Report

Thermal-hydraulic study of the MEGAPIE-target with the computer code RELAP5

Author(s):
Sentís, Manuel Lorenzo

Publication Date:
2003

Permanent Link:
https://doi.org/10.3929/ethz-a-005071957

Rights / License:
In Copyright - Non-Commercial Use Permitted
Thermal-Hydraulic Study of the MEGAPIE-Target with the Computer Code RELAP5

Manuel Lorenzo Sentís

Dr. Friedrich Groeschel (PSI)
Prof. Mireia Piera Carreté (UNED)

July 10, 2003

Abstract:

The disposal of radioactive waste might decide the future of nuclear energy. Transmuting the radioactive waste by an Accelerator Driven System (ADS) might provide a solution to this problem. The protons coming from the accelerator carry out a spallation reaction with material of the target obtaining neutrons, which transmute plutonium, minor actinides and long-lived fission products into short-lived radioisotopes or stable nuclei. The feasibility however of the ADS system has still to be proven.

The MEGAPIE (MEGAwatt PIlot Experiment) project has the purpose of demonstrating the safety operation of a Lead-Bismuth spallation target with proton beam power of 1MW. One of the tasks of the MEGAPIE Project is to design an adequate cooling system of the liquid Lead-Bismuth Eutectic used as spallation source. This cooling system has the purpose of counteracting the enormous amount of heat given from the proton source to the Lead-Bismuth Eutectic and to the structural materials.

In this Report are shown the results of the experiments that were made with RELAP5, a computer simulation code adequate for thermal-hydraulic calculations. It was analyzed the thermal-hydraulics of the cooling system under normal and transient conditions.

Some changes were made in the general input deck of RELAP5 in order to better adapt the calculations to the reality and it has been come to the conclusion, that some further improvements should be made also in the control system.
# Table of Content

Introduction ................................................................................................................................. 4

1. The Thermal-Hydraulic System of MEGAPIE .......................................................................... 6
   1.1 Thermal-Physical Properties ....................................................................................... 10
       1.1.1 Convection Heat Transfer Correlations ............................................................ 11

2. Fundamentals .......................................................................................................................... 12
   2.1 The Thermal-Hydraulic Equations ................................................................................. 12
   2.2 Finite Differences .......................................................................................................... 15
       2.2.1 Explicit or Implicit Formulation ............................................................................ 16
       2.2.2 Advantages and Disadvantages of Explicit and Implicit Methods ....................... 19

3. The RELAP5 Numerical Analysis ......................................................................................... 22
   3.1 Nearly-Implicit Method ................................................................................................. 22
       3.1.1 First Step ............................................................................................................... 22
       3.1.2 Second Step ......................................................................................................... 31
   3.2 Semi-Implicit Method ..................................................................................................... 31
   3.3 Summary ........................................................................................................................ 31

4. RELAP5 Model ....................................................................................................................... 33
   4.1 Structure of RELAP5 Code .......................................................................................... 33
   4.2 Changes made in the Input Deck of RELAP5 ............................................................... 34
   4.3 Calculation of Heat Losses to the Exterior for Different Conditions ......................... 36
       4.3.1 Heat Loss for Steady State Conditions ................................................................. 38
       4.3.2 Heat Loss for Hot Standby Temperature of 240°C .............................................. 39
       4.3.3 Heat Loss for a Hot Standby Temperature of 230°C ........................................... 40
       4.3.4 Heat Loss for a Temperature of LBE of 140°C ................................................... 40
       4.3.5 Modeling of the Heat Loss with RELAP5 ........................................................... 41

5. Steady State Conditions .......................................................................................................... 43
   5.1 Steady State for Nominal Conditions ............................................................................. 43
       5.1.1 Heat Exchangers ................................................................................................. 43
       5.1.2 Inlet Temperatures to the Active Zone ................................................................. 44
   5.2 Steady State under Different Beam Power .................................................................... 48
   5.3 Steady State under Different Beam and Pump Power .................................................. 50
   5.4 Scaling of Steady State Conditions ................................................................................. 51
   5.5 Steady State under Different Cooling Conditions ....................................................... 52
       5.5.1 With a Number of Pins not Working Properly ..................................................... 52
       5.5.2 With Less Number of Pins .................................................................................. 53
   5.6 Steady State for the Test Conditions ............................................................................. 55

6. Transient Study ....................................................................................................................... 57
   6.1 Beam Trip ......................................................................................................................... 57
       6.1.1 Normal Beam Trip ............................................................................................... 57
       6.1.2 Protected Beam Trip ............................................................................................ 68
   6.2 Pump Trip ......................................................................................................................... 76
   6.3 Start Up of the Target ....................................................................................................... 84
   6.4 Shut Down of the Target .................................................................................................. 90
       6.4.1 Without Oil Pumping ............................................................................................ 90
       6.4.2 With Oil Pumping ................................................................................................. 95
       6.4.3 Conclusion ............................................................................................................ 104

7. Conclusions and Future Tasks ............................................................................................... 105
   7.1 Conclusions ..................................................................................................................... 105
   7.2 Future Tasks ..................................................................................................................... 106

Appendix A .................................................................................................................................. 107

References .................................................................................................................................... 117
Acknowledgements

I would like to thank F. Gröschel for giving me the opportunity of doing this thesis within the MEGAPIE project at PSI. I thank my professor of the UNED M. Piera Carreté for being willing to have my thesis done within this project. Thanks to W.H. Leung for showing me the basics of the RELAP5 code and to D. Lübbesmeyer and his assistant D. Spaziani for his excellent willingness to help me in obtaining an adequate graphic environment for RELAP5 and for answering doubts about the RELAP5 code. I thank also B. Sigg for having maintained with me a couple of very enlightening talks about the MEGAPIE project. Thanks also to my colleagues in the office: to S. Joray for having maintained with me very interesting and instructive talks about the MEGAPIE project, to F. Barbagallo who has shown me some experiments related to the MEGAPIE project. But above all, thanks to both for having made my stay at PSI very pleasant.

Thanks also to E. Schmider for the support and for having helped me in the realisation of many drawings of the work and in the correction of the text. Thanks also to my family for the constant support.
Introduction

The installation of the MEGAPIE project consists of the following subsystems:

- The Proton Source (620kW) provided by SINQ
- The Target system
- The Ancillary System

The Proton Source uses the SINQ facilities. SINQ is a neutron spallation source situated at the end of a cascade of three accelerators (a Cockcroft-Walton column and two cyclotrons). Protons enter the spallation source with energy of 570 Mev and roughly 1.2 mA, which results in a power of approximately 0.68 MW. Taking into account the heat losses of the external containment of the target this value reduces to 0.62 MW, which I use for the calculations with the computer simulation code RELAP5.

The Target System includes the spallation source filled with liquid Lead-Bismuth Eutectic (LBE), which has been studied to be the best solution, the LBE loops together with the main and bypass pumps, the oil-LBE heat exchanger, which has the purpose to remove the beam power, electrical controls, the material structures and an insulation filled with Helium.

The Ancillary System consist of the Fill & Drain System, the cover gas system, the expansion tank, the insulations’ gas system and the heat removal system. The latter is aimed to remove the heat given by the proton source and it includes the cooling systems formed by oil (Diphy1 THT), Lead-Bismuth Eutectic and water.

It is difficult to distinguish each subsystem because like every system the different parts are interrelated. For example one of the interchangers (the THX) of the heat removal system is included in the Target System.

This report is concentrated on the thermal-hydraulic system formed by the LBE loops and the oil loop. For the study of this multi-loop system I used the computer simulation code RELAP5. RELAP5 is a program written with Fortran77, used above all for the calculation of Loss of Coolant Accidents in reactors (LOCA). In reactors RELAP5 is usually used with two-phase systems (generally water and steam). However, RELAP5 can also be used to simulate one-phase systems. That is important because MEGAPIE is a three-fluid (three loop) as well as a one-phase system. The thermal-physical properties of the fluids LBE and oil THT and the dimensions of the elements were added to the input of RELAP5 by the Italian firm Ansaldo.

In appendix A I include a list of all material structures and hydraulic components with its main measures. These values were taken from the input deck of RELAP5 and compared with
the technical report of Ansaldo. It has been observed some divergences that should be corrected in the future.

In chapter 1 it will be explained the MEGAPIE project from a thermal-hydraulic point of view. In chapter 2 it will be made a brief review of the fundamental thermal-hydraulic equations and of the finite elements method. In chapter 3 it will be explained with some more detail the numerical methods used by RELAP5. In chapter 4 it will be explained the changes that it was made in the RELAP5 input in order to have a better approximation to the reality. It will be justified these changes with a table of calculations. In the chapters 5 and 6 it will be shown the results of my calculations, in chapter 5 for steady state calculations and in chapter 6 for transient calculations. In chapter 7 there are the conclusions and what might be necessary to do in the future taking into account that MEGAPIE is an evolving project.

In many figures of this report are indicated some characteristics of some elements of the thermal-hydraulic cycle from the calculations with RELAP5. In these figures the number of the elements refer to the Figure 14 on page 42. For example Temp-503(4) means the temperature of the volume element 4 of the hydrodynamic component 503 of Figure 14.
1. The Thermal-Hydraulic System of MEGAPIE

In Figure 1 are represented the basics of the thermal-hydraulic system of MEGAPIE. The system operates with three liquids:

- Lead-Bismuth Eutectic (LBE) used as spallation material and also as a coolant of the target materials
- Diphyl-THT Oil as a coolant of the LBE
- Water as a coolant of the oil

![Figure 1 Target and Intermediate Cooling Loop](image-url)
The system consists of three loops:

- The **Primary LBE Loop** with liquid Lead-Bismuth Eutectic (red)
- The **Intermediate Cooling Loop** (ICL) with the oil (green)
- The **Secondary Water Loop** (SWL) with water (blue)

The **Primary LBE Loop** includes two loops the *main loop* and the *bypass loop*. Both loops are in the target and Lead-Bismuth Eutectic (LBE) is chosen because of the good spallation properties and also because of the cooling properties for the materials in the target. The *main loop* goes through the beam window, where the heat given by the proton beam has to be removed, cools it, ascends through the Riser driven by the electromagnetic main pump until a branch at the upper volume of the target circuit. From this container the LBE enters into the 12 pins, which form the Target Heat Exchanger (THX). There the LBE is cooled by the oil (in the Figure 1 are represented only two pins, the others are symmetric in this concentric geometry). After the THX the LBE descends through the Downcomer annulus until reaching again the lower part of the target in the beam window completing the cycle. From the 40.6 kg/s (in nominal conditions) total mass flow rate going out of the THX, a tiny portion of it 3.5 kg/s is separated from the general flow through the *bypass loop*. This bypass flow is driven by the electromagnetic bypass pump. From the pump the fluid descends to the active zone through a pipe, the bypass pipe. In the active zone this flow mixes with the flow of the downcomer (37.1 kg/s) given again the nominal flow of 40.6kg/s. The purpose of the bypass loop is to cool the active zone more locally than the main flow. In Ref.[3] it was calculated the best geometry for the bypass pipe, as for example the form of the nozzle, the inclination, the orientation, also the height or gap between the beam window and the riser (see Figure 2) etc.

In the middle of the target is the **Central Rod**. It is an electrical heater of 22kW used to avoid the solidification of the LBE (at T=125°C) during the operation of the system. The **Intermediate Cooling Loop** (ICL) is aimed to cool the LBE, which is done by the Target Heat Exchanger (THX). The temperature of the outgoing fluid of this THX is regulated by a control system. This control system consists basically of the two valves indicated on the top of Figure 1 (also included as valves 740 and 741 in Figure 14 on page 42). The input for this control system are the inlet and outlet temperatures of the LBE in the THX. The regulation is based on maintaining the THX outlet temperature of the LBE in the *set point* of 230°C. In order to keep the set point of 230°C the two valves permit to pass more or less oil through the IHX or through the bypass line. For example if the LBE became warmer than the nominal conditions, the valve 740 (the upper valve on Figure 1) would open more and the 741 would close more. In this way passing through the heat exchanger IHX more fluid than before, the
oil would become colder and could transfer more heat from the LBE. On the contrary if the
LBE became colder, more oil would go through the bypass line and less through the IHX.
This loop has also an oil pump, an expansion tank in order to degas the oil, two other trip
valves that are either closed or open (valves 739 and 742 in Figure 14 on page 42) and the
Intermediate Heat Exchanger (IHX). This IHX exchanger cools the oil with water. It is a plate
heat exchanger with a number of modules depending on the power to be exchanged, each of
them with 8 effective plates.
The secondary water loop consists of several water loops, which cool the water itself and the
oil. These will not be studied here and in the RELAP5 input they are simulated simply by the
conditions at the inlet and at the outlet of the heat exchanger with the oil (IHX).
MEGAPIE Liquid Metal Target for SINQ conceptual draft

Figure 2 MEGAPIE Target and detail of the Window
1.1 Thermal-Physical Properties

Four materials are mainly used in the MEGAPIE project, the Lead–Bismuth Eutectic, the Oil THT, Steel and water. There are many tables for the last two.

However for the first two much less information exists. The phase diagram of lead-bismuth is shown in Figure 3. Important is the melting point at 125°C.

The melting of the LBE could be a serious danger for the installation. Therefore a heater in the central part of the target is added to the thermal–hydraulic loop in order to avoid the melting of the liquid metal.

The LBE has been chosen between Hg, Bi, and Pb because of its better properties, like low thermal neutron cross section, low radiation damage (except for the beam window), low activation of cooling water and also the fact that LBE is liquid in a wide range of temperatures, which is interesting for the heat removal in the target.

<table>
<thead>
<tr>
<th>Melting Temperature (°C)</th>
<th>Boiling Temperature (°C)</th>
<th>Heat of Melting(kJ/kg)</th>
<th>Density (kg/m³)</th>
<th>Heat capacity (kJ/kgK)</th>
<th>Thermal conductivity(W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solid</td>
<td>Liquid</td>
<td>Solid</td>
</tr>
<tr>
<td>123.5</td>
<td>1670</td>
<td>38.8</td>
<td>10474</td>
<td>10150</td>
<td>0.128</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.128</td>
<td>146</td>
<td>12.6</td>
</tr>
</tbody>
</table>

Table 1 Thermophysical properties of Lead-Bismuth Eutectic (LBE)

The Table 2 compares the thermal properties of the four materials of the MEGAPIE project.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Density ρ [Kg/m³]</th>
<th>Heat capacity c_p [J/Kg°K]</th>
<th>Conductivity k [W/m°K]</th>
<th>ρc_p</th>
<th>Diffusivity α [m²/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil THT (430°K)</td>
<td>9.10E+02</td>
<td>2.01E+03</td>
<td>1.06E-01</td>
<td>1.83E+06</td>
<td>5.78E-08</td>
</tr>
<tr>
<td>Steel (295°K)</td>
<td>7.87E+03</td>
<td>4.96E+02</td>
<td>1.50E+01</td>
<td>3.90E+06</td>
<td>3.85E-06</td>
</tr>
<tr>
<td>Water (298°K)</td>
<td>1.00E+03</td>
<td>4.19E+03</td>
<td>6.32E-01</td>
<td>4.19E+06</td>
<td>1.50E-07</td>
</tr>
<tr>
<td>LBE (568°K)</td>
<td>1.03E+04</td>
<td>1.46E+02</td>
<td>1.16E+01</td>
<td>1.50E+06</td>
<td>7.71E-06</td>
</tr>
</tbody>
</table>

Table 2 Thermophysical properties of materials in MEGAPIE
1.1.1 Convection Heat Transfer Correlations

The following correlations are included in the input deck of RELAP5:

- For LBE the following convection heat transfer correlation is used in the input of RELAP5:

\[
Nu = 5 + 0.025 (Re \ Pr)^{0.8}
\]

where \( Nu \) is the Nusselt number:

\[
Nu = \frac{h D_h}{k}
\]

\( Re \) and \( Pr \) the Reynolds and Prandtl numbers:

\[
Re = \frac{\rho u D_h}{\mu}
\]

\[
Pr = \frac{\nu}{\alpha}
\]

where \( h \) is the heat transfer coefficient, \( D_h \) the hydraulic diameter, \( \mu \) the dynamic viscosity and \( \nu \) the cinematic viscosity, \( \alpha \) the diffusivity.

Other correlations for the LBE in the literature are:

\[
Nu = \left(4.36 + 0.025 Pe^{0.8}\right)1.7 \left(\frac{D_h^{1.1 \rho_{in}}}{L}\right)^{0.16}
\]

see Ref.[8]

By making a numerical approximation in Ref.[9] it is obtained:

\[
Nu = 1.882 + 0.118 Pe^{0.8}
\]

(2)

- For water we use the Dittus-Boelter correlation:

\[
Nu = 0.023 Re^{0.8} Pr^{0.33}
\]

(3)

- For oil Diphy THT, see Ref.[8]:

\[
Nu = 0.021 Re^{0.8} Pr^{0.43}
\]

(4)
2. Fundamentals

2.1 The Thermal-Hydraulic Equations

The MEGAPIE project operates with a two-fluid (lead–bismut eutectic and oil THT) one-phase model. For each of these fluids the following thermal-hydraulic equations must be solved:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \]  Continuity equation  

\[ \rho \vec{g} - \nabla p + \nabla \cdot \tau = \rho \frac{d\vec{u}}{dt} \]  Momentum equation  

\[ \rho \frac{de}{dt} + \vec{u} \cdot \nabla p = \nabla \cdot \vec{q} + \nabla \cdot \left( \vec{u} \cdot \tau \right) \]  Energy equation  

where $\rho$ is the density, $\vec{u}$ the three-dimensional velocity, $\vec{g}$ the gravity vector, $p$ the pressure, $e$ the internal energy and $\tau$ the viscous stress tensor.

These equations can be written in a simplified form as:

\[ \frac{\partial (\rho \vec{u})}{\partial t} + \nabla (\rho \vec{u} \cdot \vec{u}) + \nabla \cdot (\vec{J}) - \rho \vec{\phi} = 0 \]  

Table 3

<table>
<thead>
<tr>
<th>Properties</th>
<th>Parameters</th>
<th>$\vec{\psi}$</th>
<th>$\vec{J}$</th>
<th>$\vec{\phi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>$\vec{u}$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Momentum</td>
<td>$\vec{u}$</td>
<td>$p I - \tau$</td>
<td>$\vec{g}$</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>$e + \vec{u} \cdot \vec{u}/2$</td>
<td>$\vec{q} + (p I - \tau) \vec{u}$</td>
<td>$\vec{g} \cdot \vec{u} + Q / \rho$</td>
<td></td>
</tr>
</tbody>
</table>
\[
\langle g \rangle = \frac{1}{V} \int_V g dV
\]  

(9)

where \( V = V(\tau, t) \) is an averaging volume variable in space and time and is assumed to be large enough to include a representative sample of the fluid in order to define a smoothly varying average.

We have for example for (8):

\[
\int \frac{\partial (\rho \vec{u})}{\partial t} dV + \int \nabla (\rho \vec{u} \cdot \vec{u}) dV + \int \nabla \cdot (\rho \vec{f}) dV - \int \rho \vec{f} dV = 0
\]

(10)

This last averaged formulation is still an instantaneous description of the flow and it will have high frequency variations, therefore we average in time the last equations to avoid the high frequency behavior of the instantaneous solution.

Using now the Leibnitz rule, Gauss theorem and taking into account that the flow is basically one-dimensional (x-direction), we arrive to the following three time-space averaged equations, where the variables have to be interpreted in a mean sense:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} = 0
\]

(11)

\[
\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} = -\frac{\partial p}{\partial x} - \frac{P}{A} f + \rho g \cos \theta
\]

(12)

\[
\frac{\partial (p e)}{\partial t} + \frac{\partial (p e u)}{\partial x} = \frac{P}{A} q - \frac{\partial u}{\partial x} + \frac{P}{A} f u
\]

(13)

where \( P \) is the perimeter of the channel, \( A \) the cross-sectional area, \( \theta \) the inclination of the channel with respect to the direction x and \( f \) the frictional pressure loss. The terms \( \frac{P}{A} f \) and \( \frac{P}{A} f u \) comes from \( \int \tau_x dP_x \) and \( \int \tau_x u dtdP_x \) and represent the force and work acting on the walls of the channel respectively. The unknown variables of (11), (12) and (13) are \( T, P \) and \( u \).

If we know the geometrical parameters \( P, A, \theta \) then we still need \( 7 - 3 = 4 \) relations (7 variables: \( u, p, e, \rho, T, f, q \)) in order to close the problem, first the Boussinesq approximation:

\[
\rho = \rho_0 \left[ 1 - \beta (T - T_0) \right]
\]

(14)

Where \( \beta = \beta(T) \) is the expansion coefficient, \( T_0, \rho_0 \) the temperature and density at inlet. The internal energy is:

\[ e = c_v T \]

(15)

and the friction is given by:
The parameter $\zeta$ is a dimensionless resistance coefficient, which includes effects due to form losses as well as wall roughness and is a function of the local Reynolds number $Re$ and the flow geometry. This coefficient is known from tables.

The heat from the wall can be modeled as:

$$q = h(T_w - T)$$ (17)

Where $h$ is the heat transfer coefficient, which is tabulated usually in terms of the Nusselt number:

$$Nu = \frac{hD_h}{k}$$ (18)

Where $D_h$ is the hydraulic diameter and $k$ is the thermal conductivity.

Considering the equations from (11) to (17), we see that we have three partial differential equations, four closure relations and seven variables, that is to say, we have a just-set system. Now since an analytical solution of (11), (12) and (13) does not exist, we discretise the equations from (11) to (17). The idea is to reduce the infinite unknown in the continuum space-time to a number of finite unknown in a discretised space-time grid. In this process the partial differential equations are reduced to finite difference equations. This method of discretise partial differential equations is called finite differences method.
2.2 Finite Differences

This method of solving partial differential equations is based in replacing the partial derivatives with suitable algebraic quotients, i.e. a finite difference.

Figure 4

If \( u^n_i \) represents the velocity at space \( i \) and at time \( n \), then we can do the following Taylor expansion:

\[
\begin{align*}
    u^n_{i+1} &= u^n_i + \left( \frac{\partial u}{\partial x} \right)_{i,n} \Delta x + \left( \frac{\partial^2 u}{\partial x^2} \right)_{i,n} \frac{(\Delta x)^2}{2} + \left( \frac{\partial^3 u}{\partial x^3} \right)_{i,n} \frac{(\Delta x)^3}{6} + \cdots \\
\end{align*}
\]

(19)

Thus we can write:

\[
\begin{align*}
    \left( \frac{\partial u}{\partial x} \right)_{i,n} &= \frac{u^n_{i+1} - u^n_i}{\Delta x} + \left( \frac{\partial^2 u}{\partial x^2} \right)_{i,n} \frac{(\Delta x)^2}{2} + \left( \frac{\partial^3 u}{\partial x^3} \right)_{i,n} \frac{(\Delta x)^3}{6} + \cdots \\
\end{align*}
\]

(20)

In this way we write:

\[
\begin{align*}
    \left( \frac{\partial u}{\partial x} \right)_{i,n} &= \frac{u^n_{i+1} - u^n_i}{\Delta x} + O(\Delta x) \\
\end{align*}
\]

(21)

In the same way it is easy to see that:

\[
\begin{align*}
    u^n_{i-1} &= u^n_i + \left( \frac{\partial u}{\partial x} \right)_{i,n} (-\Delta x) + \left( \frac{\partial^2 u}{\partial x^2} \right)_{i,n} \frac{(-\Delta x)^2}{2} + \left( \frac{\partial^3 u}{\partial x^3} \right)_{i,n} \frac{(-\Delta x)^3}{6} + \cdots \\
\end{align*}
\]

(22)

\[
\begin{align*}
    \left( \frac{\partial u}{\partial x} \right)_{i,n} &= \frac{u^n_i - u^n_{i-1}}{\Delta x} + O(\Delta x) \\
\end{align*}
\]

(23)

The sum of equations (21) and (23) gives us:
\[
\left( \frac{\partial u}{\partial x} \right)_{i,n} = \frac{u^n_{i+1} - u^n_{i-1}}{2\Delta x} + O(\Delta x)^2
\]

(24)

The last three approximations are correct and are different approximations to the same problem. For some problems it is better to use an approximation, for some other problems the other. Even in the same equation for example the heat conduction equation, it is sometimes much better to evaluate some terms at different grid points of Figure 4. We will see an example of it in the next paragraph for the one-dimensional heat conduction equation:

\[
\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}
\]

(25)

For the second partial derivatives, summing (19) and (22) we have:

\[
u^n_{i+1} + u^n_{i-1} = 2u^n_i + \left( \frac{\partial^2 u}{\partial x^2} \right)_{i,n} (\Delta x)^2 + \left( \frac{\partial^4 u}{\partial x^4} \right)_{i,n} \frac{(\Delta x)^4}{12} + \cdots
\]

(26)

\[
\left( \frac{\partial^3 u}{\partial x^3} \right)_{i,n} = \frac{u^n_{i+1} - 2u^n_i + u^n_{i-1}}{(\Delta x)^3} + O(\Delta x)^2
\]

(27)

2.2.1 Explicit or Implicit Formulation

The accuracy of the finite difference approximation for the time derivative and the stability of the procedure is dependent on the time level at which the flux terms in the conservation equation is evaluated. Three common time levels for evaluating the flux terms are shown below (on the Figure 5, Figure 6 and Figure 7 below). The points in space where the dependent variables are evaluated are denoted by the index \( i \) for this one-dimensional illustration. It has been assumed that the spatial difference terms in the flux require the values at \( x_{i-1}, x_i \) and \( x_{i+1} \) for the finite difference equation at \( x_i \). The points in space and time at which the values of the dependent variable appear in the finite difference equation are shown as the solid disks and are connected by the solid lines.
Forward Time Formulation

The “forward” formulation evaluates the spatial differences for the flux terms at the old time level, $t_n$, using the known values of the dependent variable. Thus, the difference approximation in time moves the solution forward from $t_n$ to $t_{n+1}$ since each finite difference equation has only one unknown (the value of the dependent variable at $x_i$ and $t_{n+1}$) the formulation is said to be an “explicit” procedure. That is to say only known values at time levels $n$, $n-1$, … are needed to advance the calculation to time level $n+1$.

For the heat equation (25) we have:

$$\frac{T_{i+1}^{n+1} - T_i^n}{\Delta t} = \alpha \frac{T_{i+1}^n - 2T_i^n + T_{i-1}^n}{(\Delta x)^2}$$  \hspace{1cm} (28)

That is to say:

$$T_{i+1}^{n+1} = T_i^n + \alpha \frac{\Delta t}{(\Delta x)^2} \left( T_{i+1}^n - 2T_i^n + T_{i-1}^n \right)$$  \hspace{1cm} (29)

Backward Time Formulation

The “backward” formulation evaluates the spatial differences for the flux terms on the new time level, $t_{n+1}$ using the yet unknown values of the dependent variable. Thus, the difference approximation in time couples the finite difference equation backwards in time to the known value of the dependent variable at the old time level, $t_n$. Each finite difference equation has
several (three in this illustration) unknown values of the dependent variable at the new time level. Since the dependent variable at the new time level has to be computed by solving a system of equations, this formulation is said to be an “implicit” procedure. That is to say in order to advance the calculation at level \( n+1 \) it is necessary to obtain a simultaneous solution of a system of equations at level \( n+1 \).

In this case we have for the heat equation (25):

\[
\frac{T_i^{n+1} - T_i^n}{\Delta t} = \alpha \left( \frac{T_{i+1}^{n+1} - 2T_i^{n+1} + T_{i-1}^{n+1}}{(\Delta x)^2} \right) \quad (30)
\]

That is to say:

\[
T_i^{n+1} = T_i^n + \alpha \left( \frac{\Delta t}{(\Delta x)^2} \right) \left( T_{i+1}^{n+1} - 2T_i^{n+1} + T_{i-1}^{n+1} \right) \quad (31)
\]

Similar equations are obtained for the points \( i-1 \) and \( i+1 \), in this way we obtain a system of equations with three unknown. The system is solved first for the boundary points of the space interval and then we obtain iteratively the other values for the dependent variable.

**Central Time Formulation**

![Figure 7](image)

The “central” approximation evaluates the flux terms at both the old and new time levels and uses an average value. It is central in the sense that the finite difference equation is centered between the old and new time levels. This method is also often known as the Crank-Nicholson procedure. It is also implicit as each finite difference equation will contain several unknown dependent variables. This method has a time truncation error that is second order correct. Stability analysis for this method applied to the parabolic problems show it to be unconditionally stable but is conditionally oscillatory if the problem has derivative (Neumann) boundary conditions.

In this case we have for the heat equation (25):

\[
\frac{T_i^{n+1} - T_i^n}{\Delta t} = \alpha \left( \frac{1}{2}(T_{i+1}^{n+1} + T_{i-1}^{n+1}) - \frac{1}{2}(2T_i^{n+1} + T_i^n) + \frac{1}{2}(T_{i+1}^{n+1} + T_{i-1}^{n+1}) \right) \quad (32)
\]
That is to say:

\[ T_i^{n+1} = T_i^n + \frac{\alpha}{2(\Delta x)} (T_{i+1}^n - 2T_i^n + T_{i-1}^n) + \frac{\alpha}{2(\Delta x)^2} (T_{i+1}^{n+1} - 2T_i^{n+1} + T_{i-1}^{n+1}) \]  \hspace{1cm} (33)

A combination of forward difference, backward difference, and/or central difference procedures may be used to solve the finite difference equations. For example, the implicit pressure-explicit saturation (IMPES) procedure uses the backward difference (implicit) procedure for pressures and the forward difference (explicit) procedure for saturations. On the other hand, there are totality implicit simulators, which use the backward difference (implicit) procedure for both pressure and saturations.

2.2.2 Advantages and Disadvantages of Explicit and Implicit Methods

Explicit Methods

**Advantage:**
Relatively simple to set up and program

**Disadvantages:**
For a given \( \Delta x, \Delta t \) must be less than some limit imposed of stability constraints. In many cases \( \Delta t \) must be very small to maintain stability. This can result in long computer running times to make calculations over a given interval of \( t \).

In the analysis of the stability of explicit methods appears the following number, called the Courant number:

\[ C = \frac{u \Delta t}{\Delta x} \]  \hspace{1cm} (34)

where \( u \) is the propagation velocity of the perturbation, and \( \Delta t, \Delta x \) the mesh sizes of time and space.

The stability requirement for the solution of a explicit difference equation is:

\[ C = \frac{u \Delta t}{\Delta x} \leq 1 \]  \hspace{1cm} (35)

which is known as the *Courant-Friedrichs-Lewy condition* (CFL condition). Many of the more precise applications of CFD (computational fluid dynamics) require close spaced grid points in some regions of the flow, which taking into account (35) would demand large
computer running times due to the small marching time $\Delta t$ required. This has made the implicit methods more attractive, because of the possibility of working with large time steps even for a fine grid.

As an example let us suppose that we begin with $\Delta x_1$ and $\Delta t_1$ so that $T = N_1 \Delta t_1$ is the total time interval if we wish to repeat the calculation with a halved mesh size $\Delta x_2 = \frac{\Delta x_1}{2}$ then

$$\Delta t_2 = C \frac{\Delta x_2}{u} = C \frac{\Delta x_1}{2u} = \frac{1}{2} \Delta t_1$$

$$\Delta t = \frac{\Delta x}{c}$$

Thus, to reach the same time $T$, twice as many time levels are required i.e.

$$T = N_2 \Delta t_2 = N_2 \frac{1}{2} \Delta t_1 = N_1 \Delta t_1$$

Furthermore, each time-level calculation takes twice as long, since $\Delta x_2 = \frac{\Delta x_1}{2}$ means there are twice as many node points in the field. Thus for the one-dimensional case, halving the mesh size increases the computer time 4-fold.

**Implicit Methods**

**Advantage:**
Stability can be maintained over much larger values of $\Delta t$ hence using considerably fewer time steps to make calculations over a given interval of $t$. This results in less computer running time.

**Disadvantages:**
- More complicated to set up and program.
- Since massive matrix manipulations are usually required at each time step, the computer time per time step is much larger than in the explicit approach.
- Since large $\Delta t$ can be taken, the truncation error is large, and the use of implicit methods to follow the exact transients (time variation of the independent variable) may not be as accurate as an explicit approach. However, for a time-dependent solution in which the steady state is the desired result, this relative time-wise inaccuracy is not important.
Although the use of implicit methods allows a large time step, it generally takes many interactions to solve that step. There is then no gain over just using the explicit method many times.

Many methods for steady problems can be regarded as solving an unsteady problem until a steady state is reached. The principal difference is that, when solving an unsteady problem, the two steps are chosen so that an accurate history is obtained, while, when a steady solution is sought, large time steps are used to try to reach the steady state quickly. Implicit methods are preferred for steady and slow-transient flows, because they have less stringent time step restrictions than explicit schemes (they may not have any).
3. The RELAP5 Numerical Analysis

RELAP5’s numerical approach to the equations (11), (12) and (13) combines the advantages and disadvantages of the explicit and implicit methods using a mixture of both methods. RELAP5 uses semi-implicit and nearly-implicit method.

The semi-implicit method is a one-step method, in which only one computational step is required to advance to a new time level. In contrast, the nearly-implicit method needs two steps to advance to a new time level. This method is used in the cases where it is necessary to reach the steady state in a fast way. The main difference between these two approaches is that the convective terms in the momentum equation are evaluated implicitly in the nearly-implicit method instead of explicitly as is done in the semi-implicit scheme, see equations (41) and (102).

We will analyze in the next section as an example the nearly implicit method.

3.1 Nearly-Implicit Method

3.1.1 First Step

Numerical Expression of the Conservation Equations

Our first purpose is to obtain the time marching solution of p and u, that is to say, we try to obtain recursive relations for the values $u^{n+1}$ and $p^{n+1}$ in function of the values $u^n$ and $p^n$. Doing this we will obtain a pressure Poisson-kind equation for values of $p^{n+1}$ in adjacent points of the staggered grid.
Figure 8 Normal and Staggered Grid

Using the methods of the former chapter the equations of conservation of mass (11), momentum (12) and energy (13) can be written:

\[
\frac{\rho_i^{n+1} - \rho_i^n}{\Delta t} + \frac{\left( \rho^n u_{i+1}^n \right)_{i+\frac{1}{2}} - \left( \rho^n u_{i-1}^n \right)_{i-\frac{1}{2}}}{\Delta x} = 0
\]

(36)

\[
\frac{\left( \rho^n u_{i+1}^n \right)_{i+\frac{1}{2}} - \left( \rho^n u_{i}^n \right)_{i-\frac{1}{2}}}{\Delta t} + \left[ \frac{\partial (\rho u^2)}{\partial x} \right]_{i+\frac{1}{2}} + \frac{p_{i+1}^{n+1} - p_i^{n+1}}{\Delta x} = -\frac{P}{A} f_{i+\frac{1}{2}} + \rho_{i+1}^n g \cos \theta
\]

(37)

\[
\frac{(\rho e)_i^{n+1} - (\rho e)_i^n}{\Delta t} + \frac{(\rho e u)_i^{n+1} - (\rho e u)_i^{n-1}}{\Delta x} + p_i^n \left[ \frac{u_{i+1}^{n+1} - u_{i-1}^{n+1}}{\Delta x} \right] = \frac{P}{A} \left( q_{i+1}^{n+1} + f_{i}^{n} u_{i}^{n} \right)
\]

(38)

where we define for any variable different from \( u \):

\[
x_{i+\frac{1}{2}} = s_{i+\frac{1}{2}} x_i + \left( 1 - s_{i+\frac{1}{2}} \right) x_{i+1}
\]

(39)

with:

\[
s_{i+\frac{1}{2}} = \begin{cases} 
1 & \text{if } u_{i+\frac{1}{2}} \geq 0 \\
0 & \text{if } u_{i+\frac{1}{2}} < 0
\end{cases}
\]

(40)
The velocities in these equations are evaluated at the **staggered grid** (the same grid as for the other variables but displaced $\Delta x/2$ to the right, see Figure 8). The reason for that is that this inclusion improves the consistency and the stability of the approach. A finite difference representation of a partial differential equation is said to be **consistent** when the difference equation reduces to the original differential equation as the number of grid points goes to infinity, i.e., as $\Delta x \to 0$. By solving the numerical approximation of the differential equation we obtain a difference between the real solution and the approximation that is called the error $\varepsilon_i^n$ (for each grid point). If the error $\varepsilon_i^n$ shrinks or remains the same as the solution progresses from step $n$ to $n+1$ the solution is **stable**. If the error $\varepsilon_i^n$ grows then the solution is unstable.

The term \( \frac{\partial (\rho u^2)}{\partial x} \) is evaluated at \( i+\frac{1}{2} \) because it includes velocities and these are evaluated in the staggered grid.

To achieve a fast execution speed, implicit evaluation is used only for those terms responsible for the sonic wave propagation time step limit and those phenomena known to have small time constants. Thus implicit evaluation is used for the velocity in the convective terms of the mass and energy equations, for the velocity and pressure included in the viscous transport terms of the momentum equation (that is to say for the pressure and viscous tensor terms), for the convective term of the momentum equation and also for the heat of the energy equation.

To further increase the computing speed, time-level evaluations are selected so that the resulting implicit terms are linear in the new time variables. Linearity results in high computing speed by eliminating the need to iteratively solve systems of nonlinear equations.

In order to increase computational speed we linearise the friction term in equation (37).

The nonlinear term of equation (37) is developed as follow:

\[
\left[ \frac{\partial (\rho u^2)}{\partial x} \right]_{i+\frac{1}{2}}^{n+1} = \frac{1}{\Delta x} \left\{ \rho u^2_{i+\frac{1}{2}}^{n+1} - [\rho u^2]_{i+\frac{1}{2}}^{n+1} \right\} = \frac{1}{\Delta x} \rho^n_{i+\frac{1}{2}} \left( \frac{u_{i+\frac{1}{2}}^{n+1} + u_{i+\frac{1}{2}}^{n+1}}{2} \right)^2 - \frac{1}{\Delta x} \rho^n_{i+\frac{1}{2}} \left( \frac{u_{i+\frac{1}{2}}^{n+1} + u_{i+\frac{1}{2}}^{n+1}}{2} \right)^2 \\
= \frac{1}{4\Delta x} \rho^n_{i+\frac{1}{2}} \left( u_{i+\frac{1}{2}}^{n} + u_{i+\frac{1}{2}}^{n} \right) \left[ \frac{2}{2} \left( u_{i+\frac{1}{2}}^{n+1} + u_{i+\frac{1}{2}}^{n+1} \right) - \left( u_{i+\frac{1}{2}}^{n} + u_{i+\frac{1}{2}}^{n} \right) \right] - \\
- \frac{1}{4\Delta x} \rho^n_{i+\frac{1}{2}} \left( u_{i+\frac{1}{2}}^{n} + u_{i+\frac{1}{2}}^{n} \right) \left[ \frac{2}{2} \left( u_{i+\frac{1}{2}}^{n+1} + u_{i+\frac{1}{2}}^{n+1} \right) - \left( u_{i+\frac{1}{2}}^{n} + u_{i+\frac{1}{2}}^{n} \right) \right]
\]

That is to say:

\[
\left[ \frac{\partial (\rho u^2)}{\partial x} \right]_{i+\frac{1}{2}}^{n+1} = \rho^n_{i+\frac{1}{2}} \frac{1}{\Delta x} \left[ u_{i+\frac{1}{2}}^{n} \left( u_{i+\frac{1}{2}}^{n+1} + u_{i+\frac{1}{2}}^{n+1} \right) - (u^2)_{i+\frac{1}{2}}^{n} \right] - \rho^n_{i+\frac{1}{2}} \frac{1}{\Delta x} \left[ u_{i+\frac{1}{2}}^{n} \left( u_{i+\frac{1}{2}}^{n+1} + u_{i+\frac{1}{2}}^{n+1} \right) - (u^2)_{i+\frac{1}{2}}^{n} \right] \\
\]

(41)
Where the values required at the normal grid of the velocities \((u_n^\ast, u_i^\ast)\) are obtained by averaging the nearest points of the staggered grid, for example:

\[
u_i^n = \frac{u_i^{n+1} + u_i^{n-1}}{2} \tag{42}\]

The friction term (16) is linearised as follow:

\[
f_{i,\frac{1}{2}}^{n+1} = \frac{1}{2}(\rho \zeta)^n_i \frac{1}{\Delta x} \left[ \left( u_i^{n+1} + u_i^{n-1} \right) \right] = \pm \frac{1}{2}(\rho \zeta)^n_i \left[ u_i^{n+1} + \left( u_i^{n+1} - u_i^{n-1} \right) \right] = \pm \frac{(\rho \zeta)^n_i}{2} (2u_i^{n+1} - u_i^{n-1}) + o(u_i^{n+1} - u_i^{n-1}) \approx \frac{1}{2} (2s_i^{n+1} - 1) (\rho \zeta)^n_i \left( 2u_i^{n+1} - u_i^{n-1} \right) \tag{43}\]

where \(s_{i,\frac{1}{2}}\) was defined in (40) and we have used a Taylor expansion of first order in the time.

For the convective term in the energy equation (38) we make the following approximation:

\[
\frac{\left(\rho e\right)_i^{n+1} - \left(\rho e\right)_i^{n-1}}{\Delta x} \approx \frac{1}{\Delta x} \left( \left(\rho e\right)_i^{n+1} u_i^{n+1} - \left(\rho e\right)_i^{n-1} u_i^{n-1} \right) \tag{44}\]

The heat term of (38) is evaluated as:

\[
q_i^{n+1} = h_i^n (T_w - T_i^{n+1}) \tag{45}\]

where \(T_w\) is the temperature of the wall limiting the target with the exterior.

Now we substitute all these expressions in (36), (37) and (38), we consider the variables with superscript \(n\) as known and the ones with \(n+1\) as unknown.

We have for example for the continuity equation (36):

\[
\rho_i^{n+1} + \Delta t \frac{\rho_i^n}{\Delta x} u_i^{n+1} - \Delta t \frac{\rho_i^n}{\Delta x} u_i^{n-1} = \frac{\rho_i^n}{\Delta t} \tag{46}\]

\[
\begin{array}{|c|c|}
\hline
\rho_i^{n+1} + K_{11} u_i^{n+1} - K_{12} u_i^{n-1} = K_{13} \\
\hline
\end{array}
\]

Conservation of Mass

where previous-time known values are:

\[
K_{11} = \Delta t \frac{\rho_i^n}{\Delta x} \tag{47}\]

\[
K_{12} = \Delta t \frac{\rho_i^n}{\Delta x} \tag{48}\]

\[
K_{13} = \frac{\rho_i^n}{\Delta t} \tag{49}\]
and for the values in the staggered grid of all variables except $u$ we consider (39). It is necessary to remark that the $K$ values depend on $i$, but it is not written in order to not complicate more the notation.

In the same way we have for the momentum equation (37), using (41) and (43):

$$
\left(\rho^{n+1} u^{n+1}\right)_{i+\frac{1}{2}} - \left(\rho^n u^n\right)_{i+\frac{1}{2}} \frac{\Delta t}{\Delta x} + \rho^n_{i+\frac{1}{2}} \frac{1}{\Delta x} \left[u^n_{i+\frac{1}{2}} \left(u^n_{i+\frac{1}{2}} + u^n_{i+\frac{1}{2}}\right) - (u^n)^2\right] - \rho^n_{i+\frac{1}{2}} \frac{1}{\Delta x} \left[u^n_{i+\frac{1}{2}} + u^n_{i+\frac{1}{2}}\right] - (u^n)^2\right] - \rho^n_{i+\frac{1}{2}} \frac{1}{\Delta x} \left[u^n_{i+\frac{1}{2}} + u^n_{i+\frac{1}{2}}\right] - (u^n)^2\right] + \frac{p^{n+1}_{i+\frac{1}{2}} - p^n_{i+\frac{1}{2}}}{\Delta x} = -\frac{P}{A} \left[2s_{i+\frac{1}{2}} - 1\right] \frac{1}{2} \left(\rho \zeta\right)_{i+\frac{1}{2}} \left(2u^n_{i+\frac{1}{2}} - u^n_{i+\frac{1}{2}}\right) + \rho^n_{i+\frac{1}{2}} \rho \cos \theta
$$

From here it is not difficult to see the result:

$$K_{21} u_{i+\frac{1}{2}}^{n+1} + K_{22} u_{i+\frac{1}{2}}^{n+1} + K_{23} u_{i+\frac{1}{2}}^{n+1} + K_{24} \left(p^{n+1}_{i+\frac{1}{2}} - p^n_{i+\frac{1}{2}}\right) = K_{25}$$

Conservation of Momentum

With the $K$ values ($i$ depending):

$$K_{21} = -\frac{\Delta t}{\Delta x} \rho^n_i u_i^n$$

$$K_{22} = \rho^n_i + \frac{\Delta t}{\Delta x} \left(\rho^n_{i+1} u^n_{i+1} - \rho^n_i u^n_i\right) + \frac{\Delta t}{\Delta x} \left(2s_{i+\frac{1}{2}} - 1\right) \left(\rho \zeta\right)_{i+\frac{1}{2}}$$

$$K_{23} = \frac{\Delta t}{\Delta x} \rho^n_{i+1} u^n_{i+1}$$

$$K_{24} = \frac{\Delta t}{\Delta x}$$

$$K_{25} = \rho^n_{i+\frac{1}{2}} u^n_{i+\frac{1}{2}} + \frac{\Delta t}{\Delta x} \left[\rho^n_i \left(u^2\right)_{i+\frac{1}{2}} - \rho^n_i \left(u^2\right)_{i+\frac{1}{2}}\right] + \frac{\Delta t}{\Delta x} \rho^n_{i+\frac{1}{2}} \rho \cos \theta + \frac{\Delta t}{\Delta x} \left(2s_{i+\frac{1}{2}} - 1\right) \frac{1}{2} \left(\rho \zeta\right)_{i+\frac{1}{2}} u^n_{i+\frac{1}{2}}$$

For the energy equation we need first some relations:

From the Boussinesq approximation (14), we have:

$$\Delta \rho^n = \rho^{n+1} - \rho^n = -\beta \rho^n \left(T^{n+1} - T^n\right)$$

We can also put the equation (15) in the following form:

$$\left(\rho c_T\right)^{n+1} - \left(\rho c_T\right)^n = c_v \left(\rho^{n+1} + \Delta \rho^n \left(T^{n+1} + \Delta T^n\right) - c_v \left(\rho T\right)^n\right) = c_v \left(\rho^{n+1} - \rho^n \left(T^{n+1} - T^n\right)\right)$$

where we have used (57). In this way we have the temperature and density increments:
\[ T_i^{n+1} - T_i^n = \frac{1}{c_i (\rho_i^n - \beta \rho_0 T_i^n)} [ (\rho e)_i^{n+1} - (\rho e)_i^n ] \]  

(59)

\[ \rho_i^{n+1} - \rho_i^n = \frac{-\beta \rho_0}{c_i (\rho_i^n - \beta \rho_0 T_i^n)} [ (\rho e)_i^{n+1} - (\rho e)_i^n ] \]  

(60)

Using these relations we have for the energy equation (38), taking into account the term (44):

\[ \frac{(\rho e)_i^{n+1} - (\rho e)_i^n}{\Delta t} + \frac{1}{\Delta x} \left[ (\rho e)_i^{n+1} u_i^{n+1} - (\rho e)_i^n u_i^n \right] + \frac{p_i^n}{\Delta x} = \frac{P}{A} \left[ h_i^n \left( T_i^n - T_i^n \right) - \left( T_i^{n+1} - T_i^n \right) \right] + f_i^n u_i^n \]  

(61)

With this expression and the above (59), it is easy to obtain from the energy equation (38):

\[
K_{31} (\rho e)_i^{n+1} + K_{32} u_i^{n+1} + K_{33} u_i^{n+1} = K_{34}
\]

Conservation of Energy  

(62)

With the following K values:

\[ K_{31} = \frac{1}{1 + \Delta t \frac{P}{A} \frac{h_i^n}{c_i (\rho_i^n - \beta \rho_0 T_i^n)}} \]  

(63)

\[ K_{32} = \frac{\Delta t}{\Delta x} \left[ (\rho e)_i^{n+1} + p_i^n \right] \]  

(64)

\[ K_{33} = -\frac{\Delta t}{\Delta x} \left[ (\rho e)_i^n + p_i^n \right] \]  

(65)

\[ K_{34} = \left( \rho e \right)_i^n + \Delta t \frac{P}{A} h_i^n \left[ \left( T_i^n - T_i^n \right) + \Delta t \frac{1}{c_i (\rho_i^n - \beta \rho_0 T_i^n)} (\rho e)_i^n \right] + f_i^n u_i^n \]  

(66)

**Recursive Relation for the Pressure**

The next objective is by means of the equations (46), (51) and (62) by successive elimination steps to obtain a finite difference equation for the pressure.

First we begin with equations (46), (62) and (60) and try to eliminate the terms \( \rho_i^{n+1} \) and \( (\rho e)_i^{n+1} \), we will use the shorter notation:

\[ \sigma := \frac{c_i (\rho_i^n - \alpha \rho_0 T_i^n)}{\alpha \rho_0} \]  

(67)

then we have:

\[ (\rho e)_i^{n+1} = \sigma (\rho_i^{n+1} - \rho_i^n) + (\rho e)_i^n \]  

(68)
\[ \rho_i^{n+1} = -K_{11} u_{i,\frac{1}{2}}^{n+1} + K_{12} u_{i-\frac{1}{2}}^{n+1} + K_{13} \]  

(69)

\[ K_{31} \left[ \sigma \left( -K_{11} u_{i,\frac{1}{2}}^{n+1} + K_{12} u_{i-\frac{1}{2}}^{n+1} + K_{13} - \rho_i^n \right) + (\rho_i^e)_n \right] + K_{32} u_{i,\frac{1}{2}}^{n+1} + K_{33} u_{i-\frac{1}{2}}^{n+1} = K_{34} \]  

(70)

That is to say:

\[ K_{41} u_{i,\frac{1}{2}}^{n+1} + K_{42} u_{i-\frac{1}{2}}^{n+1} = K_{43} \]  

(71)

with:

\[ K_{41} = K_{32} - \sigma K_{11}, K_{31} \]  

(72)

\[ K_{42} = \sigma K_{12} K_{31} + K_{33} \]  

(73)

\[ K_{43} = K_{44} - \sigma K_{31} (K_{13} - \rho_i^n) - \sigma K_{31} (\rho_i^e)_n \]  

(74)

All these K values depend on i, because they were calculated for this cell, for the adjacent cells we have:

\[ K_{41}^+ u_{i,\frac{1}{2}}^{n+1} + K_{42}^+ u_{i-\frac{1}{2}}^{n+1} = K_{43}^+ \]  

(75)

\[ K_{41}^- u_{i,\frac{1}{2}}^{n+1} + K_{42}^- u_{i-\frac{1}{2}}^{n+1} = K_{43}^- \]  

(76)

where the + and – mean K values for the i+1 cell and i-1 cell respectively.

The discretised momentum equation (51) was derived for the staggered grid that is for the cell i+1/2, the equation for the adjacent cell i-1/2 is:

\[ K_{21} u_{i,\frac{1}{2}}^{n+1} + K_{22} u_{i+\frac{1}{2}}^{n+1} + K_{23} u_{i-\frac{1}{2}}^{n+1} + K_{24} \left( \rho_{i+1}^{n+1} - \rho_i^{n+1} \right) = K_{25} \]  

\[ K_{21}^- u_{i,\frac{1}{2}}^{n+1} + K_{22}^- u_{i+\frac{1}{2}}^{n+1} + K_{23}^- u_{i-\frac{1}{2}}^{n+1} + K_{24}^- \left( \rho_{i+1}^{n+1} - \rho_{i-1}^{n+1} \right) = K_{25}^- \]  

(77)

\[ K_{41}^+ u_{i,\frac{1}{2}}^{n+1} + K_{42}^+ u_{i-\frac{1}{2}}^{n+1} = K_{43}^+ \]  

\[ K_{41}^- u_{i,\frac{1}{2}}^{n+1} + K_{42}^- u_{i-\frac{1}{2}}^{n+1} = K_{43}^- \]  

\[ K_{41}^- u_{i,\frac{1}{2}}^{n+1} + K_{42}^- u_{i+\frac{1}{2}}^{n+1} = K_{43}^- \]  

\[ K_{41}^+ u_{i,\frac{1}{2}}^{n+1} + K_{42}^+ u_{i+\frac{1}{2}}^{n+1} = K_{43}^+ \]  

We have now 5 equations (51), (71), (75), (76), (77), with which we will eliminate the four velocities \( u_{i,\frac{1}{2}}^{n+1}, u_{i+\frac{1}{2}}^{n+1}, u_{i+\frac{1}{2}}^{n+1}, u_{i-\frac{1}{2}}^{n+1} \).

From (75) and (51):

\[ u_{i,\frac{1}{2}}^{n+1} = \frac{1}{K_{41}} \left( K_{43}^+ - K_{43}^- u_{i,\frac{1}{2}}^{n+1} \right) \]  

(78)

\[ K_{21} u_{i,\frac{1}{2}}^{n+1} + K_{22} u_{i+\frac{1}{2}}^{n+1} + K_{23} \frac{1}{K_{41}} \left( K_{43}^+ - K_{43}^- u_{i+\frac{1}{2}}^{n+1} \right) + K_{24} \left( \rho_{i+1}^{n+1} - \rho_i^{n+1} \right) = K_{25} \]  

(79)
substituting now \( u_{i-\frac{1}{2}}^{n+1} \) from (71):

\[
\frac{K_{21}}{K_{42}} \left( K_{43} - K_{41}u_{i-\frac{1}{2}}^{n+1} \right) + K_{22}u_{i-\frac{1}{2}}^{n+1} + K_{23} \frac{1}{K_{41}} \left( K_{43} - K_{42}u_{i-\frac{1}{2}}^{n+1} \right) + K_{24} \left( p_{i+1}^{n+1} - p_{i-1}^{n+1} \right) = K_{25} \quad (80)
\]

That is to say:

\[
K_{51}u_{i-\frac{1}{2}}^{n+1} + K_{52} \left( p_{i+1}^{n+1} - p_{i-1}^{n+1} \right) = K_{53} \quad (81)
\]

with:

\[
K_{51} = -\frac{K_{21}}{K_{42}} K_{41} + K_{22} - K_{23} \frac{K_{42}^{+}}{K_{41}}
\]

\( K_{52} = K_{24} \) \( (83) \)

\[
K_{53} = K_{25} - \frac{K_{21}}{K_{42}} K_{43} - K_{23} \frac{K_{43}^{+}}{K_{41}}
\]

\( (84) \)

In a same way from (76) and (77) we can eliminate \( u_{i-\frac{1}{2}}^{n+1} \):

\[
u_{i-\frac{1}{2}}^{n+1} = \frac{1}{K_{42}} \left( K_{43} - K_{41}u_{i-\frac{1}{2}}^{n+1} \right)
\]

\( (85) \)

\[
K_{21} \frac{1}{K_{42}} \left( K_{43} - K_{41}u_{i-\frac{1}{2}}^{n+1} \right) + K_{22}u_{i-\frac{1}{2}}^{n+1} + K_{23}u_{i-\frac{1}{2}}^{n+1} + K_{24} \left( p_{i+1}^{n+1} - p_{i-1}^{n+1} \right) = K_{25}^{-}
\]

\( (86) \)

\[
u_{i-\frac{1}{2}}^{n+1} = \frac{K_{43} - K_{41}u_{i-\frac{1}{2}}^{n+1}}{K_{42}}
\]

Substituting now \( u_{i-\frac{1}{2}}^{n+1} \) from (71):

\[
K_{21} \frac{1}{K_{42}} \left( K_{43} - K_{41}u_{i-\frac{1}{2}}^{n+1} \right) + K_{22} \frac{K_{43} - K_{41}u_{i-\frac{1}{2}}^{n+1}}{K_{42}} + K_{23}u_{i-\frac{1}{2}}^{n+1} + K_{24} \left( p_{i+1}^{n+1} - p_{i-1}^{n+1} \right) = K_{25}^{-}
\]

\( (87) \)

That is to say:

\[
K_{61}u_{i-\frac{1}{2}}^{n+1} + K_{62} \left( p_{i+1}^{n+1} - p_{i-1}^{n+1} \right) = K_{63}
\]

\( (88) \)

With:

\[
K_{61} = \frac{K_{21}^{-}}{K_{42}^{-}} K_{41}^{-} - K_{22}^{-} K_{41}^{-} \frac{K_{42}^{-}}{K_{42}^{-}} + K_{23}^{-}
\]

\( (89) \)

\[
K_{62} = K_{24}^{-}
\]

\[
K_{63} = K_{25}^{-} - \frac{K_{21}^{-}}{K_{42}^{-}} K_{43}^{-} + \frac{K_{21}^{-}}{K_{42}^{-}} K_{41}^{-} K_{42}^{-} - \frac{K_{22}^{-}}{K_{42}^{-}} K_{43}^{-}
\]

\( (90) \)
Now from (81) and (88) we can eliminate finally $u_{i+1}^n$:

$$u_{i+1}^n = \frac{1}{K_{61}} \left( K_{63} - K_{62} \left( p_{i+1}^n - p_{i-1}^n \right) \right)$$  \hspace{1cm} (91)

$$K_{51} \frac{1}{K_{61}} \left( K_{63} - K_{62} \left( p_{i+1}^n - p_{i-1}^n \right) \right) + K_{52} \left( p_{i+1}^n - p_i^n \right) = K_{53}$$  \hspace{1cm} (92)

and finally we have:

$$A p_{i+1}^n + B p_i^n + C p_{i-1}^n = D$$  \hspace{1cm} (93)

with:

$$A = K_{52}$$  \hspace{1cm} (94)

$$B = - K_{51} \frac{K_{62}}{K_{61}} - K_{52}$$  \hspace{1cm} (95)

$$C = K_{51} \frac{K_{62}}{K_{61}}$$  \hspace{1cm} (96)

$$D = K_{53} - K_{51} \frac{K_{63}}{K_{61}}$$  \hspace{1cm} (97)

If the number of cells is $N+2$, for the internal cells that is to say from the cell 1 to the N-1 we can apply (93) but for boundary cells we need two equations more.

For example if we know the pressures at the inlet $p_0^n$ and at the outlet $p_N^n$, the next and previous pressure can be calculated using linear interpolation as:

$$p_i^n = \frac{2p_0^n + p_2^n}{3}$$  \hspace{1cm} (98)

$$p_N^n = \frac{2p_{N-1}^n + p_N^n}{3}$$  \hspace{1cm} (99)

One solves (93) recursively with the help of the last two boundary conditions for the first and last cells.

From equation (98) we obtain for the time step $n+1$ $p_2$ in function of $p_1$ then from (93) at cell 2 we obtain $p_3$ in function of $p_1$ etc. At cell N-1 we obtain from (93) the pressure $p_N$ in function of $p_1$ and finally from equation (99) we obtain $p_1$.

From the values of the pressure for all the cells it is straightforward to calculate the other variables. For the velocities one uses (80) or (86). The densities are obtained from (46). The internal energies are obtained from (62) and finally the temperatures are obtained from (59).

This is the first step of the nearly-implicit method.
3.1.2 Second Step

The second step of this method is used to stabilize the convective terms in the mass and energy balance equations. This step uses the values of the velocities of the first step in order to calculate new values for the density and internal energy for the time \( n+1 \). The principal difference of this step is that the continuity and energy equations have the convected variables evaluated at the \( n+1 \) time level, as compared to their explicit evaluation in the first step.

The two equations to be solved in this step are:

\[
\frac{\rho_i^{n+1} - \rho_i^n}{\Delta t} + \frac{(\rho_i^{n+1} u_i^{n+1})_{i+\frac{1}{2}} - (\rho_i^{n+1} u_i^{n+1})_{i-\frac{1}{2}}}{\Delta x} = 0
\]

\[
\frac{(\rho e)_i^{n+1} - (\rho e)_i^n}{\Delta t} + \frac{1}{\Delta x} \left[ (\rho_i^{n+1} e_i^{n+1})_{i+\frac{1}{2}} u_i^{n+1} - (\rho_i^{n+1} e_i^{n+1})_{i-\frac{1}{2}} u_i^{n+1} \right] + p_i^n \left[ \frac{u_i^{n+1} - u_i^{n+1}}{\Delta x} \right] = \frac{P}{A} \left( q_i^{n+1} + f_i^n u_i^n \right)
\]

From these two equations are obtained the new values of density \( \rho^{n+1} \) and internal energy \( e^{n+1} \).

The velocities are taken from the former step.

3.2 Semi-Implicit Method

For the semi-implicit method one uses for the convective term of the equation of the conservation of the momentum instead of (41) the following approximation:

\[
\left[ \frac{\partial (\rho u^2)}{\partial x} \right]_i^n = \rho_i^n \frac{1}{\Delta x} (u_i^n)^2 - \rho_i^n \frac{1}{\Delta x} (u_i^n)^2
\]

Except this change the procedure is similar to the one shown before for the nearly-implicit method. This method consists only of one step.

3.3 Summary

RELAP5 uses a special numerical method. The advantage in relation with pure finite differences method is that it permits to vary in a bigger order the magnitude of the mesh size and of the time step. In the case of MEGAPIE these methods permit to have big mesh size as we can see in the diagram of volume elements of Figure 14 on page 42.
In RELAP5 according to the problem to be handled it is used a semi-implicit method or a nearly-implicit method. The first one is a one-step method and is used when we want to study transient processes or variations of a variable for a close time interval. The nearly-implicit method is a two-step method and is used in order to reach some steady conditions in a fast way, in this case is the steady state in which we are interested and no in the process of reaching this state. This steady state is often an initial condition for a transient calculation. In this chapter I have shown the numerical basics of the nearly-implicit method.

Using a three-dimensional model can be in many cases prohibitive because a simulation would require many computational steps in comparison with a one-dimensional one. Besides, using a one-dimensional model we need much less constitutive relations, which simplifies the calculation a lot. In case of RELAP5 it is used a one-dimensional model that has been proven to be adequate by calculating with nuclear reactors. In order to justify a reduction to one spatial dimension, we must assume or know from additional information that the flow parameters are either constant, vary slowly with respect to the y and z directions, and/or are symmetric with respect to the x direction. In this approximation the parameters of the flow are a volume average.
4. RELAP5 Model

4.1 Structure of RELAP5 Code

In the Diagram on page 42 there is a representation of the volume elements into which the thermal-hydraulic system of MEGAPIE is divided in order to do the RELAP5 calculations. The thermal-hydraulic system in RELAP5 consists of two kinds of elements:

- Hydrodynamic Components
- Heat Structures

The Hydrodynamic Components (in white in the Diagram on page 42) consist of hydraulic pipes (p in the diagram) or annulus (symbol a, and ring-shaped cross section), which are linked by another element. In MEGAPIE this element can be a branch (b), a pump (p), a valve (v) or a junction (j). Each of these components can have one or more volumes. The Hydrodynamic Components models the characteristics of the flow, such as the type of fluid flowing, or the flow cross sections etc.

The Heat Structures (in blue in the Diagram on page 42) are used to model the materials of the target (in general steel), to model the heat exchange of the fluids circulating and also the heat exchange with the exterior.

The main characteristics of the input deck of RELAP5 have been introduced by the firm Ansaldo. The input includes the principal geometrical measures of all the volumes in the loops (pipes, channels etc.). In Appendix A it has been included a table of all the components with their measures and I have compared the values given by Ansaldo with the ones it has been used in the input deck of RELAP5.

The characteristic curves of the pump are also put into the input. For the two LBE pumps the pressure is given as a function of the flow rate for each electrical current. For the oil pump the pressure is given as a function of the flow rate for each rotation speed.

The twelve pins of the THX have been simulated as a single equivalent heat exchanger. The IHX heat exchanger is a plate heat exchanger with three modules of eight plates each. It has been simulated also as a single equivalent plate heat exchanger.
4.2 Changes made in the Input Deck of RELAP5

In order to improve the approximation of the model to the reality it has been made the following changes in the input deck of RELAP5. The numbers refer to the diagram in Figure 14 on page 42:

- It has been put the heat loss of the oil to the exterior in the input deck of RELAP5 taking the value 0.45kW of Ansaldo. These losses have been accumulated in the heat structures number 1171 and 1051 at the exit of the target heat exchanger. So far no loss for the oil had been put in the input.

- Heat losses of 12kW have been considered in the input for the oil pump. So far the input did not have any heat loss for the oil pump yet. It has been taken the value of 12kW from the characteristic properties of the pump of the manufacture.

- In order to include the 12 kW of heat loss of the pump, it has been changed the heat structure 1111. Of the three volumes of this heat structure, two remain as heat structures for the hydraulic component 111 and one becomes a new heat structure with number 8871, to which the loss has been added.

- Heat losses of 10kW have been taken for the main pump of the LBE. So far a value of 5 kW had been taken by Ansaldo. The value 10 kW agrees with the specifications of the manufacture.

- Heat losses of 10kW have been taken for the bypass pump of the LBE. Up to now a value of 5 kW had been taken by Ansaldo. The value 10 kW agrees with the specifications of the manufacture.

- Between the hydraulic components 115 and 116 it has been added a check valve with the number 744. The purpose of this valve is to avoid the reverse flow of 0.1kg/s coming from the bypass line in the IHX heat exchanger when the valve 740 closes. This flow caused problems in the stability of the system.

- It has been put the heat losses of the LBE loop to the exterior. So far no loss for the LBE to the exterior had been put in the input. These losses have been specifically calculated in this work and depend on the work conditions. As results it was obtained: 23.15 kW in steady state conditions, 17.98kW for hot standby conditions, and 8.1kW for the start up of the target at 140°C. These values have been put in the input of RELAP5 for each condition. These values will be discussed and justified in the following paragraph.
A natural consequence of the variation of the input must be a variation of the results with respect to the ones calculated by the firm Ansaldo. In fact the results for steady state and for transient conditions are different from former results but the variation is not so high, as explained below. For nominal conditions the variation is different for oil and LBE. For LBE the highest variation is for the inlet temperature of the bypass pipe to the active zone. Before the value was 253.6°C and with the new input it is 257.23°C. That is because the bypass pump gives now 10kW to the LBE and before it was only 5kW. In general the bypass loop has a variation of 4°C with respect to the Ansaldo input. The LBE loop has less variation: it goes from 0.4°C to 0.6°C, the latter for the inlet temperature of the THX, the value of which now is 333.54°C and before 332.96°C. These differences are within the normal deviation. The fact that the values of the temperatures of the LBE loop do not vary so much is due to the compensation between the gains and losses of heat added in the new input. The value of the heat losses of each LBE pump has been increased to 10kW (before it was 5kW for each LBE pump) but the losses to the external air have been increased also to 13.15kW (before it was 10kW and now 23.15kW). Therefore the LBE system has a global loss of 3.15kW. This small value makes that the temperatures do not vary very much. In principle with this value the temperatures of LBE should decrease a little but it is the oil that makes the contrary effect as we will see now. The oil obtains 12kW from the heat loss of the oil pump and loses 0.45kW to the exterior, that is to say a global increase of 11.55kW. This value is considerable and makes that the oil temperatures vary more than the LBE ones. For example the outlet temperature of the IHX takes a value of 104.20°C, which compared with 98.79°C of the Ansaldo input, i.e. 5.5°C of difference. This is the highest variation.

Other values are:

<table>
<thead>
<tr>
<th>Element</th>
<th>THX Inlet Temperature</th>
<th>THX Outlet Temperature</th>
<th>IHX Inlet Temperature</th>
<th>IHX Outlet Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old Input</td>
<td>129.79</td>
<td>165.76</td>
<td>166.49</td>
<td>98.79</td>
</tr>
<tr>
<td>New Input</td>
<td>131.10</td>
<td>166.86</td>
<td>168.19</td>
<td>104.20</td>
</tr>
</tbody>
</table>

*Table 4 Variation of values of the oil temperatures in nominal conditions (in °C)*

This increase in mean of 2°C of the oil temperatures causes that the LBE temperatures also increase.

35/120
To counteract the increase of the oil temperatures in the new input, the control system makes that the valve 740 opens more and the valve 741 closes more. The variation of the mass flow rate is of 0.4kg/s as it is seen in the Table 5.

<table>
<thead>
<tr>
<th>Line</th>
<th>Bypass m.f.r.</th>
<th>IHX m.f.r.</th>
<th>Degassing m.f.r.</th>
<th>THX m.f.r.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old Input</td>
<td>3.87</td>
<td>4.88</td>
<td>0.1</td>
<td>8.75</td>
</tr>
<tr>
<td>New Input</td>
<td>3.56</td>
<td>5.19</td>
<td>0.1</td>
<td>8.75</td>
</tr>
</tbody>
</table>

Table 5 Variation of the mass flow rate (m.f.r.) of oil (in kg/s)

As a consequence of more heat the temperature of the outlet of the water at IHX increases from 59.0°C to 59.24°C.

**4.3 Calculation of Heat Losses to the Exterior for Different Conditions**

In this paragraph there are:
- Four tables of heat loss for different conditions that it has been calculated
- The modifications that it has been done in the Ansaldo input deck of RELAP5 for steady state in order to take into account different results

The calculations are based on Ref.[5] but taking (104) instead of (103), which is an approximation of (104) for the case that the logarithm can be approximated by a fraction.

\[
Q_{\text{cond.}} = k \left( T_1 - T_2 \right) \frac{F}{d}
\]  

(103)

In this work it has been preferred to use the following formula for the calculation of the convective heat transfer for a co-cylindrical geometry:

\[
Q_{\text{cond.}} = \frac{2\pi L \left( T_1 - T_2 \right)}{\ln \frac{r_2}{r_1}} \frac{1}{k} \left( \frac{r_2}{r_1} \right) 
\]  

(104)

The geometry of the target has been modeled as follows: In the lower containment there is an annular gap filled with Helium. The purpose of it is to minimize the heat losses and also to have a double barrier between the water and the LBE. In this gap are installed the mechanisms...
to detect leaks of LBE. The outer enclosure consists of heavy water coolant with a temperature of 40°C. For the calculations of heat losses, the lower containment has been divided into two parts: the containment in spallation zone and the rest of the lower containment.

The upper containment is not directly cooled but a shroud at a temperature of 50°C cooled by heavy water is used as coolant. In this part two gaps in series have to be considered, the first one filled with helium and the second one with air. This schema is shown in Figure 9.

Convection heat losses can be neglected and only conductive and radioactive heat losses have been considered.

For the calculation I have taken the following formulas:

For one gap:

$$Q_{\text{cond.}} = \frac{2\pi L (T_i - T_2)}{k \left( \frac{1}{L_i} - \frac{1}{L_o} \right)}$$

(105)

$$Q_{\text{rad.}} = F \frac{C_o}{1 + \frac{D_i}{D_o} \left( \frac{1}{\varepsilon_i} - 1 \right)} \left( T_i^4 - T_o^4 \right)$$

(106)

And for two gaps:

$$Q_{\text{cond.}} = \frac{2\pi L (T_i - T_3)}{k_a \left( \frac{1}{L_i} + \frac{1}{L_b} \right) + k_b \left( \frac{1}{L_b} + \frac{1}{L_o} \right)}$$

(107)

$$Q_{\text{rad.}} = \frac{T^4_i - T^4_o}{R_i + R_2}$$

(108)

with:
\[ R_i = \frac{1}{\varepsilon_i} + \frac{D_i}{D_o} \left( \frac{1}{\varepsilon_o} - 1 \right) \]

\[ F \cdot C_s \]

(109)

and similar expressions for R2. In these expressions k is the conductivity, L the height of the cylinder, r the radius, D the diameter, T the temperature, F the surface, \( \varepsilon \) the emissivity and the constant \( C_s = 5.67 \times 10^{-8} \text{W/m}^2\text{K}^4 \).

As an example I show the calculations for steady state conditions. For the other three cases the procedure is the same.

### 4.3.1 Heat Loss for Steady State Conditions

The temperatures of the different parts of the target have been taken from the results of the calculations with RELAP5. These results will be shown in the next chapters:

**Containment in Spallation Zone, \( T_{500} = 355^\circ\text{C} \)**

\[ Q_{\text{cond}} = \frac{2\pi L(T_1 - T_i)}{k_a} \frac{1}{Ln \frac{r_2}{r_1}} = \frac{2\pi \times 0.5(355 - 40)}{0.197 \times 9.6 \times 10^{-2}} = 3020.70\text{W} \]

\[ Q_{\text{rad}} = F \frac{C_s}{\varepsilon_i} \left( T_i^4 - T_o^4 \right) = 0.283 \left( 628.15^4 - 313.15^4 \right) = 797.91\text{W} \]

**Rest of lower Containment**

\[ T_{507(15)} + T_{505} = \frac{252 + 230}{2} = 241^\circ\text{C} \approx 240^\circ\text{C} \]

Therefore in this case the results of hot standby at 240\(^\circ\text{C}\) are used.

**Upper Containment, T=310^\circ\text{C}**

\[ Q_{\text{cond}} = \frac{2\pi L(T_1 - T_i)}{k_a} \frac{1}{Ln \frac{r_2}{r_1}} + \frac{1}{Ln \frac{r_2}{r_2}} = \frac{2\pi \times 1.8(310 - 50)}{0.1955 \times 0.1955 + 0.0332 \times 0.198} = 5738.28\text{W} \]

\[ Q_{\text{rad}} = \frac{T_i^4 - T_o^4}{R_1 + R_2} = 2141.59\text{W} \]
\[
R_1 = \frac{1 + \frac{D_i}{D_o} \left( \frac{1}{\varepsilon_i} - 1 \right)}{F \cdot C_i} = \frac{1}{0.5} + \frac{0.38}{0.38 + 0.0055 \times 2} \left( \frac{1}{0.5} - 1 \right) = 2438983.07^\circ K^4 / W
\]

\[
R_2 = \frac{1 + \frac{D_i}{D_o} \left( \frac{1}{\varepsilon_i} - 1 \right)}{F \cdot C_i} = \frac{1}{0.5} + \frac{0.3855}{0.3855 + 0.0025 \times 2} \left( \frac{1}{0.25} - 1 \right) = 24517155.65^\circ K^4 / W
\]

<table>
<thead>
<tr>
<th>Section I</th>
<th>Diameter D_i [m]</th>
<th>Height [m]</th>
<th>Surface Fli [m²]</th>
<th>Gap D_i [mm]</th>
<th>Conductive Heat Loss Q_i cond [kW]</th>
<th>Radioactive Heat Loss Q_i rad [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Containment in Spallation Zone</td>
<td>0.180</td>
<td>0.5</td>
<td>0.283</td>
<td>6.0</td>
<td>3.02</td>
<td>0.80</td>
</tr>
<tr>
<td>Rest of Lower Containment</td>
<td>0.184</td>
<td>1.8</td>
<td>1.041</td>
<td>4.0</td>
<td>10.26</td>
<td>1.19</td>
</tr>
<tr>
<td>Upper Containment</td>
<td>0.380</td>
<td>1.8</td>
<td>2.149</td>
<td>5.5/2.5</td>
<td>5.74</td>
<td>2.14</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Heat Loss</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.02</td>
<td>4.13</td>
</tr>
</tbody>
</table>

Table 6

4.3.2 Heat Loss for Hot Standby Temperature of 240°C

It exists a great controversy about the value of the hot standby temperature. On one hand it is said to be a temperature of 240 °C, on the other hand it is said to be a temperature of 230 °C. Therefore I have included the heat losses to the exterior for both temperatures. In any case my report as also the old and new input deck of RELAP5 are based on a hot standby temperature of 230°C.

Calculating in the same way as before we obtain the following table:

<table>
<thead>
<tr>
<th>Section I</th>
<th>Diameter D_i [m]</th>
<th>Height [m]</th>
<th>Surface Fli [m²]</th>
<th>Gap D_i [mm]</th>
<th>Conductive Heat Loss Q_i cond [kW]</th>
<th>Radioactive Heat Loss Q_i rad [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Containment in Spallation Zone</td>
<td>0.180</td>
<td>0.5</td>
<td>0.283</td>
<td>6.0</td>
<td>1.88</td>
<td>0.33</td>
</tr>
<tr>
<td>Rest of Lower Containment</td>
<td>0.184</td>
<td>1.8</td>
<td>1.041</td>
<td>4.0</td>
<td>10.26</td>
<td>1.19</td>
</tr>
<tr>
<td>Upper Containment</td>
<td>0.380</td>
<td>1.8</td>
<td>2.149</td>
<td>5.5/2.5</td>
<td>4.19</td>
<td>1.19</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16.33</td>
<td>2.71</td>
</tr>
<tr>
<td>Total Heat Loss</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.04</td>
<td></td>
</tr>
</tbody>
</table>

Table 7
4.3.3 Heat Loss for a Hot Standby Temperature of 230°C

The following table is used for the steady state in nominal conditions and also for transients from this steady state.

<table>
<thead>
<tr>
<th>Section I</th>
<th>Diameter $D_i$ [m]</th>
<th>Height $H$ [m]</th>
<th>Surface $F_{li}$ [m$^2$]</th>
<th>Gap $D_{li}$ [mm]</th>
<th>Conductive Heat Loss $Q_{i\text{, cond}}$ [kW]</th>
<th>Radioactive Heat Loss $Q_{i\text{, rad}}$ [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Containment in Spallation Zone</td>
<td>0.180</td>
<td>0.5</td>
<td>0.283</td>
<td>6.0</td>
<td>1.79</td>
<td>0.30</td>
</tr>
<tr>
<td>Rest of Lower Containment</td>
<td>0.184</td>
<td>1.8</td>
<td>1.041</td>
<td>4.0</td>
<td>9.74</td>
<td>1.09</td>
</tr>
<tr>
<td>Upper Containment</td>
<td>0.380</td>
<td>1.8</td>
<td>2.149</td>
<td>5.5/2.5</td>
<td>3.97</td>
<td>1.09</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15.5</td>
<td>2.48</td>
</tr>
<tr>
<td>Total Heat Loss</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>17.98</td>
<td></td>
</tr>
</tbody>
</table>

Table 8

4.3.4 Heat Loss for a Temperature of LBE of 140°C

This calculation is necessary for the start up of the target. Before the normal operation of the target, the target must be filled with the LBE coming from a container at a temperature of 140°C. After that the LBE has to be heated till the hot standby temperature (230°C). When this temperature is reached the beam power can be turned on.

This process will be simulated with RELAP5, in the input of which, there are included the heat loss for such condition. The results of the calculations of the heat losses are:

<table>
<thead>
<tr>
<th>Section I</th>
<th>Diameter $D_i$ [m]</th>
<th>Height $H$ [m]</th>
<th>Surface $F_{li}$ [m$^2$]</th>
<th>Gap $D_{li}$ [mm]</th>
<th>Conductive Heat Loss $Q_{i\text{, cond}}$ [kW]</th>
<th>Radioactive Heat Loss $Q_{i\text{, rad}}$ [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Containment in Spallation Zone</td>
<td>0.180</td>
<td>0.5</td>
<td>0.283</td>
<td>6.0</td>
<td>0.82</td>
<td>0.11</td>
</tr>
<tr>
<td>Rest of Lower Containment</td>
<td>0.184</td>
<td>1.8</td>
<td>1.041</td>
<td>4.0</td>
<td>4.49</td>
<td>0.39</td>
</tr>
<tr>
<td>Upper Containment</td>
<td>0.380</td>
<td>1.8</td>
<td>2.149</td>
<td>5.5/2.5</td>
<td>1.92</td>
<td>0.37</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.23</td>
<td>0.87</td>
</tr>
<tr>
<td>Total Heat Loss</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 9
4.3.5 Modeling of the Heat Loss with RELAP5

Taking the results of the former section the next step is to modify the RELAP5 input deck putting these loses in the input. These values have been put in the heat structures of the input deck of RELAP5. The heat losses evolve with the time since the temperatures of LBE evolve also with the time. It is necessary to approach these variations to the reality and this approach will be shown here. Usually the conditions to be studied in each analysis of transients suppose the evolution of the system from a state to another. The losses have been assumed to vary linearly from a state to the other during the time that takes this variation.

For example for Steady State according to former calculations I have taken that the heat loss evolves to reach steady state as shown in the Figure 10 (from 17.98kW to 23.15kW):

![Steady State Heat Loss](image1)

![Start up of the Target Heat Loss](image2)

![Protected Beam Trip Heat Loss](image3)

![Shut down of the Target Heat Loss](image4)
5. Steady State Conditions

5.1 Steady State for Nominal Conditions

In Table 10 on page 47 are summarized the principal values calculated with RELAP 5 for the nominal conditions (beam power 620kW). Many of these values are different from the ones in Ref.[1] of Ansaldo. The reason is that as explained in the last chapter it has been considered different values for some input parameters. For example it has been considered for the heat losses to the exterior a value of 23.2kW instead of the value 10kW of Ansaldo.

5.1.1 Heat Exchangers

![Thermal Properties of the Target Heat Exchanger (THX), elements 103 and 503](image-url)

Figure 15 Thermal Properties of the Target Heat Exchanger (THX), elements 103 and 503
5.1.2  Inlet Temperatures to the Active Zone

In nominal conditions the temperature of 507(15) (inlet at the active zone) is smaller than the temperature of 525(15) (inlet of the bypass pipe to the active zone). Let us analyze the changes in temperature that have both parts from the element 505. The important elements in this analysis are 507 and 889. These are represented in Figure 17 with the heat gains and losses.

\[ Q_1 = 2.16746 \times 10^5 \text{W} \]
\[ Q_2 = 1.73193 \times 10^5 \text{W} \]
\[ Q_3 = 1.39619 \times 10^5 \text{W} \]
\[ Q_4 = 1.13807 \times 10^5 \text{W} \]
\[ Q = 643.365 \text{kW} \]

Figure 16 Thermal Properties of the Intermediate Heat Exchanger (IHX), elements 303 and 114

Figure 17

\( Q_1 \) is the heat loss to the exterior; this value has been put into the input as explained in the former chapter. The value is \( Q_1 = 10.31 \text{kW} \) (of the total heat losses to the exterior of the LBE, part of it has been put in the element 507 and part in the element 503). \( Q_2 \) is the heat exchanged between the downcomer and the riser, which is much warmer. The value
calculated with RELAP5 is $Q_2 = 123kW$. $Q_3$ is the heat exchanged between the bypass pipe and the downcomer, the value of RELAP5 is $Q_3 = 4.78kW$.

$Q_4$ is the heat given by the bypass pump $Q_4 = 10kW$ and finally $Q_5$ is the heat interchanged between the elements 517 of the upper riser and 889. The value of RELAP5 is $Q_5 = 10.53kW$.

That is to say:

$$Q_{507} = -Q_1 + Q_2 + Q_3 = 117.47kW$$

$$Q_{889} = Q_4 + Q_5 = 20.53kW$$

(110) (111)

The heat gained is much higher for 507 than for 889 but the volume of 507 is also much larger. The values of the volumes can be taken from appendix A: $V_{507} = 0.0276m^3$ and $V_{889} = 0.00133m^3$ and thus the heat densities are:

$$q_{507} = 4256.16kW / m^3$$

$$q_{889} = 1543.61kW / m^3$$

For the bypass loop we have to consider also 523 and 525. $Q_{523}$ is the interchange of heat between 503 and 523 $Q_{523} = 1.41kW$ with $V_{523} = 0.000363$. After the element 523 the fluid goes by 525 and it loses the value before mentioned $Q_{525} = Q_3 = 4.78kW$ and $V_{525} = 0.00095$ that is to say:

$$q_{523} = 3884.30kW / m^3$$

$$q_{525} = 5031.58kW / m^3$$

and finally the heat gained by the bypass line from 505 to 525(17) is:

$$q_{bypass} = q_{889} - q_{523} - q_{525} = 6520.22kW / m^3$$

Which is higher than $q_{507}$, and that results in the difference in temperature of the inlets to the active zone. Let us calculate more precisely this difference:

With the following formula we can estimate the temperature of the inlet in the active zone:

$$Q = \dot{m}c_p \Delta T$$

$$T_{507(15)} - 230 = \frac{1}{\dot{m}c_p} Q_{507} = \frac{1}{37.1 \times 150.37} 117.47 	imes 10^3 = 21.05^\circ C$$

i.e. a value of

$$T_{507(15)} = 251.06^\circ C$$

which is a good approximation to the value calculated by RELAP5 of 251.24°C, taking into account that we have taken a mean temperature and a mean pressure of 240°C and 5 bar
respectively in order to calculate the specific heat of LBE in the downcomer. The values of the specific heat have been taken from Ref.[4].

In the same way we can use (112) and we have with $Q_{525} = Q_3$:

$$Q_{\text{bypass}} = Q_{389} - Q_{323} - Q_{525} = 14.34\, kW$$

$$T_{525(15)} - 230 = \frac{1}{mc_p} Q_{\text{bypass}} = \frac{1}{3.5 \times 150.37} 14.34 \times 10^3 \approx 27.25^\circ C$$

i.e a value of

$$T_{525(15)} = 257.25^\circ C$$

Which is an excellent approximation to the value of RELAP5 of 257.23°C, despite the rough approximation of taking a mean temperature of 248°C and a mean pressure of 5 bar for the calculation of the specific heat of LBE in the bypass line. The values of the specific heat have been taken from Ref.[4].
Steady State for Nominal Conditions

Beam power: 620 kW

### LBE Cycle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>LBE active zone</td>
<td>354.81 °C</td>
</tr>
<tr>
<td>THX inlet</td>
<td>333.54°C</td>
</tr>
<tr>
<td>THX outlet</td>
<td>230.00°C</td>
</tr>
<tr>
<td>Active zone inlet</td>
<td></td>
</tr>
<tr>
<td>• Main flow</td>
<td>251.24°C</td>
</tr>
<tr>
<td>• By pass</td>
<td>257.23°C</td>
</tr>
<tr>
<td>Mass Flow Rate</td>
<td></td>
</tr>
<tr>
<td>Main pump</td>
<td>40.6 kg/s</td>
</tr>
<tr>
<td>By pass pump</td>
<td>3.5 kg/s</td>
</tr>
<tr>
<td>Pump Power to the Liquid Metal (heat)</td>
<td></td>
</tr>
<tr>
<td>Main pump</td>
<td>10 kW</td>
</tr>
<tr>
<td>By pass pump</td>
<td>10 kW</td>
</tr>
<tr>
<td>Heat Loss</td>
<td>Heat loss to the external air</td>
</tr>
</tbody>
</table>

### Diathermic Fluid Cooling System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>THX inlet</td>
<td>131.10°C</td>
</tr>
<tr>
<td>THX outlet</td>
<td>166.86°C</td>
</tr>
<tr>
<td>IXH inlet</td>
<td>168.19°C</td>
</tr>
<tr>
<td>IXH outlet</td>
<td>104.20°C</td>
</tr>
<tr>
<td>Mass Flow Rate</td>
<td></td>
</tr>
<tr>
<td>Pump</td>
<td>8.850 kg/s</td>
</tr>
<tr>
<td>THX oil</td>
<td>8.748 kg/s</td>
</tr>
<tr>
<td>IHX oil</td>
<td>5.192 kg/s</td>
</tr>
<tr>
<td>By pass oil</td>
<td>3.556 kg/s</td>
</tr>
<tr>
<td>Degassing oil</td>
<td>0.102 kg/s</td>
</tr>
<tr>
<td>Pump Power (heat)</td>
<td>Oil</td>
</tr>
<tr>
<td>Heat Loss</td>
<td>External heat loss</td>
</tr>
</tbody>
</table>

### Cooling Water Loop

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>IHX inlet</td>
<td>40.00°C</td>
</tr>
<tr>
<td>IHX outlet</td>
<td>59.24°C</td>
</tr>
<tr>
<td>Mass Flow Rate</td>
<td>IHX</td>
</tr>
</tbody>
</table>

Table 10
5.2 Steady State under Different Beam Power

It has been studied the response of the system under different beam power. This would correspond to the scenario where the power of the accelerator changes unintentionally.

<table>
<thead>
<tr>
<th>P-Beam Heating kW</th>
<th>Mass Flow Rate kg/s</th>
<th>Pump</th>
<th>Pressure Head, bar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LBE</td>
<td>THT</td>
<td>H₂O</td>
</tr>
<tr>
<td>700</td>
<td>40.6</td>
<td>8.85</td>
<td>8.00</td>
</tr>
<tr>
<td>620</td>
<td>40.6</td>
<td>8.85</td>
<td>8.00</td>
</tr>
<tr>
<td>400</td>
<td>40.6</td>
<td>8.85</td>
<td>8.00</td>
</tr>
<tr>
<td>350</td>
<td>40.6</td>
<td>8.85</td>
<td>8.00</td>
</tr>
</tbody>
</table>

Table 11

<table>
<thead>
<tr>
<th>P-Beam Heating kW</th>
<th>Temp. °C</th>
<th>THX</th>
<th>IHX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top of Active Zone</td>
<td>Inlet Temperature, °C</td>
<td>Outlet Temperature, °C</td>
</tr>
<tr>
<td>700</td>
<td>LBE</td>
<td>THT</td>
<td>LBE</td>
</tr>
<tr>
<td>700</td>
<td>397.71</td>
<td>372.76</td>
<td>153.99</td>
</tr>
<tr>
<td>620</td>
<td>354.81</td>
<td>333.54</td>
<td>131.10</td>
</tr>
<tr>
<td>400</td>
<td>309.74</td>
<td>297.01</td>
<td>173.20</td>
</tr>
<tr>
<td>350</td>
<td>299.58</td>
<td>288.76</td>
<td>181.33</td>
</tr>
</tbody>
</table>

Table 12

In Table 11 and Table 12 the values of the temperatures are given for different powers. It is seen that without any other change in the system except the beam power, the control system does not succeed in fixing the outlet temperature of the THX at 230°C. For beam power higher than 620kW the outlet temperature of THX is always bigger than 230°C. In order to maintain the value of 230°C during the operating phase of the installation an automatic change of some parameters of the control system would be required. Changing these parameters it has been checked that the control system successfully controls the outlet temperature of THX at 230°C.
Figure 18

Beam Power 300kW
LBE Temperatures

Figure 19

Beam Power 300kW
Oil Temperatures
In Figure 18 and Figure 19 are represented the oscillations of the temperature of the system for a beam power of 300kW.

Conclusion:

- Under 350kW it is not possible to obtain a stable steady state condition without any further change in the nominal conditions except the beam power.
- Over 620kW the control system does not succeed in maintaining the set point temperature. In order to obtain this set point temperature I have modified some parameters of the control system. In normal operation this change should be made automatic to prevent unforeseeable changes of the beam power over 620kW.

5.3 Steady State under Different Beam and Pump Power

In this case, apart from the variation of the beam power, it has been varied also the pump power. This scenario would correspond to the case when the variation of the power of SYNQ is foreseeable. In this case one tries to choose the best mass flow rate of the pumps according to the heat to be removed. The values of these flows have been taken from the scaling hypothesis explained in the next paragraph.

<table>
<thead>
<tr>
<th>P-Beam Heating kW</th>
<th>Mass Flow Rate kg/s</th>
<th>Pump</th>
<th>Pressure Head, bar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LBE</td>
<td>THT</td>
<td>H₂O</td>
</tr>
<tr>
<td>700</td>
<td>42.28</td>
<td>9.22</td>
<td>8.00</td>
</tr>
<tr>
<td>620</td>
<td>40.6</td>
<td>8.85</td>
<td>8.00</td>
</tr>
<tr>
<td>400</td>
<td>35.08</td>
<td>7.65</td>
<td>8.00</td>
</tr>
</tbody>
</table>

Table 13

<table>
<thead>
<tr>
<th>P-Beam Heating kW</th>
<th>Temp. °C</th>
<th>THX</th>
<th>IHX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top of Active Zone</td>
<td>Inlet Temperature, °C</td>
<td>Outlet Temperature, °C</td>
</tr>
<tr>
<td></td>
<td>LBE</td>
<td>THT</td>
<td>LBE</td>
</tr>
<tr>
<td>700</td>
<td>388.53</td>
<td>365.25</td>
<td>151.97</td>
</tr>
<tr>
<td>620</td>
<td>354.81</td>
<td>333.54</td>
<td>131.10</td>
</tr>
<tr>
<td>400</td>
<td>323.61</td>
<td>307.36</td>
<td>169.16</td>
</tr>
</tbody>
</table>

Table 14

Under 350 kW the temperatures of the system oscillate as in the former paragraph.
Conclusion:

- Under 350 kW it is not possible to obtain a stable steady state condition without changing the inlet temperature of the water at IHX.

### 5.4 Scaling of Steady State Conditions

For natural circulation using the Boussinesq approximation (14) and since the friction loss and the gravitation head are equal for this case:

\[ \Delta p_f = \Delta p_{gr} \]  

(113)

That is to say:

\[ \frac{1}{2} \rho u^2 f \frac{L}{D} = \rho_0 \beta T g L \]

from this equation it follows the proportionality:

\[ u^2 \propto \Delta T \]

using that:

\[ c_p \dot{m} \Delta T = Q \]

\[ \dot{m} = \rho u A \]

we have the following relations, on which the scaled experiment is based:

\[ \dot{m} \propto Q^{\frac{1}{3}} \]

\[ \Delta T \propto Q^{\frac{2}{3}} \]

Using the notation of Ref.[10]:

\[ \frac{\dot{m}_s}{\dot{m}_n} = \left( \frac{Q_s}{Q_n} \right)^{\frac{1}{3}} \]

\[ \frac{\Delta T_s}{\Delta T_n} = \left( \frac{Q_s}{Q_n} \right)^{\frac{2}{3}} \]

where the subscripts s and n denote the scaled and nominal value respectively. With these two equations we can calculate the temperatures’ differences and the mass flow rates for a known beam power. In order to do the following table it has been used that:

\[ \Delta p_{pump} = \Delta p_f - \Delta p_{gr} \]  

(114)
Table 15

<table>
<thead>
<tr>
<th>P-Beam Heating kW</th>
<th>Mass Flow Rate kg/s</th>
<th>Pump</th>
<th>Pressure Head, bar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LBE</td>
<td>THT</td>
<td>H₂O</td>
</tr>
<tr>
<td>700</td>
<td>42.28</td>
<td>9.22</td>
<td>8.33</td>
</tr>
<tr>
<td>620</td>
<td>40.6</td>
<td>8.85</td>
<td>8</td>
</tr>
<tr>
<td>400</td>
<td>35.08</td>
<td>7.65</td>
<td>6.91</td>
</tr>
<tr>
<td>200</td>
<td>27.84</td>
<td>6.07</td>
<td>5.19</td>
</tr>
<tr>
<td>150</td>
<td>25.30</td>
<td>5.51</td>
<td>4.98</td>
</tr>
</tbody>
</table>

Table 16

<table>
<thead>
<tr>
<th>P-Beam Heating kW</th>
<th>Temp. ºC</th>
<th>THX</th>
<th>IHX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top of Active Zone</td>
<td>Inlet Temperature, ºC</td>
<td>Outlet Temperature, ºC</td>
</tr>
<tr>
<td></td>
<td>LBE</td>
<td>THT</td>
<td>LBE</td>
</tr>
<tr>
<td>700</td>
<td>365.17</td>
<td>342.29</td>
<td>112.82</td>
</tr>
<tr>
<td>620</td>
<td>354.81</td>
<td>333.54</td>
<td>131.10</td>
</tr>
<tr>
<td>400</td>
<td>332.61</td>
<td>307.36</td>
<td>169.16</td>
</tr>
<tr>
<td>200</td>
<td>290.41</td>
<td>279.00</td>
<td>194.83</td>
</tr>
<tr>
<td>150</td>
<td>280.46</td>
<td>269.40</td>
<td>200.65</td>
</tr>
</tbody>
</table>

These same calculations were made in Ref.[10] with the old input deck of RELAP5. Some differences are observed in the values of the temperatures. That is because of the use of different inputs.

5.5 Steady State under Different Cooling Conditions

It has been studied two different cases:

5.5.1 With a Number of Pins not Working Properly

In this case there are still 12 pins in the THX but some of them do not exchange efficiently energy, that is to say, the cooling surface area of heat exchange is reduced. This analysis corresponds to the case in which a layer of oxide or crust lay on the surface of the heat exchanger reducing in this way the heat exchange surface area.

In this case part of the fluid goes through the pins but does not interchange heat at the THX.

We could say that part of the mass flow rate does not interchange energy properly.
Table 17

<table>
<thead>
<tr>
<th>Effective Number of Cooling Pins</th>
<th>Oil Mass Flow Rate kg/s</th>
<th>Opening of the valves</th>
<th>Heat Exchanged, kW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In Oil Pump</td>
<td>In IHX</td>
<td>In Bypass</td>
</tr>
<tr>
<td>12</td>
<td>8.85</td>
<td>5.19</td>
<td>3.56</td>
</tr>
<tr>
<td>11</td>
<td>8.85</td>
<td>6.78</td>
<td>1.97</td>
</tr>
<tr>
<td>10</td>
<td>8.85</td>
<td>8.7432</td>
<td>6.06e-05</td>
</tr>
<tr>
<td>9</td>
<td>8.85</td>
<td>8.74</td>
<td>3.67e-05</td>
</tr>
</tbody>
</table>

Table 18

<table>
<thead>
<tr>
<th>Number of Cooling Pins</th>
<th>Temp. °C</th>
<th>THX</th>
<th>IHX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top of Active Zone</td>
<td>Inlet Temperature, °C</td>
<td>Outlet Temperature, °C</td>
</tr>
<tr>
<td></td>
<td>LBE</td>
<td>THT</td>
<td>LBE</td>
</tr>
<tr>
<td>12</td>
<td>354.81</td>
<td>333.54</td>
<td>131.10</td>
</tr>
<tr>
<td>11</td>
<td>354.81</td>
<td>333.55</td>
<td>111.63</td>
</tr>
<tr>
<td>10</td>
<td>362.76</td>
<td>341.37</td>
<td>96.19</td>
</tr>
<tr>
<td>9</td>
<td>379.87</td>
<td>358.20</td>
<td>96.15</td>
</tr>
</tbody>
</table>

Table 19

Conclusion:

- The task of the control system is efficiently done till an effective heat exchange area at THX between the values corresponding to 10 and 11 pins. Under this value the set point temperature increases.

5.5.2 With Less Number of Pins

In this case we eliminate physically some of the 12 pins. In this case there is also less area of interchange at THX but the entire mass flow rate is working in the interchange of heat at the THX.
### Table 20

<table>
<thead>
<tr>
<th>Number of Cooling Pins</th>
<th>Temp. °C</th>
<th>THX</th>
<th>IHX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top of Active Zone</td>
<td>Inlet Temperature, °C</td>
<td>Outlet Temperature, °C</td>
</tr>
<tr>
<td>12</td>
<td>LBE</td>
<td>354.81</td>
<td>333.54</td>
</tr>
<tr>
<td>11</td>
<td>THT</td>
<td>354.81</td>
<td>333.54</td>
</tr>
<tr>
<td>10</td>
<td>LBE</td>
<td>354.69</td>
<td>333.49</td>
</tr>
<tr>
<td>9</td>
<td>THT</td>
<td>360.82</td>
<td>339.45</td>
</tr>
</tbody>
</table>

**Conclusions:**

- The response of the system under a reduction of the pin number is to open more the IHX valve. This opening has evidently a limit, which is reached with 10 pins.
- The system THX has a wide design margin. Under 10 pins the oil does not succeed in controlling the outlet LBE temperature at THX.
5.6 Steady State for the Test Conditions

Before operating with the proton beam in the target some experiments must be done to study the thermal-hydraulic of the system. A test is planned with an electric heater of 190kW inserted in the main flow guide tube through the beam window. It has been analyzed the steady state for this test. The parameters planned for this test are:

<table>
<thead>
<tr>
<th>Water Pressure</th>
<th>Inlet temperature of the water at IHX</th>
<th>Water mass flow rate</th>
<th>Oil mass flow rate</th>
<th>LBE mass flow rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 bar</td>
<td>142°C</td>
<td>5.5 kg/s</td>
<td>6.11 kg/s</td>
<td>27.4 kg/s</td>
</tr>
</tbody>
</table>

Table 21

It is planned that the test will have a good insulation, therefore the losses to the exterior have been taken equal to zero. The heat losses of the pump have been reduced proportionally with respect to the nominal value.

With these parameters the result of the RELAP5 calculations are shown in the Table 22.
### Steady State for Test Conditions

Heater power: 190 kW

<table>
<thead>
<tr>
<th>LBE Cycle</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature</strong></td>
<td>LBE active zone</td>
<td>260.27°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>THX inlet</td>
<td>250.47°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>THX outlet</td>
<td>204.00°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Active zone inlet</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Main flow</td>
<td>213.64°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• By pass</td>
<td>220.62°C</td>
<td></td>
</tr>
<tr>
<td><strong>Mass Flow Rate</strong></td>
<td>Main pump</td>
<td>27.37 kg/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>By pass pump</td>
<td>2.36 kg/s</td>
<td></td>
</tr>
<tr>
<td><strong>Pump Power to the Liquid Metal (heat)</strong></td>
<td>Main pump (15.17 A)</td>
<td>6.85 kW</td>
<td></td>
</tr>
<tr>
<td></td>
<td>By pass pump (12.68 A)</td>
<td>6.85 kW</td>
<td></td>
</tr>
<tr>
<td><strong>Heat Loss</strong></td>
<td>Heat loss to the external air</td>
<td>0 kW</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diathermic Fluid Cooling System</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature</strong></td>
<td>THX inlet</td>
<td>171.87°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>THX outlet</td>
<td>187.02°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IXH inlet</td>
<td>188.12°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IXH outlet</td>
<td>161.04°C</td>
<td></td>
</tr>
<tr>
<td><strong>Mass Flow Rate</strong></td>
<td>Pump</td>
<td>5.97 kg/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>THX oil</td>
<td>5.90 kg/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IHX oil</td>
<td>3.57 kg/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>By pass oil</td>
<td>2.32 kg/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Degassing oil</td>
<td>0.07 kg/s</td>
<td></td>
</tr>
<tr>
<td><strong>Pump Power (heat)</strong></td>
<td>Oil (31.29 Hz)</td>
<td>8.23 kW</td>
<td></td>
</tr>
<tr>
<td><strong>Heat Loss</strong></td>
<td>External heat loss</td>
<td>0.45 kW</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cooling Water Loop</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature</strong></td>
<td>IHX inlet</td>
<td>142.00°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IHX outlet</td>
<td>150.37°C</td>
<td></td>
</tr>
<tr>
<td><strong>Mass Flow Rate</strong></td>
<td>IHX</td>
<td>5.5 kg/s</td>
<td></td>
</tr>
</tbody>
</table>

Table 22
6. Transient Study

6.1 Beam Trip

A beam trip is an interruption of the power coming from the SYNQ accelerator. As a consequence less protons reach the spallation zone and the target cools down. Without taking measures the LBE could solidify which would have serious consequences. Trips are normal in the accelerator operation and there can be hundreds of them per week. Therefore the study of these transients is very important. It has been studied two kinds of beam trips, the normal beam trip and the protected beam trip.

6.1.1 Normal Beam Trip

As normal Beam trip we mean a beam trip followed by a return of the beam power after no more than 30 seconds. For the calculation it has been taken the beam power variation represented in Figure 20. After a time of normal operation (in the figure 1100 seconds) the beam power fails at \( t=1100 \text{ s} \), the system is during 10 seconds, i.e., until \( t=1110\text{ s} \), without power and then begins to recover it. For the simulation of the power recovering, it was proposed a ramp function, which lasts 20 seconds until the full recovery of the beam power.
After the failure of the beam power, a regulation chain programmed in the RELAP5 code comes into service controlling the three-way oil valve (represented in the input deck of RELAP5 by the valves 740 and 741 see Figure 14 on page 42).

The temperatures of the lead–bismuth eutectic cycle obtained from the RELAP5 calculation are represented in Figure 22. The temperature of the active zone (component 509 in the Figure 14 on page 42) is evidently the one that suffers the highest variation. It is interesting to see that this variation is as big as 110°C; this is important in order to study the thermal tensions in the material of the beam window under the influence of such a trip. The temperature of the LBE in the outlet of the LBE-oil heat exchanger (element 505) is the first that takes its former value, although it has an oscillation due to the control system, which is based on this temperature.

In Figure 22 it is represented the time that it takes for the whole LBE of the target to recover its initial condition once the beam power is recovered (at time 1110s). We can use the following formula for the time $\Delta t$ of heating the whole target of mass $m$ a temperature $\Delta T$ with the total heat $Q_T$:

$$\Delta t = \frac{c_p m \Delta T}{Q_T}$$  

(115)
That is evidently an approximation, because the fluid is flowing and the temperatures are different in distinct parts of the loop. For the heat of the beam power it has been taken a mean value in the interval from 1110 to 1150 seconds of 465kW, the external losses are 22kW a little smaller than the nominal value, the heat losses of the LBE pumps are 20kW and to the oil at THX is given a mean heat of approximately 405.3kW in this interval of time. This value can be calculated from the table of Figure 21, interpolating the values between 1110 and 1150 with a parabola and calculating by integration the averaged value in this interval. The values in Figure 21 have been obtained from the calculations with RELAP5.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Heat (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1060</td>
<td>617.339</td>
</tr>
<tr>
<td>1070</td>
<td>617.559</td>
</tr>
<tr>
<td>1080</td>
<td>617.936</td>
</tr>
<tr>
<td>1090</td>
<td>618.133</td>
</tr>
<tr>
<td>1100</td>
<td>617.7</td>
</tr>
<tr>
<td>1105</td>
<td>613.271</td>
</tr>
<tr>
<td>1110</td>
<td>560.472</td>
</tr>
<tr>
<td>1120</td>
<td>371.775</td>
</tr>
<tr>
<td>1130</td>
<td>345.296</td>
</tr>
<tr>
<td>1140</td>
<td>395.423</td>
</tr>
<tr>
<td>1150</td>
<td>489</td>
</tr>
<tr>
<td>1160</td>
<td>567.56</td>
</tr>
<tr>
<td>1170</td>
<td>605.34</td>
</tr>
<tr>
<td>1180</td>
<td>613.624</td>
</tr>
<tr>
<td>1190</td>
<td>615.715</td>
</tr>
<tr>
<td>1200</td>
<td>617.236</td>
</tr>
</tbody>
</table>

Figure 21 Variation of the Heat exchanged with the oil during the transient

The material structures react very fast to the beam trip and at the beginning they give heat to the LBE but at time 1130s the situation changes and it is the LBE that gives heat to the structures. That can be seen in Table 23. Therefore in average the heat exchanged between material structures and LBE is small:

\[
Q_{struct} = \frac{103480.5 - 24870.5}{3} - 68274.5 = 3.44kW
\]

With these values the total heat is:

\[
\dot{Q}_T = 465 - 22 + 3.44 - 405.3 = 61.14kW \tag{116}
\]

taking a mean temperature of the LBE in the target at the beginning (1110s) of 260°C and at the end (1150s) of 290°C (see Figure 22):

\[
\Delta t = \frac{150 \times 814 \times 30}{61.14 \times 10^3} = 59.91s \tag{117}
\]
the value of 814 Kg was taken from the calculations of RELAP5. This time is indicated in Figure 22.

![Normal Beam Trip](image)

**Figure 22**

The total time that the system takes to recover its initial condition is about 60 seconds. The next table shows the values of the heat exchanged between LBE and the material structures:

<table>
<thead>
<tr>
<th>Structure</th>
<th>Time</th>
<th>1110 s</th>
<th>1130 s</th>
<th>1140 s</th>
<th>1150 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>5171</td>
<td>18300</td>
<td>-1900</td>
<td>-2100</td>
<td>-3900</td>
<td></td>
</tr>
<tr>
<td>5172</td>
<td>14000</td>
<td>1400</td>
<td>-3500</td>
<td>-3000</td>
<td></td>
</tr>
<tr>
<td>5173</td>
<td>7400</td>
<td>681</td>
<td>-2000</td>
<td>-1600</td>
<td></td>
</tr>
<tr>
<td>5271</td>
<td>30200</td>
<td>-2700</td>
<td>-12000</td>
<td>-9900</td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td>7200</td>
<td>-2300</td>
<td>-1500</td>
<td>-630</td>
<td></td>
</tr>
<tr>
<td>5201</td>
<td>21200</td>
<td>7300</td>
<td>-6800</td>
<td>-5000</td>
<td></td>
</tr>
<tr>
<td>5202</td>
<td>18700</td>
<td>3900</td>
<td>-7000</td>
<td>-6400</td>
<td></td>
</tr>
<tr>
<td>5231</td>
<td>6200</td>
<td>5800</td>
<td>-6600</td>
<td>-3200</td>
<td></td>
</tr>
<tr>
<td>5072</td>
<td>9600</td>
<td>-15000</td>
<td>-4500</td>
<td>-3000</td>
<td></td>
</tr>
<tr>
<td>5251</td>
<td>0</td>
<td>450</td>
<td>-450</td>
<td>-300</td>
<td></td>
</tr>
<tr>
<td>5032</td>
<td>36802</td>
<td>24553</td>
<td>-19000</td>
<td>-17034</td>
<td></td>
</tr>
<tr>
<td>5071</td>
<td>12400</td>
<td>2775</td>
<td>-9320</td>
<td>-7845</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>182002</td>
<td>24959</td>
<td>-74700</td>
<td>-61849</td>
<td></td>
</tr>
</tbody>
</table>
Table 23 Heat given or removed from the LBE by the material structures, Values in Watts

![Diagram of Normal Beam Trip Temperatures of PbBi](image)

**Figure 23**

In Figure 24 we see the temperatures of the lead-bismuth entering the active zone. The Bypass pipe (element 525) temperature reacts slower than the downcomer one but however the temperature of the element 525 reaches before the nominal condition. That is because the regulation system acts on the outlet of the heat exchanger (element 505), what has more consequences for the downcomer since this has a bigger mass flow (40.6 kg/s for the downcomer and 3.5 kg/s for the bypass).
Figure 24

The Figure 25 shows the behavior of the temperatures of the lead-bismuth part in the heat exchanger. Interesting is to see that the inlet evolves first in an approximately parabolic way and then in an approximately exponential form. The outlet is controlled by the oil.
In Figure 26 and Figure 27 we can see the variation of the mass flow, in normal conditions we have 3.56\(\text{kg/s}\) for the bypass mass flow rate and 5.19\(\text{kg/s}\) for the IHX mass flow rate. During the beam trip the bypass flow rate increments to 8.61\(\text{kg/s}\), that is because the the lead-bismuth does not need so much cooling without the beam power. The IHX mass flow rate takes the value 0.24\(\text{kg/s}\). At \(t=1130\text{s}\) the flow rate returns to the values of steady state. We can see that the control system reacts very well to the trip, fast and with a small over oscillation.
THX oil flow rate

Degassing oil flow rate 0.1kg/s

Bypass oil flow rate

Figure 26

Figure 27
In Figure 28 it can be seen the flow area of the valves 740 and 741. The reaction of them is immediate. It is represented the stability time that is to say the time that it takes until the response enters and remains in the zone around 5% of the equilibrium value.

In order to reach the set point temperature of 230°C at the outlet of the THX, the valve 740 closes. The consequence is that the oil becomes warmer. This result is seen in Figure 29.

![Normal Beam Trip](image)

**Figure 28**

In Figure 29 we see also that all temperatures react very fast to the trip except the inlet temperature of the IHX (element 113 of diagram in Figure 14). The small flow 0.24kg/s that enters this element causes this delay. On the other hand this small flow makes it easier for the water of the IHX to cool the oil. Therefore the outlet of the IHX is the only point where the oil temperature descends.
Figure 29
That is seen more clearly in Figure 30 and Figure 31.

Figure 30
To finish this paragraph, in Figure 32 it is represented the variation of the oil temperature at the THX. The inlet temperature of the oil side of the THX (element 100) has a variation of 56°C during the transient. The outlet temperature of the oil side of the THX (element 103(6)) has a variation of 33°C during the transient.
A protected beam trip is a beam trip without return of the beam power. In order to avoid the solidification of the LBE it is used an electrical heater in the central part of the target. After 12 seconds of the beam trip the heater begins to heat and reaches the full power of 22kW after 42 seconds of the beam trip. Without the heat of the beam the LBE has much less heat, therefore the set point temperature of 230°C would descend if the control system did not react. The control system closes the valve 740 avoiding in this way the cooling of the oil by the IHX.
Using (115) we can estimate the time required to reach the hot standby temperature. This time is indicated in Figure 33.

In order to calculate the time that the system takes to reach the standby temperature we need a heat balance for LBE: 22kW is the power of the heater, 20kW the heat loss of the two LBE pumps, 17.98kW is according to Table 8 the heat loss to the exterior for a temperature of 230°C. We also need the heat removed by the THX and the heat removed by the structural materials. For these two values I will take an averaged value over the interval between 1200 and 1800 seconds. These averaged values are obtained from the results of Figure 34 and Table 24. I divide the former interval into subintervals, after that I calculate an averaged value over each subinterval and then an averaged value of all subintervals’ mean values:

\[
Q_{THX} = \frac{52.378 + 28.412 + 23.405 + 21.429 + 20.546 + 20.187}{6} = 27.72\, kW
\]

\[
Q_{struct} = \frac{21.823 - 1.168 - 3.507}{3} = 5.71\, kW
\]

\[
\Delta t = \frac{c_p m \Delta T}{Q_T} = \frac{150 \times 814.85 \times 10}{(22 + 20 + 5.71 - 17.98 - 27.72) \times 10^5} = 608.1\, s
\]  

(118)
Table 24 Heat removed from the LBE by the material structures, Values in Watts

The variation of the temperatures in the THX can be seen in the Figure 35. We see an oscillation of around 0.5°C in the temperatures of the outlet of the THX and of the active zone. As it is seen in the figures the temperatures increase until the set point temperature is reached. Then the valve 740 of the control system opens when the outlet temperature of the THX is greater than 230°C and closes in the opposite case. That causes the system to oscillate. The oscillations are seen more clearly in Figure 37. These oscillations are not very important. However a way to avoid them is to try that the gains and losses of heat compensate each other at the point that the system reaches the set point temperature. In order to do that we can control the power of the heater, maybe controlling this power could be the solution. Another solution maybe more efficient could be to optimize the parameters of the control system in order to avoid these oscillations.
Figure 35

Protected Beam Trip
Temperatures of PbBi

Figure 36

Protected Beam Trip
Temperatures of PbBi in the Active Zone
Figure 37

The oscillations for the oil are more important reaching maximum values of 4°C at the IHX. This can be seen in Figure 38 and Figure 39. The cause of these oscillations is the same as for the LBE as explained before. The oscillations begin again once the system reaches the set point temperature of 230°C.

The oil temperatures rise to 230°C except the temperature of the outlet of the IHX which takes the value of the water inlet IHX temperature i.e. 40°C. The oscillations in temperature reach the maximum for the element 100 that is to say at the inlet of the THX. That is because the oscillations of the temperature at the outlet of IHX are amplified at the junction between the bypass line of the oil and the IHX line. The oscillations in temperature of the other elements can be neglected, namely about 1°C for the outlet of the IHX, 0°C for the inlet.

A minimum flow of 0.1kg/s see Figure 41 through the IHX was set in order to avoid higher oscillations see also Ref.[7].
Figure 38

Protected Beam Trip

Temperatures of Oil

Figure 39

Protected Beam Trip

Temperatures of Oil in the THX
The temperatures in the IHX are much more stable as it can be seen in Figure 40.

![Figure 40](image)

This flow oscillates a little due to the same reasons explained before. These oscillations would be higher without this minimum flow as it can be seen in Ref.[7], reaching values of 0.9 kg/s, in our case the oscillations are about 0.2 kg/s. Without this minimum flow the oscillations in the temperatures of the oil would have been 60°C, which would be inadmissible.

To finish this paragraph it is shown in Figure 42 the opening of the valves 740 and 741. It can be seen how the oscillations begin in the moment that the system reaches the set point temperature.
Protected Beam Trip

Flow rate $Q_1$

Figure 41

Protected Beam Trip

Valves 740 and 741

Figure 42
I have studied also this trip with the old input see also Ref.[7]. The differences are the following:

- With the old input it takes for the system longer to reach the set point temperature. That is because the oil in the new input is warmer, because it has been added the losses of the oil pump. Therefore the oil takes less heat from the THX during the warming of the LBE until 230°C which using (118) implies less time for the warming.
- The oscillations for both inputs are in the same order of magnitude. In the old input the oscillations appear later since the system reaches the stability also later.

### 6.2 Pump Trip

A pump trip is a variation of the pump power from its nominal value to zero. I have studied the beam trip of the lead-bismuth main pump (the element number 888 in Figure 14 on page 42). The logical result is a rise of the temperature of the lead-bismuth cycle as is seen in Figure 43. Without the pump we lose a source of cooling, since forced circulation of lead-bismuth help by cooling. In this case we have only natural circulation and as it was seen in Table 15 for this case:

\[
\Delta p_{gr} = \rho_0 L g \alpha \Delta T
\]

in this case with:

\[
\Delta T = 447 - 230 = 217°C
\]

and:

\[
\Delta p_{gr} = 0.066 \text{ bar}
\]

\[
\frac{\Delta p_{gr}}{\Delta p_{gr\;\text{nominal}}} = \frac{0.066}{0.041} = 1.61
\]

That is to say in this case we have an increase of 161% of the buoyancy forces with respect to the steady state which is considerable.
The fact that the natural convection increases during a pump trip is seen also in Figure 44, where the mass flow rate reaches a value of 24.76 kg/s, which is not so small in comparison with the nominal value of 40.6 kg/s. In this figure are also represented the mass flow rates of the bypass loop, which takes a value of 3.362 kg/s (nominal value of 3.5 kg/s).
In Figure 45 is represented the value of the temperature of the active zone, which reach values of 447°C, which can be dangerous for the materials of the beam window.
In Figure 47 we see that the temperature difference at the THX exchanger suffers an increase from 103.5°C in nominal conditions to 167.67°C.
On the other hand the mass flow rate of LBE is lower. Therefore the THX exchanger has to cool less quantity of fluid per second. The latter compensates the increment of the temperature difference at THX and therefore the valve 740 closes a little more than in nominal conditions. This can be seen in Figure 48 where the opening of the valve 740 changes from 63% in nominal conditions to 43.45% in the pump trip. In this way the mass flow rate of the oil has the variation indicated in Figure 49. The bypass flow takes the value of 4.71 kg/s (in nominal conditions 3.56 kg/s) and the IHX flow takes the value 4.02 kg/s (in nominal conditions 5.19 kg/s).

In Figure 46 are represented the temperatures at the inlet of the active zone. In nominal conditions the temperature of 507(15) (inlet at the active zone) is smaller than the temperature of 525(15). That was already explained on page 44. In the same way as it was done in that paragraph one can proof the values of the temperatures of 276.05°C and 274.28°C for the inlets into the active zone from the downcomer and from the bypass pipe. In this case the heat exchanged between the riser and the downcomer is much bigger, that is due to the fact that the active zone temperature is 446.98°C instead of 354.81°C for nominal conditions.

In this case with the notations of Figure 17 $Q_1 = 10.56$ kW, $Q_2 = 154.69$ kW and $Q_3 = 3.869$ kW. With these results we can calculate the temperature of the inlet:
Figure 48

Pump Trip
Valves 740 and 741

Figure 49

Pump Trip
Flow Rate of Oil

81/120
\[ Q_{507} = -Q_1 + Q_2 + Q_3 = 147.99 kW \]

the mass flow rate through 507 is 24.76-3.362=21.398kg/s

for a mean pressure of 5.5 bar and a mean temperature of 526.15°C in Ref.[4] we find 
\[ c_p = 149.95 j/kgK. \]

\[
T_{517(15)} - 230 = \frac{1}{mc_p} Q_{507} = \frac{1}{21.398 \times 149.95} 147.99 \times 10^3 = 46.12°C
\]

That is to say:

\[
T_{517(15)} = 276.12°C
\]

which compared with the RELAP5 calculation of 276.05°C is an excellent approximation.

For the bypass, the heat of the pump given to the element 889 is \( Q_4 = 10 kW \) and the heat exchanged between 889 and 517 is \( Q_5 = 18.33 kW \), the heat exchanged between 503 and 523 is \( Q_{523} = 2.148 kW \) and with 507 the pipe 525 exchanged the value already mentioned \( Q_{525} = 3.869 kW \), that is to say:

\[
Q_{\text{bypass}} = Q_{889} - Q_{523} - Q_{525} = 22.313 kW
\]

\[
T_{525(15)} - 230 = \frac{1}{mc_p} Q_{\text{bypass}} = \frac{1}{3.362 \times 149.94} 22.313 \times 10^3 = 44.26°C
\]

and the inlet temperature of the bypass line in the active zone has the value:

\[
T_{525(15)} = 274.26°C
\]

in comparison with the estimated value of RELAP5 of 274.28°C the value calculated is a good approximation.

The temperature of the bypass at the inlet of the active zone rises with respect to the nominal value but it becomes smaller than the value of the inlet temperature at the active zone of the downcomer. This last temperature is higher because of the increase of exchanged energy with the riser.
In Figure 50 are the temperatures of oil at different points of the intermediate cooling loop, after the trip at t=1000s the system oscillates, it lasts 320 seconds till the system reaches the equilibrium.

6.3 Start Up of the Target

This operation will be done once in the “lifetime” of the MEGAPIE project. First the target is preheated with argon, and then LBE is put into the target from a container through a pipe. This pipe goes by the head of the target. The temperature of the LBE in the container is 140°C; with the help of the heater in the central rod the LBE is warmed until the hot standby temperature of 230°C. Here I will analyze the transient of warming the LBE from 140°C to 230°C. There are many ways of doing that. I have studied a possible alternative. The pump oil continues working during the process of working but at a smaller power. The velocity of the
oil pump for this transient has been taken as 206.2 rad/s. The other pumps are working at full power. I have supposed that the heat loss to the exterior varies linearly from the value for 140°C to the value for 230°C calculated on page 40.

Evidently the time of warming depends on the mass flow rate of the oil. The fastest way to warm the LBE is without oil but we lose the possibility of control the temperatures of the LBE.

![Start up of the Target](image)

**Figure 53**

The temperature of LBE at the outlet of the THX is shown in Figure 54.
The heat losses to the exterior are modeled as a linear interpolation between the value 8.1kW for 140°C and the value 17.98kW for the hot standby temperature of 230°C (see Table 8 and Table 9 on page 40). We can take for the interval of warming an averaged value of:

\[ Q_{\text{loss}} = \frac{17.98 + 8.1}{2} = 13.04 \text{kW} \]

22kW is the power of the heater, 20kW the heat loss of the pumps. Looking at Figure 55, it is easy to see that it can be considered a mean value of 18kW for the heat given to the oil at the THX during the warming of the target (from 1050s to 4200s). In this case the structural materials play an important role in determining the time of warming. As it can be seen in Table 25 the material structures are absorbing heat during the process of heating of the target, in this way the heating process takes longer as it could be at first imagined. The averaged heat removed by the structures is from Table 25:

\[ Q_{\text{struc}} = \frac{8911 + 8625.3 + 7348.3 + 5322.2}{4} = 7551.7 \text{W} \]
The total time of heating is:

\[
\Delta t = \frac{c_p m \Delta T}{\bar{Q}_T} = \frac{151 \times 814.85 \times (230 - 140)}{(22 + 20 - 13 - 18 - 7.5) \times 10^3} = 3163.95 \text{s}
\]

The value of RELAP5 is 3200 seconds. This value is represented in Figure 54.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Heat (W)</th>
<th>Time (s)</th>
<th>Heat (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>9036.7</td>
<td>2660</td>
<td>17372.2</td>
</tr>
<tr>
<td>1090</td>
<td>17869.2</td>
<td>2760</td>
<td>17493.5</td>
</tr>
<tr>
<td>1160</td>
<td>18341.7</td>
<td>2860</td>
<td>17610.8</td>
</tr>
<tr>
<td>1260</td>
<td>18126</td>
<td>2960</td>
<td>17719.5</td>
</tr>
<tr>
<td>1360</td>
<td>18018.3</td>
<td>3060</td>
<td>17822.2</td>
</tr>
<tr>
<td>1460</td>
<td>17969.7</td>
<td>3160</td>
<td>17921.4</td>
</tr>
<tr>
<td>1560</td>
<td>17938.9</td>
<td>3260</td>
<td>18061.4</td>
</tr>
<tr>
<td>1660</td>
<td>17903.7</td>
<td>3360</td>
<td>18166.2</td>
</tr>
<tr>
<td>1760</td>
<td>17855.6</td>
<td>3460</td>
<td>18256.2</td>
</tr>
<tr>
<td>1860</td>
<td>17797.5</td>
<td>3560</td>
<td>18340.3</td>
</tr>
<tr>
<td>1960</td>
<td>17776.1</td>
<td>3660</td>
<td>18417.7</td>
</tr>
<tr>
<td>2060</td>
<td>17722.1</td>
<td>3760</td>
<td>18488.4</td>
</tr>
<tr>
<td>2160</td>
<td>17625.8</td>
<td>3860</td>
<td>18553.9</td>
</tr>
<tr>
<td>2260</td>
<td>17560.1</td>
<td>3960</td>
<td>18615.8</td>
</tr>
<tr>
<td>2360</td>
<td>17487.1</td>
<td>4060</td>
<td>18675.3</td>
</tr>
<tr>
<td>2460</td>
<td>17386</td>
<td>4160</td>
<td>18745</td>
</tr>
<tr>
<td>2560</td>
<td>17308</td>
<td>4260</td>
<td>21461.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4360</td>
<td>22845.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4460</td>
<td>23976.5</td>
</tr>
</tbody>
</table>

Figure 55 Heat Power removed from the LBE in the THX

<table>
<thead>
<tr>
<th>Structure</th>
<th>Time</th>
<th>1060 s</th>
<th>2060 s</th>
<th>3060 s</th>
<th>4060 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>5171</td>
<td>324</td>
<td>187.56</td>
<td>153</td>
<td>112</td>
<td></td>
</tr>
<tr>
<td>5172</td>
<td>366</td>
<td>310</td>
<td>254</td>
<td>188</td>
<td></td>
</tr>
<tr>
<td>5173</td>
<td>189</td>
<td>155</td>
<td>127</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>5271</td>
<td>660</td>
<td>155</td>
<td>381</td>
<td>279</td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td>39</td>
<td>24</td>
<td>20.1</td>
<td>14.7</td>
<td></td>
</tr>
<tr>
<td>5201</td>
<td>1934</td>
<td>1636</td>
<td>1340</td>
<td>944</td>
<td></td>
</tr>
<tr>
<td>5202</td>
<td>702</td>
<td>731</td>
<td>605</td>
<td>446</td>
<td></td>
</tr>
<tr>
<td>5231</td>
<td>1219</td>
<td>2002</td>
<td>1650</td>
<td>1221</td>
<td></td>
</tr>
<tr>
<td>5072</td>
<td>157.5</td>
<td>165</td>
<td>142.5</td>
<td>52.5</td>
<td></td>
</tr>
<tr>
<td>5251</td>
<td>37.5</td>
<td>45</td>
<td>40.5</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>5032</td>
<td>1982.3</td>
<td>1970.37</td>
<td>1551.5</td>
<td>1105</td>
<td></td>
</tr>
<tr>
<td>5071</td>
<td>1300.7</td>
<td>1244.4</td>
<td>1083.7</td>
<td>837</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8911</td>
<td>8625.3</td>
<td>7348.3</td>
<td>5322.2</td>
<td></td>
</tr>
</tbody>
</table>

Table 25 Heat removed from the LBE by the material structures, Values in Watts
The openings of the valves 740 and 741 are shown in Figure 57. Oscillations of magnitude 0.3 are observed when the system reaches the hot standby temperature. In Figure 58 are represented the temperatures of the oil, also oscillations of magnitude 5°C are observed when the system reaches the hot standby temperature.
Figure 57

Start up of the Target
Temperatures of Oil

Figure 58
6.4 Shut Down of the Target

Once the experiment is finished, the final phase of operation follows, which first consists of turning off the beam power, then the LBE reaches the hot standby temperature and finally the LBE is cooled till the temperature of 140°C. Care must be taken in avoiding that LBE reaches the melting temperature of 125°C.

In this paragraph I analyze the cooling of the LBE from 230°C to 140°C. During the transient the control system makes that the LBE reaches the set point temperature which in this case is 140°C. Two cases are analyzed: with and without oil pumping.

6.4.1 Without Oil Pumping

In this case I have turned off the oil pump. A similar effect can be obtained by closing the two valves 739 and 742. Without the oil pump the cooling process takes longer.

![Shut down of the Target](image)

**Figure 59**

The necessary time to cool the LBE is about 3500 seconds as it is seen in Figure 59. The exponential decay is because the THX heat power decays exponentially.
After reaching 140°C the LBE oscillates as it can be seen in Figure 60. After that, the temperature begins to decrease with the danger of melting of the LBE. Therefore it is recommended to use a heater 3500 seconds after the transient to avoid it. The heat power of THX at $t=3500\text{s}$ is 35.7kW and descends to 13.7kW at $t=6500\text{ s}$. The heat loss to the exterior for this temperature is 8.1kW and the heat of the LBE pumps is 20kW. That is to say it will be necessary at least a heat power of 1.8kW. This power has to be increased with the time since the oil becomes colder and more energy is necessary to avoid the melting of LBE.

![Figure 60](image-url)

**Figure 60**
Figure 61

The temperatures of the oil are shown in Figure 61.
Figure 62

The mass flow rate of the oil is shown in Figure 62; the mass flow rate through the THX has a value at t=6500 s of 0.092 kg/s.
The opening of the valves 740 and 741 is shown in Figure 63, at t=3000 s the valve 740 opens completely in order to cool the LBE till the temperature of 140°C. When this temperature is reached valve 740 closes.

Conclusions:

• The time of cooling is approximately 3500 seconds. After that a heater must be used in order to avoid the melting of LBE.

• Despite the small mass flow rate of the oil, the oil has some control over the LBE set point temperature of 140°C.

• This is the slowest way to cool the LBE but combined with a heater at the end of the process, it is also the safer one.

• The temperatures of LBE do not sink under 140°C at least 4000 seconds after the transient. That is an advantage with respect to the other possibilities of cooling because it reduces the risk of LBE melting.
6.4.2 With Oil Pumping

6.4.2.1 With Heater

Figure 64

Figure 65
The power of the heater is 22kW. The purpose of the heater is to assure that the LBE does not melt.

For the calculation of the time of cooling we have divided the time from 3000s to 3400 s into two intervals, the first from 3000s to 3190s and the second from 3190s to 3400s.

For the first interval:
For the heat loss to the exterior in this interval we have taken a mean value of the results of Table 8 and Table 9 on page 40:

$$Q_{\text{ext}} = \frac{17.98 + 8.1}{2} = 13.04 kW$$

From Table 26 it has been taken an averaged value of 90kW in the interval between 3000 and 3180 seconds for the heat given by the material structures to the LBE. For the same interval the values from Figure 66 of the heat removed at THX have been interpolated by means of a parabola. With the help of Matlab we have calculated the polynomial and by integration the averaged value in this interval. The result was 187.12kW, taking all the results together we have:

$$\Delta t = \frac{c_p m \Delta T}{Q_T} = \frac{151 \times 814.85 \times (134-230)}{(22+20+13+90-187.12)\times10^3} = 173.4 s$$

For the second interval:
Interpolating linearly in Table 26 the value of the heat for t=3190 s we obtain 60.23kW. In the same way for t=3400 s we obtain 7.3kW. The next step is to find an averaged value of the heat given by the structures in this interval. Taking the mean value in each interval and then the mean of these values we obtain:

$$Q_{\text{struc}} = \frac{35.61 \times 110 + 9.27 \times 100}{210} = 23.06 kW$$

For the heat removed from the LBE we use the results of Figure 66 taken from the RELAP5 calculation. We take the average value of each interval and then the mean value of all these values, that is to say:

$$Q_{\text{THX}} = \frac{70.6 \times 110 + 32.95 \times 100}{210} = 52.67 kW$$

For the heat loss we take the value 8.1kW of Table 9, which was inserted also in the input deck of RELAP5. The losses of the pumps are 20kW, taking all these results we can estimate the last of the second interval:

$$\Delta t = \frac{c_p m \Delta T}{Q_T} = \frac{151 \times 814.85 \times (140-134)}{(22+20+23.06-8.1-52.67)\times10^3} = 172.1 s$$
That is to say \( 173.4 + 172.1 = 345.5 \) seconds for the process of cooling, which is an approximation to the RELAP5 value of 370 seconds, see Figure 64.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Heat (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
<td>17.279</td>
</tr>
<tr>
<td>3005</td>
<td>127.642</td>
</tr>
<tr>
<td>3010</td>
<td>231.84</td>
</tr>
<tr>
<td>3020</td>
<td>257.253</td>
</tr>
<tr>
<td>3030</td>
<td>259.139</td>
</tr>
<tr>
<td>3040</td>
<td>246.12</td>
</tr>
<tr>
<td>3050</td>
<td>236.301</td>
</tr>
<tr>
<td>3060</td>
<td>229.315</td>
</tr>
<tr>
<td>3070</td>
<td>222.771</td>
</tr>
<tr>
<td>3080</td>
<td>216.365</td>
</tr>
<tr>
<td>3090</td>
<td>209.985</td>
</tr>
<tr>
<td>3100</td>
<td>203.611</td>
</tr>
<tr>
<td>3110</td>
<td>197.277</td>
</tr>
<tr>
<td>3120</td>
<td>191.04</td>
</tr>
<tr>
<td>3130</td>
<td>184.977</td>
</tr>
<tr>
<td>3140</td>
<td>179.088</td>
</tr>
<tr>
<td>3150</td>
<td>173.353</td>
</tr>
<tr>
<td>3160</td>
<td>110.734</td>
</tr>
<tr>
<td>3200</td>
<td>100.804</td>
</tr>
<tr>
<td>3300</td>
<td>30.587</td>
</tr>
<tr>
<td>3400</td>
<td>35.308</td>
</tr>
<tr>
<td>3500</td>
<td>26.324</td>
</tr>
<tr>
<td>3600</td>
<td>20.41</td>
</tr>
<tr>
<td>3700</td>
<td>24.993</td>
</tr>
<tr>
<td>3800</td>
<td>29.834</td>
</tr>
<tr>
<td>3900</td>
<td>23.72</td>
</tr>
<tr>
<td>4000</td>
<td>18.557</td>
</tr>
</tbody>
</table>

**Figure 66** Heat Power removed from the LBE in the THX

<table>
<thead>
<tr>
<th>Structure</th>
<th>Time</th>
<th>3030 s</th>
<th>3130 s</th>
<th>3300 s</th>
<th>3600 s</th>
<th>3900 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>5171</td>
<td>3123</td>
<td>2526</td>
<td>-21</td>
<td>48.4</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>5172</td>
<td>2696</td>
<td>3858.4</td>
<td>756.4</td>
<td>75.2</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>5173</td>
<td>1436</td>
<td>1955.5</td>
<td>341.58</td>
<td>39.316</td>
<td>37.5</td>
<td></td>
</tr>
<tr>
<td>5271</td>
<td>9300</td>
<td>5881.9</td>
<td>-240</td>
<td>29</td>
<td>129</td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td>856.8</td>
<td>300</td>
<td>-21.6</td>
<td>6.6</td>
<td>35.1</td>
<td></td>
</tr>
<tr>
<td>5201</td>
<td>12215.4</td>
<td>17096.3</td>
<td>5483.85</td>
<td>458.91</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>5202</td>
<td>5815.9</td>
<td>7584.9</td>
<td>2183.99</td>
<td>397</td>
<td>116.9</td>
<td></td>
</tr>
<tr>
<td>5231</td>
<td>21141.51</td>
<td>23132.46</td>
<td>4470</td>
<td>-255.7</td>
<td>387.72</td>
<td></td>
</tr>
<tr>
<td>5072</td>
<td>4950</td>
<td>1950</td>
<td>-225</td>
<td>-195</td>
<td>-63</td>
<td></td>
</tr>
<tr>
<td>5251</td>
<td>765</td>
<td>525</td>
<td>-30</td>
<td>-37.5</td>
<td>-50</td>
<td></td>
</tr>
<tr>
<td>5032</td>
<td>36083.5</td>
<td>27270.3</td>
<td>-1102</td>
<td>-568.2</td>
<td>-584.7</td>
<td></td>
</tr>
<tr>
<td>5071</td>
<td>-1438.9</td>
<td>-5085</td>
<td>-420</td>
<td>-390</td>
<td>-1491</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>96944.21</td>
<td>86995.76</td>
<td>11176.22</td>
<td>-391.98</td>
<td>-1314.4</td>
<td></td>
</tr>
</tbody>
</table>

**Table 26** Heat removed from the LBE by the material structures, Values in Watts
Figure 67

Shut down of the Target
Temperatures of Oil

Figure 68

Shut down of the Target
Opening of the valves 740 and 741
Conclusions:

- The shut down of the target with a heater and with oil pumping takes less time than the other possibilities.
- The oscillations in the temperature of oil and LBE are higher than in the other cases studied. As alternative the power of the heater can be regulated obtaining in this way slightly less oscillations.
- In order to avoid the oscillations completely an optimization of the control system would be needed.

A result of regulating the power of the heater is shown in the next figure:

**Figure 69**
The oscillation decreases a little as compared with Figure 65
Figure 70

Shut down of the Target
Set Point Temperature

Figure 71

Shut down of the Target
Valves 740 and 741
6.4.2.2 Without Heater

The calculations are very similar to the case with heater. Therefore I only show the results.

![Shutdown of the Target](image)

**Figure 72**

In this case as it can be seen in Figure 72, the system reaches the equilibrium after approximately 900 seconds. The minimal temperature during the transient is 134°C. Comparing with Figure 64 we see that the decrease of the temperature until 134°C is faster than in the case with heater; however the increase of the temperature until 140°C takes longer in this case. This results in a longer time of cooling for the case without heater.
In Figure 73 are represented the temperatures of LBE in THX, the temperatures keep on the value 140°C with tiny oscillations.

For the calculation of the time of cooling I have divided the time from 3000s to 3900 s into two intervals, the first from 3000s to 3180s and the second from 3180s to 3900s.

The calculations for this case are very similar to the case without heater. From RELAP5 I have obtained results similar to the ones represented in Figure 66 and Table 26. However in this case more heat is removed from LBE by the THX (because of the heater). At the beginning the difference is not so high 177kW instead of 187kW but in the second interval the difference is much higher. For the case with heater it was an averaged value of 52.67kW and for the case without heater it is 22.84kW. The heat given by the material structures is now bigger during the first interval (now 98.1kW and before 90kW) and smaller during the second (now 11.9kW and before 23.06kW). The other parameters are similar to the case without heater. Taking all the results together we have:

For the first interval:

$$\Delta t = \frac{c_p m \Delta T}{\dot{Q}_T} = \frac{151 \times 814.85 \times (134 - 230)}{(20 - 13 + 98.19 - 177) \times 10^3} = 164.4s$$
For the second interval:

\[ \Delta t = \frac{c_p m \Delta T}{Q_r} = \frac{151 \times 814.85 \times (140 - 134)}{(20 + 11.9 - 8.1 - 22.84) \times 10^3} = 703.10 \text{s} \]

That is to say 164.4 + 703.1 = 867.5 seconds for the process of cooling, which is an approximation to the RELAP5 value of 900 seconds, see Figure 72.

Figure 74

In Figure 74 are represented the oil temperatures. By reaching the steady state the oil temperatures at THX present small oscillations of about 1°C.
Figure 75
In Figure 75 are represented the openings of the valves 740 and 741. As already seen before the oscillations in the valves begin when the steady state is reached. To avoid these tiny oscillations a refinement of the control system is required.

6.4.3 Conclusion
After having done the experiments of the two cases with oil pumping, it was tried to find an alternative and it was found that the process without oil pumping has some advantages over the others. The disadvantage of the slowness of this variant is compensated with the fact that this slowness makes the system more easy to be controlled, above all taking into account the danger of melting of LBE.
7. Conclusions and Future Tasks

7.1 Conclusions

- The MEGAPIE thermal-hydraulic system reaches a stable steady state within a variation of the beam power from 700kW till 350kW. Under 350kW the steady state oscillates. To avoid this oscillation other parameters like the inlet temperature and the pressure of the water and in some cases the pump mass flow rates have to be varied.

- After a beam trip the temperature of the top of the active zone reaches a value of 446.98°C, that is to say an increase of 92.17°C with respect to the nominal conditions. This temperature could be a problem for the material structures.

- At the start up of the target the hot standby temperature is reached after 3200 seconds.

- I think the best alternative for the shut down of the target is without oil pumping. In this case the process takes longer, namely 3500 seconds but the temperature of the LBE does not decrease below 140°C.

- The control system works very well under normal beam trip.

- The control system does not work completely well when reaching some constant temperatures for the LBE; for example:
  - when reaching the hot standby temperature of 230°C in a protected beam trip
  - or at the start up of the target
  - when reaching 140°C during the shut down of the target.

- The central Rod has some influence in the oscillations of LBE and oil temperatures. A control over the heater reduces the oscillations but not completely. To reduce them completely a refinement of the control system is required.

- The structural materials have a big influence in the response of the system under transient conditions.

- Making manual calculations considering the behavior of the structural material is very difficult. RELAP5 has turned out to be a very powerful tool, not only for general-purpose calculations, but also because it complements particularly well the exactness of manual calculations in which the behavior of the structural materials plays a role.

- I think the results in this work are an improvement to former results. However, when I started with this diploma work and the computational experiments it implied, I did not
know RELAP5. I had to study it first and I had to familiarize with it through learning by doing. With the RELAP5 experience I am having now at the end of the diploma work I realize that I would do certain experiments slightly differently in order to adapt them even more to reality.

### 7.2 Future Tasks

- Optimize the control system. I think RELAP5 is ideal for this purpose, because it can be easily tested with it.
- Compare the measures given in Table A with the measures given by the manufactures. In case that there are important discrepancies change the input deck of RELAP5.
- Include the Secondary Water Loop (SWL) in the input deck of RELAP5.
- Verify the exactitude of the heat losses of the pumps.
- Estimate the oil heat loss to the exterior and if it is different from the value already included in the input deck of RELAP5 then change it.
- Study the possibility of including a control system for the electrical heater of the central rod.
- Study the empirical correlations for the heat transfer coefficient and in particular the ones that RELAP5 uses in order to include the better ones in the input deck of RELAP5.
- Study the plate IHX and in particular optimize the number of necessary modules.
Appendix A

In this Appendix the values of the principal dimensions of the hydraulic components and material structures are shown. I have taken them from the input deck of RELAP5 of the firma Ansaldo.

In each column the measures of the technical report of Ansaldo in orange are compared with the measures put in the input of RELAP5 by Ansaldo. I have calculated the deviation of these two values, which have the following colors:

- The deviations are zero or not considerable
- The deviations are less than 5%
- The deviations are bigger than 5%
- Probably a typing mistake

With the material structures the following notation is used:

N1: Number of radial mesh points
N2: Number of intervals; N1 mesh points define N1-1 intervals
N3: Number of axial structures in which the structures is divided
## HYDRAULIC COMPONENTS

<table>
<thead>
<tr>
<th>Element</th>
<th>Calculated</th>
<th>Mass[Kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 Branch</td>
<td>1.0830E+00 1.0830E+00 4.6070E-03 4.6070E-03 4.9800E+00 4.9894E-03</td>
<td>4.5403E+00</td>
</tr>
<tr>
<td>101 Pipe (7)</td>
<td>1.4140E+00 1.4140E+00 3.0536E-03 3.0536E-03 4.3100E+00 4.3178E-03</td>
<td>1.8000E-02 1.8000E-02 3.9292E+00</td>
</tr>
<tr>
<td>102 Junction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>103 Annulus</td>
<td>2.8800E+00 2.8800E+00 2.0448E-03 2.0448E-03 5.8800E+00 5.8890E-03 3.9000E-03 3.9000E-03 4.0000E-03 4.0000E-03 5.3590E+00</td>
<td></td>
</tr>
<tr>
<td>104 Branch</td>
<td>1.0830E+00 1.0830E+00 7.9540E-03 7.9540E-03 8.8470E+00 8.8470E+00 9.5813E-03 9.5813E-03 8.7190E+00</td>
<td></td>
</tr>
<tr>
<td>171 Pipe(2)</td>
<td>1.0000E+00 1.0000E+00 3.3160E-03 3.3160E-03 3.3200E+00 3.3200E+00 6.5000E-02 6.5000E-02 6.4977E-02 6.4977E-02 3.0176E+00</td>
<td></td>
</tr>
<tr>
<td>105 Pipe(2)</td>
<td>1.7300E+00 1.7300E+00 3.3160E-03 3.3160E-03 5.7400E-03 5.7400E-03 6.5000E-02 6.5000E-02 6.4977E-02 6.4977E-02 5.2204E+00</td>
<td></td>
</tr>
<tr>
<td>106 Pipe</td>
<td>1.7520E+00 1.7520E+00 3.3160E-03 3.3160E-03 5.8100E-03 5.8100E-03 6.5000E-02 6.5000E-02 6.4977E-02 6.4977E-02 5.2868E+00</td>
<td></td>
</tr>
<tr>
<td>Elements</td>
<td>Length [m]</td>
<td>Flow Cross Section [m²]</td>
</tr>
<tr>
<td>----------</td>
<td>------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td></td>
<td>Ansaldo</td>
<td>RELAP5</td>
</tr>
<tr>
<td>108 Pipe</td>
<td>2.0000E+00</td>
<td>2.0000E+00</td>
</tr>
<tr>
<td>149 Branch</td>
<td>5.4500E-01</td>
<td>5.4500E-01</td>
</tr>
<tr>
<td>123 Pipe(2)</td>
<td>2.0000E+00</td>
<td>2.0000E+00</td>
</tr>
<tr>
<td>113 Branch</td>
<td>6.3500E-01</td>
<td>6.3500E-01</td>
</tr>
<tr>
<td>114 Pipe</td>
<td>7.9200E-01</td>
<td>7.9200E-01</td>
</tr>
<tr>
<td>115 Branch</td>
<td>6.3500E-01</td>
<td>6.3500E-01</td>
</tr>
<tr>
<td>116 Pipe(2)</td>
<td>4.3400E-01</td>
<td>4.3400E-01</td>
</tr>
<tr>
<td>117 Junction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>118 Pipe(2)</td>
<td>2.2700E+00</td>
<td>2.2700E+00</td>
</tr>
<tr>
<td>119 Pipe</td>
<td>2.2700E+00</td>
<td>2.2700E+00</td>
</tr>
<tr>
<td>Elements</td>
<td>Length [m]</td>
<td>Flow Cross Section [m²]</td>
</tr>
<tr>
<td>-------------------</td>
<td>------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td></td>
<td>Ansaldo</td>
<td>RELAP5</td>
</tr>
<tr>
<td>169 Junction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>170 Pipe (2)</td>
<td>6.0000E-01</td>
<td>6.0000E-01</td>
</tr>
<tr>
<td>120 Pipe (2)</td>
<td>1.6000E+00</td>
<td>1.6000E+00</td>
</tr>
<tr>
<td>122 Pipe (2)</td>
<td>7.9600E-01</td>
<td>7.9600E-01</td>
</tr>
<tr>
<td>111 Pipe (2)</td>
<td>1.6220E+00</td>
<td>1.6220E+00</td>
</tr>
<tr>
<td>Maximum Capacity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>of oil (m³)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Mass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>of oil (Kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150 Branch</td>
<td>2.5000E+01</td>
<td></td>
</tr>
<tr>
<td>299 Branch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>303 Pipe (4)</td>
<td>7.9200E-01</td>
<td>7.9200E-01</td>
</tr>
<tr>
<td>Elements</td>
<td>Length [m]</td>
<td>Flow Cross Section [m²]</td>
</tr>
<tr>
<td>---------------</td>
<td>------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td></td>
<td>Ansaldo</td>
<td>RELAP5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Components</td>
<td></td>
<td></td>
</tr>
<tr>
<td>305 Branch</td>
<td>1.0000E+00</td>
<td>1.0000E+00</td>
</tr>
<tr>
<td>500 Branch</td>
<td>1.0000E-01</td>
<td>6.9000E-02</td>
</tr>
<tr>
<td>600 Branch</td>
<td>2.8980E-02</td>
<td>6.9000E-02</td>
</tr>
<tr>
<td>503 Annulus(6)</td>
<td>1.2120E+00</td>
<td>8.7420E-03</td>
</tr>
<tr>
<td>505 Branch</td>
<td>1.1439E-01</td>
<td>8.7420E-03</td>
</tr>
<tr>
<td>507Annulus(15)</td>
<td>2.3250E+00</td>
<td>1.2050E-02</td>
</tr>
<tr>
<td>509 Branch</td>
<td>5.2710E-02</td>
<td>1.2050E-02</td>
</tr>
<tr>
<td>513 Annulus(2)</td>
<td>3.4700E-01</td>
<td>1.1680E-02</td>
</tr>
<tr>
<td>513 Annulus(2)</td>
<td>3.7100E-01</td>
<td>1.1190E-02</td>
</tr>
<tr>
<td>513Annulus(11)</td>
<td>1.6070E+00</td>
<td>9.0430E-03</td>
</tr>
<tr>
<td>Elements</td>
<td>Length [m]</td>
<td>Flow Cross Section [m²]</td>
</tr>
<tr>
<td>---------------</td>
<td>------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td></td>
<td>Ansaldo</td>
<td>RELAP5</td>
</tr>
<tr>
<td>517 Annulus(3)</td>
<td>6.3000E-01</td>
<td>6.0600E-01</td>
</tr>
<tr>
<td>888 Pump(1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>520 Annulus(1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>889 Pump(1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>523 Pipe (3)</td>
<td>6.0600E-01</td>
<td>6.0600E-01</td>
</tr>
<tr>
<td>525 Annulus(15)</td>
<td>2.3250E+00</td>
<td>2.2950E+00</td>
</tr>
<tr>
<td>Maximum Capacity of PbBi(m³)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Mass of PbBi(Kg)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## MATERIAL STRUCTURES

<table>
<thead>
<tr>
<th>Structure</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>Left Radius [m]</th>
<th>Right Radius [m]</th>
<th>Height [m]</th>
<th>Volume [m³] per element</th>
<th>Mass [Kg] total</th>
</tr>
</thead>
<tbody>
<tr>
<td>5031</td>
<td>6</td>
<td>5</td>
<td>6</td>
<td>2.5500E-02</td>
<td>2.5500E-02</td>
<td>2.7000E-02</td>
<td>2.4240E+00</td>
<td>5.9969E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5131</td>
<td>6</td>
<td>5</td>
<td>13</td>
<td>0.0000E+00</td>
<td>2.8500E-02</td>
<td>2.9000E-02</td>
<td>1.5300E-01</td>
<td>4.0420E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5171</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td>0.0000E+00</td>
<td>2.9E-3</td>
<td>31E-3</td>
<td>2.0200E-01</td>
<td>1.8300E-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5172</td>
<td>17</td>
<td>5</td>
<td>2</td>
<td>0.0000E+00</td>
<td>2.9E-3</td>
<td>31E-3</td>
<td>2.0200E-01</td>
<td>2.6860E-03</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5173</td>
<td>17</td>
<td>5</td>
<td>1</td>
<td>0.0000E+00</td>
<td>2.9E-3</td>
<td>31E-3</td>
<td>2.0200E-01</td>
<td>1.3430E-03</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5071</td>
<td>6</td>
<td>5</td>
<td>15</td>
<td>8.8000E-02</td>
<td>9.0000E-02</td>
<td>9.0000E-02</td>
<td>1.5300E-01</td>
<td>2.5667E-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5072</td>
<td>6</td>
<td>5</td>
<td>15</td>
<td>6.1000E-02</td>
<td>6.2500E-02</td>
<td>6.2500E-02</td>
<td>1.5300E-01</td>
<td>1.3356E-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5251</td>
<td>6</td>
<td>5</td>
<td>15</td>
<td>1.4500E-02</td>
<td>1.6000E-02</td>
<td>1.6000E-02</td>
<td>1.5300E-01</td>
<td>2.1990E-05</td>
</tr>
<tr>
<td>Structure</td>
<td>N1</td>
<td>N2</td>
<td>N3</td>
<td>Left Radius [m]</td>
<td>Right Radius [m]</td>
<td>Height [m]</td>
<td>Volume [m³]</td>
<td>Mass [Kg]</td>
</tr>
<tr>
<td>-----------</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----------------</td>
<td>-----------------</td>
<td>------------</td>
<td>-------------</td>
<td>-----------</td>
</tr>
<tr>
<td></td>
<td>Ansaldo RELAP5</td>
<td>Ansaldo RELAP5</td>
<td>Ansaldo RELAP5</td>
<td>per element</td>
<td>total</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PbBi Structures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5202</td>
<td>35</td>
<td>1</td>
<td>23 10</td>
<td>6.1000E-02</td>
<td>6.1000E-02</td>
<td>62.5E-03</td>
<td>62.5E-03</td>
<td>1.0200E-01</td>
</tr>
<tr>
<td>5201</td>
<td>38</td>
<td>1</td>
<td>14 11</td>
<td>6.1000E-02</td>
<td>6.1000E-02</td>
<td>62.5E-03</td>
<td>62.5E-03</td>
<td>1.0200E-01</td>
</tr>
<tr>
<td>5231</td>
<td>32</td>
<td>1</td>
<td>10 9</td>
<td>11</td>
<td>7.2500E-02</td>
<td>7.2500E-02</td>
<td>74E-03 94E-03</td>
<td>74E-03</td>
</tr>
<tr>
<td>5271</td>
<td>16</td>
<td>1</td>
<td>13</td>
<td>1</td>
<td>5.1000E-02</td>
<td>5.1000E-02</td>
<td>53E-03</td>
<td>53E-03</td>
</tr>
<tr>
<td>5232</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>8.0000E-03</td>
<td>8.0000E-03</td>
<td>1.0000E-02</td>
<td>1.0000E-02</td>
<td>6.0600E-01</td>
</tr>
<tr>
<td>5032</td>
<td>18</td>
<td>17</td>
<td>1</td>
<td>6</td>
<td>1.7300E-01</td>
<td>1.7300E-01</td>
<td>1.9000E-01</td>
<td>1.9000E-01</td>
</tr>
<tr>
<td>8881</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1.0000E-02</td>
<td>2.0000E-02</td>
<td>5.0000E+00</td>
<td>4.7123E-03</td>
</tr>
<tr>
<td>8891</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1.0000E-02</td>
<td>2.0000E-02</td>
<td>2.0000E+00</td>
<td>1.8849E-03</td>
</tr>
<tr>
<td>5091</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>1.0000E-02</td>
<td>2.0000E-02</td>
<td>1.5000E+01</td>
<td>1.4137E-02</td>
<td>7.0686E-02</td>
</tr>
<tr>
<td>Structure</td>
<td>N1</td>
<td>N2</td>
<td>N3</td>
<td>Left Radius [m]</td>
<td>Right Radius [m]</td>
<td>Height [m]</td>
<td>Volume [m³]</td>
<td>Mass [Kg]</td>
</tr>
<tr>
<td>-----------</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>-----------------</td>
<td>-----------------</td>
<td>----------</td>
<td>-------------</td>
<td>----------</td>
</tr>
<tr>
<td>6000</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>8.0000E-03</td>
<td>1.0000E-02</td>
<td>2.0200E-01</td>
<td>2.2800E-05</td>
<td>6.8500E-05</td>
</tr>
<tr>
<td>1011</td>
<td>4</td>
<td>3</td>
<td>6</td>
<td>9.0000E-03</td>
<td>2.3500E-02</td>
<td>2.4200E+00</td>
<td>3.5880E-03</td>
<td>2.1532E-02</td>
</tr>
<tr>
<td>1171</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3.3000E-02</td>
<td>3.8000E-02</td>
<td>5.0000E-01</td>
<td>5.5760E-04</td>
<td>1.1150E-03</td>
</tr>
<tr>
<td>1051</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3.3000E-02</td>
<td>3.8000E-02</td>
<td>1.1180E+00</td>
<td>1.2468E-03</td>
<td>2.4937E-03</td>
</tr>
<tr>
<td>1061</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3.3000E-02</td>
<td>3.8000E-02</td>
<td>8.7600E-01</td>
<td>9.7697E-04</td>
<td>1.9539E-03</td>
</tr>
<tr>
<td>1111</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>3.3000E-02</td>
<td>3.8000E-02</td>
<td>1.00E00</td>
<td>0.811</td>
<td>2.9242E-03</td>
</tr>
<tr>
<td>Structure</td>
<td>N1</td>
<td>N2</td>
<td>N3</td>
<td>Left Radius [m]</td>
<td>Right Radius [m]</td>
<td>Height [m]</td>
<td>Volume [m³]</td>
<td>Mass [Kg]</td>
</tr>
<tr>
<td>-----------</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>-----------------</td>
<td>-----------------</td>
<td>------------</td>
<td>-------------</td>
<td>-----------</td>
</tr>
<tr>
<td>1221</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3.3000E-02</td>
<td>3.8000E-02</td>
<td>3.9800E-01</td>
<td>4.4387E-04</td>
<td>8.8775E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.9866E+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1161</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3.3000E-02</td>
<td>3.8000E-02</td>
<td>2.1700E-01</td>
<td>2.4200E-04</td>
<td>4.8400E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.8091E+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1201</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>3.3000E-02</td>
<td>3.8000E-02</td>
<td>0.293</td>
<td>0.293</td>
<td>1.0996E-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.200</td>
<td>0.200</td>
<td>8.6539E+00</td>
</tr>
<tr>
<td>1181</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>3.3000E-02</td>
<td>3.8000E-02</td>
<td>2.270</td>
<td>2.270</td>
<td>5.0630E-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.9846E+01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1181</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>3.3000E-02</td>
<td>3.8000E-02</td>
<td>1.067</td>
<td>1.067</td>
<td>2.3790E-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.8723E+01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1170</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3.3000E-02</td>
<td>3.8000E-02</td>
<td>3.0000E-01</td>
<td>3.3458E-04</td>
<td>6.6916E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.2663E+00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume of Oil Structures (m³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.0601E-02</td>
<td></td>
</tr>
<tr>
<td>Mass of Oil Structures (Kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.1953E+02</td>
<td></td>
</tr>
<tr>
<td>3031</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>6.0000E-04</td>
<td></td>
<td>1.5375E+00</td>
<td>6.9550E-06</td>
<td></td>
</tr>
</tbody>
</table>
References

Ref.[1]  A. Alemberti, M. Petrazzini; MEGAPIE, Input and RELAP5 model description MPIE 1 TRIX 200 AnsaldoEnergia.
Ref.[3]  N. I. Tak, X. Cheng; Numerical Design of the Active Part of the MEGAPIE Target.
Ref.[4]  XADS 20 TRIX 003Ansaldo Energia.
Ref.[5]  B. Sigg; Estimate of Target Heat-Losses and Comparison with Available Heating Power.
Ref.[7]  M. Petrazzini, A. Alemberti; MEGAPIE RELAP5 Steady State and Transient Analysis, Ansaldo Energia.
Ref.[12] W. H. Leung, Termal Hydraulics Arguments of MEGAPIE Integral Test; PSI.
Ref.[13] W. H. Leung, RELAP5 Model of the MEGAPIE Target System, PSI.
Ref.[15] V.H.Ransom, The RELAP5 two-fluid Model and Associated Numerical Methods, June 1994, School of Nuclear Engineering Purdue University, West Lafayette.
Ref.[17] Introduction to Computational Fluid Dynamics, Annual Lecture Series, Von Karman Institute for Fluid Dynamics Belgium.
Ref.[27] J. C. Tannehill, D A Anderson, R H Pletcher, Computational fluid mechnics and heat transfer
Ref.[29] Helmig Rainer, Einführung in die numerischen Methoden der Hydromechanik, Universität Stuttgar.
Ref.[30] A. Biran, M. Breiner, Matlab5 für ingenieure, Addison Wesley.
Ref.[31] Societa Italiana di Fisica, Stato e Prospettive dell’energia Nucleare:Fissione e Fusione.
Ref.[33] H. M. Kottowski-Dümenil, Liquid metal thermal hydraulics.
Ref.[34] T. J. Barth, H Deconinck, Error estimation and adaptive discretization methods in computational fluid dynamics.
Ref.[35] T. J. Chung, Computational fluid dynamics.
Ref.[38] J. D. Anderson, Computational Fluid Dynamics, The basics with Applications,
Ref.[41] B. Sünd er, Thermisches Brüten mit dem Spallations-Neutronen Induzierten Core, Technischen Hochscule Aachen.


Ref.[58] G. S. Bauer, Physics and Technology of Spallation Neutron Sources; PSI 1998.


