MASTER THESIS:

Simulation of transient dryout heat transfer in the HWAT loop using the TRACE code

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TRITA – FYS 2012:55
ISSN 0280-316X
ISRN KTH/FYS/--12:55—SE

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Abstract:

In this master thesis suitability of TRACE code was examined for prediction of dryout under transient conditions. The result is that TRACE can be used for this purpose with satisfactory results. For the given geometry (round pipes) it was found that the best correlation was BIASI correlation.

A TRACE model of HWAT was also created in order to support further research at KTH. The model was tested for broad range of conditions to ensure its stability. Among other things, the novelty of the model is its control structure that makes execution of transient scenarios possible. The model is stable in wide range of variables for pressures over 40 bars and is thus applicable for research given the fact that pressures of interest are between 70 and 90 bars.

Finally, TRACE test section model is compared with Westinghouse inhouse codes, VIPRE and BISON with satisfactory results. It was found that TRACE and BISON follow each other well, with BISON predicting slightly higher mass flow collapse during rapid pressure transients. VIPRE was somewhat off owning to differences in modeling of mass flow and power transients.
# Contents

**Mandate:**

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1. **Introduction**
   - 1.1. Dryout ............................................................................................................................... 6
   - 1.2. Dryout correlations ................................................................................................................ 7
   - 1.3. TRACE code overview ............................................................................................................ 8
   - 1.4. TRACE code calculation logic .............................................................................................. 8
   - 1.4.1. Field equations .................................................................................................................... 8
   - 1.4.2. Heat conduction equations ................................................................................................ 9
   - 1.4.3. Drag models ....................................................................................................................... 9
   - 1.4.4. Interfacial heat transfer model ............................................................................................ 10
   - 1.4.5. Wall heat transfer models .................................................................................................. 11
   - 1.5. SNAP ....................................................................................................................................... 11
   - 1.6. High-pressure Water Test loop (HWAT) ............................................................................... 12

2. **Approach and organization of the work effort**
   - 2.1. Phases of the work ............................................................................................................ 14
   - 2.2. Brief comment on the phases ........................................................................................... 14
   - 2.3. Technical work .................................................................................................................. 14

3. **Creation of the model**
   - 3.1. Reducing reliance on table controlled thermal components ............................................ 16
   - 3.2. Control units ..................................................................................................................... 16
   - 3.3. Modeling condenser .......................................................................................................... 18
   - 3.4. Dynamic model of the condenser ....................................................................................... 19
   - 3.5. Model summary ................................................................................................................ 20
   - 3.6. Stability trials ...................................................................................................................... 21

4. **Onset of dryout: stationary measurements**
   - 4.1. TRACE CHF correlations .................................................................................................. 24
   - 4.1.1. IPPE ................................................................................................................................... 24
   - 4.1.2. GE-CISE .......................................................................................................................... 24
   - 4.1.3. Biasi correlation ............................................................................................................... 25
   - 4.2. Test section measurements ............................................................................................... 27
   - 4.4. Result comparison and assessment .................................................................................. 31

5. **Transient measurements, uniform power distribution**
   - 5.1. Raw input data: .................................................................................................................. 32
   - 5.2. Scenarios overview .......................................................................................................... 36
   - 5.2.1. Load rejection ................................................................................................................... 36
   - 5.2.2. Pump trip ......................................................................................................................... 36
   - 5.3. Approach to the testing and aims ...................................................................................... 37
   - 5.4. Test geometry and scaling ............................................................................................... 37
5.5. TRAC E model ..................................................................................................................................... 39
5.6. Flow data ......................................................................................................................................... 41
5.7. Dryout assessment ............................................................................................................................. 41
  5.7.1. Original BIASI correlation ............................................................................................................. 42
  5.7.2. Extension of application of Biasi correlation ................................................................................... 43
5.8. Results .............................................................................................................................................. 45
  5.8.1. Pump trip ................................................................................................................................... 45
  5.8.2. Load rejection ............................................................................................................................. 49
6. Transients measurements, non-uniform power distribution ............................................................. 50
  6.1. Pump trip ................................................................................................................................... 50
  6.2. Load rejection ................................................................................................................................ 51
7. Transient analysis in the loop, uniform-power distribution ............................................................... 53
  7.1. Pump trip ................................................................................................................................... 53
  7.2. Load rejection ................................................................................................................................ 56
8. Comparison of TRACE with other codes ............................................................................................. 58
  8.1. Background ................................................................................................................................ 58
  8.2. VIPRE-W and BISON ........................................................................................................................... 59
  8.3. Modification to the TRACE model from previous chapters .................................................................. 59
  8.4. Preliminary result comparison .............................................................................................................. 60
    8.4.1. Load rejection ............................................................................................................................. 60
    8.4.2. Pump trip ................................................................................................................................... 63
  8.5. Analysis of TRACE and VIPRE condensation models ........................................................................ 65
    8.5.1. Uniform power distribution ........................................................................................................... 65
    8.5.2. Non – uniform power distribution ............................................................................................... 68
    8.5.3. Constant quality at the inlet with no heating .................................................................................. 70
    8.5.4. TRACE and MEFISTO-T dryout prediction ...................................................................................... 73
9. Conclusion .......................................................................................................................................... 74
APPENDIX A: PROBLEM INVESTIGATION ................................................................................................. 76
APPENDIX B: PUMP TRIP RESULTS ........................................................................................................... 84
APPENDIX C: PUMP TRIP DRYOUT INITIATION ....................................................................................... 91
APPENDIX D: LOAD REJECTION ................................................................................................................ 98
APPENDIX E: CHF PREDICTION, NEW AND OLD BIASI .......................................................................... 105
APPENDIX F: PUMP TRIP, NON-UNIFORM POWER ................................................................................ 108
APPENDIX G: LOAD REJECTION, NON-UNIFORM POWER ..................................................................... 114
APPENDIX H: DATA MANAGEMENT ........................................................................................................ 120
LITERATURE ........................................................................................................................................... 122
A personal note from the author:

During the past six months, the author has had honor to give his humble contribution to the work that is ongoing on both KTH and Westinghouse. It is to be hoped that work provided will make future work at KTH easier and that it will contribute with the new knowledge in the field.

During the whole report the word “we” is used. This is not only due to writing convention but rather to stress the fact that the work would never have been possible without the help of dedicated people I have had honor to work with. All omissions, errors and deficiencies in this text are author’s responsibility alone.

The work that lies before you would never have been possible without unselfish dedication and patience of my two supervisors: Henryk Anglart (KTH) and Jean-Marie Le Corre (Westinghouse). They always had time for my sometimes very exhausting briefings and were always available for questions and ready to give advices.

I would also like to thank Ionut Anghel whose door were always opened for his younger colleague and who provided invaluable input in this thesis, both with advices and the steady state model which has been used as starting point in my further work.

My work was commissioned and sponsored by Westinghouse which took me onboard and gave me full confidence which was necessary for success of my work. For me as a young nuclear engineer this was a privilege which was never taken lightly. I hope that I have justified the trust that was put to me and thank Stig Andersson, chief of section I was affiliated with (BTA) for giving me this opportunity.

Finally last, by in no way least I would like to thank my family and all others that have supported me, both financially and morally during my two years at KTH. Without their dedicated support I would never have succeed in realizing my dream, a dream of becoming a nuclear engineer.

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Mandate:

The possibility of the occurrence of dryout is one of the important limitations in Boiling Water Reactors (BWR). Since dryout is not allowed under stationary and transient BWR operations, it is important to be able to predict the thermal margins in the reactor cores under such conditions. To this end proper models are developed to calculate the limiting conditions under which the dryout occurs. Such models need to be validated against measurements. This procedure is very well established for BWRs under normal stationary conditions. However, under transient conditions, especially when pressure transients are considered, the prediction methods still require some development and experimental data are very scarce.

The transient dryout/postdryout measurements can be performed in the NRT laboratory using the HWAT loop. The suggested project consists of (1) a critical review of available transient modelling approach and (2) calculations in preparation for these experiments using the TRACE system code and, if time allows, the Westinghouse MEFISTO-T film flow analysis code. In the project, different heat loads and flow conditions will be examined in order to establish the expected heat transfer behaviour in the loop, including dryout occurrence. The results will be used in the decision on experimental setup and conditions.
1. **Introduction**

1.1. **Dryout**

Figure 1 represents a cylindrical pipe which is heated uniformly. At the inlet of the pipe the fluid is subcooled and there is no boiling. As thermal energy is transferred to the fluid, its temperature will increase and subcooled boiling will start, that is first bubbles of vapor will appear even though bulk temperature is less than saturation temperature. Temperature of the wall of the pipe is slightly superheated. [1]

Once the bulk of the fluid becomes saturated, saturated boiling is initiated. Bubbles take more and more of the volume of the pipe eventually restricting liquid phase in the areas near the wall. This is called *annular configuration* and corresponding flow *annular flow*. In this setting, water is wetting the wall of the pipe while vapor forms the core of the flow. Heat transfer mechanism changes from boiling to heat transfer through liquid film and finally evaporation at the other surface. Some authors (e.g Collier and Thome) indeed object to this process being called annular boiling instead choosing in their opinion more correct name of *two-phase forced convective region* alluding to the fact that it is evaporation and forced convection that is doing heat transfer, and not boiling. [1, 2]

The film wetting the wall will be reduced due to evaporation of liquid but also entrainment, that is, detachment of droplets and their diffusion to the void core. By the same token, some droplets will join with the liquid film, increasing its thickness, a process that is called deposition. [3]

At some point this liquid film will reduce in thickness and altogether disappear upon which phenomena called dryout will occur. Since liquid film is gone heat transfer from the wall to the vapor and entrained droplets is predominantly conducted on wall-vapor interface. Since this heat transfer mechanism is significantly worse than the one encountered in boiling or annular region wall temperature will increase dramatically as can be seen in Figure 1. [1, 3]

It goes without saying that dryout is something that should be avoided since such a rapid increases of wall temperature are undesirable from the point of nuclear safety. Cladding of the nuclear fuel could suffer damage for example with fuel damage being a consequence. It is therefore no wonder that a significant effort has been directed into predicting dryout or CHF (critical heat flux, heat flux that will cause dryout) as it is also called. As a result much is known about occurrence of dryout under stationary conditions.[1, 4]

Our aim in this paper will be to adapt this body of data obtained in steady-state experiments to transient cases that have been provided to us.

By doing this we would be able to ascertain our margins more precisely making it possible to operate reactor at higher power without compromising on safety.
1.2. Dryout correlations

As mentioned before, significant effort has been put into predicting dryout occurrence. Two major types of correlations are empirical and mechanistic. Empirical correlations predict occurrence of dryout based on experiments done in test installations. Mechanistical correlations on the other hand try to describe nature of the process and in such way predict its onset. [1, 3]

In the first part of this report we will relay on empirical correlations, while in later phases we will also look into possibility of using mechanistical ones.

Empirical correlations are made by conducting experimental measurements and systematizing data in a function that can be applied to predict dryout in real-world conditions. These correlations are in general limited by extensiveness of their database, that is, spread of parameters used in the experiments. These correlations might also have other limitations such as geometry and het-flux distribution and almost all of them are derived for steady state cases. [1]

Focusing now on empirical correlations, they can be further classified in two types of correlations:

- Local, generally being of the form $q_{CHF}=f(x,...)$ where $q_{CHF}$ is critical heat flux and $x$ local quality
- Global, taking into consideration processes that occur on the whole boiling length, form: $x=f$

Local correlations are more or less obsolete and focus in our paper as well as in modern research is on global correlations. [4, 5]
1.3. TRACE code overview

TRACE is an abbreviation for TRAC/RELAP Advanced Computational Engine. As its name suggests, it has its origin in other codes namely TRAC (both PWR and BWR), RELAP5 as well as RAMONA. The aim of the developers was to develop modern, maintainable and extensive code while at the same time maintaining compatibility with the models made in abovementioned codes. The program is component oriented analysis code designed to analyze transients and accidents. The code can also be coupled to external codes for more extensive analyses (e.g. CONTAIN, PARCS). [5-8]

Development of TRACE started in 1997 with significant refurbishment and modernization of than in use TRAC-P code to Fortran 95. The development has continued since then and is still ongoing. The most recent version is version no 5 that we are using in this paper. [9]

TRACE is a finite volume, two-fluid compressible flow code with one, two and three dimensional flow geometry, using 6-equations modeling approach. Having said this, most of the components are modeled with a simple one-dimensional model with 3D modeling being reserved for reactor vessel. In our models one-dimensional modeling is used. [5, 8]

It would be impossible to mention here all principles and assumptions that TRACE uses. Interested reader is directed to the manual [5]. We will however mention some of them as need arises. A general overview is given in 1.4.

Even though it is based on old codes TRACE in itself is new code and not much data is available regarding its assessment and performance. The data that exist however suggest that TRACE is good in predicting behavior of installations both under steady state and transient conditions with reasonable accuracy, under condition that it is applied in predicted area of operation. [8, 9]

Most extensive transient assessment we were able to find was done in Taiwan in June 2010. In this assessment complex model of the whole plant was done in TRACE and predicted results compared with measured ones during plant start-up. Assessment results were very favorable. [8]

How TRACE behaves during more extreme occurrences such as LOCA and similar is still not researched properly, but conclusions from current batch of data is that TRACE can be unduly conservative in some cases, a problem that remains to be solved in future versions. [9]

1.4. TRACE code calculation logic

During our thesis work it was noted that concerned parties expressed considerable interest in TRACE calculation logic. The opinion of the author is however that including all relevant information is neither plausible nor practical. To address this interest without going into too many details this will be presented in introductory part. Interested reader will further be directed to the literature that will provide him or her with more details. Specific things that are of interest to this thesis will of course be treated in more details. The text that follows is more or less borrowed from [5] and adapted for our case where applicable.

1.4.1. Field equations

Derivation of the equation set used in TRACE starts with single phase Navier – Stokes equations in each phase, and jump conditions between the phases. These equations are further time averaged to attain set
of two-fluid, two-phase conservation equations. Reader interested in these derivations is directed to the following papers[10-12] or TRACE user manual. [5]

The basic two-fluid, two-phase field equation set consists of separate mass, energy and momentum conservations for the liquid and vapor fields. This gives a starting point for six partial differential equations to model steam or water flows. [5]

The TRACE code, similar as other codes, uses a quasi-steady approach to the heat transfer coupling between the wall and the fluid as well as the closure relations for interfacial and wall-to-fluid heat transfer and drag. This approach assumes detailed knowledge of the local fluid parameters and ignores time dependencies so that the time rate of change in the closure relationships becomes infinite and the time constants are zero for every time step. This approach is simple and does not require previous knowledge of given transient. [5]

1.4.2. Heat conduction equations

TRACE is designed to treat heat scenarios in both PWR and BWR. In our case what we are concerned about is a simple heated pipe structure. However, the problem is not trivial. The code must calculate the heat conduction in the pipe material and simulate correctly heat transfer in thermal – energy transport. Also, the passive solid structures, such as piping walls as well as internal structures, represent significant metal masses that can store or release large amounts of thermal energy depending upon other factors. [5]

TRACE of course uses Fourier equation of heat equation [2, 5]:

\[ \rho \cdot c_p \cdot \frac{\partial T}{\partial t} = \nabla(k \nabla T) + q'' \]

Where:

\( \rho \) - density

\( c_p \) - heat capacity

\( T \) - temperature

\( k \) - heat conductivity

\( q'' \) - heat flux

Here it is implicitly assumed that product of density and heat capacity is constant for the purpose of taking time derivative.

1.4.3. Drag models

Given the fact that TRACE is two-fluid, two-phase model it is to be expected that there will be some friction between phases as well between fluid and solids. Closure of these equations thus requires that we specify interfacial drag coefficient and the phasic wall drag coefficients. Typically only one of these wall drag coefficients has non-zero value (either vapor or liquid), as it can be concluded from Figure 1. In the event of annular flow for example, only liquid is in contact with wall, rendering vapor-wall drag equal to 0. Both interfacial and wall drag depend on flow regime and TRACE uses involved logic to determine flow type in question and determine drag coefficients accordingly. More on this can be read in the manual. [5]
1.4.4. **Interfacial heat transfer model**

Interfacial heat transfer models are required for closure of both the mass and energy equations. In TRACE code, the interfacial mass transfer rate per unit volume, here denoted as $\Gamma$, is defined as the sum of two terms: mass transfer rate from interfacial heat transfer and mass transfer rate from subcooled boiling. [5]

$$\Gamma = \Gamma_i + \Gamma_{\text{sub}}$$

Where:

- $\Gamma_i$ - mass transfer per unit volume due to interfacial heat transfer.
- $\Gamma_{\text{sub}}$ - mass transfer per unit volume due to subcooled boiling.

We will briefly mention mass transfer due to subcooled boiling in section 1.4.5. Here we briefly discuss mass transfer due to interfacial heat transfer.

When heat is transferred across interface and liquid part of mixture is close to saturation or saturated, part of the liquid will become vapor and mass transfer between interfaces will occur. Mathematically this can be written in the following way [5]:

$$\text{HEAT LATENT EXCHANGED HEAT} = \frac{\text{HEAT EXCHANGED}}{\text{LATENT HEAT}}$$

Here denominator is modified latent heat depending on the situation defined in the following way [5]:

$$h^*_l - h^*_v = \begin{cases} h_{l,\text{sat}} - h_i; & \Gamma > 0 \\ h_v - h_{\text{sat}}; & \Gamma < 0 \end{cases}$$

In a sense this modification is rather intuitive and easy to understand. When more vapor is produced and $\Gamma$ is positive "latent heat" is defined as energy needed to warm up liquid to saturation and further evaporate it. In the opposite case it is defined as energy needed to be taken away from the vapor to take it down to energy level of prevailing liquid. Subscript "sat" denotes saturation conditions. [5]

Heat exchange between phases and interface is defined in the following way [5]:

$$q_{li}^i = h_i \cdot A_i^* \cdot (T_i - T_w)$$ - heat exchange from liquid phase to the interface

$$q_{vi}^i = h_i \cdot A_i^* \cdot (T_v^0 - T_w)$$ - heat exchange from vapor phase to the interface

Where:

- $h_i, h_v$ - heat transfer coefficients (determined depending on flow regime)
- $A_i^*$ - interface area per unit volume
- $q_{li}^i = h_i \cdot A_i^* \cdot (T_i - T_w)$

In TRACE, the liquid-vapor interface is assumed to be at the saturation temperature corresponding to the bulk vapor partial pressure (i.e. not total pressure) for the mass-energy computational cell. [5]
1.4.5. Wall heat transfer models

TRACE contains staggering amount and correlations to cover all eventualities that can arise in its area of application. These models can be divided in [5]:

- Pre – CHF heat transfer: models of wall – liquid convection, nucleate boiling and subcooled boiling.
- Critical Heat Flux (CHF): models for the peak heat flux in the nucleate boiling heat transfer regime and the wall temperature at which it occurs (4.1)
- Minimum film boiling temperature: the temperature above which wall-liquid contact does not occur.
- Post-CHF heat transfer: models for transition and film boiling heat transfer.
- Condensation heat transfer: models for film condensation and the non – condensable effect.

Wall heat transfer models are required for closure of both the mass and energy equations. The phasic energy equations contain the terms that represent heat transfer per unit volume from the wall to the liquid and from the wall to the vapor. These are computed from [5]:

\[
q_{wi} = h_{wi} \cdot A_w \cdot (T_w - T_i) \quad \text{- heat transfer rate per unit volume from the wall to the liquid}
\]

\[
q_{wst} = h_{wst} \cdot A_w \cdot (T_{st} - T_{sat}) \quad \text{- heat transfer rate per unit volume during boiling process}
\]

\[
q_{wg} = h_{wg} \cdot A_w \cdot (T_w - T_g) \quad \text{- heat transfer rate per unit volume from the wall to the vapor}
\]

Nomenclature is the same as in 1.4.4 with surface area per volume being calculated as \(4/D_h\).

Normally, only one of the phasic wall heat transfer coefficients is zero as only one phase is in contact with the wall as explained previously. [5]

In the chapter 1.4.4. we have mentioned \(\Gamma_{\text{sub}}\) - mass transfer per unit volume due to subcooled boiling. Now it’s the time to define it as well [5]:

\[
\Gamma_{\text{sub}} = \frac{h_{wst} \cdot (T_w - T_i) \cdot A_w}{h_{fg}}
\]

Which represents vapor generation rate at the wall due to subcooled nucleate boiling. Latent heat is defined as in 1.4.4. [5]

It is apparent that the biggest challenge is determining heat transfer coefficients (marked as h in previous formulas). To this end, TRACE possess a library of heat transfer correlations and a selection logic algorithm. Together these produce a continuous heat transfer surface that is used to determine the phasic heat fluxes and hence heat transfer coefficients. [5]

1.5. SNAP

TRACE is advance computational engine that processes input data and generates models. In the past, input models were hard to make and were generated by writing long text ASCII files where all necessary geometry data and parameters were inputted. [13]

In order to simplify this procedure TRACE can be paired with a graphic user interface (GUI) called SNAP, which is acronym for Symbolic Nuclear Analysis Program. With this tool, building of model is easier and faster. SNAP was used extensively in all our models. [13]
1.6. **High-pressure Water Test loop (HWAT)**

Future work will be conducted in so called HWAT loop. One of the aims of our work is to devise effective model (chapter 3) and assess model’s suitability (chapter 7). It is however appropriate to begin by describing the device in question.

The loop was designed to operate on pressures of up to 250 bars and working fluid temperature of up to 340°C. All parts in contact with water are made of stainless steel. The only exception to this rule is test section that is made of INCONEL. Different lengths of test sections may be accommodated but the maximum length is 7.5m. [14]

The loop has two pre-heaters, one stronger and one small. Stronger pre-heater has power of 155 kW. Small pre heater is located directly in front of test section. The purpose of this pre-heater is to compensate for heat loss between main pre-heater and the test-section inlet. [14]

The working principle of the loop is as follows:

The water is injected by feed-pump that both supplies new fluid to the system and helps maintain desired pressure. If we want pressure increased, more water will be pumped into the system. In the event we want pressure reduced, water/vapor will be removed through relieve valves. Water than passes flow meter followed by flow regulating valve whereupon it is directed to the pre-heater. After this, water continues its journey towards test-section. However since distance from pre-heater to the test section is relatively long modest temperature drops occur on the order of kelvin. To compensate for this there is a small pre-heater just before the inlet to the test section. Water is than boiled in the test section. [14]

From the test section, the coolant flows towards condenser. The condenser has two separate circuits: a main circuit where the working fluid form the main loop condenses to liquid and second circuit where the level of the cooling water is controlled using two automatically operated vales. Both temperature of cooling water and water exiting condenser is measured continuously. To avoid pump cavitation water exiting condenser should have temperature of at least 30 degrees under saturation for the given pressure. [14]

Schematic drawing of the loop is presented in Figure 2.
Figure 2: HWAT schematics
2. **Approach and organization of the work effort**

2.1. **Phases of the work**

- Development of the workable model of HWAT loop
- Stability trials of the model under wide selection of parameters
- Stationary tests with both the whole loop and test section and comparison of obtained results
- Transient runs with data provided by Westinghouse in both test section and whole loop
- Brief comparison of results

2.2. **Brief comment on the phases**

One of the products of this thesis will be a model that will be used in future research of transient CHF. The ambition is that model is robust and easy to understand and use. The produced model will be tested and its stability analyzed in order to obtain area of its operation.

Following this, stationary CHF trials will be done. The aim here is to compare TRACE predictions with real-world data that have been obtained in measurements conducted at KTH in 1980s[15]. The aim here is to determine which of TRACE’s correlations gives best predictions as well as how precise predictions are. Furthermore we are also interested into finding out if there are significant differences between results obtained with test section with inlet and outlet conditions determined with boundary conditions and test section as a part of the whole loop. In another master thesis[16] this difference was noticed and we were interested to know if it will also appear in our model and what are its causes. Following this work, the most appropriate CHF correlation will be selected and work progress to the next phase.

Series of transient runs will be provided with the data provided by Westinghouse BTA division. The aim here will be to extract data of interest and compare it with data obtained in codes used by Westinghouse. Furthermore assessment of dryout margin will be given as well as in-depth dryout analysis.

All the tests will be executed in a simple test section with boundary conditions serving as inlet and outlet conditions. Some tests will also be simulated in the loop as a whole in order to observe how well the loop mimics experiments in the test section. In this case it is loop that has to provide conditions at the inlet and outlet, and not predetermined boundary conditions.

2.3. **Technical work**

Even though TRACE is very advanced code its data management code is very rudimentary. Plotting is limited to relatively simple and limited program called APT plotter. As a result, dedicated codes and scripts have been made for both import of quantities of interest into MATLAB and calculation of missing parameters. Some of this work is documented in appendix H.

Furthermore in order to accommodate request from Westinghouse special routine was written in order to make results readable for Westinghouse codes.
3. **Creation of the model**

In order to achieve aims set forth in this project it was first necessary to develop a model that can handle transient behavior.

The starting point of developing such a model was a static model that was available. [16, 17]

![Outline of the new model](image)

**Figure 3: Outline of the new model**

The major shortcomings of this model in terms of transient analysis are:
- Use of tables for control of thermal components and specifically
- Condenser modeled as table controlled thermal flux device

Using table controlled thermal components in principle means that all thermal structures are instructed when to supply thermal energy and how much of it. While this is arguably practical and straightforward way of modeling the system in question it is not useful in case of transient analysis that we are dealing with. Furthermore filling and adjusting this table for each and every test run with different parameters is clearly impractical even for stationary case given the large amount of experimental testing performed (more than 100 of different test runs performed only in stationary mode).

In the old model, condenser is modeled as a pipe with table controlled thermal structure (flux controlled). We believe however that more appropriate model would be constant surface temperature given the fact that condenser consists of a vessel containing boiling liquid on the outer side (Figure 3). It is namely well known that in case of boiling, surface temperature can be treated as being slightly higher than saturation temperature at that side [2]. To that end we developed completely new model for the condenser which we will discuss in chapter 3.3.
3.1. Reducing reliance on table controlled thermal components

In order to reduce reliance on table controlled components control blocks were used. Given the fact that control blocks can be sources of instability great effort has been invested to choose parameters wisely. Furthermore, loop has undergone weeks of testing to ensure stable operation in wide range of parameters.

Two components are controlled by two control blocks controlling:

- Pre-heater
- Condenser

The role of the pre-heater controlling control block is to ensure controlled temperature at the inlet of the test section. The roll of the condenser controlled control block is to ensure realistic dynamic behavior of the condenser (to be discussed later).

3.2. Control units

For the whole system two control blocks are employed; one for the condenser and one for the pre-heater. For the pre-heater PID (proportional, integral, derivative) controller was deployed. Testing experience as well as background research suggests that this controller is more stable than the alternative PI (to be discussed later).

Since control system plays such a crucial role in our model we believe that more detailed explanation of its structure and the way it operates is in order.

PID has two input parameters:

- Value that is desired for the controlled parameter
- Controlled parameter (Feedback)
Controlled parameter in our case is temperature at the pre-heater outlet while desired value is the value we want to have at the pre-heater’s outlet, which in its turn determines subcooling at the section’s inlet. Control unit calculates difference between attained value at the outlet and the desired value, which we will in continuation refer to as controller error. Controller applies correcting action (component action A) in order to eliminate controller error. PID calculates correcting action by using the following formula [18, 19]:

\[
A = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t)
\]

Where:
- \( K_p \) - proportional gain
- \( K_i \) - integral gain
- \( K_d \) - derivative gain
- \( e \) - controller error

The first term in the equation is proportional to error giving large component action for large error. Second term is integral in its nature and it corrects the phase of the change. For example, if proportional term is too slow in its approach integral term can increase this phase or vice-versa. Finally, differential term provides for gradual attainment of desired value without unnecessary oscillations or overshoots. [18, 19]

TRACE implementation [6]:

\[
A = G \left[ \Delta e + \frac{1}{\Delta t_d} \int \Delta edt + \Delta t_d \left( \frac{d\Delta F}{dt} \right) + \Delta e \right]
\]

As it can be seen, through variation of parameters \( G \) and \( \Delta t_d \) user can influence characteristics of control system. Optimization was rather tedious and involved and the author came to optimal parameters through tedious trial and error approach and use of custom-made MATLAB scripts in order to estimate stability and attainment times (time needed to achieve certain accuracy of controlled parameter). [19]

It suffices to say that there is no perfect control structure, nor parameters that suit all possible purposes. For example, too high proportional gain may give oscillating instabilities due to constant overshoots; too high integral gain may on the other hand make approach to the target value too fast causing repetitive overshoots. Finally, too high derivative gain may make controlling system too sluggish. Too weak gains may make control system too weak. [18, 19]

Everything that was said previously applies equally to PI controller with the difference that differentiating part is missing [6]. The reason that PI system was chosen for the condenser control is that significant amount of noise is expected in controlled variable (outlet temperature) due to numerical instabilities and PID controllers are sensitive to noise [18].

<table>
<thead>
<tr>
<th>Chosen controllers and their parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-heater</strong></td>
</tr>
<tr>
<td>Controller structure</td>
</tr>
<tr>
<td>G (gain)</td>
</tr>
<tr>
<td>( t_0 )</td>
</tr>
<tr>
<td>Controlled variable</td>
</tr>
<tr>
<td>Corrective action delivered via</td>
</tr>
</tbody>
</table>
3.3. **Modeling condenser**

In the opinion of the author the most sensible way of modeling the condenser is as a pipe with temperature controlled boundary condition (at the outside of the pipe).

![Diagram of system's condenser](image)

**Figure 5: System’s condenser**

The reason for this is the setup of the condenser in question which will have fluid boiling at the outside of the condenser pipe. Since heat transfer coefficient of boiling is significant it is common practice to assume that temperature of the wall is roughly equal to temperature of saturation at the pressure in question [2]. Since outside of the condenser pipe is at the atmospheric pressure the appropriate wall temperature would be $100^\circ$C $(373K)$. This outside wall temperature is achieved when water tank is filled with the water to the top and the whole volume of it is boiling.

All previously stated makes it quite apparent that modeling the condenser is a challenging task. We should be clear at this point that our aim is not to give high-level detail model of the condenser since this task would merit a report of its own. Instead, we will content ourselves with providing a model that will:

- Provide realistic temperature sink for the system
- Approximately emulate dynamic behavior of the condenser during transients

The simplest and most convenient way to model the condenser is to choose beforehand realistic outside temperature of the pipe. This approach requires no use of PI control logic described above and it is simple to understand. The downside is static behavior of the condenser. It is therefore another dynamic model has been developed and implemented. Nevertheless this alternative can be used as simplification or back-up option if the main model does not work.
3.4. **Dynamic model of the condenser**

Model assumes following about the condenser:

- The condenser is stabilizing component tending to retain subcoolig (liquid outlet temperature)
- In case of steam of higher quality (and therefore higher amount of energy stored in it) being introduced to the condenser, boiling on the outer side will intensify increasing heat transfer. We can think about this as increasing thermal demand on the condenser
- In the opposite case of introducing vapor of lower quality (and energy content) boiling will slow down and heat transfer will be less intensive.

![Figure 6: Symbolic representation of the condenser model](image)

If the previous three criteria are fulfilled our model can be used for dynamic approximation of the condenser.

The model is implemented with PI control unit, controlling surface temperature and monitoring liquid outlet temperature. If higher quality vapor is introduced to the system, control system will automatically reduce temperature of the pipe’s surface mimicking the second condition. If on the other hand opposite happens the temperature of the wall will be increased. Combined effect will be a stable condenser that tends to retain its outlet temperature (and thus subcoolig).

This model is of course simplification of the reality but we believe that it is better in modeling condenser’s dynamic behavior than the static model. Furthermore, user does not have to choose wall temperature, since control system will do that.

By choosing appropriate control system parameters stability of the control structure can be maintained. During our testing we have not managed to find any instabilities being caused by condenser control system. Furthermore, parameters (low gain) are conservatively chosen to guarantee stability. Nevertheless in case of instabilities, static model can be used.
3.5. **Model summary**

The static model from start was almost completely rewritten. Major changes are:

- Implementation of control logic.
- Condenser has been moved directly behind the test section to provide for better representation of the loop.
- Model rescaled and components reoriented to facilitate model usage in the future.
- Section between pre-heater and test section thermally insulated to avoid usage of second preheater.
3.6. **Stability trials**

Our ambition was to use our model to analyze transient behavior of the loop and the onset of dryout. However, precondition for such a tests was model stability at steady state. In order to assess stability of our model 132 test runs have been ran in the following broad range of variables:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>20 - 220 bar</td>
</tr>
<tr>
<td>Mass flow</td>
<td>0.03 - 1 kg/s</td>
</tr>
<tr>
<td>Quality</td>
<td>20 - 90%</td>
</tr>
</tbody>
</table>

**How we ran our tests**

Following parameters were used throughout testing:

- Condenser outlet temperature ("subcooling") 30°C subcooled
- Initial liquid temperature 40°C subcooled

**Identified issues:**

- **Problem 1:** All stabilities over 60 bars were conclusively linked to too low subcooling. All stabilities can be removed by increasing subcooling by 10 degrees.
- **Problem 2:** Intensive instabilities at condenser in experimental run 24. All stabilities can be removed by increasing subcooling by 10 degrees.
- **Problem 3:** Other instabilities under 40 bars. Currently unsolved.
- **Problem 4:** TRACE repeatedly crashes with little warning. Reducing time step does not work. Using steam tables solves this problem.

Investigation into these issues is presented in Appendix A:

On the following page summary of the tests is presented:

- Minor instabilities (accuracy of at least 0.1K attained)
- Explained instabilities
- Unexplained instabilities
STABILITY MAP
4. Onset of dryout: stationary measurements

Series of measurements were conducted to ascertain the onset of dryout in stationary conditions. Measurements were conducted for 15 different points featuring 2 different pipe lengths of the same diameter of 8.11 mm. Points were selected in order to give wide spread over different inlet conditions such as pressure, inlet subcooling and mass flow. In the following measurements it was noticed that points in the vicinity of critical pressures where more complicated to process as these required use of steam tables (as opposed to equations of state that are usually used) [6]. Given the fact that such high pressures would probably not be of any practical interest in our project we decided to discard these points leaving 10 points. Following points were used:

<table>
<thead>
<tr>
<th>RUN</th>
<th>G [kg/m²s]</th>
<th>M [kg/s]</th>
<th>TSUB</th>
<th>p [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>190</td>
<td>751.4</td>
<td>0.039</td>
<td>10.3</td>
<td>70.1</td>
</tr>
<tr>
<td>225</td>
<td>750.5</td>
<td>0.039</td>
<td>100.1</td>
<td>99.8</td>
</tr>
<tr>
<td>261</td>
<td>750.3</td>
<td>0.039</td>
<td>10.7</td>
<td>140.1</td>
</tr>
<tr>
<td>199</td>
<td>6034.8</td>
<td>0.312</td>
<td>9.4</td>
<td>69.6</td>
</tr>
<tr>
<td>234</td>
<td>6015.9</td>
<td>0.312</td>
<td>100.2</td>
<td>100.1</td>
</tr>
<tr>
<td>269</td>
<td>5060.1</td>
<td>0.259</td>
<td>9.9</td>
<td>139.9</td>
</tr>
<tr>
<td>1140</td>
<td>752.1</td>
<td>0.039</td>
<td>10.2</td>
<td>100.1</td>
</tr>
<tr>
<td>1184</td>
<td>751.8</td>
<td>0.039</td>
<td>9.5</td>
<td>140.2</td>
</tr>
<tr>
<td>1159</td>
<td>5021.7</td>
<td>0.259</td>
<td>100.6</td>
<td>99.8</td>
</tr>
<tr>
<td>1192</td>
<td>5008.5</td>
<td>0.259</td>
<td>10.4</td>
<td>140.0</td>
</tr>
</tbody>
</table>

Measurements from 190-269 were conducted in 2m long tube and others in 5m long tube. Measurements were conducted in two rounds for both the whole loop and only test section with attached boundary conditions. Results were then compared against real measurements conducted at KTH in 1983[15].

In both cases special care was taken to obtain high precision. In the first measuring round power was increased with moderate phase and as result of this measurement rough value of dryout onset was obtained. After this the interval was narrowed to within 1% of the assumed value in order to obtain high precision. In the case dryout did not occur, power interval was increased 1% in one or both directions in order to obtain the value, whereupon another round of measurements would be done to increase precision. Time during which this power was increased was 200 seconds in the case of whole loop and 3000 seconds in the case of only test section.

In the case of loop following running stages were run:

- 0 – 100 s Pump start – up
- 100 – 200 s Heater start – up
- 300 – 500 s Test

In the case of test section, test is commenced immediately.

Dryout onset was defined as wall temperature increasing over 25 degrees over saturation temperature.

Pipe measurements were conducted for all three offered correlations:

1. IPPE (local state correlation)
2. GE-CISE (critical quality)
3. BIASI (critical quality)
4.1. **TRACE CHF correlations**

4.1.1. **IPPE**

This correlation is in fact a table of values that serves to predict dryout. It was developed as a joint venture between AECL Research (Canada) and Institute of Power and Physics in Oblinsk (Russia). It was found that this correlation was appropriate for TRACE because of its good accuracy and wide range of applicability. Correlation is appropriate when the aim is to determine critical heat flux in case of upward flow of steam-water mixture. While the database covers a wide range of flow conditions, the look-up table was designed to provide CHF values for 8 mm tubes at discrete values of pressure, mass flux, and dryout quality. The database contains 22,946 data points covering the following range of conditions [5]:

\[
3\text{mm} \leq D \leq 40\text{mm}
\]
\[
0.1\text{MPa} \leq p \leq 20\text{MPa}
\]
\[
6\text{kg/m}^2/\text{s} \leq G \leq 8000\text{kg/m}^2/\text{s}
\]
\[
-0.5 \leq D \leq 1
\]
\[
80 \leq L/D \leq 2485
\]

The resulting table was constructed to provide CHF values for 8 mm tubes at discrete values of pressure, mass flux, and dryout quality, and includes empirical correction factors to extend the table to other tube diameters and for rod bundles. [5]

TRACE implementation of the given correlation is presented below:

The value of the CHF is given with:

\[
q_{CHF} = K_1 \cdot K_2 \cdot K_8 \cdot fn(p, G, x)
\]

where following symbols represent:

- \( K_1 \) - correction factor for tube diameter
- \( K_2 \) - correction factor for rod bundle geometry if applicable
- \( K_8 \) - correction factor for low flow conditions
- \( fn(p, G, x) \) - table lookup value based on pressure, mass flux and quality

For further details about TRACE implementation and given correction factors the reader is directed to TRACE manual [5].

It is important to note that given correlation is local, i.e. it only takes into consideration local conditions and not development of annular flow upstream from the dryout. Next two correlations have more global perspective.

4.1.2. **GE-CISE**

As we previously mentioned in 1.1 dryout is global phenomenon influenced by development of annular film layer. The dryout of the liquid film on the wall is determined by a balance between losses due to vaporization and entrainment and gains due to droplet deposition. More advanced, so called three fluid models, like MEFISTO[3], treat this problem mechanistically by modeling droplets, vapor and film separately. However these capabilities are missing in TRACE and that is why more constitutive model is needed. [5]

Currently, most widely used empirical approach is so called “critical quality-boiling length” approach. The inclusion of the boiling length - the axial distance from the location where the bulk fluid enthalpy reaches saturation to the dryout point - in this approach gives a measure of the upstream history that is important
for prediction of film dryout that is not available in a local conditions approach such as the IPPE look-up table discussed in 4.1.1. [5]

GE-CISE correlation has following form:

\[ x_{\text{crit}} = \frac{A \cdot L_B}{B + L_B} \left( \frac{1.24}{R_f} \right) \]

Where:

\[ A = 1.055 - 0.013 \left( \frac{P - 600}{400} \right)^2 - 1.233 \cdot G + 0.907 \cdot G^2 - 0.285 \cdot G^3 \]

\[ B = 17.98 + 78.873 \cdot G - 35.464 \cdot G^2 \]

\( L_B \) - boiling length

\( R_f \) - peaking factor

Correlation is provided for bundle of 7x7 fuel rods, but it can be also corrected for 8x8 bundle. [5]

From everything said about this correlation it can be concluded that the correlation is improvement from local correlations such as IPPE but unfortunately not appropriate for round tubes. We therefore expect somewhat lower accuracy than with following correlation that will be presented in continuation of this text.

4.1.3. Biasi correlation

Original Biasi correlation was developed in 50s and was from beginning local correlation much like IPPE presented in 4.1.1[1]. This correlation was used in TRAC and there are many papers published about it. We will come back to it in chapter 5, but for now we can limit ourselves to the new and improved BIASI correlation that is available in TRACE (new Biasi). [5]

New Biasi correlation was developed by Phillips et. al. in 1981[20]. From the name of the paper one can draw conclusion that this correlation can be used in case of transients as well (original Biasi correlation was developed for steady state cases). Its inclusion in TRACE also suggests the same thing [9]. We will however investigate this in chapter 5.

New Biasi correlation has the following form:

\[ x_{\text{crit}} = \max \left( x_{\text{crit,1}}, x_{\text{crit,2}} \right) \]

\[ x_{\text{crit,1,k}} = \frac{A_k \cdot L_B}{B_k + L_B} \left( \frac{P_h}{P_w} \right) \left( \frac{1}{R_f} \right)^{1/2} \]

\( A_k = 1.0 \)

\[ B_k = 1.048 \cdot 10^{-8} \cdot G^{1.6} \cdot D_{h}^{1.4} \cdot \frac{h_{fg}}{H(p)} \]

\[ A_2 = F(p) \cdot G^{-1/6} \]

\[ B_2 = 5.707 \cdot 10^{-8} \cdot G^{7/6} \cdot D_{h}^{1/6} \cdot h_{fg} \]
\[ F(p) = 0.7249 + 0.099 \cdot p \cdot \exp(-0.032 \cdot p) \]
\[ H(p) = -1.159 + 0.149 \cdot p \cdot \exp(-0.019 \cdot p) + \frac{8.99 \cdot p}{(10 + p^2)} \]

Where:

- \( L_B \) - boiling length [m]
- \( P_h, P_w \) - heated and wetted perimeter
- \( h_{fg} \) - latent heat [J/kg]
- \( p \) - pressure [bar]

Biasi correlation is in principle only appropriate for tubes and not fuel bundles. Investigation into this matter featuring old Biasi (5.7.1.) showed poor prediction for real reactor geometry[21]. It is therefore prudent to caution for using this correlation for fuel bundle geometry.

For our purposes however we believe that this correlation is appropriate. Significant issue with this correlation is that it is difficult to find any information about its conversion from local to global (old to new). That is why we will revisit this correlation in chapter 5 and compare predictions for old and new Biasi correlations and prove that new one is indeed capable of handling transients. [22]

Biasi correlation is applicable for following parameters[1]:

- \( 3 \text{mm} \leq D \leq 37.5 \text{mm} \)
- \( 200 \text{mm} \leq L \leq 6000 \text{mm} \)
- \( 0.27 \text{MPa} \leq p \leq 14 \text{MPa} \)
- \( 100 \text{kg/m}^2\text{/s} \leq G \leq 6000 \text{kg/m}^2\text{/s} \)
- \( \frac{1}{1 + \frac{\rho_f}{\rho_g}} \leq x \leq 1 \)
- \( 80 \leq \frac{L}{D} \leq 2485 \)
4.2. Test section measurements

In this section we investigated all correlations in the test section. Model is simple and is composed of test section accompanied with boundary conditions as shown in Figure 7. Geometry and test section properties are provided at the beginning of chapter 4.

For the test section, following results have been obtained:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>190</td>
<td>84.3</td>
<td>84.3</td>
<td>52.6</td>
<td>103.1</td>
<td>18.23</td>
<td>18.23</td>
<td>48.98</td>
</tr>
<tr>
<td>225</td>
<td>80.8</td>
<td>81.0</td>
<td>69.8</td>
<td>103.5</td>
<td>21.93</td>
<td>21.74</td>
<td>32.56</td>
</tr>
<tr>
<td>261</td>
<td>40.2</td>
<td>40.2</td>
<td>30.9</td>
<td>50.8</td>
<td>20.87</td>
<td>20.87</td>
<td>39.17</td>
</tr>
<tr>
<td>199</td>
<td>224.7</td>
<td>284.4</td>
<td>284.4</td>
<td>229.5</td>
<td>2.09</td>
<td>23.92</td>
<td>23.92</td>
</tr>
<tr>
<td>234</td>
<td>274.6</td>
<td>275.1</td>
<td>275.1</td>
<td>342.1</td>
<td>19.73</td>
<td>19.58</td>
<td>19.58</td>
</tr>
<tr>
<td>269</td>
<td>121.2</td>
<td>121.2</td>
<td>121.8</td>
<td>159.9</td>
<td>24.20</td>
<td>24.20</td>
<td>23.83</td>
</tr>
<tr>
<td>1140</td>
<td>33.7</td>
<td>33.8</td>
<td>23.5</td>
<td>26.4</td>
<td>27.65</td>
<td>28.03</td>
<td>10.98</td>
</tr>
<tr>
<td>1184</td>
<td>26.6</td>
<td>24.9</td>
<td>16.2</td>
<td>19.5</td>
<td>36.41</td>
<td>27.69</td>
<td>16.92</td>
</tr>
<tr>
<td>1159</td>
<td>129.9</td>
<td>130.3</td>
<td>130.3</td>
<td>156.8</td>
<td>17.16</td>
<td>16.90</td>
<td>16.90</td>
</tr>
<tr>
<td>1192</td>
<td>65.8</td>
<td>153.2</td>
<td>71.0</td>
<td>92.5</td>
<td>28.86</td>
<td>65.62</td>
<td>23.24</td>
</tr>
</tbody>
</table>
Figure 8: IPPE correlation, dashed lines represent 20% deviation

Figure 9: GE-CISE correlation, dashed lines represent 20% deviation
Figure 10: BIASI correlation, dashed lines represent 20% deviation
4.3. **LOOP measurements**

In this chapter we investigated the same scenarios as in 4.1 but here using whole loop model as shown on Figure 2. For the whole loop only BIASI equation has been employed and following results have been obtained:

<table>
<thead>
<tr>
<th>RUN</th>
<th>CHF BIASI [W/cm^2]</th>
<th>Measured CHF [W/cm^2]</th>
<th>Error BIASI %</th>
</tr>
</thead>
<tbody>
<tr>
<td>190</td>
<td>84.3</td>
<td>103.1</td>
<td>18.23</td>
</tr>
<tr>
<td>225</td>
<td>81.1</td>
<td>103.5</td>
<td>21.64</td>
</tr>
<tr>
<td>261</td>
<td>40.3</td>
<td>50.8</td>
<td>20.67</td>
</tr>
<tr>
<td>199</td>
<td>222.6</td>
<td>229.5</td>
<td>3.01</td>
</tr>
<tr>
<td>234</td>
<td>275.0</td>
<td>342.1</td>
<td>19.61</td>
</tr>
<tr>
<td>269</td>
<td>119.3</td>
<td>159.9</td>
<td>25.39</td>
</tr>
<tr>
<td>1140</td>
<td>33.82</td>
<td>26.4</td>
<td>28.11</td>
</tr>
<tr>
<td>1184</td>
<td>26.0</td>
<td>19.5</td>
<td>33.33</td>
</tr>
<tr>
<td>1159</td>
<td>161.53</td>
<td>161.6</td>
<td>0.04</td>
</tr>
<tr>
<td>1192</td>
<td>65.7</td>
<td>92.5</td>
<td>28.97</td>
</tr>
</tbody>
</table>
Finally, differences between using the whole loop to assess onset of dryout as opposed to model of test section alone have also been analyzed:

<table>
<thead>
<tr>
<th>RUN</th>
<th>TEST SECTION [W/cm^2]</th>
<th>LOOP [W/cm^2]</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>190</td>
<td>84.3</td>
<td>84.3</td>
<td>0.04</td>
</tr>
<tr>
<td>225</td>
<td>80.8</td>
<td>81.1</td>
<td>0.40</td>
</tr>
<tr>
<td>261</td>
<td>40.2</td>
<td>40.3</td>
<td>0.23</td>
</tr>
<tr>
<td>199</td>
<td>224.7</td>
<td>222.6</td>
<td>0.93</td>
</tr>
<tr>
<td>234</td>
<td>274.6</td>
<td>275.0</td>
<td>0.13</td>
</tr>
<tr>
<td>269</td>
<td>121.2</td>
<td>119.3</td>
<td>1.60</td>
</tr>
<tr>
<td>1140</td>
<td>33.7</td>
<td>33.82</td>
<td>0.35</td>
</tr>
<tr>
<td>1184</td>
<td>26.6</td>
<td>26.0</td>
<td>2.26</td>
</tr>
<tr>
<td>1159</td>
<td>161.53</td>
<td>161.0</td>
<td>0.04</td>
</tr>
<tr>
<td>1192</td>
<td>65.8</td>
<td>65.7</td>
<td>0.02</td>
</tr>
</tbody>
</table>

It is apparent that model of the whole loop and only test section can be used interchangeably in regard to CHF investigation since differences in CHF is insignificant in almost all cases analyzed.

Only significant differences were noticed in runs 1184 and 269. The reason for these differences is that TRACE code generally experienced difficulties in predicting CHF for these conditions, yielding several small jumps (around 5 degree each) that came in cascade eventually rising temperature 25°C over saturation triggering dryout detection. We however believe that this will not be of concern for us given the fact that this phenomenon was only observed at relatively high pressures of 140 bar which is considerably higher than 70 – 80 bar that will feature in our experiments.

The fact that results are not identical in other cases is primarily due to the fact that experiments in only test section were more precise with power being slowly increased under period of 3000 seconds. In case of loop this time was only 500 seconds as described at the beginning of this chapter.

In regards to tested correlations following conclusions are drawn:

IPPE correlation has RMSE of 31.16%.

GE-CISE is overtly conservative and its RMSE is 30.32%. This is what was expected[5]. GE-CISE is furthermore meant to be used for fuel assemblies and not pipes.

BIASI correlation is deemed to be most precise of the three yielding RMSE of 24.04%. Furthermore, there are many assessments that recommend Biasi correlation for dryout assessment[22, 23]. Therefore it is decided to use it in further work.
5. Transient measurements, uniform power distribution

5.1. Raw input data:

Following data was provided by Westinghouse. They refer to Optima 3 quarter bundle.

Two series of measurements are planned:

1. Load rejection
2. Pump trip

Following data is supplied:

![Graph showing load rejection, pressure variation at the section outlet](Image)

**Figure 11:** Load rejection, pressure variation at the section outlet
Figure 12: Load rejection, mass flow variation at section inlet

Figure 13: Load rejection, power variation
Figure 14: Load rejection, inlet temperature variation

Figure 15: Pump trip, pressure variation at the section outlet
Figure 16: Pump trip, mass flow variation at section inlet

Figure 17: Pump trip, power variation
Data is provided in MEFISTO/BISON format. MATLAB code converting it to TRACE/SNAP input format has been devised, and implemented to create these graphs.

5.2. Scenarios overview

5.2.1. Load rejection

Load rejection is scenario in which turbine valves would close, but bypass valves would not open which would generate rapid pressure increase in the reactor.

Load rejection scenario lasts for 10 seconds. After little more than one second there is a rapid pressure increase of more than 10 bars in less than 2 seconds.

Reactor is scrammed but there is a small power peak due to rapid void collapse in the core. Mass flow is reduced albeit in slower phase compared to the pump trip scenario.

5.2.2. Pump trip

Pump trip is scenario in which feed pump would fail reducing feed water mass flow to the reactor.

Pump trip scenario lasts for 5 seconds. After 1 second pump trip occurs and almost 2/3rds of the flow is lost in less than 0.5 s.

Sudden decrease of flow is followed by moderate pressure pulse (2 bar increase in 0.5 s). Reactor is scrammed and power is reduced.

Temperature variation at the inlet is insignificant.
5.3. Approach to the testing and aims

In order to conduct testing we first have to scale all given parameters to the test section geometry that will be used in the experiments in HWAT loop, that is a round tube. Conversion of data and scaling is done in chapter 5.4. Here we will also present our testing geometry.

Following this dedicated MATLAB program will be used that will scale all necessary data as explained in 5.4 and prepare relevant input data for TRACE model.

TRACE simulations will be conducted and relevant data extracted/calculated using another dedicated MATLAB code. Data management is dealt with in appendix H.

Results will be processed and analyzed, again using MATLAB. Here it is also appropriate to present our CHF prediction logic as well as reasoning about applicability of Biasi correlation to transient analysis. We will talk more about this in chapter 5.7.2.

Finally it is also appropriate to state the aim of our testing. We are first of all interested to answer a simple question:

Will there be a dryout during the two hypothetical transients or not?

From this one following two questions follow:

If not, how big is our safety margin?
How much we can increase our steady-state power without risking a CHF event?

5.4. Test geometry and scaling

It was decided to conduct tests in a simple test section as opposed to the full loop. The reason for this decision is that exact input conditions were provided. As such it was natural to specify two boundary conditions; one at the inlet and one at the outlet, as well as heat flux. Full loop testing (to test model) will be conducted later in chapter 7.

Following geometry data were provided:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>23.6 cm²</td>
<td>Cross-section area</td>
</tr>
<tr>
<td>P&lt;sub&gt;HEATED&lt;/sub&gt;</td>
<td>742 mm</td>
<td>Heated perimeter</td>
</tr>
<tr>
<td>P&lt;sub&gt;TOTAL&lt;/sub&gt;</td>
<td>998 mm</td>
<td>Total perimeter</td>
</tr>
<tr>
<td>L</td>
<td>3.7 m</td>
<td>Heated length</td>
</tr>
</tbody>
</table>

With this data characteristics of the heated tube were assessed[24]:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D&lt;sub&gt;H&lt;/sub&gt;</td>
<td>9.46 mm</td>
<td>Hydraulic diameter</td>
</tr>
<tr>
<td>P&lt;sub&gt;HEATED&lt;/sub&gt;</td>
<td>29.72 mm</td>
<td>Heated perimeter</td>
</tr>
<tr>
<td>L</td>
<td>3.7 m</td>
<td>Heated length</td>
</tr>
<tr>
<td>δ</td>
<td>1 mm</td>
<td>Wall thickness</td>
</tr>
</tbody>
</table>
Data is imported using dedicated MATLAB script that was written specially for this purpose. Following this input files for TRACE were prepared. Following parameters were specified at the inlet:

- Liquid velocity [m/s]
- Liquid temperature [K]
- Pressure [bar]

These values were provided for variable time-step depending on the case with the aim of facilitating data input to TRACE without compromising on data datelines and accuracy.

Scaling was conducted in the following way, as per instructions[25]: The aim was to maintain mass flux. To this end, mass flow was scaled down to accommodate this. In order to maintain same exit enthalpy, power was also scaled down by the equivalent amount.
5.5. TRACE model

Data is imported using dedicated MATLAB script that was written specially for this purpose. Following this input files for TRACE were prepared. Following parameters were specified at the inlet (Generalized input):

- Liquid velocity [m/s]
- Liquid temperature [K]
- Pressure [bar]

Value supplied for generalized break is pressure.

Pressure is defined at two places, generalized input and break. However this does not lead to an overdetermined system since only generalized break actually influences the pressure of the system. The pressure provided to generalized input is only used to assess thermodynamical properties of water at the inlet[7]. A program of correction of this pressure has been made (resulting in general input as it is at the inlet of the test section), but test run with it provided identical results as test run when no program was used. This is to be expected given the small magnitude of pressure drop as well as weak dependence of water properties with its pressure. [7]

Mass flow was scaled in order to preserve mass flux while power was scaled to provide same outlet conditions in relation to thermodynamical parameters as explained in 5.4.
Test section is divided in 25 sections, and property for each and every one of those are assessed by solving appropriate flow/thermal equations [5]. In most cases TRACE is calculating average values of properties for every cell (for detailed description of equations used consult manual [5]). In case of mass flows however, these are calculated at the every dividing surface.[5-7]
5.6. **Flow data**

**Load rejection**

- $G_R = 1363 – 610.7 \text{ kg/m}^2/\text{s}$  
  Real mass flux range

- $G_T = 1361 – 612.9 \text{ kg/m}^2/\text{s}$  
  Test section mass flux range

- $q_R = 175824 - 28788 \text{ W/m}^2$  
  Real heat flux range

- $q_T = 339000 - 55817 \text{ W/m}^2$  
  Test section heat flux range

**Pump trip**

- $G_R = 1214.6 – 380.7 \text{ kg/m}^2/\text{s}$  
  Real mass flux range

- $G_T = 1214.6 – 380.7 \text{ kg/m}^2/\text{s}$  
  Test section mass flux range

- $q_R = 194310 - 98477 \text{ W/m}^2$  
  Real heat flux range

- $q_T = 374630 - 190030 \text{ W/m}^2$  
  Test section heat flux range

**Brief comments on the flow data**

Careful reader will notice major difference between heat fluxes for both pump trip and load rejection. The reason for this marked difference is that heated perimeters in these two cases are markedly different owning to the different geometries in the two cases. At the same time power was reduced with respect to outlet enthalpy (quality) without taking into consideration heat flux as such. This approach was taken in order to follow instructions given to us [25].

One can also notice slight difference in mass fluxes in the case of load rejection. The reason for this minor discrepancy is that it was not possible to input mass flow directly in generalized input (chapter 5.5). Instead MATLAB function XSteam was used to convert mass flow to flow velocity. It is apparent that there are minor differences in density assessment between XSteam and TRACE implementation, but we do not believe that these differences, that are small indeed, would have any impact on our results.

5.7. **Dryout assessment**

All work related to the dryout in TRACE is done under the hood, meaning that results are not available to the user, other as temperature jump on the inner surface.

![Figure 21](image-url)
It is however not possible to assess how close one is to the dryout. To solve this problem we developed our own implementation for TRACE Biasi correlation that gives needed results, and provides information about proximity to the dryout, as well as facilitate assessment of CPR.

Two correlations are used for this purpose:

- Modified Biasi correlation to include boiling length (New Biasi) [5]
- Original local Biasi improved by [26, 27] (Old Biasi)

We believe that it is appropriate to discuss original local Biasi here. New Biasi has already been discussed in 4.1.3.

5.7.1. Original BIASI correlation

In the chapter 4.1.3. we discussed the New Biasi correlation that is used in TRACE. The problem with this correlation is that we were not able to find any papers where it was explained how this correlation was converted from original Biasi correlation (that is the main topic of this article) to the new one. The two major differences between these two are:

- New Biasi correlation is global (boiling length) while the old one is local.
- New Biasi can be used for transient scenarios while the old one is strictly local.
- We do not know if new Biasi can be used for non-uniform power distribution, old Biasi can't.

Since we were unable to find Philips papers where he explains this conversion we decided to pursue an alternative approach; we will achieve three abovementioned aims, by converting old Biasi ourselves so that it fulfills abovementioned requirements and then check if predicted results are similar with the new one. If this is the case than these correlations can be used interchangeably and papers that were stated in support of conversion of old Biasi are relevant for both Biasi correlations. More about this in appendix E.

In the late 60s the group of scientists lead by L. Biasi systematized present empirical knowledge about CHF in round tubes and published the Biasi correlation. The correlation has the following form[1, 27]:

\[
q_{\text{CHF1}} = \frac{1.883 \cdot 10^3}{D^{0.4} \cdot G^{6}} \left( \frac{f(p)}{G^{5}} - x \right)
\]

\[
q_{\text{CHF2}} = \frac{3.78 \cdot 10^3 \cdot h(p)}{D^{0.6} \cdot G^{5.6}} \cdot (1 - x)
\]

Where:

\( n = 0.4 \) for \( D \geq 1 \text{ cm} \)
\( n = 0.6 \) for \( D < 1 \text{ cm} \)

\( f(p) = 0.7249 + 0.099 \cdot p \cdot \exp(-0.032) \)

\( h(p) = -1.159 + 0.149 \cdot p \cdot \exp(-0.019 \cdot p) + \frac{8.99}{10 + p^2} \)
The reader should be aware that correlation was published before SI system took hold and correlation is instead in CGS system (cm,g,s).

As in new correlation CHF value is obtained by choosing the higher value of the two. It is worth noting that this correlation depends on quality, and that this dependence is significant. Instead of critical quality, critical flux is obtained.

5.7.2. **Extension of application of Biasi correlation**

Taking into account how it was defined and obtained the Biasi correlation can be used:

- For round pipes
- For steady-state cases
- For uniformly heated pipes

Second and third points are troublesome since we want to conduct tests under transient and both uniform and non-uniform heat flux distribution (chapter 6).

Can a correlation meant to be used for steady-state cases also be used for transients?

There are several papers that investigate this question [1, 26, 28, 29]. Conclusion is that steady-state correlation can be used if so called “quasi-steady” approach [28, 29] is used. The essence of the approach is that correlation’s prediction (in our case Biasi) should be applied to local and instantaneous values of local properties [30]. In the case of flow rate transient, experimental data lies within 25% band for almost all experimental data. In case of power transient prediction is slightly less precise but still mostly within 25% band. [28]

Given the similarity of experiments conducted by Celata and Cumo [28, 29] with ours we believe that our accuracy is the same, and possibly even better due to use of more sophisticated software for prediction of local parameters. Same can be said for combination of the two. [28]

Quasi-steady approach is so prevailing and well established that it can be considered norm for these kinds of measurements at least when one considers constitutive empirical models and the fact that this approach is used in TRACE as well. [1, 5, 28-30]

Nevertheless, if more accuracy is desired, quasi-steady approach can be corrected with mechanistic correction factors proposed by Chang and Groeneveld. However it is worth noting that CHF during flow transients, power excursion or a loss of coolant accident can be predicted reasonably well with quasi-steady approach without any corrections. [26]

Great value of this correction is that it can also make steady-state correlations for uniformly-heated pipes applicable to non-uniformly heated ones with reasonable accuracy. [26]

For the sake of completeness these correction factor will be presented here [26]:

The mechanistic correction is applied with two factors, multiplying predicted CHF flux given by uncorrected local old Biasi correlation[27].
First of these factors is so called heat-flux history effect factor and is denoted as $\eta_{UN}$. The logic behind introduction of this factor is that Biasi is in essence a local correlation taking into account only local conditions at the location of the dryout onset. According to more accepted global approach, dryout is influenced by upstream effects as well. In order to take these into account the heat flux upstream up to the point of the dryout has to be averaged in some way, and it is this averaged heat flux that is of interest, rather than local heat flux. The method of averaging selected by the authors is BLA (boiling-length-average) meaning that cells where boiling occurs should be determined and heat flux across them averaged [26]:

$$\eta_{UN} = \frac{q_l}{q_{BLA}}$$

Where:

$q_l$ - local heat flux

$q_{BLA}$ - averaged heat flux across boiling length average

It is reasonable to assume that similar correction was done by Phillips.

The second correction effect has to do with changes in mass flux. This so called mass-flux-history effect can be important during power transients as well as flow transients. During power transients a change in power will change the acceleration pressure drop, thus changing the flow for a constant pressure head system. During a flow transient a flow change will result in a change in the boiling length which will in turn affect CHF. In modeling of the mass-flux-history effect it is assumed that the transient CHF depends on some boiling length equivalent mass flux and not on the local one. This mass effect on CHF can be derived directly from experimental data or good prediction method. It is fortunate that authors have chosen Biasi correlation in order to model this influence. By using old Biasi equation given in 5.7.1 this correction factor is now defined as [26]

$$\eta_{UG} = \left( \frac{G_l}{G_{BLA}} \right)^{0.6}$$

Where:

$G_l$ - local mass flux

$$G_{BLA} = \frac{4 \cdot L_b \cdot q_{BLA}}{h_f \cdot X \cdot D}$$ - boiling-length-equivalent mass flux

$X$ - cross-section average quality

$D$ - equivalent diameter

It is also important to note that fluid can’t distinguish if changes in heat flux during its journey through the pipe are due to non-uniform axial heat flux distribution or due to transient or both. In this sense Biasi correlation corrected in this way can be used for both uniform and non-uniform heat flux distributions. [26]
5.8. Results

We will begin presenting results for pump trip since we believe they are more insightful. To avoid clogging of thesis wide selection of extracted data will be given in appendix B and C. Here we will focus our attention to important data that answers questions posed in chapter 5.3.

5.8.1. Pump trip

In the chapter 5.7.2. we have seen that we can use both new and old Biasi correlation for transient cases even though they were originally developed for steady-state cases provided that we use quasi-steady approach and local parameters. Most interesting parameter in this context is local quality at the section outlet.

Since quality will be highest at the outlet, it is there critical quality (as determined by the new Biasi correlation) will be attained first which is the case in uniform-heat flux distribution. This parameter is shown on Figure 22:

![Figure 22: Quality at the test section outlet (last cell)](image)

During initial phases of work so called dryout flag was developed in order to assess proximity to the dryout and dryout margin. This indicator has however been abandoned in favor of industry accepted transient CPR (CPR\text{TRA}).
Dryout flag is defined in the following way (legacy):

\[ \text{FLAG} = \frac{x_{\text{critical}}}{x_{\text{local}}} \]

Local flag is defined in the following way:

\[ \text{FLAG}_{\text{LOCAL}} = \frac{q''_{\text{critical}}}{q''_{\text{local}}} \]

Transient CPR is defined in the following way [31]:

\[ \text{CPR}_{TR} = \frac{x_{\text{critical}} - x_{\text{in}}}{x_{\text{local}} - x_{\text{in}}} \]

Where:

- \( x_{\text{critical}} \) - critical quality as defined by new Biasi correlation
- \( q''_{\text{critical}} \) - critical heat flux provided by old Biasi correlation
- \( x_{\text{in}} \) - quality at the test section inlet
- \( x_{\text{local}} \) - local quality (in our case at the test section outlet)
- \( q''_{\text{local}} \) - local heat flux (in our case at the test section outlet)

Figure 23: Transient CPR in case of pump trip
We conclude that dryout will not occur for this case. However as a consequence of pump trip dryout margin will be significantly eroded from almost 2.1 to around 1.26 when it is at its minimum. There are two CPR minimums occurring at 2.75 s (1.29) and 4.37 s (1.26)

In order for dryout to occur power should be increased by additional 25%. CPR would then look like on Figure 24 depicting verge of dryout:

![Figure 24: Verge of dryout](image)

It is worth noting that even though CPR is strictly speaking larger than 1 (1.003), trace will trigger dryout initiation. Interested reader is directed to appendix C where retrieved data is plotted. This is probably due to overconservatism of the code[9]. It is also interesting to note that dryout will occur two times (Figure 65), at 2.61 s and 4.30 s, slightly different than predicted as minimums in Figure 21.

Finally we will also briefly comment on predictions of old improved Biasi correlation (chapter 5.7.2.)
Even though the shape of Figure 25 and Figure 73 (legacy flag) is different they predict in essence the same thing; that dryout will not occur. As power is increased the graphs will become more and more similar predicting dryout for roughly the same power and at roughly the same time. This is the trend that will hold during all trials, which allowed us to draw conclusion that both of these correlations can be used to assess dryout margins and risks, delivering very similar results. We will however limit ourselves to the new correlation since it is more intuitive and easier to use. This correlation and local flag will be used more extensively in chapter 6 where we will analyze non uniform power distribution.

It is also appropriate here to come back to an issue we first razzed in 5.6, namely the differences between heat fluxes in case of heated pipe and fuel assembly.

New Biasi correlation does not rely on heat flux so here it is not expected this will have any influence. What is important is quality that due to scaling is retained as in bundle geometry case.

Old Biasi predictions of critical heat quality does not either depend on the heat flux. However, correlation will give critical heat flux (and not quality as New Biasi correlation) which will then have to be compared with a local heat flux given by TRACE. One would think that it is here influence of different heat fluxes will be felt. However, it is noteworthy to point out that both correlations give same qualitative predictions of dryout margin as well as development of the transient with regards to CHF. Furthermore, both correlations predict the same critical power for which transient will be encountered during proposed transient as it is discussed in appendix E. Encountered differences in heat fluxes are thus not of concern in our model.
5.8.2. **Load rejection**

In this scenario, where we are applying uniform power distribution there is no risk for dryout. Lowest CPR is 2.27. The reason for this is that quality and void falls down as time passes as it can be seen in appendix C.

It is however important to point out here that sense of security is deluding. When non-uniform power distribution is applied (which is what realistically happens in a fuel bundle) dryout margin will be slashed dramatically. We will discuss this in chapter 6.

Finally as in previous case we incrementally increased power (in 1% steps) in order to find out when the dryout will occur for this case. Our Biasi implementation predicts that this will happen when initial power is increased by 215%. TRACE implementation is on the other hand more conservative and predicts dryout when power is increased by 190%. This results is however believed to be overconservative [9].

We will also use this case to further clarify our opinion that these new and old Biasi correlations can be used interchangeably. Interested reader is directed to appendix E.
6. **Transients measurements, non-uniform power distribution**

In this section we will discuss results that we obtained when we took into consideration the fact that non-uniform power distribution was applied to the test section. Distribution was provided by Westinghouse, and it was scaled so that it gives total power when summed up across the whole section. In other words, the shape of power distribution was maintained, but its magnitude was scaled in order to accommodate total power that was prescribed.

6.1. **Pump trip**

In this section we will focus our attention to the dryout assessment. Reader that is interested in other parameters is directed to appendix F.

![Figure 27: Transient CPR in case of Pump trip](image)

We observe here that CPR reaches its minimal value at \( t = 2.66 \) s. CPR than is 1.18 which is a bit more than 6% reduction in our dryout margin.

Reduction of dryout margin is to be expected given the fact that non-uniform power distribution rarely improves it. In fact dryout margin may be extensively reduced if power peak is situated at the outlet from the test section, something that will be the case in load rejection. [1]

Having said all this, Biasi correlation is correlation that was developed for uniform power distribution which is not the case here. For plot at Figure 27 to be valid we implicitly assumed that new Biasi correlation can
be used for such cases. This is natural given the fact that paper in which it was published dealt with improved CHF prediction in BWR reactors\[20\]. However, since we have not succeeded in finding this paper, we developed our own improved Biasi correlation as explained in 5.7.1. and its results will be given parallel with the new Biasi.

![Graph of local dryout flag](image)

**Figure 28: Local dryout flag**

Here we note that critical moment is predicted at $t=2.55s$ which is 0.11 seconds less than in new Biasi correlation. Having said this, both correlations predict that dryout will not occur as well that location most close to dryout will be at the outlet.

Considering similarity of both predictions, as well as exact prediction of the location as well as background presented in previous chapters as well in appendix E we believe that new Biasi correlation can be used for these purposes. If in doubt, old Biasi can be used for which significant literature background has been obtained. In continuation of the report only new Biasi will be stated while results obtained using old Biasi will be presented in appendixes.

### 6.2. Load rejection

In case of load rejection there is significant neutronic influence and this effect is captured by using non-uniform power distribution. Once power pulse enters reactor core, it will cause void collapse in it. Since it is well known that most of the void is situated at the reactor outlet void collapse will be mostly felt in that area of the core. Nuclear fission will accelerate which will lead to power pulse at the outlet from the core.
(or test section in our case). We expect this to have significant impact on CHF margin which should be eroded.

![Transient CPR for load rejection](image)

**Figure 29: Transient CPR for load rejection**

It is apparent that CHF margin is thoroughly eroded from 2.27 for uniform-power distribution to 1.26. This is reduction of roughly 56%. This minimum occurs at \( t=2.91s \).

A significant reduction of dryout margin is to be expected as explained earlier. Ambition was to use transient CPR in all cells for every time step in order to show proximity of every cell to the dryout condition. This approach has been abandoned however since problems appeared in cells with very low quality where unrealistically low CPR was recorded.

Until this deficiency is explained local flag will be used for this purpose and it is provided in appendix G.
7. **Transient analysis in the loop, uniform-power distribution**

7.1. **Pump trip**

Measurements have been conducted in the loop presented in the chapter 3. Following conditions were set:

- Pressure measured at the test section’s outlet was inputted in the pressurizer
- Control unit was programmed to maintain constant temperature at the inlet
- Pump was adjusted to provide the same mass flow that was measured at test section’s inlet

Setting outlet section pressure as target pressure for the pressurizer is approximation since real pressure is somewhat different at the locality where pressurizer is located. However, we believe that results will not be affected much by this.

The same can be said about trying to keep inlet temperature constant since it is apparent that inlet temperature changes very slightly in both cases. In addition to that, temperature will change slightly since control system will not be able to keep it constant as prescribed.

In this chapter we want to answer to the following questions:

- How close are model CPR predictions to the ones that were done in the test section with boundary conditions (chapter 6)? Can we use the whole loop with given conditions to replace this setup? Is loop model representative?
- What will happen in the event of failure of the control system so that pre-heater power remains “frozen” at certain level?

![Figure 30: Comparison of transient CPRs obtained from test-section and the whole loop](image)
The biggest practical difference between two CPRs is 0.02, a difference of 1.8%. Given the rough approximations that were adopted during this measurement as well the fact that LOOP CPR is more conservative we believe that loop is well representative of the test section and can be used for simulation and prediction of CHF. In other words, for the purpose of assessment of CHF loop and test section can be used interchangeably.

It is also appropriate to note that one can’t expect total match of the results since loop has its own characteristics (e.g. inertia) that might be different from theoretical model of test section with boundary conditions. We therefore believe that the first question can be answered positively.

On Figure 31 we are outlying behavior of the pre-heater during the transient. Changes in the period of 0-100s are designed to develop steady state condition, while events happening from 100-105 s are results of the transient.

![Figure 31: Pre-heater power during transient](image)

The blue line represents power level of pre-heater under normal circumstances. The green line represents hypothetical failure of the control system where regulator stays stuck at a certain power level.
Consequences (water outlet temperature deviation, that is difference from the prescribed temperature) is shown at Figure 32:

![Figure 32: Temperature deviation at pre-heater outlet during transient](image)

It can be seen that outlet temperature diverges immediately after control system fails and that this divergence is significantly increased once the transient starts, mostly due to rapid decrease of mass flow. In case of engaged control system deviation is insignificant. It is apparent from the graph that failure of control system can cause temperature excursions that are of course unwanted.
7.2. **Load rejection**

Figure 33: Comparison of transient CPRs obtained from test-section and the whole loop

Graphs in this chapter make it possible for us to draw same conclusions as in 7.1.
Figure 34: Pre-heater power during transient

Figure 35: Temperature deviation at pre-heater outlet during transient
8. **Comparison of TRACE with other codes**

8.1. **Background**

For the purposes of mechanistic prediction of dryout Westinghouse is developing dedicated code called Mefisto. [3]

Mefisto is a three field code that treats separately water droplets, water film and vapor in the boiling channel. This is in contrast to so called two field codes that only differentiate between vapor and liquid. Three field codes are more suitable for mechanistic approach for predicting dryout since they treat liquid film separately, meaning that film thickness/mass flow can be obtained from these. Once film disappears a dryout is achieved which is both elegant and physical way of predicting dryout. Two-film codes can't do this however since they do not treat liquid film separately (instead bundling both liquid film and droplets in one term, liquid) but instead relay on dryout correlations. Considering the fact that TRACE is two-phase code, this way of predicting dryout has been covered extensively in the previous chapters. [3]

Major disadvantage of thre-field codes is that they generally require much longer execution time in order to run. This is of course intuitive, given the fact that three fields have to be followed. Long execution times limit the number of runs and spread of values obtained by these codes. Compared to these two phase codes are considerably faster but can't give mechanistic predictions of dryout. [3, 32]

The solution proposed by Westinghouse is a new code called MEFISTO which uses significantly different approach compared to similar three-field codes. MEFISTO relays on two field codes for information about vapor and liquid fractions and using its post-processing capabilities converts these into three-field information (it separates water film and droplets in liquid term). The major advantage of this approach is that it provides multitude of data of three-field code with speed of execution comparable to two-phase codes. Prediction capabilities of the program are very good and the program is already used extensively by the company. Envisioned aim is total replacement of correlations with mechanistic MEFISTO approach. [3, 32, 33]

There are two versions of the program: MEFISTO and MEFISTO-T, the former being used for steady state and latter for transient analysis.

In order to perform well MEFISTO relies on two-field code as explained before. To this end VIPRE-W is used to provide needed information with another code called BISON being used for verification of two-field data. [34]

During steady state analysis both codes perform well. During significant pressure transients (e.g. load rejection) however, there are differences in predictions that VIPRE-W [35] and BISON [36] give. [33]

To definitely answer the question why and which program gives better solution an experiment is needed. However given the fact that experiment requires rapid pressure increase (5-6 bars per second) the experiment itself is challenging. Nevertheless this work will be undertaken at the KTH as part of PhD position to be opened soon.

The experiments will however take time so the aim of this paper is to give some explanations by comparing the answers between 3 codes and drawing conclusions that can be drawn.
It is very important to understand the difference since wrong prediction will propagate to MEFISTO results as well, giving wrong dryout prediction.

8.2. **VIPRE-W and BISON**

VIPRE-W is two-fluid, two-phase sub-channel code that is capable of simulating reactor core, vessel and internal structures. It uses 3 equations. It was developed by Electric Power Research Institute (EPRI) in late 80s in order to replace other similar programs, most notably COBRA. It is used by MEFISTO for obtaining information about void and liquid distribution. The code can be used for both BWR and PWR. [35, 37]

BISON is one dimensional dynamic analysis code for BWR. The code was developed in Sweden by ABB Atom (today part of Westinghouse). It is two-phase system code similar to TRACE. It uses 3 equations. Novelty of this code is great care taken in the case of rapid pressure transient modeling such as rapid depressurization (leading to rapid boiling, flashing) as well as rapid increase in pressure, similar to load rejection scenario (leading to void collapse). [36]

8.3. **Modification to the TRACE model from previous chapters**

The TRACE model has been changed to better meet the demands of comparison. In previous chapters flow was scaled to meet with the loop geometry discussed in chapter 5.4. In chapter 8 however we are not interested in loop anymore but rather in comparing the three codes. To this end, and in order to eliminate scaling, new geometry that is matching fuel bundle dimensions will be used.

Furthermore, new power distribution was proposed by Westinghouse to simulate better heat flux distribution during scram. It was agreed that uniform power distribution be used in trials given the fact that differences between uniform and newly proposed non-uniform distribution were found to be small.

Following geometry data were provided:

- $A = 23.6 \text{ cm}^2$ Cross-section area
- $P_{HEATED} = 742 \text{ mm}$ Heated perimeter
- $P_{TOTAL} = 998 \text{ mm}$ Total perimeter
- $L = 3.81 \text{ m}$ Heated length
8.4. Preliminary result comparison

8.4.1. Load rejection

Figure 36: Total flow at the outlet

Figure 37: Liquid flow at the outlet
In the Figure 36 it can be clearly seen that all three codes predict flow collapse in the initial phases of the transient as the consequence of rapid pressure increase (Figure 11). Trends are same in both BISON and TRACE but values are somewhat different with BISON predicting somewhat larger flow collapse. VIPRE however predicts considerable smaller void collapse.

The reason for this discrepancy can be found in Figure 37. It is namely mass flow of the liquid that is predicted differently by the three codes. Mass flow of the vapor is predicted almost identical in the three codes as it can be seen in Figure 38. Similarities between TRACE and VIPRE are especially astonishing given the fact that the two codes are profoundly different, TRACE being six-equation code[5] and BISON having four[36].

In our opinion, the reason for this discrepancy is difference in how pressure transient is treated in three codes.

Unfortunately, the issue of how condensation due to pressure transient is treated is not thoroughly discussed in either TRACE [5] or VIPRE [37] manuals. This point has however been discussed in BISON manual [36].

From abovementioned sources it is concluded that BISON uses so called non-equilibrium model. This in essence means that in the event of rapid pressure swings the code can support unstable or metastable states. This would in a sense mean that not all void would collapse when pressure is increased and liquid become subcooled (since increase of pressure leads to increase of temperature of saturation).

The non equilibrium model is in essence limit to energy transfer between phases defined by so called time constant. If the transient itself is much longer than the constant in question an equilibrium model can be used without much loss in accuracy. On the other hand, if transient length is comparable to the time constant non equilibrium model is of importance. The time constant is of the order 0.1 – 0.001 seconds indicating that the model will not be of great importance in our trials. [36]
Given the fact that load rejection is transient combining pressure, mass flow, power and pressure transient there are many factors that could create difference between BISON and TRACE.

We postulated however that the major reason for this difference was due to significant pressure transient. To confirm our hypothesis, we repeated load rejection transient but this time pressure was kept constant during the whole transient. Following total mass flow was obtained:

![Figure 39: Total flow for imaginary load rejection case with constant pressure](image)

The conclusion from the Figure 39 is self-evident. It is pressure and associated flow collapse that is producing differences in results between the three codes. To examine this more closely it was decided to run series of synthetic pressure tests varying pressure only while keeping everything else constant.

It can be also noted that VIPRE is giving predictions that are somewhat off from both TRACE and BISON. The reasons for this could be instabilities that code is displaying in the runs accompanied with considerably larger timestep than for TRACE and BISON.

VIPRE is running with the time step of 0.1 seconds while TRACE is running with 0.001s and BISON with 0.02s.
8.4.2. **Pump trip**

**Figure 40:** Total flow at the outlet

**Figure 41:** Liquid flow at the outlet
Comparing predictions by all three codes we can draw conclusion that they are much closer to each other than in the load rejection case. Furthermore TRACE and BISON seem to follow each other well especially when it comes to gas flow (Figure 42) where predictions are identical. VIPRE seems to be somewhat off but the difference is not large except for a period between 1.5 and 3 seconds.

The reason for this discrepancy is not immediately apparent but it is possible that it is due to larger time step in the boundary conditions (input file). Sharp swings in VIPRE predictions seem to indicate that.

In any case, the conclusion is that predictions of all three codes are close to each other with BISON and TRACE being closer to each other. This would indicate that there are similarities between these two codes, which are also apparent in the load rejection model. The reason for this is that major transient force in this case is large mass flow reduction, while in load rejection we have large pressure increase.

Since pressure transients here are not of significance the difference between equilibrium and non equilibrium model is not as important as it is in load rejection model. This is why TRACE and BISON follow each other better in this case.
8.5. **Analysis of TRACE and VIPRE condensation models**

The aim of this chapter is to analyze response of three codes to rapid pressure transient. To test this large pressure transient will be simulated in which pressure increases by 10 bars in one second, stays at the new value for short period of time (so that new equilibrium can be established) and later reverts to the old value.

![Synthetic pressure transient](image)

**Figure 43: Pressure transient**

8.5.1. **Uniform power distribution**

Selected boundary conditions as defined in TRACE:

- **Pressure**: 74-84 bar
- **Inlet temperature**: 278.3 °C
- **Mass flow**: 2.23 kg/s
- **Power**: 1.034 MW

Inlet boundary conditions are chosen so to match values during the real load rejection transient at 3s. Pressure change is amplified.
Figure 44: Comparison of saturation and liquid temperature in TRACE

Figure 45: Total flow at the outlet
In Figure 44 the reader will immediately notice slight superheating of liquid which is not physical but this is characteristic of TRACE code and superheating is mild (under 0.4 degrees). This will not be discussed further.

More importantly, it is apparent that liquid temperature follows temperature of superheating closely suggesting that TRACE either uses equilibrium model, or that non-equilibrium model is not applicable for this transient. Has this not be the case the change of liquid temperature would be more gradual. Instead, liquid temperature stops increasing the very moment pressure reaches its top. This is observed in all cases that were executed.
In Figures 46-47 the prediction of diverse mass flows is given. The reader will notice small discrepancy in mass flow of liquid and vapor in Figures 46 and 47. The reason for this is slight difference in boundary conditions in VIPRE, TRACE and BISON due to different ways provided for their definition in the three codes. The difference is however small and does not obscure prediction trends.

It can be concluded that all three codes give similar predictions in this case. TRACE and VIPRE predict the same depth of mass flow collapse while BISON predicts somewhat deeper collapse which is consistent with the realistic transient as well. Furthermore the phase of recovery after the flow collapse is different with TRACE recovering faster than BISON and VIPRE which predict slower recovery to old mass flow. Similarity of two peaks (condensation and flashing) show that same models are used in all three codes for these phenomena.

**8.5.2. Non-uniform power distribution**

Boundary conditions are the same as in 8.5.1 with power being non-uniformly distributed. Power is profile is given in Figure 48.
Figure 49: Total flow at the outlet

Figure 50: Liquid flow at the outlet
Conclusions that can be drawn from the Figures are the same as for uniform-power distribution. TRACE and VIPRE predict the same depth of the collapse while BISON predicts somewhat deeper collapse. BISON and VIPRE also predict faster recovery than TRACE in this case as well. Small discrepancy at the inlet is present here as well, explanation of which is given in 8.5.1.

8.5.3. **Constant quality at the inlet with no heating**

Selected boundary conditions as defined in TRACE:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>Variable, recorded from the outlet 8.5.1</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>Saturation</td>
</tr>
<tr>
<td>Mass flow</td>
<td>2.23 kg/s</td>
</tr>
<tr>
<td>Power</td>
<td>1.034 MW</td>
</tr>
<tr>
<td>Quality</td>
<td>27.3%</td>
</tr>
</tbody>
</table>

In order to further simplify the transient in question a model with unheated pipe was brought forward. In previous inlet boundary conditions values of temperature and mass flow were fixed. This model can't be used here since we need to have mixture of vapor and liquid already at the inlet. Furthermore we need to make sure that mixture is at saturation at all times.

For this purpose script was devised that guarantees both fixed quality and mass flow during the whole pressure transient. Due to technical reasons this case could not be simulated with BISON.
Figure 52: Total flow at the outlet

Figure 53: Liquid flow at the outlet
Figure 54: Vapor flow at the outlet

Even in this case the predictions are similar although there are some differences, especially rapid peak recovery between 3rd and 4th second as seen on Figure 52 and 53. These however might come from boundary conditions since procedure of defining boundary conditions in two codes is not the same.

In VIPRE case enthalpy is taken from the outlet of uniformly heated pipe (8.5.1) while in TRACE quality is fixed from the steady state and maintained nearly constant throughout the whole transient. In both cases the liquid is saturated. This explains different levels in intermediate steady state (between 4th and 6th second) in Figure 53 and 54.
8.5.4. **TRACE and MEFISTO-T dryout prediction**

Looking at dryout prediction shown in Figure 55 we note that TRACE predicts dryout at $t=2.45s$ while MEFISTO-T predicts it at $t=2.59s$. This is good result considering that MEFISTO-T’s timestep is set at 0.1s and that the time of $t=2.59s$ was achieved by interpolation.

The dryout is terminated at $t=3.5s$ according to TRACE and $t=3.46s$ according to MEFISTO-T.

We believe that these are good results and show that TRACE and MEFISTO-T predictions in the case of pressure transients predict good results, both in terms of trends and numbers.

It is hardly intuitive to expect that dryout would occur in this case since pressure is rapidly increased and looking only at steady states the margin should be only slightly decreased in the final states. However, contrary to what intuitively could be expected, the transformation between these two states will cause dryout if power level is high enough.

The reason can be seen in Figures 45-47 even though dryout case has somewhat higher power than those in order to achieve dryout. According to predictions vapor mass flow will be rapidly reduced due to void collapse and remain approximately constant during the duration of the transient. Reduction of the liquid flow will be slower however and it will reach its maximum at the end of the transient before starting to recover. This means in other words that at the beginning of the transient there will be rapid reduction of vapor flow while liquid flow is initially not significantly changed. This will lead to prompt reduction of quality and prompt increase of the margin. As liquid flow starts reducing however, the quality will increase reducing the margin and eventually causing dryout. Our simulation shows that this reduction in margin is as high as 10 percentage points.
9. Conclusion

The functional model that was created and described in chapter 3 is well representing test section and it is to be hoped that it will be valuable help in future experiments to be conducted. A dedicated control structure has also been devised and proposed in order to regulate both condenser and inlet conditions. It is our hope that these will be implemented in practice at HWAT loop. The model has undergone extensive testing and its parameters were adjusted accordingly in order to guarantee stability. The model with its default settings is stable between 40 and 180 bars.

Tests were further conducted on test section to analyze available dryout correlations. Here new BIASI correlation was chosen as most accurate of the ones provided. The correlation and its improvements were critically reviewed using available scientific data and papers and results show that new BIASI correlation can be accepted and used.

Provided models combined with TRACE make it possible to quickly predict occurrence of dryout and predict dryout margins or “depth” of dryout. The accuracy of these predictions is however limited by correlations in question. As we already noticed, BIASI correlation is good in case of simple heated pipes, but if it is applied to non-circular geometries or fuel bundles it does not perform well. In this case more involved and often proprietary correlations, limited to certain geometry should be used. Both BISON and VIPRE use these proprietary Westinghouse correlations as standard so there can be no direct comparison between TRACE CPR results and BISON/VIPRE ones. We decided to present three parameters for comparison; total mass flow as well as its two components: liquid and vapor in the code comparison part (chapter 8). Reader might be also interested in void fraction but these were left out due to the fact that three codes use different approaches to assess these resulting in numerically different results, even for steady state. [5, 21, 36, 37]

TRACE results were also compared with data obtained by Westinghouse codes, VIPRE and BISON as well as MEFISTO-T postprocessing dryout prediction methodology. Good match was achieved in pump trip transient (Figure 40) but some differences were observed in load rejection transient (Figure36). In both cases results given by TRACE and BISON are similar and trends are followed well. VIPRE also follows trends but the nature of its predictions is somewhat different. For example, the reduction of flow as a consequence of pressure increase is much less pronounced in VIPRE than in TRACE or BISON. Vapor mass flow prediction for all three codes is matching good, with almost complete match for TRACE and BISON and satisfactory for VIPRE (Figure 38). The reason for differences in results for three codes is in prediction of liquid mass flow (Figure 37), triggered by the pressure transient in load rejection model. Indeed, the differences in question do not show to the same extent in pump trip case and once pressure transient is removed (with all other features of load rejection case retained), the difference between TRACE and BISON disappears (Figure 39), leading to the conclusion that three codes treat rapid pressure transients somewhat differently while power, mass flow and pressure transients did not produce significant differences between BISON and TRACE. VIPRE is deviant in both load rejection and pump trip cases. In pump trip the predictions are close to other codes if differences due to boundary conditions are ignored. In load rejection however there are differences during pressure transient. Subsequent investigation will show that differences seen at Figure 36 originate only from mass flow and power changes. Furthermore, VIPRE is run with considerably higher time step than the other three codes (VIPRE:0.1s, BISON:0.02s, TRACE:0.001s) which could also create difference.

In extended investigation dealing with pressure transient only (with all other properties being kept constant) it was found that TRACE and VIPRE treat this very similarly in terms of mass flow collapse with
BISON predicting somewhat higher collapse which is consistent with realistic transient predictions (even there BISON predicted somewhat higher collapse). The question can then be asked: “If TRACE and VIPRE give same predictions for synthetic pressure transient how is it possible that there is such a difference in realistic transient between the two codes?” Our opinion is that the reason for this difference is difference in flow estimates due to change of mass flow/power in VIPRE and other two codes. Indeed, even in realistic transient both TRACE and VIPRE predict the same magnitude of flow reduction (around 0.2 kg/s for t=3s) but, even without any pressure transient (Figure 39) there is a difference between the two codes due to changes of mass flow/power that is retained once effects of the pressure are added. It is our conclusion therefore that the cause for VIPRE deviation should be searched in its reaction to flow reduction and power alteration.

In this area more work remains in order to fully understand differences that exist. We see our thesis as a beginning on this, having concluded that TRACE, BISON and VIPRE give similar predictions in rapid pressure transients, with subtle differences in handling liquid flow in this cases being primary reason for the difference. Developing and perfecting code predictions can only be done if they are also combined with real experiments. The definite answer on which of the three models is best describes reality in transients that can be encountered in practice will be given once real simulations are conducted in HWAT. It is to be hoped that results will point in the direction of one of the three proposed models.

Finally, TRACE dryout prediction logic developed in the first part of the thesis was compared with MEFISTO film flow rate dryout prediction. We can with satisfaction note that two methods give very similar predictions of the dryout occurrence.

In the end, on a personal note, the author can conclude that the work during the past sixth months was exciting and the subject of the dryout was analysed from two very different angles: correlative and mechanistic. That these two approaches gave same predictions is encouraging, but more work remains before we can be confident that that our model truly delivers in the case of rapid pressure transients. Here the question is not much if our dryout prediction logic works or not, but rather if our codes are giving us right predictions in regard to void fraction, quality, mass flows etc. Unfortunately not many studies have been done in this regard. The only serious one that we have been able to find is Peach Bottom Turbine Trip test II[38, 39]. To our surprise no paper dealing with PB turbine trip test discussed in detail void collapse even though void collapse is the driving force for the phenomena that occurs (rapid power increase). Instead byproduct of this collapse was discussed, namely power increase. This is however easy to understand; it is much more challenging and unforgiving to talk about void collapse than power increase. A power increase can be adjusted by adjusting feedback from neutronic model while predictions of mass flow or quality can much harder be altered. A total power is single number for the whole core while other properties depend on location and are much complicated to present. Nevertheless, obtaining more fundamental understanding of void collapse is paramount to understand predictions of the code better and decide which one should be used. That is why upcoming PhD position that will look into the problem is both important and in the opinion of the author groundbreaking.
APPENDIX A: PROBLEM INVESTIGATION

Problem 1

At the pressure of 120 bars and the highest mass flow violent temperature oscillations were observed in the test section and condenser. In certain cases system would stabilize and complete the test run.

It was however observed that control unit has shutdown pre-heating unit completely. Further investigation concluded that already at the entrance of the test section temperature was higher than target temperature at the outlet from pre-heating section making pre-heating section unable to control the temperature.

The issue is caused by the fact that our model controls outlet temperature from the condenser. Result of our investigation is that this however is not the subcooling temperature. The reason for this discrepancy is that in TRACE model, even though liquid is subcooled there is still considerable amount of steam mixed in it. This liquid-steam mixture continues condensation in the downstream sections increasing water temperature. This increase can be over 15 degrees. This can cause increase of feed-water temperature to temperatures in excess of pre-heater outlet temperature making it in turn unable to control feed water temperature. TRACE responds by violent unphysical oscillations that propagate from the test section further to the condenser where they are picked up by our control system.

On the issue of why these instabilities only occur in case of highest mass flow, there is a following explanation. Our condenser model requires setting maximum possible temperature of condensing pipe’s outer surface. In the case of lower flows it happens that this temperature is attained and rise of condenser temperature is stopped. The consequence of this is that condenser outlet temperature is lower than the one that was prescribed by us (30°C subcooled). In those cases there is margin for temperature increase.
without adverse effects. In the case of highest flow however larger temperature difference is needed to attain subcooling temperature in question. As consequence of that lower condenser pipe surface temperature is sought for (which is usually under maximum temperature limit) making condenser attain required temperature at the outlet.

The reason why instabilities appear first for pressures of 120 bar and higher is following. To find out why investigation was conducted and two states were compared, run 60 and 73. Run 60 was selected because it was the last run that produced good results, and 73 since it was first unstable run. Results are following:
Figure 57: Comparison of major parameters of run 60 and 73
As can be seen from Figure 57, both cases experience oscillations but in the case 73 this escalates while in the case of 60 they stabilize without much significance for what happens later. The reason for this markedly different behavior is that in run 60, boundary temperature for condenser outlet is closer to interim equilibrium (between 20 and 100 second). The interim equilibrium is in its term influenced by outside temperature of condenser pipe (here fixed to 500K). Once temperature for condenser outlet is reached (marked on the diagram as horizontal black line), condenser control system reacts and reduces outside temperature in accordance with our dynamic model. This reduction reduces overall temperature and prevents continuation of instabilities. In the run 73 the threshold for condenser outlet is set much higher and this temperature is first reached by the liquid 20 seconds later (as compared to run 60). By this time temperature at the preheater is so high that instabilities are inevitable. Temperature at the run 73 also penetrates temperature limit at the later time when heat flux is higher, making instabilities more intensive.

Resolution of the issue: Our tests show conclusively that the easiest way to deal with this problem is to recognize the fact that condenser outlet temperature is not the same as subcooling temperature. Instead, the real subcooling temperature (temperature at the pre-heater inlet) will be higher. The solution is therefore to prescribe lower condenser outlet temperature than desired subcooling. By how much however is not trivial since this depends on the expected quality. Recommendation at the moment is to reduce by 15°C if quality is unknown or over 50%, or 10°C for lower quality. Reducing temperature by higher amount is not recommended since this could overwhelm pre-heater and its rated power, making desired pre-heater outlet temperature unattainable. 

Runs affected by this issue: 109, 106, 103, 96, 97, 94, 91, 85, 82, 79, 73, 69, 66.

Problem 2
In this problem lowest condenser temperature of 373K is achieved and can’t go any lower. Once heaters in test section are turned on after 100 seconds condenser responds by reducing its outside surface temperature. This process is however abruptly stopped when the lowest temperature of 373K is attained resulting in prompt temperature jump at the condenser’s outlet, which in turn rises pre-heater inlet temperature over threshold for onset of instabilities. Solution of this problem is adjusting capacity of the condenser which will be implemented if deemed necessary. To clarify this issue further run 24 is compared to run 36 where desired quality and flow are the same but where pressures and saturation temperatures are different. As a result condenser can continue sinking its temperature further.

Runs affected by this issue: 24
Figure 58: Comparison of major parameters of run 24 and 36
Problem 3

Detailed investigation has been done in relation to these instabilities. These oscillations are distinctively different from the ones appearing at higher pressures (over 40 bars), major difference being that these oscillations come without any warning or any apparent cause in close proximity to activation of main section heaters. As illustration of these oscillations major parameters of experimental run 8 are given in Figure 59.

At present there is neither satisfactory explanation in regard to the cause of these oscillations nor advice on how to avoid them.

Current hypothesis is that these instabilities are caused by numerical instabilities in the TRACE code. Following statements can be made in support of this hypothesis:

- Currently there is nothing that points in direction that these instabilities may have physical character. Even if there might be slight oscillations in inlet temperature (on the order of 1-2 degrees) this would result in quality reduction or increase that would be very modest [40]. Impact on void quality would be even less significant. TRACE is however giving void fraction swings of 10 percentage points or even more in some cases. It is clear that this result has no physical foundation.
- Reducing time step by the order of 10 greatly reduces or in some cases completely eliminates void fraction oscillations (Figure 60) clearly pointing in the direction of mathematical instability.
- This effect progressively diminishes with increasing pressure and disappears altogether over 60 bars.

**Figure 59: Severe instabilities in experimental run 8**
Figure 60: Unstable and stabilized void fraction for pressure of 20 bars
Problem 4
Problem manifests itself in TRACE reporting error related to too big time-step and crashes. Reducing timestep only in the vicinity of the problem does not work since TRACE than crashes at the point where timestep change has been attempted. Data provided before the crash does not seems to point anything extraordinary.
Problem can be mitigated by using steam tables, instead for default model to predict steam properties.

Conclusions
- Model is stable between 60 and 180 bars for all checked configurations.
- Instabilities encountered in this area have been successfully accounted for.
- Model is stable for most configurations between 40 and 60 bars.
- Instabilities in the area at low (under 40 bars) pressures have not been accounted for despite detailed investigation into these.
APPENDIX B: PUMP TRIP RESULTS

Figure 61
Figure 62

Figure 63
Figure 64

Pump trip: Liquid flow

Figure 65

Pump trip: Gas flow
Figure 66

Pump trip: Wall surface temperature

Figure 67

Pump trip: Wall superheat
Figure 68

Pump trip: Inlet mass flow

Figure 69

Pump trip: Outlet pressure
Figure 70

Pump trip: Inlet temperature

Figure 71

Pump trip: Total power
Figure 72

Pump trip: Power deviation

Figure 73

PUMP TRIP: DRYOUT FLAG according to BIASI
Appendix C: Pump Trip Dryout Initiation

Figure 74
Figure 75

Pump trip: Actual quality

Figure 76

Pump trip: Pressure distribution
Figure 77

Pump trip: Liquid flow

Figure 78

Pump trip: Gas flow
Figure 79

Pump trip: Wall surface temperature

Figure 80

Pump trip: Wall superheat
Figure 81

Figure 82
Figure 83

Pump trip: Power deviation

Figure 84

PUMP TRIP: DRYOUT FLAG according to BIASI
Figure 85

Pump trip: Wall superheat at the outlet

Superheat [K]

Time [s]

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

0 5 10 15 20 25 30
APPENDIX D: LOAD REJECTION

Figure 86
Figure 87

Figure 88
Figure 89

Load rejection: Liquid flow

Figure 90

Load rejection: Gas flow
Figure 91

Figure 92
Figure 93

Load rejection: Inlet mass flow

Figure 94

Load rejection: Outlet pressure
Figure 95

Load rejection: Inlet temperature

Figure 96

Load rejection: Total power
Figure 97
APPENDIX E: CHF PREDICTION, NEW AND OLD BIASI

In this chapter we want to show that old and new Biasi can be used interchangeably to predict dryout and dryout margin. Background to this appendix has been brought forward in chapter 5.7.1. Here however we briefly repeat most important points.

New Biasi correlation that is employed by TRACE is modification of old Biasi correlation done by Phillips and associates in 1981[20]. This new correlation is improvement in comparison with the old one because it is global boiling length correlation. However, user is warned in TRACE manual [5] that the new correlation is subject to constrains and limitations which can be found in Phillips work [20]. We were unable to find this paper, so it was decided that we should modify old Biasi correlation ourselves and convert it from local to global. This was done with support of following paper proposed by Chang et al[26]. New correlation can even be used for non-uniform power distribution which was utilized in chapter 6.

In order to asses CHF margin we first assessed given transients and roughly predicted heat flux that would cause dryout. We would then proceeded and increase power in 1% steps until dryout was attained. Both correlations predicted dryout for the same power. Here we give diagrams from load rejection case (uniform power).

Figure 98
Figure 99

LOAD REJECTION: LOCAL DRYOUT FLAG according to ORIGINAL BIASI

Figure 100

LOAD REJECTION: TRANSIENT CPR
Figure 98 and 100 are produced using new Biasi while Figure 99 is produced by using old Biasi. Dryout will namely occur for 215% increase of power and dryout event will occur 2.42 seconds into transient.

Careful reader will notice that all dryout indicators are slightly short of their critical values (Flag=99.3%, Local Flag=99%, CPR=1.006). The reason for this is that we kept increasing power by 1% point and noted the last values before going over the limit and initiating dryout. Increasing power by one more percentage point would have put us over the limit. Therefore these diagrams represent verge of dryout.

Furthermore, this is also proof that our implementations of both Biasi correlations are correct.
Figure 101
Figure 102

Figure 103
Figure 106

Pump trip: Wall surface temperature

Figure 107

Pump trip: Wall superheat
Figure 108

Pump trip: Total power

Power [kW] vs. Time [s]

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

25 30 35 40 45 50
PUMP TRIP MAP COMES HERE
APPENDIX G: LOAD REJECTION, NON-UNIFORM POWER

Figure 109
Figure 112

Load rejection: Liquid flow

Figure 113

Load rejection: Gas flow
Figure 114

Load rejection: Wall surface temperature

Figure 115

Load rejection: Wall superheat
Figure 116
LOAD REJECTION MAP COMES HERE
APPENDIX H: DATA MANAGEMENT

Following execution of calculations, results that TRACE provides are stored in a file having extension .xtv. Properties for each cell/surface are reported separately. At present the only possibility to extract data is to use special dedicated program called APT plot.

APT plot is however inappropriate to use in this project for several reasons:

- All properties can be plotted against time only rendering plotting along the pipe length impossible.
- The program can handle maximum of 30 different series (30 properties against the time can be plotted).
- Exporting data to another program is very rudimentary with only one export format supported.
- Maximum of 30 properties can be exported.
- Many properties are not evaluated at all (e.g. quality, enthalpy...) and APT has no possibility to evaluate them based on other available properties.

In order to address these problems and produce results that are needed data handling method has been devised that addresses the shortcomings presented above. Here we will in short terms explain the principles behind data management logic that has been used extensively in all phases of the work.

Following calculation run, an xtv file is created that stores all available results for every cell or surface. Properties that are calculated are duly listed in TRACE manual [6, 7]. Here it is enough to say that amount of data and results is intimidating and it increases rapidly with increase in number of cells. It is therefore necessary for user to have some idea about what data is needed.

Once this decision has been made user selects groups of properties and commissions export of these. Since there is limit of 30 properties each group should contain maximum of 30 different properties. Since usually more is needed several groups should be selected each having up to 30 different properties and each group should be saved in a separate file. These files can then be merged in a single file by copy-pasting content of all files into a single file. Since there are usually many files, dedicated program can be used for this purpose. In our case MS-DOS command “copy *.txt" was used.

ASCII file generated by APT file has the following form:

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>xxxx</td>
</tr>
<tr>
<td>0.002</td>
<td>xxxx</td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>

File showed here is of course truncated with gray header added for clarity. Each time frame has its own property and merged file we discussed earlier has all properties piled one after the other. In other words the file has the same structure as the one presented above but after property is showed for each writing time step (which is 0.001 in the example), a new series starts from the beginning with a new property.

It goes without saying that this data structure is both difficult to comprehend and manage as well as hard to use for further processing.
In order to address this problem a dedicated MATLAB program IMPORTT has been written which converts data in more appropriate form which is easy to manage:

<table>
<thead>
<tr>
<th>Property 1</th>
<th>Property 2</th>
<th>Property 3</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>xxxxx</td>
<td>xxxxx</td>
<td>xxxxx</td>
<td>0.001</td>
</tr>
<tr>
<td>xxxxx</td>
<td>xxxxx</td>
<td>xxxxx</td>
<td>0.002</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

IMPORTT command independently analyses data and decides appropriate number of columns and rows. In this format analysis as well as processing of data is easier since structure is easy to understand and intuitive.

Depending on number of data and complexity of data processing it can happen that newly generated array of the aforementioned form is fairly extensive. For example, array containing necessary results of load rejection matrix is 303x1000 (it contains 303 different properties and 1000 time steps).

It is certainly appropriate to try to make the data more manageable. In order to achieve this we derived MATLAB program “im1” which split this array into group of smaller arrays containing properties that are connected to each other. For example, this function will extract pressure for each cell from the primary matrix and create the following structure:

<table>
<thead>
<tr>
<th>Cell no 1</th>
<th>Cell no 2</th>
<th>Cell no 3</th>
<th>...</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xxx</td>
<td>xxx</td>
<td>xxx</td>
<td>...</td>
<td>0.001</td>
</tr>
<tr>
<td>Xxx</td>
<td>xxx</td>
<td>xxx</td>
<td>...</td>
<td>0.002</td>
</tr>
<tr>
<td>Xxx</td>
<td>xxx</td>
<td>xxx</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

This is done for all properties creating intuitive overview of all results that can be easily plotted or processed further.
LITERATURE

[38] B. Akdeniz, K. Ivanov, A. Olson, Boiling water reactor turbine trip (TT) benchmark, in, Nuclear energy agency, USA, 2005, pp. 133.