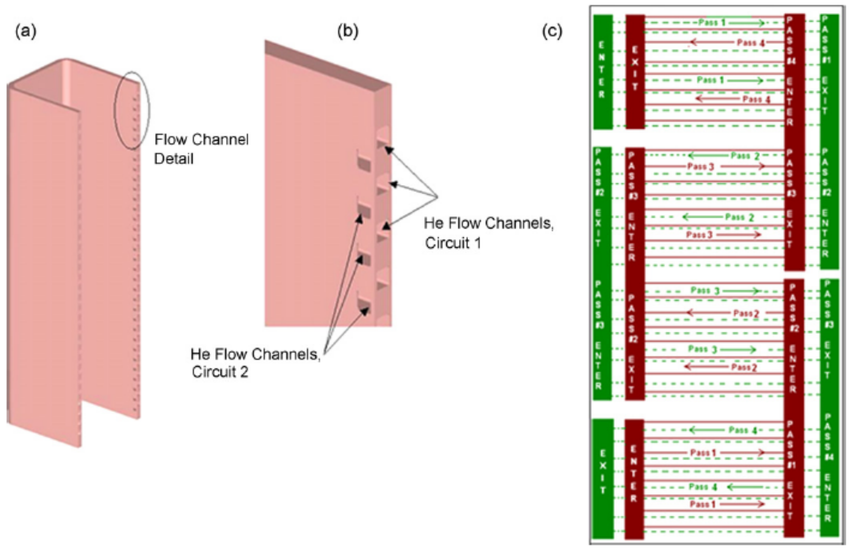

Figure 2.4: Schematic of FW helium circuit in the blanket module.[15]

2.2.2 He Flow Distribution Network in First Wall (FW) structure

The design of this FW cooling scheme is adopted from US DCLL Test Blanket Module. The FW structure is having 64 helium coolant channels, which are divided into two circuits as shown in Fig.2.4. One circuit (circuit 1) of the He flow channels have openings at the edge face of the FW and other circuit (circuit 2) have the channel openings on the inner face of the FW (Fig.2.4). This multi-pass arrangement is to meet the heat transfer requirements and maintain a minimum temperature of the FW. These two circuits are always in a counter flow arrangement in order to achieve a uniform temperature distribution across the FW surface. The two He circuits flowing through the FW channels are separated from each other and only mixed in the outlet manifold prior to entering into the outlet pipe. The manifolds are designed to cover the FW height with four consecutive passes. The cooling channel in the FW module is designed to withstand the maximum He pressure of 8 MPa. Each circuit is

Table II: Main parameters of the FW in a DEMO blanket module[15]

Parameters	Value
FW structural material	RAFMS
FW dimension (poloidal*toroidal*radial)	1.7 m*0.5 m*0.5 m
Thickness of FW structure	28 mm
Thickness of Be coating	2 mm
FW surface area facing plasma (m^2)	0.85
Heat flux on the FW (MW/m^2)	0.5
Coolant fluid	Helium gas
Cooling channel dimension	$20mm * 20mm$
Coolant inlet pressure	80 bar (8 MPa)
Coolant inlet/out (^0C)	300/380

having four passes and each pass contains eight cooling channels. In circuit 1 the He starts from the bottom (poloidal) of the FW and flows from one pass to another pass (say pass one to pass two). This continues four times until the He reaches the top location (poloidal) of the last pass as shown in Fig.2(c). Similarly the flow in circuit 2 starts with the pass one and continues four times until it reaches the bottom location (poloidal) of the last pass in this circuit as shown in this same figure (Fig. 2.4). The flow of He is in opposite direction in two different cooling circuits. Different flow parameters and various cooling layouts have been examined to select the optimum thermalhydraulic parameters and tube layout for FW cooling. Figure shows the He exit temperature and mass flow required for two different cooling layouts (four passes and eight passes).

In the paper by Paritosh Chaudhuri, et al [15] provided detail design of FW thermal-hydraulics, thermo-structural analysis, and He flow distribution network. The first wall (FW) is one of the most important components of any fusion blanket design. India has developed two concepts of breeding blanket for the DEMO reactor: the first one is LeadLithium cooled Ceramic Breeder (LLCB), and the second one is Helium-Cooled Ceramic Breeder (HCCB) concept. Both the concept has the same kind of FW structure. Reduced Activation Ferritic Martensitic steel (RAFMS) used as the structural material and helium (He) gas is used to actively cool the FW structure. Cooling channels running in radialtoroidalradial direction in the RAFMS structure are designed to withstand the maximum He pressure of 8MPa. Heat transfer coefficients (HTC) obtained form the correlations revealed that required cooling could be achieved by artificially roughened surface towards the plasma-side wall of He cooling channel which helps to keep the RAFMS temperatures below the allowable limit. A 1D analytical and 2D thermalhydraulic simulation studies using ANSYS has been performed based on the heat load obtained from neutronics calculations to confirm the heat removal and structural integrity under various conditions including ITER transient events. The required helium flow through the cooling channels are evaluated and used to optimize the suitable header design.

E. Rajendra Kumar, et al[4] provided the design description, preliminary analysis, some of the related ancillary systems and Research and development activities for LLCB TBM.Presently the primary focus is on the design and analysis of the LLCB TBM to assess the performance of LLCB concept for DEMO relevance. The LLCB TBM will be tested from day 1 operation of ITER in one-half of a designated test port. The tests in ITER include the simultaneous function of all subsystems including the TBM as well as its ancillary system. The tritium produced in PbLi and ceramic breeder zones will be extracted by separate external ancillary systems.

2.3 Helium Cooling System

The first wall structure helium cooling circuit extracts the thermal power directly from the first wall, side plates, and top and bottoms plates of LLCB TBM. The cold helium gas is pre-heated to 300^0C through the electrical heater, and fed to the channels of the FW structure. After the helium cools the TBM and flows out from manifold of the TBM at 370^0C, the hot gas passes through the gas filter, which removes the possible particulate impurities that result in erosion and corrosion of components. After the filter, the helium flows into the helium/water heat exchanger where the extracted heat is transferred to the TCWS cooling water circuit. From there the cold helium flows into the circulator inlet for re-circulation. The schematic of the He flow is shown in figure 2.5.

It shows that the system consists of two helium loops, one of which, the primary heat transport loop is for cooling the FW and box structure using helium, while the secondary helium loop is for heat exchange with the liquid Pb-Li breeder and this secondary loop serves as the liquid breeder loop (Pb-Li - He loop). Both loops are connected to the secondary helium to water loop, which will be located in the ITER tokomak cooling water system (TCWS) for utilizing the water from ITER cooling system. The secondary heat removal system has been designed to supply cold water with the temperature of 35^0C and accept hot water with the temperature of 75^0C. The major components and units of the helium cooling system loop are described as follows: heat exchanger to the TCWS cooling water, pressure control unit, helium purification unit, main circulator, storage tank, electrical heater, valves, filter and sensors, etc.

In the paper by H. Neuberger , et al[7] the primary loop for the Helium Cooled Peb-

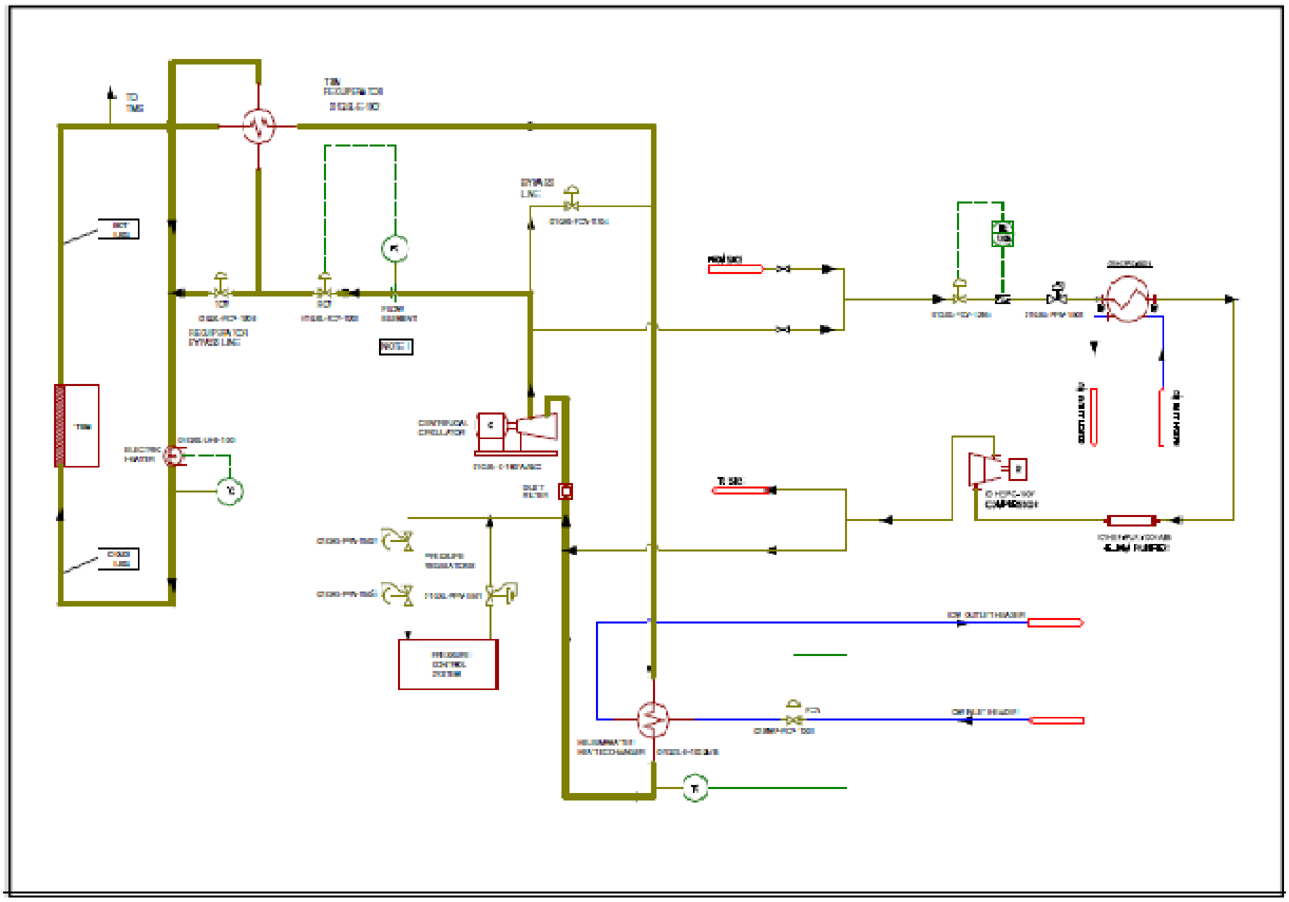

Figure 2.5: Schematic of primary helium cooling system[3] .

ble Bed Test Blanket Module (HCPB-TBM) was investigated with regard to layout definition, selection and dimensioning of components including piping and mechanical integration of the circuit into the different sections of ITER. The accommodation of the main components of the helium loop into the Torus Coolant Water System (TCWS) vault turned out as the most challenging point. Additionally operational states have been defined and the dynamic circuit behaviour has been investigated during transitions between operational states and accident situations with the RELAP5-code.

In the paper by V.A. Chuyanov, et al[18] an initial assessment of the TBM and ITER interface requirements is presented. Four areas of interface were identified. The first area is the port cell interface area, including components like the port plug frame, backside shield, dummy TBM and corresponding tools needed for the TBM maintenance and replacement. The second area is the hot cell, including the needed additional hardware for the service of TBMs, additional remote handling tools, and additional building space needed for the maintenance of the TBM ancillary equipment and the corresponding testing utilities and tools. The third area is the tokamak cooling water system (TCWS) with the need to accommodate six TBM heat transfer systems, each with a footprint of $57m^2$. The fourth area of interface is the tritium plant. In all these areas modifications in the current ITER design are needed to accommodate the TBM testing. These changes must be incorporated in the new ITER baseline design which is now under preparation. The latest experiments on JET revealed unexpectedly high sensitivity of plasmas in H-mode of confinement to ripples of the magnetic field. The ferromagnetic test modules can create additional ripples. This new issue of interface between ITER and TBMs is also addressed.

In the paper by Vilas Chaudhari, et al[19] discuss about the transient analysis results of the safety assessment. The accidental event analyzed starts with a Postulated Initiating Event (PIE) of ex-vessel loss of first wall helium coolant due to guillotine rupture of coolant pipe with simultaneous assumed failure of plasma shutdown system. Three different variants of the sequences analyzed include simultaneous additional failures of TBM and ITER first wall, failure of TBM box resulting in to spilling of lead lithium liquid metal in to vacuum vessel and reactor trip on Loss of Coolant Accident (LOCA) signal from TBM system. The analysis address specific reactor safety concerns, such as pressurization of confinement buildings, vacuum vessel pressurization, release of activated products and tritium during these accidental events and hydrogen production from chemical reactions between leadlithium liquid metal and beryllium with water. An in-house customized computer code is developed and through these deterministic safety analyses the prescribed safety limits are shown to be well within limits for Indian LLCB-TBM design and it also meets overall safety goal for ITER.

In the paper by B.E. Ghidersa, et al[1] the thermal-hydrodynamic model used to simulate the behavior of the Helium Loop Karlsruhe (HELOKA) facility and description of the mechanism used to control various loop parameters is done. An accurate control of the temperature during the warm-up and flat top phases is achieved solely by controlling the heater power. During testing campaign, when the helium flow has to be cooled, the power of the heater is set to zero and the temperature is controlled using a control valve installed in the by-pass of the heater. The adopted solution reduces the harmonic distortions when operating at reduced power while keeping the investment cost low.

In the paper by Mu-Young Ahn, et al[13] the accident analyses for several loss of coolant accident (LOCA) cases were performed in order to assess safety aspects of the TBM design using RELAP5. Since the TBM forms a loop with helium cooling system (HCS) which is one of ancillary systems required for removing heat deposited in the TBM by neutron wall loading and surface heat flux from plasma, it is necessary to model the complete loop for accident analysis. In this study, the helium passage including the TBM and HCS was nodalized for each accident scenario. The TBM and HCS components were modeled as the associated heat structures provided by RELAP5 to include heat transfer across solid boundaries. Based on computational results it was found that current design of the TBM is robust from the safety point of view.

In the paper by Haibo LIU, Kaiming FENG[12] an introduction of the transient accidents analysis for Chinese Helium Cooled Solid Breeder Test Blanket Module (CN-HCSB TBM) and its cooling system using RELAP5 code is provided. The submodules bypass is used to control the first wall (FW) coolant temperature increase.

The In-Vessel Loss of Coolant Accident (LOCA) results indicate that the induced over-pressurization of the vacuum vessel is within the ITER design limit pressure 200kPa. The Ex-Vessel LOCA will induce the melting of FW beryllium armor after 86s of this LOCA beginning. The In-Box LOCA will induce the pressure increase of the purge gas to about 7.3MPa within one second. Installing the fast isolation valve for tritium extraction system (TES) and pressure relief valve to TBM box are very important. The maximum temperature of FW beryllium armor induced by Loss of Flow Accident reaches 764^0c and the final pressure of vacuum vessel is 28kPa. The Loss of Heat Sink accident induces the FW beryllium armor maximum temperature of 800^0c, and then the armor temperature decreases. The coolant water of heat exchanger (HX) secondary side begins to evaporate after 415s accident beginning.

Literature Survey Table is given below:

The summary of the literature reviewed is presented in Table III.

Table III: Literature Survey Summary

Author/Publisher	Title	Summary
Document of Institute for Plasma Research	Design Description document for Indian Lead-Lithium Cooled Ceramic Breeder (LLCB) Blanket	Over all description of of integrated structure and Details of test blanket module.
Document of Institute for Plasma Research	Accidental Safety Analysis Analysis Problem Definition Document for LLCB TBM	Postulated initiating events in In-vessel and in Ex-vessel.
Document of Institute for Plasma Research	Safety Analysis Procedure And TBM System Simulation	Accidents occurring in test blanket module HCS loops.
Information Systems Laboratories, Rockville, Idaho Client:-Division of Systems Research office of Nuclear Regulatory Research U. S. Nuclear Regulatory Commission Washington	RELAP5/MOD3.3 CODE MANUAL VOLUME USERS GUIDELINES	RELAP5 modeling details for various , components like Pipe Heat structure etc.
Information Systems Laboratories ,Rockville, Idaho Client:-Division of Systems Research office of Nuclear Regulatory Research U. S. Nuclear Regulatory Commission Washington, DC	Input deck manual RELAP5	Input codes for transient analysis, Input code for each and every structure, Major and minor input codes
H.Neuberger,X.Jin R.Meyder*Fusion Engineering design* 82(2007)2288-2293	Helium loop for the HCPB test Blanket module	Cooling loop design, operational status
Haibo LIU, Kaiming FENG	Transient safety study of Chinese helium	Steady state analysis RELAP5 nodalization

Vilas Chaudhari, Ram Kumar Singh, Paritosh Chaudhuri, Brijesh Yadav, Chandan Danani, E. Rajendra Kumar, *Fusion Engineering and Design* 87 (2012) 747752.	Analysis of the reference accidental sequence for safety assessment of LLCB TBM system	Transient analysis of loss of coolant accident (LOCA) in test blanket system (TBM).
Vilas Chaudhari, Chandan Danani, Paritosh Chaudhuri, R. Srinivasan, E. Rajendra Kumar, S.P. Deshpande,*Fusion Engineering Design* 85 (2010) 19661969.	Current status of design and engineering analysis of Indian LLCB TBM	LLCB TBM design; Optimize the flow & parameter. Temperature variation in FW in Ceramic breeder.
E. Rajendra Kumara, T. Jayakumar, A.K. Suri, *Fusion Engineering and Design* 87 (2012) 461465	Overview of TBM R&D activities in India	Liquid breeder flow type and Effect on pressure drop
V. Chaudhari,E. Rajendra Kumar, C. Danani, I.Sandeep, Ch.Chakrapani,N. Ravi Pragash, C. Rotti, P.M. Raole,, J. Alphonsa, S.P. Deshpande *Fusion Engineering and Design* 83 (2008) 11691172	Preliminary design of Indian Test Blanket Module for ITER	Test blanket concepts for testing in ITER. Tritium production rate and extraction.
V.A Chuyanov,S.C Kin, L.M Giancarli *Fusion Engineering design*(2008)817-823	The integration of TBM systems in ITER	Port cell interface Tokamak cooling water system interface.
B.E Ghidersa,V.marchese, M.Lonescu,T.H. Ihl *Fusion engineering design*83(2008)1792-1796	HELOKA facility; Thermal-hydrodynamic model and control	TBM hydrodynamic model, temperature control
Mu-Young Ahn,Seungyon cho, Duck young ku *fusion engineering design*84(2009)380-384	LOCA analysis for Korean helium cooled solid breeder	Accident analysis HCSB TBM , In-vessel LOCA, Ex-vessel LOCA
Paritosh Chaudhuri, Chandan danani, Vilas Chaudhari, *Fusion engineering design*84(2009)573-577	Thermal-hydraulic and thermal-structural Analysis of FW for Indian DEMO	Schematic of First wall, He flow distribution network in FW structure blanket module

Chapter 3

Helium Cooling System Description

3.1 Primary Helium Cooling System

The PHCS is meant to remove the incident heat load on the first wall according to the modes of operations of ITER. Hence this system is designed to remove 0.3 MW of the total heat load.

This hot helium after cooling the TBM FW passes through recuperator which helps hot helium to cool down by exchanging heat with cold helium from circulator discharge. The recuperator is designed such that in normal operating condition heat addition through electric heater is minimum or nil.

This so far cooled helium rejects heat in the helium-water heat exchanger. The water heat exchanger is designed such that total heat added to the system will be rejected in water along with any system cooling down requirement. This equipment is having redundancy to ensure heat removal from loop. Dust filter upstream to the circulator suction refrains and retains fabrication particles spreading in the system. Dust filter is such designed that any erosion, corrosion or foreign particles is retained in this with minimum pressure drop. The cold helium is circulated again in the system with the circulator. The circulator is chosen such that it works as a flow circulation device taking a high pressure suction and discharge to overcome the system pressure drop.

It is a medium flow and medium pressure differential device with self lubrication and hermetically sealed for helium leakage. This equipment is having redundancy for ensuring flow in the loop. An electric heater, non-intrusive type, is used to cope up with the insufficient recuperation and during warming up. The pipe material itself is heated up by flowing current through it and helium flowing inside gets heated up. Transformer and Rectifier units are used to supply the desired current to the electric heater unit.[2]

The water flow rate required to remove the heat from hot helium in the helium-water heat exchanger is modulated on the basis of maintaining helium coolant temperature of $50-70^0C$ at compressor suction. The same is achieved by providing control valve in the cooling water line. The pressure in the system is maintained at 8 MPa with the help of Pressure control system. A single point connection at the suction of the main circulator, downstream to the inline dust filter is used for the system to respond to any fluctuations of the system pressure by addition and withdrawal of the inventory as and when required by the main coolant loop.

The pressure control system operates with combination of two Storage Tanks, a Source Tank and a Buffer Tank. The pressure control system is designed to store the entire inventory required in a campaign. The initial storage pressure in the tanks at the time of system charging is above 17 MPa. The initial charging is done via a compressor. The compressor is used to bring the main loop, Source and Buffer Tank pressure at the desired values. The Buffer Tank acts as recipient of all discharges and maintained at lower pressure, Source Tank supplies inventory to main loop and is maintained at high pressure. Storage Tank pressure is in between these pressure values during the regular operations of the PCS. Pressure regulators are provided in the upstream and the downstream of the loop for regulating maximum and minimum pressure respectively while operating in normal operation mode. The regulators remain inoperative within a dead band, set in a particular operating pressure. If loop pressure increases beyond this dead band upstream pressure regulator opens and discharges some inventory to Buffer Tank to reduce the pressure and bring it back to within the dead band. Similarly if the loop pressure decreases below the dead band, some amount of inventory is added through downstream pressure regulator from Source Tank to bring back the loop pressure within the dead band. Pressure relief devices are provided for reducing excess pressure that might build up due to sudden power surge or temperature increase. Loop pressure surge invokes opening the relief valve if upstream pressure regulator capacity is not sufficient to relieve the pressure. Source Tank and Storage Tank relief devices are provided to protect the equipment. Discharges from all relief valves are collected in Buffer Tank initially to retain the inventory within the system itself. In case the Buffer Tank pressure increases beyond design value inventory is relieved to ITER disposal through relief valve. A coolant purification system is provided to purify the system of any impurities generated during its operation. Only 0.1% of total 1.6 kg/sec (for PHCS) and 0.2% for SHCS helium flow is taken out for purification and fed back into the loop after purification. The main helium gas circulation system operates at 8.0 MPa and in the temperature range of $300-500^0C$. The purification system operates at low pressure. So from circulator discharge, helium is depressurized to 0.3 MPa and cooled from 80^0C to 40^0C in He-Water cooler. This cooled stream then passes through to helium purifier. The purified helium gas is then compressed and sent back to main stream.

The helium purifier contains inorganic substrate with high surface area, very reactive; bonds with impurities remain stable under normal conditions. No impurity is released during the process. To check the impurity level before and after the purifier, Gas Chromatography is provided.

Table I: Temperature distribution across the various components[2]

Mass Flow Rate, kg/s	Temperature ^0C	Temperature ^0C	Temperature ^0C	Temperature ^0C	Temperature ^0C
Main loop flow	Bypass flow	TBM FW inlet/outlet	TBM Recuperator hot inlet/outlet -cold inlet/outlet	He-Water HX inlet/outlet	Circulator suction/ discharge
1.8	0.00	300/332	332/117-80/295	117/60	60/80
1.6	0.20	300/336	336/116-80/300	112/60	60/80
1.0	0.80	300/300	300/107-80/273	95/60	60/80

3.1.1 Helium-Helium Recuperator

The cold helium from compressor discharge is recuperated with hot helium from the first wall / LMHX. This Recuperator is hairpin type shell and tube heat exchanger.

3.1.2 Dust Filter

Dust particles such as erosion particles, fabrication particles, and corrosion particles are expected at high velocities and high pressuretemperature conditions. These particles are of micron sizes. Dust filter is fitted just before the circulator suction in the cold leg of the system having due to less stringent design requirement and removal of the particles just before the suction of the circulator ensures clean stream enters into the moving parts. A cartridge filter containing sintered stainless steel fibers is sufficient for the said purpose.

3.1.3 Circulator

This is a centrifugal compressor which is the driving / recirculation equipment for the closed loop. The cooled helium is compressed to overcome the pressure drop in the cooling system. The suction temperature to the compressor is restricted to $50 - 70^0C$ for keeping the compressor power requirement low and less stringent design condition of circulator. For PHCS 3*50% capacity circulators are used with two working and one standby. For SHCS 2*100% capacity circulators are used with one working and one standby. These are connected to 6.6 kV line and each having a rating of 225 kW.[2]

3.1.4 Helium-Water Heat Exchanger

Helium-Water Heat Exchanger [10] or main heat exchanger is the ultimate heat rejection point in the system. This is a U-tube shell and tube type heat exchanger. This is an interface with ITER cooling system which supplies water at 28^0C for the purpose and maximum outlet temperature of 75^0C. The pressure of the water loop is 1 to 1.1 MPa. Helium flows through tube side and water in shell side. This equipment is having 100% redundancy.

3.1.5 Electric Heater

Electric heater is used to supplement the heat due to insufficient recuperation and maintaining the temperature in the loop under different modes of operation. It is proposed to use heater for fine temperature control at TBM inlet. It is not desirable to use Heater for Bulk Heating and that is done by Recuperator. The pipe material itself is heated up by flowing current through it and helium flowing inside gets heated up. Transformer and Rectifier units are used to supply the desired current to the electric heater unit and heater power is modulated as per the requirement[16].

3.1.6 Associated Piping and Valves

All the equipment interconnected by piping and valves are required for different controlling purpose and isolation. Helium being highly diffusive, as far possible flange joints will be avoided, welded joints are used. Since the piping is having high temperature fluid, proper bends in piping are provided for taking care of thermal expansion. Insulation is provided for conservation of heat energy and personnel protection. Pipe size will be chosen that velocity of gas will be maintained in the range of 45-50 m/sec to restrict the pressure drop in the loop and at the same time minimizing inventory and vibration related problem. In this system mainly three kinds of valves are envisaged (a) Pressure control, (b) Flow control and (c) Isolation valve. For flow and pressure control mostly butterfly valves and for isolation purpose mainly gate / ball valves will be used. Valve actuators will be mostly pneumatic, solenoid and manual type as and where required.

3.1.7 Pressure Control System

In main cooling system for proper control of process parameters, mainly three controlling parameters are identified i.e. Pressure, Temperature and Flow at the TBM inlet. Temperature and Flow controls are done by using the valve operations within the main cooling system itself; but for pressure control another subsystem is introduced.

Pressure Control System (PCS) is envisaged to maintain the pressure in the system at 8 MPa as a normal operating pressure. It is also meant for the overpressure protection of the system. It is having helium charging and discharging subsystem. PCS is designed to store the entire inventory of Helium which is required for system operation. The system is capable of accumulating overpressure discharge from the system as well as supplies the helium at high pressure in case pressure falls below the operating pressure range. The system is also utilized for evacuation.

Table II: Primary HCS flow conditions[2]

Flow Condition	Mass flow rate, kg/sec	Operating Pressure, MPa
Maximum Flow	1.8	8.0
Normal Operating Flow	1.6	8.0
Minimum Flow	1.0	8.0
Baking operation flow	0.18	1.0

3.1.8 Storage Tank

The Storage Tank is basically a gas bank of cylinders. During normal operations, this tank serves for inventory storage of HCS. This tank will be charged from the helium charging system of the ITER at pressure of 175 MPa with the help of the helium compressor of the PCS. It serves as the intermediate storage during loop operation. To reduce the storage volume helium is stored at high pressure. There are two such bottles in PHCS and one in SHCS.

3.1.9 Buffer Tank

This tank is receives the discharge from the loop during normal operation. This tank will be kept at low pressure than that of the system for any instant. Loop pressure exceeding the dead band range upstream pressure regulator operates and discharges helium to the Buffer Tank. Apart from this, this tank also receives relief discharge for the Source and Storage Tank, which might pressurize during any incident of temperature rise like fire. Since any radioactive discharge should be confined within as far as possible, the initial discharges are retained in the Buffer Tank and any further increase in pressure to the Buffer Tank is relieved to containment through relief valve. If the pressure rises above desired value, is again brought back by emptying helium via compressor to Storage Tank. There is one tank in PHCS and one in SHCS.

3.1.10 Source Tank

This tank is kept at higher pressure than that of the system at any instant. This tank discharges into the system as pressure in the system falls below the dead band of the operating pressure of the system. Low pressure is sensed by the downstream pressure regulator and helium is charged into the system from the Source Tank. The pressure of Source Tank if falls below the desired value, is again raised by filling helium via compressor from Storage Tank. There is one bottle in PHCS and one in SHCS.

3.1.11 Compressor

The compressor is required for the various operations of the PCS such as initial charging of the PCS and also the total HCS, filling of Buffer and Source Tank as and when required at desired pressure. The compressor may also be required to perform various tests in the system in isolation and with respect to other subsystem as well. This also required for storing the helium of the entire loop into the Storage Tank during maintenance activity. This is a three stage reciprocating compressor cooled by water. Compressor takes suction at 0.1 MPa and having discharge pressure up to 20 MPa.

3.1.12 Vacuum Pumps

Need of the vacuum pump is envisaged in the view for the evacuation of the system during maintenance and at the time of preparing the system for operation. A combination of booster pump and a mechanical vacuum pump is used to achieve high vacuum in the system.

Table III: Operating parameters of PHCS[2]

Flow Condition	Mass flow rate, kg/sec	Operating Pressure, MPa	Operating Temperature, ^0C	Design Pressure, MPa	Design Temperature, ^0C
Design Flow	2.0	8.0	300-500	10.0	RT-525
Maximum Flow	1.8	8.0	300-500	10.0	RT-525
Normal Operating Flow	1.6	8.0	300-500	10.0	RT-525
Minimum Flow	1.0	8.0	300-500	10.0	RT-525
Baking operation flow	0.18	1.0	300	10.0	RT-525

3.1.13 Coolant Purification System (CPS)

The Coolant Purification System is the important subsystem of the helium system. The CPS removes contaminants like CO, CO_2, H_2O, Non Methane Hydrocarbons, O_2 and H_2 with maximum concentration of 10 ppm each. The outlet impurity level is less than 1 ppb. Only a small fraction of coolant flow, about 0.1% of PHCS stream and 0.2 %of SHCS stream, is fed to the CPS. Considering the mass flow rate of the helium to be 1.8 Kg/s in PHCS and 0.9 kg/s in SHCS, the stream to the CPS amounts to be 1.8 gm/s. Diverting such a low mass fraction doesnt affect the course of main operation. The main helium gas circulation system operates at 80 bar and in the temperature range of 300-500^0C. The purification system operates at low pressure. So from circulator discharge, helium is depressurized to 3 bar and cooled from 80^0C to 40^0C in He-Water cooler. This cooled stream then goes to helium purifier. The purified helium gas is then compressed and sent back to main stream.The schematic of entire cooling system of TBM is shown in figure locating port cell , TCWS vault and other systems{2.

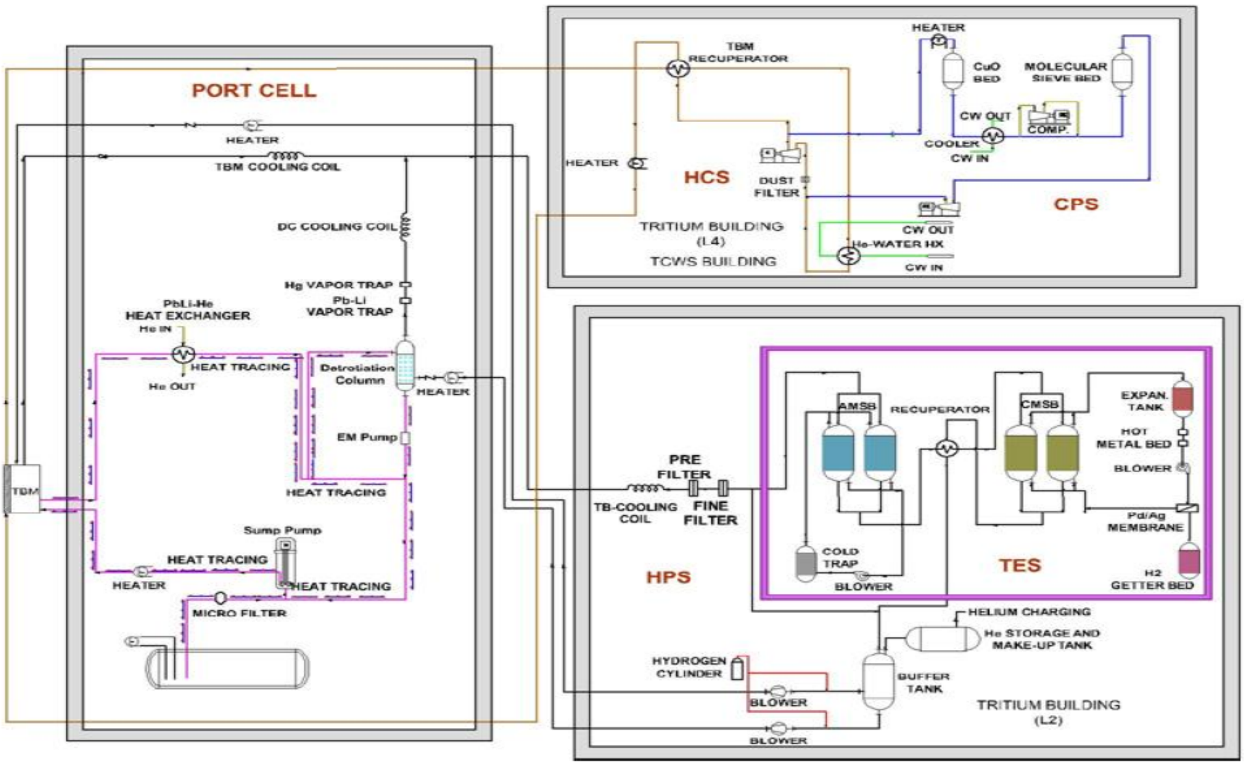

Figure 3.1: Schematic of cooling system of TBM[3] .

Chapter 4

RELAP5 Helium Cooling System Loop Model

4.1 Description of Thermal Hydraulic Analysis

The hydrodynamic model is a one-dimensional transient non-homogenous, non-equilibrium model for flow of helium. 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 users choice. So-called heat structures provided in RELAP5 permit calculation of heat transferred across solid boundaries of hydrodynamic components. Heat structures are assumed to be represented by one-dimensional heat conduction in rectangular, cylindrical or spherical geometry. Temperature dependent thermal conductivities and volumetric heat capacities are provided in tabular or functional form either from built-in or user-supplied data.
The helium cooling system has been modelled by RELAP5 components. The model includes primary and secondary side pipework, heat exchanger, helium circulator valves and electrical heater. The flow diagram of modelling in RELAP5 is given figure 4.1. 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

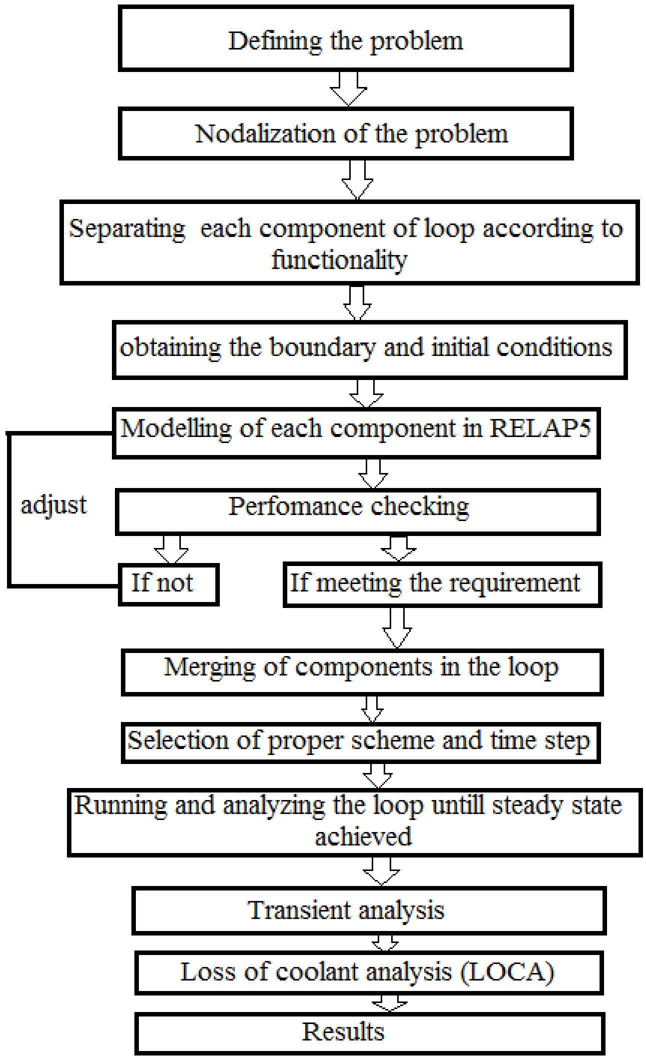

Figure 4.1: Flow diagram of modelling in RELAP5 .

junctions. Velocities are located at the junctions and are associated with mass and energy flow between control volumes an example is given below to show the modelling of components in RELAP5 is given figure 4.2.

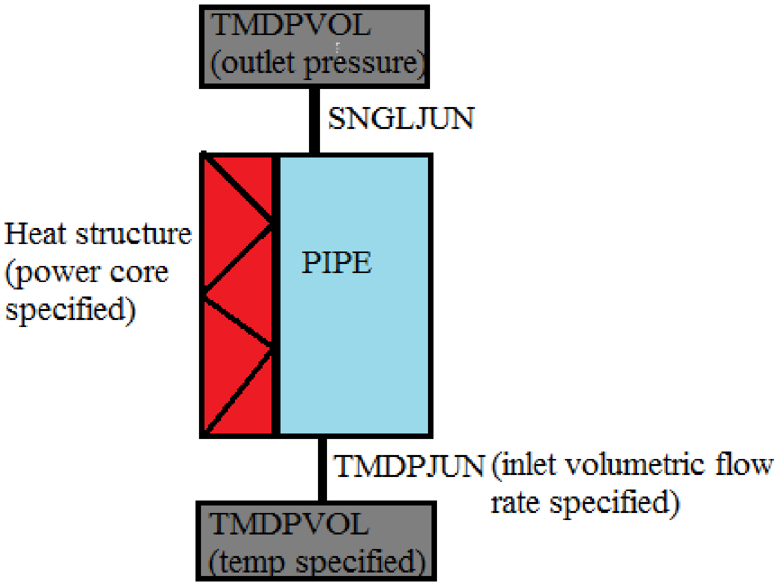

Figure 4.2: Example of separate effect core model[10].

4.2 Nodalization of Primary Helium Cooling System (PHCS)

Based on the flow path in the TBM and the cooling system, the nodalization of TBM and HCS is illustrated in Fig. 4.3.

4.2.1 TBM Hydrodynamic MODEL

In RELAP5 entire loop can not be simulated as it is. Its a lumped parameter approach as there are numerous channels, branches, sub-channels, bends etc. Hence for RELAP5 analysis of the components must be strongly simplified, and groups of channels or or sub channels have to be lumped together to give manageable numbers of components. TBM is divided into two sections i.e two branches and first wall.

4.2.2 First Wall

The FW assembly is designed to withstand the heat flux from the plasma and neutronics heat generation on the FW structure to maintain its temperature below the allowable limits.The U-shaped FW structure is composed of a 28 mm thick RAFMS

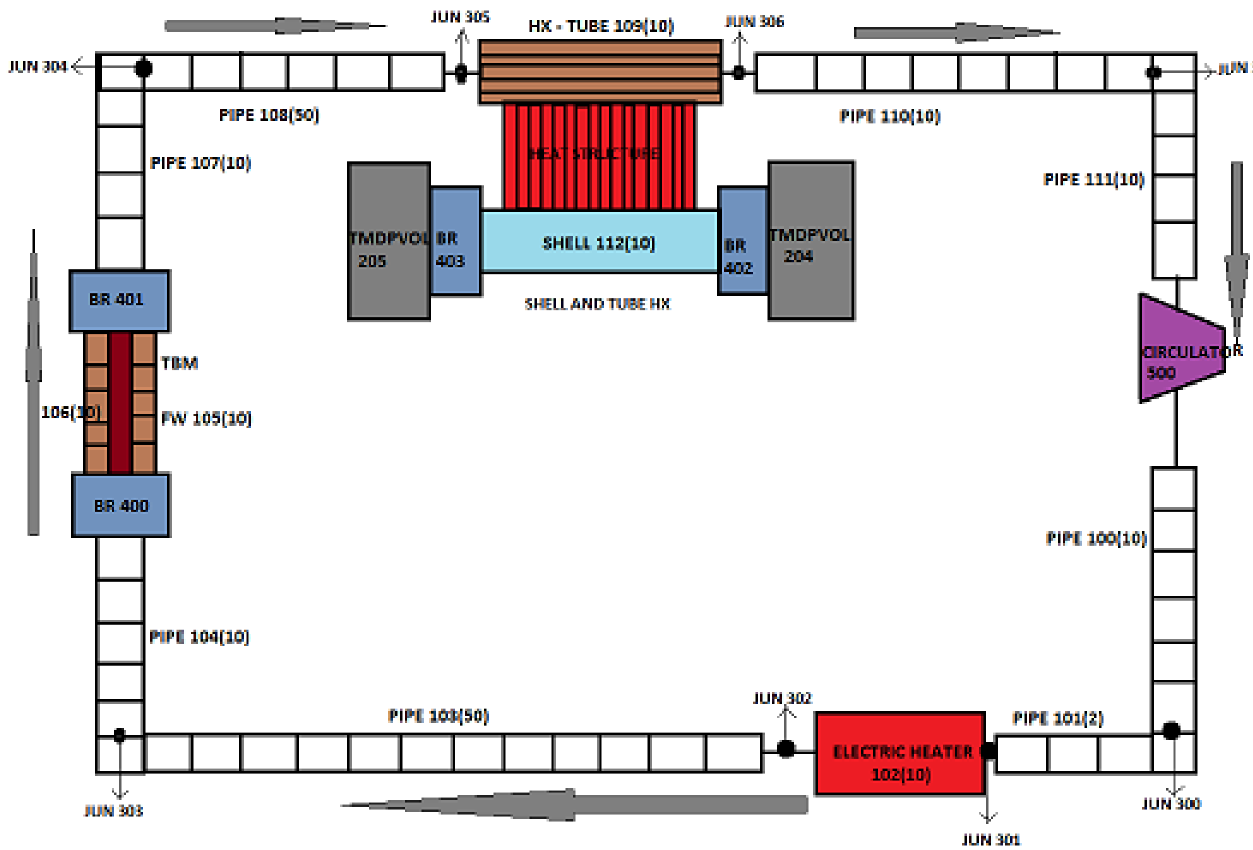

Figure 4.3: RELAP5 nodalization of TBM cooling system

structure, having internal cooling channels of 20 mm*20 mm cross section, and a Be layer of 2 mm coated on the plasma side of the FW. The coolant channels are designed to allow multiple passes of helium coolant across the FW in order to maximize the heat removal. The number of helium passes has been optimized such that the maximum temperature in the RAFMS remains below the design limit of 500^0C. The FW structure is having 64 helium coolant channels, which are divided into two circuits. Each circuit is having four passes and each pass contains eight cooling channels. In circuit 1 the He starts from the bottom (poloidal) of the FW and flows from one pass to another pass (say pass one to pass two). In the RELAP5 model FW is divided in to two pipe components , one large one having 14 channels and 2 channels separate having component no 105 divided in 10 volumes. Where the 2 channels is to fail as a double-ended break. Therefore these two components have an extra cross flow junction connected to valves which are normally closed but will be opened for special transient cases. The flow in FW is split in two branches (component 400 and 401) of almost equal size, creating counter-flow in adjacent channels.

4.2.3 Piping Hydrodynamic Model

The architecture of the pipe work of the helium cooling system is determined by the space allocation given by the ITER team. All together the piping has a total length of about 199 m (92 m for the cold leg and 93 m for the hot leg, and 14 m between HCS components). An inner diameter have been chosen for all pipes, except for some short sections between components which have bigger diameter. Pipes have generally been modelled as RELAP5 pipe components consisting of several volumes junctions between volumes have been placed at all pipe bends. In RELAP5 all pipe bends cannot be modelled because even a micro gap in closing the loop will create an obstacle in running the program so instead of considering all bends in loop the junction loss coefficient is given to compensate the effect of all 90 degree bends. The table showing the pipe naming is given in Table I.

Whereas the junction loss coefficient and friction factor f_T for various pipes is given

Table I: Table for pipe dimensions[2]

Pipe no	ID of pipe mm	pipe length m	No of bends	no of valves
1001ESA1PP	73.66	2.054	4	1
1003ESA1PP	97.18	6.508	7	1
1005ESA1PP	49.25	2.374	2	1
10006ESA1PP	97.18	8.224	6	0
10010ESA1PP	97.18	76.50	21	1
10012ESA1PP	97.18	3.685	7	1
10013ESA1PP	97.18	1.475	3	1
10014ESA1PP	97.18	2.981	5	1
10015ESA1PP	97.18	1.07	2	1
10016ESA1PP	97.18	7.052	12	0
10018ESA1PP	97.18	4.041	6	0
10127EEA1	97.18	50.18	15	0
10126EEA1	97.18	30.19	10	0

in table II and III respectively.

Table II: Standard junction loss coefficient for 90^0 bends [8]

r/d	K	r/d	K
1	20 f_T	8	24 f_T
1.5	14 f_T	10	30 f_T
2	12 f_T	12	34 f_T
3	12 f_T	14	38 f_T
4	14 f_T	16	42 f_T
6	17 f_T	20	50 f_T

Table III: pipe friction data for clean commercial SS316L [8]

Nominal size (inch)	Friction factor (f_T)
1/2	0.027
3/4	0.025
1	0.023
5/4	0.022
3/2	0.021
2	0.019
5/2 , 3	0.018
4	0.017
5	0.016
6	0.015
8-10	0.014
12-16	0.013
18-24	0.012

4.3 HCS Components Hydraulic Modelling

Components of the Helium cooling system include heat exchanger, circulater and electric heater. For circulator and valves special 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.

4.3.1 Shell and Tube Heat Exchanger

Shell and tube heat exchanger is modelled as a counterflow heat exchanger employing straight tubes the helium flows inside of the tube whereas water flows in the shell. Helium flow path is represented by component (101) and shell side component No. is (100). Tube side and shell side are connected via two-sided RELAP5 heat structure.

4.3.2 Tube Side

- Tube side- No. of tubes = 366.
- Total heated tube length = 366*3.0 = 1098 m.
- Heated diameter for inside heat transfer coefficient is taken as I.D of tube = 0.00702 m.
- Hydraulic diameter for tube side pressure drop is taken as I.D of tube = 0.00702 m.
- Heated diameter for outside side heat transfer coefficient is calculated which is (De) = 0.011388 m.
- Cross sectional area of single tube = $(\pi/4) * (0.00702)^2 = 0.0000386m^2$.
- Now all 366 tubes flow area is assumed to be lumped together in a single pipe component No 100.
- Total flow area of component 100 =$0.01415m^2$.
- In the preliminary design of tube side the tubes are connected to two time dependent volume(TMDPVOL) on either side of tube and simulated till the desired temperature is achieved thus it is inserted in the main loop .

- A source and sink is connected to tube side for continuous flow of helium inlet to 80 bar and 610 K and outlet to 78.97 bar and 333 K.

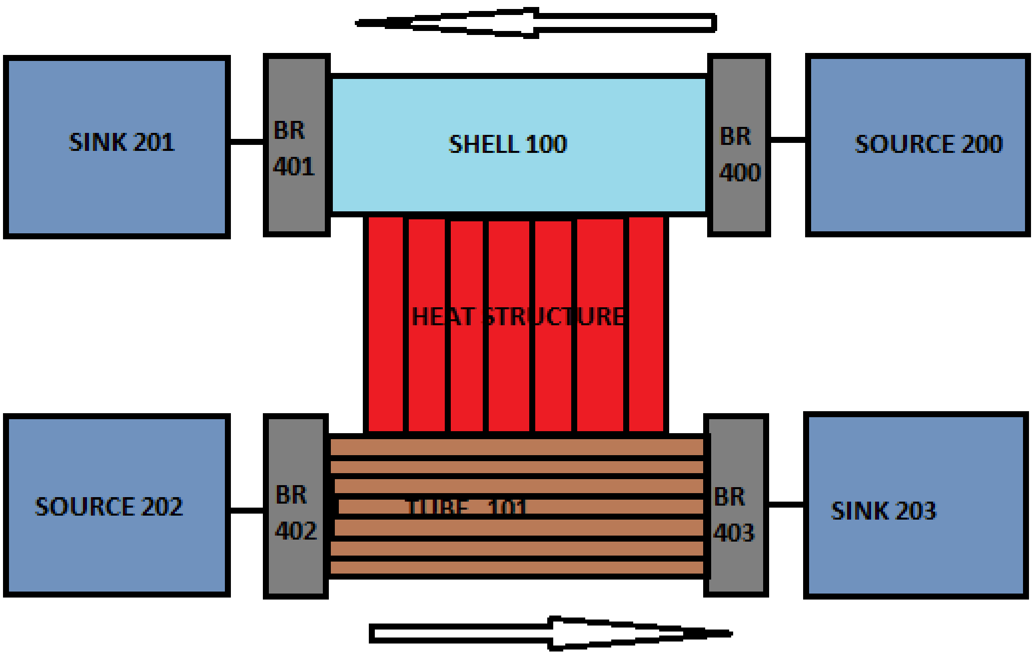

Figure 4.4: RELAP5 nodalization of shell and tube HX

4.3.3 Shell Side

- In the preliminary design of shell side the tubes are connected to two time dependent volume(TMDPVOL) on either side of the shell and simulated till the desired temperature is achieved thus it is inserted in the main loop .

- A source and sink is connected to tube side for continuous flow of water inlet to 10 bar and 308 K and outlet to 9.789 bar and 604 K.

- Heated diameter for inside heat transfer coefficient is taken as 0.28 m.

- Shell Hydraulic diameter (De) = 0.011388 m.

4.3.4 Electric Heater

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 is positioned after circulator. The heater is modelled as a pipe component (102) in to the main loop having 10 volumes and length , energy loss coefficient, wall roughness, hydraulic diameter are specified. Nodalization for electric heater is shown in figure 4.5.

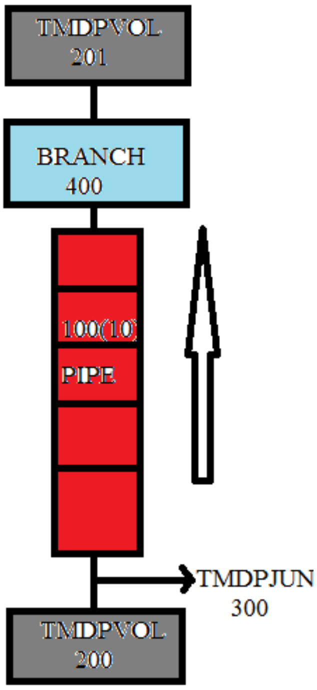

Figure 4.5: Nodalization diagram for heater

4.3.5 Circulator

The helium circulator is identified by a RELAP5 pump component(500). The hydrodynamic model consists of one volume and two associated junctions. In RELAP5 model in-built circulator (Bingham) is used.

4.3.6 Additional Components for Transient Analysis

As a postulated accident a break inside the TBM may occur. This would allow the helium gas leak into the various chambers like TCWS and port cell area. The result would be pressurisation of of the blanket box and of the vacuum vessel. For transient analysis a single volume is attached and a valve is attached which will be tripped according to the requirement. the additional component needed to simulate such process are shown in below figure

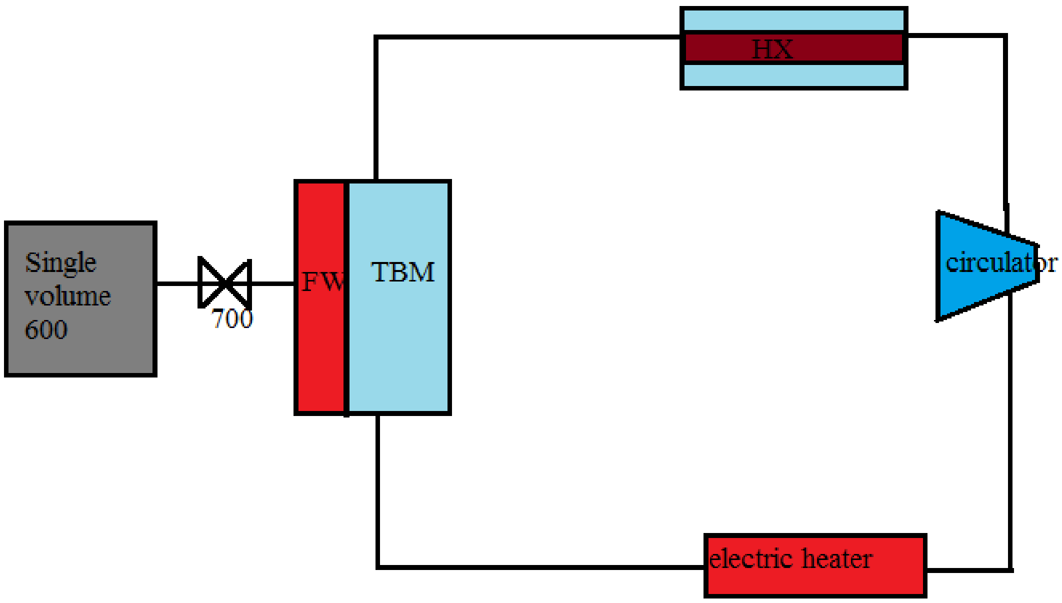

Figure 4.6: RELAP5 model for loss of coolant analysis

4.4 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. The modelling capabilities of RELAP5 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 cylindrical heat structures.

4.4.1 First Wall Heat Structure

The structure of the blanket box, of which the plasma facing part constitutes the first wall is modelled by cylindrical heat structure. The FW is divided in two volumes one is 14 channels and other is 2 channels and heat structure is provided to both. For 14 channel power given is 268.842 kW. The heater is divided into 10 parts which is connected to flow , so power of each heat structure is 268.842/10 ie equal to 26.8842 kW. Where as 2 channels are supplied with 38.46 kW. The heater is divided into 10 parts, which is connected to flow , so power of each heat structure is 38.406/10 ie is equal to 3.846 kW.

4.4.2 Heat Exchanger Heat structure

The structure of heat exchanger consist of 366 No. of tubes which are lumped together as one pipe . Cold fluid is flowing on shell side which get heat from hot fluid (tube side). Total resistance of heat transfer comprises of convective resistance due to flow of water, conduction resistance offer by tubes of Incoloy steel and convective resistance of helium.

4.4.3 Electric Heater Heat structure

The structure of electric heater in RELAP5 is component (102). Mass flow rate of fluid entering electric heater is 1.6 kg/sec. Electric heater is provided with a power of 1826.880 kW. The heater is divided into 10 parts which is connected to flow. power of each heat structure is 1826.880/10 ie equal to 182.880 kW.

4.5 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 . besides this, the code needs the thermal conductivity and the volumetric heat capacity and density. these quantities need to be entered as function of temperature , either in forms of table or as equations below table is given showing heat structure material overview.

Table IV: Heat structure material overview[16]

Material name	Application
AISI 316L	Piping and components
INCOLOY 800	Heat exchanger tubes
MANET(EUROFER)	TBM structure
RAFMS	FIRST WALL

Chapter 5

Results

The RELAP5 model of Primary Helium cooling system was run in steady state for 250 sec. After 250 sec LOCA happens and the transient scenarios of loop are given below.

5.1 Transient-State Analysis Results

Vacuum vessel modelled as Single volume component No. 600 and a trip valve component No. 700 is attached to the main loop for LOCA analysis gives the various graphs of flow parameters while running in transient state.
In fig 5.1 when LOCA happens after 250 sec because of double-ended pipe break of the TBM FW helium cooling loop leads to sudden pressurization of vessel and after that pressure increases gradually and ultimately reaches to steady state.

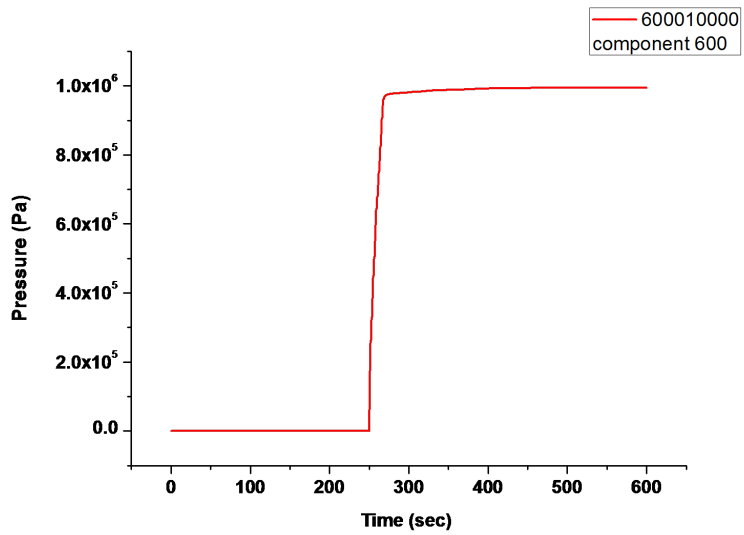

Figure 5.1: Pressure of Component 600 for LOCA

Fig 5.2 shows the mass flow rate of the junction that is attached to single volume 600. When LOCA happens at 250 sec the mass flow rate drastically increases and when the pressure of single volume attains the loop pressure mass flow rate comes to zero.

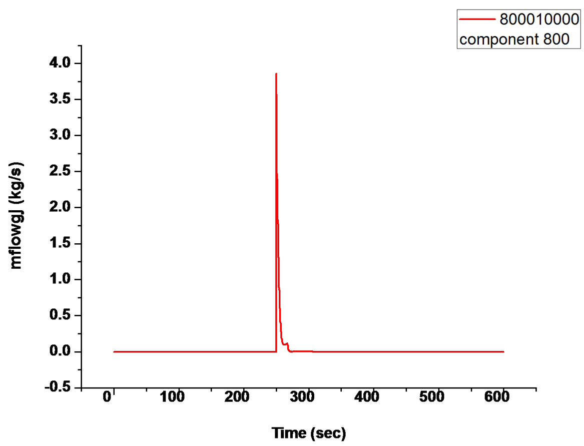

Figure 5.2: Mass flow rate of pipe attached to single volume

In fig 5.3 when LOCA happens at 250 sec due to double ended pipe break of FW there is a loss of helium coolant resulting in temperature evolution of TBM and vessel that causes sudden temperature rise of component 600 and finally achieves steady state.

In fig 5.4 when LOCA happens after 250 sec due to double ended rupture of FW

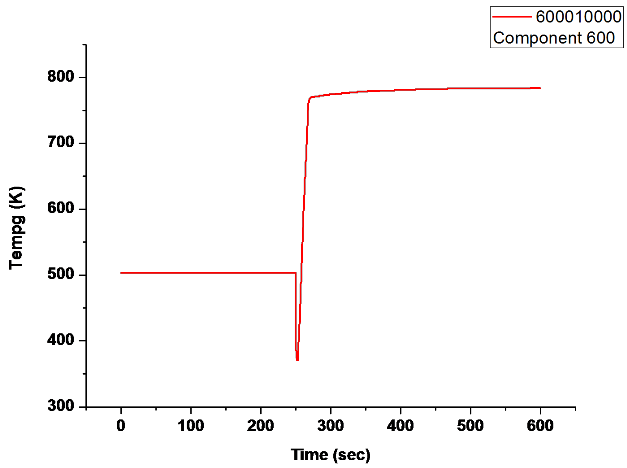

Figure 5.3: Temperature of component 600 for LOCA

there is a sudden pressure drop and then it achieves steady state.

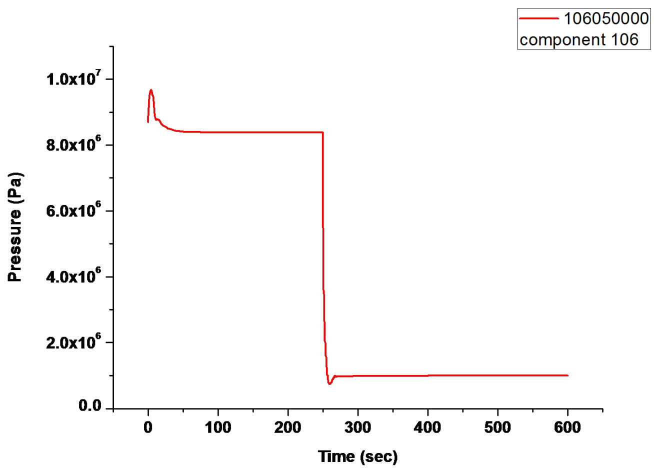

Figure 5.4: Pressure of FW 2 channel LOCA

Fig 5.5 shows the mass flow rate of FW 2 channel during accident.

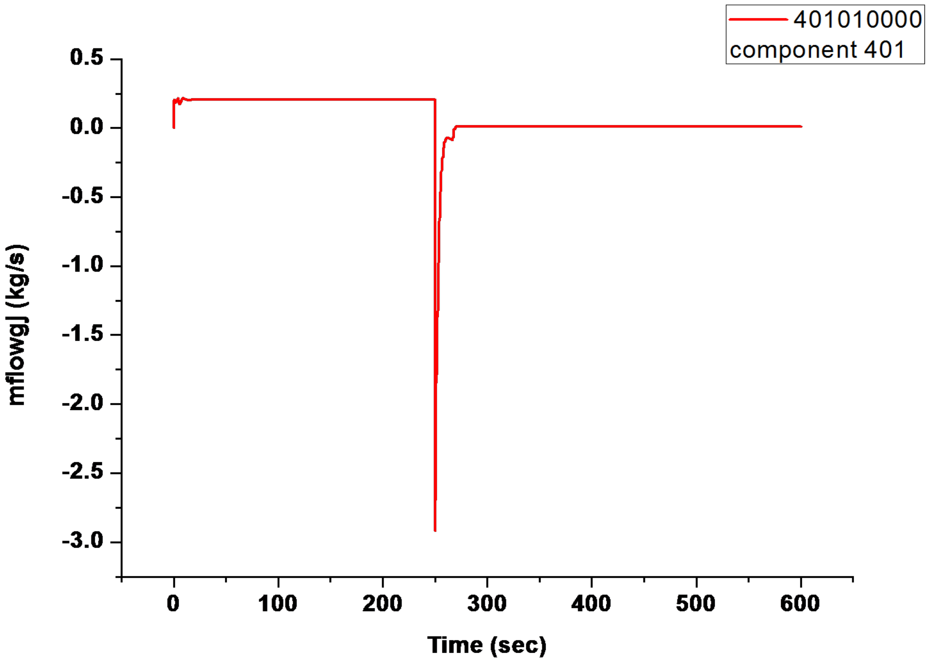

Figure 5.5: Mass flow rate of FW 2 channel LOCA

In fig 5.6 when LOCA happens due to double ended rupture. The pressure decreases and then comes to steady state resulting in pressurization of vacuum vessel.

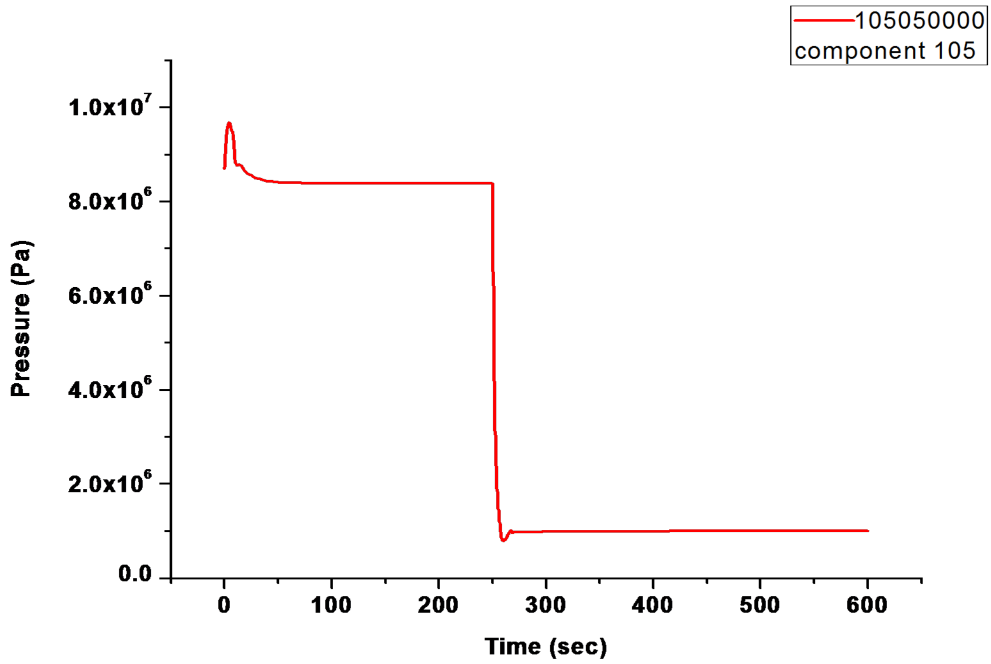

Figure 5.6: Pressure of FW 14 channel LOCA

In fig 5.7 when LOCA happens at 250 sec there is a sudden increase and decrease in the flow rate of helium and then it comes to steady state.

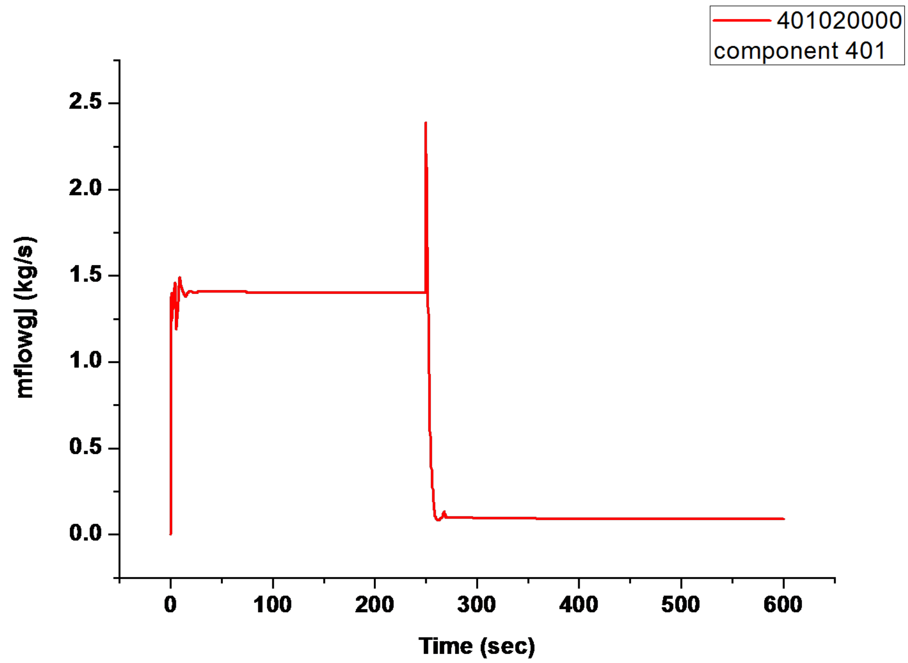

Figure 5.7: Mass flow rate of FW 14 channel LOCA

The below graphs shows the pressure, temperature and mass flow rate of pipe below the circulator component 100. When LOCA happens the pressure in the pipe decreases and achieves steady state. The temperature rises when there is a leak and then decreases and stays in the design limit after achieving steady state. Where as the mass flow rate during LOCA decreases and then comes to steady state.

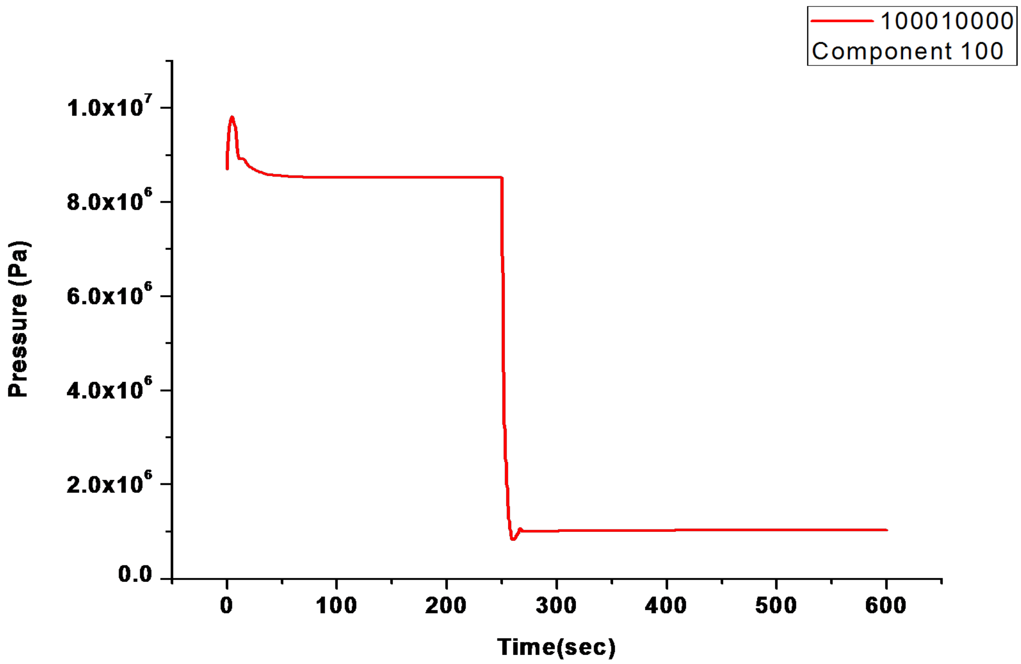

Figure 5.8: Pressure of component 100 during LOCA

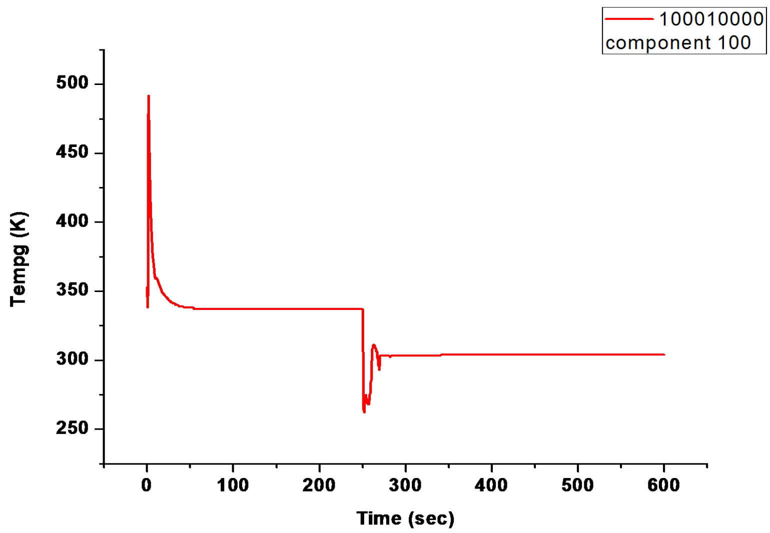

Figure 5.9: Temperature of component 100 during LOCA

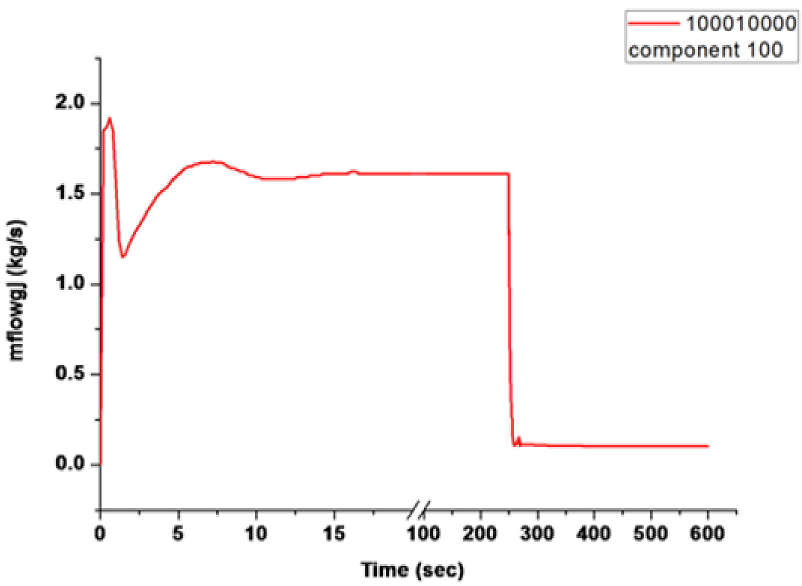

Figure 5.10: Mass flow rate of component 100 during LOCA

The below graphs shows the pressure and temperature of component 111 ie the pipe above circulator or after heat exchanger. When LOCA happens, pressure decreases in the loop component and then comes to steady state. While the temperature suddenly increases and then decreases so as to attain steady state.

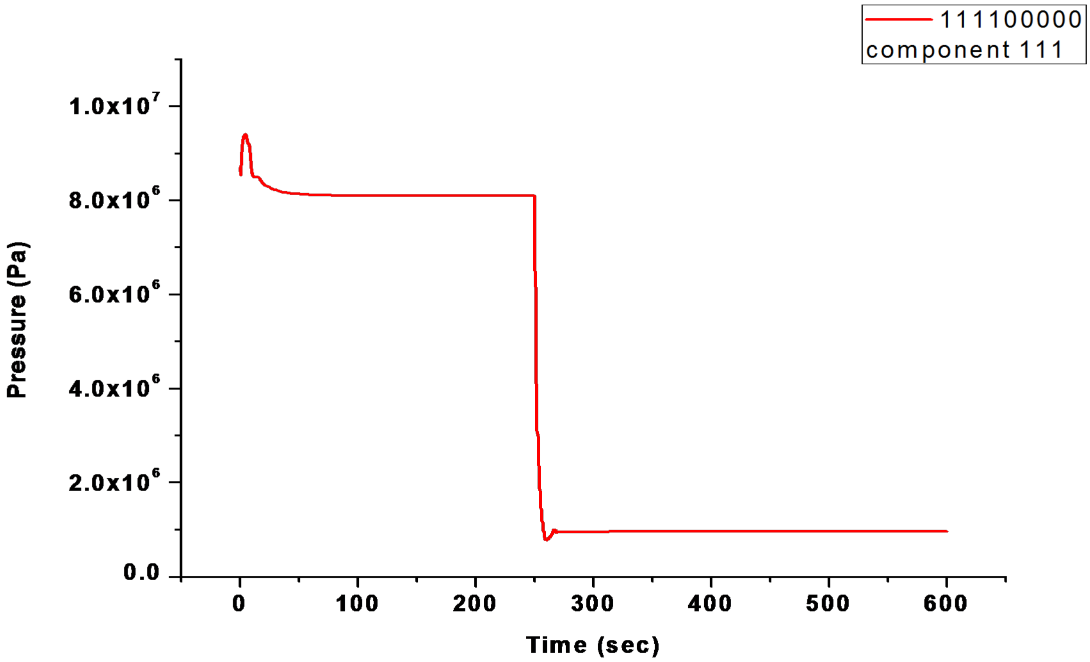

Figure 5.11: Pressure of component 111 during LOCA

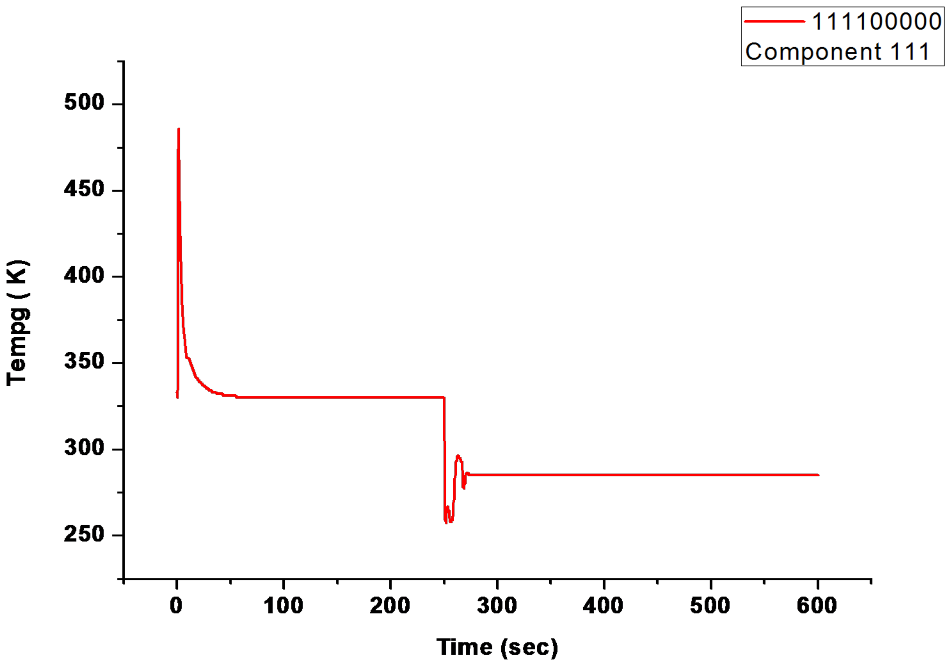

Figure 5.12: Temperature of component 111 during LOCA

Chapter 6

Conclusions and Future Scope

Based on the work conducted , the following conclusion are drawn:

- The helium cooling system, which is designed for operating under ITER-like conditions, has been successfully simulated using the system code RELAP5.
- The thermalhydraulic behavior and safety performance is investigated for the latest accident sequences occuring in the helium cooling system.
- During LOCA, helium coolant leads to the break of First wall channels causing the pressurization of vacuum vessel and temperature evolution of TBM which remains with in the design limit of the ITER safety guidelines.

Based on these results it was found that the helium cooling system is designed with sufficient capability for the accident scenarios.

6.1 Future Scope of Work

As the ITER TBM Programme moves forward, there are many changes which are expected to be occurring in future . So with this model of RELAP5 one can change the flow parameters and analyse the loop for variant LOCA positions.

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Appendix A

Fluid Properties Table

Isobaric property table for Helium and Water is given below:

Table I: Property Table For Helium

Temperature (K)	Density $(kg/(m^3))$	Specific Heat $Cp(J/(g*K))$	Viscosity $(Pa*s)$	Thermal Cond. $(W/(m*K))$
330	10.86	5.18	$2.15*e^{-5}$	0.171
350	10.26	5.187	$2.23*e^{-5}$	0.178
370	9.722	5.186	$2.32*e^{-5}$	0.184
390	9.2383	5.1867	$2.40*e^{-5}$	0.191
410	8.800	5.186	$2.48*e^{-5}$	0.198
430	8.401	5.1866	$2.57*e^{-5}$	0.204
450	8.037	5.1866	$2.63*e^{-5}$	0.210
470	7.703	5.1867	$2.73*e^{-5}$	0.217
490	7.396	5.1868	$2.81*e^{-5}$	0.223
510	7.112	5.1869	$2.89*e^{-5}$	0.229
530	6.850	5.1870	$2.96*e^{-5}$	0.235
550	6.606	5.1871	$3.04*e^{-5}$	0.241
570	6.378	5.1872	$3.12*e^{-5}$	0.247
590	6.166	5.1875	$3.19*e^{-5}$	0.253
610	5.967	5.1875	$3.27*e^{-5}$	0.259

Table II: Property Table For Water

Temperature (K)	Density $(kg/(m^3))$	Specific Heat $Cp(J/(g*K))$	Viscosity $(Pa*s)$	Thermal Cond. $(W/(m*K))$
310	993.76	4.1771	$69*e^{-5}$	0.62647
330	985.16	4.1818	$48*e^{-5}$	0.65162
350	974.11	4.1926	$36*e^{-5}$	0.668
370	960.99	4.2102	$29*e^{-5}$	0.678
390	946.00	4.2365	$23*e^{-5}$	.683
410	929.25	4.2738	$20*e^{-5}$	.683

Appendix B

RELAP5 Input Deck

B.1 Flow Chart for Analysis

The flow chart for modelling a loop in RELAP5 is given below:

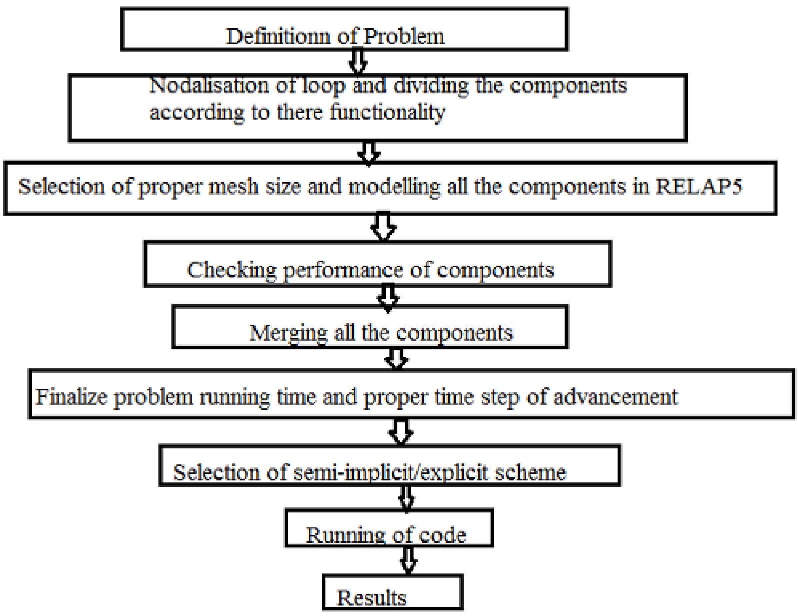

Figure B.1: Flow chart for Analysis

B.2 RELAP Input Deck for PHCS

Firstly coding of individual components is given.

Table I: Syntax for RELAP5 Coding

Component	Label	Primary uses
Pipe Or Annulus	Pipe	Represents a pipe in the system. PIPE can have 1 to 100 sub volumes.
Branch	Branch	Represents a stream-tube flow juncture that can have as many as 10 junctions defined.
Single-junction	SNGLJUN	Designed to connect one component to another.
Time-dependent Volume	TMDPVOL	Specifies boundary conditions on system model.
Heat Structure		Various type of heat exchangers
Valve	VALVE	Simulates six different valve types: check, trip, inertial, motor servo, and relief.
Pump	PUMP	Simulates the actions and presence of a centrifugal pump.
Steady state	stdy-st	
Transient	transt	
Time dependent junction	TMDPJUN	

B.2.1 Input Deck for Shell and Tube HX

```
*** helium water heat exchanger
100 new transnt
110 helium
115 1.0
201 1000.0 1.0e-6 0.2 3 100 100 100
***helium side
** source as TMDPVOL
2000000 tmdpvo1 tmdpvol
2000101 0.014159 1.0 0.0 0.0 0.0 0.0 1.6e-6 0.00702 0
```

```
2000200 104
2000201 0.0 80.0e5 610.0 0.0
*** time dependent junction
3000000 tmdpjun1 tmdpjun
3000101 200010000 400000000 0.0
3000200 1
3000201 0.0 0.0 1.6 0.0
** branch going to pipe
4000000 branch1 branch
4000001 1 1
4000101 0.014159 0.2 0.0 0.0 0.0 0.0 1.6e-6 0.00702 0
4000200 104 80.0e5 610.0 0.0
4001101 400010000 100000000 0.0 0.0 0.0 0
4001201 0.0 1.6 0.0
* HEAT EXCHANGER PIPE
1000000 pipe pipe
1000001 10
1000101 0.014159 10
1000301 0.3 10
1000601 0.0 10
1000801 1.6e-6 0.00702 10
1001001 0 10
1001101 0 9
1001201 104 80.0e+5 610.0 0.0 0.0 0.0 10
1001300 1
1001301 0.0 1.6 0.0 9
**branch connecting TMDPVOL to PIPE
4010000 branch2 branch
4010001 2 1
4010101 0.014159 0.2 0.0 0.0 0.0 0.0 1.6e-6 0.00702 0
4010200 104 78.97202e5 610.0 0.0
```

4011101 100010000 401000000 0.0 0.0 0.0 0

4011201 0.0 1.6 0.0

4012101 401010000 201000000 0.0 0.0 0.0 0

4012201 0.0 1.6 0.0

**end time dependent volume

2010000 tmdpvol2 tmdpvol

2010101 0.014159 1.0 0.0 0.0 0.0 0.0 1.6e-6 0.00702 0

2010200 104

2010201 0.0 78.97202e5 333.0 0.0

****second part water side

**source as TMDPVOL

2020000 tmdpvol3 tmdpvol

2020101 0.03683 1.0 0.0 180.0 0.0 0.0 1.6e-6 0.01138 0

2020200 103

2020201 0.0 10.0e5 280.0

***time dependent junction

3010000 tmdpjun2 tmdpjun

3010101 202010000 402000000 0.0

3010200 1

3010201 0.0 5.6021 0.0 0.0

** branch connecting to heat exchanger

4020000 branch3 branch

4020001 1 1

4020101 0.03683 0.2 0.0 180.0 0.0 0.0 1.6e-6 0.011388 0

4020200 103 10.0e5 280.0

4021101 402010000 101000000 0.0 0.0 0.0 0

4021201 5.6021 0.0 0.0

**shell connected to pipe 100

1010000 shell pipe

1010001 10

1010101 0.03683 10

1010301 0.3 10

1010501 180.0 10

1010601 0.0 10

1010801 1.6e-6 0.011388 10

1011001 0 10

1011101 0 9

1011201 103 10.0e5 280.0 0.0 0.0 0.0 10

1011300 1

1011301 5.6021 0.0 0.0 9

**branch b/w pipe and TMDPVOL

4030000 branch4 branch

4030001 2 1

4030101 0.03683 0.2 0.0 180.0 0.0 0.0 1.6e-6 0.01138 0

4030200 103 9.78906e5 280.0

4031101 101010000 403000000 0.0 0.0 0.0 0

4031201 5.6021 0.0 0

4032101 403010000 203000000 0.0 0.0 0.0 0

4032201 5.6021 0.0 0

** last tmdpvol (sink)

2030000 tmdpvol4 tmdpvol

2030101 0.03683 1.0 0.0 180.0 0.0 0.0 1.6e-6 0.01138 0

2030200 103

2030201 0.0 9.78906e5 375.0

***heat exchanger

**helium side

11000000 10 5 2 0 0.00351 0 0 128

11000100 0 1

11000101 4 0.00476

11000201 111 4

11000301 0.0 4

11000400 0

```
11000401 610.0 5
11000501 100010000 010000 1 1 109.8 10
11000601 101100000 -010000 1 1 109.8 10
11000701 0 0.0 0.0 0.0 10
11000801 0.00702 12.0 12.0 0.0 0.0 0.0 0.0 1.0 10
11000901 0.01138 12.0 12.0 0.0 0.0 0.0 0.0 1.0 10
20111100 tbl/fctn 1 1
20111101 16.3
20111151 40.0e5
***water side
11010000 10 5 2 0 0.140 0 0 128
11010100 0 1
11010101 4 0.160
11010201 222 4
11010301 0.0 4
11010400 0
11010401 290.0 5
11010501 101010000 010000 1 1 0.3 10
11010601 0 0 0 1 0.3 10
11010701 0 0.0 0.0 0.0 10
11010801 0.280 12.0 12.0 0.0 0.0 0.0 0.0 1.0 10
20122200 tbl/fctn 1 1
20122201 16.3
20122251 40.0e5
**plot request
301 p 401010000
302 p 403010000
303 tempg 401010000
```

304 tempf 403010000

305 mflowfj 403020000

306 mflowgj 403020000

20300010 p 401010000

20300020 p 403010000

20300030 tempg 401010000

20300040 tempf 403010000

20300050 mflowfj 403020000

20300060 mflowgj 403020000

.

B.2.2 Input Deck for First Wall 2 Channel

***** first wall heater

100 new transnt

110 helium

115 1.0

201 100.0 1.0e-6 0.2 3 100 100 100

*first Tmdpvol

2000000 tmdpvol1 tmdpvol

2000101 0.8e-3 1.0 0.0 0.0 90.0 1.0 1.6e-6 0.0 0

2000200 104

2000201 0.0 80.0e5 573.0 0.0

**tmdpjun b/w branch and tmdpvol

3000000 tmdpjun tmdpjun

3000101 200010000 400000000 0.0

3000200 1

3000201 0.0 0.0 0.2 0.0

** branch for checking

4000000 branch1 branch

```
4000001 1 1
4000101 0.8e-3 0.2 0.0 0.0 90.0 0.2 1.6e-6 0.0 0
4000200 104 80.0e5 573.0 0.0
4001101 400010000 100000000 0.0 0.0 0.0 0
4001201 0.0 0.2 0.0
** pipe
1000000 pipe1 pipe
1000001 10
1000101 0.8e-3 10
1000301 0.15 10
1000601 90.0 10
1000801 1.6e-6 0.0 10
1001001 0 10
1001101 0 9
1001201 104 80.0e5 573.0 0.0 0.0 0.0 10
1001300 1
1001301 0.0 0.2 0.0 9
*branch for checking
4010000 branch1 branch
4010001 2 1
4010101 0.8e-3 0.2 0.0 0.0 90.0 0.2 1.6e-6 0.0 0
4010200 104 79.0e5 573.0 0.0
4011101 100010000 401000000 0.0 0.0 0.0 0
4011201 0.0 0.2 0.0
4012101 401010000 201000000 0.0 0.0 0.0 0
4012201 0.0 0.2 0.0
**last tmdpvol
2010000 tmdpvol2 tmdpvol
2010101 0.8e-3 1.0 0.0 0.0 90.0 1.0 1.6e-6 0.0 0
2010200 104
```

```
2010201 0.0 79.0e5 610.0 0.0
** heat structure
11000000 10 5 2 0 0.031923 0 0 128
11000100 0 1
11000101 4 0.035923
11000201 111 4
11000301 1.0 4
11000401 610.0 5
11000501 100010000 010000 1 1 0.15 10
11000601 0 0 0 1 0.15 10
11000701 222 0.0 1.0 0.0 10
11000801 0.0 12.0 12.0 0.0 0.0 0.0 0.0 1.0 10
20111100 tbl/fctn 1 1
20111101 25.70
20111151 43.0e5
20222200 power
20222201 0.0 4.14e3
**minor edit
301 tempg 400010000
302 tempg 401010000
303 p 400010000
304 p 401010000
305 mflowgj 401010000
** plot request
20300010 tempg 400010000
20300020 tempg 401010000
20300030 p 400010000
20300040 p 401010000
20300050 mflowgj 401010000
.
```

B.2.3 Input Deck for First Wall 14 Channel

small***** first wall heater (14 CHANNEL)

**** first wall heater

100 new transnt

110 helium

115 1.0

201 100.0 1.0e-6 0.2 3 100 100 100

*first Tmdpvol

2000000 tmdpvol1 tmdpvol

2000101 5.6e-3 1.0 0.0 0.0 90.0 1.0 1.6e-6 0.0 0

2000200 104

2000201 0.0 80.0e5 573.0 0.0

**tmdpjun b/w branch and tmdpvol

3000000 tmdpjun tmdpjun

3000101 200010000 400000000 0.0

3000200 1

3000201 0.0 0.0 1.4 0.0

** branch for checking

4000000 branch1 branch

4000001 1 1

4000101 5.6e-3 0.2 0.0 0.0 90.0 0.2 1.6e-6 0.0 0

4000200 104 80.0e5 573.0 0.0

4001101 400010000 100000000 0.0 0.0 0.0 0

4001201 0.0 1.4 0.0

** pipe

1000000 pipe1 pipe

1000001 10

1000101 5.6e-3 10

1000301 0.15 10

1000601 90.0 10

1000801 1.6e-6 0.0 10

1001001 0 10

1001101 0 9

1001201 104 80.0e5 573.0 0.0 0.0 0.0 10

1001300 1

1001301 0.0 1.4 0.0 9

*branch for checking

4010000 branch1 branch

4010001 2 1

4010101 5.6e-3 0.2 0.0 0.0 90.0 0.2 1.6e-6 0.0 0

4010200 104 79.0e5 573.0 0.0

4011101 100010000 401000000 0.0 0.0 0.0 0

4011201 0.0 1.4 0.0

4012101 401010000 201000000 0.0 0.0 0.0 0

4012201 0.0 1.4 0.0

**last tmdpvol

2010000 tmdpvol2 tmdpvol

2010101 5.6e-3 1.0 0.0 0.0 90.0 1.0 1.6e-6 0.0 0

2010200 104

2010201 0.0 79.0e5 610.0 0.0

** heat structure

11000000 10 5 2 0 0.0422345 0 0 128

11000100 0 1

11000101 4 0.0462345

11000201 111 4

11000301 1.0 4

11000401 610.0 5

11000501 100010000 010000 1 1 0.15 10

11000601 0 0 0 1 0.15 10

11000701 222 0.0 1.0 0.0 10

11000801 0.0 12.0 12.0 0.0 0.0 0.0 0.0 1.0 10

20111100 tbl/fctn 1 1

20111101 25.70

20111151 43.0e5

20222200 power

20222201 0.0 29.0e3

**minor edit

301 tempg 400010000

302 tempg 401010000

303 p 400010000

304 p 401010000

305 mflowgj 401010000

** plot request

20300010 tempg 400010000

20300020 tempg 401010000

20300030 p 400010000

20300040 p 401010000

20300050 mflowgj 401010000

.

B.2.4 Input Deck for Inlet Heat Structure

***** first wall heater

100 new transnt

110 helium

115 1.0

201 200.0 1.0e-6 0.2 3 100 100 100

*first Tmdpvol

2000000 tmdpvol1 tmdpvol

2000101 7.4135e-3 1.0 0.0 0.0 0.0 0.0 1.6e-6 0.0 0

2000200 104

```
2000201 0.0 81.8e5 353.0 0.0
**tmdpjun b/w branch and tmdpvol
3000000 tmdpjun tmdpjun
3000101 200010000 400000000 0.0
3000200 1
3000201 0.0 0.0 1.6 0.0
** branch for checking
4000000 branch1 branch
4000001 1 1
4000101 7.4135e-3 0.2 0.0 0.0 0.0 0.0 1.6e-6 0.00 0
4000200 104 81.8e5 353.0 0.0
4001101 400010000 100000000 0.0 0.0 0.0 0
4001201 0.0 1.6 0.0
** pipe
1000000 pipe1 pipe
1000001 10
1000101 7.4135e-3 10
1000301 0.1 10
1000601 0.0 10
1000801 1.6e-6 0.0 10
1001001 0 10
1001101 0 9
1001201 104 81.8e5 353.0 0.0 0.0 0.0 10
1001300 1
1001301 0.0 1.6 0.0 9
*branch for checking
4010000 branch1 branch
4010001 2 1
4010101 7.4135e-3 0.2 0.0 0.0 0.0 0.0 1.6e-6 0.0 0
4010200 104 81.5e5 353.0 0.0
4011101 100010000 401000000 0.0 0.0 0.0 0
```

```
4011201 0.0 1.6 0.0
4012101 401010000 201000000 0.0 0.0 0.0 0
4012201 0.0 1.6 0.0
**last tmdpvol
2010000 tmdpvol2 tmdpvol
2010101 7.413e-3 1.0 0.0 0.0 0.0 0.0 1.6e-6 0.0 0
2010200 104
2010201 0.0 81.5e5 573.0 0.0
** heat structure
11000000 1 5 2 0 0.04859 0 0 128
11000100 0 1
11000101 4 0.05359
11000201 111 4
11000301 1.0 4
11000401 353.0 5
11000501 100010000 010000 1 1 0.1 1
11000601 0 0 0 1 0.1 1
11000701 222 0.0 1.0 0.0 1
11000801 0.0 12.0 12.0 0.0 0.0 0.0 0.0 1.0 1
20111100 tbl/fctn 1 1
20111101 25.70
20111151 43.0e5
20222200 power
20222201 0.0 183.0e4
**minor edit
301 tempg 400010000
302 tempg 401010000
303 p 400010000
```

304 p 401010000

305 mflowgj 401010000

** plot request

20300010 tempg 400010000

20300020 tempg 401010000

20300030 p 400010000

20300040 p 401010000

20300050 mflowgj 401010000

.

B.2.5 Input Deck for Nodalization Diagram of HCS Loop

**phcs coding

100 new transnt

110 helium

115 1.0

201 600.0 1.0e-12 0.2 3 1 1 10

** trip

501 p 111100000 lt null 0 20.0e5 l

502 time 0 ge null 0 250.0 l

**starting from component 100

1000000 pipe1 pipe

1000001 10

1000101 4.26e-3 10

1000301 1.04 10

1000601 -90.0 10

1000801 1.6e-6 0.0 10

1001001 0011000 10

1001101 0001100 9

1001201 104 87.0e5 353.0 0.0 0.0 0.0 10

1001300 1

1001301 0.0 0.0 0.0 9

** single junction b/w pipe 100 and 101

3000000 sngljun1 sngljun

3000101 100010000 101000000 0.0 0.0 0.0 0001100

3000201 1 0.0 0.0 0.0

** pipe 101 goes to heat tracing

1010000 pipe2 pipe

1010001 2

1010101 1.9e-3 2

1010301 1.5 2

1010501 180.0 2

1010601 0.0 2

1010801 1.6e-6 0.0 2

1011001 0011000 2

1011101 0001100 1

1011201 104 87.0e5 353.0 0.0 0.0 0.0 2

1011300 1

1011301 0.0 0.0 0.0 1

*** single junction b/w pipe 101 and heat tracing (102)

3010000 sngljun2 sngljun

3010101 101010000 102000000 0.0 0.0 0.0 0001100

3010201 1 0.0 0.0 0.0

** heat tracing pipe and heater

****

****

** pipe

1020000 pipe3 pipe

1020001 10

1020101 7.4135e-3 10

1020301 0.1 10

```
1020501 180.0 10
1020601 0.0 10
1020801 1.6e-6 0.0 10
1021001 0011000 10
1021101 0001100 9
1021201 104 87.0e5 353.0 0.0 0.0 0.0 10
1021300 1
1021301 0.0 0.0 0.0 9
** heat structure
11020000 10 5 2 0 0.04859 0 0 128
11020100 0 1
11020101 4 0.05359
11020201 111 4
11020301 1.0 4
11020401 573.0 5
11020501 102010000 010000 1 1 0.1 10
11020601 0 0 0 1 0.1 10
11020701 222 0.0 1.0 0.0 10
11020801 0.0 12.0 12.0 0.0 0.0 0.0 0.0 1.0 10
20111100 tbl/fctn 1 1
20111101 25.70
20111151 43.0e5
20222200 power
20222201 0.0 183.0e3
***junction b/w heat structure(102) and pipe 103
3020000 sngljun3 sngljun
3020101 102010000 103000000 0.0 0.0 0.0 0001100
3020201 1 0.0 0.0 0.0
** pipe 103 from heat tracing
1030000 pipe4 pipe
1030001 50
```

```
1030101 7.413e-3 50
1030301 1.77 50
1030501 180.0 50
1030601 0.0 50
1030801 1.6e-6 0.0 50
1031001 0011000 50
1031101 0001100 49
1031201 104 87.0e5 573.0 0.0 0.0 0.0 50
1031300 1
1031301 0.0 0.0 0.0 49
*junction b/w pipe 103 and 104
3030000 sngljun4 sngljun
3030101 103010000 104000000 0.0 0.0 0.0 0001100
3030201 1 0.0 0.0 0.0
*** pipe 104 goes to TBM
1040000 pipe5 pipe
1040001 10
1040101 7.4135e-3 10
1040301 0.9 10
1040601 90.0 10
1040801 1.6e-6 0.0 10
1041001 0011000 10
1041101 0001100 9
1041201 104 87.0e5 573.0 0.0 0.0 0.0 10
1041300 1
1041301 0.0 0.0 0.0 9
** branch connecting pipe 104 and TBM
4000000 branch1 branch
4000001 3 1
4000101 7.4135e-3 0.5 0.0 0.0 90.0 0.5 1.6e-6 0.0 0
4000200 104 87.0e5 573.0 0.0
```

4001101 104010000 400000000 0.0 0.0 0.0 0001100

4001201 0.0 0.0 0.0

4002101 400010000 106000000 0.0 9.0 9.0 0001000

4002201 0.0 0.0 0.0

4003101 400010000 105000000 0.0 10.0 10.0 0001000

4003201 0.0 0.0 0.0

***TBM splited in to two parts one is having 14 channel and other one containing 2

** two channel combition with heat structure

**** first wall 2 channel with heat structure

1060000 pipe7 pipe

1060001 10

1060101 0.8e-3 10

1060301 0.15 10

1060601 90.0 10

1060801 1.6e-6 0.0 10

1061001 0011000 10

1061101 0001100 9

1061201 104 87.0e5 573.0 0.0 0.0 0.0 10

1061300 1

1061301 0.0 0.0 0.0 9

** heat structure

11060000 10 5 2 0 0.031923 0 0 128

11060100 0 1

11060101 4 0.035923

11060201 333 4

11060301 1.0 4

11060401 610.0 5

11060501 106010000 010000 1 1 0.15 10

11060601 0 0 0 1 0.15 10

11060701 444 0.0 1.0 0.0 10

11060801 0.0 12.0 12.0 0.0 0.0 0.0 0.0 1.0 10

```
20133300 tbl/fctn 1 1
20133301 25.70
20133351 43.0e5
20244400 power
20244401 0.0 4.14e3
*** first wall 14 channel with heat structure
** pipe
1050000 pipe1 pipe
1050001 10
1050101 5.6e-3 10
1050301 0.15 10
1050601 90.0 10
1050801 1.6e-6 0.0 10
1051001 0011000 10
1051101 0001100 9
1051201 104 87.0e5 573.0 0.0 0.0 0.0 10
1051300 1
1051301 0.0 0.0 0.0 9
** heat structure
11050000 10 5 2 0 0.0422345 0 0 128
11050100 0 1
11050101 4 0.0462345
11050201 555 4
11050301 1.0 4
11050401 610.0 5
11050501 105010000 010000 1 1 0.15 10
11050601 0 0 0 1 0.15 10
11050701 666 0.0 1.0 0.0 10
11050801 0.0 12.0 12.0 0.0 0.0 0.0 0.0 1.0 10
20155500 tbl/fctn 1 1
20155501 25.70
```

```
20155551 43.0e5
20266600 power
20266601 0.0 29.0e3
**branch connecting TBM all channel and pipe 107
4010000 branch2 branch
4010001 3 1
4010101 7.4135e-3 0.5 0.0 0.0 90.0 0.5 1.6e-6 0.0 0
4010200 104 87.0e5 610.0 0.0
4011101 106010000 401000000 0.0 0.0 0.0 0001100
4011201 0.0 0.0 0.0
4012101 105010000 401000000 0.0 0.0 0.0 0001100
4012201 0.0 0.0 0.0
4013101 401010000 107000000 0.0 0.0 0.0 0001100
4013201 0.0 0.0 0.0
*** pipe 107
1070000 pipe8 pipe
1070001 10
1070101 7.4135e-3 10
1070301 0.95 10
1070601 90.0 10
1070801 1.6e-6 0.0 10
1071001 0011000 10
1071101 0001100 9
1071201 104 87.0e5 610.0 0.0 0.0 0.0 10
1071300 1
1071301 0.0 0.0 0.0 9
** junction connecting 107 and 108
3040000 sngljun5 sngljun
3040101 107010000 108000000 0.0 0.0 0.0 0001100
3040201 1 0.0 0.0 0.0
** pipe 108 goes to helium water heat exchanger
```

1080000 pipe9 pipe

1080001 50

1080101 7.4135e-3 50

1080301 1.61 50

1080501 0.0 50

1080601 0.0 50

1080801 1.6e-6 0.0 50

1081001 0011000 50

1081101 0001100 49

1081201 104 87.0e5 610.0 0.0 0.0 0.0 50

1081300 1

1081301 0.0 0.0 0.0 49

*junction b/w pipe 108 and heat exchanger(109)

3050000 sngljun6 sngljun

3050101 108010000 109000000 0.0 0.0 0.0 0001100

3050201 1 0.0 0.0 0.0

** helium water heat exchanger

* HEAT EXCHANGER PIPE

1090000 pipe pipe

1090001 10

1090101 0.014159 10

1090301 0.3 10

1090601 0.0 10

1090801 1.6e-6 0.00702 10

1091001 0011000 10

1091101 0001100 9

1091201 104 76.85e+5 610.0 0.0 0.0 0.0 10

1091300 1

1091301 0.0 0.0 0.0 9

****secound part water side

**source as TMDPVOL

2040000 tmdpvol3 tmdpvol

2040101 0.03683 1.0 0.0 180.0 0.0 0.0 1.6e-6 0.01138 0

2040200 103

2040201 0.0 10.0e5 280.0

***time dependent junction

3990000 tmdpjun2 tmdpjun

3990101 204010000 402000000 0.0

3990200 1

3990201 0.0 5.6021 0.0 0.0

** branch connecting to heat exchanger

4020000 branch3 branch

4020001 1 1

4020101 0.03683 0.2 0.0 180.0 0.0 0.0 1.6e-6 0.011388 0

4020200 103 10.0e5 280.0

4021101 402010000 112000000 0.0 0.0 0.0 0

4021201 5.6021 0.0 0.0

**shell connected to pipe 100

1120000 shell pipe

1120001 10

1120101 0.03683 10

1120301 0.3 10

1120501 180.0 10

1120601 0.0 10

1120801 1.6e-6 0.011388 10

1121001 0 10

1121101 0 9

1121201 103 10.0e5 280.0 0.0 0.0 0.0 10

1121300 1

1121301 5.6021 0.0 0.0 9

**branch b/w pipe and TMDPVOL

4030000 branch4 branch

```
4030001 2 1
4030101 0.03683 0.2 0.0 180.0 0.0 0.0 1.6e-6 0.01138 0
4030200 103 9.78906e5 280.0
4031101 112010000 403000000 0.0 0.0 0.0 0
4031201 5.6021 0.0 0
4032101 403010000 205000000 0.0 0.0 0.0 0
4032201 5.6021 0.0 0
** last tmdpvol (sink)
2050000 tmdpvol4 tmdpvol
2050101 0.03683 1.0 0.0 180.0 0.0 0.0 1.6e-6 0.01138 0
2050200 103
2050201 0.0 9.78906e5 375.0
***heat exchanger
**helium side
11090000 10 5 2 0 0.00351 0 0 128
11090100 0 1
11090101 4 0.00476
11090201 777 4
11090301 0.0 4
11090400 0
11090401 610.0 5
11090501 109010000 010000 1 1 109.8 10
11090601 112100000 -010000 1 1 109.8 10
11090701 0 0.0 0.0 0.0 10
11090801 0.00702 12.0 12.0 0.0 0.0 0.0 0.0 1.0 10
11090901 0.01138 12.0 12.0 0.0 0.0 0.0 0.0 1.0 10
20177700 tbl/fctn 1 1
20177701 16.3
20177751 40.0e5
***water side
11120000 10 5 2 0 0.140 0 0 128
```

11120100 0 1

11120101 4 0.160

11120201 888 4

11120301 0.0 4

11120400 0

11120401 290.0 5

11120501 112010000 010000 1 1 0.3 10

11120601 0 0 0 1 0.3 10

11120701 0 0.0 0.0 0.0 10

11120801 0.280 12.0 12.0 0.0 0.0 0.0 0.0 1.0 10

20188800 tbl/fctn 1 1

20188801 16.3

20188851 40.0e5

** junction b/w pipe 109 and pipe 110

3060000 sngljun7 sngljun

3060101 109010000 110000000 0.0 55.0 55.0 0001000

3060201 1 0.0 0.0 0.0

**pipe 110

1100000 pipe11 pipe

1100001 10

1100101 7.4135e-3 10

1100301 0.9 10

1100601 0.0 10

1100801 1.6e-6 0.0 10

1101001 0011000 10

1101101 0001100 9

1101201 104 87.0e5 333.0 0.0 0.0 0.0 10

1101300 1

1101301 0.0 0.0 0.0 9

**junction b/w pipe 110 and 111

3070000 sngljun8 sngljun

```
3070101 110010000 111000000 0.0 60.0 60.0 0001000
3070201 1 0.0 0.0 0.0
** pipe 111 goes to circulator
1110000 pipe12 pipe
1110001 10
1110101 7.4135e-3 10
1110301 1.0 10
1110601 -90.0 10
1110801 1.6e-6 0.0 10
1111001 0011000 10
1111101 0001100 9
1111201 104 87.0e5 333.0 0.0 0.0 0.0 10
1111300 1
1111301 0.0 0.0 0.0 9
** circulator
5000000 pump pump
5000101 0.0 0.6 0.005 0.0 -90.0 -0.6 0
5000108 111100002 0.0 0.0 0.0 0001000
5000109 100010001 0.0 0.0 0.0 0001000
5000200 104 87.0e5 333.0 0.0
5000201 1 0.0 0.0 0.0
5000202 1 0.0 0.0 0.0
5000301 -2 -1 -3 -1 -1 0 0
5000302 628.3 0.86 0.25 3907.0 150.0 0.55 0.0 0.0 0.0 6.0 0.0
0.0
**********
*******leak in v.v.
*valve connecting to leakage volume open after 150 second
7000000 valve valve
7000101 106050004 800000000 0.8e-3 0.0 0.0 0001100
7000201 1 0.0 0.0 0.0
```

```
7000300 trpvlv
7000301 502
******* pipe 800 for mass flow check
8000000 pipe7 pipe
8000001 2
8000101 0.8e-3 2
8000301 0.1 2
8000501 180.0 2
8000601 0.0 2
8000801 1.6e-6 0.0 2
8001001 0011000 2
8001101 0001100 1
8001201 104 1.0 503.0 0.0 0.0 0.0 2
8001300 1
8001301 0.0 0.0 0.0 1
***small pipe for checking mass flow
*junction b/w pipe 800 and vol 600
3200000 sngljun4 sngljun
3200101 800010000 600000000 0.8e-3 0.0 0.0 0001100
3200201 1 0.0 0.0 0.0
******8leakege volume
6000000 lvol snglvol
6000101 0.0 2.0 20.0 180.0 0.0 0.0 1.6e-6 0.0 0011000
6000200 104 1.0 503.0 0.0
*minor edit request
301 p 111100000
302 tempg 111100000
303 p 100010000
304 tempg 100010000
305 mflowgj 100010000
306 mflowgj 401010000
```

307 mflowgj 401020000

308 tempg 106100000

309 tempg 105100000

310 p 106050000

311 p 105050000

312 p 600010000

313 tempg 600010000

314 mflowgj 800010000

*plot

20300010 p 111100000

20300020 tempg 111100000

20300030 p 100010000

20300040 tempg 100010000

20300050 mflowgj 100010000

20300060 mflowgj 401010000

20300070 mflowgj 401020000

20300080 tempg 106100000

20300090 tempg 105100000

20300100 p 106050000

20300110 p 105050000

20300120 p 600010000

20300130 tempg 600010000

20300140 mflowgj 800010000

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B.2.6 The Graph Obtained from RELAP5 Input Deck

The graph obtained by running the RELAP5 input deck for various coding of components is given below:

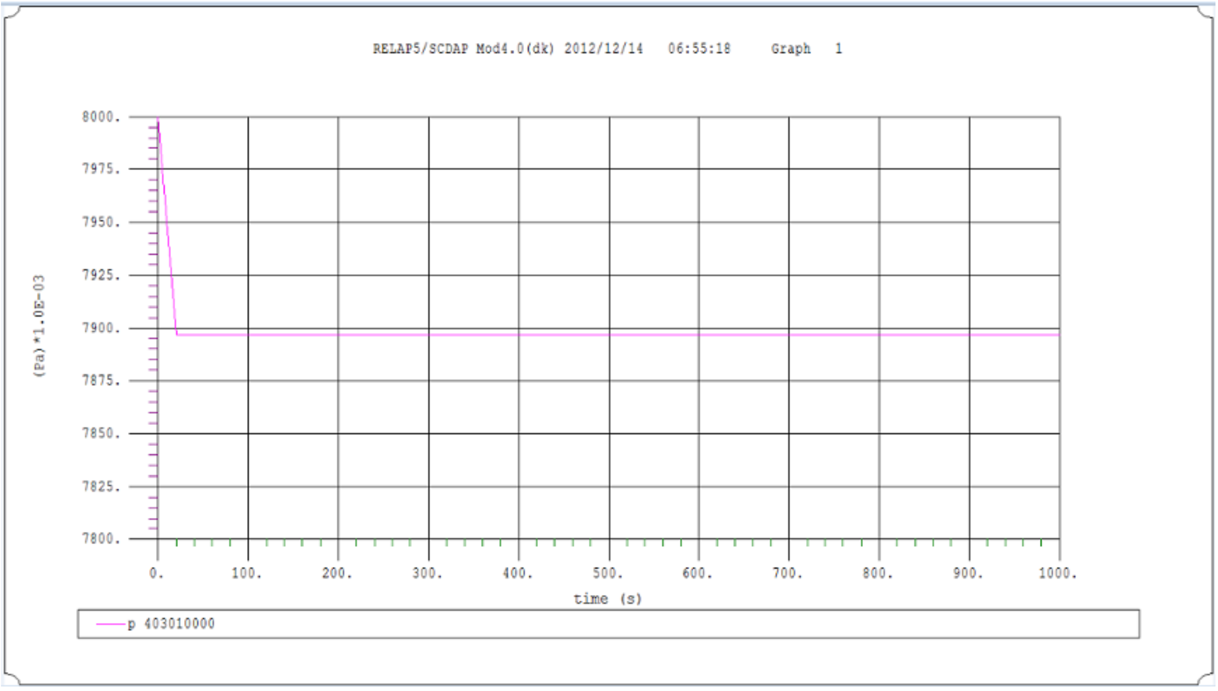

Figure B.2: HX Graph for outlet pressure

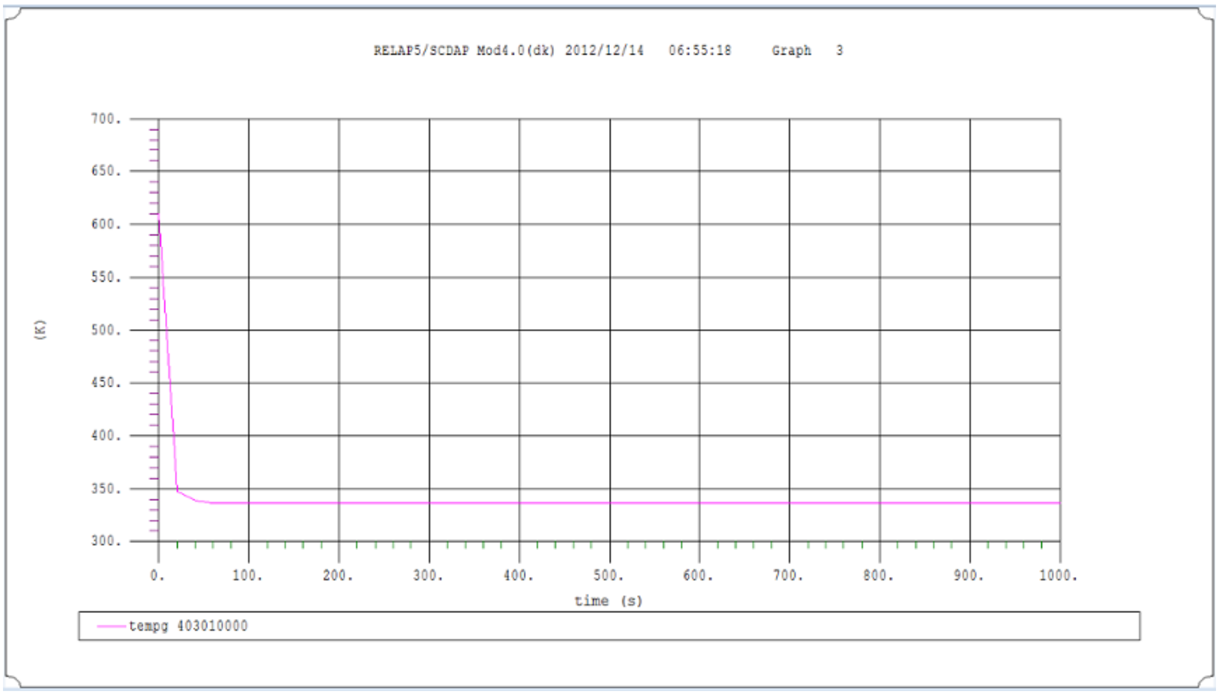

Figure B.3: HX Graph for outlet Temperature

Figure B.4: Heat Tracing Graph for outlet pressure

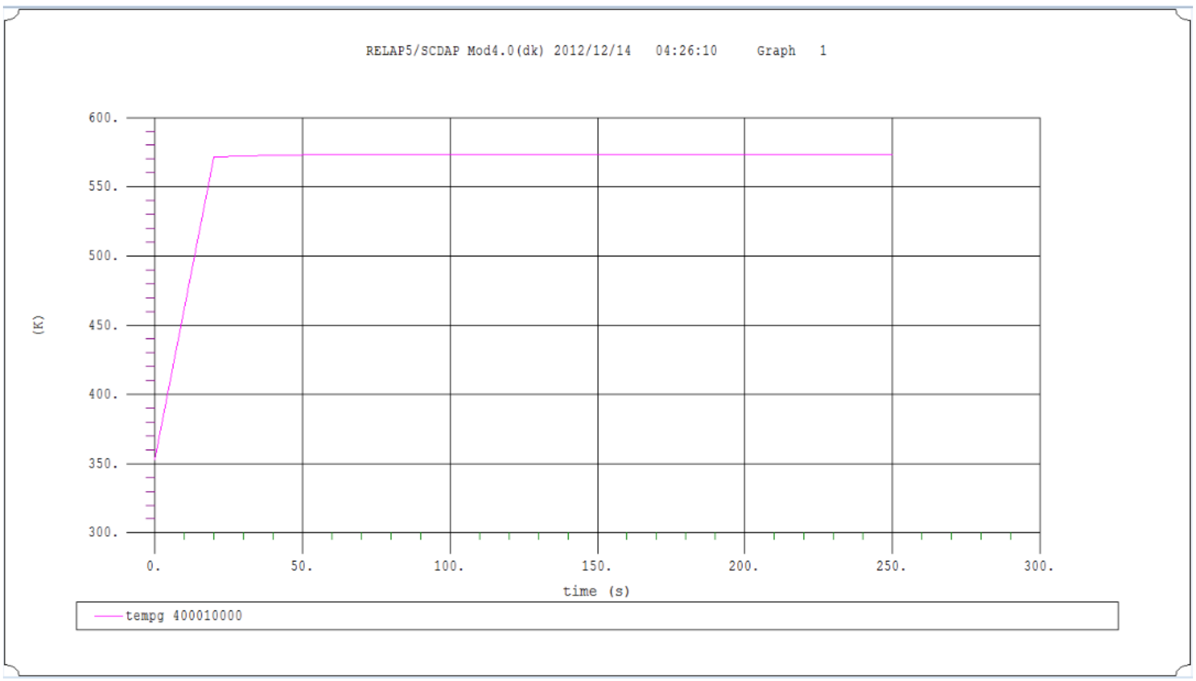

Figure B.5: Heat Tracing Graph for outlet Temperature

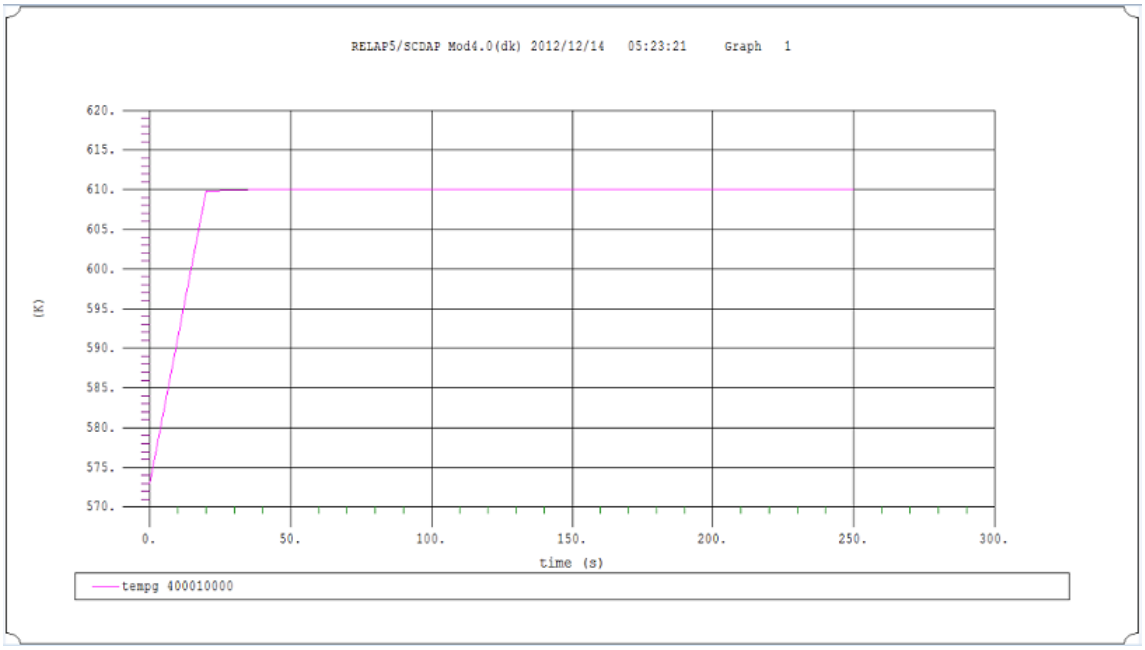

Figure B.6: First Wall 14 channel outlet Temperature

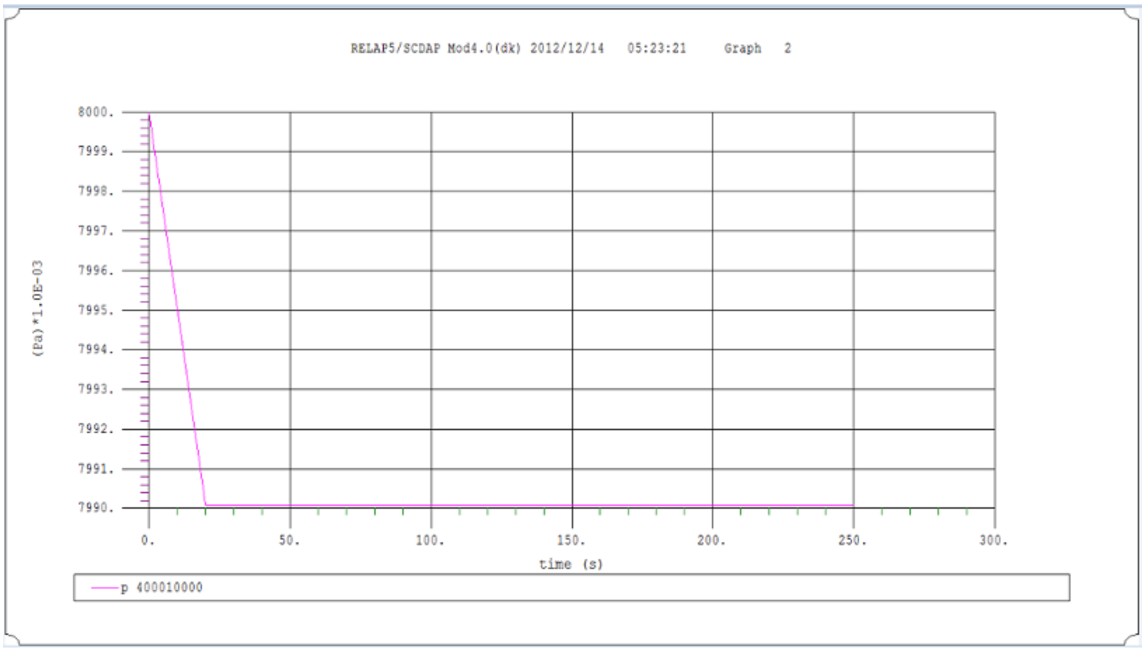

Figure B.7: First Wall 14 channel outlet Pressure

Figure B.8: First Wall 2 channel outlet Pressure

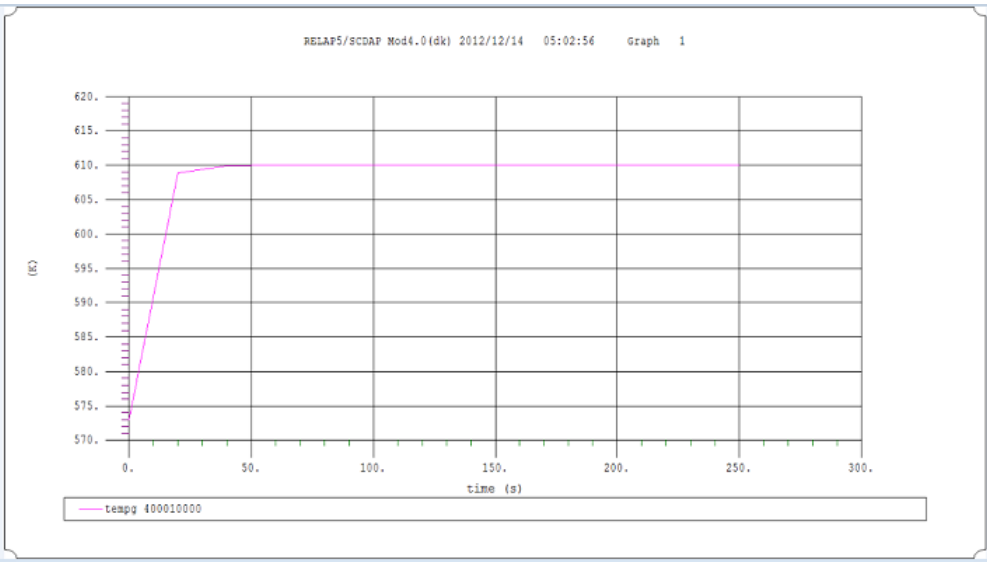

Figure B.9: First Wall 2 channel outlet Temperature