Thermal-hydraulic analysis of the LORELEI test device for the Jules Horowitz Reactor

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Abstract

LORELEI (Light Water One-Rod Equipment for LOCA Experimental Investigation) test device is currently under design in the framework of the planned experimental facilities of the Jules Horowitz Reactor. The main objective of this device is to analyze the thermal-mechanical behavior of the fuel rod and its consequences during a Loss of Coolant Accident (LOCA). The objective of this Thesis is to produce a comprehensive thermal analysis of the LORELEI apparatus by means of CATHARE2 code in order to verify the behavior of the device and to determine the best thermal-hydraulic conditions for the experimental performing. The preliminary part of this thesis aims to illustrate the system and mathematical architecture of the code with a general explanation of the thermal mechanical laws implemented for the FUEL module. An overview of the experimental apparatus, devised so far, is briefly presented to show the characteristics of LORELEI apparatus that can be considered the State of the Art of the LOCA-type facilities. According to the last updated LORELEI geometry, an exhaustive description of apparatus is finalized for a better understanding the CATHARE modeling proposed. This work is aimed to simulate the experimental phase called Re-irradiation phase. This is not a part of the LOCA accidental sequence but it is modeled to provide a study concerning the nominal conditions and to find out the device thermal-hydraulic limits. In this first phase, needed to create a realistic fission product inventory, the device is filled with water and the fuel rod is cooled by using convection flow. The work of this Thesis starts with the simulation of the first part of a LOCA accidental scenario. The fuel cladding temperature is increased and a small amount of water is set in the bottom of the device to produce steam needed for exothermic reactions of the fuel cladding. The final objective is to determine the best thermal conditions to reach an acceptable fuel cladding temperature profile. The distribution of all the gases present inside the device (steam and non condensable gases) is investigated and a thermal-mechanical analysis for the fuel rod is performed. An analysis of the velocity of the device toward the core is analyzed in order to limit the heat-up rate of the fuel cladding. The final part of this work is dedicated to a preliminary thermal-hydraulic analysis of the last experimental phase during which the device is completely re-flooded. We show the results of the fuel quenching behavior and the evolution of the system pressure. This phase is performed with a certain value of liquid mass flow injected, in accordance with different operational conditions.
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Introduction

Since the 1970s, the behavior of the nuclear reactor during the lost of coolant accident (LOCA), has been the accident of reference in the framework of the electric power industry. The occurrence of this type of accident causes possible knock-on phenomena which compromise the safety of the entire nuclear power plant. The increase of the fission gases pressure inside the fuel cladding, following the loss of the liquid cooling inventory, leads to the deformation and the burst of the cladding itself. The failure of the fuel cladding also means the loss of the first primary barrier for the generated fission products which start spreading inside the primary circuit. The zirconium over-heating reacts with the steam and the hydrogen produced could be source of dangerous explosions such as those occurred in 2011 for the containment buildings in the units 1, 2 and 3 in the Fukushima-Daichi Nuclear Power Plant (Song and Kim, 2014). All these chain events must be prevented by the Emergency Core Cooling System (ECCS) whose triggering should lead to a gradual safety of the site. Obviously, the time-line of the events previously described changes in accordance with the thermal-hydraulic conditions, fuel and cladding materials in agreement with different types of nuclear reactors. The interest to study these important issues has inspired the world of the Nuclear Research to design new type of experimental facilities in order to expand the State of Art of the fuel behavior during a LOCA condition. By the way, a large number of separate-effects test facilities, tests-with-moderate-integration or fully-integrated-tests has been design to investigate particular issues which may occur in this kind of Design Basic Accident (DBA). The objective of several experimental campaigns has been to analyze the mechanical aspects of the fuel cladding rather then the thermal-hydraulic phenomena or both of them. In these last 50 years, the French Nuclear Industry has concentrated its efforts on this topic. In order to understand the evolution of the technology in this field, one must think back to the test devices with moderate integration as EDGAR and EDGAR-2 (Forgeron et al., 2000) where the creep test in steam atmosphere have been conducted, or the LOCA test series program performed in the PHEBUS experimental reactor at the CEA Nuclear Center of Cadarache (Adroguer et al., 1983). During this test, both the mechanical and thermal-hydraulic phenomena have been studied in a 5x5 fuel bundle reactor. In the scientific literature it is also worth remembering some integral test campaigns such as those ones performed inside the FR2 research reactor and inside the Power Burst Facility at the Idaho National Laboratory (McCardell and MacDonald, 1983; Clément
et al., 2003; Wiesenack, 2013) etc. A step forward on this topic is the LORELEI test facility.

LORELEI (Light Water One-Rod Equipment for LOCA Experimental Investigation) apparatus is currently under design in the framework of the planned experimental facilities of the Jules Horowitz Reactor (Bignan, 2016). The objectives of this experimental device is to analyze the thermal-mechanical behavior of the fuel rod and the radiological consequences during a Loss of Coolant Accident. This LOCA-type device is based on single rod experimental strategy and it will be installed in the water channel inside the Jules Horowitz reflector together with other experimental devices. In order to investigate the real conditions of the LOCA scenario, this apparatus passes through three different phases which are briefly described below and in more detail in the Chapter 3 of this Thesis. The first experimental phase is called Re-irradiation phase during which the pressure inside the device is of the order of 70 bar and the fluid is water below the saturation temperature in a natural circulation loop. This phase is correctly designed to create a short life fission products inventory in the fuel. The Dry-out phase is the second experimental phase during which all the water is discharged out of the device, the internal pressure inside the apparatus device is reduced and the displacement device moves toward the core in order to increase the fuel power. During this phase the cladding temperature increases up to 800-1100 °C (according to the initial condition of the fuel sample) leading to the cladding ballooning and burst. Once the plateau phase around 1200 °C is reached, the high temperature oxidation steam-zirconium is studied. During the last phase of the experimental sequences, some cold water is injected inside the device and the fuel sample quenching is studied.

In the case of the LORELEI apparatus the IAEC (Israel Atomic Energy Commission), who is in charge of the design of the device, has conducted several studies. In particular the IAEC has started some important studies on the Re-irradiation phase and Dry phase by means of software such as COMSOL Multiphysics® and FLUENT® (Gitelman et al., 2014; Korotkin et al., 2014; Ferry et al., 2014). However, the results obtained by these simulations refer only to single-phase case and neglect some two-phase phenomena that may occur inside the device. For this reason it has been considered necessary to conduct further examinations to verify the previous calculations with a two-phase system code such as CATHARE (Code for Analysis of THERmal hydraulics during an Accident of Reactor and safety Evaluation). In general, in the framework of the Jules Horowitz project, the CATHARE code is an important calculation tool for the licensing process of the JHR itself and in the analysis of the consequences of possible abnormal conditions that could arise in the conduct of all the experimental programs. The CATHARE code (Geffraye et al., 2011) is the result of a collaboration among the major leaders of the French nuclear industry such as AREVA-NP, CEA, EDF and IRSN. As widely described in the first introductory chapter of this Thesis, the CATHARE code has a modular structure where every module represents the elements composing the circuit. In order to create the entire layout, the modules must be connected with others through junctions. The energy, momentum and mass balance equations are solved numerically at the junctions and grid points.
Chapter 1

CATHARE code

The CATHARE (Code for Analysis of THermal hydraulics during an Accident of Reactor and safety Evaluation) is a system code for the thermal-hydraulic analysis of nuclear power plants. The code is used to evaluate the safety of complex systems during accidental conditions and to define criteria for licensing procedure. This code is the result of a long collaboration among the major leaders of the French nuclear industry such as the reactor vendor AREVA-NP, the France Alternative Energies and Atomic Energy commission CEA, the French utility EDF and the Nuclear Safety Institute IRSN. At the beginning of the development, the code was employed to simulate mainly the design basis accidents (DBAs) in the framework of water nuclear plants such as, for example, Loss Of Coolant Accidents (LOCAs) and Main Stream Line Break accident (MSLB). Recently new modules has been introduced to the study of new reactors types such as Sodium-cooled Fast-Breeder Reactors (SFR), Gas Cooled Reactors (GCR) and Supercritical Water-Cooled Reactors (SCWR). The CATHARE code may evaluate important thermal-hydraulic phenomena such as forced-natural convection, mono-two phase turbulent flow, changing phase due to boiling or condensation in different flow regimes, etc. All the thermal-hydraulic quantities are obtained by resolving the one-dimensional equations for the two-phase-two-field model for the mass, momentum and energy balance together with some closure laws. The code might include up to 4 type of non-condensable gases and 12 type of radio-chemical components. Successive versions of the code have been developed in order to improve the structure and its framework. The objective of this continuous improvement is to include new modules, sub-modules and to implement update corrections of errors contained in previous versions. The aim of this chapter is to describe the general structure of the code and illustrate the main equations implemented. Clearly for a far more comprehensive explanation, one can recommend the consultation of manuals and tutorials such as the manual (Lavialle, February, 2006)
1.1 The modular structure of the code

The CATHARE code has a modular structure. This means that the entire circuit layout is created by connecting some specific operators called modules. Volume and surface modules properties can be modified with the use of sub-modules and gadgets. The energy, momentum and the mass balance equations are solved numerically at the junctions and grid points.

1.1.1 Code modules

The main used modules are: axial 1-D, volume 0-D and boundary condition modules. Below the main module features are summarized.

**Axial 1-D module.** This module describes the components within which the fluid motion is fundamentally one-dimensional as for example pipes, steam generators, down-comer etc. The mesh nodalization is specified by the user in accordance with the physical phenomena considered.

**Volume 0-D module.** This module is used, for example, to model pressurizer, accumulator and plenum of steam generator. Also by using this module it is possible to study the water-level variation and its partial stratification by considering two sub-volumes divided by a water free surface. Inside these sub-volume all the physical properties are constant along the horizontal plane and all the inertial forces are neglected compare to the gravitational force. On the surface of the two sub-modules an equation describes the mass exchange which may take into account the formation and separation of droplets. If the heat exchange may occur, then the condensation or liquid evaporation are modeled.

**Volume 3-D module.** The 3-D module is based on the porous two-fluid six equations model. For each phase, the mass, momentum and energy equations are defined. For this module is also implemented the \((k-\epsilon)\) model to describe the turbulence diffusion of one or both the phases. The main utilization of this module is made to describe the PWR vessel or for a three-dimensional modeling of an empty of solid structures element.

**Boundary condition module.** These modules are connected through junctions which allow to set one or more hydraulic conditions such as, for example, pressure, velocities, liquid mass flow and void fraction. The figure 1.1 shows an example of BC3B type boundary condition. In this specific case the liquid and gas temperatures TL and TG, the void fraction ALFA, the mass fraction of one non-condensable gas \(X1\) and the liquid and gas velocities, \(VL\) and \(VV\) are assigned. The command ABSTIME defines the time intervals where the variables assigned change linearly.
Figure 1.1: Example of boundary conditions.

1.1.2 Code sub-modules

Sub-modules are elements which allow to modify the module attributes. Usually one sub-module modifies the thermal hydraulic behavior of the modules to which it is connected. Below are listed the most used sub-modules.

**Thermal structure.** There are three types of thermal structures: sub-modules for multilayer walls (WALL), heat exchangers (EXCHANGER) and fuel rod (FUEL). A more detailed description of the sub-module FUEL is presented in the last part of this chapter. Inside the multilayer walls and the heat exchanger, the 1-D equation of heat conduction is solved by finite element scheme. The conditions imposed could be of Newman type (heat flux imposed) or can be assigned the values of external temperature together with the heat transfer coefficient. With the sub-module EXCHANGER it is possible to couple thermally two modules belonging to the same or different circuit. To define a wall and a heat exchange is necessary to assign the type of material they are made of, the heating perimeter, the thickness and, if present, a power source.

**Reflooding.** This sub-module is used to calculate the quenching along the hot wall or along the fuel rods. The quenching can be distinguished into two types based on the liquid-front direction respect to the surface to quench: from the bottom towards the top bottom-up re-flooding and from the top towards the bottom top-down re-flooding.

1.1.3 Gadgets

In order to complete the circuit layout, further elements called Gadget can be connected to a specific module. The main gadget are listed below:
• **SOURCE/SINK**: they are utilized to inject or to extract inside the system a certain volume of a scalar quantity such as the mass of the liquid/gas or a certain amount of power;

• **TEE** junction: this gadget is utilized to simulate a tee branch;

• **CCFL**: this gadget allows to model the *Counter Current Flow Limitation* for complex geometries;

• **BREAK**: this gadget makes possible the modeling of a rupture along the modules to which is connected.

### 1.2 Equations for two-phase flow

In order to describe the behavior of two-phase flow inside a 1-D module the set of equations which describe the energy, momentum and the mass balance equation are solved. Together with the steam-liquid phases, a number of non condensable gases may be considered. Since all the equations are integrated over the cross section area $A$, they depend on the axial coordinate along the length of the pipe. The main simplifications used to define these equations are listed below (Lavialle, February, 2006):

- The axial component of the viscous stress tensor and its work are neglected;
- The axial heat conduction is neglected;
- The axial mass diffusion is neglected (in case of non condensable gas transport);
- The liquid and gas proprieties which are valid for local instantaneous variables are assumed also valid for averaged variables and they are calculated with the value of the mean pressure and not with the phase pressure ($P = \alpha P_v + (1 - \alpha) P_l$);
- The work of inter-facial forces and pressure distribution forces are neglected in the energy balance equation.

The equation of the mass, momentum and energy balance at the interfaces of the different phases are written by considering the following hypothesis:

- The interface has not thickness and mass;
- In the momentum equation, the superficial tension is neglected;
- In the energy balance, the contribution of the superficial tension is neglected;
- Both phases have the same velocity at the interface which is supposed uniform.
1.2. EQUATIONS FOR TWO-PHASE FLOW

Mass conservation. For the liquid phase we write (Scardovelli and Manservisi, 2012):

$$\frac{\partial}{\partial t}((1 - \alpha) \rho_l A) + \frac{\partial}{\partial z}((1 - \alpha) \rho_l u_l A) = - \Delta \Gamma + S_l,$$

(1.1)

and for the gas phase

$$\frac{\partial}{\partial t}(\alpha \rho_g A) + \frac{\partial}{\partial z}(\alpha \rho_g u_g A) = \Delta \Gamma + S_v + \sum_{j=1}^{n_I} S_j$$

(1.2)

where \(n_I\) is the number of non-condensable gases which are described with the following mass balance equation:

$$\frac{\partial}{\partial t}(\alpha \rho_g X_j A) + \frac{\partial}{\partial z}(\alpha \rho_g u_g X_j A) = S_j$$

(1.3)

The terms \(S_l, S_v, S_j\) represent the source of mass for unit volume for each phase. \(\Gamma\) is the mass flux on the interface due to the changing phase

$$\Gamma = \frac{-q''_{\text{in} \rightarrow \text{l}} - q''_{\text{in} \rightarrow \text{v}} + \chi h q''_{\text{w} \rightarrow \text{in}}/A}{h_v - h_l} + \Gamma_r,$$

(1.4)

where

- \(q''_{\text{in} \rightarrow \text{l}}\): interface to liquid heat flux \([W/cm^3]\);
- \(q''_{\text{in} \rightarrow \text{v}}\): interface to vapor heat flux \([W/cm^3]\);
- \(q''_{\text{w} \rightarrow \text{in}}\): wall to interface heat flux \([W/m^2]\);
- \(\chi h\): wet perimeter \([m]\).

The parameter \(\Gamma_r\) is a parameter given by

$$\Gamma_r = \begin{cases} -\rho_g \left(\frac{\alpha - \alpha_{\text{min}}}{\theta_v}\right) & \text{when } \alpha < \alpha_{\text{min}} \text{ vaporization} \\ 0 & \text{when } \alpha_{\text{min}} < \alpha < \alpha_{\text{max}} \\ -\rho_l \left(\frac{\alpha - \alpha_{\text{max}}}{\theta_l}\right) & \text{when } \alpha_{\text{max}} < \alpha \text{ condensation} \end{cases}$$

(1.5)

with \(\alpha_{\text{min}} = 10^{-5}, \alpha_{\text{max}} = 10^{-6}\) and \(\theta_v = \theta_l = 10^{-5}\).

The momentum equation. For the liquid phase we write

$$(1 - \alpha)\rho_l A \left(\frac{\partial}{\partial t} + u_l \frac{\partial}{\partial z}\right) u_l + (1 - \alpha) A \frac{\partial P}{\partial z} + P_{\text{in}} A \frac{\partial(1 - \alpha)}{\partial z} -$$

$$\beta\alpha(1 - \alpha) \rho_{\text{mix}} A \left(\frac{\partial}{\partial t} + u_g \frac{\partial}{\partial z}\right) u_g - \left(\frac{\partial}{\partial t} + u_l \frac{\partial}{\partial z}\right) u_l =$$

$$- \Delta \Gamma (u_{\text{in}} - u_l) + A r_{\text{in}} - \chi_f C_l \frac{\rho_l}{2} u_l |u_l| + (1 - \alpha) \rho_l A g_x + R \frac{\alpha}{4} P_{\text{in}} \frac{\partial A}{\partial z} + m_l$$

(1.6)
and for the gas phase we have
\[
\alpha \rho_g A \left( \frac{\partial}{\partial t} + u_g \frac{\partial}{\partial z} \right) u_g + \alpha A \frac{\partial P}{\partial z} + P_{in} A \frac{\partial \alpha}{\partial z} + \beta \alpha (1 - \alpha) \rho_{mix} A \left( \frac{\partial}{\partial t} + u_g \frac{\partial}{\partial z} \right) u_g - \left( \frac{\partial}{\partial t} + u_l \frac{\partial}{\partial z} \right) u_l = \frac{\partial \alpha}{\partial z} + \alpha \rho_g \frac{\partial A}{\partial z} + m_g .
\] (1.7)

In order to simplify the model, the stress \( \tau_{xx} \) and the surface tension \( \sigma \) are neglected. Table 1.1 provides a detailed explanation of all the terms appeared in the [1.7].

Conservation of energy. For the liquid phase we write
\[
A \frac{\partial}{\partial t} \left( (1 - \alpha) \rho_l (h_l + \frac{u_l^2}{2}) \right) + \frac{\partial}{\partial z} \left( (1 - \alpha) \rho_l A u_l (h_l + \frac{u_l^2}{2}) \right) - (1 - \alpha) A \frac{\partial P}{\partial t} = A q''_{in \rightarrow l} + \chi c q''_{w \rightarrow l} - A \Gamma (h_l + \frac{u_{in}^2}{2}) + (1 - \alpha) \rho_l A u_l g_x + S E_l .
\] (1.8)

and for the gas phase we have
\[
A \frac{\partial}{\partial t} \left( \alpha \rho_g (h_g + \frac{u_g^2}{2}) \right) + \frac{\partial}{\partial z} \left( \alpha \rho_g A u_g (h_g + \frac{u_g^2}{2}) \right) - \alpha A \frac{\partial P}{\partial t} = A q''_{in \rightarrow v} + \chi c q''_{w \rightarrow v} + A \Gamma \left( h_v + \frac{u_{in}^2}{2} \right) + \alpha \rho_g A u_g g_x + S E_g .
\] (1.9)

The first and the second term are respectively the variation of the density of energy over the time and its gradient, the third term is the variation of the pressure over the time. In the second member, the first two terms are the power exchanged per unit of volume between the interface and the liquid/steam \( (q''_{in \rightarrow l}/q''_{w \rightarrow l}) \) and the power per unit area between the wall of the pipe and the fluid/steam \( (q''_{w \rightarrow l}/q''_{w \rightarrow v}) \), see figure 1.2. The last three terms represent the change of the phase on the surface, the work done by the weight force and any external power source.

If in the system are present \( n_I \) number of non-condensable gases, the total density \( \rho_j \), the pressure \( P \) and the gas enthalpy \( h_g \) are written as
\[
\rho_j = X_j \rho_g ,
\] (1.10)

with
\[
\rho_g = \sum_{j=1}^{n_I} \rho_j + \rho_v (T_g, h_v) ;
\] (1.11)

\[ P_j = \rho_j R_j T_g \] (1.12)

with
\[ P = \sum_{j=1}^{n_I} P_j + P_v , \] (1.13)
Table 1.1: List of the terms constituting the momentum equation [1.7].

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha \rho_g A \left( \frac{\partial}{\partial t} + u_g \frac{\partial}{\partial z} \right) u_g$</td>
<td>Inertial term</td>
</tr>
<tr>
<td>$\alpha A \frac{\partial P}{\partial z}$</td>
<td>Pressure gradient</td>
</tr>
<tr>
<td>$P_{in} A \frac{\partial \alpha}{\partial z}$</td>
<td>Pressure difference $P_{in}$ on the interface and the variation of the level of the stratified flow due to the changing of the void fraction along the $z$-axis</td>
</tr>
<tr>
<td>$\beta \alpha (1 - \alpha) \rho_{mix} A \left( \frac{\partial}{\partial t} + u_g \frac{\partial}{\partial z} \right) u_g - \beta \alpha (1 - \alpha) \rho_{mix} A \left( \frac{\partial}{\partial t} + u_l \frac{\partial}{\partial z} \right) u_l$</td>
<td>$\beta$ is the added mass coefficient. This term represents the inertia added to the single phase: the fluid during the acceleration/deceleration must move a volume of the other fluid adjacent</td>
</tr>
<tr>
<td>$A \Gamma (u_{in} - u_l)$</td>
<td>Phase changing on the interface, $u_{in}$ is the velocity of the interface between the two phases. $u_{in} = \alpha u_l + (1 - \alpha) u_g$</td>
</tr>
<tr>
<td>$A \tau_{in}$</td>
<td>$\tau_{in}$ is the interfacial friction [N/m$^3$]. This term represents the pressure drop on the interface (opposite sign in the [1.6])</td>
</tr>
<tr>
<td>$\chi_f C_g \frac{\rho_g}{A}</td>
<td>u_g</td>
</tr>
<tr>
<td>$\alpha \rho_g A g_x$</td>
<td>Gravitational term, $g_x$ is the projection of the gravity vector onto the axis of the pipe</td>
</tr>
<tr>
<td>$R \frac{(1 - \alpha)}{4} P_{in} \frac{\partial A}{\partial z}$</td>
<td>Level changing in the stratified flow due to the variation of the cross section along the pipe. $R_s$ is the rate of stratification</td>
</tr>
<tr>
<td>$m_g$</td>
<td>Source of momentum</td>
</tr>
</tbody>
</table>

\[
h_g = \left(1 - \sum_{j=1}^{n_f} X_j \right) h_v + \sum_{j=1}^{n_f} X_j \left( h_0 + C_{p_j} (T_g - T_0) \right),
\]

(1.14)

where the gas perfect hypothesis as assumed, $h_v = h_v(P_v, T_g)$ is the steam enthalpy and $h_0$ and $T_0$ are two referent values.
1.3 Closure equations

In total CATHARE contains 13 closure laws for: $q_{w\rightarrow l}''$, $q_{w\rightarrow v}''$, $q_{in\rightarrow l}''$, $q_{in\rightarrow v}''$, $E$, $P_{in}$, $R_e$, $\tau_{in}$, $\beta$, $u_{in}$, $C_\alpha$ and $C_l$. These closure laws are derived from physical considerations and/or empirical data from appropriate experiments (Ghione, 2015).

1.3.1 Flow patterns

Some variables, such as pressure drop, void fraction and velocity vary according to flow pattern or regime. In CATHARE, the flows patterns are characterized by several values of the stratification ratio $R_s$ and the entrainment rate $E$.

For every type of pipe (Annulus, Rod bundle, Pipe), the typical representation of the flow patterns is showed in figure 1.3. The solid lines are the transitions explicitly modeled: the transition between stratified and not stratified flows and the transition between annular and annular-mist flow. The dashed line marks the transition between the annular and bubbly/churn flow. In this last case, the transition is derived from the void fraction criteria and it is taken into account only for inter-facial friction and heat transfer.

1.3.2 Convective heat exchange: forced or natural convection in liquid

In case of natural or forced convection in liquid, the heat transfer $q_{con}|_l$ from the heated surface to the liquid can be expressed with the Newton’s cooling law:

$$q_{con}|_l = h_{con}|_l \Delta T.$$  (1.15)
Figure 1.3: Flow patterns described in CATHARE code.

$h_{\text{conv}|l}$ is the heat transfer coefficient and $\Delta T$ is termed as *excess temperature*. In CATHARE this last term can be expressed according to the values of $T_{\text{sat}}(P)$, $T_l$ and $T_w$, in particular:

$$\Delta T = \begin{cases} 
(T_w - T_l) & \text{if } T_l < T_w < T_{\text{sat}}(P) \text{ single phase flow} \\
(T_{\text{sat}}(P) - T_l) & \text{if } T_l < T_{\text{sat}}(P) < T_w \text{ sub saturated boiling} \\
0 & \text{if } T_{\text{sat}}(P) < T_l < T_w \text{ saturated boiling} 
\end{cases} \quad (1.16)$$

$h_{\text{conv}|l}$ is expressed as:

$$h_{\text{conv}|l} = \max (h_{\text{lam},NC}|l, h_{\text{tur},NC}|l, h_{\text{lam},FC}|l, h_{\text{tur},FC}|l) , \quad (1.17)$$

where the subscript *lam* and *tur* indicates the flow regime which can be respectively laminar or turbulent, *NC* and *FC* if the mechanism of the heat transport is by natural (free) or by forced convection. The expression [1.17] does not consider the case when both the natural and forced convection are present. Normally $Nu_l = f(Re_l, Gr_l, Pr_l)$ and the combined effects of free and forced convection should be considered when $Gr_l/Re_l^2 \approx 1$, where $Gr_l$, $Re_l$ and $Pr_l$ are respectively the Grashof, Reynold and Prandtl numbers for liquid flow defined as:

$$Gr_l = \frac{\text{buoyancy forced viscous forces}}{\rho_i u_l D_{h,l} \mu_i} = \frac{g \beta \rho_l^2 D_{h,l}^3}{\mu_l^2} (T_w - T_l) \quad (1.18)$$

$$Re_l = \frac{\text{inertia viscous forces}}{\mu_l} = \rho_i u_l D_{h,l}^2 \frac{\mu_i}{\mu_l} , \quad (1.19)$$

$$Pr_l = \frac{\text{momentum thermal diffusivity}}{k_l} = \frac{c_{p,l} \mu_l}{k_l} , \quad (1.20)$$

with $\beta = -\frac{1}{\rho_i} \left( \frac{\partial \rho_l}{\partial T_l} \right)_p$.

The Nusselt number for liquid flow is defined as

$$Nu_l = \frac{\text{convection heat transfer}}{\text{conduction heat transfer}} = \frac{h D_{h,l}}{k_l} . \quad (1.21)$$
$D'_{h,l}$ is a modified hydraulic diameter defined by

$$D'_{h,l} = D_{h,l}(1 - \sqrt{\alpha F_{num}}),$$  \hspace{1cm} (1.22)$$

where $F_{num}$ is a numerical correction that limits the minimum liquid film thickness to the value $10^{-3}D_{h,l}$; in single-phase flow $D'_{h,l} = D_{h,l}$.

**Natural convection in liquid.** In the natural convection flow ($Gr_l/Re_l^2 >> 1$), the forced convection effects may be neglected and $Nu_l = f(Gr_l, Pr_l)$. Two cases can be distinguished:

- for laminar flow
  $$Nu_{lam,NC}|_l = 0.55(Ra_l)^{1/4}; \hspace{1cm} (1.23)$$

- for turbulent flow
  $$Nu_{tur,NC}|_l = 0.13(Ra_l)^{1/3}; \hspace{1cm} (1.24)$$

where $Ra_l = Gr_l Pr_l$ is the Rayleigh number.

**Forced convection in liquid.** In the forced convection flow ($Gr_l/Re_l^2 << 1$), the free convection effects may be neglected and $Nu_l = f(Re_l, Pr_l)$. Two cases can be distinguished:

- for laminar flow
  $$Nu_{lam,FC}|_l = 3.66; \hspace{1cm} (1.25)$$

- for turbulent flow the heat transfer coefficient is computed with the the Dittus-Boelter equation (Dittus and Boelter, 1985)
  $$Nu_{tur,FC}|_l = 0.023Re_l^{0.8}Pr_l^{0.4}. \hspace{1cm} (1.26)$$

### 1.3.3 Nucleate boiling and critic flux regions

In order to take into account heat transfer in boiling phenomena in the code are implemented many correlations.

**Nucleate boiling.** In CATHARE code the Thom correlation (Thom et al., 1967) is used to describe the heat exchanged between the wall and the liquid for pressure $P$ between 5-14 MPa. In particular the code sets

$$T_w - T_{sat}(P) = 22.5(q'')^{0.5} e^{0.22}, \hspace{1cm} (1.27)$$

where $P$, $q''$ and $T$ are expressed respectively in MPa, MW/m² and K. The heat flux $q''$ is therefore computed as:

$$q'' = 1.97 10^{3}(T_w - T_{sat}(P))^2 e^{0.23P}. \hspace{1cm} (1.28)$$
Point of Net Vapor Generation (NVG). The NVG or Onset of Significant Void (OSV) is the point at which the amount of bubble becomes significant in the sub-cooled region. To determine this point is very important to study the transient response in a reactor. In CATHARE the analysis of this point depends on the Peclet number $P_c$ defined as

$$P_c = RePr = \frac{Nu}{St},$$

(1.29)

where $St$ is the Stanton number:

$$St = \frac{q''}{GC_p(T_{sat} - T_l)},$$

(1.30)

with $G$ is the mass velocity $[kg/m^2s^{-1}]$. In particular the sub-cooled liquid reaches the NVG point if $\Delta h_{c*} = \max(\Delta h_{c*}; 10^4)$, where the value $10^4$ has been introduce for numerical reasons.

The value $\Delta h_{c*}$ depends on the Peclet number (Saha and Zuber, 1974). In particular one sets

$$\Delta h_{c*} = \begin{cases} 
\frac{5q''C_pD_{h,t}}{k_1P_{c0}0.510^{-4}} & \text{if } P_c < 0.52P_{c0}, \\
\frac{2q''C_pD_{h,t}}{k_1P_{c0}0.510^{-4}(P_c/P_{c0})} & \text{if } P_c > 0.52P_{c0},
\end{cases}$$

(1.31)

for $P_{c0} = 70000$ and below this value the local Nusselt number is a constant ($Nu \approx 455$), for values greater than $P_{c0}$ the Stanton number is a constant ($St \approx 0.0065$). The criteria expressed in the [1.31] is a modified version of the Saha correlation validated at the CEA-Grenoble using KIT experiments (Sabotinov, 1974). The NGV point is reached if $h_{l,sat} - h_l \leq \Delta h_c$.

Pre-CHF region. In the Pre-CHF region the total heat flux $q''$ imposed on the wall can be expressed as:

$$q'' = q''_{w\rightarrow l} + q''_{w\rightarrow in}.$$  

(1.32)

The values of $q''_{w\rightarrow l}$ and $q''_{w\rightarrow in}$ depend on the values of $T_l$, $T_w$, $T_{sat}(P)$ and $\Upsilon$. This last parameter, varies between 0 and 1 and it determines the rate of vaporization in sub-cooled boiling regime. $\Upsilon$ is based on the NVG criteria, in particular:

$$\Upsilon = \begin{cases} 
1 & \text{if } h_l - h_{l,sat} > 10000 \\
1 - (\Delta h_{aux} - 1)6(1 + 6\Delta h_{aux}) & \text{if } -\Delta h_c < h_l - h_{l,sat} < 10000 \\
0 & \text{if } h_l - h_{l,sat} < -\Delta h_c,
\end{cases}$$

(1.33)

with

$$\Delta h_{aux} = \max\left(0; \frac{\Delta h_c + (h_l - h_{l,sat})}{\Delta h_c + 10000}\right).$$

(1.34)

Three different cases can be distinguished:

- Single-phase flow: $T_w < T_{sat}(P)$:

$$q''_{w\rightarrow l} = q''_{conv}, \quad q''_{w\rightarrow in} = 0, \quad T_w = T_l + \frac{q''}{h_{conv}}.$$  

(1.35)
• Sub-cooled boiling: $T_l < T_{sat} < T_w$:

$$q''_{w\rightarrow l} = q''_{\text{conv}} + (1 - \Upsilon)q''_{\text{nb}}, \quad q''_{w\rightarrow l} = \Upsilon q''_{\text{nb}}. \quad (1.36)$$

• Saturated boiling: $T_l > T_{sat}$:

$$q''_{w\rightarrow l} = 0, \quad q''_{w\rightarrow in} = q''_{\text{nb}}. \quad (1.37)$$

**Critical heat Flux (CHF).** Once the mass flux $\hat{G}$, the pressure $P$ and steam quality $\hat{x}$ are known, the CHF is calculated by interpolating with the cubic splines the values obtained by the look-up table of Groeneveld (Groeneveld et al., 1986). The mass flux is given by the following expression:

$$\hat{G} = |G_g| + |G_l| = |\alpha \rho_g u_g| + |(1 - \alpha) \rho_l u_l|. \quad (1.38)$$

The steam quality $\hat{x}$ is defined as:

$$\hat{x} = \frac{\alpha \rho_g + (1 - \alpha) \rho_l x}{\alpha \rho_g + (1 - \alpha) \rho_l} \quad \text{with} \quad x = \frac{h_l - h_{l,sat}}{h_l\rightarrow g}. \quad (1.39)$$

The critical heat flux (CHF) is expresses as:

$$q''_{CHF} = F_1 F_2 F_3 q''_{CHF}(I)(\hat{G}, P, \hat{x}), \quad (1.40)$$

where $q''_{CHF}(I)$ is the value obtained by the interpolation. $F_1$, $F_2$ and $F_3$ represent the correction factors expressed as:

$$F_1 = \max\left(8 \times 10^{-3}, 0.79\right)^{1/3}, \quad (1.41)$$

$$F_2 = \begin{cases} 1 & \text{standard value} \\ 0.6 & \text{bundle geometry} \end{cases}, \quad (1.42)$$

$$F_3 = \begin{cases} 1 & \text{if } \hat{x} < 0.9 \\ 10(1 - \hat{x}) & \text{if } \hat{x} \geq 0.9 \end{cases}. \quad (1.43)$$

**Dry-out mechanism.** In the dry-out condition the main heat exchange mechanism is by natural or forced convection in gas. In particular in CATHARE code the dry out criteria is reached if one of the three following conditions are satisfied:

• The flow is in pure gas $\alpha > 0.99999$.

• The wall temperature is such that $T_w > T_{mfs}$. 
• The heat flux wall-to-liquid $q_{wl}$ and the heat flux wall-to-interface $q''_{w\rightarrow in}$ are such that:
  $q''_{w\rightarrow l} + q''_{w\rightarrow in} > q''_{CHF}$.

For natural convection two cases can be distinguished:

<table>
<thead>
<tr>
<th>Case</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>for laminar flow</td>
<td>$Nu_{lam,NC}</td>
</tr>
<tr>
<td>for turbulent flow</td>
<td>$Nu_{turb,NC}</td>
</tr>
</tbody>
</table>

The Grashof number $Gr_g$ and $D'_{h,g}$ are defined as:

$$Gr_g = \frac{g \beta_g \rho_g^2 D_{h,g}^3 |T_w - T_g|}{\mu_g^2}$$  \hspace{0.5cm} (1.46)$$

$$D'_{h,g} = D_{h,g} (1 - \sqrt{\max(0; 0.9999 - \alpha)})$$  \hspace{0.5cm} (1.47)

For the forced convection two cases can be distinguished:

<table>
<thead>
<tr>
<th>Case</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>for laminar flow</td>
<td>$Nu_{lam,FC}</td>
</tr>
<tr>
<td>for turbulent flow</td>
<td>$Nu_{turb,FC}</td>
</tr>
</tbody>
</table>

For the gas convection $Pr_g = 1$ and $Re_g$ is computed as:

$$Re_g = \frac{\rho_g u_g D_{h,g}}{\mu_g}$$  \hspace{0.5cm} (1.50)

**The heat transfer coefficient in boiling.** Boiling heat transfer occurs when the heat transfer involves the change of phase. The literature identifies two main types of boiling, see (Tong and Tang, 1997): pool boiling and flow boiling. In the first case the heating surface is submerged in a pool of initially quiescent liquid, in the flow boiling the heating surface may be the channel wall confining the flow. In both cases there are several boiling regimes, in particular the buoyancy effects are significant in a pool boiling system while the forced-convection effects are significant in the flow boiling inside the channel.

The structure of CATHARE code is based on the typical regimes of pool boiling, see figure 1.4. All these regimes are previously observed by Leidenfrost (1756), Lang (1888), Nukiyama (1934), McAdams et al. (1941) and Farber and Scorah (1948). In the CATHARE code, the boiling heat transfer shall be divided in three cases: A, B and C. The zone A in turn is classified in 5 sub-zones depending on whether the liquid is heated or cooled by convection, with or without
nucleated boiling or only nucleated boiling. The zone B includes only one heat flux, the zone C is subdivided in three sub-zones which depend on the way to reach this point. All the heat flux are selected on the basis of a table which contains all the numerical index which values depends on the heat flux considered.

**Zone A**  *Convection in liquid (zone a-b).* In this range the water is heated by single phase natural convection. The heat transfer coefficient is calculated by applying the criteria expressed in the [1.17].

*Sub-cooled and nucleated boiling (zone b-c).* This zone starts with a point called *Onset of Nucleated Boiling* ONB, starting from this point, local bubble near to the wall tend to condense. In this region the contribution to the nucleated boiling is calculated with the [1.28].

**Zone B**  *Transition boiling (zone d-e).* By increasing the heat flux, the average temperature of the liquid rises above the saturation temperature, in this case the bubbles do not collapse, some of these start to merge into jets that feed into large over head bubble or “slugs” of vapor. Near to the point (d) the bubbles may obstruct the path of incoming liquid, the vapor forms an insulating blanket which covers the heating surface by deteriorating dramatically the heat exchange. The maximum heat flux just before the thermal crisis is called *Critical Heat Flux* q\(_{CHF}\) which value is computed with the expression [1.40]. The temperature calculated in this point is called \( T_{bo} \) (burnout temperature).

![Simplified boiling curve](image-url)
1.4. SPACE AND TIME DISCRETIZATION

**Zone C**  *Heat flux to dry wall (zone e-f).* In this region the film condensation in contact with a sub-cooled wall may occur. In case of convection, the expression [1.17] for the gas is utilized. The Berenson correlation is used to take into account the heat flux for film evaporation. By increasing the wall temperature the heat flux is mainly dissipated by radiation.

1.4 Space and time discretization

Figure 1.5: Example of a hydraulic circuit composed by the assembling of two axials and one volume element.

Figure 1.5 shows an example of a 1-D (axial) and 0-D (volume) elements connected each others. All the scalar variable (eg. void fraction, the enthalpy etc.) are computed in the center of the cell (0), while the velocities are computed on the cell faces (X). The scalar variables and the velocities can be staggered along the length of the axial element. To define the flux it is necessary to interpolate the values of the velocities in the points where are defined the scalar variables and vice-versa. The interpolation is based on a first order upwind scheme and the time integration is fully implicit. The system of non-linear equations is solved by Newton-Raphson method and the time step can be changed to optimize the number of the iterations.

1.5 Fuel rods in CATHARE code

In this section are described a general description of the main physic laws implemented in the Fuel sub-module. The Fuel rod in CATHARE is constituted by four different materials: the fuel pellet, the gap, the internal oxide layer, the cladding and the external oxide layer, see figure 1.6. Below are listed some ad hoc assumptions necessary for the mathematically modeling of this object.
• The fuel rod has a perfect symmetry of revolution;
• Along the fuel rod only the radial conduction is taken into account;
• The convection exchange inside the fuel gap is negligible;
• The fragility of the retained-alpha layer is not considered;
• There is no contact pellet-cladding (the thermal expansion of the fuel pellet never influences the cladding deformation).

Table 1.2 lists all fuel alloy types that the User can use. In the following a brief mathematically description of the physic models implemented inside this sub-module are presented, see figure 1.7.

![Figure 1.6: Graphical representation of the fuel sample in CATHARE code.](image)

1.5.1 The thermal expansion

In the fuel pellet and in the cladding zone, the thermal expansion is taken into account. In particular for cylinder of radius \( r \), it is possible to write the following thermal expansion equation

\[
\frac{1}{R} \frac{\partial R}{\partial t} = \alpha_{\text{exp}} \frac{\partial T}{\partial t},
\]

where \( \alpha_{\text{exp}} \) is the coefficient of the thermal expansion. Obviously, in parallel with the resolution of the [1.51], for each fuel and cladding mesh, the mass balance (continuity equation) must be satisfied.
Table 1.2: Fuel cladding type in CATHARE code.

<table>
<thead>
<tr>
<th>Keyword</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZRPHEBUS</td>
<td>PHEBUS type cladding (stress relieved Zircaloy)</td>
</tr>
<tr>
<td>ZRCEA</td>
<td>CEA type cladding (recrystallised Zircaloy)</td>
</tr>
<tr>
<td>ZRFRA</td>
<td>Framatome-ANP Zircalloy-4 type 1 cladding</td>
</tr>
<tr>
<td>ZRFRA2</td>
<td>Framatome-ANP Zircalloy-4 type 2 cladding</td>
</tr>
<tr>
<td>ZRM5</td>
<td>Framatome-ANP alloy-M5™ type cladding</td>
</tr>
<tr>
<td>ZR4</td>
<td>Framatome-ANP Zircalloy-4 AFA-2G type cladding</td>
</tr>
<tr>
<td>ZR4H600</td>
<td>Framatome-ANP Zircalloy-4 AFA-2G hydrided to 600 ppm type cladding</td>
</tr>
</tbody>
</table>

Figure 1.7: Summary of the physical phenomena implemented inside the Fuel rod sub-module.
1.5.2 The creep strain

In the fuel cladding the creep strain is expressed as

$$\dot{\varepsilon} = \frac{1}{R_m'} \frac{\partial R_m}{\partial t} = A_c \sigma_{es}^{n_c} \exp\left(- \frac{Q_c}{RT}\right).$$

(1.52)

$R_m'$ is the initial value of the cladding mean radius, $\sigma_{es}$ is the elastic stress expressed as

$$\sigma_{es} = \Delta P \frac{R_m}{\zeta_{clad}},$$

(1.53)

where $\Delta P$ is the pressure difference between the fuel gap and the exterior, $\zeta_{clad}$ is the cladding thickness and $R_m$ is the average value of the cladding radius defined as

$$R_m = \frac{R_{clad,e} + R_{fuel} + \zeta_{gap}}{2}.$$

(1.54)

$\zeta_{gap}$ is the fuel-cladding gap thickness. In the [1.50], $A_c$ is an experimental constant which depends on the material and the particular creep mechanism, $n_c$ is the stress exponent, $Q_c$ is the activation energy. The [1.52] can be expressed also as

$$\ln \dot{\varepsilon} = \ln A_c + n_c \sigma_{es} - \frac{Q_c}{RT}.$$

(1.55)

By using the [1.55] is possible to derive experimentally:

(i) $Q_c$ by plotting the natural logarithm of the creep strain against the reciprocal of temperature.

(ii) $n_c$ by plotting the natural logarithm of the creep strain as a function of the natural logarithm of the elastic stress.

In the LORELEI test device design, a re-crystallized CEA type cladding is used. For this specific cladding, the Code implements the some specific correlations to calculate the the creep strain Holta (1970).

1.5.3 The elastic strain

To take into account the elastic strain, the following equation is implemented

$$\frac{1}{R_m} \frac{\partial R_m}{\partial t} = \frac{1}{E} \frac{\partial \sigma_{es}}{\partial t},$$

(1.56)

where $E$ is the Young modulus.

1.5.4 Criterion for the Rupture of fuel cladding

Three different criteria are implemented inside the Code to take into account the fuel cladding failure:
The radiative heat transfer inside the fuel gap

- the Burst Criterion;
- the Strain Criterion;
- the Fragile Rupture criteria.

The fuel sample placed inside the LORELEI apparatus, satisfies always the first criteria, in particular the cladding failure is due mainly to a burst produced by a pressure difference between the fuel gap and external pressure. In the following the Burst Criterion is described.

**Burst Criterion**

To calculate the pressure gap $P_{\text{gap}}$ inside the fuel sample, the code divides the fuel sample in $m$ volumes $v$, see figure 1.8. Inside the $i$-th volume the temperature can be considered uniform. Once the temperature in all the volumes has known, the perfect gas law is used

$$P_{\text{gap}} = \frac{nR}{\sum_{i=1}^{m} \frac{v_i}{T_i}}.$$  \hspace{1cm} (1.57)

The criteria of the rupture of the fuel cladding is derived from the EDGAR test analysis. In particular, the rupture occurs if the total cladding stress $\sigma_{es}$ satisfies the following condition

$$\sigma_{es} = \Delta P \frac{R_m}{\zeta_{\text{clad}}} > \sigma_{es,b}.$$  \hspace{1cm} (1.58)

The burst stress $\sigma_{es,b}$ depends on many factors as the average temperature of the cladding and the $\alpha \rightarrow \beta$ transition in the molecular structure of the zirconium alloy.

![Figure 1.8: Graphical representation of the axial nodalization of the fuel sample in CATHARE code.](image)

1.5.5 The radiative heat transfer inside the fuel gap

The radiation between the fuel pellet and the cladding is taken into account by considering an equivalent thermal resistance $R_{rad}$ (Delhaye, 2012). In particular, the global thermal resistance
22 CATHARE code

$R_{tot}$ inside the fuel gap is expressed as

$$\frac{1}{\Omega_{tot}} = \frac{1}{\Omega_{cond}} + \frac{1}{\Omega_{rad}} . \quad (1.59)$$

$\Omega_{con}$ is the conduction resistance expressed as

$$\frac{1}{\Omega_{cond}} = \frac{k_{gap}}{\zeta_{gap}} , \quad (1.60)$$

where $k_{gap}$ is the coefficient of conduction inside the gas gap. The resistance due to the radiation $\Omega_{rad}$ is obtained as

$$\frac{1}{\Omega_{rad}} = \frac{\sigma_{sb}}{\epsilon_{fuel}} + \frac{1}{\epsilon_{clad}} - \frac{1}{T_{fuel} - T_{clad,i}} \left( T_{fuel} - T_{clad,i} \right) , \quad (1.61)$$

where $\sigma_{sb}$ is the Stefan-Boltzman constant, $\epsilon_{fuel}$ and $\epsilon_{clad}$ are respectively the fuel and cladding emissivity.

1.5.6 The oxidation process

The reaction between the zirconium and steam is also taken into account in the Fuel rod sub-module. The exothermic reaction occurs for high value of temperature ($T > 1000 \, ^\circ C$) and the chemical reaction is expresses in the form

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 + 586 \, kJ .$$

If $\omega$ is the mass of Zircaloy reached per unit area [kg/m$^2$], this can be expressed as

$$\omega^2 = K_p t . \quad (1.62)$$

In the [1.62] $t$ is the Reaction Time and $K_p$ is the Parabolic Reaction Rate constant which is expressed by using the Arrhenius equation

$$K_p = Ae^{\frac{E}{RT}} . \quad (1.63)$$

In the [1.63] $A$ is the Pre-exponential factor expressed in [kg$^2$/m$^4$s$^{-1}$], $E$ is the reaction activity energy [J/mole], $R$ is the gas constant [J/K mole$^{-1}$] and $T$ [K] is the temperature. Several studies have carried out to investigate the value of $K_p$, in particular in the table 1.3 are listed the values of $K_p$ for some common correlations found in the literature (Urbanic and Heidrick, 1978; Baker and Just, 1962; Cathcart et al., 1977; Leistikow and Schanz, 1987). By using the Fuel rod sub-module, only the Cathcart and the Baker and Just correlations may be chosen by the Code’s User. By substituting $\omega = \rho_{Zr} \zeta_{oxy}$ in the [1.62] and by differentiating with respect to the time $t$, we obtain

$$\frac{d\zeta_{oxy}}{dt} = \frac{K_p}{2\rho_{Zr} \zeta_{oxy}} . \quad (1.64)$$
The oxidation process

<table>
<thead>
<tr>
<th>Reference</th>
<th>$K_p\ [kg^2/m^4s^{-1}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urbanic and Heidrick</td>
<td>$29.6\ exp(-16820/T)$</td>
</tr>
<tr>
<td>Baker and Just</td>
<td>$3330\ exp(-22896/T)$</td>
</tr>
<tr>
<td>Cathcart</td>
<td>$294.2\ exp(-20100/T)$</td>
</tr>
<tr>
<td>Leistikow and Schanz</td>
<td>$425.8\ exp(-20962/T)$</td>
</tr>
</tbody>
</table>

where $\zeta_{oxy}$ is the thickness of the zirconium oxidized and $\rho_{Zr}$ is the zirconium density. We assume that the total energy released by 1 kg of zirconium oxidized is nearly $6.45\times10^6\ J$. Therefore it is easy to find the value of the heat flux $q''\ [W/m^2]$ released on the Zircaloy surface as

$$q'' = (6.45\times10^6)(\rho_{Zr})\frac{d\zeta_{oxy}}{dt} = 2.13\times10^6\frac{K_p}{\rho_{Zr}^2\zeta_{oxy}}.$$  \hspace{1cm} (1.65)

If $\Delta\zeta_{oxy}$ is the thickness of zirconium reached in a period of time $\Delta t$ then the total number of moles of hydrogen released per unit area is

$$\Phi_{H_2} = \frac{2\rho_{Zr}}{M_{Zr}}\zeta_{oxy} = 1.44\times10^5\Delta\zeta_{oxy}.\hspace{1cm} (1.66)$$

The Reaction Rate (R.R.) defines the speed of the chemical reaction, it may be defined as the variation of the concentration of substance along the time

$$\text{R.R} = -\frac{dN_{Zr}}{dt} = -\frac{1}{2}\frac{dN_{H_2O}}{dt} = \frac{dN_{ZrO_2}}{dt} = \frac{1}{2}\frac{dN_{H_2}}{dt}.\hspace{1cm} (1.67)$$

The hydrogen mass flow produced $\dot{m}_{H_2}$ is then determined as

$$\dot{m}_{H_2} = \frac{1}{2M_{H_2}}\frac{1}{M_{ZrO_2}}\dot{m}_{ZrO_2}.\hspace{1cm} (1.68)$$

If $H$ is the height of the fuel cladding, the zirconium dioxide mass flow can be expressed as

$$\dot{m}_{ZrO_2} = 2\pi HR_{clad,e}\rho_{ZrO_2}\frac{d\zeta_{oxy}}{dt}.\hspace{1cm} (1.69)$$

By substituting the [1.69] in the [1.68], we obtain the mass flow of hydrogen released

$$\dot{m}_{H_2} = 4\frac{M_{H_2}}{M_{ZrO_2}}(\pi HR_{clad,e}\zeta_{oxy})\frac{d\zeta_{oxy}}{dt}.\hspace{1cm} (1.70)$$

By substituting the [1.63]-[1.64] in the [1.70], we obtain

$$\dot{m}_{H_2} = 2\frac{M_{H_2}}{M_{ZrO_2}}\frac{\rho_{ZrO_2}}{\rho_{Zr}}\frac{\pi HR_{clad,e}A_e}{\zeta_{oxy}}.\hspace{1cm} (1.71)$$

As said previously, numerically the Fuel sub-model is divided into $m$ different meshes to which the height $h_j$ is associated. Considering that the densities depends on the temperature computed
in each single mesh, the total hydrogen mass flow produced may be expresses as

$$m_{H_2} = 2\pi \frac{M_{H_2}}{M_{ZrO_2}} \sum_{j=1}^{m} \left( \frac{\rho_{ZrO_2} \cdot H R_{\text{clad},e} A_{\text{oxy}}}{\rho_{Zr} \cdot \zeta_{\text{oxy}} - E_{RT_{\text{clad}}}} \right)_j. \tag{1.72}$$

If $R_{\text{oxy},e}$ is the radius of the cladding included the thickness of the external oxide then the variation in volume of the thickness oxide can be expressed as

$$\frac{\partial V_{\text{oxy}}}{\partial t} = \frac{[R_{\text{oxy},e}^2(t + \Delta t) - R_{\text{clad},e}^2(t + \Delta t) + R_{\text{clad},e}^2(t) - R_{\text{oxy},e}^2(t)]\pi H}{\Delta t}, \tag{1.73}$$

or if we consider the $n$th numerical time step as

$$\frac{\Delta V_{\text{oxy}}}{\Delta t} = \frac{[R_{\text{oxy},e}^2|_{n+1} - R_{\text{clad},e}^2|_{n+1} + R_{\text{clad},e}^2|_{n} - R_{\text{oxy},e}^2|_{n}]\pi H}{\Delta t}. \tag{1.74}$$

Finally the instantaneous power generated by the zirconium oxidation may be expressed as

$$P_{\text{oxy}}|_{n} = (586 \times 10^6) \sum_{j=1}^{m} \left( \frac{\Delta V_{\text{oxy}}^j \rho_{ZrO_2}}{\rho_{Zr} \cdot \zeta_{\text{oxy}} - E_{RT_{\text{clad}}}} \right)^n. \tag{1.75}$$
Chapter 2

Overview of the LOCA accident and description of some integral LOCA-test devices

The study of the LOCA testing methodology involves a large number of different science-based approaches, this because this field of engineering differs in accordance with the specific purpose of study. In general, in the LOCA literature, a series of facilities go from a complete fuel bundle to a non-irradiated fuel assembly, are needed to investigate the thermal and mechanical stress of the fuel alloy elements, such as the alpha-beta transformation, the zirconium-steam oxidation or, physical problems involving the thermal-hydraulic of the system. Sometimes, the entire technical apparatus are quite expensive and complicated, in fact they require sophisticated instrumentation and post-test evaluation. This chapter describes a typical LOCA accident and its definition in a common Nuclear Regulatory, furthermore it provides to a general view of the main experimental facilities used to support this field of research in the previous years. At the end, a classification of LORELEI test device and an analysis of its technological similarities with other experimental devices is described.

2.1 Definition of Loss of coolant accident

The definition of Loss of coolant accident (LOCA) given by the United States Nuclear Regulatory Commission (U.S.NRC) can be summarized by the following definition. *Loss of coolant accident means those postulated accidents that result from the loss of reactor coolant at the rate in excess of the capability of the reactor coolant makeup system from breaks in the reactor coolant pressure boundary, up to and including a break equivalent in size to the double-ended rupture of the largest*
Overview of the LOCA accident and description of some integral LOCA-test devices

In the nuclear industry the accidental scenario are divided into three main categories, the Anticipated Operational Occurences (AOO’s), the Design Basic Accident (DBA’s) and Severe Accident. The AOO’s are expected to occur one or more times during the operation life of the nuclear reactor. The DBA’s are more serious events which are not expected to occur during the life in a nuclear power plant. The Severe Accidents are a very low frequency events during which the reactor core configuration might modify and a significant radionuclide released from the damage core is expected. For all the typologies of accident, numerous acceptance criteria must be fulfilled in such a way as to minimize the radiological consequences to the public. In the field of the DBA’s inspection measures, every nuclear power plant before their licensing must follow some important norms introduced in a state-of-art report (Parson et al., 1986) and reported in the U.S.NRC regulation (Utited States Nuclear Regulatory Commission, b) or in others Nuclear Regulatory Commissions stabilized for various countries engaged in the nuclear industry. In this chapter we refer only to the rules applied by the U.S. Nuclear Regulatory Commission.

2.2 Emergency Core Cooling System (ECCS)

If we are talking about of the DBA, it is necessary to define the concept of Emergency Core Cooling System (ECCS) which is the primary security system for this type of accident scenario. An Emergency Core Cooling system is a system needed to provide abundant emergency core cooling. The system safety function shall be to transfer heat from the reactor core following any loss of reactor coolant at a rate such that (1) fuel and clad damage that could interfere with continued effective core cooling is prevented and (2) clad metal-water reaction is limited to negligible amounts.

Generally, inside a standard PWR the ECCS shall be divided into different parts: high, intermediate and low Pressure Injection System. For details one can refer to figure 2.1.

**HPIS** When the internal reactor pressure decreases under a certain limit, a signal triggers the High Pressure Injection System (HPIS) that provides water from the Refueling Water Storage Tank (RWST) through the use of a high pressure pump. The water is injected in the cold leg.

**IPIS** The Intermediate Pressure Injection System (IPIS) shall be activated when the internal pressure is still high (small and intermediate size of the break). The water is pumped from the RWST and injected inside the cold leg.

**Cold leg Accumulator** This is a passive system formed by a tank that contains a large amount of borated water with a pressurized nitrogen gas bubble in the top. When the pressure inside the primary system drops below a certain limit, the nitrogen forces the borated water out the tank into the reactor cooling system.
LPIS The Low Pressure Injection System (LPIS) is designed to be operational when the reactor pressure reaches very low values following a large break. This system allows to pump the water spilled from the break and collected in the containment sump. Before being injected inside the cold leg, the water passes through an exchanger called Residual Heat Removal (RHR).

Acceptance criteria for the ECCS in the LWR

According to the United States Nuclear Regulatory Commission (U.S.NRC) the current legislation in the field of the *Acceptance criteria for emergency core cooling system for light-water nuclear power reactors* is readily available by visiting the web site of the U.S.NRC. The Appendix K sets forth the documentation requirements for each ECCS evaluation model. For example, the reader can find all the documentation of the Appendix K by consulting the U.S.NRC web site (United States Nuclear Regulatory Commission, c) or in other regulations written for different countries. The acceptance criteria for emergency core cooling systems for light-water nuclear power reactors can be summarized in five classes: criteria for the Peak cladding temperature (a), Maximum cladding oxidation (b), Maximum hydrogen generation (c), Coolable geometry (d), and Electric power generation (e).
Overview of the LOCA accident and description of some integral LOCA-test devices

(d) and Long-term cooling point (e). In details we have:

(a) Each boiling or pressurised light-water nuclear power reactor fueled with uranium oxide pellets within cylindrical Zircaloy or ZIRLO1 cladding must be provided with an emergency core cooling system (ECCS) that must be designed so that its calculated cooling performance following postulated loss-of-coolant accidents conforms to the criteria set forth in paragraph (b) of this section. ECCS cooling performance must be calculated in accordance with an acceptable evaluation model and must be calculated for a number of postulated loss-of-coolant accidents of different sizes, locations, and other properties sufficient to provide assurance that the most severe postulated loss-of-coolant accidents are calculated.

(b) The maximum fuel element cladding temperature shall not exceed 2200° F.

(c) The calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation. As used in this subparagraph total oxidation means the total thickness of cladding metal that would be locally converted to oxide if all the oxygen absorbed by and reacted with the cladding locally were converted to stoichiometric zirconium dioxide. If cladding rupture is calculated to occur, the inside surfaces of the cladding shall be included in the oxidation, beginning at the calculated time of rupture. Cladding thickness before oxidation means the radial distance from inside to outside the cladding, after any calculated rupture or swelling has occurred but before significant oxidation. Where the calculated conditions of transient pressure and temperature lead to a prediction of cladding swelling, with or without cladding rupture, the unoxidized cladding thickness shall be defined as the cladding cross-sectional area, taken at a horizontal plane at the elevation of the rupture, if it occurs, or at the elevation of the highest cladding temperature if no rupture is calculated to occur, divided by the average circumference at that elevation. For ruptured cladding the circumference does not include the rupture opening.

(d) The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical amount that would be generated if all of the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum volume, were to react.

(e) Calculated changes in core geometry shall be such that the core remains amenable to cooling.

(f) After any calculated successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be be removed for the extended period of time required by the long-lived radioactivity remaining in the core.
2.3 PWR large break LOCA

The Loss of Coolant Accident is one of the DBA’s that might occur in a LWR. In this type of accident, the initiating event is the double-ended guillotine break of the large coolant pipe that connect the reactor vessel with the main circulation pump, see figure 2.2(a)-(b). In accordance with the break size the LOCA are subdivided in small, medium and large break LOCA accident. Figure 2.3 shows a typical large breach LOCA transient:

1. Blow down period [0-30 s] During this first step, all the primary coolant is lost and the core voids within a few seconds after the break; the cladding temperature increases and departure from nuclear boiling is reached (first peak in the figure 2.3). The negative void reactivity and the SCRAM procedure immediately shut down the core. This leads to a fuel pellet central temperature drop and a flattening of the radial temperature profile. With the cooling decreasing and redistribution of fuel stored energy the cladding temperature increases. The dynamic interaction between the pump and the break might cause intermittent flow reversal. When the break occurs, the pressure inside the system decreases, the HPIS is triggered in order to pump water inside the reactor, see figure 2.2(c). When most of the water injected is lost by the break the injection from the Cold Leg Accumulator begins. However much of the injected water is swept around the downcomer into the cold leg and out of the break. Thanks to the RHR some water begins to cover the lower plenum vessel, see figure 2.2(d).

2. Refill period [30-40 s] The water accumulated begins to fill the lower plenum. However the fuel temperature increases due the decay heat and the pressure decrease leads to ballooning and burst when the cladding temperature (depending on the initial conditions) is around 700-1000 °C. This cladding ballooning could lead to a blockage of some of the flow channels.

3. Reflood period [40-200 s] After the lower plenum has filled, the water starts to refill the core. The quenching progress generates a two-phase mixture which cools slightly the upper part of the core. However the fuel cladding temperature continues to increase up to 1000-1200 °C by leading to its oxidation. In this phase some additional fuel rods may burst. The hydrogen produced by the oxidation can interact with the metal (hydriding). When the quench front reaches the higher temperature fuel, the abrupt change of heat exchange and hence the thermal shock can lead to brittle fracture. Once the liquid enters into this fracture other fission products are released.
2.4 Overview of LOCA testing methodology

2.4.1 Introduction

The entire methodology to understand the main effects occurring following a LOCA required a large number of different techniques which differ according to the effects one want to investigate. The experimental experiences might consider the use of a complete fuel bundle irradiated or not, furthermore to set up the entire apparatus is quite complicated and requires specific instrumentation. A general classification of the different tests typology with regard to the study of the LOCA experimental apparatus is summarized in the figure 2.4. In the next paragraph a brief description of some fully integrated test (In-reactor test and Out-of-reactor-test) is presented. The reader can find a more detailed description of all the different type of test by consulting the Nuclear Energy Agency report (Pettersson et al., 2009).

Figure 2.2: Nuclear reactor vessel: during the nominal condition (a), when the break in the cold break occurs (b), when ECCS is triggered and the water starts to be injected inside the reactor vessel (c), when the water overflow goes out from the break before being injected again in the reactor core by means of the LPIS (d), from (Hewitt, G F)
2.4.2 Fully integrated test

In-reactor test

The FR2 facility. The FR2 is a research reactor whose construction began in 1957 in Eggenstein-Leopoldshafen in Germany. The organization charged to build this heavy water cooled reactor was the Kernforschungszentrum Karlsruhe evolved today in the Karlsruhe Institute of Technology (KIT). The main objective of this test campaign was to provide information about the effect on the fuel rod under a LOCA condition. Figure 2.5 shows a vertical section of the “in-pile” test. During the steady state, the pressure inside the system was maintained at 60 bar, the steam temperature at 300 °C and the coolant mass flow along the sample was of 120 kg/s. The fuel rod had the same dimension of those located in a typical PWR German 1300 MW reactor with an active length of 50 cm. The tests were conducted with unirradiated and pre-irradiated fuel rod. The main parameters modified for each test were the burn-up, which varied between 2500 and 35000 MWd/t, the internal pressure gap $P_{gap}$ between 25 and 125 bar and the heat-up rate between $6 \div 20$ K/s. A certain number of reference tests by using an electrical heater were
Overview of the LOCA accident and description of some integral LOCA-test devices

Some main phenomena studied:
- Creep tests
- Determination of the diffusion constant in the β layer
- α to α+β to β transformation temperatures
- Ductility test
- Oxidation test

Some main experimental devices:
- FR2 facility
- PFB-LOC experiment
- PHEBUS test
- LOCA test in the Halden Reactor

Some main experimental devices:
- REBEKA programme
- Test at Japanese Atomic Energy Institute (JAERI)
- MRBT programme

Some main experimental devices:
- DEZIROX facility
- PROPAT facility
- EDGAR facility
- EDGAR-2 facility

Some main experimental devices:
- BEREKA programme
- Test at Japanese Atomic Energy Institute (JAERI)

Figure 2.4: LOCA testing methodology.

conducted. During the pre-irradiation phase, the fuel rod was pressurized with helium at 0.3 bar and the coolant temperature was fixed at 60 °C at 2.5 bar. The pre-irradiation phase started with the fuel rod pressurization by injecting helium into the fuel gap. During this phase, the rod was exposed to standard conditions associated to a typical PWR LB-LOCA transient with a Linear heat generation rate which varied from 250 to 425 W/cm². The accidental scenario started with the interruption of the coolant liquid flow by closing the Shutoff valve. The depressurization occurred by opening the Relief valve (up to 0.1 bar within 8 to 10 s), see figure 2.6. Once the fuel cladding reached the target value of temperature, the Reactor is triggered. When the fuel cladding stabilized, the Shutoff valve was opened again and the cooling mass flow was reactivated in order to study the quenching phase. Table 2.1 shows the results obtained from this test campaign (Karb et al., 1982).

PBF-LOC experiment in the Power Burst Facility. The Power Burst Facility (PBF) was a water cooled and moderated tank research reactor at the Idaho National Lab (INL). The “in-pile” device PFB-LOC located inside the reactor was utilized to simulate a large break LOCA. The test was performed with unirradiated and irradiated fuel rods, the entire apparatus
was designed to investigate the major parameters determining the cladding circumferential strain during the ballooning, the corresponding cladding temperature and the differential pressure. The cross section view in the figure 2.7, depicts the four fuel rods installed inside the “in-pile” device. The active length of a single rod was of 0.91 m. The test sequence started with the steady-state transient during which the fuel rods were cooled with a certain liquid mass flow and the power maintained at 45 kW/cm. The accidental simulation started with the opening of the control valves and consequent water discharging. The maximum fuel cladding temperature was controlled in order to remain in a target range. Table 2.2 summarizes the main results of this test campaign (Pettersson et al., 2009, pp.246).

**PHEBUS LOCA program.** Placed at the CEA Nuclear Research Center of Cadarache, the PHEBUS facility was an experimental reactor that has been operational since 1978. The first part of this vast test campaign was to study the thermal-hydraulic and the mechanical behavior of the fuel cladding during a Large Break LOCA. This first part of the entire experience, performed
Overview of the LOCA accident and description of some integral LOCA-test devices

Table 2.1: Summary of the results conducted in the FR2 facility.

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<td>9.8</td>
<td>29</td>
<td>1023</td>
<td>1220</td>
<td>111</td>
<td>128</td>
<td>32</td>
<td>32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Notes</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{rod leaked; no burst} )</td>
<td>a</td>
</tr>
<tr>
<td>( \text{no internal overpressure, no burst} )</td>
<td>b</td>
</tr>
<tr>
<td>( \text{abnormal heat-up; burst during temperature plateau} )</td>
<td>c</td>
</tr>
<tr>
<td>( \text{rod leaked; no max. pressure} )</td>
<td>d</td>
</tr>
</tbody>
</table>

in a 5x5 fuel bundle reactor with pressurized rods, was called Phebus LOCA program and was divided in two different parts.

I) Eight tests were conducted between the years 1980-1982. The aim of these tests was to reach a prototypical tests series to reach the thermal-hydraulic conditions in order to evaluate the power history of the system, the size and the location of the break and the proper working of the ECCS.

II) Six more test were conducted between the years 1982-1984. During these tests, the study of the thermal-mechanical behavior involves the fuel rod during the LOCA accident was performed.
Figure 2.7: Cross section of the PBF-LOC, from (Pettersson et al., 2009, pp.117).

Table 2.2: Summary of the results conducted in the PFC-LOC facility.

<table>
<thead>
<tr>
<th>Test</th>
<th>Gap [bar]</th>
<th>Burnup [MWd/t]</th>
<th>( \Lambda ) [K/s]</th>
<th>Maximum circumferential elongation [%]</th>
<th>( t_{fail} ) [s]</th>
<th>( T_{clad,b} ) [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOC-3</td>
<td>24.5</td>
<td>4.3</td>
<td>29</td>
<td>15.0</td>
<td>1190</td>
<td></td>
</tr>
<tr>
<td></td>
<td>32.8</td>
<td>20.0</td>
<td>40</td>
<td>7.9</td>
<td>1100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>49.2</td>
<td>15</td>
<td>20</td>
<td>10.1</td>
<td>1110</td>
<td></td>
</tr>
<tr>
<td></td>
<td>47.5</td>
<td>15</td>
<td>41.6</td>
<td>13.1</td>
<td>1120</td>
<td></td>
</tr>
<tr>
<td>LOC-5</td>
<td>24.1</td>
<td>0</td>
<td>35</td>
<td>10.5</td>
<td>1350</td>
<td></td>
</tr>
<tr>
<td></td>
<td>48.3</td>
<td>100</td>
<td>19</td>
<td>2.75</td>
<td>1160</td>
<td></td>
</tr>
<tr>
<td></td>
<td>48.3</td>
<td>70</td>
<td>48</td>
<td>7.8</td>
<td>1350</td>
<td></td>
</tr>
<tr>
<td>LOC-6</td>
<td>24.1</td>
<td>0</td>
<td>&lt;1</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24.1</td>
<td>100</td>
<td>13.6</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>47.4</td>
<td>0</td>
<td>31</td>
<td>5.2</td>
<td>1098</td>
<td></td>
</tr>
<tr>
<td></td>
<td>48.3</td>
<td>0</td>
<td>74</td>
<td>18.2</td>
<td>1066</td>
<td></td>
</tr>
</tbody>
</table>

Basically, the loop of the entire apparatus was composed by a pool type reactor inside which the nuclear power was supplied (LHGR\textsubscript{hp} up to 57 W/cm) and a hydraulic loop to obtain the same hydraulic conditions inside a typical french PWR. During the LOCA phase, the power of the core was controlled to simulate the residual power in the experimental fuel rods. The test train was changed in accordance with the test performed. In the first Steady State phase (see figure 2.8), the fuel rods were cooled by a forced-convection liquid flow. To calibrate the inlet water temperature, the water, before being pumped in the bottom part of the core, passed inside in a heater to be heated up to 320 \(^\circ\)C. At the end of this phase, the blowdown phase started,
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see figure 2.9. The blowdown started by opening the by-pass valves which allowed to deviate the feed water flow. The opening of some valves allowed to discharge out all the water remained inside the primary circuit in a blowdown tank by depressurizing the entire system. In the follow re-flooding phase, the water extracted from an accumulator was flowed inside an injection line connected with the reactor core. Tables 2.3-2.4 summarize the values obtained during the Part I and II of the Phebus LOCA program (Adroguer et al., 1983; CEN).

**LOCA test at the Halden Reactor.** The Halden nuclear Reactor is an experimental reactor became operative in the 1958 at the Institute of Energy Technology (IFE). Inside the reactor, the experimental experiences IFA-511X, IFA-54X and IFA-650X were conducted in order to investigate the behavior of the fuel rod during a LOCA accident.
Table 2.3: Results obtained from the Part I of the PHEBUS LOCA program.

<table>
<thead>
<tr>
<th>Test</th>
<th>Break Location</th>
<th>LHGR_{hp} [W/cm]</th>
<th>P_{gap} [bar]</th>
<th>Max. T_{clad} [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>206</td>
<td>Hot leg</td>
<td>0</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>207</td>
<td>Hot leg</td>
<td>270</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>208</td>
<td>Cold leg</td>
<td>0</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>209</td>
<td>Cold leg</td>
<td>270</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>210</td>
<td>CL+HL X=1.3</td>
<td>0</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>21</td>
<td>CL+HL X=1.3</td>
<td>320</td>
<td>10</td>
<td>933</td>
</tr>
<tr>
<td>212</td>
<td>CL+HL X=1.3</td>
<td>460</td>
<td>10</td>
<td>1040</td>
</tr>
<tr>
<td>213A</td>
<td>CL+HL X=1.3</td>
<td>490</td>
<td>10</td>
<td>1380</td>
</tr>
</tbody>
</table>

X Ratio between the break size along the cold Leg (CL) and along the hot leg (HL).

Table 2.4: Results obtained from the Part II of the PHEBUS LOCA program.

<table>
<thead>
<tr>
<th>Test</th>
<th>215P</th>
<th>215R</th>
<th>216</th>
<th>217 ter</th>
<th>218</th>
<th>219</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady state</td>
<td>LHGR_{hp} [W/cm]</td>
<td>488</td>
<td>500</td>
<td>470</td>
<td>500</td>
<td>460</td>
</tr>
<tr>
<td></td>
<td>P_{gap} [bar]</td>
<td>154</td>
<td>155</td>
<td>152</td>
<td>154</td>
<td>156</td>
</tr>
<tr>
<td></td>
<td>Mass flow rate [kg/s]</td>
<td>10.1</td>
<td>10.2</td>
<td>10.1</td>
<td>10.2</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>P_{gap} [bar] at 20 °C</td>
<td>40</td>
<td>40</td>
<td>30</td>
<td>30</td>
<td>30.5</td>
</tr>
<tr>
<td>Blow-down</td>
<td>t_{fail} [s]</td>
<td>50-60</td>
<td>23-26</td>
<td>146-171</td>
<td>23-33</td>
<td>115-127</td>
</tr>
<tr>
<td></td>
<td>P_{gap,fail} [bar]</td>
<td>60-75</td>
<td>60-75</td>
<td>33-37</td>
<td>40</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>T_{clad,b} [°C]</td>
<td>800-860</td>
<td>800-860</td>
<td>900</td>
<td>900</td>
<td>850</td>
</tr>
<tr>
<td></td>
<td>Max. T_{clad} [°C]</td>
<td>900</td>
<td>1250</td>
<td>1400</td>
<td>1200</td>
<td>1400</td>
</tr>
<tr>
<td></td>
<td>Max. x_e [μm]</td>
<td>30</td>
<td>41</td>
<td>77</td>
<td>50</td>
<td>80</td>
</tr>
</tbody>
</table>

IFA-511 and IFA-54 apparatus. The IFA-511X and IFA-54X were pure thermal-hydraulic experimental tests. The cross section of the IFA-511 was composed by 7 fuel rods (6 peripheral rods and one central reference rod) in a circular configuration, see figure 2.10. Four triangular tubes were used as downcomers for the liquid coolant.

Figure 2.11 shows the cross section of the IFA-54 experimental device. In particular 5 instrumented fuel rods were located in a cruciform disposition. The IFA-511X test series were devised to compare possible thermal-hydraulic differences between the utilization of a real fuel rods and an electrical rod simulators during the quenching phase. The IFA-54X test series were performed to examine the thermal efficiency of the fuel cooling, once a significant reduction of the coolant flow area (as a result of the clad ballooning), has verify. Tables 2.5-2.6 summarize the type of the tests performed and the rod types utilized. Each IFA-511.2 test series were performed with a reflood liquid velocity of nearly 10 cm/s with a average LHGR equal to 10 W/cm (series A), 20 W/cm (series B) and 30 W/cm (series C). The other test series (D, E, F, G, and H) were conducted at an intermediate power of 20 W/cm with a low and intermediate flow rate (2÷7 cm/s). Some test with or without the blowdown phase, were performed by means of a semiscale
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Figure 2.10: Cross section of the IFA-511 assembly, from (Pettersson et al., 2009, pp.121).

Figure 2.11: Cross section of the IFA-54 assembly, from (Pettersson et al., 2009, pp.121).

electrical heater and a heater just like utilized for the REBEKA test which design is described in the follow of this chapter. During the test without the blowdown phase, the heat-up phase begun once dry condition has already started. In this last condition, the LHGR and the reflood liquid velocity could vary between the 18 and 26 W/cm and between 2.25 and 10.1 cm/s.

IFA-650 test series. The Halden IFA-650 LOCA tests were conducted in 2003. In this thesis are
Table 2.5: Summary of all the test series of the IFA-511X and IFA-54X.

<table>
<thead>
<tr>
<th>Test series</th>
<th>Heating Elements</th>
<th>Test identification</th>
<th>Test type</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFA-511.2</td>
<td>Nuclear rods</td>
<td>A1-A3,B1-B3, C1-C3</td>
<td>Blowdown-reflood tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B4-B9, D1, E1-E7</td>
<td>Blowdown-reflood tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F1-F3, G1, H1, H2</td>
<td>Blowdown-reflood tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K1-K4, J1, J2</td>
<td>Blowdown-reflood tests</td>
</tr>
<tr>
<td>IFA-511.3</td>
<td>Semiscale electrical heater</td>
<td>B5-B9, E5-E7, F1, G1</td>
<td>Blowdown-reflood tests</td>
</tr>
<tr>
<td>IFA-511.4</td>
<td>Rebeka electrical heater</td>
<td>7404-7410</td>
<td>Reflood test without blowdown</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7822-7829</td>
<td>Reflood test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7830-7832</td>
<td>Reflood test</td>
</tr>
<tr>
<td>IFA-511.5</td>
<td>Semiscale electrical heater</td>
<td>9332-9337,9345-9347</td>
<td>Reflood test without blowdown</td>
</tr>
<tr>
<td>IFA-541</td>
<td>Nuclear rods</td>
<td>A1-A10, B1, B2, C1-C4</td>
<td>Blowdown-reflood tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D1-D6</td>
<td>Blowdown-reflood tests</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9771-9780</td>
<td>Blowdown-reflood tests</td>
</tr>
<tr>
<td>IFA-543</td>
<td>Nuclear rods</td>
<td>-</td>
<td>Ballooning test</td>
</tr>
<tr>
<td>IFA-544</td>
<td>Rebeka electrical heater</td>
<td>-</td>
<td>Ballooning test</td>
</tr>
<tr>
<td>IFA-545</td>
<td>Nuclear rods</td>
<td>-</td>
<td>Ballooning test</td>
</tr>
<tr>
<td>IFA-546</td>
<td>Rebeka electrical heater</td>
<td>-</td>
<td>Ballooning test</td>
</tr>
<tr>
<td>IFA-547</td>
<td>Nuclear rods</td>
<td>-</td>
<td>Ballooning test</td>
</tr>
</tbody>
</table>

Table 2.6: Summary of the power rod used in the IFA-511X and IFA-54X test series.

<table>
<thead>
<tr>
<th></th>
<th>Nuclear Rod (IFA-511)</th>
<th>Nuclear rod (IFA-54X)</th>
<th>Semicale EH</th>
<th>REBEKA EH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel rod $D$ [mm]</td>
<td>9.07</td>
<td>8.196</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pellet height [mm]</td>
<td>9</td>
<td>10.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Filler gas $He$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$D_{clad,c}$ [mm]</td>
<td>9.30±0.02</td>
<td>10.75</td>
<td>-</td>
<td>0.75</td>
</tr>
<tr>
<td>Heated length [mm]</td>
<td>1500±2</td>
<td>1482</td>
<td>1486±10</td>
<td>1500</td>
</tr>
<tr>
<td>Aluminia pellet $D_e$ [mm]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.08</td>
</tr>
<tr>
<td>Aluminia pellet $D_i$ [mm]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.08</td>
</tr>
</tbody>
</table>

presented the results of the test series 4, 9, 10 and 14. The objective of the IFA-650X test series were to evaluate the ballooning size and the consequences of the fuel cladding oxidation, the fuel fragment relocation inside the ballooned region and the “secondary transient hydriding” on the inner side of the cladding (around the burst region). The “in-pile” section of the apparatus is shown in the figure 2.12, figure 2.13 shows a cross section of the device at the height of the heated parts. The length of the inner active rod varied between the 360-480 mm. The fuel rod was surrounded by an electrical heater shroud and a pressure flask. The heater provided to
simulate the heating effect of the nearby fuels with a similar power. Looking at the hydraulic layout depicted in the figure 2.14, during the nominal condition the device was connected to the loop and filled with heavy water at pressure around 70 bar and a temperature of 515 K. Suddenly the apparatus was isolated and the fuel sample was cooled by a natural convection loop. The second stage consisted to detect the total transport activity by bypassing the outer circuit. Once that the correct level of power has reached, the valves that connected the “in-pile” part with the dump tank (TA6301) were opened by depressurizing the entire system. As a result
of the sharp system depressurization, the coolant immediately flashed and the steam produced was collected inside an external tank where it was condensate. At the end of the transient, the pressure could reach values around the 0.2–0.3 bar. The time required for the blowdown phase depended on the way to discharge the water from the device, from the bottom part (65–75 s) or, simultaneously, from the bottom and the top part (30–35 s). In most of the tests performed, to regulate the clad temperature, a small amount of water was sprayed inside the “in-pile” test. Tables 2.7-2.8 summarize the characteristics of the rod utilized and the results obtained from this test campaign.

Table 2.7: Summary of the rod parameters in the IFA-650X test series.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IFA-650.4</th>
<th>IFA-650.9</th>
<th>IFA-650.10</th>
<th>IFA-650.14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active length of sample [mm]</td>
<td>480</td>
<td>480</td>
<td>440</td>
<td>360</td>
</tr>
<tr>
<td>$P_{gap}$ [bar]</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>$D_{fuel}$ [mm]</td>
<td>9.13</td>
<td>913</td>
<td>8.19</td>
<td>8.19</td>
</tr>
<tr>
<td>Fuel burn-up [MWd/kg]</td>
<td>92.3</td>
<td>89.9</td>
<td>61.0</td>
<td>70.8</td>
</tr>
<tr>
<td>Cladding material</td>
<td>Zircaloy-4</td>
<td>Zircaloy-4</td>
<td>Zircaloy-4</td>
<td>Zircaloy-2</td>
</tr>
<tr>
<td>$D_{fuel,e}$ [mm]</td>
<td>10.75</td>
<td>10.75</td>
<td>9.50</td>
<td>9.62</td>
</tr>
<tr>
<td>Cladding thickness [mm]</td>
<td>0.725</td>
<td>0.725</td>
<td>0.570</td>
<td>0.630</td>
</tr>
<tr>
<td>$\varpi$ (mean) [$\mu$m]</td>
<td>10</td>
<td>7</td>
<td>27</td>
<td>32</td>
</tr>
</tbody>
</table>
Table 2.8: Results obtained from the IFA-650X test series.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>650.4</th>
<th>650.9</th>
<th>650.10</th>
<th>650.14</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHGR (fuel) [W/cm]</td>
<td>9.3</td>
<td>26</td>
<td>13.7</td>
<td>9.7</td>
</tr>
<tr>
<td>LHGR (heater) [W/cm]</td>
<td>15</td>
<td>16</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>Max. $T_{clad}$ [K]</td>
<td>1075</td>
<td>1475</td>
<td>1114</td>
<td>1065</td>
</tr>
<tr>
<td>Blowdown type $^a$</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Blowdown duration [s] $^b$</td>
<td>58</td>
<td>35</td>
<td>71</td>
<td>75</td>
</tr>
<tr>
<td>$t_{fail}$ [s] $^b$</td>
<td>336</td>
<td>133</td>
<td>249</td>
<td>None</td>
</tr>
<tr>
<td>$t$ spraying [s] $^b$</td>
<td>566</td>
<td>149-175</td>
<td>261</td>
<td>None</td>
</tr>
<tr>
<td>Reactor scram [s] $^b$</td>
<td>617</td>
<td>316</td>
<td>417</td>
<td>274</td>
</tr>
</tbody>
</table>

$^a$ Water discharged out from the bottom part (1), from the bottom and top part (2).

$^b$ Time after the beginning of the blowdown.

### Out-of-reactor tests

**The REBEKA program**  The REBEKA (REactor typical Bundle Experiment KArlsruhe) was an experimental device built at the KIT institute. The objective of this facility was to investigate the fuel cladding deformation during the refilling and the reflooding phases. The active length of the rods simulators was of 3900 mm see figure 2.15, the bundle configuration was in a 5x5 and 7x7 square, the figure 2.16 shows the layout loop. The experimental sequences of the device are listed below:

1) With the opening of the valve V1, the water and the steam were injected inside the test section from the bottom. At the same time, the control valve CV was opened. During the first phase, the test bundle was heated and pressurized in order to reach a target cladding temperature of 800 K.

2) The power inside the electrical rods simulators was increased up to reach nearly 9 kW in order to produce a heat-up rate of 7 K/s.

3) With the closure of the control valves, the water was forced to flow up the test section (beginning of the reflooding phase). During this phase the power inside the fuel bundle was reduced to mitigate the greater heat capacity of the electrical heaters (respect to the real fuel rod).

Table 2.9 summarized the results from this test campaign.

**MRBT programme**  At the Oak Ridge National Laboratory (ORNL) a test campaign sponsored by the NRC (Nuclear Regulatory Commission) was conducted with a single and multi-rod test assembly. Figure 2.17 shows the pin simulator placed in a test chamber. The heat-up rate reached was nearly of 28 K/s. In the multi-rod test, the fuel rod simulators were composed by Zircaloy-4 cladding with an external diameter of 10.9 mm. The power generated inside the fuel
rods was produced by an electrical heater of the same dimension of those utilized in the REBEKA test with an active length of 915 mm. To allow a vertical movement, the 8x8 array contained the fuel pins was suspended, see figure 2.18. During the preliminary phase, the electrical heaters were calibrated and a small amount of super-heated steam circulated inside the loop. When the cladding burst, the experience was considered terminated and the fuel simulators were switched off. Some of the objectives of the multi-rod test were to investigate:

- The effects of rod-to-rod interaction on failure behavior;
- The relation between the temperature and pressure rupture;
Overview of the LOCA accident and description of some integral LOCA-test devices

Table 2.9: Results obtained from the REBEKA test series.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Bundle size</th>
<th>$\dot{\Lambda}$ [K/s]</th>
<th>$T_{\text{clad,b}}$ [°C]</th>
<th>$P_{\text{gap,b}}$ [bar]</th>
<th>Circumferential strain $\varepsilon$ [%]</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5x5</td>
<td>7</td>
<td>810</td>
<td>60</td>
<td>28</td>
<td>Only 2 rods burst</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>7</td>
<td>870</td>
<td>55</td>
<td>54</td>
<td>3X3 pressurized</td>
</tr>
<tr>
<td>3</td>
<td>5x5</td>
<td>7</td>
<td>830</td>
<td>51</td>
<td>44</td>
<td>3X3 pressurized</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>7</td>
<td>830</td>
<td>53</td>
<td>46</td>
<td>3X3 pressurized</td>
</tr>
<tr>
<td>5</td>
<td>7x7</td>
<td>7</td>
<td>800</td>
<td>68</td>
<td>49</td>
<td>All rods pressurized</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>7</td>
<td>790</td>
<td>62</td>
<td>42</td>
<td>2 rods not pressurized</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>7</td>
<td>790</td>
<td>57</td>
<td>55</td>
<td>All pressurized</td>
</tr>
</tbody>
</table>

$^a$ Values averaged on all the rods.

- The flow resistance coefficient as a function of flow blockage;
- The magnitude of the blockage patterns.

Classification of LORELEI

LORELEI is a single rod experimental device with a real fuel sample. The position of LORELEI inside the Jules Horowitz reflector lays this facility half-way between a in-reactor and a out-of-reactor device. The evolution of the dry phase, allows us to study in detail the mechanical behavior of the fuel sample during the accidental and the post-accidental condition. In particular it is possible to investigate some phenomena as the oxidation growth and, how this formed oxide would affect the mechanical behavior of the fuel alloy during the re-flooding phase. LORELEI as in IFA-650, provides an electrical heater placed along the flow separation tube which simulates the heating effect of the nearby fuels. As in IFA-650 test, a preliminary experimental phase is performed in order to create a detectable fission product inventory. As happened in some of the experiences such as IFA-511.4 and IFA-511.5, in LORELEI, the blowdown phase, is not simulated, but the steam required for the dry-phase, is produced indirectly by activating an
Figure 2.18: 4x4 multi-rod test assembly in the MRBT, from (Pettersson et al., 2009, pp.130).

electrical heater in the bottom of the device. This electrical heater heats up a small amount of water remained from the previous emptying.
Overview of the LOCA accident and description of some integral LOCA-test devices
Chapter 3

LORELEI test device

3.1 The Jules Horowitz material testing reactor

In the last 50 years, the MTRs (Materials Test Reactor) have been an important way for the development and the qualification of materials and nuclear fuel. Most of these reactors have reached 50 years of operational life and their shutdown may be imminent, probably not later than 2020. In this contest, the Jules Horowitz Reactor, which has been planned also with the support of the European Commission Research, will be a key factor to improve and show the
safety of existing reactors and the support of new ones. This reactor, which is under construction in Cadarache, is a high flux test reactor, born from the collaboration between various partnership in the nuclear field. It will be an important facility for research and development for the nuclear industry. The planned full power is 100 MWt and it is designed to provide a high neutron flux ($5.5 \times 10^{14} n/cm^2 s$). The Jules Horowitz Reactor (JHR) complex figure 3.1, consists of a reactor building and a nuclear auxiliary building. The first one has a diameter of 37 m and is constructed in reinforced concrete. The reactor building contains three storage pools for spent fuel and irradiated fuel experimental devices. A transfer channel allows to move the spent fuel and experimental devices between these two places. Other infrastructure contains the circuit for cooling and ventilation, the emergency diesel generators and a “cold workshop” which allows to test the experimental devices before moving inside the reactor. The JHR complex includes also some online laboratories which monitor the fuel samples under radiation.

3.1.1 The irradiation devices

Simultaneously to the JHR construction, the CEA has planned to install some experimental loops aiming at testing materials and fuel under irradiation, see figure 3.2. These testing components are composed by one (or a few) samples of limited length, below are briefly described the mains test devices.

**MADISON** The objective of this device is the study of the fuel under normal working situation (for PWR, BWR and VVER-type reactors). In particular this device allows to investigate the evolution of the fuel proprieties (e.g. the microstructure, the fission gas release etc.) in function of the burn-up or the Linear Heat Generation Rates (LHGR).

**ADELINE** By using a new or pre-irradiated fuel rod, this device is able to reproduce several scenarios such as (see CEA Nuclear Center, The Irradiation Devices, www-rjh.cea.fr)

- Power ramp test;
- Rod internal over-pressurization of fuel rod;
- Rod internal free volumes gas sweeping in the fuel rod;
- Fuel pellet center melting condition approach

**MICA** This loop is a capsule experimental device whose objective is to study the behavior of the structural materials under irradiation for LWRs in a temperature range of 300 ÷ 450°C.

**MELODIE** This apparatus is designed for online bi-axial constrain analysis on materials.

**CLOE** Loop for the study of the corrosion under radiation for PWR and BWR reactors.
LORELEI Test device whose objective is to analyze the thermal-mechanical behavior of the fuel rod and the radiological consequences during a Loss of Coolant Accident (LOCA). The design and manufacturing of the test device are made in collaboration with the Israel Atomic Energy Commission (IAEC).

![Figure 3.2: Mind map of the experimental devices within the JHR project.](image.png)

### 3.2 Objective and motivations of LORELEI

The main objectives of the LORELEI device is to simulate the thermal-mechanical behavior of one LWR (Light Water Reactor) rod during a LOCA accident. The final results are be devoted in prior to: (Moran et al., 2014; Ferry et al., 2014):

(i) Understand the mechanical behavior governing the fuel sample during a LOCA accident (e.g. ballooning, clad burst etc.);

(ii) Understand the corrosion at high temperature, in particular the steam-zirconium oxidation and the clad embrittlement;

(iii) Investigate the fuel rod behavior during the quenching and post-quench phases;

(iv) Quantify the radionuclide released fraction (e.g. gaseous, volatile; semi-and non-volatile, and fissile material);
(v) Supply and validate numerical code and if possible to implement new models and laws.

The LORELEI test device will contribute to characterize new fuel cladding, new fuel (e.g. $UO_2$, MOX and additives) and to design new fuel assemblies. The test campaign will be important to investigate peculiar aspects such as fuel relocation (within the rod and out-of rod), impact of grids on the fuel relocation, etc.

3.3 Description of LORELEI

In the figure 3.3 is depicted a simplified representation of the in-pile device. The in-pile device has been designed to work as a closed capsule where the fuel rod is held by a sample holder. The total height of this closed capsule is about 3.4 m and has a change in diameter in the middle of its vertical axis. In particular, the diameter of the device is smaller at the bottom in order to minimize the gamma power buildup coming from the reactor and bigger at the top to increase the cooling by the cooling channel. The pressure flask is formed by two stainless steel parts: the inner part is designed to withstand the internal pressure, it forms a gas gap
3.3. DESCRIPTION OF LORELEI

Table 3.1: List of materials

<table>
<thead>
<tr>
<th>Element</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>$UO_2$</td>
</tr>
<tr>
<td>Cladding</td>
<td>Zircaloy</td>
</tr>
<tr>
<td>Sample holder</td>
<td>Zircaloy</td>
</tr>
<tr>
<td>Peripheral Heater</td>
<td>Inconel</td>
</tr>
<tr>
<td>Flow separation tube</td>
<td>SST</td>
</tr>
<tr>
<td>Inner Flask</td>
<td>SST</td>
</tr>
<tr>
<td>Outer Flask</td>
<td>SST</td>
</tr>
<tr>
<td>Neutron Screen</td>
<td>Hafnium</td>
</tr>
<tr>
<td>Device Holder</td>
<td>Zircaloy</td>
</tr>
</tbody>
</table>

with the second part which ensures the thermal insulation and gives indication of leakage in the flasks. A flow separation tube (FST) forms two concentric channels: a hot channel surrounding the fuel sample and the cold channel between the FST and the internal pressure flask. Due to the FST, a convective (thermosiphon) flow can be formed ensuring the cooling of the fuel rod during the first experimental sequence called the re-irradiation phase. The gap between the device holder and the pressure flask forms a cooling channel, where the water pumped from the reactor pool, flows in a forced convection regime. An hafnium neutron screen is used to flatten the axial fuel flux and to adjust the distance from the reactor core. Placed at the bottom of the hot channel, an electrical heater produces steam during the dry phase. The debris catcher
LORELEI test device collects all the fragments of the fuel and the cladding that are expected to come down during the fuel ballooning/burst and during the quenching phase. Table 3.1 shows all the materials of the device. The in-pile part of the device will be installed in the water channel inside the nuclear reflector, see figure 3.4. The displacement device (DD) allows radial movement toward the core. The total power produced inside the device depends on the value of the linear power produced by the fuel sample whose length is 60 cm and on the gamma power coming from the reactor which will be accumulated inside the materials and water along the NFZ.

3.4 Experimental sequence in LORELEI

Figure 3.5 shows all the experimental sequences which the LORELEI test device undergoes.

![Experimental sequences of LORELEI test device](image)

Figure 3.5: Experimental sequences of LORELEI test device.

**Re-irradiation phase** The irradiation phase occurs before the simulation of the real LOCA transient. During this phase the fuel is re-irradiated for few days in order to generate detectable short lived fission products. The fuel is cooled by single-phase thermosiphon (convective) flow
3.4. EXPERIMENTAL SEQUENCE IN LORELEI

Figure 3.6: Simplified layout of LORELEI test device (a), during the Emptying and Dry phase (b), during the Pre-cooling and Re-flooding phase (c).

and the LHGR is 30 W/cm (the red arrows in the figure 3.6(a) point out the flow direction of the liquid inside the device during this phase). The pressure inside the device is fixed at 70 bar.

Emptying phase During the emptying phase, the device moves away from the core and the LHGR decreases, the water is ejected from the device and helium is injected to take its place. The pressure inside the device decreases to about 3 bar. A small amount of water remains at the bottom of the device in order to provide a saturated steam during the dry phase. At a specific moment, the EH (Electrical Heater) at the bottom of the device is switched on in order to produce some steam for the next phase, see figure 3.6(b).

Dry-phase The dry phase consists, in turn, of two different steps:

Heating phase. The device moves towards the core to heat the fuel sample. During this phase, when the cladding temperature range is 700÷1000 °C, the cladding balloons and bursts. This phase ends when the fuel cladding temperature reaches a temperature around 1200°C.

Plateau phase. In this phase, the maximum fuel cladding temperature is maintained at 1200°C, the equilibrium between the power produced inside the device and the power lost and dissipated by radiation ensure that the temperature of the fuel cladding does not increase.
For high values of temperature, the exothermic oxidation between steam and the zirconium will be studied. The duration of this phase will be set according to the amount of Zirconium oxidized.

**Passive cooling phase.** This phase is a pre-cooling phase where the device moves back up to reduce the nuclear power and to reach defined values of temperature. The fuel will be cooled passively at a rate of -1 to -10 °C/s.

**Reflooding phase.** In this phase the quenching is studied by injecting cold water from the bottom of the device, see figure 3.6(c). The reflooding will be initiated when reaching a pre-defined cladding temperature between 800 and 1200 °C. The internal pressure flask will be designed to resist the pressure peaks associated with this phase.
Chapter 4

Modelling of LORELEI with CATHARE

The modeling by means of CATHARE begins with the geometry description during which are introduced all the constants and chosen the specific modules that best represent each single element of the entire layout. In this phase the User simplifies the layout by finding out which modules are related to the single component, chooses the initial boundary conditions and the appropriate thermal structures. With the introduction of some specific Subroutine, the User may modify the standard calculation or include new physical correlations. An example is the introduction of new materials that may not be present inside the default library or because is necessary to modify some of their physical parameters. For any system that we are interested in studying, there is not a single modeling but the user will provide to give one which appears to be more valid and realistic. Once that the proper modeling has been found, the steady state calculation begins. The real transient part shall be enabled only after a stable steady state is reached.

4.1 Geometry of LORELEI

Figure 4.1 shows a technical drawing of LORELEI. In the table A.1 in a the Appendix A are listed the geometrical values and the materials of all the elements of the device.

4.1.1 Modules utilized for the circuit layout

A schematic layout of the modeling for the LORELEI apparatus is shown in the figure 4.2. The entire layout is composed by two separate circuits: the first circuit consists of the hot and cold channel and the second one of the external cooling channel. The two circuits are coupled
Figure 4.1: LORELEI test device.
Figure 4.2: Modeling of LORELEI test device with GUITHARE graphic interface.
thermally by a heat exchanger. The hydraulic modules and the boundary conditions are listed below:

- 3 VOLUME elements to module the debris catcher (DEB_CAT) and the lower part (VOL-BOT) and the upper part (VOLTOP) of the device. Tables A.2, A.3 and A.4 in the Appendix A summarize the geometrical values for those elements.

- 3 AXIAL elements to model the hot channel (HOT_CH), cold channel (COLD_CH) and the cooling channel (COOL_CH). Tables A.5, A.6 and A.7 in the Appendix A summarize the geometrical values for those elements.

- 4 boundary conditions:
  
  - BC_OUT connected to the volume VOLTOP and BC_INLET connected to the lower volume VOLTOP.
  - BC_COO_O and BC_COO_I are connected to the cooling channel.

The conditions imposed in the boundary conditions BC_OUT and BC_INLET change according to the experimental phase to simulate. The hydraulic conditions imposed to the cooling channel are a liquid mass flux \( Q_{\text{cool}} \) at the BC_COO_I and the external pressure (pool reactor pressure) \( P_{\text{pool}} \) at the BC_COO_O, see figure 4.3. A SINK/SOURCE operator is connected to the volume VOLBOT to extract and to inject a certain amount of water during the dry and quenching phase.

```
BC_COO_I = BCNDIT j_{t, co} DSTREAM ;
MODEL bc_coo_i BC3E TL ( REALLIST 35. 35. )
TG ( REALLIST -1. -1. )
ALFA ( REALLIST 1.D-5 1.D-5 )
X1 ( REALLIST 1.D-5 1.D-5 )
QL ( REALLIST Q_{cool} Q_{cool} )
QG ( REALLIST 1.D-5 1.D-5 )
ABSTIME ( REALLIST 0.0D0 tendf ) ;

BC_COO_O = BCNDIT j_{b, co} USTREAM ;
MODEL bc_coo_o BC4A
P ( REALLIST P_{pool} P_{pool} )
ABSTIME ( REALLIST 0. tendf ) ;
```

Figure 4.3: Boundary conditions imposed to the cooling channel.
4.1.2 Modeling of thermal sources

In the table 4.1 all the thermal structures utilized inside the model are shown.

<table>
<thead>
<tr>
<th>Description</th>
<th>sub module</th>
<th>absolute coordinate</th>
<th>elements associated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel sample</td>
<td>FUEL</td>
<td>0.900-1.500</td>
<td>hot channel</td>
</tr>
<tr>
<td>Gamma heating in the water ($G_{hc}$)</td>
<td>WALL</td>
<td>0.850-1.550</td>
<td>hot channel</td>
</tr>
<tr>
<td>Gamma heating in the water ($G_{cc}$)</td>
<td>WALL</td>
<td>0.850-1.550</td>
<td>cold channel</td>
</tr>
<tr>
<td>Gamma heating in the water ($G_{cool}$)</td>
<td>WALL</td>
<td>0.850-1.550</td>
<td>cooling channel</td>
</tr>
<tr>
<td>FST (bottom part)</td>
<td>EXCHANGER</td>
<td>0.194-0.744</td>
<td>hot channel ↔ cold channel</td>
</tr>
<tr>
<td>FST (middle part)</td>
<td>EXCHANGER</td>
<td>0.744-1.600</td>
<td>hot channel ↔ cold channel</td>
</tr>
<tr>
<td>FST (upper part)</td>
<td>EXCHANGER</td>
<td>1.600-3.400</td>
<td>hot channel ↔ cold channel</td>
</tr>
<tr>
<td>Pressure flask (bottom part)</td>
<td>EXCHANGER</td>
<td>0.194-0.744</td>
<td>cold channel ↔ cooling channel</td>
</tr>
<tr>
<td>Pressure flask (middle part)</td>
<td>EXCHANGER</td>
<td>0.744-1.600</td>
<td>cold channel ↔ cooling channel</td>
</tr>
<tr>
<td>Pressure flask (upper part)</td>
<td>EXCHANGER</td>
<td>1.600-3.400</td>
<td>cold channel ↔ cooling channel</td>
</tr>
<tr>
<td>DD (bottom part)</td>
<td>WALL</td>
<td>0.000-0.744</td>
<td>cooling channel</td>
</tr>
<tr>
<td>DD (middle part)</td>
<td>WALL</td>
<td>0.744-1.600</td>
<td>cooling channel</td>
</tr>
<tr>
<td>DD (upper part)</td>
<td>WALL</td>
<td>1.600-3.400</td>
<td>cooling channel</td>
</tr>
<tr>
<td>Electrical heater</td>
<td>WALL</td>
<td>0.194-0.306</td>
<td>hot channel</td>
</tr>
<tr>
<td>Wall to recover the power $W_1$</td>
<td>WALL</td>
<td>0.000-0.194</td>
<td>cooling channel</td>
</tr>
<tr>
<td>Wall to recover the power $W_2$</td>
<td>WALL</td>
<td>3.276-3.400</td>
<td>cooling channel</td>
</tr>
</tbody>
</table>

Linear Heat Generation Rate (LHGR)

The neutronic calculation was performed by means of the Monte Carlo code TRIPOLI4 V4.9 (Brun et al., 2013) by considering the core in equilibrium with the Xenon and the control rods inserted in a position to achieve the critical reactivity. The Linear Heat Generation Rate (LHGR) [W/cm] is modeled by the following equations

\[
LHGR_{\text{water}} = 593e^{-0.180x_c},
\]

\[
LHGR_{\text{steam}} = 375e^{-0.160x_c}.
\]

They express respectively the value of the LHGR (Linear Heat Generation Rate) produced by the fuel sample as a function of distance from the core $x_c$, when inside the device (hot-cold channels), is present water or steam. The equations 4.1-4.2 are derived from the total neutron flux inside the fuel sample. The nuclear heating inside the structure is calculated from the energy deposited by the neutron and photons inside the material volume. The normalized LHGR axial fuel profile imposed in the fuel rod expressed by the [4.3], was obtained from neutronic calculation by assuming the $x_c=17$ cm (LHGR=25 W/cm), with a 1 mm of hafnium screen, see figure 4.4(a).

\[
LHGR(z) = 3.501 \times 10^{-6}z^4 - 1.402 \times 10^{-5}z^3 - 2.375 \times 10^{-2}z^2 - 5.662 \times 10^{-2}z + 31.33\ [W/cm].
\]
Gamma power sources

The normalized axial profile imposed in the thermal structure takes into account the gamma power along the neutron flux zone and it is fitted with the following symmetric polynomial distribution (Blandin et al., 2013), see figure 4.4-(b).

\[
f_{\gamma}(z) = \begin{cases} 
(1 - 0.2z - 9.7z'^2 - 15.8z'^3 - 7.4z'^4) \\
& \text{for } -0.35 \text{ m} \leq z' \leq 0 \\
(1 + 0.2z' - 9.7z'^2 + 15.8z'^3 - 7.4z'^4) \\
& \text{for } 0 \leq z' \leq 0.35 \text{ m}
\end{cases}
\]

with \( z' = z - 1.2 \). The extension of the NFZ is 70 cm and all the specific powers due to the gamma heating inside the materials and the water are averaged on this length. In the tables 4.2-4.3, are listed the values expressed in \( W/g \) on 10 peripheral sections when inside the device is present water or steam, see figure 4.5. These values were obtained for an uranium enrichment equals to 4.95 %, a fuel burn up of 80 GWd/t for a core power of 100 MW. During the re-irradiation phase, the volumes VOLTOP and VOLBOT lose a certain amount of power by exchanging with the external cooling channel. In CATHARE is not possible to couple thermally a volume element with an axial one, for this reason an alternative solution has been designed to overcome this problem. In particular, two sinks of power (Candle1 and Candle2), see figure 4.2, are connected respectively to the volume VOLTOP and VOLBOT, two internal walls \( W_1 \) and \( W_2 \) are placed on the bottom and on the top part of the cooling channel. During the calculation, the total power lost by the dry side through the walls is extracted from the volumes by means of the sinks of power. The liquid temperatures calculated inside the two volumes are then imposed in all the meshes composed the two walls. A thermal wall EH is placed on the bottom of the hot channel.

![Figure 4.4: Normalized fuel axial profile (a), normalized gamma power profile (b).](image-url)
to produce the power required to produce the steam during the dry phase. Figure 4.6 shows the radial nodalization of the thermal structures corresponding to the cross-section A-A defined in figure 4.2.

Table 4.2: Specific gamma power generated inside the device (water environmental).

<table>
<thead>
<tr>
<th>Angles</th>
<th>108°</th>
<th>144°</th>
<th>180°</th>
<th>216°</th>
<th>252°</th>
<th>288°</th>
<th>324°</th>
<th>0°</th>
<th>36°</th>
<th>72°</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel cladding</td>
<td>2.8</td>
<td>2.6</td>
<td>2.4</td>
<td>2.6</td>
<td>2.8</td>
<td>2.9</td>
<td>3.1</td>
<td>2.9</td>
<td>3.1</td>
<td>2.9</td>
<td>2.8</td>
</tr>
<tr>
<td>Water (hot_ch)</td>
<td>3.8</td>
<td>3.5</td>
<td>3.4</td>
<td>3.2</td>
<td>3.7</td>
<td>4.0</td>
<td>4.1</td>
<td>4.4</td>
<td>4.3</td>
<td>4.1</td>
<td>3.8</td>
</tr>
<tr>
<td>FST</td>
<td>2.8</td>
<td>2.6</td>
<td>2.5</td>
<td>2.6</td>
<td>2.8</td>
<td>3.1</td>
<td>3.3</td>
<td>3.4</td>
<td>3.3</td>
<td>3.0</td>
<td>2.9</td>
</tr>
<tr>
<td>Water (cold_ch)</td>
<td>3.5</td>
<td>3.1</td>
<td>2.9</td>
<td>3.0</td>
<td>3.6</td>
<td>4.3</td>
<td>4.8</td>
<td>5.0</td>
<td>4.9</td>
<td>4.1</td>
<td>3.9</td>
</tr>
<tr>
<td>IPF</td>
<td>2.7</td>
<td>2.3</td>
<td>2.2</td>
<td>2.4</td>
<td>2.8</td>
<td>3.4</td>
<td>3.8</td>
<td>4.0</td>
<td>3.8</td>
<td>3.3</td>
<td>3.1</td>
</tr>
<tr>
<td>Helium gap</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.1</td>
</tr>
<tr>
<td>OPF</td>
<td>2.9</td>
<td>2.3</td>
<td>2.2</td>
<td>2.4</td>
<td>2.9</td>
<td>3.7</td>
<td>4.3</td>
<td>4.5</td>
<td>4.2</td>
<td>3.6</td>
<td>3.3</td>
</tr>
<tr>
<td>Water (cool_ch)</td>
<td>4.0</td>
<td>3.2</td>
<td>3.0</td>
<td>3.1</td>
<td>4.1</td>
<td>5.7</td>
<td>6.8</td>
<td>7.6</td>
<td>6.9</td>
<td>5.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Hafnium (neutron screen)</td>
<td>5.6</td>
<td>4.5</td>
<td>4.2</td>
<td>4.6</td>
<td>5.9</td>
<td>7.7</td>
<td>9.3</td>
<td>9.7</td>
<td>9.1</td>
<td>7.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Device holder</td>
<td>2.4</td>
<td>1.8</td>
<td>1.7</td>
<td>1.9</td>
<td>2.4</td>
<td>3.3</td>
<td>4.2</td>
<td>4.5</td>
<td>4.1</td>
<td>3.2</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Table 4.3: Specific gamma power generated inside the device (steam environmental).

<table>
<thead>
<tr>
<th>Angles</th>
<th>108°</th>
<th>144°</th>
<th>180°</th>
<th>216°</th>
<th>252°</th>
<th>288°</th>
<th>324°</th>
<th>0°</th>
<th>36°</th>
<th>72°</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel cladding</td>
<td>2.5</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
<td>2.4</td>
<td>2.7</td>
<td>2.7</td>
<td>2.8</td>
<td>2.8</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Water (hot_ch)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.0</td>
</tr>
<tr>
<td>FST</td>
<td>2.6</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.6</td>
<td>2.8</td>
<td>3.0</td>
<td>3.0</td>
<td>2.9</td>
<td>2.8</td>
<td>2.7</td>
</tr>
<tr>
<td>Water (cold_ch)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.9</td>
</tr>
<tr>
<td>IPF</td>
<td>2.6</td>
<td>2.4</td>
<td>2.3</td>
<td>2.4</td>
<td>2.7</td>
<td>3.1</td>
<td>3.5</td>
<td>3.6</td>
<td>3.5</td>
<td>3.0</td>
<td>2.9</td>
</tr>
<tr>
<td>Helium gap</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.1</td>
</tr>
<tr>
<td>OPF</td>
<td>2.7</td>
<td>2.4</td>
<td>2.3</td>
<td>2.4</td>
<td>2.8</td>
<td>3.4</td>
<td>4.0</td>
<td>4.2</td>
<td>3.9</td>
<td>3.4</td>
<td>3.2</td>
</tr>
<tr>
<td>Water (cool_ch)</td>
<td>4.4</td>
<td>3.7</td>
<td>3.6</td>
<td>3.8</td>
<td>4.4</td>
<td>5.6</td>
<td>6.8</td>
<td>7.3</td>
<td>6.7</td>
<td>5.4</td>
<td>5.2</td>
</tr>
<tr>
<td>Hafnium (neutron screen)</td>
<td>5.8</td>
<td>4.7</td>
<td>4.5</td>
<td>4.8</td>
<td>5.8</td>
<td>7.3</td>
<td>8.6</td>
<td>9.0</td>
<td>8.4</td>
<td>7.3</td>
<td>6.6</td>
</tr>
<tr>
<td>Device holder</td>
<td>2.3</td>
<td>1.9</td>
<td>1.8</td>
<td>1.9</td>
<td>2.4</td>
<td>3.2</td>
<td>4.0</td>
<td>4.3</td>
<td>3.9</td>
<td>3.1</td>
<td>2.9</td>
</tr>
</tbody>
</table>
Figure 4.5: Partitions of the device.

Figure 4.6: Radial nodalization of the thermal structures.
Chapter 5

Analysis of the Re-irradiation phase

In this Chapter, the thermal-hydraulic study of the Re-irradiation phase is described. At first it has been necessary to evaluate the behavior of the device during the nominal condition, in particular, in this situation, the pressure inside the device is maintained constant and the fuel sample is cooled by a natural circulation loop between the hot and cold channel. In this first stage, an assessment of the evolution of the water temperature along the channels and the thermal structures are performed in accordance with the previous CFD studies as well (Gitelman et al., 2014; Korotkin et al., 2014; Ferry et al., 2014). The second part of this chapter is dedicated to the study of some abnormal conditions which provides to answer to some specific questions such as for example, what are the limits of the termosyphon liquid flow (TLF) or how the fuel cladding temperature changes if the natural circulation loop between the hot and cold channel decreases. For this second part, a more representative set of simulations are described. In some case, some simplify mathematical expressions are formulated to better understand the physic problem.

5.1 Nominal condition

As already described in the Chapter 3, during this phase, the fuel sample is cooled by a convection (thermosyphon) liquid flow generated between the hot and cold channel; the pressure of the system is fixed to 70 bar. The results performed and shown in this Manuscript, refer to conservative value for the LHGR=40 W/cm instead of 30 W/cm. Figure 5.1 shows the values of the temperatures of the water and the thermal structures that comprising the apparatus. Looking at the green curve, from the bottom, one can see that the liquid, inside the hot channel, starts to warm up when enters in the neutron zone reaching 144°C. Then it cools down slightly by
transferring heat to the liquid inside the cold channel. Following the liquid temperature inside the cold channel (orange curve), from the top, the liquid is at first cooled down by the external cooling channel, then in the gamma zone the liquid warms up to 141°C and comes out of the channel at 135°C. Figure 5.2 shows the temperature of the device holder and of the liquid inside the cooling channel. The liquid enters inside the channel at 35 °C (conservative average temperature of the reactor pool) and it exits the device at 38 °C. Figure 5.3 shows the liquid velocity inside the hot, cold, and cooling channel. Analytically, it is possible to estimate the

![Figure 5.1: Map of temperatures, LHGR=40 W/cm.](image1)

![Figure 5.2: Device holder temperature and liquid temperature inside the cooling channel, LHGR=40 W/cm.](image2)

temperature \( T_i(2) \) of the sub-saturated liquid inside the hot channel outgoing from the fuel zone during the Re-irradiation phase. In particular, it is possible to write the following heat balance
Figure 5.3: Liquid velocity inside the hot (a) cold (b) and cooling (c) channel, LHGR=40 W/cm. The gray zone marks the fuel zone.

\[2\pi \int_0^z \left( q_{fuel}'' R_{fuel} + q_{FST}'' R_{FST,i} \right) dz + \int_0^z \gamma_{hc} \rho_l \left( R_{FST,i}^2 - R_{fuel}^2 \right) \pi dz - Q_{lost} = \int_{T_l(1)}^{T_l(2)} \dot{m}_l C_p dT. \]  

(5.1)

In the eq.[5.1] \( T_l(1) \) is the liquid temperature before passing through the fuel zone. \( \gamma_{hc} \) is the specific power [W/kg] released in the water due to the gamma heating, \( \dot{m}_l \) is the liquid mass flow [kg/s] and \( Q_{lost} \) is the power loss to the cold channel. By neglecting the term \( Q_{lost} \), by resolving
the [5.1] is possible to find the value of $T_l(2)$ as

$$T_l(2) = T_l(1) + z \left( \frac{2\pi (q''_{fuel} R_{fuel} + q''_{FST} R_{FST,i})}{\dot{m} C_p l} + \frac{\gamma \rho_l \pi (R_{FST,i}^2 - R_{fuel}^2)}{\dot{m} C_p l} \right). \quad (5.2)$$

Let us consider the case just analyzed with CATHARE with a LHGR=40 W/cm, $q''_{fuel}=1400000$ W/m$^2$, $q''_{FST}=30000$ W/m$^2$, the liquid mass flux $\dot{m}_l=0.12$ kg/s, $D_{fuel}$ and $D_{FST,i}$ respectively 9.5 mm and 25 mm and the $T_l(1)=136^\circ C$. By substituting these values in the [5.2], the value of the liquid temperature outgoing from the fuel zone is given by

$$\frac{(\pi q''_{fuel} D_{fuel} + q''_{FST} D_{FST,i}) z}{\dot{m} C_p l} = \frac{1.7 \times 10^6 (3.14 (0.025^2 - 0.0095^2) \pi)}{4 \times 10 \times 4270} = 0.26^\circ C$$

$$T_l(2) = 136 + 7.65 + 0.26 = 143.91^\circ C.$$

Figure 5.4 presents the water bulk temperature along the thermosyphon loop and the cladding wall temperature for a nominal power of 40 W/cm obtained by a CATHARE and CFD analysis (Gitelman et al., 2014; Korotkin et al., 2014; Ferry et al., 2014) The comparison indicates an acceptable agreement, except for a deviation in the flux zone at the cold channel. In this zone, the main flow direction is downward, where buoyancy forces generated by the gamma power in the structure, generates opposing buoyancy forces. Therefore, the deviation in this zone is expected since the CATHARE software 1D model cannot model the 3D phenomena caused by the opposing buoyancy forces and the 3D power distribution in the system. The 3D model predicts higher water temperatures in flux zone due to the different flow regime.

![Figure 5.4: Liquid temperature along the in-pile device channels loop and cladding temperature, comparison between CATHARE2 and FLUENT 3D models, LHGR=40 W/cm.](image-url)
5.1.1 Pressure drop calculation

The CATHARE code does not take into account the singular concentrated pressure drop, for this reason the user will impose the values in accordance with the kind of singularity. These pressure drops correspond to head losses due to geometric changing and they are always the following form (Lavialle, February, 2006):

\[
\Delta P_{\text{sing}} = \frac{1}{2} k_p \rho v^2.
\]  

(5.3)

In the [5.3], \( k_p \) is the constant pressure drop coefficient given by the user. The user could tune the values of \( k_p \) with the pressure drops calculated by a previous CFD analysis. If one cannot determine experimentally the single value of the \( k_p \) is possible as a first approximation to evaluate these values by consulting a specific manual. For details see (Idelchik and Friend, 1986). Figure 5.5 shows the pressure drops inside the hot channel due to the presence of a sudden expansion or a sudden contractions during the Re-irradiation phase. In particular, by considering the bottom-up liquid flow inside the hot channel, the liquid encounters two sudden contractions and one sudden expansion. The first two pressure drop appear at the beginning of the fuel holder and when the liquid pass through the Linear Variable Differential Transformer (LVDT). The sudden expansion occurs at the end of the LVDT itself. On the other hand, inside the cold channel the top-bottom liquid flow encounters a numerous cross section variation due to some heater connections along the flow separation tube (FST), see figure 4.1. By comparing the sum total of the pressure loses inside the two channels with the total pressure inside the device (70 \( 10^5 \) Pa), those can be neglected without making a significant error.

Figure 5.5: Concentrated pressure drop calculation inside the hot channel.
5.1.2 Convective flow at constant pressure

The objective of these first simulations is to understand the limit condition of the device, in particular to study how the thermosiphon liquid flow (TLF) changes as a function of the linear heat generation rate (LHGR) and check a possible threshold value for the LHGR above which the TLF between the hot and cold channel is negligible. The pressure inside the device is artificially maintained constant at 70 bar for every value of LHGR. In the real conditions, the device is a closed capsule and the pressure increases in accordance with the internal power source. The results of this simulation show that the ONB occurs after the LHGR reaches nearly 100 W/cm, see figure 5.6. The liquid remains sub-saturated up to 220 W/cm and a limit was found for the TLF for LHGR=260 W/cm. In this case, the steam collected on the top of the device prevents the ingress of water from the hot to the cold channel and TLF stops, see the void fraction in figure 5.7. Table 5.1 summarizes some principals thermal-hydraulic parameters and the figure 5.8 shows the values of the thermosyphon liquid flow as a function of the LHGR. To obtain an estimation of the evolution of the fuel temperature in accordance with different levels of power, below is presented a simplified analysis from the Lumped-Method Theory. This last assumption considers that the temperature of the solid is spatially uniform at any instant during the transient process. Mathematically this assumption is expressed as \( Bi << 1 \), where \( Bi \) is the Biot number. This assumption implies that temperature gradients within the solid are negligible. The absence of a temperature gradient implies the existence of infinite thermal conductivity. By considering the fuel sample in LORELEI and its multilayer materials, such condition is clearly impossible, however, this simple model allows us to illustrate the physic problem in general. We consider that the fuel sample inside the LORELEI apparatus is associated to a cylinder with the same geometrical characteristics. Hypothetically, the liquid cools the cylinder remains single phase. It is possible to write the following heat balance equation

\[
\rho V c_p \frac{dT'}{dt} = -hA(T'(t) - T_{\infty}) + \Delta q''''_0 V ,
\]

with \( T'(0) = T_1 \).

(5.4)

\( T_1 \) is the liquid temperature at infinity distance from the cylinder, \( \Delta q''''_0 \) is the difference of the volume power between two values of power. The solution of the [5.4] can be written as

\[
T(t) = \frac{\Delta q''''_0}{hA} \left( 1 - e^{-\lambda t} \right) + T(1).
\]

(5.5)

\( \lambda = \frac{hA}{\rho c_p V} \) is the Characteristic constant of the system. Table 5.2 summarizes some thermal-hydraulic values obtained according to different values of LHGR. \( T' \) is the value of the temperature derived by the [5.5]. The values of \( Re_l \) and the other values are obtained directly from the CATHARE calculation in a mesh point of the hot channel corresponding to the middle of the fuel sample. The value of \( h \) is obtained from the equation 1.24.
5.1.3 Convective flow at constant volume

For the analysis of the abnormal condition, the device is assumed closed and isolated from the cubicle. In this case, particular attention must be focused on the helium blanket on the top
Table 5.1: Summary of the mains thermal-hydraulic parameters.

<table>
<thead>
<tr>
<th>LHGR [W/cm]</th>
<th>max $T_{cl}$ $^\circ$C</th>
<th>max $T_{l,h}$ $^\circ$C</th>
<th>max $T_{l,c}$ $^\circ$C</th>
<th>max $T_{l,coo}$ $^\circ$C</th>
<th>TLF [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>198</td>
<td>143</td>
<td>139</td>
<td>38.1</td>
<td>0.093</td>
</tr>
<tr>
<td>60</td>
<td>238</td>
<td>167</td>
<td>162</td>
<td>38.8</td>
<td>0.105</td>
</tr>
<tr>
<td>80</td>
<td>272</td>
<td>187</td>
<td>181</td>
<td>39.4</td>
<td>0.115</td>
</tr>
<tr>
<td>100</td>
<td>288</td>
<td>205</td>
<td>199</td>
<td>40.5</td>
<td>0.124</td>
</tr>
<tr>
<td>140</td>
<td>292</td>
<td>236</td>
<td>230</td>
<td>41.5</td>
<td>0.140</td>
</tr>
<tr>
<td>180</td>
<td>293</td>
<td>261</td>
<td>255</td>
<td>42.0</td>
<td>0.158</td>
</tr>
<tr>
<td>220</td>
<td>295</td>
<td>289</td>
<td>280</td>
<td>42.8</td>
<td>0.198</td>
</tr>
</tbody>
</table>

Figure 5.8: TLF in function of LHGR, the pressure inside the system is maintained constant at 70 bar.

Table 5.2: Fuel temperature and summary of the mains physic parameters for three different values of LHGR.

<table>
<thead>
<tr>
<th>LHGR [W/cm]</th>
<th>$Re_l$</th>
<th>$\mu_l$ [kg/m s]</th>
<th>$C_p_l$ [J/kg K]</th>
<th>$k_l$ [W/m K]</th>
<th>$Pr_l$</th>
<th>$h$ [W/m$^2$ K]</th>
<th>$T'$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>17700</td>
<td>0.000195</td>
<td>4275</td>
<td>0.693</td>
<td>1.203</td>
<td>1439</td>
<td>144</td>
</tr>
<tr>
<td>60</td>
<td>23500</td>
<td>0.000166</td>
<td>4328</td>
<td>0.686</td>
<td>1.047</td>
<td>1690</td>
<td>180</td>
</tr>
<tr>
<td>80</td>
<td>28850</td>
<td>0.000134</td>
<td>4390</td>
<td>0.676</td>
<td>0.870</td>
<td>1823</td>
<td>200</td>
</tr>
</tbody>
</table>

part of the device that in the CATHARE modeling is placed inside the volume VOLTOP. Let us consider for example an unexpected acceleration of the device towards the core; the power produced inside the device starts to increase and the internal pressure will rise according to the
5.2. STUDY OF SOME ACCIDENTAL CONDITIONS DURING THE RE-IRRADIATION PHASE

Dilatation of the water inside the device. The increase depends on the initial volume of the $He$ blanket. The objective of the study is to determine the consequences on the pressure evolution. Figure 5.9 shows the value of the internal pressure of the device as a function of the LHGR when inside the volume $VOLTOP$ are present $5 \text{ l}$ of helium. It can be seen that the change of internal pressure by varying the LHGR from 40 to 60 $W/cm^2$ is almost 10 $bar$; just before the device pressure has reached a value around 90 $bar$, in accordance with the safety procedures the reactor SCRAM is triggered and for pressure greater than 90 $bar$, two pressure relief valves (PRV) are set to open.

![Graph showing internal pressure of the device in function of LHGR, inside the device are present 5 l of helium.](Image)

Figure 5.9: Internal pressure of the device in function of LHGR, inside the device are present 5 l of helium.

5.2 Study of some accidental conditions during the Re-irradiation phase

5.2.1 Failure of the displacement device

During this accidental scenario, the displacement device (DD) which allows the movement of the apparatus along the reflector, fails and starts to accelerate towards the core. The DD starts to accelerate towards the core in a time of 2 s up to reach its maximum velocity value of 6.5 $mm/s$. When the security system detects an incorrect position of the DD, the classified withdrawal is triggered ($t_1=2 \text{ s}$) and the heating elements are switched off ($t_2=t_1+0.1 \text{ s}$). At $t_3=3 \text{ s}$ the DD decelerates, stops in in 1 s and starts to move backward by reaching the maximal withdrawal velocity of 5.5 $mm/s$ in a time of 2 s. In this section the case during which the classified withdrawal is defective is analyzed. In this situation, the device continues to move towards the core at its maximal speed until is stopped by a mechanical stop block. In this last case, at $t=t_1+5$
s the preventive shut down (PSD) is triggered while the device keeps moving towards the core, see figure 5.10. Figures 5.11(a)-(b) and (c)-(d) show respectively the values of the velocity and the distance covered by the device when the classified withdrawal is triggered and when it is not. During the approach of the DD toward the core, the power generated inside the fuel sample increase up to 2.2 times its initial value according to the [4.1]. The fuel cladding temperature increases about of $30^\circ C$, see figure 5.12(a). The power due the gamma heating increases up to 1.4 its initial value, the temperatures calculated in the FST, inner pressure flask and hafnium neutron screen increases by approximately $\Delta T$ such that $\Delta T < 10^\circ C$, see figures 5.12(b)-(c)-(d).
5.2.2 Failure of the cooling channel

Once the coolant loop pump has failed, the system which provides to secure the device is triggered. Below is listed the chronological sequences before and after the reactor SCRAM triggering.

Before the SCRAM triggering

1) The pump fails, the inertia of the pump assures a small amount of cooled water inside the channel of the reflector.

2) Once the liquid flow inside the circuit has decreased, the pressure inside the cooling circuit increases.

3) The reactor SCRAM is triggered when the suction pressure increases up to exceed the high pressure threshold (nearly 8 s after the failure).

After the SCRAM triggering  If the internal pressure of the cooling loop increases up to a certain limit, some natural convection valves are set to be opened. The new temperature distribution inside the cooling channel shall be such that the liquid inside the cooling channel is reversed In the following sections an analysis of the apparatus after the REP pumps failure, is presented.
Failure of the REP pumps, reactor SCRAM is not triggered

Without more water that circulates with a certain velocity inside the the cooling channel the heat sink strongly decreases, all the power generated inside the hot and cold channel is no more dissipated inside the JHR reactor pool. In the first 200 $s$ from the pumps failure, the thermostyphon liquid flow (TLF) between the hot and the cold channel assures an adequate cooling and maintains the fuel temperature low. After that, the temperatures of the fuel cladding and the internal FST increase. After nearly 100 minutes from the beginning of the accidental scenario, the dry-out condition inside the cooling channel occurs. Figure 5.13 shows the temperature evolution along the fuel cladding, the FST, the inner pressure flask and the hafnium screen. Figure 5.14 shows the behavior of the pressure inside the device.

Failure of the REP pumps, reactor SCRAM is triggered

In this case, after 7 $s$ from the failure of the cooling circuit pumps, the reactor SCRAM is triggered. The initial pressure inside the system is fixed at 65 $bar$ in the first simulation and 75 $bar$ in the second, see figure 5.15. Figure 5.16 shows the evolution of the temperature along the thermal structures. In particular, looking at the figure 5.16(a)-(b) the temperature shows
Failure of the cooling channel

![Graphs showing temperature and pressure over time for different heights](a) (b) (c) (d)

Figure 5.13: Walls temperatures at different heights: fuel cladding (a), inner part of FST (b), inner pressure flask (c), hafnium neutron screen (d).

Figure 5.14: Internal pressure.

A stable behavior due to the thermal inertia of the TLF which, after the first seconds from the accidental scenario, does not decrease sharply. In particular, after 500 s the TLF stabilizes at nearly 0.025 kg/s, see 5.17. Inside the cooling channel Once the pump has failed, the mass flow decreases immediately, the heat transfer coefficient between the water and the outer pressure flask reduces significantly as demonstrated looking at the small temperature spike figure 5.16(c).
and the temperature along the hafnium neutron screen figure5.16(d). The liquid temperature inside the cooling channel does not reach the saturation temperature and no bubbles are formed inside it.

5.3 Conclusion

The results derived from the analysis on the working limits of the TLF (thermosyphon liquid flow) confirms a stable behavior of the device even for high LHGR values. By considering the in-pile pressure inside the device as a constant, fixed at 70 bar, the results show a stable behavior of the TLF even for LHGR of the order of 220 W/cm. If the device is considered as a closed capsule, an important role is played by the cushion of helium on the top part of the device. In this chapter the case when a volume of 5 l of helium is considered. In particular, the results suggest that for this specific amount of gas, between the 40 and 100 W/cm, the internal pressure inside the in-pile device increases almost linearly of order of 0.5 bar for every W/cm of linear power (LHGR) injected inside the fuel sample, see figure 5.9. As a first accidental scenario, the case during which the classified withdrawal is defective, is analyzed. In this condition, as a result of an increasing of the fuel factor of 2.2 times its initial value, the fuel temperature could increases its value of 2.7 °C/s in the first 9 s after the beginning of the transient. The fuel temperature starts to decrease of nearly -2 °C/s after 2 s the triggering of the preventive shut down (PSD), see figure 5.12. The temperature decreasing ratio depends on the thermal structure analyzed and the axial coordinate where the temperature is computed. The second accidental scenario
5.3. CONCLUSION

Figure 5.16: Walls temperatures at different heights: fuel cladding (a), inner part of FST (b), inner pressure flask (c), hafnium neutron screen (d).

Figure 5.17: Liquid mass flow inside the hot and cold channel.

presented in this chapter, shows a more critical case. In this situation, the heat sink produced by the cooling channel ceases (for example, failure of the re-circulating pump) and the preventive shut down (PSD) is not detected. The results derived from this simulation suggest that the time before which the dry-out condition occurs is approximately of 6000 s. The aim of this simulation is to investigate the evolution of the in-pile pressure, for this reason, the opening of the pressure relief valves (PRV) are not covered. In this condition, as the figure 5.14 shows, the internal pressure of the in-pile device reaches the 90 bar in a matter of 500 s. In this case, it is quite interesting to observe the evolution of the temperature of the thermal structures computed along
the fuel, the flow separation tube (FST) and the inner pressure flask (IPF), those do not increase immediately but they remain at the same temperature for nearly 200 s. After this initial time, the increasing of temperature along the fuel cladding and the flow separation tube (FST) varies between $0.075 \div 0.085$ °C/s and nearly 0.1 °C/s for the IPF. The last scenario presented, shows the evolution of the temperature of the thermal structures if the preventive shout down (PSD) is detected. In this condition, the triggering of the PSD prevents the formation of boils inside the cooling channel. Looking at the thermosyphon liquid flow (TLF) between the cold and hot channel, this ensures a big thermal inertia for the fuel cladding and the flow separation tube (FST), which temperature do not increase during the transient. A small increase of temperature in visible along the inner pressure flask. The temperature computed along the hafnium screen increase in the fist 50 s and subsequently remains quite stable.
Chapter 6

Analysis of the Dry and Quenching phase

The aim of this Chapter is to understand the behavior of the device during the Dry phase and to obtain a preliminary assessment of the Quenching phase. The first part of this chapter shows the results obtained by the thermal and mechanical analysis of the dry phase. At the end of the re-irradiation phase, the device empties, only a small amount of water remains at the bottom of the device. In order to produce some steam necessary to perform the dry phase, the EH placed on the bottom of the device is switched on. Once the vapor has been generated, the device (DD) can move toward the core (Heating phase). For this first part a set of simulations are studied in order to understand the best conditions to perform the Dry-phase correctly. For this purpose, different initial conditions with different fuel sample configurations are set to determine the evolution of the system and the fuel sample itself. In the second part of this chapter, a preliminary study of the behavior of the device during the re-flooding phase, is analyzed. In particular the evolution of the internal pressure and the behavior of the cladding temperature are investigated.

6.1 Dry phase

6.1.1 Hypothesis and initial conditions

Radiation model

During the CATHARE calculation of the dry phase, a special subroutine is implemented to the standard input file to take into account the radiative heat transfer between the structures. For each mesh located along the fuel zone, the radiative transfer is activated when the local void fraction calculated in the hot and the cold channel, is greater than a threshold value imposed
Analysis of the Dry and Quenching phase

by the user. To better understand the modus operandi of this subroutine, the figure 6.1 shows a view of the LORELEI apparatus at the height where the fuel sample is located. From the point of view of calculation, once the subroutine has been activated, at every time step, for the \( j \) -th mesh composing the innermost and outermost radial mesh of the thermal structures involved (marked in gray in the figure 6.1), the total powers exchanged by radiation are calculated as follows

\[
P_{r,fuel} = -\sigma_{sb} \sum_j \left[ \frac{(T_{\text{clad}}^4 - T_{\text{FST,}i}^4) S_{\text{clad}|j}}{\epsilon_{\text{ZR}} + (1-\epsilon_{\text{IN}})R_{\text{clad}} R_{\text{FST,}i}} \right],
\]

\[
P_{r,FST} = \sigma_{sb} \sum_j \left[ \frac{(T_{\text{clad}}^4 - T_{\text{FST,}i}^4) S_{\text{FST,}i} - (T_{\text{FST,}e}^4 - T_{\text{IPF,}i}^4) S_{\text{FST,e}|j}}{\epsilon_{\text{IN}} + (1-\epsilon_{\text{SS}})R_{\text{FST,}e}} \right],
\]

\[
P_{r,IPF} = \sigma_{sb} \sum_j \left[ \frac{(T_{\text{FST,}e}^4 - T_{\text{IPF,}i}^4) S_{\text{IPF,}i} - (T_{\text{IPF,}e}^4 - T_{\text{OPF,}i}^4) S_{\text{IPF,e}|j}}{\epsilon_{\text{IN}} + (1-\epsilon_{\text{SS}})R_{\text{IPF,}e}} \right],
\]

\[
P_{r,OPF} = \sigma_{sb} \sum_j \left[ \frac{(T_{\text{IPF,}e}^4 - T_{\text{OPF,}i}^4) S_{\text{OPF,}i}}{\epsilon_{\text{SS}} + (1-\epsilon_{\text{SS}})R_{\text{OPF,}e}} \right],
\]

with

\[
S_{\text{clad}|j} = 2\pi R_{\text{clad}|j} h_j \\
S_{\text{FST,}i|j} = 2\pi R_{\text{FST,}i} h_j \\
S_{\text{FST,e}|j} = 2\pi R_{\text{FST,e}} h_j \\
S_{\text{IPF,}i|j} = 2\pi R_{\text{IPF,}i} h_j \\
S_{\text{IPF,e}|j} = 2\pi R_{\text{IPF,e}} h_j \\
S_{\text{OPF,}i|j} = 2\pi R_{\text{OPF,}i} h_j.
\]

In the [6.2] are expressed the external and internal surfaces \( S \) with the related radius \( R \), see figure 6.1. During the calculation, if the FUEL sub-module is activated, the fuel cladding radius \( R_{\text{clad}|j} \) may changes in accordance with the thermal expansion ([1.50]). The values of \( \alpha_{hc}|j \) and \( \alpha_{cc}|j \) are stabilized by the user, in general the choice of those values is done in accordance with the physic of the problem.

**Fuel sample configuration and control of the displacement device**

For this phase some simulations have been performed. Table 6.1 divides the simulations in accordance with the initial conditions of the fuel utilized. At the beginning, a new fuel sample with a low initial pressure gap and a minimum value of the cladding oxide, is used. For a second type of simulation, a fuel with a thicker external oxidation and higher internal gap pressure is utilized. At first, the case during which the displacement device (DD) remains at fixed position
Hypothesis and initial conditions

once the cladding temperature has reached a target value, is analyzed. Other simulations analyze the behavior of the DD when this can move in accordance with the target value of the fuel cladding temperature. For this last case, an ON/OFF type-regulator was implemented to maintain the middle of the fuel cladding at 1200 °C (set point value) with a maximum permissible error of ±50 °C. Some specific velocities of the displacement device \( u_{DD} \) are chosen in order to verify the maximum fuel heat-up rate. For all the simulation analyzed, the power generated inside the electrical heater \( P_{EH} \) can vary between three different values 1-1.5-2 kW. In particular, by setting \( P_{EH} < 0.8 kW \), the calculations suggest that the steam does not penetrate inside the hot channel and the dry phase cannot be studied. In a benchmark simulation, in order to evaluate the impact of power produced by the cladding oxidation, the activation of the electrical heater placed at the bottom of the device is activated after the approach of the device toward the core.

Table 6.1: Initial condition of the fuel sample.

<table>
<thead>
<tr>
<th>Fuel sample configuration</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{fuel} ) [mm]</td>
<td>4.15</td>
<td>4.15</td>
</tr>
<tr>
<td>( \zeta_{gap} ) [(\mu m)]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( R_{clad,e} ) [mm]</td>
<td>4.75</td>
<td>4.75</td>
</tr>
<tr>
<td>( \zeta_{oxy,e} ) [(\mu m)]</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>( \zeta_{oxy,i} ) [(\mu m)]</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>( P_{gap} ) [bar]</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Fuel sample type</td>
<td>ZRCEA</td>
<td>ZRCEA</td>
</tr>
</tbody>
</table>
(heating phase). In the simulations performed, the dry phase lasts nearly 25 minutes. Actually, when the device becomes operational, the whole dry phase lasts in accordance with the level of the clad oxidized reached.

Limit of the heat-up of the fuel cladding

During the approach of the device toward the core, in order to minimize the non-homogeneous peripheral temperature distribution around the fuel sample, an electrical heater is placed on the flow separation tube (FST) along the total height of the fuel sample. The use of this electrical heater is required to take into account the heating effect of the nearby fuels which surrounded the rod in a real fuel bundle. However, the change of power over the time of this electrical heater, has a technological limit above which it cannot go. The IAEC (Israel Atomic Energy Commission), which is in charge of the design the apparatus, has planned to install an electrical heater which temperature heat-up rate shall not exceed the 20 °C/s (before the clad burst). For this reason the fuel sample heat-up rate, shall not exceed this threshold limit as well. The heat-up rate \( \Lambda \) may be expressed as the derivative of the fuel cladding temperature over the time.

6.1.2 Simulations

Introduction

Table 6.2 summarized the characteristics of the four simulations which has been performed for the dry phase. In particular each simulation differs from the other by the fuel sample configuration, if the ON/OFF fuel temperature regulator is activated, at what time and at how much power is injected inside the electrical heater (EH) to produce the steam required. For all the simulations performed, the threshold value imposed for the void fraction inside the hot and cold channel, is such that \( \alpha_{hc|j} = \alpha_{cc|j} = 0.98 \). The choice of this value is done according to the physic of the problem. In this case, as it will be discussed afterwards, some steam tends to condense not only in the coldest zone inside the device but also inside the channel in zone 2, see figure 6.2. In particular, the zone 2 could include the top part of the fuel zone and some liquid could cool a part of the fuel sample. The constant values of the emissivity coefficient for the materials are listed in the table 6.3.

Simulation 1

Within 20 minutes from the beginning of the transient and the activation of the electrical heater (EH), all the steam produced in the hot channel has pushed the helium above the fuel zone. After that, the nodes which comprise the fuel cladding reach the saturation temperature and the system pressure stabilizes. At this point the device moves towards the core \( (t=1000 \text{ s}) \). In the first calculation performed, once the DD has reached the position corresponding to the
Table 6.2: Characteristics of the simulations for the Dry phase.

<table>
<thead>
<tr>
<th>Simulation no</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel sample configuration</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Temperature Regulator</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Steam production(^a)</td>
<td>Before</td>
<td>Before</td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>(P_{EH} [kW])</td>
<td>1-1.5</td>
<td>1-1.5-2</td>
<td>1-1.5-2</td>
<td>1</td>
</tr>
</tbody>
</table>

\(^a\)The steam production necessary for the dry phase can occur before or after the approach of the displacement device (DD) towards the reactor core.

Figure 6.2: Zone 2 along the hot channel.

<table>
<thead>
<tr>
<th>Zircaloy</th>
<th>Inconel</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\epsilon_{ZR})</td>
<td>(\epsilon_{IN})</td>
<td>(\epsilon_{SS})</td>
</tr>
<tr>
<td>0.8</td>
<td>0.7</td>
<td>0.5</td>
</tr>
</tbody>
</table>

target value of temperature, it remains there for all the duration of the plateau phase. For this specific calculation, the initial pressure inside the system is fixed to 3 bar and some water \((1.2 l)\) remains at the bottom of the device to produce the required steam. For this simulation we set the LHGR=25 \(W/cm\) and \(P_{EH}=1 kW\). The results obtained from this calculation reveal two phenomena which might modify the cladding temperature profile during the dry phase.

1. The first phenomenon occurs at the beginning of the dry phase. When the device starts to
move towards the core, the cladding surface on the top of the fuel sample remains too wet and its temperature equals the saturation temperature of the system. The code suggests that the temperature in the two last nodes is computed by nucleated boiling mechanism. Figure 6.3 shows the behavior of the fuel cladding temperatures in some points along the fuel sample. In particular the cladding temperature computed between the points 1-22 (0-55 cm) increases according to $x_c$ (12 °C/s) while the temperature calculated in the last 5 cm remains low.

2. The second phenomenon occurs during the plateau phase, when the zone 2 includes all or a part of the fuel zone and some liquid cools the cladding surface. In figure 6.4 the gray bands mark the zone 2 where the gas and the liquid mass flow determine the cycles of vaporization and condensation along the hot channel; the negative values of the liquid mass flow indicates the liquid direction which goes from the top towards the bottom of the hot channel. Between the water level and the zone 2 a stagnant zone is formed where only the gas phase is present. In the first 300 s the liquid flow remains at the top part of the fuel sample, see figure 6.4(a), after nearly 450 s the liquid front covers and cools all the fuel sample. For the remaining time of the dry phase, the liquid remains along all the fuel length, as shown in figure 6.4(b)-(c)-(d) and the cooling effects do not decrease.

When the $P_{EH}$ is changed from 1 to 1.5 kW, the effects of the condensation increase, see figure 6.5. The results have shown that, when the DD remains at fixed position for all the duration of the dry phase, for any $P_{EH}$ chosen, these cooling effects make the cladding temperature profile very sensible to these phenomena. It should be noted that if the activation of the EH is delayed with respect to the approach of the device towards the core, the steam could start to cover the fuel cladding when this is already hot (above 1000 °C) by producing a peak in power due to steam-zicalloy reaction which could lead to a temperature disturbances on the fuel cladding.

**Simulation 2**

A second way of functioning for the DD corresponds to a movement in accordance with the target value of the fuel cladding temperature. The ON/OFF controller measures the error between the set point and the temperature in the middle of the fuel cladding. The regulation should be done by changing the distance of the DD and consequently by varying the LGHR in agreement with [4.1]. The velocity of the DD is set to 6 mm/s. Figure 6.6 and figure 6.7 show respectively the distance of the device from the core and the corresponding value of the LHRG during all the dry phase for $P_{EH}=1-1.5-2$ kW. In this case the minimum value allowable for $x_c$ is 10 cm. The figures 6.8(a)-(b)-(c) show the fuel cladding profile for three different values of $P_{EH}=1-1.5-2$ kW after 500-1000-1500 s from the approach of the device towards the core. The best condition is found for $P_{EH}=1$ kW where the cladding temperature profile is uniform along all the fuel length. The general cooling at the beginning of the dry phase becomes evident for $P_{EH} \approx 1.5$ kW. The
temperature calculated on the top of the fuel sample, for $P_{EH}=2 \text{ kW}$, shows that the extension of the cladding surface that remains wet, involves nearly the last 7 cm of fuel length. The second problem related to the cooling effects during the dry phase appears for the $P_{EH}=1.5 \text{ kW}$ when the liquid tends to cool down the last nodes. By increasing the $P_{EH}$ up to 2 kW the last 20 cm of the fuel sample are cooled. Despite some condensation phenomena for $1.5 \text{ kW} \leq P_{EH} \leq 2 \text{ kW}$, the cladding temperature profile meets the necessary requirements. For the entire dry phase, the cladding temperature remains quite uniform over 40 cm, i.e. from 1 to 1.4 m where the fuel ballooning is expected.

**Gas distribution inside the device** The figures 6.9-6.10-6.11 show the evolution of the steam and the non-condensible gases mass inside the hot channel (HOT\_CH), the upper volume (VOLTOP) and the cold channel (COLD\_CH).

*Hot channel.* Once the Dry phase has begun, the steam produced inside the hot channel increases in accordance with the value of $P_{EH}$. For $P_{EH}=1-1.5 \text{ kW}$, all the helium introduced inside the channel during the emptying phase, is pushed upward from the steam flow (for $P_{EH}=2 \text{ kW}$ all the helium is ejected from the hot channel before the dry phase has started). When the fuel cladding temperature has reached a temperature around 1000 °C, the zirconium in the fuel alloy reacts with the steam as demonstrated looking at the hydrogen mass produced. For $P_{EH}=2 \text{ kW}$, the continuous phenomena of condensation-vaporization are visible looking at the the steam fluctuation which occurs with a constant frequency after 600 s from the beginning of the transient. The same steam decreasing before nearly 600 s is always produced as a result of the condensation. The magnitude and the frequency of the spikes in $m_{H_2}$ in the first 200 s are
Figure 6.4: Gas and liquid mass flow inside the hot channel after 300 s (a), 600 s (b), 1200 s (c) and 1800 s after the approach of the device towards the core.
Figure 6.5: Cladding temperature profile after 1500 s from the approach of the device towards the core.

Figure 6.6: $x_c$ during the dry phase.

Figure 6.7: LHGR during the dry phase.

mainly due to two phenomena:

- The oscillation of the cladding temperature during its regulation (see the fuel temperature in the middle of the fuel sample in the following of this thesis).
Figure 6.8: Cladding temperature profile after 500 (a), 1000 (b), 1500 (c) s from the approach of the device towards the core.
• The different gas stratification at the beginning of the dry phase. In particular, for $P_{EH}=1$ kW the greater concentration of helium in the top of part of the device, coupled with a less steam production, shall be such that the hydrogen produced remains longer inside the hot channel, by increasing its mass concentration (first peak at nearly 75 s after the beginning of the Dry-phase). This phenomena does not appear for $P_{EH}=1.5-2$ kW where the hydrogen produced is immediately ejected from the hot channel.

**Upper volume (gas blanket).** In this volume, the steam produced inside the hot channel tends to accumulate. For $P_{EH}=1-1.5$ kW, the helium present at the beginning of the dry phase, increases its concentration because receives other gas dragged by the steam produced in the hot channel. When the steam increases, the helium is dragged in the upper part of the cold channel. The hydrogen in this upper volume tends to be accumulated.

**Cold channel.** Figure 6.12 shows the gas fraction distribution inside the cold channel at the end of the dry-phase for $P_{EH}=1$ kW, a similar gas distribution is observed for $P_{EH}=1.5-2$ kW. As
it can be seen, the steam covers all the neutron flux zone (NFZ) up to reach a height of nearly 1.8 m. Between 1.8 m and 2.5 m a mix of steam and helium fills the channel. Starting from 2.5 m up to the end of the channel, the hydrogen produced increases its concentration. The largest percentage of helium is accumulated in this channel (83% of the total $m_{He}$ for $P_{EH}=2 \text{ kW}$). The mass of hydrogen increases up to the end of the transient ($m_{H_2}$ is more the 200 mg for $P_{EH}=2 \text{ kW}$).

![Figure 6.12: Gas fraction inside the cold channel at end of the dry phase $t=1500 \text{ s}$, $P_{EH}=1 \text{ kW}$. The gray zone marks the neutron flux zone (NFZ).](image)

**Oxidation process** When the cladding temperature has reached a temperature of order of $\approx 1000^\circ C$, the exothermic reaction between the steam and the zirconium in the fuel cladding can be studied. In this thesis, the Cathcart-Pawel law (Cathcart et al., 1977) has been utilized for the calculation of the oxidation process. Figure 6.13 correlates the power released by the cladding oxidation with the cladding temperature calculated in the middle of the fuel sample, for $P_{EH}=1-1.5-2 \text{ kW}$. For all the three cases analyzed, the peak of power varies between 220 and 250 W. Figure 6.14(a)-(b)-(c) shows the thickness of the external cladding oxidized. As mentioned before, the low levels of the thickness in the top of the fuel sample for $P_{EH}=1.5-2 \text{ kW}$ are due to low value of temperature in the upper part of the fuel alloy. For $P_{EH}=1.5 \text{ kW}$, at the end of the dry phase, the maximum thickness of fuel cladding oxidize is reached at the height of nearly 15 cm of the fuel alloy. In this last case, a thickness of 140$\mu m$ i.e. 23% of the initial cladding thickness, is reached.

**Thermal-mechanical behavior of the fuel cladding** Figure 6.15 shows the pressure inside the fuel gap $P_{gap}$, the times $t_1 < t_2 < t_3$ are the instants when the fuel cladding bursts. For $P_{EH}=1.5-2 \text{ kW}$, the lower value of the pressure in the fuel cladding gap is due to the low level of temperature reached in the top of the fuel sample in accordance with the [1.57]. For $P_{EH}=1 \text{ kW}$ the rupture of the fuel alloy occurs faster and the condition [1.58] is reached quickly. Figure 6.16 shows the average value of the cladding temperature weighed over all the radial points.
Figure 6.13: Power due to the cladding oxidation for $P_{EH}=1-1.5-2$ kW (top), fuel cladding temperature computed in the middle of the fuel sample (bottom).

Table 6.4: Results obtained by considering a velocity of the displacement device of 6 cm/s.

<table>
<thead>
<tr>
<th>$P_{EH}$ [kW]</th>
<th>$t_b$ [s]</th>
<th>$T_{clad,b}$ [°C/s]</th>
<th>$\Lambda$ [°C/s]</th>
<th>$\omega^a$ [%]</th>
<th>$\zeta_{oxy,m}^a$ [µm]</th>
<th>$m_{H_2,tot}^a$ [g]</th>
<th>max $P_{oxy}$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27.5</td>
<td>964</td>
<td>30</td>
<td>23.6</td>
<td>86.6</td>
<td>0.31</td>
<td>250</td>
</tr>
<tr>
<td>1.5</td>
<td>37.2</td>
<td>1045</td>
<td>24</td>
<td>34.8</td>
<td>91.6</td>
<td>0.35</td>
<td>241</td>
</tr>
<tr>
<td>2</td>
<td>39.4</td>
<td>1075</td>
<td>23</td>
<td>25.8</td>
<td>70.8</td>
<td>0.26</td>
<td>220</td>
</tr>
</tbody>
</table>

* Values referred at the end of the transient.

for a given height of the fuel, and the cladding radius in the first instants of time after the beginning of the dry phase. Always looking at the figure 6.16, the red vertical line marks the axial coordinate where the cladding rupture occurs. The figures 6.17-6.18, show the values of the cladding temperature at the same time steps. For $P_{EH}=1.5-2$ kW the zone of fuel ballooning zone involves nearly 40 cm i.e. from 1 to 1.4 m, for $P_{EH}=1$ kW the area affected is reduced at 30 cm, i.e. from 1.05 to 1.35 m. The maximum cladding elongation of nearly 34.8 % the initial radius, occurs for $P_{EH}=1.5$ kW. In all the three simulations performed, the rupture of the cladding occurs in the middle of the fuel sample. Table 6.4 summarizes some result obtained with this second simulation. As written before, for a conservative calculation, the velocity of the displacement device (DD) is those maximum of 6 cm/s. As it can be seen, by looking at
Figure 6.14: External thickness of cladding oxide after 500 (a), 1000 (b), 1500 (c) s from the approach of the device towards the core.
Simulations

Figure 6.15: Pressure inside the fuel gap in the first 50 s from the beginning of the dry phase.

Figure 6.16: Average fuel cladding radius (a) and corresponding fuel cladding temperature (b), $P_{EH}=1\ kW$.

The fourth column of the table 6.4, by considering this displacement device velocity, $\Lambda$ is always greater than the limit required ($23^\circ\ C/s<\Lambda<30^\circ\ C/s$), for all the three cases analyzed. In the table 6.5 are listed the values of $\Lambda$ for different lower values for the DD velocity, the numbers marked in bold are the values acceptable. The results show that $\Lambda$ depends not only on the DD velocity but also on the $P_{EH}$, in fact for the same DD velocity, the heat-up rate decreases in accordance with the increase of $P_{EH}$. Indeed, greater is the $P_{EH}$ and hence the steam production, faster is the time required for the steam to drag the mass of gases along the fuel sample. This phenomenon increases the average gas velocity along the fuel sample $\bar{v}_{gas}$, and hence the heat transfer coefficient. This phenomenon is more evident switching the $P_{EH}$ from 1 kW to 1.5 kW.
4.4

4.6

4.8

5

5.2

5.4

5.6

5.8

6

0.9  1  1.1  1.2  1.3  1.4  1.5

rm [mm]

z[m]

25 s

30 s

40 s

45 s

rupture

Figure 6.17: Average fuel cladding radius (a) and corresponding fuel cladding temperature (b), $P_{EH}=1.5kW$.

(a)

(b)

200

400

600

800

1000

1200

1400

0.9  1  1.1  1.2  1.3  1.4  1.5

T [°C]

z [m]

25 s

30 s

40 s

45 s

(b)

Figure 6.18: Average fuel cladding radius (a) and corresponding fuel cladding temperature (b), $P_{EH}=2kW$.

Simulation 3

For this simulation a fuel with the second type of configuration has been utilized (see table 6.2). The thermal-hydraulic behavior of the device is quite similar to the Simulation 2. Figure 6.19 shows the temperature along the fuel sample. As happened in the Simulation 2, for a $P_{EH}=2 kW$, the temperature calculated in the last nodes remain low, as well as the thickness of the external oxidation, see figure 6.20. The mechanical ballooning of the fuel sample remains asymmetric respect to the mid point of the fuel sample as demonstrated looking at the cladding radius and the respectively cladding temperatures, see figures 6.21,6.22 and 6.23. The average value of the cladding temperature is certainly lower respect to the Simulation 2 due to the lowest power generated by the cladding oxidation. As the simulation 2, the rupture of the fuel cladding occurs always in the middle of the fuel sample. Figure 6.24 shows the evolution of the pressure inside the fuel gap.
Table 6.5: Results obtained by considering a velocity of the displacement device which varies between 0.5 and 1.5 cm/s.

<table>
<thead>
<tr>
<th>$P_{EH}$</th>
<th>$u_{DD}$ [cm/s]</th>
<th>$t_b$ [s]</th>
<th>$T_{clad,b}$</th>
<th>$\Lambda$ [$°C/s$]</th>
<th>$\dot{u}_g$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>58</td>
<td>1030</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 kW</td>
<td>1.0</td>
<td>43</td>
<td>1006</td>
<td>20.1</td>
<td>0.175</td>
</tr>
<tr>
<td>1.5</td>
<td>37</td>
<td>980</td>
<td>22.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>62</td>
<td>1055</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5 kW</td>
<td>1.0</td>
<td>48</td>
<td>1050</td>
<td>18.7</td>
<td>0.350</td>
</tr>
<tr>
<td>1.5</td>
<td>44</td>
<td>1050</td>
<td>20.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>69</td>
<td>1075</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>1.0</td>
<td>52</td>
<td>1077</td>
<td>18.0</td>
<td>0.375</td>
</tr>
<tr>
<td>1.5</td>
<td>46</td>
<td>1070</td>
<td>20.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\* $\dot{u}_g$ is the gas velocity inside the hot channel calculated at the height of the middle of the fuel sample, averaged over the first 40 s.

Figure 6.19: Wall temperature along the fuel cladding after 1500 s from the approach of the device towards the core.

Simulation 4

Figure 6.25 shows the cladding temperature in the middle of the fuel cladding when the steam produced by the EH is produced after that the fuel cladding temperature has reached a value of 1200 °C. At time $t=700$ s, the steam generated reaches the fuel sample and the oxidation starts. The power generated by the oxidation increases the cladding temperature and the temperature regulator system moves the device back at nearly $x_c=22$ cm from the core, see figure 6.26.
Figure 6.20: External thickness of cladding oxide after 1500 s from the approach of the device towards the core.

Figure 6.21: Average fuel cladding radius (a) and corresponding fuel cladding temperature (b), $P_{EH}=1kW$.

Figure 6.22: Average fuel cladding radius (a) and corresponding fuel cladding temperature (b), $P_{EH}=1.5kW$. 
6.1.3 Proposed improvements

When the device will be in operation, some differences between the calculations and the experimental measurements can be expected. In particular some phenomena of condensation, which
Figure 6.26: $x_c$ during the dry phase.

might occur on the top of the fuel sample, should be taken into account. For this reason it is important to devise some technical solutions which can increase the range of operation of the dry phase. A solution that could prevent the phenomena related to the cladding surface too wet at the beginning of the dry phase, could be to divide this phase in two parts, see figure 6.27. In the first part the device moves towards the core to reach an appropriate cladding temperature $T'$ such that the mechanical properties of the entire fuel sample are maintained unaltered, at this point the electrical heater (EH) can be activated. This procedure could maintain the surface of the cladding hot enough to reduce the condensation. This specific transient is still under investigation, in particular the results concerning the fuel ballooning need to be investigated.

A technical solution that could increase the operating range of the $P_{EH}$ by ensuring a suitable cladding temperature profile, is the introduction of a new electrical heater (EH1) on the FST above the NFZ, as shown in figure 6.28. This EH1 will maintain dry the top part of the fuel at the beginning of the dry phase and, according to its length, it will increase the stagnant zone along the fuel zone by reducing the liquid cooling during the plateau phase, see figure 6.29. The EH1 should be activated at the beginning of the dry phase; for $P_{EH}=2$ kW, the minimal length found for the EH1 to reach an acceptable value of cladding temperature profile was found for nearly 20 cm, see figure 6.30 while to exclude completely the zone 2 along the fuel zone is necessary a EH1 nearly 60 cm length. In the CATHARE calculation, the regulation of the EH1 can be done by a ON/OFF-type regulator, in particular the variable controlled is the temperature of the EH1 which is maintained at 50 °C above $T_{sat}(P)$. The regulator should be activated by injecting 2 kW of power every time the temperature condition is not satisfied.
Proposed improvements

Figure 6.27: Beginning of the dry phase in the new configuration.

Figure 6.28: Position of the EH1 around the FST.

Figure 6.29: Liquid flow inside the hot channel for $P_{EH}=2\ kW$. 
6.2 Quenching phase

6.2.1 Re-flooding phase

In this last experimental phase, the water is injected from the bottom part of the device, the experimental device remains closed for all the duration of this phase and no water is discharged out of the cubicle. The case studied in this paper analyses the case during which the liquid mass flow injected inside the device is 0.45 \text{kg/s} and its inlet temperature is 35 °C. The water injection shall be carried out by a SOURCE operator placed in the bottom of the device, see figure 4.2. The end of the re-flooding phase occurs when the liquid front has covered the upper opening and the thermosyphon flow (convective) between the two channels is formed. The first calculation analyzes the case when the Re-flooding phase is preceded by a Pre-cooling phase and the displacement device (DD) moves away from the reactor before the water injection occurs. The second case studied, investigates the injecting of the cold water inside the device immediately after the dry phase. Both the analysis performed consider the fuel axial temperature profile obtained at the end of the dry phase by considering a $P_{EH}=1$ kW.

6.2.2 Re-flooding preceded by the Pre-cooling phase

In this case, at the end of the dry phase, the DD moves away from the reactor core to reduce the LHGR and hence to decrease the fuel cladding temperature. The duration of the pre-cooling is set in accordance to the regulation of the fuel cladding temperature which is maintained in the middle point at 800 °C (±50 °C). Figure 6.31 shows the evolution of the cladding temperature (middle height of fuel sample) and the internal pressure of the system during the entirely duration of the dry, pre-cooling and re-flooding phase. The internal pressure varies from 3.5 bar (initial pressure once the steam has produced by the EH) to nearly 9 bar at the end of the dry phase. During the pre-cooling phase, the DD moves away from the core and the temperature computed in the middle of the fuel cladding varies in the order of 4 °C/s. The internal pressure reaches
Re-flooding phase without the Pre-cooling phase

a plateau around 7 bar in around 200s. The immediate vaporization of the water that covers the hot walls in the NFZ, produces a peak of pressure of approximately 25 bar in around 227 s before stabilizing at 16 bar in 13 minutes. At 1300 s from the beginning of the pre-cooling phase, the fuel sample is cooled by a thermosyphon liquid flow (TLF) formed between the hot and cold channel. The liquid mass flow between the hot and the cold channel stabilizes at 0.5 kg/s after nearly 800 s, see figure 6.32.

![Figure 6.31](image)

Figure 6.31: Evolution of the cladding temperature and the internal pressure of the system during the dry, pre-cooling and re-flooding phase.

![Figure 6.32](image)

Figure 6.32: Mass liquid flow in the hot and cold channel during the re-flooding phase, the negative sign means the opposite flow direction.

6.2.3 Re-flooding phase without the Pre-cooling phase

In this case the water injection occurs immediately after the dry phase, when the maximum fuel cladding temperature reaches approximately 1200 °C. In this situation, the peak of pressure
Analysis of the Dry and Quenching phase

Figure 6.33: Evolution of the cladding temperature and the internal pressure of the system during the dry and re-flooding phase.

Figure 6.34: Fuel temperature during the re-flooding phase.

generated by the steam production, reaches approximately 38 bar in 27 s before stabilizing in 200 s, see figure 6.33. The variation of the cladding temperature computed in the middle of the fuel sample, following the beginning of the water injection, is nearly 77 °C/s. Figure 6.34 shows the profile of the fuel temperature for several instants of time. It can be seen that the clad starts to quench after 4 s and it is completely quenched after 18 s. Figure 6.35 shows the values of the void fraction computed inside the hot channel during the first seconds after the re-flooding.
Figure 6.35: Void fraction inside the hot channel after 3 s (a), 6 s (b), 9 s (c), 12 s (d), 15 s (e), 18 s (f).
In particular, after 3 s the water level arrives up to the bottom of the fuel sample. Once the cold water has touched the hot fuel cladding temperature ($T_{\text{clad}} \approx 1000^\circ C$ on the bottom part of the fuel sample) a mix of steam and water cools down the bottom part of the fuel sample. When the liquid front covers all the length of the fuel sample, the mechanism of heat exchange between the fuel sample and the external environmental passes from the natural convection in gas to sub-cooled film boiling. In this last condition, some vapor patch can be formed on the hot surface of the cladding by preventing the quenching, see the temperature profile after 16 s from the beginning of transient. The liquid mass flow between the hot and the cold channel stabilizes at 0.9 kg/s after nearly 450 s, see figure 6.36 for details.

### 6.3 Conclusion

In this chapter a set of simulations are investigated to conduct the dry phase as well possible. The first simulation proposed, analyzes the behavior of the displacement device during which, any sort of temperature regulation is set up. The importance of this first benchmark simulation is to analyze the general behavior of the device, in particular the physic condition inside the hot channel and cold channel. The results have showed that, if the displacement device remains at a predefined distance from the core, then some thermal-hydraulic conditions make the device sensitive to the phenomena of condensation which make difficult the achievement of an uniform fuel cladding profile. By considering other different type of configurations for the fuel sample, we have imposed other working conditions on the device. In this case, we have assume that the displacement device can move according to the cladding temperature target. In this case the cooling effects due to the presence of liquid inside the hot channel, are obstructed by the LHGR which changes according to the position of the displacement device. At the beginning, for a conservative analysis, the maximum velocity of the displacement device (6 mm/s) has been considered. For both these two types of fuel utilized, the results have suggested that, for $P_{EH} = 1kW$ the cladding temperature profile is uniform along all the fuel length. For
$P_{EH} \geq 1.5\text{kW}$, the top of fuel remains wet and the cladding temperature low. For $P_{EH} = 1\text{kW}$, the homogeneous cladding temperature distribution ensures a greater pressure inside the fuel gap and the fuel burst takes place prematurely. An important result, shown for all the cases analyzed, is that the clad ballooning and cladding rupture are not perturbed by these possible condensation phenomena. The total amount of hydrogen produced, which varies between from $0.25 \div 0.35\text{g}$ and $0.20 \div 0.26\text{g}$ in accordance with the fuel, is accumulated mainly in the top of the cold channel and in the upper volume. The total power produced by the cladding oxidation is nearly $4\text{W/cm}$. For the both of type of fuel sample analyzed, the maximum thickness of oxide is reached for $P_{EH}=1.5\text{kW}$. A benchmark calculation has been analyzed to evaluate the consequences of the steam production once the cladding temperature have reached the target value of $1200 \degree \text{C}$. The results have showed that, as a consequence of the exothermic reaction steam-zirconium, the increase of the fuel temperature is offset by the temperature regulator which moves the device away from the core by perturbing the fuel cladding temperature. In the real condition the velocity of the displacement device is related to the maximum heat-up rate of the electrical heater surrounded the fuel sample on the FST ($\Delta<20 \degree \text{C/s}$). By considering three different values of DD velocities and a new fuel, the results have shown that for a $P_{EH} = 1\text{kW}$, the velocity of the DD should not be greater than $0.5\text{cm/s}$ and less than $1.0\text{cm/s}$ for $P_{EH} =1.5-2\text{kW}$.

The last part of this final chapter, has been devoted to investigated the behavior of the fuel cladding temperature and the evolution of the internal pressure of the system following the reflooding phase. In this analysis two cases has been considered. In the first one, the DD moves away from the core to reach a intermediate value around $800 \degree \text{C}$ before the water injection occurs. This case considers that the liquid mass flow injected inside the device is $0.45\text{ kg/s}$ and its inlet temperature nearly $35 \degree \text{C}$ ($11.7 \text{ l}$ of the total amount of water injected). The results have been showed that the water starts to cover the bottom part of the fuel sample after nearly 3$s$. In the second case we have that the peak of pressure due to the liquid vaporization reaches approximately $25 \text{ bar}$ in around $227\text{ s}$ and $35 \text{ bar}$. After $24\text{ s}$ the water level reaches the upper holes and the convective (thermosyphon) flow between the hot and cold channel is formed again.
Analysis of the Dry and Quenching phase
Conclusions

In this thesis we have developed a detailed analysis of the LORELEI apparatus by using computational tools. We have first introduced the characteristics of the code CATHARE and the mathematical equations implemented in the code with regard to the main closure laws for a single and a double phases system flow. An analysis of the equations implemented for the sub-module FUEL, have been written in order to clarify the sensitive parameters which are interest for us to analysis the dry phase. A short chapter has been devoted to describe the facility and a typical LOCA scenario by emphasizing the structure of an Emergency Core Cooling System. The layout analysis has revealed that LORELEI presents some similarities with the the IFA-650X apparatus. For example one can find the electrical heater placed around the fuel sample which is necessary to recreate the adiabatic condition during the heating phase. As it has happened in the IFA-650X, a preliminary experimental phase is needed to be performed in order to create a fission product inventory. After an accurate description of the geometry of the in-pile device, we have described all the possible experimental phases.

The first research objective of this Ph.D Thesis is the implementation and the simulation of the CATHARE model for LORELEI. All the geometrical values of any elements of the apparatus, have been obtained from the Israel Atomic Energy Commission (IAEC). The IAEC also performed a preliminary CFD analysis of the re-irradiation and the dry phase in accordance with some specific initial conditions. This has allowed us, without experimental data available, to match the results with those obtained with CATHARE. The results derived from the analysis on the working limits of the thermosyphon liquid flow have confirmed a stable behavior of the device even for high LHGR values. Furthermore, another analysis of the evolution of the pressure of the system has been performed in order to evaluate the behavior of the device during abnormal working conditions. For a safe point of view, to verify the stability of the system, it has been necessary to perform an analysis of some accidental conditions that may verify during the normal operation of the re-irradiation phase.

A comprehensive analysis of the dry phase has been crucial to determined the thermal behavior of the fuel cladding. If one consider valid the CATHARE modeling proposed then, in some specific conditions, some thermal-hydraulic phenomena might lead the fuel cladding profile to reach unsafe limits.
All these benchmark cases exposed in this thesis, starting from the study of the Re-irradiation phase up to the Dry-phase, are important for us to predict the general behavior of LORELEI test design. In addition, when the real test device will be in fact active, all the results obtained from its experimental campaign will be of considerable importance on the validation of the results obtained and discussed in this Thesis. In this context, it will be very interesting to verify the discrepancy between the real behavior of the fuel sample during the dry phase, such as the time which leads to the clad ballooning and burst with the results presented.
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CEN. Phebus loca program. Institute de Protection et de la Sûreté Nucléaire, Lecture.


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Appendices
# Appendix A

## Constant values of the Device

Table A.1: In-pile device geometry.

<table>
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<tr>
<th>Element</th>
<th>Material</th>
<th>$D_{\text{int}}$ [mm]</th>
<th>$D_{\text{ext}}$ [mm]</th>
<th>Length [mm]</th>
<th>Refer. Coordinate [mm]</th>
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<td>9.5</td>
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<td>406 - 900</td>
</tr>
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<td>$UO_2$</td>
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<td>600</td>
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</tr>
<tr>
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<td>800</td>
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<td>46</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>99.4</td>
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<td>0 - 1700</td>
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### Table A.2: Bottom volume (VOLBOT) and its geometrical values.

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<td>1.32 (10^{-3})</td>
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### Table A.3: Debris catcher volume (DEB_CAT) and its geometrical values.

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### Table A.4: Upper volume (VOLTOP) and its geometrical values.

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<th>size [m]</th>
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<td>0.058</td>
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Table A.7: Cooling channel (COOL_CH) and its geometrical values.

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<th>section [m$^2$]</th>
<th>perimeter [m]</th>
<th>size [m]</th>
<th>length [m]</th>
<th>orientation</th>
<th>weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>j_b_co</td>
<td>0.0</td>
<td>$5.76 \times 10^{-4}$</td>
<td>0.461</td>
<td>0.075</td>
<td>0.0</td>
<td>vertical</td>
<td>1</td>
</tr>
<tr>
<td>j_t_co</td>
<td>3.4</td>
<td>$8.00 \times 10^{-4}$</td>
<td>0.640</td>
<td>0.104</td>
<td>0.0</td>
<td>vertical</td>
<td>1</td>
</tr>
</tbody>
</table>
Appendix B

LORELEI input file

B.1 Steady State input of LORELEI

* LORELEI - TEST SECTION
* STEADY STATE OF LORELEI BEFORE THE DRY PHASE STARTS
* 1) DEVICE IS EMPTIED BY
   * LEAVING ONLY HELIUM AND
   * A SMALL AMOUNT OF STEAM
* 2) A SMALL AMOUNT OF WATER (1.2 l)
   * IS INJECTED INSIDE THE DEVICE
   * INITIAL PRESSURE 3.0 bar
* CREATED BY PAOLO BATTISTONI
* *********************************************************
* adapted geometry as proposed by
* Thermohydraulic Design
* of the LORELEI Test Device
* CDR Version 1.4.2016
* reference steady state
* initial data ;
* title ' LORELEI - TEST SECTION' ;
* pi = 3.141592654d0 ;
* list_gaz = noncond 2 helium hydrogen ;
* tendf = 10000.0 ;
* *********************************************************
* list of heaters connectors inside the
cold channel
* *********************************************************
* heater connectors4
  z_he_4_b = 670.e-3 ;
  z_he_4_t = 744.e-3 ;
  d_he_4_e = 36.e-3 ;
* periphery heater
  z_he_3_b = 759.e-3 ;
  z_he_3_t = 1559.e-3 ;
* heater connectors5
  z_he_5_b = 1574.e-3 ;
  z_he_5_t = 1648.e-3 ;
  d_he_5_e = d_he_4_e ;
* *********************************************************
* fuel geometry
* *********************************************************
  d_fuel = 8.3e-3 ;
  z_fuel_b = 900.e-3 ;
  z_fuel_t = 1500.e-3 ;
  h_fuel = z_fuel_t - z_fuel_b ;
  d_if_a_e = d_fuel ;
  d_if_a_i = 0.1e-3 ;
* *********************************************************
* inner flask geometry
* *********************************************************
  z_if_b = 1708.e-3 ;
  z_if_t = 1808.e-3 ;
  d_if_b_i = 58.e-3 ;
  d_if_b_e = 66.1e-3 ;
  d_if_t_i = 84.4e-3 ;
  d_if_t_e = 95.e-3 ;
* *********************************************************
**OUTER FLASK GEOMETRY**

- **HEIGHT OF DIVERGENT PART**
  
  \[
  z_{of,b} = 1700 \times 10^{-3} ; \\
  z_{of,t} = 1800 \times 10^{-3} ;
  \]

- **OUTER FLASK BOTTOM (INTERNAL-EXTERNAL)**
  
  \[
  d_{of,b,i} = 67.9 \times 10^{-3} ; \\
  d_{of,b,e} = 70.92 \times 10^{-3} ;
  \]

- **OUTER FLASK TOP (INTERNAL-EXTERNAL)**
  
  \[
  d_{of,t,i} = 96.38 \times 10^{-3} ; \\
  d_{of,t,e} = 99.4 \times 10^{-3} ;
  \]

- **-35/+35 cm for the gamma power z-profile among the structures (averaged along 70 cm)**
  
  \[
  z_{po,b} = 850 \times 10^{-3} ; \\
  z_{po,t} = 1550 \times 10^{-3} ;
  \]

- **difference diameters inner flask bottom part**
  
  \[
  dd_{if,b} = d_{if,b,e} - d_{if,b,i} ; \\
  dd_{if,t} = d_{if,t,e} - d_{if,t,i} ;
  \]

- **difference diameters inner flask top part**
  
  \[
  dd_{of,b} = d_{of,b,e} - d_{of,b,i} ; \\
  dd_{of,t} = d_{of,t,e} - d_{of,t,i} ;
  \]

**GEOMETRY OF LVDT**

- **SINGLE HELMEL + TC WIRING**
  
  \[
  d_{lvdt} = 15 \times 10^{-3} ; \\
  z_{lvdt,b} = 2300 \times 10^{-3} ; \\
  z_{lvdt,t} = 2370 \times 10^{-3} ;
  \]

**SAMPLE HOLDER + TC WIRING**

- **BEGINNING OF UPPER OPENINGS**
  
  \[
  a_{in,open} = 3276 \times 10^{-3} ;
  \]

- **DEVICE HELSBERG**
  
  \[
  a_{de} = 3400 \times 10^{-3} ;
  \]

- **DEVICE HELSBERG BOTTOM (INTERNAL-EXTERNAL)**
  
  \[
  d_{de,b,i} = 75 \times 10^{-3} ; \\
  d_{de,b,e} = 85 \times 10^{-3} ;
  \]

- **DEVICE HELSBERG TOP (INTERNAL-EXTERNAL)**
  
  \[
  d_{de,t,i} = 104.4 \times 10^{-3} ; \\
  d_{de,t,e} = 114.4 \times 10^{-3} ;
  \]

**HAFNIUM NEUTRON SCREEN**

- **GEOMETRY OF THE ELECTRICAL HEATER (EH)**
  
  \[
  \frac{s_{he,1} = (\pi/4) \times (d_{he,1,e})^2 ; \\
  p_{he,1} = \pi \times d_{he,1} ;
  \]

- **TO PRODUCE STEAM DURING THE DRY PHASE**
  
  \[
  \text{DEHEAT} = 27 \times 10^{-3} ; \\
  \text{HEAT} = 0.112 ;
  \]

**GEOMETRY OF THE ELECTRICAL HEATER**

- **BEGINNING OF UPPER OPENINGS**
  
  \[
  a_{in,open} = 3276 \times 10^{-3} ;
  \]

- **DEVICE HELSBERG**
  
  \[
  a_{de} = 3400 \times 10^{-3} ;
  \]

- **DEVICE HELSBERG BOTTOM (INTERNAL-EXTERNAL)**
  
  \[
  d_{de,b,i} = 75 \times 10^{-3} ; \\
  d_{de,b,e} = 85 \times 10^{-3} ;
  \]

- **DEVICE HELSBERG TOP (INTERNAL-EXTERNAL)**
  
  \[
  d_{de,t,i} = 104.4 \times 10^{-3} ; \\
  d_{de,t,e} = 114.4 \times 10^{-3} ;
  \]

**HAFNIUM NEUTRON SCREEN**

- **GEOMETRY OF THE ELECTRICAL HEATER (EH)**
  
  \[
  \frac{s_{he,1} = (\pi/4) \times (d_{he,1,e})^2 ; \\
  p_{he,1} = \pi \times d_{he,1} ;
  \]

- **TO PRODUCE STEAM DURING THE DRY PHASE**
  
  \[
  \text{DEHEAT} = 27 \times 10^{-3} ; \\
  \text{HEAT} = 0.112 ;
  \]

**GEOMETRY OF THE ELECTRICAL HEATER**

- **BEGINNING OF UPPER OPENINGS**
  
  \[
  a_{in,open} = 3276 \times 10^{-3} ;
  \]

- **DEVICE HELSBERG**
  
  \[
  a_{de} = 3400 \times 10^{-3} ;
  \]

- **DEVICE HELSBERG BOTTOM (INTERNAL-EXTERNAL)**
  
  \[
  d_{de,b,i} = 75 \times 10^{-3} ; \\
  d_{de,b,e} = 85 \times 10^{-3} ;
  \]

- **DEVICE HELSBERG TOP (INTERNAL-EXTERNAL)**
  
  \[
  d_{de,t,i} = 104.4 \times 10^{-3} ; \\
  d_{de,t,e} = 114.4 \times 10^{-3} ;
  \]

**HAFNIUM NEUTRON SCREEN**

- **GEOMETRY OF THE ELECTRICAL HEATER (EH)**
  
  \[
  \frac{s_{he,1} = (\pi/4) \times (d_{he,1,e})^2 ; \\
  p_{he,1} = \pi \times d_{he,1} ;
  \]

- **TO PRODUCE STEAM DURING THE DRY PHASE**
  
  \[
  \text{DEHEAT} = 27 \times 10^{-3} ; \\
  \text{HEAT} = 0.112 ;
  \]

**GEOMETRY OF THE ELECTRICAL HEATER**

- **BEGINNING OF UPPER OPENINGS**
  
  \[
  a_{in,open} = 3276 \times 10^{-3} ;
  \]

- **DEVICE HELSBERG**
  
  \[
  a_{de} = 3400 \times 10^{-3} ;
  \]

- **DEVICE HELSBERG BOTTOM (INTERNAL-EXTERNAL)**
  
  \[
  d_{de,b,i} = 75 \times 10^{-3} ; \\
  d_{de,b,e} = 85 \times 10^{-3} ;
  \]

- **DEVICE HELSBERG TOP (INTERNAL-EXTERNAL)**
  
  \[
  d_{de,t,i} = 104.4 \times 10^{-3} ; \\
  d_{de,t,e} = 114.4 \times 10^{-3} ;
  \]

**HAFNIUM NEUTRON SCREEN**

- **GEOMETRY OF THE ELECTRICAL HEATER (EH)**
  
  \[
  \frac{s_{he,1} = (\pi/4) \times (d_{he,1,e})^2 ; \\
  p_{he,1} = \pi \times d_{he,1} ;
  \]

- **TO PRODUCE STEAM DURING THE DRY PHASE**
  
  \[
  \text{DEHEAT} = 27 \times 10^{-3} ; \\
  \text{HEAT} = 0.112 ;
  \]
B.1. STEADY STATE INPUT OF LORELEI

***************************************
* Hypothesis to take into account:
* 2.5 l inside the cushion line
* 2.5 l inside the pressure line
* inside the voltop (5 l)=> 0.89 m height
* the level of water inside the voltop during
* the cold condition is 20 cm

\[ z_{\text{voltop}} = z_{\text{de}} - z_{\text{u\_open}}; \]
\[ z_{\text{voltop}} = 0.89 + 0.2; \]
\[ \text{s}_{\text{voltop}} = \frac{\pi}{4} \cdot (d_{\text{if\_t\_i}})^2; \]

***************************************
* DIMENSION OF THE SOURCE/SINK WATER
\[ D_{\text{DN6}} = 6 \times 10^{-3}; \]
\[ S_{\text{DN6}} = \pi \cdot D_{\text{DN6}} \cdot D_{\text{DN6}}/4; \]

***************************************
* GEOMETRY OF HOLES BETWEEN THE VOLTBOT
* AND DEBRIS (BOTTOM)
* FOUR UPPER OPENINGS WITH A HEIGHT OF
* 9 mm AND A WIDTH OF 29 mm

\[ h_{\text{hole\_b}} = 9 \times 10^{-3}; \]
\[ w_{\text{hole\_b}} = 29 \times 10^{-3}; \]
\[ s_{\text{hole\_b}} = (h_{\text{hole\_b}}) \cdot (w_{\text{hole\_b}}); \]
\[ p_{\text{hole\_b}} = 2 \times (h_{\text{hole\_b}} + w_{\text{hole\_b}}); \]
\[ d_{\text{hole\_b}} = \frac{4 \times s_{\text{hole\_b}}}{p_{\text{hole\_b}}}; \]

***************************************
* GEOMETRY DEBRIS CATHER

***************************************
* GEOMETRY VOLBOT

***************************************
* HOT CHANNEL
\[ \text{HOT\_CH} = \text{AXIAL} j_{b\_hc} \text{ DSTREAM} j_{t\_hc} \text{ USTREAM}; \]
\[ \phi_{\text{1}} = \text{AXIS} \{0.0\}; \]
\[ \phi_{\text{2}} = \text{AXIS} \{s_{\text{volbot}}\}; \]
\[ \phi_{\text{3}} = \text{AXIS} \{s_{\text{volbot}} + 1 \times 10^{-3}\}; \]
\[ \phi_{\text{4}} = \text{AXIS} \{z_{\text{volbot}} - 1 \times 10^{-3}\}; \]
\[ \phi_{\text{5}} = \text{AXIS} \{z_{\text{volbot}} + 1 \times 10^{-3}\}; \]
\[ \phi_{\text{6}} = \text{AXIS} \{z_{\text{volbot}} + 1 \times 10^{-3}\}; \]
\[ \phi_{\text{7}} = \text{AXIS} \{z_{\text{volbot}} + 1 \times 10^{-3}\}; \]

***************************************
* COLD CHANNEL
\[ \text{COLD\_CH} = \text{AXIAL} j_{b\_cc} \text{ DSTREAM} j_{t\_cc} \text{ USTREAM}; \]
\[ \psi_{\text{1}} = \text{AXIS} \{0.0\}; \]
\[ \psi_{\text{2}} = \text{AXIS} \{s_{\text{volbot}}\}; \]
\[ \psi_{\text{3}} = \text{AXIS} \{s_{\text{volbot}} + 1 \times 10^{-3}\}; \]
\[ \psi_{\text{4}} = \text{AXIS} \{z_{\text{volbot}} - 1 \times 10^{-3}\}; \]
\[ \psi_{\text{5}} = \text{AXIS} \{z_{\text{volbot}} - 1 \times 10^{-3}\}; \]
\[ \psi_{\text{6}} = \text{AXIS} \{z_{\text{volbot}} - 1 \times 10^{-3}\}; \]
\[ \psi_{\text{7}} = \text{AXIS} \{z_{\text{volbot}} - 1 \times 10^{-3}\}; \]
\[ \psi_{\text{8}} = \text{AXIS} \{z_{\text{volbot}} - 1 \times 10^{-3}\}; \]
\[ \psi_{\text{9}} = \text{AXIS} \{z_{\text{volbot}} - 1 \times 10^{-3}\}; \]
\[ \psi_{\text{10}} = \text{AXIS} \{z_{\text{volbot}} - 1 \times 10^{-3}\}; \]
\[ \psi_{\text{11}} = \text{AXIS} \{z_{\text{volbot}} - 1 \times 10^{-3}\}; \]
\[ \psi_{\text{12}} = \text{AXIS} \{z_{\text{volbot}} - 1 \times 10^{-3}\}; \]
\[ \psi_{\text{13}} = \text{AXIS} \{z_{\text{volbot}} - 1 \times 10^{-3}\}; \]
\[ \psi_{\text{14}} = \text{AXIS} \{z_{\text{volbot}} - 1 \times 10^{-3}\}; \]

***************************************
* GEOMETRY OF HOLES BETWEEN THE VOLTBOT
* AND DEBRIS (BOTTOM)
* FOUR UPPER OPENINGS WITH A HEIGHT OF
* 9 mm AND A WIDTH OF 29 mm

\[ h_{\text{hole\_b}} = 9 \times 10^{-3}; \]
\[ w_{\text{hole\_b}} = 29 \times 10^{-3}; \]
\[ s_{\text{hole\_b}} = (h_{\text{hole\_b}}) \cdot (w_{\text{hole\_b}}); \]
\[ p_{\text{hole\_b}} = 2 \times (h_{\text{hole\_b}} + w_{\text{hole\_b}}); \]
\[ d_{\text{hole\_b}} = \frac{4 \times s_{\text{hole\_b}}}{p_{\text{hole\_b}}}; \]
Pc15 = BASIS (x_fuel_b - z_volbot) ;
Pc16 = BASIS (x_fuel_t - z_volbot) ;
Pc17 = BASIS (x_po_t - z_volbot + 1.E-3) ;
Pc18 = BASIS (x_hea_t - z_volbot) ;
Pc19 = BASIS (x_he_5_b - z_volbot) ;
Pc20 = BASIS (x_he_5_b - z_volbot + 1.E-3) ;
Pc21 = BASIS (x_ha_t - z_volbot) ;
Pc22 = BASIS (x_he_5_t - z_volbot - 1.E-3) ;
Pc23 = BASIS (x_he_5_t - z_volbot) ;
Pc24 = BASIS (x_If_b - z_volbot) ;
Pc25 = BASIS (x_if_t - z_volbot) ;
Pc26 = BASIS (x_lvdt_b - z_volbot) ;
Pc27 = BASIS (x_lvdt_b - z_volbot + 1.E-3) ;
Pc28 = BASIS (x_lvdt_t - z_volbot - 1.E-3) ;
Pc29 = BASIS (x_lvdt_t - z_volbot) ;
Pc30 = BASIS (z_u_open - z_volbot) ;

M_cold = pc1
SEGMENT -25 pc2 COS 1.0 RATIO 1.0584
SEGMENT 1 pc3 COS 1.0
SEGMENT 6 pc4 COS 1.0
SEGMENT 1 pc5 COS 1.0
SEGMENT 4 pc6 COS 1.0
SEGMENT 1 pc7 COS 1.0
SEGMENT 8 pc8 COS 1.0
SEGMENT 1 pc9 COS 1.0
SEGMENT 5 pc10 COS 1.0
SEGMENT 1 pc11 COS 1.0
SEGMENT 2 pc12 COS 1.0
SEGMENT 2 pc13 COS 1.0
SEGMENT 3 pc14 COS 1.0
SEGMENT 5 pc15 COS 1.0
SEGMENT 24 pc16 COS 1.0
SEGMENT 5 pc17 COS 1.0
SEGMENT 3 pc18 COS 1.0
SEGMENT 2 pc19 COS 1.0
SEGMENT 1 pc20 COS 1.0
SEGMENT 1 pc21 COS 1.0
SEGMENT 5 pc22 COS 1.0
SEGMENT 1 pc23 COS 1.0
SEGMENT 5 pc24 COS 1.0
SEGMENT 5 pc25 COS 1.0
SEGMENT 6 pc26 COS 1.0
SEGMENT 1 pc27 COS 1.0
SEGMENT 4 pc28 COS 1.0
SEGMENT 1 pc29 COS 1.0
SEGMENT -25 pc30 COS 1.0 RATIO 0.978 ;

MESH cold_ch m_cold ;

GEOM cold_ch
(pc1 AND pc2) SECT s_cc_1 PERI p_cc_1 SIZE d_cc_b
(pc2 AND pc6) SECT s_cc_2 PERI p_cc_2 SIZE d_cc_b
(pc5 AND pc6) SECT s_cc_3 PERI p_cc_3 SIZE d_cc_b
(pc7 AND pc8) SECT s_cc_b_1 PERI p_cc_b SIZE d_cc_b
(pc9 AND pc10) SECT s_cc_4 PERI p_cc_4 SIZE d_cc_b
(pc11 AND pc12) SECT s_cc_b_1 PERI p_cc_b SIZE d_cc_b
(pc15 AND pc16) SECT s_cc_b_1 PERI p_cc_b SIZE d_cc_b
(pc25 AND pc32) SECT s_cc_5 PERI p_cc_5 SIZE d_cc_b
(pc26 AND pc34) SECT s_cc_1 PERI p_cc_1 SIZE d_cc_b
(pc27 AND pc36) SECT s_cc_b_1 PERI p_cc_b SIZE d_cc_b

* COOLING CHANNEL

cool_ch = AXIAL j_b_cc DSTREAM j_t_cc USTREAM ;

MESH cool_ch m_cool ;

GEOM cool_ch
(pc6 AND pc20) SECT s_co_b PERI p_co_b SIZE d_co_b
(pc24 AND pc25) SECT s_co_b PERI p_co_b SIZE d_co_b

VOLTOP = VOLUME j_t_cc DSTREAM j_t_cc USTREAM j_t_vt USTREAM

GEOM voltop
0.0 s_voltop
s_voltop = s_voltop
B.1. STEADY STATE INPUT OF LORELEI 125

j_t_cc BOTTOM LENGTH 0.
SECT s_cc_t_1 PERI p_cc_t SIZE d_cc_t VERTICAL
j_t_vt TOP LENGTH 0.
SECT (d_if_t_i*PI)/4. PERI (d_if_t_i*PI) SIZE d_if_t_i VERTICAL;

DEB_CAT = VOLUME j_b_hc USTREAM j_t_dc_2 DSTREAM
*GEOM DEB_CAT
0.0 s_dc
h_dc s_dc
j_b_hc TOP LENGTH 0.0
SECT s_hc PERI p_hc SIZE d_hc VERTICAL
j_t_dc_2 ELEV h_dc LENGTH 3.E-3 WEIGHT 4
SECT s_hole_b PERI p_hole_b SIZE d_hole_b HORIZONT;

VOLBOT = VOLUME j_b_cc USTREAM j_t_dc_2 USTREAM j_b_vb DSTREAM
*GEOM volbot
0.0 s_vb_1
(z_vb_1-1.E-3) s_vb_1
z_volbot s_vb_2
j_b_cc TOP LENGTH 0.
SECT s_cc_1 PERI p_cc_1 SIZE d_cc_b VERTICAL
j_t_dc_2 ELEV z_volbot LENGTH 0. WEIGHT 4
SECT s_hole_b PERI p_hole_b SIZE d_hole_b HORIZONT

* DEFINITION OF THE SINK/SOURCE OF WATER
SINWEI = SOURCE VOLUME VOLBOT EXTERNAL ELEV z_volbot SECT (s_dn6)*2.0 LENGTH 0.0 ;

**************************************
* BOUNDARY CONDITIONS of the device
**************************************

* BOUNDARY CONDITION TOP .
* PRESSURE FIXED
bc_out = BCONDIT j_b_vb USTREAM;
MODEL bc_out BC4C
P (REALLIST 3.0E+5 3.0E+5 )
ABSTIME (REALLIST 0. 10000. );

* BOUNDARY CONDITION BOTTOM.
bc_inlet = BCONDIT j_t_vt DSTREAM;
MODEL bc_inlet BC3B
TL (REALLIST 50. 50. 50. 50. 50. 50. )
TG (REALLIST 100. 250. 250. 250. 250. 250. )
ALFA (REALLIST 1.0 1.0 1.0 1.0 1.0 1.0 )
E1 (REALLIST 1.0 1.0 1.0 1.0 1.0 1.0 )
Q1 (REALLIST 0.1 0.1 0.1 0.1 0.1 0.1 )
ABSTIME (REALIST 0.000 tendf );

bc_coo_o = BCONDIT j_b_co USTREAM;
MODEL bc_coo_o BC4A
P (REALIST P_ou_coo P_ou_coo)
ABSTIME (REALIST 0. tendf ) ;

**************************************
* DEFINITION OF INTERNAL POWER
**************************************

* GAMMA HEATING POWER
lawn LAW 'time' 'power' 0. 0. tendf 0. ;

* POWER ELECTRICAL HEATER
law_th= LAW 'time' 'power'
0. 0. tendf 0. ;

* DISTRIBUTION FUEL POWER ALONG THE FUEL SAMPLE
lawn_FUEL= LAW 'x' 'power'
0.00 1.00
(C_FUEL/2.0) 1.00 ;

LAW_CRA = LAW 'time' 'power'
0. 0. tendf 0. ;

* distance from the core (relative distance)
* to obtain 40 W/cm
distan = 14.08 ;

HGR = 375.2 * exp (-0.159*distan) ;

VOL_FUEL = PI*D_FUEL**2.0 *H_FUEL ;

POW_LIN = LHGR*H_FUEL*100. ;

**************************************
* POWER inside the fuel
**************************************

POW_VOL = LHGR*H_FUEL*100. /VOL_FUEL

**************************************
* POWER INSIDE THE THERMAL HEATER
**************************************

* volume of the internal heater
V_HEAT1 = PI*DE_HEAT1**2.0*H_HEAT1/4.0 ;

* Gamma average power in the different media at distance 0 cm (W/g)
* the values are averaged along 70 cm of height
* the media are in order :
* cladding
**LORELEI input file**

- hot channel
- heater
- cold channel
- inner flask
- helium gap
- outer flask
- cooling channel
- neutron screen
- device holder

```
**************************************************************
g_clad0 = 2.6 ;
g_hch0 = 5.0 ;
g_hea0 = 2.7 ;
g_cch0 = 4.9 ;
g_inPF0 = 2.9 ;
g_he0 = 5.1 ;
g_ouPF0 = 3.2 ;
g_coch0 = 5.2 ;
g_hf0 = 6.6 ;
g_devh0 = 2.9 ;
**************************************************************
* the reference for the law vs position is
* set on the SS external flask
* gamma power at the right location (W/g)
**************************************************************
g_ouPF = g_inPF0/g_inPF0*5.1711*exp (-0.087*distan) ;
g_clad = g_clad0/g_inPF0*5.1711*exp (-0.087*distan) ;
g_hch = g_hch0/g_inPF0*5.1711*exp (-0.087*distan) ;
g_hea = g_hea0/g_inPF0*5.1711*exp (-0.087*distan) ;
g_cch = g_cch0/g_inPF0*5.1711*exp (-0.087*distan) ;
g_inPF = g_inPF0/g_inPF0*5.1711*exp (-0.087*distan) ;
g_he = g_he0/g_inPF0*5.1711*exp (-0.087*distan) ;
g_coch = g_coch0/g_inPF0*5.1711*exp (-0.087*distan) ;
g_hf = g_hf0/g_inPF0*5.1711*exp (-0.087*distan) ;
g_devh = g_devh0/g_inPF0*5.1711*exp (-0.087*distan) ;
**************************************************************
* heat transfer coefficient to the pool
**************************************************************
htc_ext = 500. ;
htc_ext1 = 100000. ;
*Peaking factor for 70 cm of length gamma structures
PF =1.273 ;
*r density of materials [kg/m^3], zircalloy, water, stainless steel, helium, hafnium
r_zir = 6603.0 ;
r_wat = 980.0 ;
r_sst = 7860.0 ;
r_hel = 0.65 ;
r_haf = 13277.0 ;
r_inc = 7287.0 ;
r_steam = 2.6680 ;
* Gamma power [W/m^3] in the water, hot-cold-cooling channels
PCLA_VOL = r_zir*g_clad*1000.0 ;
PRE_VOL = r_haf*1000.0*r_hf ;
* PRESSURE DROPS HOT CHANNEL
* Handbook of Hydraulic Resistance Idelchik
**************************************************************
* Sudden contraction
* handbook of hydraulic resistance p. 216-217
SCHC_1 = (s_hc_1/ s_hc) ;
SCDP1_HC = (0.5*(1.-SCHC_1)**(3./4.)) ;
* Sudden expansion
* handbook of hydraulic resistance p. 208
SEHC_1 = (s_hc_2/ s_hc_1) ;
SEDP1_HC = (0.5*(1.-SEHC_1)**(2.));
**************************************************************
* PRESSURE DROPS COLD CHANNEL
**************************************************************
* Sudden contraction
FROM HEATER CONNECTOR 1 TO HEATER CONNECTOR 2
SCCC_1 = (s_cc_2/s_cc_1) ;
SCDP1_CC = (0.5*(1.-SCCC_1)**(3./4.)) ;
* FROM HEATER TO HEATER CONNECTOR 4
SCCC_2 = (s_cc_4/s_cc_b_1) ;
SCDP2_CC = (0.5*(1.-SCCC_2)**(3./4.)) ;
* FROM HEATER TO HEATER CONNECTOR 5
SCCC_3 = (s_cc_5/s_cc_b_1) ;
SCDP3_CC = (0.5*(1.-SCCC_3)**(3./4.)) ;
* Sudden expansion
FROM HEATER CONNECTOR 2 TO HEATER CONNECTOR 3
SECC_1 = (s_cc_2/ s_cc_3) ;
SEDP1_CC = (0.5*(1.-SECC_1)**(2.));
* FROM HEATER CONNECTOR 3 TO HEATER
SECC_2 = (s_cc_3/ s_cc_b_1) ;
SEDP2_CC = (0.5*(1.-SECC_2)**(2.));
```
B.1. STEADY STATE INPUT OF LORELEI

SEC.3 = (s_cc_4/ s_cc_b_1) ;

SEDP3_CC = (0.5*(1.-SECC_3)**(2.));

* FROM HEATER CONNECTOR 5 TO HEATER

SECC_4 = (s_cc_5/ s_cc_b_1) ;

SEDP4_CC = (0.5*(1.-SECC_4)**(2.));

SINGULAR COLD CH POINT PC3 POSITIVE SCDP1_CC NEGATIVE SEDP1_CC ;

SINGULAR COLD CH POINT PC9 POSITIVE SCDP2_CC NEGATIVE SEDP2_CC ;

SINGULAR COLD CH POINT PC20 POSITIVE SCDP3_CC NEGATIVE SEDP3_CC ;

SINGULAR COLD CH POINT PC5 POSITIVE SEDP1_CC NEGATIVE SEDP1_CC ;

SINGULAR COLD CH POINT PC7 POSITIVE SEDP2_CC NEGATIVE SEDP2_CC ;

SINGULAR COLD CH POINT PC11 POSITIVE SEDP3_CC NEGATIVE SEDP3_CC ;

SINGULAR COLD CH POINT PC23 POSITIVE SEDP4_CC NEGATIVE SEDP4_CC ;

* DIVERGENT PART; diagram 5-23, pag 316 IIdelchik

EPSI_CON = 0.46 ;

SINGULAR COLD CH POINT PC24 POSITIVE EPSI_CON NEGATIVE EPSI_CON ;

PGAM_CO = REALLIST

0.45639*P_CO 0.47728*P_CO 0.49842*P_CO 0.51975*P_CO

0.54125*P_CO 0.57916*P_CO 0.63352*P_CO 0.68748*P_CO

0.74024*P_CO 0.79094*P_CO 0.83864*P_CO 0.88235*P_CO

0.92100*P_CO 0.95344*P_CO 0.97846*P_CO 0.99479*P_CO

1.00107*P_CO 1.00107*P_CO 0.99479*P_CO 0.97846*P_CO

0.95343*P_CO 0.92099*P_CO 0.88234*P_CO 0.83862*P_CO

0.79090*P_CO 0.74019*P_CO 0.68742*P_CO 0.63345*P_CO

0.57907*P_CO 0.54116*P_CO 0.51865*P_CO 0.48631*P_CO

0.47717*P_CO 0.43427*P_CO ;

* DEFINITION FUEL SAMPLE VARIABLES

TAB1CRAD = 0.2999331E-02 ;

TAB1VEVI = 0.3076102E-06 ;

TAB1VPLS = 0.2108495E-05 ;

TAB1VPLI = 0.0000000E+00 ;

TAB1VCR = 0.8046442E-06 ;

TAB1VPOR = 0.2523035E-07 ;

TAB1TPLG = 0.0000000E+00 ;

TAB1VOLF = 0.9862677E+00 ;

TAB1PORS = 0.4294068E-01 ;

5 micron oxide (internal-external)

CRAYON = FUEL HOT CH INTERNAL

SEGMENT PH15 PH16

ISO 8 DIAM 0.0 D_FUEL

UO2 IRRAFUEL

WZUO 1.0

LAW LAW_PAST

GAP 1.0-6

SIDE ED 5.6-6 E6 5.6-6

CLADING ZRCA

RN 4.6065-3 ;

CRAYON = FUELCHN HOT CH

GAP MULTFUEL 1.0-10

GAP 10.15

GRAD TAB1CHN

FUEL INTERNAL

POWER POWER_HC1

SOURCE MEDIUM 1

LAW NEUT LAW_CRA

LAW RESI LAW_CRA

GAS VOL POWER PGAM_HC ;

**************************************

P_Dn_w =REALIST

0.00000*DH 0.00000*DH 0.00000*DH 0.46639*DH

0.47728*DH 0.49834*DH 0.51975*DH 0.54125*DH

0.57907*DH 0.63345*DH 0.68748*DH 0.74024*DH

0.79094*DH 0.83862*DH 0.88235*DH 0.92100*DH

0.95343*DH 0.92099*DH 0.88234*DH 0.83862*DH

0.79090*DH 0.74019*DH 0.68742*DH 0.63345*DH

0.57907*DH 0.54116*DH 0.51865*DH 0.48631*DH

0.47717*DH 0.43427*DH ;

P_Hn_w =REALIST

0.00000*DH 0.00000*DH 0.00000*DH 0.46639*DH

0.47728*DH 0.49834*DH 0.51975*DH 0.54125*DH

0.57907*DH 0.63345*DH 0.68748*DH 0.74024*DH

0.79094*DH 0.83862*DH 0.88235*DH 0.92100*DH

0.95343*DH 0.92099*DH 0.88234*DH 0.83862*DH

0.79090*DH 0.74019*DH 0.68742*DH 0.63345*DH

0.57907*DH 0.54116*DH 0.51865*DH 0.48631*DH

0.47717*DH 0.43427*DH ;

* DIVERGENT PART; diagram 5-23, pag 316 IIdelchik

EPSI_CON = 0.46 ;

SINGULAR COLD CH POINT PC24 POSITIVE EPSI_CON NEGATIVE EPSI_CON ;

PGAM_CO = REALLIST

0.45639*P_CO 0.47728*P_CO 0.49842*P_CO 0.51975*P_CO

0.54125*P_CO 0.57916*P_CO 0.63352*P_CO 0.68748*P_CO

0.74024*P_CO 0.79094*P_CO 0.83864*P_CO 0.88235*P_CO

0.92100*P_CO 0.95344*P_CO 0.97846*P_CO 0.99479*P_CO

1.00107*P_CO 1.00107*P_CO 0.99479*P_CO 0.97846*P_CO

0.95343*P_CO 0.92099*P_CO 0.88234*P_CO 0.83862*P_CO

0.79090*P_CO 0.74019*P_CO 0.68742*P_CO 0.63345*P_CO

0.57907*P_CO 0.54116*P_CO 0.51865*P_CO 0.48631*P_CO

0.47717*P_CO 0.43427*P_CO ;

* OXTYPE STANDARD;

INTEGRATE CRAYON NUMBER 1 CHARCRAY ;

FRAME CHCRAY; SEGMENT NUMBER 1 CRAYON ;

GAMMA POWER INSIDE THE STEAM

* NOT CONSIDERED (VERY SMALL)

*gam_hc = WALL hot_ch INTERNAL PLANE

* GAMMA POWER INSIDE THE STEAM

* gam_hc = WALL hot_ch INTERNAL PLANE

**************************************
LORALEI input file

*gm cc = WALL cold_ch INTERNAL PLANE
  * SEGMENT pc14 pc17
  * YYYY04 ISO 1 THICK 0.0D0 1.D-3
  * HPERIM CONST PE_CC_B
  * (PC5 AND PC6) PE_CC_3
  * (PC7 AND PC8) PE_CC_B
  * (PC9 AND PC10) PE_CC_4
  * (PC11 AND PC14) PE_CC_B
  * (PC15 AND PC16) PE_CC_5
  * PC17 PE_CC_B
  * C21 PE_CC_T
  * SOURCE MEDIUM 1
  * LAW lgw
  * VOLPOWER PGAM_CC;
  *
  ******************************************************
  gam_co = WALL cool_ch INTERNAL PLANE
  SEGMENT pc14 pc17
  YYYY04 ISO 1 THICK 0.0D0 1.D-3
  HPERIM CONST PE_CC_B
  *
  ******************************************************
  * Shroud lower region - Pure SS
  ******************************************************
  shr_B = EXCHANGER hot_ch cold_ch IMPLICIT
  PRIMARY CYLINDER
  SEGMENT ph1 ph2 DIRECT pc1 pc2
  INOX316 ISO 5 DIAM d_hc d_he_1_e
  HPERIM CONST (PI*d_hc) ;
  SEGMENT ph2 ph3 DIRECT pc2 pc3
  INOX316 ISO 5 DINI d_hc d_he_1_e
  DEND d_hc d_he_2_e
  HPERIM CONST (PI*d_hc) ;
  SEGMENT ph3 ph4 DIRECT pc3 pc4
  INOX316 ISO 5 DIAM d_hc d_he_2_e
  HPERIM CONST (PI*d_hc) ;
  SEGMENT ph4 ph5 DIRECT pc4 pc5
  INOX316 ISO 5 DINI d_hc d_he_2_e
  DEND d_hc d_he_3_e
  HPERIM CONST (PI*d_hc) ;
  SEGMENT ph5 ph6 DIRECT pc5 pc6
  INOX316 ISO 5 DIAM d_hc d_he_3_e
  HPERIM CONST (PI*d_hc) ;
  SEGMENT ph6 ph7 DIRECT pc6 pc7
  INOX316 ISO 5 DINI d_hc d_he_3_e
  DEND d_hc d_he_4_e
  HPERIM CONST (PI*d_hc) ;
  SEGMENT ph7 ph8 DIRECT pc7 pc8
  INOX316 ISO 5 DIAM d_hc d_he_4_e
  HPERIM CONST (PI*d_hc) ;
  SEGMENT ph8 ph9 DIRECT pc8 pc9
  INOX316 ISO 5 DINI d_hc d_he_4_e
  DEND d_hc d_he_5_e
  HPERIM CONST (PI*d_hc) ;
  SEGMENT ph9 ph10 DIRECT pc9 pc10
  INOX316 ISO 5 DIAM d_hc d_he_5_e
  HPERIM CONST (PI*d_hc) ;
  SEGMENT ph10 ph11 DIRECT pc10 pc11
  INOX316 ISO 5 DIAM d_hc d_he_5_e
  DEND d_hc d_he_6_e
  HPERIM CONST (PI*d_hc) ;
  **************************************
  Fig_B = EXCHANGER cool_ch cold_ch IMPLICIT
  PRIMARY CYLINDER
  SEGMENT pc1 pc11 DIRECT pc11 pc11
  INOX316 ISO 10 DIAM d_if_b_i d_if_b_e
  XXXXXXX ISO 4 DIAM d_if_b_e d_of_b_i
  INOX316 ISO 10 DIAM d_of_b_i d_of_b_e
  HPERIM CONST (PI*d_if_b_i) ;
  **************************************
  Fig_M = EXCHANGER cool_ch cold_ch IMPLICIT
  PRIMARY CYLINDER
  SEGMENT pc11 pc21 DIRECT pc21 pc21
  INOX316 ISO 10 DIAM d_if_b_i_d_of_b_i
  XXXXXXX ISO 4 DIAM d_if_b_e_d_of_b_e
  INOX316 ISO 10 DIAM d_of_b_i_d_of_b_e
  HPERIM CONST (PI*d_if_b_i) ;
  **************************************
  Fig_U = EXCHANGER cool_ch cold_ch IMPLICIT
  PRIMARY CYLINDER
  SEGMENT pc21 pc31 DIRECT pc31 pc31
  INOX316 ISO 10 DIAM d_if_b_i_d_of_b_i
  XXXXXXX ISO 4 DIAM d_if_b_e_d_of_b_e
  INOX316 ISO 10 DIAM d_of_b_i_d_of_b_e
  HPERIM CONST (PI*d_if_b_i) ;
  **************************************
  Fig_M = EXCHANGER cool_ch cold_ch IMPLICIT
  PRIMARY CYLINDER
  SEGMENT pc31 pc41 DIRECT pc41 pc41
  INOX316 ISO 10 DIAM d_if_b_i_d_of_b_i
  XXXXXXX ISO 4 DIAM d_if_b_e_d_of_b_e
  INOX316 ISO 10 DIAM d_of_b_i_d_of_b_e
  HPERIM CONST (PI*d_if_b_i) ;
  **************************************
  Fig_U = EXCHANGER cool_ch cold_ch IMPLICIT
  PRIMARY CYLINDER
  SEGMENT pc41 pc51 DIRECT pc51 pc51
  INOX316 ISO 10 DIAM d_if_b_i_d_of_b_i
  XXXXXXX ISO 4 DIAM d_if_b_e_d_of_b_e
  INOX316 ISO 10 DIAM d_of_b_i_d_of_b_e
  HPERIM CONST (PI*d_if_b_i) ;
  **************************************
B.1. STEADY STATE INPUT OF LORELEI

**Input Statements**

```plaintext
**B.1. STEADY STATE INPUT OF LORELEI 129**
```

---

**Additional Information**

- **Suppression of the lost heat to the cooling channel from the upper plenum**
- **Thermal resistance bottom device**
- **To produce steam**

---

**EXEC BLOCK**

```plaintext
DOUBLE TIME DT0 DT POW_FUEL
DOUBLE lost_bot t_bot lost_top t_top
PRESSU H_REG VOL_LIQ
DOUBLE LEV1 LEVELR PRESS1 XPRESS MASS MAS_REF MASS1 MASS_CIRC MDIFF
INTEGER NSTEPS ipower IPOWER1 IPOWER4 IPOWER5 IPOWER6 IPOWER7 TSATU ;
```

---

**Summary**

The document contains detailed input statements for a steady-state simulation involving various materials and geometries. The focus is on the input parameters for the simulation, including materials, dimensions, and boundary conditions. The statements are structured to define the initial and boundary conditions for the system being modeled.
130 LORELEI input file

* STEADY STATE
* Initialization
* PERMINIT displor voltop cold_ch hot_ch dem_rat volbot bc_inlet bc_out;
* PERMINIT coolinch cool_ch bc_coo_i bc_coo_o;

* Initial Conditions
REALC j_t_vt
  P 3.0E+5
  HLSAT
  TV 100.
  ALFA 1.e-5
  X1 1.e-5
  X2 1.e-5
  VL 0.01
  VV 0.01;

REALC j_t_co
  P 2.0E+5
  TL 33.
  HVSAT
  ALFA 1.0E-5
  X1 1.0E-5
  X2 1.0E-5
  VL v_co_in
  VV v_co_in;

ECHPOWER heater 0.;
ECHPOWER shr_U 0.;
ECHPOWER shr_B 0.;
ECHPOWER Fla_B 0.;
ECHPOWER Fla_M 0.;
ECHPOWER Fla_U 0.;
TIME = 0.D0;
DT0 = 1.0D-4;
NSTEPS = 3.0D+6;
ipower = 1;
IPOWER1 = 0;
IPOWER4 = 0;
IPOWER5 = 0;
IPOWER6 = 0;
IPOWER7 = 0;
H_REG = (0.125+0.05);
VOL_LIQ = (1/4)*PI*(H_REG)*(d_hc)**2;
MAS_REF = (VOL_LIQ)*r_wat;

* GOPERM
OPEN SINWEI;
*
SAVE 111 append;
PERIOD displor SECOND 500.00;
RESULT CIRCTOT SECOND 250.00;

* TRANSIENT

OPTION rocp 100.;
OPTION DTMIN 1.E-10;
OPTION MAXREP 50;

* Time step for transient
DT = DT0;

*PNRSHAPX CHARCRAY SIGNAL 1. ;
REPEAT BLOCK1 NSTEPS;
TIME = TIME + DT;
TRANSIENT CIRCTOT TIME DT;
DT = NEWDT;
IF ( DT > 1. ) THEN ;
END BLOCK1;

OPTION rocp 1.;

* Stop of forced flow; the system is closed
BCMOD bc_inlet BLIND;
BCMOD bc_out BLIND;

REPEAT BLOCK2 NSTEPS;
TIME = TIME + DT;
TRANSIENT CIRCTOT TIME DT;
DT = NEWDT;
IF ( DT > 10. ) THEN ;
DT = 10. ;
ENDIF;
TIME = TIME + DT;
TRANSIENT CIRCTOT TIME DT;
TSATU = VALUE SATTEMP VOLTOP SUP;
MESSAGE ' !!!!!!! SATTEMP IS ' TSATU ;

* Some water is injected inside the device
IF ((IPOWER4 EQ 0) AND ( TIME > 5000. )) THEN ;
MAS_CIR = VALUE LIQMASS DISPLOR ;

MESSAGE ' !!!!!!! MASS REFERENCE IS ' MAS_REF ;

MESSAGE ' !!!!!!! MASS REFERENCE IS ' MAS_REF ;
IF ((IPOWER4 EQ 0) AND ( TIME > 5000. )) THEN ;
MAS_CIR = VALUE LIQMASS DISPLOR ;
B.2 Restart input for the Dry phase

*******************************************
*******************************************
* LORELEI - TEST SECTION
* *******************************************

*** DRY PHASE P_(EH)=1 kW
*** AT 12000 s the electrical heater
*** is activated
*** AT 16000 s the device starts to move
*** toward the core at 6 cm/s
 *******************************************

* VARIABLES
*******************************************

DOUBLE TIME DT0 DT PI
lost_bot t_bot lost_top
t_top PRESSU g_coch0
LEV1 LEVELR QSOURCE QSIMKE XDIFF
XDIFFR PRESS1 XPRESS
g_he0 g_inPF0 g_he0 g_ouPF0
HTC_EXT HTC_EXT1 g_1 g_2 C1 dist
P_HE P_IN P_OU g_he0 g_inPF0
 g_he0 g_inPF PF distan0 PC RC
r_sst r_hel r_inc LHGR POW_LIN
PRESS2 T_RUP TEMP_RUP THICCLA
POWE1 POWE2 POWE3 POWE4
POWE5 POWE6 POWE7 POWE8
POWE9 POWE10 POWE11 POWE12
POWE13 POWE14 POWE16 POWE18
POWE17 POWE19 POWE20
POWE21 POWE22 POWE23 POWE24
POWE1 POWE12 POWE13 POWE14
POWE5 POWE6 POWE7 POWE8
POWE9 POWE10 POWE11 POWE12
POWE13 POWE14 POWE16 POWE18
POWE17 POWE19 POWE20
POWE21 POWE22 POWE23 POWE24
POW_LIN = LHGR*60.0 ;

INTEGER NSTEPS ipower IPOWER1 IPOWER4 IPOWER5
IPower6 IPower7 IPOWER8
IPower9 IPower10 IPower11
IPower12 IPower13 IPower14
IPower15 IPower16 IPower17
IPower18 IPower19 IPower20
IPower21 IPower22 IPower23

* to obtain 35 W/cm

LHGR = 375.2 * exp (-0.159*distan0) ;

POW_LIN = LHGR*60.0 ;

* METHOD TO REGULATE THE WALL POWER

* INITIAL DISTANCE (STEADY STATE)
dist = 14.08 ;
g_1 = g_cocoh/g_inPF0*5.1711*exp (-0.087*dist) ;

***********************************************************************
* the reference for the law vs position is
* on the SS external flask
* Gamma power at the right location (W/g)
***********************************************************************

g_ouPF = g_inPF0/g_inPF0*5.1711*exp (-0.087*dist0) ;
g_hea = g_hea0/g_inPF0*5.1711*exp (-0.087*dist0) ;
g_inPF = g_inPF0/g_inPF0*5.1711*exp (-0.087*dist0) ;
g_he = g_he0/g_inPF0*5.1711*exp (-0.087*dist0) ;

* density of materials [kg/m^3], zircalloy, water,
* stainless steel, helium, hafnium
r_sst = 7860.0 ;
r_hel = 0.6500 ;
r_inc = 7287.0 ;
PI = 3.141592654D0 ;
d_clad_e = 9.5E-3 ;

* Gamma power [W/m^3] in the water,
* hot-cold-cooling channels
P_HE = (r_inc*g_hea*1000) ;
P_IN = (r_sst*g_inPF*1000) ;
P_EL = (r_hel*g_he*1000) ;
P_OU = (r_sst*g_ouPF*1000) ;

***********************************************************************
* DEFINITION OF THE INTERNAL POWERS
***********************************************************************

***********************************************************************
* fuel power wall
***********************************************************************

PNSHAPX CHARCRAY SIGNAL 1 ;
POWER CHARCRAY POWNW LIN
ABSOLUTE REALLIST
0.0 22000.0
POWER REALLIST
0.00 0.000  ;

POWER ExtWaM1 gaz_co
ABSOLUTE REALLIST
0.0 22000.0
POWER REALLIST
0.00 0.0 ;

***********************************************************************
* ACTIVATION OF THE ELECTRICAL POWER (EH)
***********************************************************************

POWER THERMA
ABSOLUTE REALLIST
0.0 12000. 12001.0 22000.0
POWER REALLIST
0.0 0.0 0.66 0.66  ;

OPTION rocP 1.  ;

PERIOD displor second 250.D0  ;
RESULT CIRCTOT SECOND 250.D0  ;

GOFUEL CIRCTOT  ;
GERATE CHARCRAY STANDARD  ;

REPEAT BLOCK4 NSTEPS  ;
TIME = TIME + DT  ;
TRANSIENT CIRCTOT TIME DT  ;
DT = NEWDT  ;
IF ( DT > 1. ) THEN  ;
DT = 1.  ;
ENDIF  ;

***********************************************************************
* BLOCK of Temperature regulation at
* 1200 ÂµC in the middle of the fuel sample
***********************************************************************

IF (TIME GT 16000. ) THEN  ;
PERIOD displor second 50.D0  ;
RESULT CIRCTOT SECOND 50.D0  ;

TGAICONS = 1200.D0  ;
TGAIMNES = VALUE WALLWET CHARCRAY 12  ;

IF (TGAIMNES > (TGAICONS+50.) ) THEN  ;
distanew = distan0 + 6.E-1*DT  ;
ENDIF  ;

IF (TGAIMNES < (TGAICONS-50.) ) THEN  ;
distanew = distan0 - 6.E-1*DT  ;
ENDIF  ;

IF (distanew GT 35.0D0) THEN  ;
distanew = 35.0D0  ;
ENDIF  ;

IF (distanew LT 10.0D0) THEN  ;
distanew = 10.0D0  ;
ENDIF  ;

LHGR = 375.2 * exp (-0.159*distanew) ;
POW_LIN = 375.2 * exp (-0.159*distanew)*60.0 ;
PNSHAPX CHARCRAY SIGNAL 1  ;
POWER CHARCRAY POWNW LIN
RELATIVE REALLIST 0.D0 5.D5
POWER REALLIST 1.0 1.0  ;

ABSOLUTE REALLIST
0.0 12000.0 12001.0 22000.0  ;

POWER REALLIST
0.0 0.0 0.66 0.66  ；

OPTION rocP 1. ；

PERIOD displor second 250.D0 ；
RESULT CIRCTOT second 250.D0 ；

GOFUEL CIRCTOT ；
GERATE CHARCRAY STANDARD ；

REPEAT BLOCK4 NSTEPS ；
TIME = TIME + DT ；
TRANSIENT CIRCTOT TIME DT ；
DT = NEWDT ；
IF ( DT > 1. ) THEN ；
DT = 1. ；
ENDIF ；

absolutereallist
0.0 12000.0 12001.0 22000.0
power reallist
0.0 0.0 0.66 0.66 ；

option rocP 1. ；
period displor second 250.D0 ；
result circtot second 250.D0 ；
gofuel circtot ；
gerate charcray standard ；
repeat block4 nsteps ；
time = time + dt ；
transient circtot time dt ；
dt = newdt ；
if ( dt > 1. ) then ；
dt = 1. ；
endif ；

absolutereallist
0.0 12000.0 12001.0 22000.0
power reallist
0.0 0.0 0.66 0.66 ；

option rocP 1. ；
period displor second 250.D0 ；
result circtot second 250.D0 ；
gofuel circtot ；
gerate charcray standard ；
repeat block4 nsteps ；
time = time + dt ；
transient circtot time dt ；
dt = newdt ；
if ( dt > 1. ) then ；
dt = 1. ；
endif ；
B.2. RESTART INPUT FOR THE DRY PHASE

\[ g_{\text{inPF}} = g_{\text{inPF0}}/g_{\text{inPF0}} \times 5.1711 \exp (-0.087 \times \text{distanew}) ; \]
\[ g_{\text{he}} = g_{\text{he0}}/g_{\text{inPF0}} \times 5.1711 \exp (-0.087 \times \text{distanew}) ; \]
\[ g_{\text{c2}} = g_{\text{c2c0}}/g_{\text{inPF0}} \times 5.1711 \exp (-0.087 \times \text{distanew}) ; \]
\[ C_1 = g_{\text{c2}}/g_{\text{c1}} ; \]

POWER
\[ \text{ExtWaM1} \quad \text{gam_co} \]

**ABSOLUTE REALLIST**
0.0 22000.0

**POWER REALLIST**
C1 C1 ;

\[ P_{\text{HE}} = (r_{\text{inc}} \times g_{\text{hea}} \times 1000) ; \]
\[ P_{\text{IN}} = (r_{\text{sst}} \times g_{\text{inPF}} \times 1000) ; \]
\[ P_{\text{EL}} = (r_{\text{hel}} \times g_{\text{he}} \times 1000) ; \]
\[ P_{\text{OU}} = (r_{\text{sst}} \times g_{\text{ouPF}} \times 1000) ; \]

**EXCPOWER HEATER**
INCON718

**RELATIVE REALLIST**
0.0 22000.0

**POWER REALLIST**
1.0 1.0

**PROFILE REALLIST**
0.00000 0.00000 0.00000 0.00000 0.00000
0.00000 0.00000 0.45639 0.47728 0.49842
0.51975 0.54125 0.57373 0.61722 0.66060
0.70347 0.74541 0.78598 0.82470 0.86106
0.89453 0.92454 0.95051 0.97181 0.98780
0.99779 1.00109 1.00109 0.99779 0.98779
0.97181 0.95050 0.92453 0.89451 0.86104
0.82467 0.78595 0.74537 0.70342 0.66054
0.61715 0.57364 0.51416 0.47717 0.45627
0.00000 0.00000 0.00000 0.00000 0.00000

**VOLPOWER P_{\text{HE}} ;**

**EXCPOWER FLA_M**
INOX316 INOX316

**RELATIVE REALLIST**
0.0 22000.0

**POWER REALLIST**
1.0 1.0

**PROFILE REALLIST**
0.00000 0.00000 0.00000 0.00000 0.00000
0.00000 0.00000 0.45639 0.47728 0.49842
0.51975 0.54125 0.57373 0.61722 0.66060
0.70347 0.74541 0.78598 0.82470 0.86106
0.89453 0.92454 0.95051 0.97181 0.98780
0.99779 1.00109 1.00109 0.99779 0.98779
0.97181 0.95050 0.92453 0.89451 0.86104
0.82467 0.78595 0.74537 0.70342 0.66054
0.61715 0.57364 0.51416 0.47717 0.45627
0.00000 0.00000 0.00000 0.00000 0.00000

**VOLPOWER P_{\text{IN}} P_{\text{EL}} P_{\text{OU}} ;**

\[ \text{distan0} = \text{distanew} ; \]
\[ \text{MESSAGE } \text{‘distance vs core =’ distanew} ; \]
\[ \text{MESSAGE } \text{‘power of fuel (W/cm) =’ LHGR} ; \]
\[ \text{MESSAGE } \text{‘TEMPERATURE cladding (middle)=’ TGAIRMES} ; \]
\[ \text{WRITE distanew XUSER 101} ; \]
\[ \text{ENDIF} ; \]

******
* Activation of the subroutine UTIL to take into account the radiative heat transfer
******

UTIL1 ;

******
* End of temperature regulation
******

PRES2 = VALUE PRESSURE VOLTOP SUP ;

**MESSAGE**
‘PRESSURE VOLTOP’ PRES2 ;

**MESSAGE**
‘IPOWER8 IS’ IPOWER8 ;

******
* Power generated by cladding oxidation
* on internal side (W/cm)
******

POWE1 = VALUE POWEROXE CHARCRAY 1 ;
POWE2 = VALUE POWEROXE CHARCRAY 2 ;
POWE3 = VALUE POWEROXE CHARCRAY 3 ;
POWE4 = VALUE POWEROXE CHARCRAY 4 ;
POWE5 = VALUE POWEROXE CHARCRAY 5 ;
POWE6 = VALUE POWEROXE CHARCRAY 6 ;
POWE7 = VALUE POWEROXE CHARCRAY 7 ;
POWE8 = VALUE POWEROXE CHARCRAY 8 ;
POWE9 = VALUE POWEROXE CHARCRAY 9 ;
POWE10 = VALUE POWEROXE CHARCRAY 10 ;
POWE11 = VALUE POWEROXE CHARCRAY 11 ;
POWE12 = VALUE POWEROXE CHARCRAY 12 ;
POWE13 = VALUE POWEROXE CHARCRAY 13 ;
POWE14 = VALUE POWEROXE CHARCRAY 14 ;
POWE15 = VALUE POWEROXE CHARCRAY 15 ;
POWE16 = VALUE POWEROXE CHARCRAY 16 ;
POWE17 = VALUE POWEROXE CHARCRAY 17 ;
POWE18 = VALUE POWEROXE CHARCRAY 18 ;
POWE19 = VALUE POWEROXE CHARCRAY 19 ;
POWE20 = VALUE POWEROXE CHARCRAY 20 ;
POWE21 = VALUE POWEROXE CHARCRAY 21 ;
POWE22 = VALUE POWEROXE CHARCRAY 22 ;
POWE23 = VALUE POWEROXE CHARCRAY 23 ;
POWE24 = VALUE POWEROXE CHARCRAY 24 ;

* Power generated by cladding oxidation
POW1 = VALUE POWEROXI CHARCRAY 1 ;
POW2 = VALUE POWEROXI CHARCRAY 2 ;
POW3 = VALUE POWEROXI CHARCRAY 3 ;
POW4 = VALUE POWEROXI CHARCRAY 4 ;
POW5 = VALUE POWEROXI CHARCRAY 5 ;
POW6 = VALUE POWEROXI CHARCRAY 6 ;
POW7 = VALUE POWEROXI CHARCRAY 7 ;
POW8 = VALUE POWEROXI CHARCRAY 8 ;
POW9 = VALUE POWEROXI CHARCRAY 9 ;
POW10 = VALUE POWEROXI CHARCRAY 10 ;
POW11 = VALUE POWEROXI CHARCRAY 11 ;
POW12 = VALUE POWEROXI CHARCRAY 12 ;
POW13 = VALUE POWEROXI CHARCRAY 13 ;
POW14 = VALUE POWEROXI CHARCRAY 14 ;
POW15 = VALUE POWEROXI CHARCRAY 15 ;
POW16 = VALUE POWEROXI CHARCRAY 16 ;
POW17 = VALUE POWEROXI CHARCRAY 17 ;
POW18 = VALUE POWEROXI CHARCRAY 18 ;
POW19 = VALUE POWEROXI CHARCRAY 19 ;
POW20 = VALUE POWEROXI CHARCRAY 20 ;
POW21 = VALUE POWEROXI CHARCRAY 21 ;
POW22 = VALUE POWEROXI CHARCRAY 22 ;
POW23 = VALUE POWEROXI CHARCRAY 23 ;
POW24 = VALUE POWEROXI CHARCRAY 24 ;

***************************************
* power generated by cladding oxidation
* on external side (W/cm)

POTOTE = 2.5*(POWE1+POWE2+POWE3+POWE4+POWE5 +
POWE6+POWE7+POWE8+POWE9+POWE10 +
POWE11+POWE12+POWE13+POWE14+POWE15 +
POWE16+POWE17+POWE18+POWE19+POWE20+POWE21+POWE22+POWE23+POWE24) ;

***************************************
* power generated by cladding oxidation
* on internal side (W/cm)

POTOTI = 2.5*(POWI1+POWI2+POWI3+POWI4+POWI5 +
POWI6+POWI7+POWI8+POWI9+POWI10 +
POWI11+POWI12+POWI13+POWI14+POWI15 +
POWI16+POWI17+POWI18+POWI19+POWI20+POWI21+POWI22+POWI23+POWI24) ;

* flag to indicate if rupture has occurred
RUPT = VALUE INDRUP CHARCRAY ;

* node where the rupture has occurred
RUPT = VALUE INDRUP CHARCRAY ;

* time when the rupture occurs.
T_RUP = TIME ;

* temperature of external cladding when the
* rupture occurs.
TEMP_RUP = VALUE WALLTEMP CHARCRAY RUPT ;

IF ((RUPT EQ 1) AND (IPower7 EQ 0));
  T_RUP = TIME ;
  TEMP_RUP = VALUE WALLTEMP CHARCRAY RUPT ;
  IPower7 = 1 ;
ENDIF ;

WRITE T_RUP XUSER 300 ;
WRITE TEMP_RUP XUSER 305 ;

MESSAGE ‘FLAG OF THE RUPTURE’ RUPT ;
MESSAGE ‘NODE OF RUPTURE’ RUPT ;
MESSAGE ‘TIME OF RUPTURE’ T_RUP ;
MESSAGE ‘TEMPERATURE OF RUPTURE’ TEMP_RUP ;

MESSAGE ‘CALCULATION OF THE OXIDATION POWER’

*TOTAL power generated by cladding oxidation (W)

OXIPow = POTOTE + POTOTI ;

WRITE OXIPow XUSER 214 ;
WRITE TOTOTOXY XUSER 306 ;
WRITE THICCLA XUSER 307 ;
WRITE OXYRAT XUSER 308 ;

TIME = NEWTIME ;
IF ( TIME > 17600. ) THEN ;
  IF ( TIME > T.2 ) THEN ;
    QUIT BLOCK4 ;
  ENDIF ;
ENDIF ;

lost_bot = VALUE TOTLOSS FlaskBot ;
lost_top = VALUE TOTLOSS FlaskTop ;
WRITE lost_bot INJECVOL ca_volb ;
WRITE lost_top INJECVOL ca_volt ;
*t_bot = VALUE LIQTEMP volbot INF ;
t_top = VALUE LIQTEMP voltip INF ;
WRITE t_bot TEXT Flaskbot -1 ;
WRITE t_top TEXT Flashtop -1 ;

END BLOCK4 ;

SAVE 311 append ;
*
END EXEC;
## Nomenclature

### Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Area</td>
</tr>
<tr>
<td>$Bi$</td>
<td>Biot number</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat at constant pressure</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter</td>
</tr>
<tr>
<td>$D_h$</td>
<td>Hydraulic diameter</td>
</tr>
<tr>
<td>$E$</td>
<td>Entrainment rate</td>
</tr>
<tr>
<td>$Gr$</td>
<td>Grashof number</td>
</tr>
<tr>
<td>$h$</td>
<td>Enthalpy</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>$Nu$</td>
<td>Nusselt number</td>
</tr>
<tr>
<td>$P$</td>
<td>Power, Pressure</td>
</tr>
<tr>
<td>$Pe$</td>
<td>Peclet number</td>
</tr>
<tr>
<td>$Pr$</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>$q''$</td>
<td>Heat flux per unit area</td>
</tr>
<tr>
<td>$q'''$</td>
<td>Heat flux per unit volume</td>
</tr>
<tr>
<td>$R$</td>
<td>Radius</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Stratification rate</td>
</tr>
<tr>
<td>$Ra$</td>
<td>Rayleigh number</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$St$</td>
<td>Stelton number</td>
</tr>
<tr>
<td>$u$</td>
<td>Velocity</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume</td>
</tr>
</tbody>
</table>
R  Perfect gas constant

**Greek symbols**

α  Void fraction

ε  Creep strain

ε  Radiation heat transfer coefficient

Γ  Mass flux

Λ  Fuel heat-up rate

μ  Dynamic viscosity

Ω  Resistance

ρ  Density

σ  Surface tension

σes  Elastic stress

σsb  Stefan-Boltzmann constant

ω  Maximum cladding elongation

ζ  Thickness

**List acronyms**

BWR  Boiling Water Reactor

CATHARE  Code for Analysis of THERmalhydraulics during an Accident of Reactor and Safety Evaluation

CEA  Commissariat à l’énergie atomique et aux énergies alternatives

CHF  Critical Heat Flux

DBA  Design Basis Accident

DD  Displacement Device

ECCS  Emergency Core Cooling System

EDF  Électricité de France

IAEC  Israel Atomic Energy Agency

IAEC  Israel Atomic Energy Association

IRSN  Institut de Radioprotection et de Sûreté Nucléaire

JHR  Jules Horowitz Reactor

LHGR  Linear Heat Generation Rate
### B.2. RESTART INPUT FOR THE DRY PHASE

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOCA</td>
<td>Loss of Coolant Accident</td>
</tr>
<tr>
<td>LWR</td>
<td>Light Water Reactor</td>
</tr>
<tr>
<td>MOX</td>
<td>Mixed Oxide Fuel</td>
</tr>
<tr>
<td>NFZ</td>
<td>Neutron Flux Zone</td>
</tr>
<tr>
<td>ONB</td>
<td>Onset of Nucleate Boiling</td>
</tr>
<tr>
<td>PSD</td>
<td>Preventive Shut Down</td>
</tr>
<tr>
<td>PWR</td>
<td>Pressurized Water Reactor</td>
</tr>
<tr>
<td>RCS</td>
<td>Reactor Coolant System</td>
</tr>
<tr>
<td>STST</td>
<td>Stainless steel</td>
</tr>
<tr>
<td>TLF</td>
<td>Thermosiphon Liquid Flow</td>
</tr>
<tr>
<td>VVER</td>
<td>Vodo-Vodyanoi Enegetichesky Reactor</td>
</tr>
</tbody>
</table>

### Subscript

- **α**: Associated to the alpha phase in the zirconium medium
- **β**: Associated to the beta phase in the zirconium medium
- **b**: Associated to the fuel cladding burst
- **CHF**: Associated to the critical heat flux
- **clad**: Associated to the fuel cladding
- **cold**: Associated to the cold channel
- **cond**: Associated to the conduction
- **con**: Associated to the convection
- **cool**: Associated to the cooling channel
- **DD**: Associated to the displacement device
- **EH**: Associated to the electrical heater
- **e**: Associated to the external side
- **fail**: Associated to the fuel cladding failure
- **FST**: Associated to the flow separation tube
- **fuel**: Associated to the fuel sample
- **gap**: Associated to the fuel gap
- **g**: Associated to the gas phase
- **hot**: Associated to the hot channel
<table>
<thead>
<tr>
<th>Abbr.</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>hp</td>
<td>Associated to the hot point</td>
</tr>
<tr>
<td>IPF</td>
<td>Associated to the inner pressure flask</td>
</tr>
<tr>
<td>i</td>
<td>Associated to the internal side</td>
</tr>
<tr>
<td>l</td>
<td>Associated to the liquid phase</td>
</tr>
<tr>
<td>mfs</td>
<td>Associated to the minimum film boiling</td>
</tr>
<tr>
<td>mix</td>
<td>Associated to the liquid-gas mixture</td>
</tr>
<tr>
<td>m</td>
<td>Associated to the mean value</td>
</tr>
<tr>
<td>nb</td>
<td>Associated to the nucleated boiling</td>
</tr>
<tr>
<td>OPF</td>
<td>Associated to the outer pressure flask</td>
</tr>
<tr>
<td>oxy</td>
<td>Associated to the oxidation</td>
</tr>
<tr>
<td>rad</td>
<td>Associated to the radiation</td>
</tr>
<tr>
<td>sat</td>
<td>Associated to the saturation condition</td>
</tr>
<tr>
<td>sys</td>
<td>Associated to the entire system</td>
</tr>
<tr>
<td>v</td>
<td>Associated to the vapor phase</td>
</tr>
<tr>
<td>w</td>
<td>Associated to the wall</td>
</tr>
</tbody>
</table>
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