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Pilot plant for the development of a drilling technology based on the use of a hydro-thermal flame

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Table of Contents

Chapter 1

Management Summary

General Project Goals.

The project aims to the investigation of a novel drilling technology for deep geothermal heat mining. The current report is a description of the construction and commissioning of the new spallation drilling pilot plant. Its design is developed to allow for the economical and technical feasibility investigation of the technique and it is based on the findings of the preceding project carried out in our lab.

The drilling technology in question makes use of a known phenomenon used in mining in the US during the seventies. Local and rapid heating of crystalline rocks with the help of a flame jet leads to the induction of extreme thermal stresses in the mass of the rock and subsequently to fracture in disc-like spalls. The impinging heat flux from the flame to the rock is the milestone of the process, the thermal stresses being directly connected with the temperature distribution in the rock specimen.

The described project sets the aims even higher, by trying to characterize the aforementioned process in an aqueous high pressure (250 bar) environment, simulating the depth of a geothermal well. The new environment sets new challenges not only for the heat transfer problem and the transportation of the produced spalls, but also for the ignition of hydrothermal flames. Such flames are flames ignited in water under a pressure higher than its critical value and were previously produced only through self ignition of the reactants, a case not relevant in a drilling process, where the ignition must be safe and reproducible. The project was initiated in April 2009 and in accordance with the milestones defined at its beginning, the plant has now been built and commissioned. A detailed account of the work accomplished so far, and a brief outlook of the scheduled tasks follow a short description of the organization of the work in distinct phases and the accomplished milestones of each one. In summary the general goals of the project are:

- Initial design - Planning of the pilot plant.
- Construction of the plant.
- Commissioning of the pilot plant .
- Experimental investigation of the drilling technique and assessment of its technical and economical feasibility.

Accomplished project phases

Project Phase 1 - Planning of the Pilot Plant

Starting with the definition of the overall aims and the underlying research questions, we then proceeded with evaluating the available technologies and know-how in the industry as well as in research institutions. This was an integral part of the first phase, namely the planning of the pilot plant, which was scheduled to finish in January 2010. The planning of such an innovative plant was however a complex procedure, subject to constant revisions. By the time the bigger and most expensive pieces of equipment were ordered, this phase was considered as largely finished. This took place on the 23rd December 2009, and the milestone is considered as accomplished on time. This phase comprised the following work.

- Preliminary design of the plant. The preliminary design consisted of the following subtasks.
  - Process and Instrumentation (P&I) diagram for the plant.

  - Modeling of the plant with various software tools.
  - Choice of fuel and oxidation medium, based on the simulations.
  - Definition of infrastructure details of the space where the plant was to be built.
  - Choice of the generic type for each piece of equipment (pump types, heater types, etc.).
- First detailed design phase of the plant.
  - Market assessment according to the preliminary design.
  - Preliminary 3-D Drawing of the plant in the space available.
  - Preliminary safety concept for the plant.
- Second detailed design phase.
  - HAZOP (Hazard and operability analysis).
  - Adaptation of the plant design to the HAZOP Analysis.
  - Final assessment of the equipment choice, according to the HAZOP analysis.
  - Final 3-D design of the plant - optimization of the space used.
  - List with the biggest and most expensive plant parts.
- Design of the reactor of the plant.
  Parallel to the plant design the reactor of the plant was designed in co-operation with the company SITEC-AG. The design was finalized on the 15.12.2009.

Assessment of the first project phase

Taking the previous experience of our research group as a starting point and considering the challenge of the accomplished task, this project part was successfully completed. Additionally the following commissioning of the plant showed that only minor mistakes in the initial planning were made and the corresponding adaptations were carried through in a very efficient and fast way.

Project Phase 2 - Mechanical Construction of the plant

This milestone was planned to finish in June 2010. However in the course of the planning phase two issues arose, which caused some unavoidable delay. The first had to do with the renovation of the electrical installation in the space ML H/G12, where the plant was to be constructed. Although the renovation project has already been assigned in March 2009, the project was only completed in July 2010. Without the data of the electrical installation the design of the electrical network of the power plant had to be put off. Another issue that delayed the mechanical construction of the plant was the extreme difficulty of finding the material chosen for the reactor, and the TüV control we had to carry out for it. Consequently the reactor was delivered three months later than planned on the 4^{th} of June 2010. The following tasks were planned and carried out.

- Placing orders for the equipment. Delivery of the last important piece in July 2010.
- Detailed 3-D design of plant. The complete 3-D design of the plant was carried out in different steps, starting from the design of the platform for the reactor.
  - Design of the platform for the reactor and the pre-heaters of the plant. Contact with the responsible company.
  - 3-D positioning drawing of the pieces of equipment in the space available, based on the data provided from the manufacturers.
  - Implementation of the spatial safety plan.
- Definition and order placement of the tubing and smaller relevant components.
- Choice and order of the positioning devices.
- Contact with external companies for the construction of the plant. The external companies and the tasks undertaken from them were:
  - Olaer AG. This company had specialized staff for the construction of high pressure oxygen tubing networks.

  - SITEC AG. This company specializes on high pressure equipment and took over the construction of the fuel network.
  - Zyltec AG, is a company responsible for general hydraulic installation and took over the installation all other tubing components.

- Positioning of each device on the correct place, with support from our workshop.
- Construction of the platform for the plant. During this phase, which lasted three days, a special crane was implemented.
- Actual construction of the plant. The construction started at the beginning of June 2010 and the plant was ready for its commissioning at the end of October 2010.

Assessment of the second project phase

In the aforementioned project phase a mainly practical planning of the construction of the plant was necessary, and certain project management skills were used to have the project run without big delays. Although the reactor delivery delayed the construction for some months, the phase was carried through in an efficient way and the experience gained will be valuable for us in the future. As the plant did not have any structural problems and each part of it accomplished its goal during the commissioning phase, this phase of the project is also considered successful.

Project Phase 3 - Commissioning of the plant

This milestone was planned to finish in October 2010. Due to the delays of the preceding phases it was finished at the beginning of February 2011, and it consisted of the following tasks.

- Testing of the control system and of the safety concept.
- Commissioning of all the communications in the plant.
- Controllers setup.

- Correction of control problems - Plant optimization.
- Preparations for the next project phase

Assessment of the third project phase

The commissioning phase of each industrial scale plant is the time where the preceding planning and construction phases are judged and all the necessary corrections are done. The control system installed for the plant and the preceding HAZOP Study for the plant proved to be very important tools for the correct setting of all the parameters of the process. The start-up and emergency procedures are programmed in a way, that allows for their flexible adaptation in case needed. The developed control concepts proved to be correct and apart from the pressure control valve no hardware change was necessary. As the commissioning of the plant was finished with minor hardware adaptations this project phase is also considered successful.

Outlook - Project Phase 4

According to the project plan the experiments for the investigation of hydrothermal spallation drilling should start in the beginning 2011 and their end is planned for the end of 2012. Taking into consideration the limited capacity of a university and the difficulties met during the construction and the commissioning of the plant, the project succeeded in meeting the goals of the first two years. Due to a delay in the reactor delivery and the renovation of the electrical installation of the space where the plant is placed, the construction and commissioning of the plant was delayed for four months in total.

In summary the project outlook until the end of 2012 consists of the following experiment series:

- Ignition experiments - April 2011 - October 2011.
- Heat transfer experiments October 2011 - April 2012.
- Drilling experiments April 2012 - December 2012.

Additional Tasks

In parallel to the tasks presented relevant to the construction and the commissioning of the plant great effort was made for the development of a new sensor design and for the optimization of the one developed in the preceding project. A focus project running over a year and occupying three students and an additional bachelor thesis were launched in search for alternative concepts and an optimization of the sensor construction. The result of this combined effort was the design and construction of four different sensors, two of which were also functional and the third needed minor revisions. As each custom-built sensor needs a calibration to provide trustworthy and reliable measurements, a calibration facility has been built, simulating as far as possible the conditions expected in the reactor flames and the first generation of sensors was calibrated successfully. Additionally a publication on the calibration methodology and the plant was peer reviewed and accepted from experimental heat transfer Journal.

Communication - Publications

In the course of these two years different communication efforts were made, not only in the scientific community but also in the press and through contacts with various companies. The following list summarizes the communication efforts for the project.

Scientific publications.

The scientific publications for the project were in peer reviewed journals and in conferences, relevant with the corresponding topic of the presented results.

Scientific Journals Publications.

- Tobias Rothenfluh, Martin J. Schuler, and Philipp Rudolf von Rohr. Penetration length studies of supercritical water jets submerged in a subcritical water environment using a novel optical schlieren method. The Journal of Supercritical Fluids, 57(2),175-182, 2011.

- Panagiotis Stathopoulos, Florian Hofmann, Tobias Rothenfluh and Philipp Rudolf von Rohr. Calibration of a Gardon sensor in a high temperature - high heat flux stagnation facility. Experimental Heat transfer Journal, (copy editing and typesetting phase not yet in press), 2011.

Scientific Conferences.

- Tobias Rothenfluh, Martin Schuler, Philipp Rudolf von Rohr. Experimental and numerical heat transfer study of supercritical water jets penetrating subcritical water. 12th European Meeting on Supercritical Fluids, Graz, Austria, May 2010.
- Martin Schuler,Tobias Rothenfluh,Panagiotis Stathopoulos,Philipp Rudolf von Rohr.Heat Transfer of a Hydrothermal Flame in Supercritical Water towards Rock used for Contact Free Drilling. R09 Twin World Congress and World Resources Forum Davos, Switzerland, September 2009.

General publications.

- Dr. Keith Evans, Dr. Thomas Driesner, Prof. Dr. Stefan Wiemer, Prof. Dr. Philipp Rudolf von Rohr. Drei Forschungsgebiete im Fokus. Geothermie.ch Nr47, September 2009.
- Martin Schuler,Tobias Rothenfluh,Panagiotis Stathopoulos,Philipp Rudolf von Rohr. Neuartiges Bohrverfahren. Geothermie.ch Nr50, März 2011.
- Panagiotis Stathopoulos, Martin Schuler, Tobias Rothenfluh, Philipp Rudolf von Rohr. Geothermal energy: Renewable energy for heat and power. Newsletter of the Energy Science Center at ETH Zürich, No.1, March 2010.

Chapter 2

Introduction and Project goals

The old plant operating in our lab was built in the 1993 to conduct experiments on supercritical water oxidation (SWCO). Built with different goals and having been extensively used for almost two decades it was considered unsuitable for retrofitting for the intended experiments with rock probes (1). Moreover the fuel power limit of the plant did not allow a thorough investigation of the mechanisms of hydrothermal spallation drilling (2). Accordingly the construction of a new hydrothermal spallation drilling plant was deemed necessary.

On one hand the investigation of research related phenomena relevant to spallation drilling, and on the other hand technical issues of industrial interest are part of the project. Due to the complexity of the problem, the basic research questions, such as the incipient heat flux and the surface rock temperature during spallation, can not be separated from the technical feasibility questions, like the achieved drilling velocity, the size of cuttings and the resulting diameter of a hole. In order to find a connection between the two, one must conduct experiments in the same reactor. This way the drilling tool could be much easier characterized and the measurements could also be used for the optimization of the process in the future.

The gathered experience on experiments with hydrothermal flames and the results of the previous project were the initial input in the design of the new plant. Maximum fuel power of 120 kW and rock probes 10 cm in diameter and up to 35 cm length can now be used for drilling experiments.

Industrial standards were implemented in the whole planning and construction phase and a high technology PLC device was used for the control of the plant,

providing high safety standards.
The project phases and goals can be summarized as follows:

- **Project Phase 1.** Design of the new plant, its reactor and its safety and control concept.
- **Project Phase 2.** Construction of the plant.
- **Project Phase 3.** Commissioning of the plant.
- **Project Phase 4.** Technical and economical feasibility experiments.
  - External ignition experiments on hydrothermal flames.
  - Heat transfer experiments - nozzle optimization based on the heat transfer.
  - Drilling experiments - Drilling velocity and cuttings size investigation.

Table 2.1: Time plan for the different project phases

Milestone	Planned completion	Actual status
Design of plant & Reactor	01.01.2010	completed on time
Construction of plant	01.07.2010	completed two months later
Commissioning of plant	01.11.2010	completed two months later
Experiments	31.12.2012	ongoing

The following chapters give an account of the three completed phases of the project along with a description of the design of the reactor vessel.
In chapter 3, the description is limited to the process and no details about the process modeling carried out for the dimensioning of the equipment are presented.
In chapter 4, only the conceptual designs of the reactor and the positioning devices are presented, leaving out the calculations and the TüV controlling procedure, which are typical for each pressure vessel.
Chapter 5 presents the actual form of the plant as built and commissioned, and the report concludes with a short presentation of the commissioning phase of the plant.

Chapter 3

Plant Design

3.1 Plant specifications

The plant should provide the necessary infrastructure, in order to experimentally simulate a down hole environment like the one in depths over 2.5 km in a safe and efficient way. Additionally, it should allow for the investigation of spallation drilling. After a thorough literature research, the following general specifications were defined:

- Maximum continuous operating pressure at least 250 bar.
- Maximum continuous operating temperature on the reactor walls 400°C.
- The reactor should provide enough space for spallation drilling experiments on rock probes.
- Positioning of rock probes without interruption of the process.
- Sufficient fuel power for the induction of spalation on rock probes.
- Collection rock cuttings should be collected in a safe way, allowing for the investigation of their shape and their particle size distribution.
- Industrial high pressure safety standards.

3.1.1 Choice of fuel and oxidation media

Process models were developed for the operation with different fuels (i.e methanol, ethanol and propane). Apart from the chemical characteristics of the fuel, such as its heating value and its need for oxidation medium, many parameters had to be considered for its choice. Some of them were technical ones and had to do with the availability of high pressure equipment for different fuels, the respective compression costs, and the ease of heating of the fuel in temperatures as high as 400 °C. Several fuels had to be rejected, as they can only be used in open spaces, and the formation of an explosive mixture of fuel and oxidizer in the ventilation system of the installation space must be avoided at any cost. Similar considerations led to a list of characteristics for the fuel in question.

- Water soluble and liquid in atmospheric conditions.
- No harmful or toxic substances.
- Easy to store and low-cost.
- It should have a heating value leading to a comparable small fuel pump, for the heating power we need.

The aforementioned considerations led to the choice of ethanol as a fuel for the plant. Nevertheless, the fuel pump can also operate with liquid propane, in case higher fuel power values are necessary.
For the oxidation medium air, oxygen (liquid of gas) or hydrogen peroxide were possible choices. After a short market assessment, air was excluded because of the resulting compressor size and liquid oxygen and hydrogen peroxide presented high safety hazards. The only choice leading to realistic equipment sizes and a safe operation was gaseous oxygen.

3.1.2 Process specifications

As Rauenzahn (2) and Williams (3) report, both the incipient heat flux q" at the rock's surface and the rock's surface temperature T_S are crucial parameters of

the spallation drilling process. Heat fluxes of approximately 1 MW/m^2 and surface temperatures in the range of 500 °C are recommended to induce spallation in granite (Barre, USA).
In the latest contribution in 2006 Rodrigues et al. (4) investigated the penetration rates as a function of firing time. It was found that the average penetration rate decreases with firing time and levels off at a value significantly lower in comparison to the values for shorter firing times. This is an indication that the power values used in this study were extremely high.
In his PhD Thesis Wilkinson (3) computed among other parameters the so called Stanton number, as the percentage of the heat leaving the burner nozzle that reaches the rock surface. We used the values reported from him as indications for the possible stand-off distances and heating power values for the plant.
The lack of data on jet or flame impingement in the environment we are working on, led to the choice of the plant heating power at the limits of the infrastructure provided, the latter being 120 kW. The reactor design was then adapted, based on the respective requirements for spallation (see chapter (4)). A bundle of twelve 50 l oxygen bottles will suffice only for two hours of continuous operation on full power. The maximum working pressure of the plant is chosen at 400 bar, to enable the investigation of the pressure effect on the drilling process. The effluent water outlet temperature is specified to be below 80 °C to avoid cavitations during the pressure throttling for the control.

3.2 Process Description

The process concept is similar to one of the the existing plant, and it is typical for each combustion plant. It is divided in five functional parts:

- The fuel network,
- The oxygen network,
- The cooling water 2 network,
- The cooling water 1&3 networks, and

- The effluent water network

Fuel is mixed before its inlet to the fuel pump (FP-1, in Fig(3.1)), which compresses a prepared ethanol-water mixture. The compressed fuel flows through a pulsation dampener to minimize the pressure fluctuations in the tubing, and subsequently the pressure at the outlet of the pump is measured (PI-1). After flowing through a bursting disc (BS-3), its density and its mass flow rate are measured in a flow-meter (FMI-1). The flow is directed through a non-return valve to the fuel pre-heater (HX-2), at the outlet of which the temperature is measured (TIC-2). After passing through a second non-return valve, fuel is injected in the reactor.

Oxygen supplied from a 12-bottle bundle is compressed by two, in series high pressure compressors to a 300 bar reservoir, the pressure of which is measured from two contact manometers. Each manometer has two switches, one for low pressure and one for high pressure, switching each coupled compressor off and on respectively. The pressure after the reservoir is controlled by a front pressure controller (PIC-1, in Fig(3.1)), thus defining the inlet pressure for the gas line of the plant. After flowing through a bursting disc (BS-1), its flow is controlled from a flow controller (FC-1) and then directed through a non-return valve to the oxygen pre-heater (HX-1) and through a second non-return valve to the reactor.

Cooling water is supplied from two separate pumps (WP-1 & WP2), thus assuring redundancy of the water supply. WP-1 is fed directly from the desalinated water network of the installation space, and it provides the cooling mantle of the reactor (see Chapter 4) with water. WP-2 is fed from a storage tank (2.5 m^3) and it provides the cooling water stream for the combustion chamber of the reactor (CW1) and for the cooling of the effluent stream leaving the reactor (CW3).
In the CW2 network, water flows through a pulsation dampener, at the outlet of which a digital pressure switch (PI-1) is installed. After the measurement of its mass flow rate (FMI-3) it flows through a bursting disc (BS-6) and a safety valve (SV-2) and the flow is directed through a non-return valve (NRV-10) to the cooling mantle of the reactor.
In the CW1&3 network, a manually controlled by-pass valve (V-7) defines the to-

tal flow of water to the line. After a pressure measurement (PI-2), a bursting disc (BS-5) and a safety valve (SV-1) the flow is divided in the streams CW1 and CW3. The mass flow of the stream CW1, is controlled by a needle valve (FC-2) and a flow meter(FMI-2), while the CW3 stream is indirectly controlled from the by-pass valve after the pump.

The reactor has four separate outlets, two for the cooling mantle and two for the burning chamber. The temperature at each outlet is measured (TIAH-3&4) and the two streams are mixed after the reactor as a first cooling step of the combustion products. The second is realized by mixing the CW3 steam with the total stream exiting the reactor. A safety valve (SV-3) and a bursting disc (BS-8) are then installed, followed from a filter and a combined pressure and temperature measurement (P&T-1). The last component of the pant is the pressure controller (RV-10), which reduces the pressure to the atmospheric one.

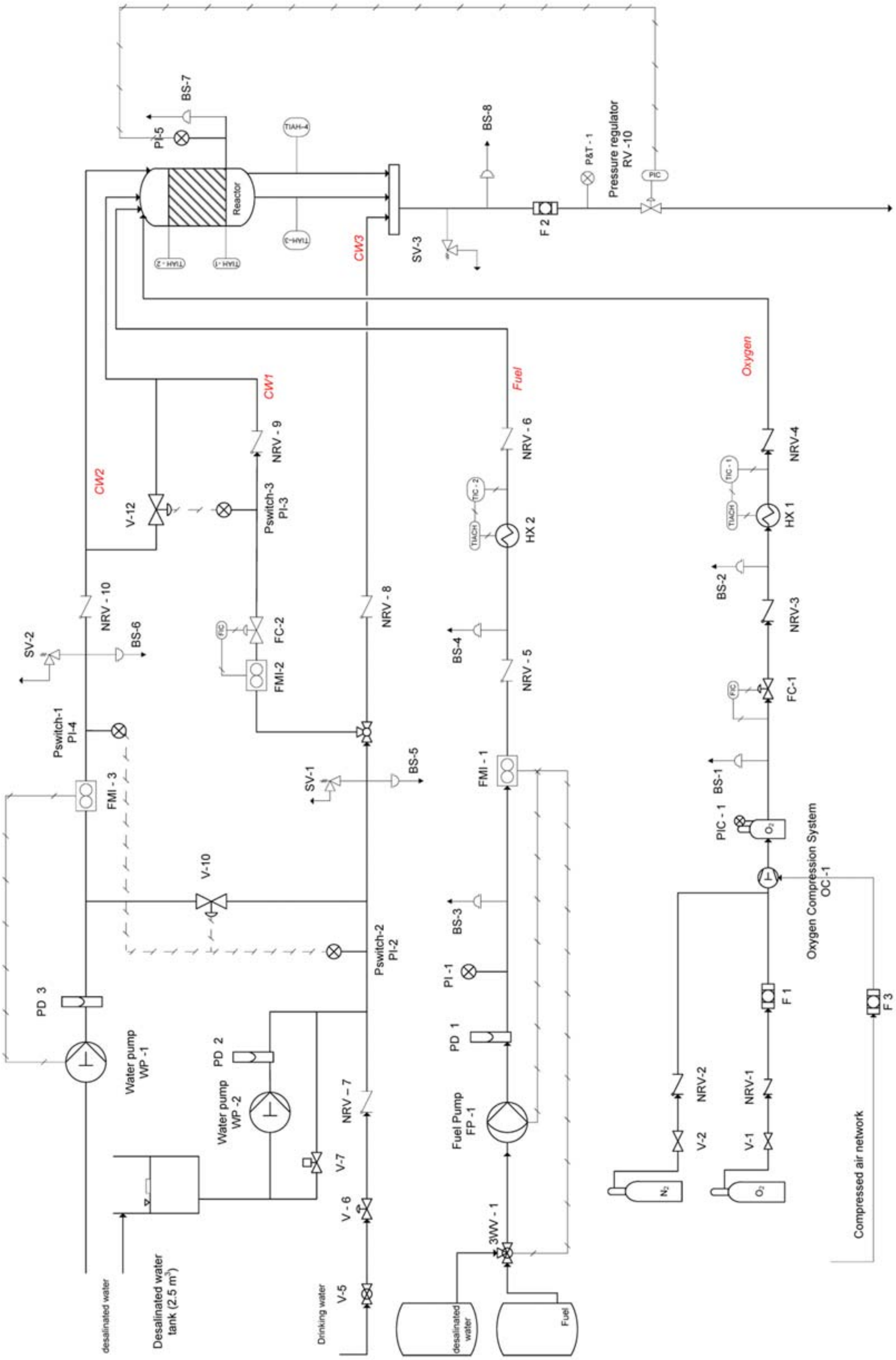

Figure 3.1: Plant piping and instrumentation diagram.

3.3 The HAZard and OPerability study for the plant

The HAZOP study was conducted with the help of Prof. Dr. Schmalz from September 2009 to November 2009. The presentation of the study in the following paragraphs is by no means comprehensive. For more details, the whole study is attached as a separate report to the present one.
In each HAZOP study the first and most important step is to define the operation intention and the reference point of operation of the plant part. The HAZOP procedure creates deviations from the process intent by combining guide words with process parameters. For example, when the guide word "No" is combined with the parameter "flow" the deviation "no flow" results. All credible causes that will result in a no flow condition for the node are then listed. A sample list of guide words is:

- No (kein) - None of the design intent is achieved
- More (mehr) - Quantitative increase in a parameter
- Less (weniger) - Quantitative decrease in a parameter
- As well as (sowohl als auch) - An additional activity occurs
- Part of (teilweise) - Only some of the design intention is achieved
- Reverse (umgekehrt) - Logical opposite of the design intention occurs
- other than (anders als) - Complete substitution - another activity takes place

It should be stressed that not all guide word/parameter combinations are meaningful. The application of each guide word to a process parameter leads to the so-called deviation from the reference operation point of the system. For each deviation produced with this methodology, possible causes are listed from the analysis team.
The next step is to define the consequences of each deviation for the system and estimate its frequency and importance. The higher each of these parameters is, the more it must be considered in the search of the necessary safeguards, which is the last step of the study for each deviation. The team should find ways to avoid the deviation either by changing the process or by implementing safeguards.

3.3.1 Operation intention and reference operation point definitions

The analysis consisted of two separate parts, one concentrated on the reactor operation and one for the whole process. For each part an operation intention was developed forming the basis of the analysis. It defines the process parameters, which could be also actions and not only measured parameters like temperature, on which the corresponding deviations are produced.

At the beginning of the analysis a draft conceptual sketch of the reactor presented on Fig.(3.2) was used, and its operation intention presented on Table 3.2, was the safety relevant part of its general specifications.

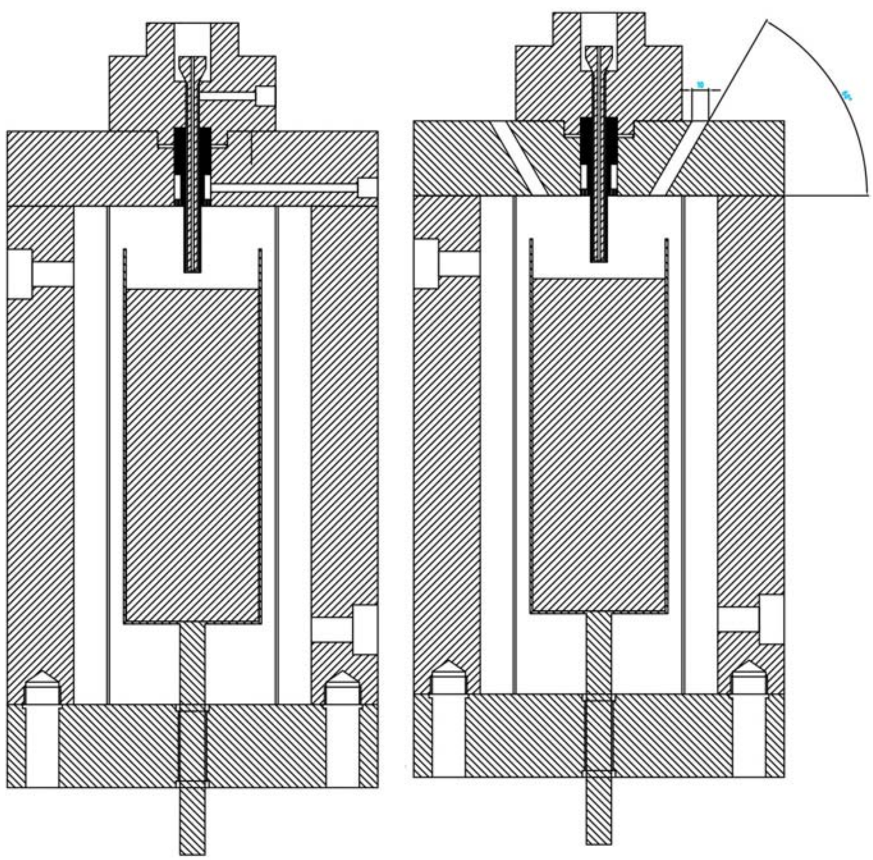

Figure 3.2: Reactor sketch at the beginning of the HAZOP study.

On the other hand, a modeled version of the process along with its P&I Diagram (see Fig.(3.4)) was available for its design intention. Additionally an extensive market analysis had been performed and many alternative solutions for the major pieces of equipment were available. The operation intention of the process is defined as the most dangerous operation case of it, summarized on Table3.1.

Table 3.1: Process operation intention

	Inlet temperature(°C)	**Mass flow (kg/h)**	**Pressure(bar)**
Fuel	400 °C	32.26 kg/h	300 bar
Oxygen	400 °C	40.332 kg/h	300 bar
Cooling water 1	100 °C	500 kg/h	300 bar
Cooling water 2	25 °C	1000 kg/h	300 bar
Cooling water 3	25 °C	1700 kg/h	300 bar

The simulation of the assumed process operation intention is presented on Fig.3.3. The fuel power is assumed 120 kW and the mass flow rate of the cooling water streams are set, so that the temperature before the pressure regulator is below 80 °C. Moreover the simulation was based on the initial P&I diagram of the plant on Fig.3.4, and not on the optimized one.

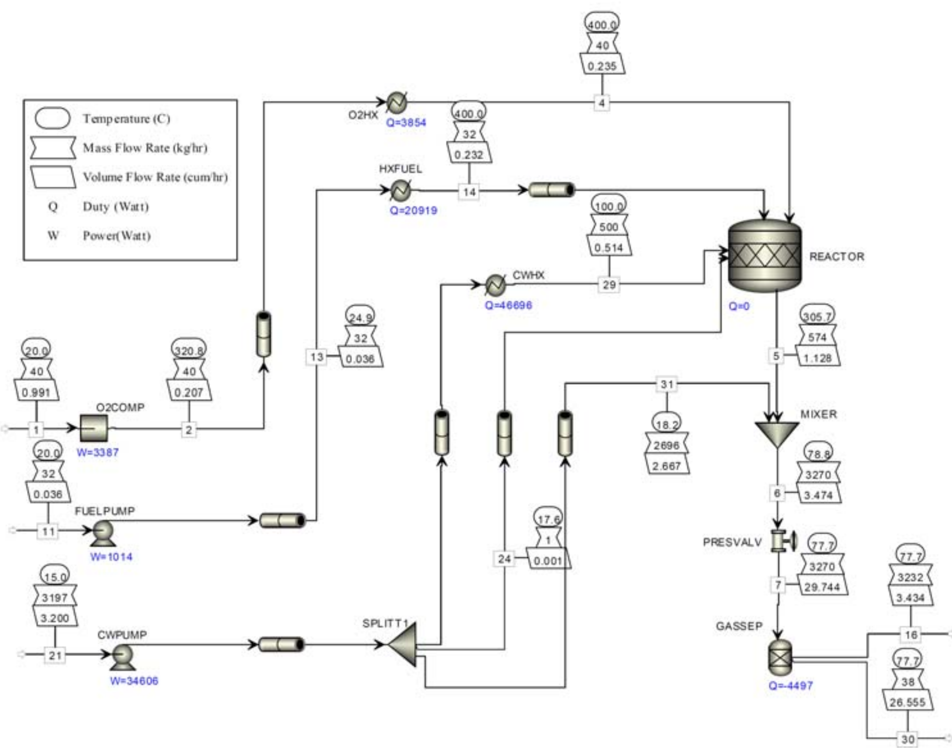

Figure 3.3: Process simulation (ASPEN PLUS) based on the initial P&I diagram of the plant.

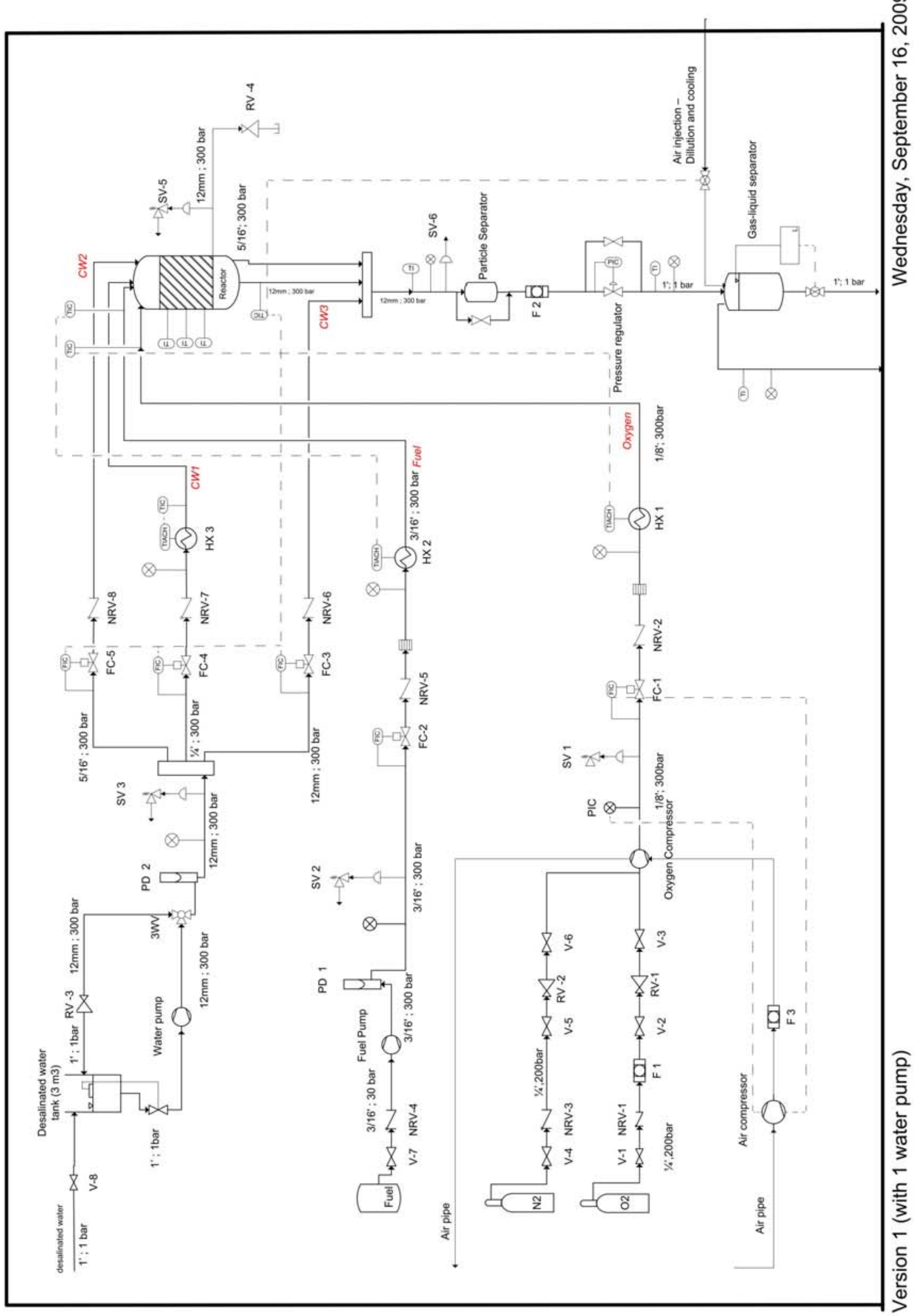

Figure 3.4: P&I diagram at the beginning of the HAZOP study.

Table 3.2: Design intention for the reactor and the process -HAZOP

Reactor Design Intention	
Sicheres Umschließen des kontinuierlichen Zerkleinerns von Gesteinproben, bei 250 bar und bei Wandtemperaturen (Deckel, Körper) $<$ 400 °C und Abführen der Produkte bei unterkritischen Bedingungen (300 °C).	Safe, continuous spalling of rock probes at a pressure of 250 bar and at reactor wall temperatures $<$ 400 °C, and outflow of the products in a sub-critical state (300 °C)
Process Design Intention	
Kontinuierliches Zerkleinern von Gesteinsproben zu Teilchen ($<$10 mm) durch Verbrennung von 20 g/s eines überkritischen (p=250 bar, T=400 °C) 50wt% Ethanol/Wasser-Gemisches mit Sauerstoff (p=250 bar, T=400 °C, $\lambda = 1,2$), bei gleichzeitiger Einspritzung von 140 g/s Kühlwasser bei T=100 °C.	Continuous spalling of rock probes in spalls ($<$10 mm) with combustion of 20 g/s of a supercritical (50wt% Ethanol/Wasser) mixture (p=250 bar, T=400 °C) with oxygen (p=250 bar, T=400 °C, $\lambda = 1,2$), with a simultaneous injection of 140 g/s cooling water at a maximum temperature of T=100 °C.

For the scope of the analysis the operation intention of the reactor was divided in the parameters, on which the deviations are be performed:

1. Safe enclosing of the spallation process.
2. Continuous spalling of rock probes.
3. p = 250 bar.
4. Reactor wall temperatures $<$ 400 °C.
5. Extraction of the products in a sub-critical state (300 °C).

In a similar way, the operation intention of the process has the following parameters:

1. Continuous spalling of rock probes
2. Spalls ($<$10 mm)
3. Combustion of 20 g/s
4. Supercritical (50wt% Ethanol/Wasser) mixture with oxygen (p=250 bar T=400 °C)
5. Continuous injection of 140 g/s cooling water at a temperature of T=100°C

3.3.2 Safety analysis results

With the experience of our research group on the operation of similar plants, the start-up and shut-down procedures were developed, prior to starting the HAZOP study. The results are summarized in Table(3.3) for the reactor and in Table(3.4) for the process.

Table 3.3: HAZOP results for the reactor

Study Result	Safeguard
The reactor and its sealing must be slowly heated-up i.e cooled down.	Start-up and Shut-down protocols must be prepared and followed.
Mounting errors should be avoided.	Assembly protocols must be prepared and followed.
	After each change in the reactor vessel, a pressure test must be carried out.
The max. operation pressure of the pre-heaters must be the same with the lift-off pressure of the safety valves.	Adaptation of the design of the heaters - Max.P:350 bar.
The valve RV-10 (Pressure control) must be dimensioned for the maximum throughput of the plant.	The valve is calculated for 4.5 m^3.
	The valve could be also supported from a by-pass hand valve.

Study Result	Safeguard
The reactor must be protected from excessive pressures.	A bursting disc and a safety valve will be installed.
A hand-controlled pressure relief would be advisable.	A hand valve could be installed for this purpose.
It must be clearly visible whether a flow exists in the CW1 pipeline.	The flow meters must be equipped with a dedicated signal for "no flow". An additional flow meter FMIAL-1 shall be installed for redundancy of the measurement.
The reactor must be protected from loss of flow in the CW1 pipeline.	FP-1 and OC-1 will be automatically turned off in such a case. The CW1 and CW2 pipelines will be connected before the heaters. The connection between the CW1 and CW2 pipelines will be automatically activated.
A temperature rise in the reactor must be detected as fast as possible.	The temperature of the reactor wall will be measured at two points, and there will be an alarm for them. The outlet temperature form the reactor will be measured at two points, one directly at the outlet of the burning chamber and one at the outlet of the cooling mantle.
A possible blockage in the pipelines must not lead to a high pressure difference between the burning chamber and the cooling mantle.	The cooling mantle will be equipped with pressure balance holes connecting the two spaces.
A flame detection system is necessary.	At least two windows with a web-cam must be installed on the reactor.

Table 3.4: HAZOP results for the process

Study Result	**Safeguard**
The plant must be protected from overpressure in case of a blockage.	The pressure of the reactor must be monitored , and each pressure measurement must have an alarm.
	Safety valves will be installed in all lines with a lift-off pressure of 350 bar.
	Each safety valve and bursting disc will have a separate expansion line.
	The filter and every vessel after the reactor must have a pressure measurements with an alarm in order to detect a potential blockage.
	The heater will be dimensioned at 350 bar.
The reactor and the plant must be protected against the fuel flow control failure.	The fuel mass flow must be controlled directly on the pump.
	The oxygen mass flow must be always kept at a value corresponding a λ value of 1.2.
	The temperature value before the pressure controller TI-5 must have a high alarm.
	The dimensioning of the water pumps must allow for a sufficient cooling and of the reactor in case the total fuel power rises unexpectedly.
The effluent water leaving the reactor must always be diluted before its pressure is reduced.	WP-2 must have sufficient capacity, so that the effluent has always 90% water before RV-10.
The reactants at the inlet of the reactor must always be at supercritical state.	The fuel and oxygen pipelines must be kept as short as possible.
	The feed pipelines must be good insulated.

Study Result	Safeguard
A leakage in the fuel pipeline must be detected.	The pressure at the fuel line will have an alarm or low values.
A leakage in the oxygen pipeline must be detected.	A gas detector must be installed (the space is also big for the total mass flow of the plant).
A heater temperature control failure must be detected.	Report this specification to the construction company of the heaters. The temperature of the heater block will be continuously measured and an uncontrolled increase will lead to an automatic trip of the heater.
The control of the cooling water system must be simple and reliable.	The water pumps must have an inverter control, if possible. The mass flow CW1 directed to the burning chamber, will be controlled with a control valve and a flow meter. If the inverter control of the flow rate proves to be very expensive, a bypass control shall be implemented.
The temperature before the pressure controller RV-10 must not exceed 80 °C).	This temperature value will have an alarm high.

In addition the standard HAZOP procedure, an impact analysis of a possible infrastructure failure in the building was considered. The analysis methodology was the same with the HAZOP analysis i.e. searching for deviations caused by the failure. As infrastructure the utilities provided from the installation space were considered comprising of, the compressed air network, the electricity network and the water supply. Table 3.5 presents the results of this analysis, in conjunction with the necessary safeguards.

Table 3.5: Infrastructure failure analysis

Failure Point	Safeguard
Water network failure	A level measurement is implemented in the water storage tank, with two alarms.
Air network failure	RV-10 must take its open position, when the air supply is cut-off, so that the pressure in the system becomes equal to the atmospheric.
Electricity failure	RV-10 must take its open position, when electricity is cut-off.
	FC1&2 must take their closed position, when electricity is cut-off.
	FC3,4,5 must take their open position, when electricity is cut-off.
	Connection with the potable water network, to ensure cleaning of the plant from fuel.
	Provision for emergency lighting.
	Provision for mechanical pressure measurements (manometer) on various points in the plant.
Blockage of the effluent water pipes of the installation space	Periodic cleaning of the pipes.
	in case of a flood, the water must not reach the electrical parts of the plant.

The HAZOP study is concluded with the simulation of an operational scenario of the plant crucial for its safety. The simulation intends to calculate the increase of the main chamber outlet temperature, in case the fuel pump control does not function properly. The most dangerous case is the uncontrolled increase of the fuel flow rate, and the respective increase in the plant combustion power. As a worst-case scenario, the full power operation of the plant presented on Table 3.6 is considered.

Table 3.6: Process simulation - Fuel control failure scenario

	Inlet temperature(°C)	**Mass flow (kg/h)**	**Pressure(bar)**
Fuel	400 °C	32.26 kg/h	300 bar
Oxygen	400 °C	40.332 kg/h	300 bar
Cooling water 1	100 °C	500 kg/h	300 bar
Cooling water 2	25 °C	0 kg/h	300 bar
Cooling water 3	25 °C	2700 kg/h	300 bar

The operation of the plant before the fuel control failure is without a cooling mantle flow, the λ value for the combustion is assumed to 1.2 and the ethanol concentration in th fuel mixture is assumed 50 % w.t. The result of the control failure is that the plant operates with a minimum λ equal to 0.9 and the corresponding heating power is 150 kW. The change on the operation of the plant is presented on Fig.3.5

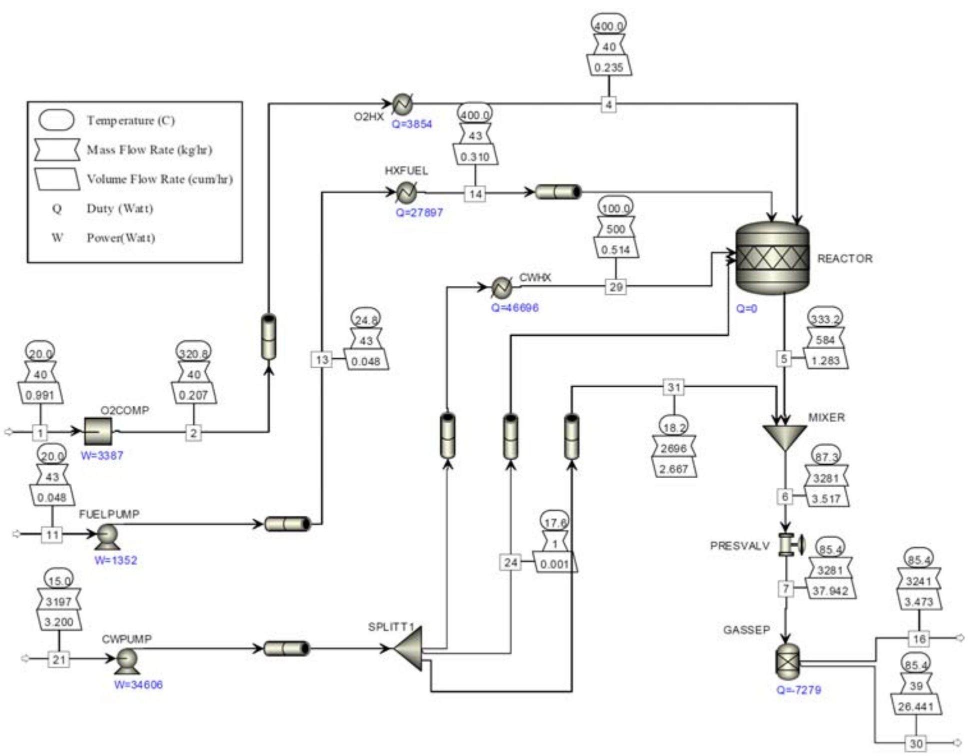

Figure 3.5: Process simulation - Fuel control failure scenario.

The temperature increase before the RV-10 and at the outlet of the reactor will be approximately 10 $^\circ$C and 30 $^\circ$C respectively. These values could be hazardous for the plant, and therefore the fuel to oxygen ratio during operation must not exceed the value $\lambda = 1.2$.

Chapter 4

Reactor Design and Construction

During the preliminary design phase of the reactor several significant parameters were not yet clarified, most significantly heat transfer details in a supercritical water environment and their influence on the drilling process. Furthermore, no data for the achievable drilling holes, with a certain nozzle diameter were available.
In summary the hydrothermal spallation drilling problem divided as follows:

- **The ignition problem.** An ignition system allowing the ignition of hydrothermal flames in a controllable and reproducible way is necessary. It would substantially improve the safety of the plant and save experimental time.
- **The heat transfer problem.** When the reactor design phase was initiated, only the water entrainment data for hydrothermal flames in a subcritical water bath were available (5). The small, hot flames made complicated the heat transfer problem. Consequently apart from the ongoing sensor development also the injection supercritical jets in a subcritical water bath should be optimized.
- **The problem of rock drilling.** The drilling process must be investigated from the beginning, because no data for the behavior of rock specimens in a supercritical environment are available.

The specifications for the reactor had to be as broad as possible, in order to allow for fast and efficient modifications the system. The problem summary is presented also on Fig.4.1.

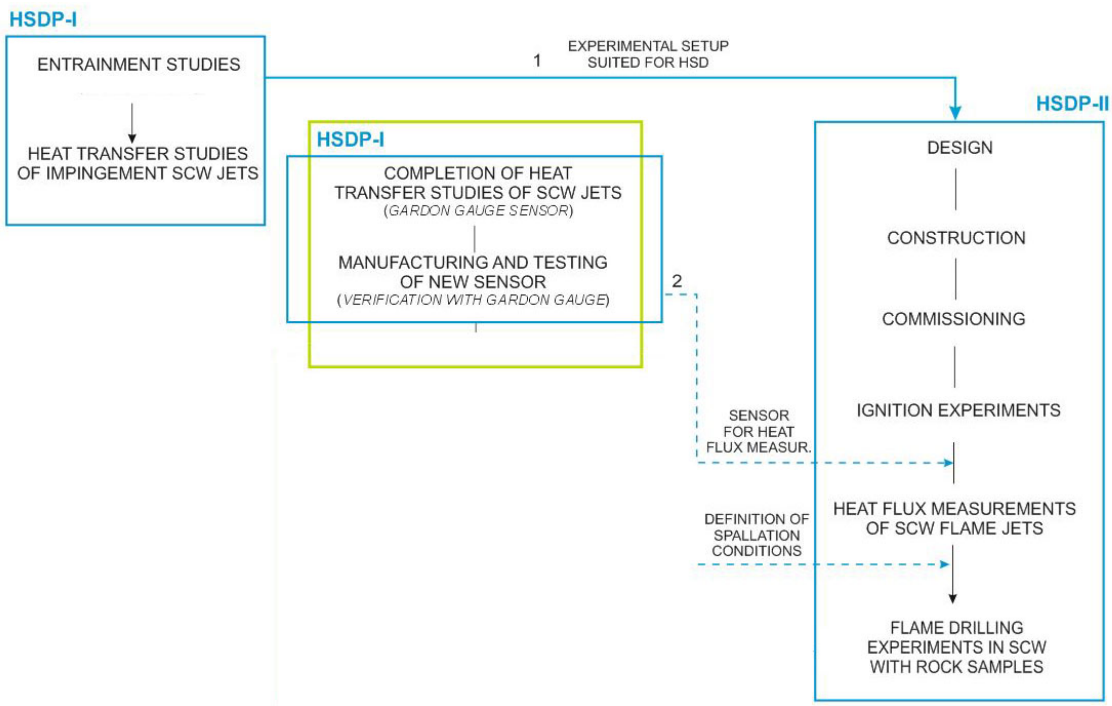

Figure 4.1: Research plan and data exchange between plants.

4.1 Reactor conceptual design

The reactor vessel must operate as a hydrothermal combustion chamber and as a hydrothermal spallation drilling reactor at the same time. For the design of a supercritical combustion chamber, a lot of data and previous experience were available ((6), (7), (8), (9)). This was not the case for the design of a spallation drilling vessel, because the only comprehensive data available came from the ambient spallation experiments conducted from Rauenzahn(2) and Wilkinson(3). The combustion chambers designed in previous studies(7) were scaled - up , based on the volumetric heat load of them. This part of the design was relevant only for the burner design of the plant where the mixture is ignited.
The general dimensions of the vessel, its length and its diameter, were relevant to the drilling process. The size of rock probes and their respective surface available for drilling, have a direct influence on the diameter of the reactor. As Preston (10)

demonstrated in his experiments, in order to spall an unconfined specimen, the heated surface must be much smaller than the total surface of the probe. As a rule of thumb Rauenzahn(2) reports that the heated surface must be below 10% of the total surface of the probe. It must be heated up quickly enough, so that the surrounding rock mass does not get heated up before the first breackage takes place. Otherwise the stresses will be relieved through expansion of the probe and no spallation will occur.

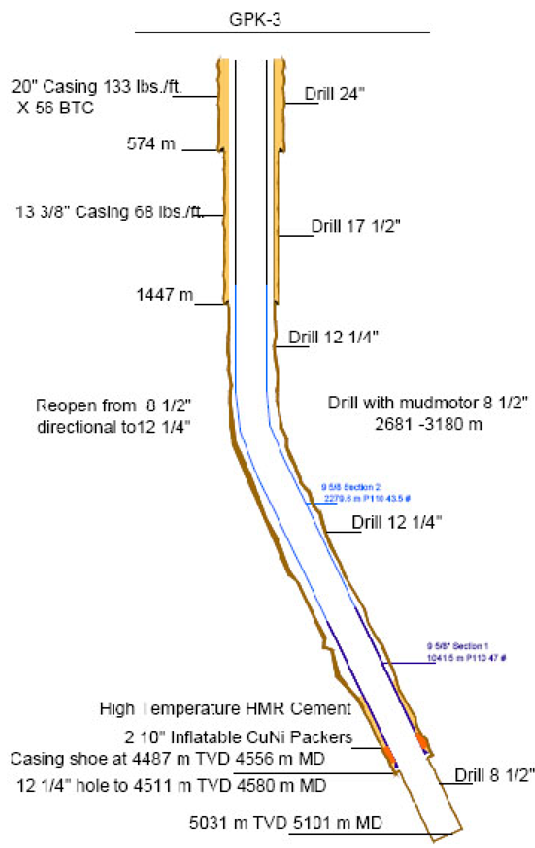

Figure 4.2: A Borehole configuration in the geothermal Plant in Soultz-sous-Forêts, France.

It follows that the diameter choice for the rock probes is actually a decision on the size of the holes, necessary for the demonstration the feasibility of hydrothermal spallation drilling. Considering the typical borehole size as shown in Fig.4.2 and evaluating data from other sources (11), the average borehole in depths higher than 2.5 km lies between 19 cm and 23 cm. Taking also into account that spallation drilling was used for the enlargement of boreholes (12), a scale down factor

10 is chosen, resulting thus in a hole diameter approximately 1.5 cm and a rock probe diameter of 9 cm. As already mentioned, previous experiments (5) showed that the supercritical jet lengths in subcritical water are very short and a considerable part of their energy is carried to the water very fast. Consequently, the combustion chamber of a spallation drilling reactor should be designed in such a way that the resulting combustion gas jets are injected in a supercritical water environment. The burning chamber must thus be separated from the load bearing walls of the reactor-pressure chamber with a cooling jacket keeping the wall temperature below 150 °C. The dimensioning of the cooling jacket led to an inner diameter of the pressure vessel of 14 cm, with a burning chamber of 10 cm diameter.

Although the length of the reactor is not significant for the mechanical dimensioning of the pressure vessel, it is nevertheless crucial for intended experiments, as the measurement of drilling velocities is a goal of the project. Since the first drilling tool will not be optimized, a mean drilling velocity of 1- m/h is assumed for the experiments. The reactor should be long enough for a reliable measurement of drilling velocities of this order of magnitude; at the same time its length should not make its construction too expensive for a demonstration plant. The chosen length of the vessel is 400 mm, its total volume is 5.83 l, its specifications are summarized as follows:

- The operating pressure of the vessel lies between 250 - 400 bar. For the highest possible internal pressure prevailing over longer time 650 bar is assumed.
- The design temperature for the whole reactor is defined to 500 °C.
- The reactor is optically accessible through two small windows on its upper part and two windows in its main body.
- Dimensions of the main body: inner diameter: 140 mm, length: 400 mm.
- Specially designed silver coated stainless steel O-rings are used as sealings.
- The high-performance 286/1.4890 alloy is used.

4.2 The design steps

The conceptual reactor design process took almost three months, starting from the very simple sketch of the vessel and gradually defining many details were.

4.2.1 First concept

Apart from the spallation drilling specifications, process specifications of the pressure vessel are specified as follows:

- The fuel is injected through the upper part of the reactor head in the axial direction. The maximum expected temperature of this stream is 450 °C.
- The oxygen stream is injected through the upper part of the reactor head in the radial direction. The maximum expected temperature of this stream is 450 °C.
- The CW1 stream is injected in the radial direction and its maximum temperature is expected to be 100 °C.
- The CW3 stream is fed radially on its upper part and the water will flow downwards. This stream will always be at room temperature.

Based on all the aforementioned specifications, the first technical drawing was developed (Fig.4.3).

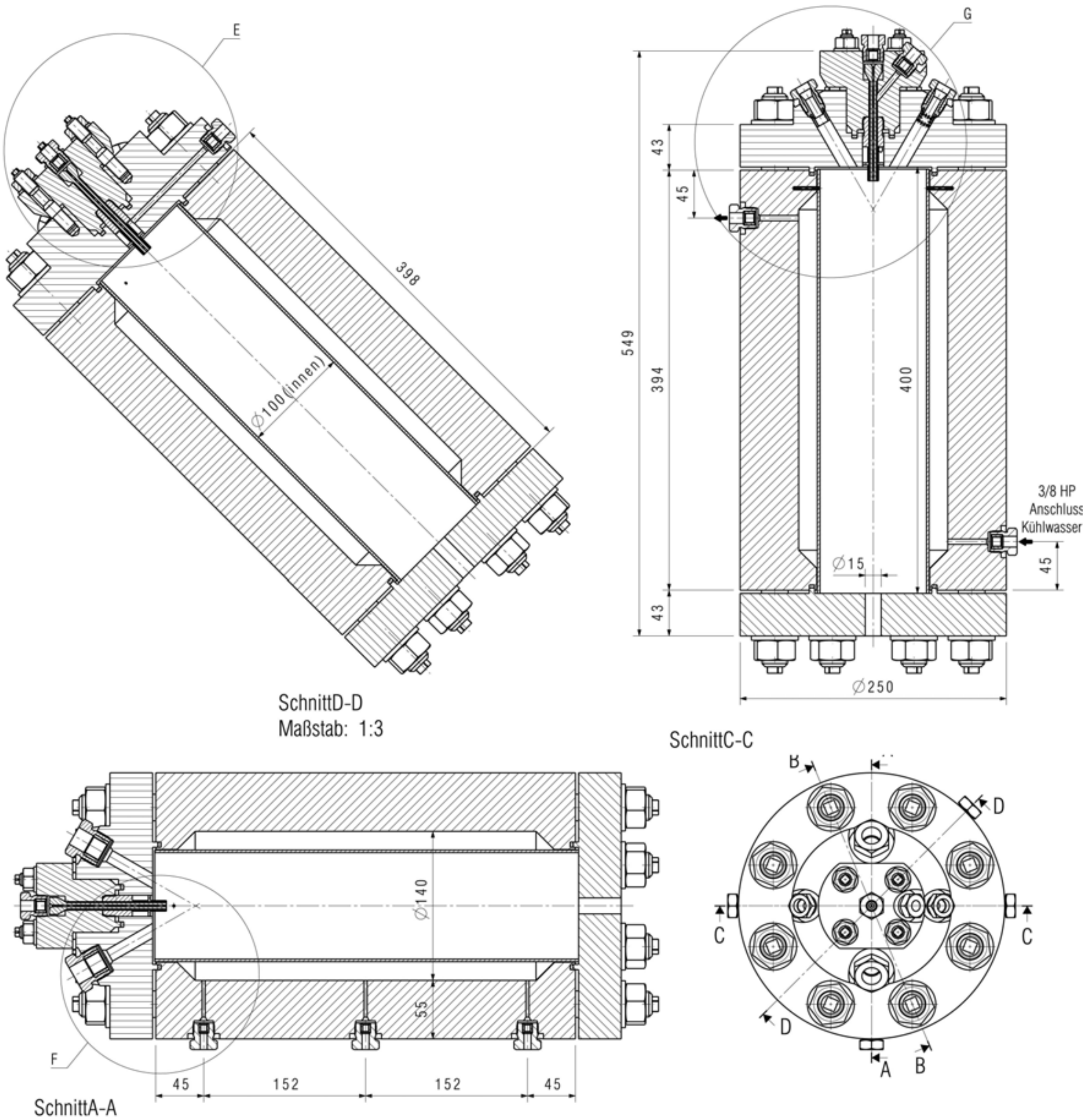

Figure 4.3: First reactor general drawing.

On the section D-D the CW1 inlet is presented, while on the section C-C the CW2 inlet and outlet, it two upper windows and the oxygen inlet are visible. The outlet of the main chamber of the reactor is presented on section view A-A, together with the safety temperature measurements on the reactor side walls.

Details of the first reactor model and its combustion chamber can also be seen on Fig.4.4, where the Details G, F and E of the drawing on Fig.4.3 are further analyzed. Detail G presents the viewing angles and the viewing depth of the windows, and also the fixation mechanism for the cooling mantle. Detail F shows the sealing mechanism and the angle of the outlet holes, as well as one hole for safety temperature measurements (see also Section A-A).

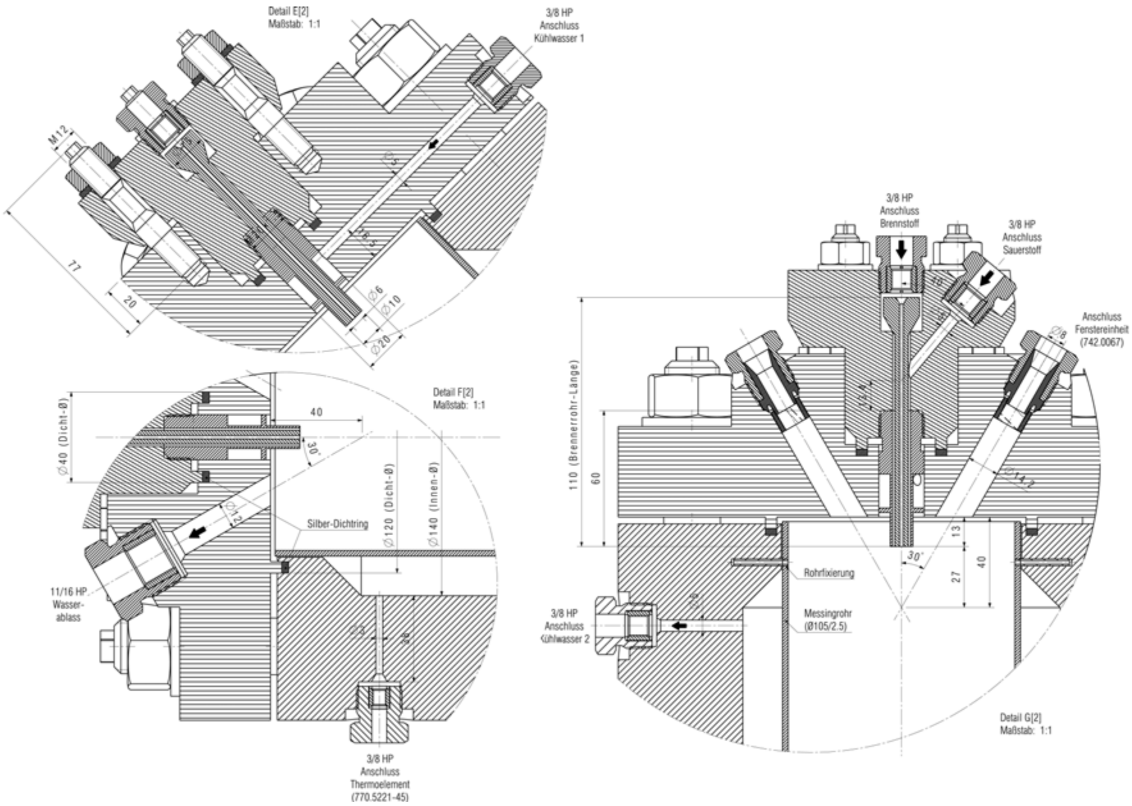

Figure 4.4: First reactor general drawing - Details.

4.2.2 The final design

Following the completion of the detailed design , the calculations for the dimensioning of the reactor and its detailed construction drawings were sent to TüV Baden-Würtenberg for controlling and certification. The control took about 3 months and the final construction of the reactor took 10 weeks, resulting to a delivery of the vessel in the first week of June 2010. Many changes were done in the initial design in order to come up with a satisfactory configuration of the vessel, which could be summarized in the following paragraphs.

Each cooling water stream is injected through 2 points. In the case of CW1 stream, this allows a better distribution in the subsequent injector (see Fig.(4.5)). The radial component of the velocity is eliminated this way, and non symmetrical flames observed in previous designs could be avoided.

The two injection points for the CW3 stream (see Fig.(4.6)) were positioned with a 15 mm offset, thus giving a radial velocity component to the water flow.

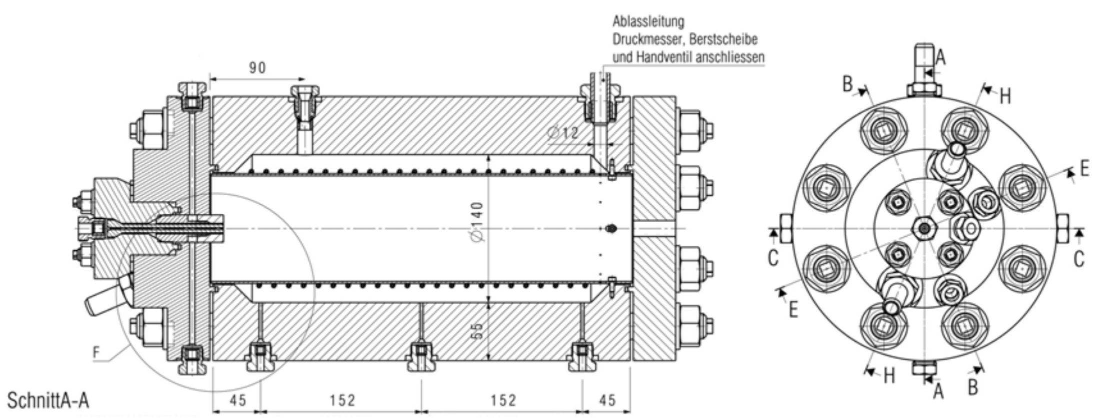

Figure 4.5: Section A-A of the final design of the reactor

A pressure measurement and a bursting disc were installed directly in the cooling mantle of the reactor (see Fig.(4.5)).
Two additional windows are positioned on the side wall of the reactor, one at 100 mm from the reactor head (see Fig.(4.6)) and one at 90 mm from it (see Fig.(4.5)). These are for the time being closed, but in case detailed studies of the flame are necessary, the cooling jacket tube could be replaced from a quartz glass tube to provide two additional optical access points.

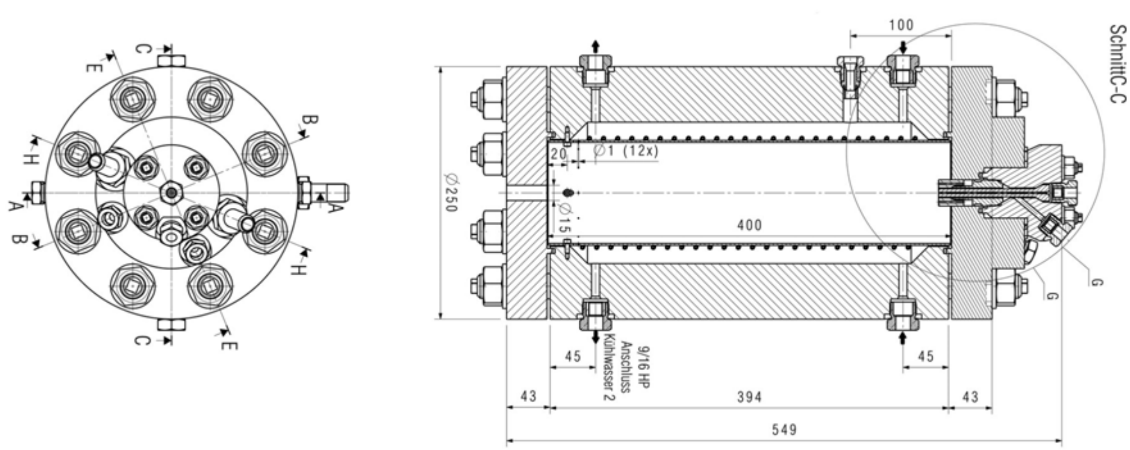

Figure 4.6: Section C-C of the final design of the reactor

The viewing angles of the windows on the reactor head were changed, so that two different points in the flame could be observed. The window shown in Fig(4.5) has a viewing depth of 80 mm, whereas the other one has 70mm. When all windows are open, three planes of the flame in four different depths could be observed. The reactor head windows had to be in the same plane due to construction reasons; however the different viewing depths were kept.

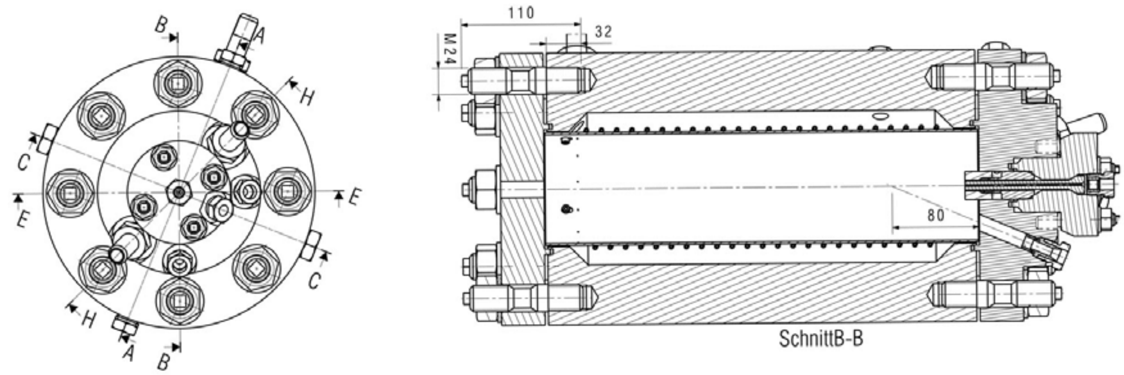

Figure 4.7: Section B-B of the final design of the reactor

During the design phase of the reactor, the question concerning the particle management and collection came up. This topic is very important because both the scientific analysis of the particle size distribution, and the protection of the pressure regulator had to be considered. Due to the lack of data on this particle size distribution, two filters in the reactor outlet are installed, as shown in Fig(4.8), while an additional filter is placed before the pressure regulator. The filters on the reactor outlet keep all the particles over 1mm in the reactor vessel, while all other particles are collected from the second filter.

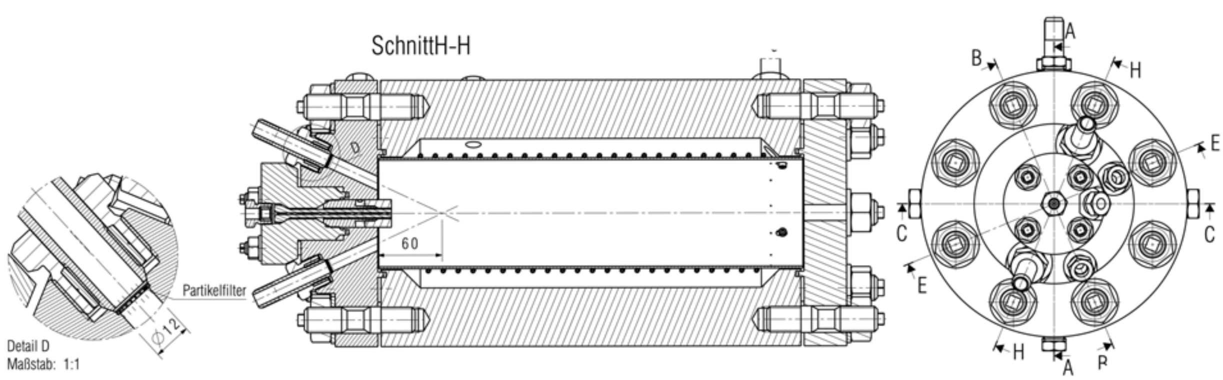

Figure 4.8: Section H-H of the final design of the reactor

Finally, the 1mm diameter/12 holes drilled in the cooling mantle ensure that there will be no pressure difference between the two spaces in the vessel and the cooling mantle will not be mechanically loaded. Besides, the cooling mantle is now fixed in the lower side of the reactor, which makes its installation much easier.
SITEC AG offered considerable help for the choice of the reactor material and their experience in the construction of high pressure components and vessels. As mentioned, the material used for the reactor is the Ni alloy 1.4980 and the sealing rings are made of stainless steel and are coated with silver to give them extra corrosion resistance. The rings with the bigger diameter have a rhomboid section, that provided a small contact area and allowed the use of smaller forces from the bolts of the vessel for its sealing.

4.3 The positioning devices

The extreme conditions of the planned experiments limit the measurements possibilities. Simple temperature measurements will not suffice and different measuring points in the flame and in the burner tubes are needed. A reliable positioning system is also necessary, to place rock probes in different distances from the burner nozzle. The positioning devices design is based on a concept developed from Prikopsky (9); a linear table for the movement of the positioning device is used. Both devices consist of a movable part connected with the linear table and a static one threaded on the reactor; their function principle is similar to a telescopic cylinder.
Both devices had to address common challenges:

- The sealing of the movable part. A periphery sealing ring, similar with the ones used for the sealing of the needle for high pressure valves, is used. A very important difference is that in the present case, the movable part travels a much higher distance than the needle of a valve.
- Both devices should allow for the insertion of probes and for the acquisition of data. Signal and power cables should be inserted through the devices and also sealed. Pressure glands made of Teflon or grafoil are used for sealing.

- The positioning accuracy is solved by the use of servo motors in conjunction with linear tables. The accuracy achieved with the servo motors is much higher than needed during the experiments.

4.3.1 The upper positioning device

The upper device offers the possibility to insert either thermocouples for temperature measurements, or power cables for ignition sources in the reactor. The positioning tube has an inner diameter of 3.2 mm and its traveling distance is 100 mm. The outer diameter is 5.6 mm and it is sealed with a special grafoil ring on its periphery. The force needed to move the probes in the reactor under 300 bar was calculated to be 350 N, and the respective linear table has an upper limit of 800 N. In Fig.(4.9) the construction drawing of this positioning device is presented.

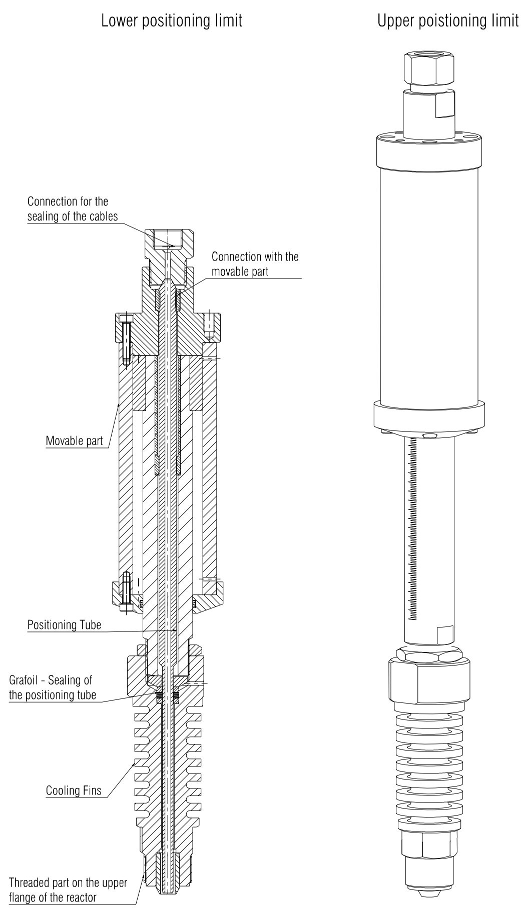

Figure 4.9: Upper positioning device for the ignition sources.

4.3.2 The lower positioning device

As shown in Fig.(4.10), this device is used for the insertion of rock probes and heat flux sensors. Its connection point to the reactor is the lower flange of the vessel and it has a traveling distance of 400 mm. The positioning tube has an inner diameter of 8 mm and outer diameter of 14 mm. Through this tube the cables of the heat flux sensors will be inserted in the vessel. The outer diameter was used for the calculation of the force needed for the dimensioning of the linear table servo motor. It was calculated that 4.8 kN should be exerted to move the probes in the reactor under 300 bar, so the linear table was selected to have an upper limit of 5.5 kN.

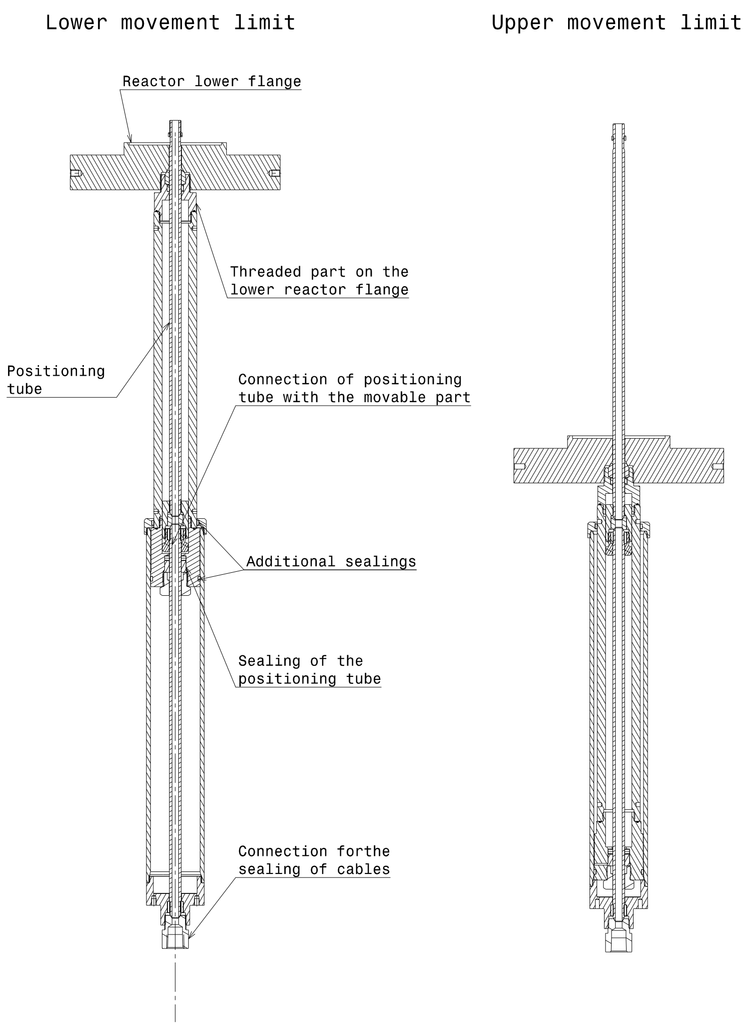

Figure 4.10: Lower positioning device for the rock probes and the heat flux sensors.

Chapter 5

Plant Construction

After several revisions and the integration of the HAZOP study results, the process and instrumentation diagram of the plant took the form presented on Fig.(3.1), consisting of five networks. The as built plans of each one of them along with pictures and a detailed function description are presented in the following paragraphs.

5.1 The fuel network

The suction line of the fuel pump, shown on Fig.(5.2(a)), consists of two feed lines one for desalinated water and one for pure ethanol, which lead to a three-way mixing valve. This valve controls the mixture composition fed to the fuel pump, which is a three-head membrane pump. The fuel flow rate is controlled from an inverter driving the fuel pump motor, and its control signal is produced from a coriolis flow meter (FMI-1). This flow meter also measures the density of the fuel mixture, which is used as the control signal of the mixing valve. Subsequently the fuel mixture passes through the pre-heater HX2 shown in Fig.(5.2(b)), where it is heated up to 420°C, prior to its injection in the reactor.

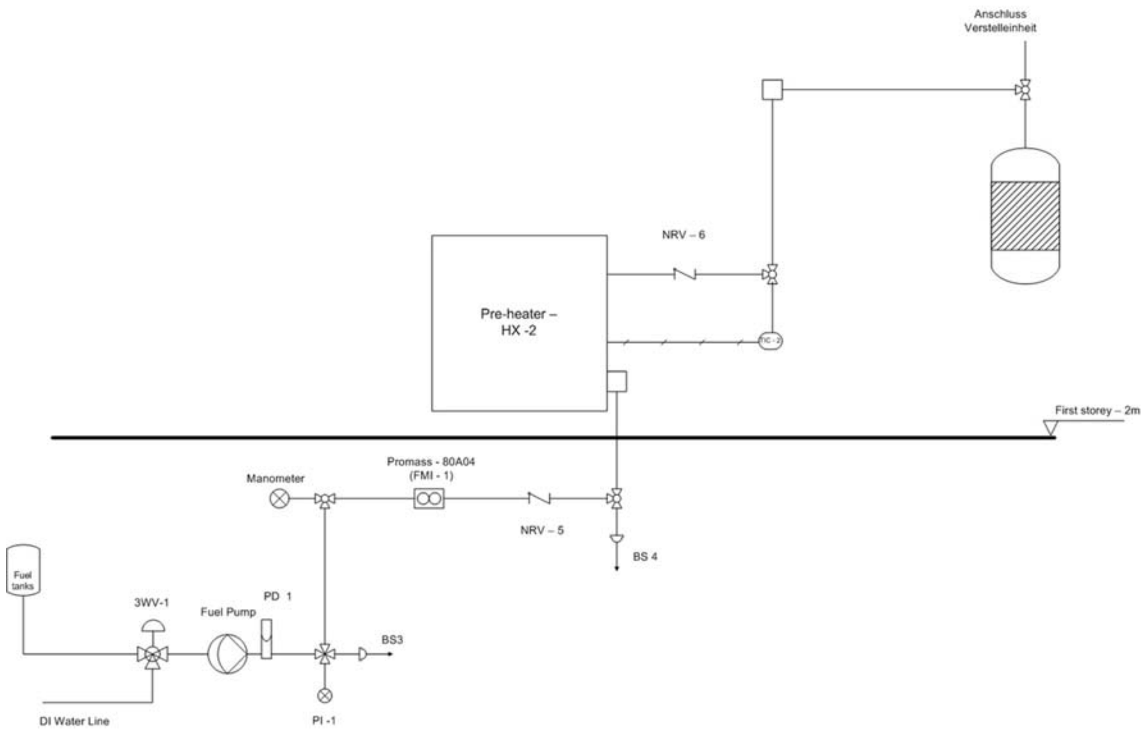

Figure 5.1: Piping and instrumentation diagram of the fuel network.

(a) Fuel pump suction line (b) Fuel heater and injection line

Figure 5.2: The fuel network

The outlet temperature of the pre-heater is measured with a K-Type thermocouple (TIC-2) and the value is fed to the control rack of the pre-heater. The line is protected against overpressure with two bursting discs (BS-3&4), and back flow is prevented from two non-return valves (NRV 5&6). Finally the pressure in the line is measured with a pressure transducer after the fuel pump (PI-1) and with a manometer before the Coriolis flow meter.

Table 5.1: List of the most important components of the fuel network

Component name	Function	Technical specifications
3WV-1	Mixing Valve	K_{VS} =0.15 m^3/h for both streams
FP-1	Fuel Pump	$\dot{V}_{max}$ =100 l/h, p_{max}=550 bar
FMI-1	Flow meter(Coriolis)	Accuracy -Flow 0.15% - Density 0.02 g/cm^3
HX-2	Pre-heater	p_{max}=350 bar, T_{max} = 420 °C Power=65 kW

SITEC AG was the industrial partner for the construction of this network, while heater and the high temperature tubing insulation was carried out from Schneider Dämmtechnik-Winterthur.

5.2 The oxygen network

The oxygen network is built on the same principle with the fuel network and it is presented on Fig.(5.4).
The compressor is a two units air driven model, each unit having two compression stages and its detailed P&I diagram is presented on Fig.5.3. The drive-air is provided from the ETH network and it is treated from a refrigerant dryer and a particle filter prior to its entrance in the compressor. After its entrance the air stream is divided in two, one stream being the drive air for the compression units and the other for the respective valves. The air pressure is set with a hand valve (V-8 & V-9) at the inlet of each oxygen unit, to provide optimum control of the oxygen outlet pressure. The drive air is then fed to the units and after the its expansion it is released in the atmosphere.
Oxygen is provided from a bundle of twelve bottles (50 l - 200 bar) and it is fed to the compressor through a filter (F-1). The subsequent pressure measurements with two contact switches (A-3 & A-4) - one for each unit, control the feed pressure

of oxygen. In case it falls below a certain limit the oxygen bottles are considered empty and the compressor is automatically switched off. After its compression oxygen is delivered to a second bottle, the pressure of which is measured by two pressure switches with a lower and an upper set-point (A-1 & A-2), each of which controlling a compression unit. When the pressure in the storage bottle falls below a set-point (low) the compression unit is activated from its switch to raise the pressure in the bottle. As soon as the pressure in the storage bottle reaches the upper set-point the compression units are deactivated. This operation ensures two limits for the pressure in the storage tank; further control of the inlet pressure of the plant oxygen line is achieved with a forward pressure regulator.

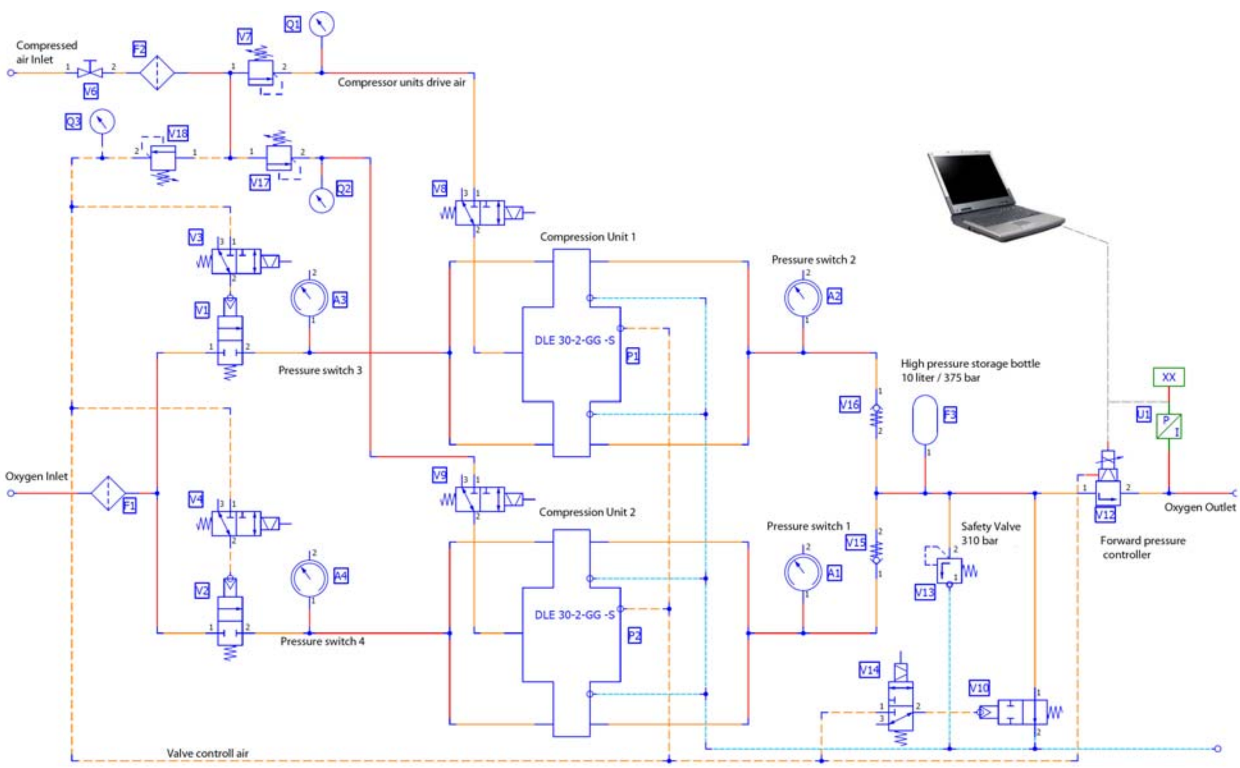

Figure 5.3: Piping and instrumentation diagram of the oxygen compressor.

The oxygen line has always an externally defined inlet pressure and outlet pressure (the one set in the reactor). The oxygen flow rate is controlled from a flow controller, which produces the necessary a pressure drop for each desired flow rate value. After the flow meter, the oxygen mixture flows through the pre-heater shown in Fig.(5.5(b)), where it is heated up to 420°C, prior its injection to the reactor.

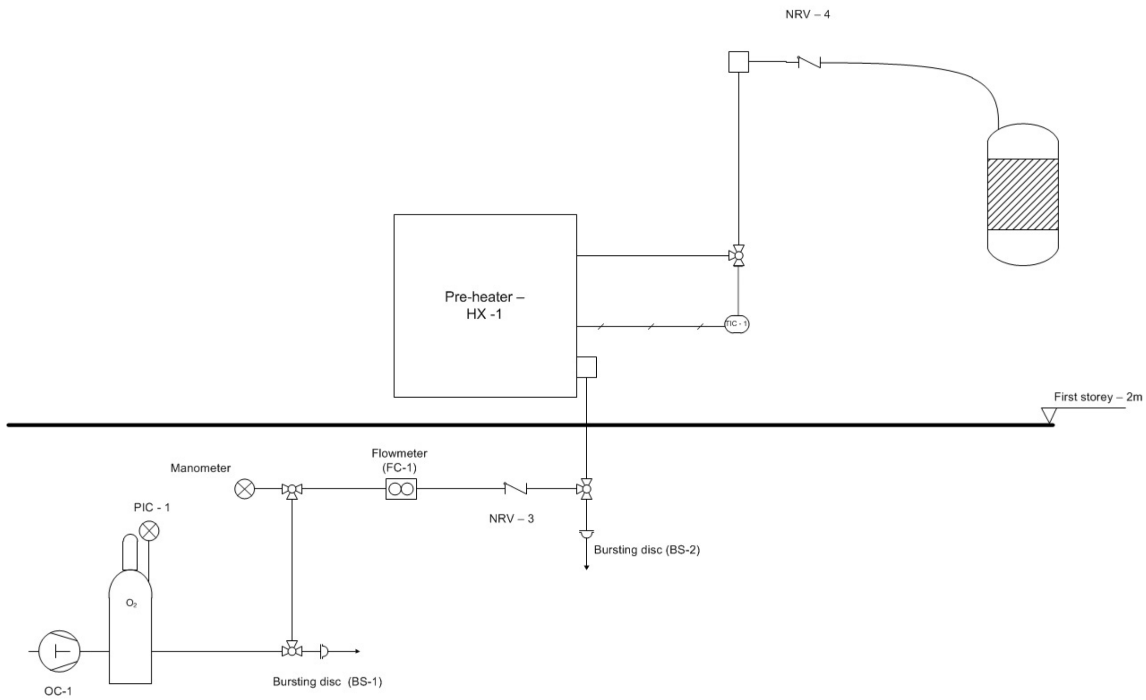

Figure 5.4: Piping and instrumentation diagram of the oxygen network.

(a) Oxygen compressor & flow controller

(b) Oxygen heater

Figure 5.5: Oxygen network pictures

Table 5.2: List of the most important components of the oxygen network

Component name	Function	Technical specifications
OC-1	Oxygen compressor	p_{max} =310 bar, $\dot{V}_{max}$=500 Nl/ min
FC-1	Flow controller	12-600 Nl/ min ,Accuracy 1%
HX-1	Pre-heater	p_{max}=350 bar,T_{max} = 420 °C
		Power=10 kW

Olaer AG was the industrial partner for the construction and the concept of the oxygen compressor. The company specializes at high pressure oxygen networks, and and was thus entrusted with the construction of the gas line.

5.3 The CW2 network

The cooling water network 2 delivers water to the cooling jacket of the reactor vessel. The volume flow of the three-head plunger pump (WP-1) is proportional to the rotational velocity of its shaft and it is controlled through setting the frequency of its motor with an inverter. The feedback control signal for the inverter controller is produced by a coriolis flow meter (FMI-3) installed directly at the outlet of the pump. A detailed P& I diagram of the network can be seen on Fig.5.6

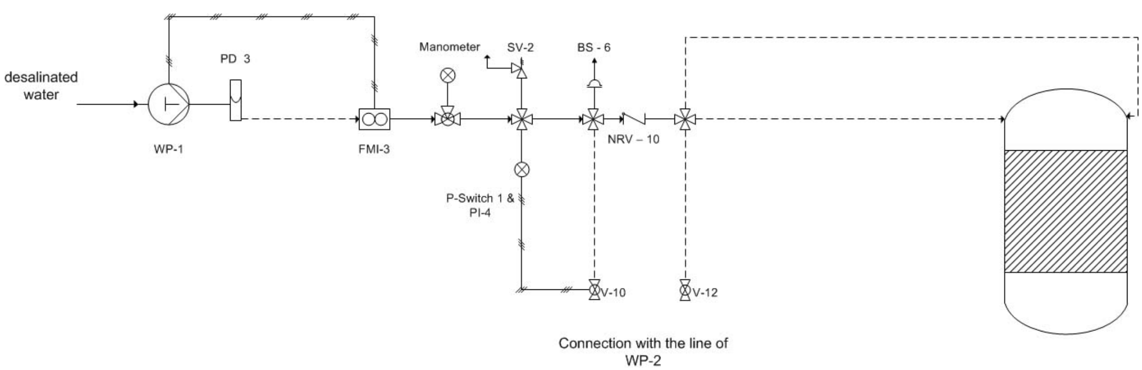

Figure 5.6: Piping and instrumentation diagram of the cooling water 2 network.

The operation of the pump is also monitored from a pressure switch-transducer (PI-1), which controls the on-off valves V-10 and V-12, and a safety valve (SV-

2) and a bursting disc (BS-6) are installed as overpressure protection. The line is connected with the other cooling water network through the valves V-10 and V-12, the installation points of which were determined during the HAZOP analysis.

(a) The high pressure pump of the cooling water 2 network.

(b) Cooling water 2 network

Figure 5.7: CW2 network pictures

Table 5.3: List of the most important components of the CW 2 network

Component name	Function	Technical specifications
WP-1	Water pump	p_{max} =400 bar, $\dot{V}_{max}$=1.5 m^3/h
Pswitch	Pressure switch	Set point:250 bar ,Accuracy 0.1%
SV-2	Safety valve	p_{set}=350 bar
BS	Bursting disc	p_{set}=400 bar
FMI-3	Flow meter(Coriolis)	Accuracy 0.15%,p_{max} =350 bar

5.4 The CW1&3 network

The cooling water network 1&3 delivers two water streams, the first of which (CW1) is the main reactor chamber cooling water, and the second is the cooling water for the effluent stream exiting the reactor. The injection points of each stream were presented in section 4.2.2 and its P&I diagram of the network can be seen on Fig.5.8.

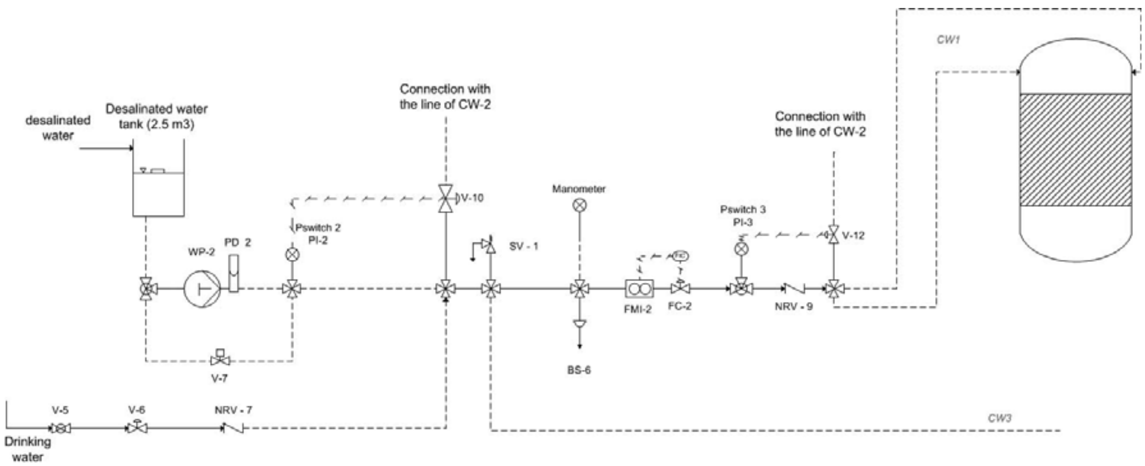

Figure 5.8: Piping and instrumentation diagram of the cooling water 1&3 network.

A storage DI water tank with volume of 2.5 m^3 is used as a feed tank for the pump (WP-2), to decouple the main water supply of the plant from the desalinated water network of the ETH. WP-2 operates always in full capacity and the by-pass valve (V-7) controls the volume flow reaching the plant, by setting the flow directed back to the suction line of the pump. Moreover its operation is monitored from a pressure switch-transducer (PI-2), connected with the on-off valves V-10 and V-12.

The first junction of the line leaving the pump is a connection with the potable water network, through a high pressure non-return valve (NRV-7). This connection is a protection against electricity failure. The hand valve (V-5) is always open and the on-off valve (V-6) is controlled from a magnetic valve connected directly with the electricity supply of the building. V-6 is always closed when electricity is supplied to its magnetic valve. In case of an electricity failure, the pressure in the plant will fall to the atmospheric (RV-10 is a NO valve) and V-6 will open, thus

connecting the plant with the potable water network. This way any fuel remaining in the plant will be swept off and a safe shut down is ensured. In the same junction the first connection with the CW2 network is realized through the valve V-10.
The valves V-10 and V-12 connect the two water networks in an emergency case or by a pump failure. Both valves are controlled from the three pressure switches of the water networks, monitoring the pressure in each line. When the pressure is below the set point of the switches the valves are open and the two water networks are connected. Once the pressure in all three points and in the reactor exceeds a pre-set value the switches close the valves, thus separating the two lines. At any case of failure or emergency a pressure fall will lead to the connection of the two water networks and a safe shut down is provided.

Figure 5.9: The high pressure pump of the cooling water 1&3 network.

The second junction of the line divides the total flow in the CW1 and the CW3 water streams. The CW1 stream passes through a manometer and its total mass flow is measured from a coriolis flow meter (FMI-2). Its mass flow control is carried out from a high pressure needle valve (FC-2), the position of which is controlled with a PID controller based on the FMI-2 signal. The CW3 mass flow is indirectly controlled from FC-2 and the by-pass valve of the pump (V-7).

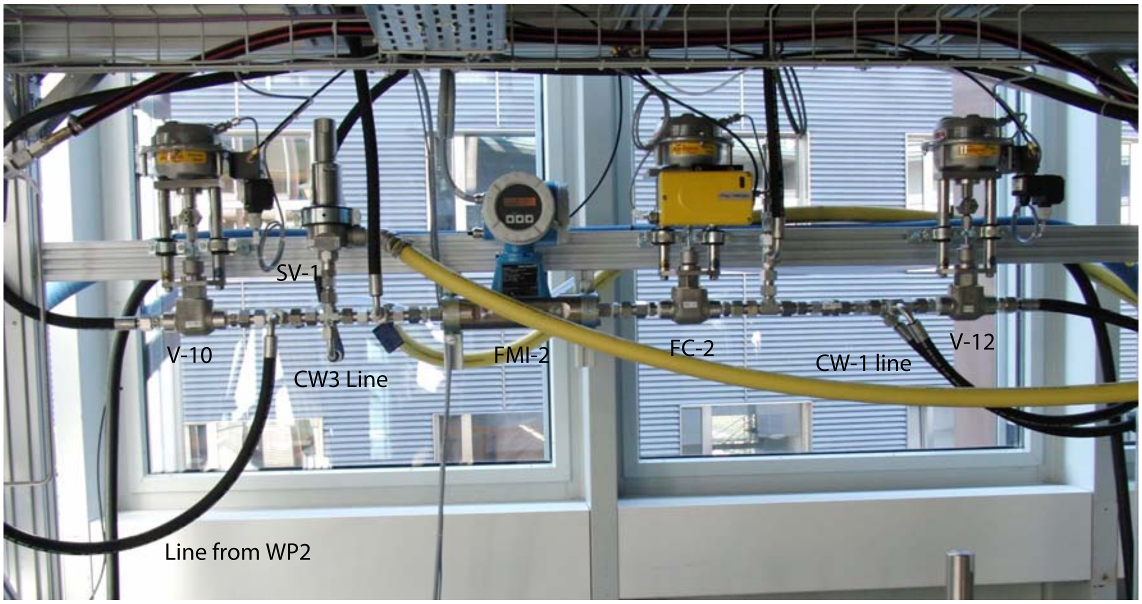

Figure 5.10: Cooling water 1&3 network

Table 5.4: List of the most important components of the CW 1&3 network

Component name	Function	Technical specifications
WP-2	Water pump	p_{max} =400 bar, $\dot{V}_{max}$=3 m^3/h
Pswitch	Pressure switch	Set point:250 bar ,Accuracy 0.1%
SV-1	Safety valve	p_{set}=350 bar
BS-6	Bursting disc	p_{set}=400 bar
FMI-2	Flow meter(Coriolis)	Accuracy 0.15%,p_{max} =350 bar
FC-2	Needle control valve	K_{VS} =1.6 m^3/h,p_{max} =400 bar

5.5 The Effluent water network

The reactor main chamber and its cooling jacket have two outlet points each. The water leaving the main chamber can reach temperatures as high as 350°C, so its cooling to below 80°C prior to the pressure reduction has to be done gradually. The stream is thus firstly mixed with the one leaving the cooling jacket and the second cooling stage is realized by mixing with the CW3 stream.

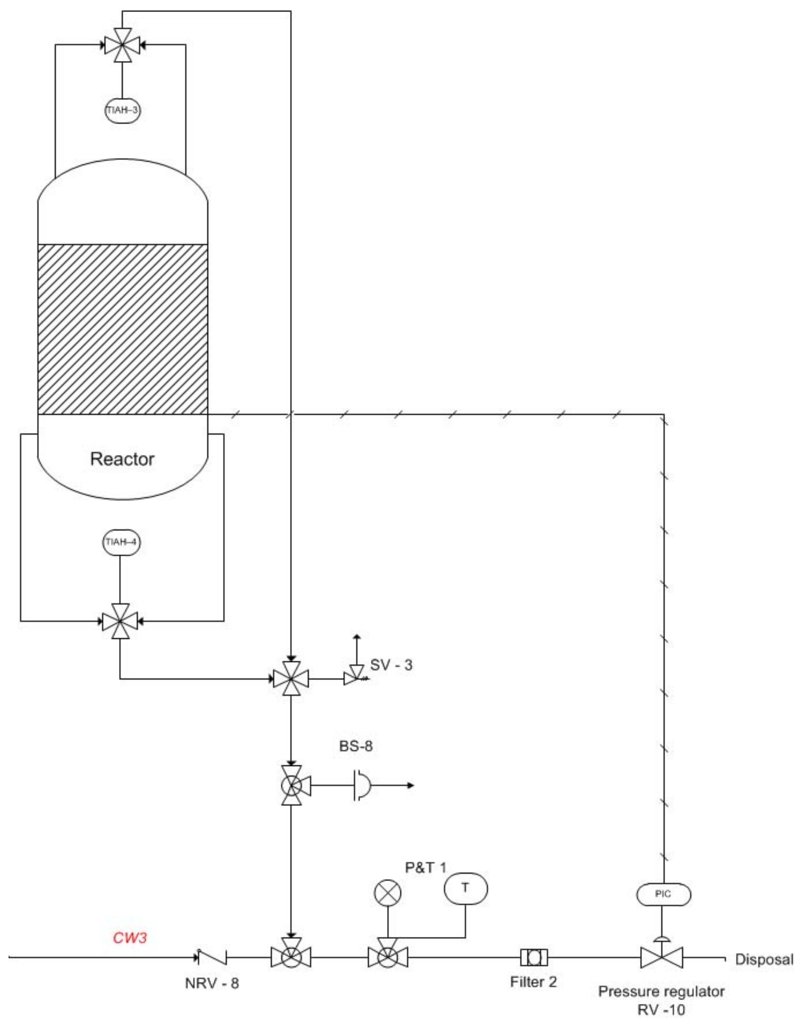

Figure 5.11: Piping and instrumentation diagram of the effluent water network.

(a) The effluent water 2 network.

(b) The pressure controller of the plant

Figure 5.12: Effluent water network pictures

The temperature is measured at each of the two reactor outlet streams and before the second mixing step a safety valve and a bursting disc are installed to protect the line from overpressure. After the final cooling of the stream, its temperature and its pressure are measured with one combined sensor (P&T -1). The temperature before the pressure regulator (RV-10) has a limit of 80 350°C, so that no steam is produced when the pressure of the liquid is reduced from 250 bar to 3 bar. RV-10 is additionally protected from a high pressure filter with a cut-off of 80 µm.

Table 5.5: List of the most important components of the effluent water network

Component name	**Function**	**Technical specifications**
SV-3	Safety valve	p_{set}=350 bar
BS-8	Bursting disc	p_{set}=400 bar
Filter-2	High pressure filter	l_{cutoff}=80 µm
RV-10	Needle control valve	K_{VS} =0.4 m^3/h(linear)

Chapter 6

Plant Commissioning

The completion of the mechanical construction of the plant (October 2010) was succeeded by the construction of the electrical and the control system. The power and signal connections construction together with the control network of the plant took 3 weeks and the first check was performed at the beginning of November 2010. For the control of the plant a programmable logical controller (PLC) with a Profi-bus control network were chosen and the design and setup of this part of the plant was carried out together with M+S automation technology. The control concept of the plant is presented in Fig.(6.1).

The user - control system communication is realized via a web server, having an dedicated IP and a touch panel. The whole system is built in a control rack, which performs all the control sequences for the plant and is also responsible for the emergency procedures. A personal computer can be connected to the web-server to keep the overview of the experiments and perform on-line data sampling. Additionally an I/O box is located near the reactor, where the local analog signals are digitalized and transported via Profi-bus to the PLC for further validation.

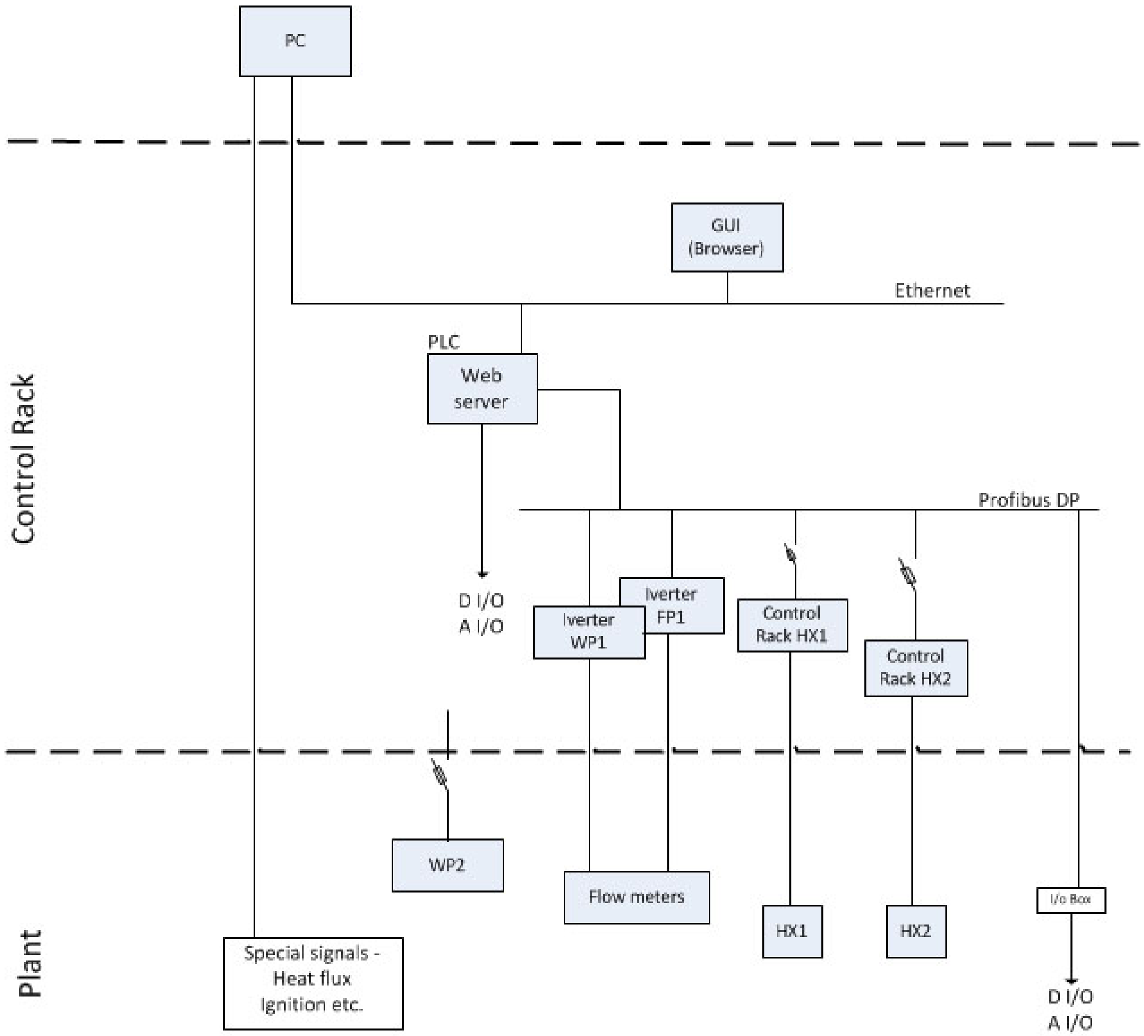

Figure 6.1: Control system architecture.

6.1 Temperature control set-up

The pre-heaters have their own control racks, mainly due to safety reasons (ATEX protection). Each heater communicates with the PLC with digital and analog signals, exchanging set-points and actual temperature values.

The heaters use a typical semiconductors resistance control, connected with a PID controller with a signal converter. The choice of the three PID parameters for the heater controllers was done with the Zieglers-Nichols method (13), by switching the control in the on - off mode. Many experiments were carried out for each controller, the result of which are presented in Fig.6.2 and in Fig.6.3. During these experiments the heaters operated with DI water and Nitrogen respectively and the plant was at 260 bar.

The oxygen heater has very slow reactions and its control has been set to reach the set point slowly with a small overshooting. Due to the low flow rate used during commissioning the heater overheated, thus not reaching its maximum set temperature. The maximum power of the heater was adjusted to the flow rate used and an outlet temperature of 400 °C was reached. Two and a half hours were necessary to reach the highest set point possible from a starting temperature of 20 °C.

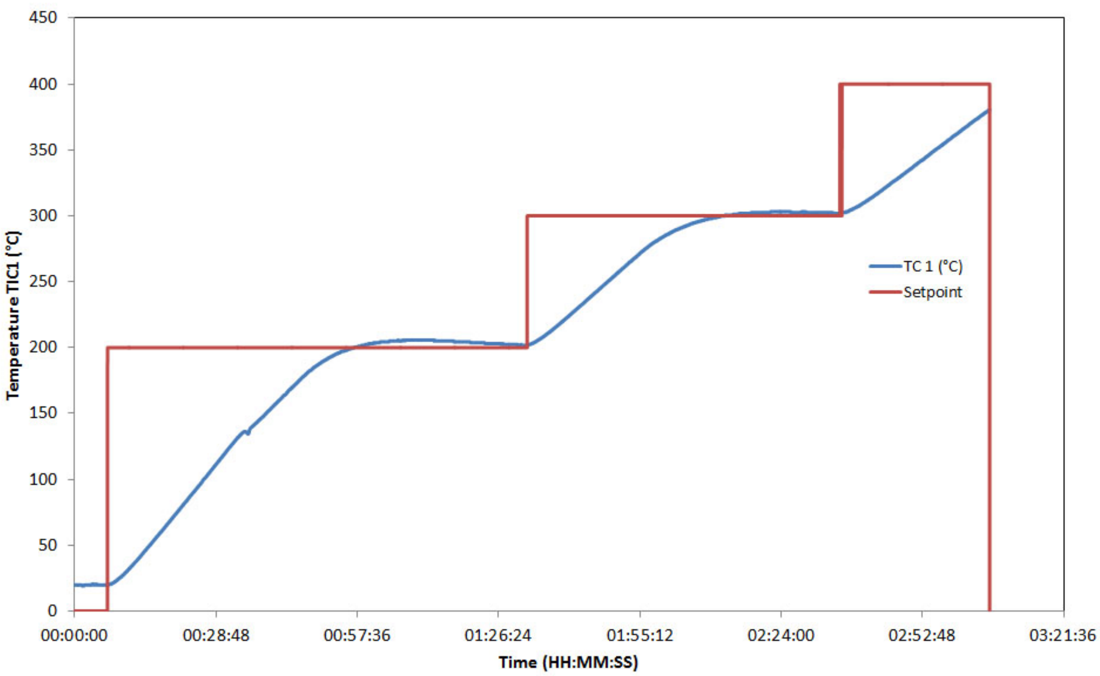

Figure 6.2: Temperature control of HX1 - Oxygen heater operated with Nitrogen for the commissioning stage.

The fuel heater has faster reactions, the overheating problem did not occur and the maximum temperature achieved was 420 °C. The heater needed ninety minutes to reach this temperature from a starting temperature of 20 °C.

The results from the heaters experiments led to an adaptation of the start-up procedures of the plant. Two consecutive experiments in two days were carried out for the measurement of colling time for each heater. After reaching its maximum temperature, each heater was switched-off and its temperature was measured on the following day. The gas heater was at approximately 300 °C, while the fuel heater was at 200 °C, due mainly to their insulation.

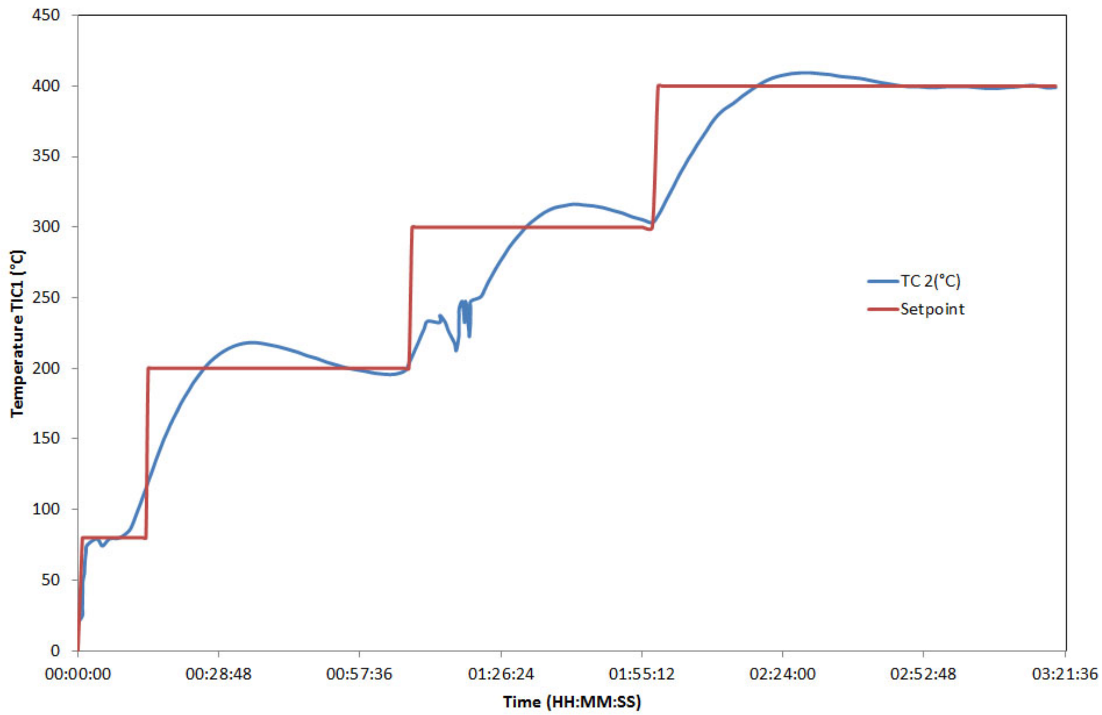

Figure 6.3: Temperature control of HX1 - Fuel heater operated with water for the commissioning stage.

6.2 Pressure control

The pressure control of the plant proved to be the most difficult part of the commissioning, because the pressure is controlled with a needle valve in one stage. The pressure of the liquid-gas mixture flow is reduced through this valve from the set point (normally 260 bar) to a value slightly higher than the atmospheric. Although this control method is the simplest possible, it nevertheless has two very important disadvantages:

- The needle and the seat of the valve are wear-sensitive, due to the very high pressure drop over them.

- There is a certain limitation in the control accuracy and in the stability of the pressure.

The valve (RV-10) is controlled directly from the PLC with a software-based PID controller, receiving the pressure of the reactor vessel as a control signal and producing the position signal for the valve.
Following the setup of the PID controller , a stable and reproducible pressure control was observed. The value was however stable for a time period (5-10 minutes) and then suddenly the behavior presented on Fig.(6.4) was observed.

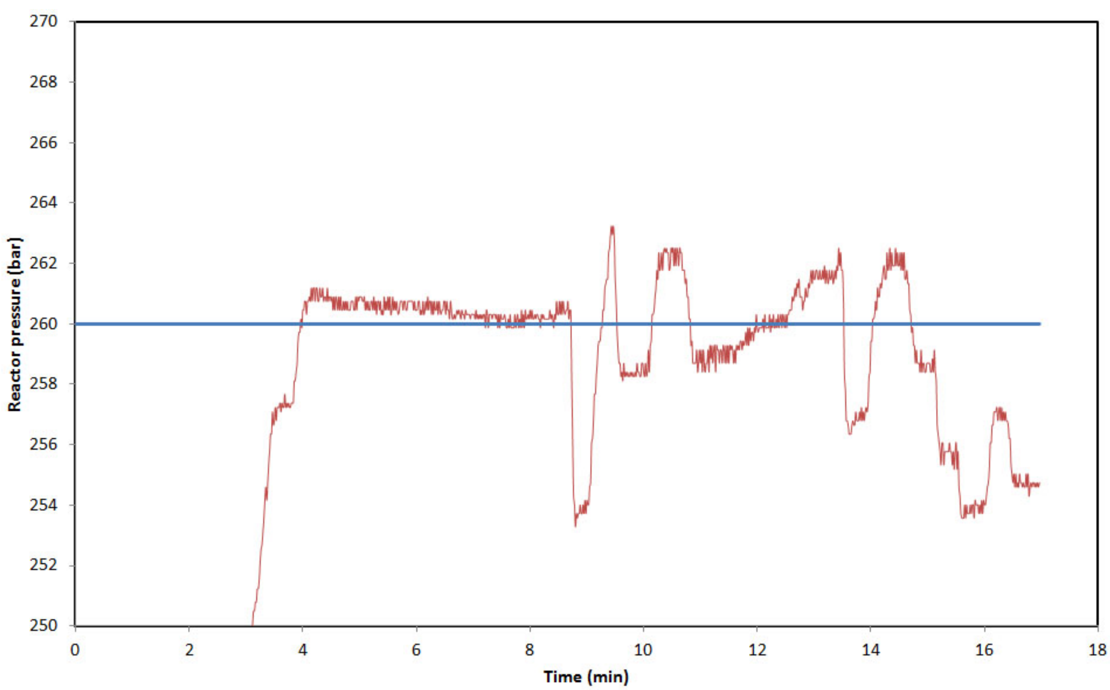

Figure 6.4: Pressure control first stages of the commissioning stage - before optimization - Set point 260 bar

After extensive series of experiments it was found that the system reached its set point normally, but due to the nature of the controlled parameter (pressure) very small stochastic changes of its value took place. These changes eventually added up and caused a traceable change on the control signal sent to the valve pneumatic actuator. The latter has a 0.3% resolution for its input control signal, meaning that a change of 0.3% (or higher) leads to a change in the position of the valve. Once this limit was reached the position of the valve changed although the mean value of the controlled quantity stayed the same. This phenomenon is known but it normally does not lead to control instabilities. In the case in question the chosen K_V value of the valve and the fact that it was a proportional valve led to this result.

A succeeding validation of these instabilities in the pressure control has shown that fluctuations of approximately 4% were induced in the flow control of the gas line and two solutions for the problem were implemented:

- A user defined buffer was implemented in the pressure PID controller as a limit value of the control error. As long as the control error lies between the two buffer limits, the controller integrating ceases and its output stays constant. For example, when the buffer value equals 2 and the pressure set point is 260 bar, the controller stops integrating when the actual pressure value lies between 258 bar and 262 bar.
- The RV-10 K_V value and type were changed from K_{VS} =0.63 m^3/h - proportional to K_{VS} =0.4 m^3/h - linear.

After these changes the control had a satisfactory accuracy of 0.7% and its stability was remarkably increased, as is presented on Fig.(6.4).

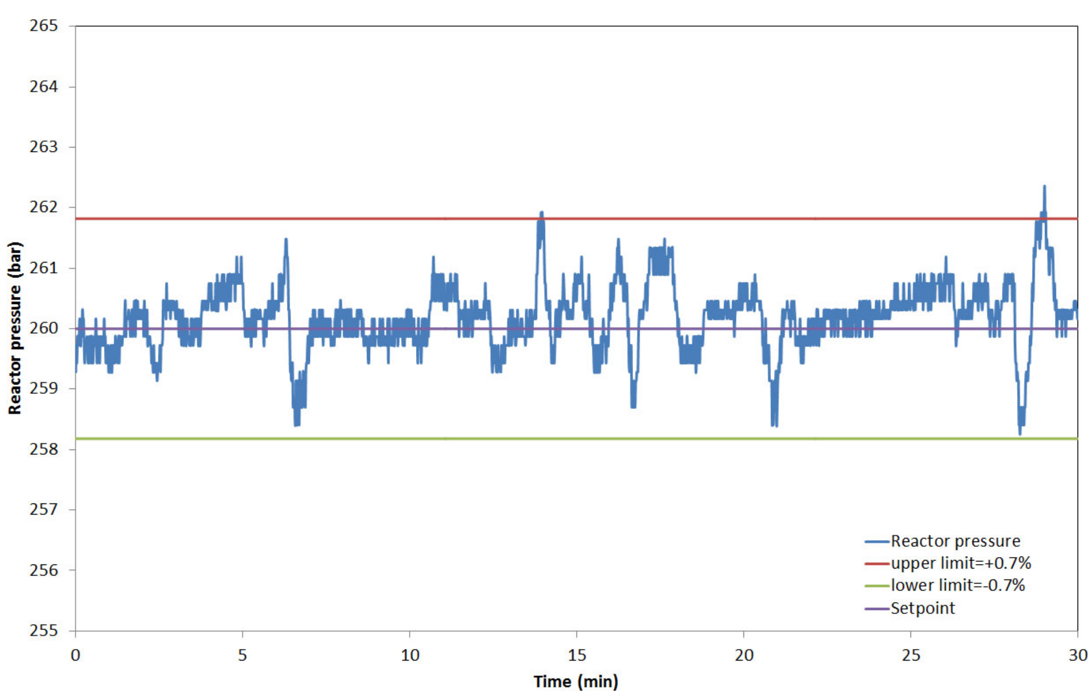

Figure 6.5: Pressure control first stages of the commissioning stage - after optimization - No buffer.

6.3 Fuel mixture composition control

During the safety analysis of the plant, the need for online control of the composition of the fuel mixture was identified due to the following reasons:

- In case of an emergency the fuel supply must be cut-off, and the fuel line must be swept clean of fuel.
- Optimization of the storage needs of the fuel.
- Fuel composition online control was the best option for the planned experiments.

For the aforementioned reasons a three-way valve is installed in the suction line of the fuel pump as shown in section 5.1. There are no standard direct ways to measure the composition of ethanol-water mixtures, a characteristic value directly connected to it should be measured. Two such properties are its pH value and its density, the latter being the best choice because the coriolis flow meter FMI-1 offers an additional density measurement.

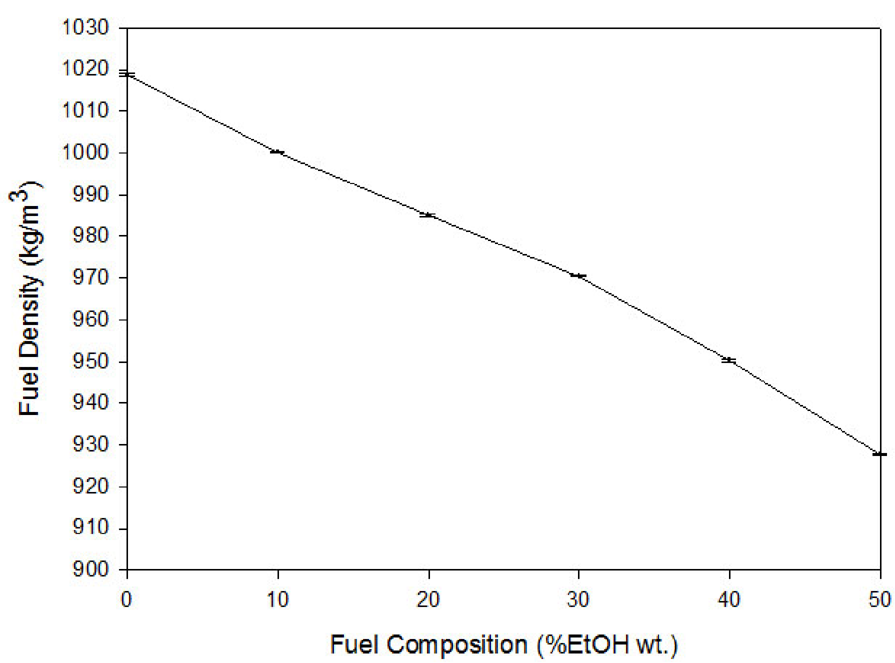

Figure 6.6: Density values of ethanol-water mixtures at 260 bar and room temperature.

Due to the lack of density data for the mixture in question at elevated pressure, its values were measured for different fuel mixtures at 260 bar and are presented on Fig.6.6. The experiments were carried out for three different flow rates, in order to account for the compressibility effect, caused by the pressure loss in the line. The three way valve (3WV-1) is controlled from a software-based PID controller of the PLC, receiving the density value of the mixture as a control signal and producing the position signal for the valve.

The four meters installation height of the fuel tanks leads to a pressure at the inlet of the three way valve of 1.4 bar, while its DI water inlet is directly connected to the DI water line of the ETH, where the pressure is approximately 6 bar. A hand valve is installed in the DI water line to adjust its pressure at the three way valve inlet. The result of the density controller setting is presented in Fig.6.7.

The controller is adjusted to prevent overshooting from the set point of the density, so that the plant power could be controlled precisely, and without tripping the plant.

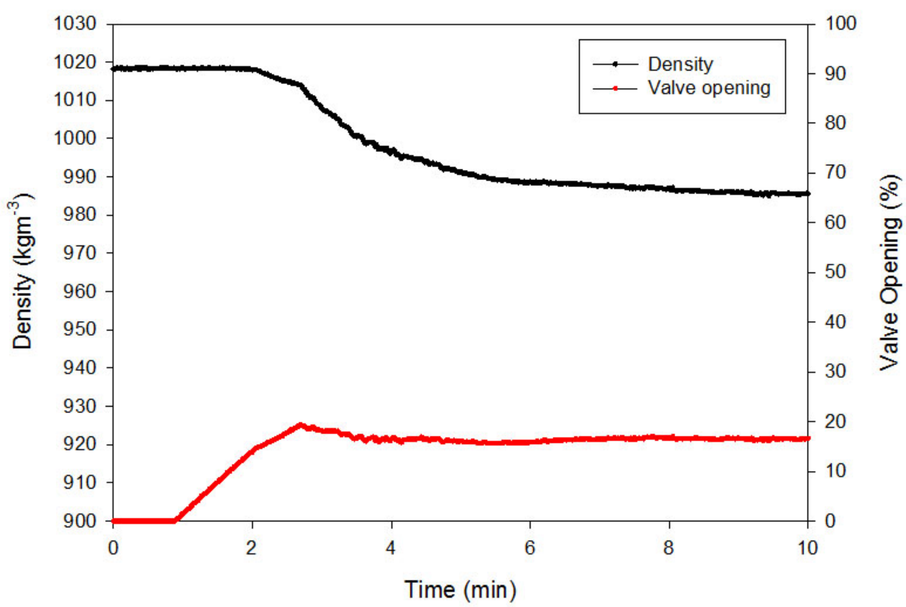

Figure 6.7: Density control results of ethanol-water mixtures at 260 bar.

6.4 Oxygen flow control

As already described in section 5.2, the oxygen line has always an externally defined inlet and outlet pressure and the flow rate is controlled from a flow controller, producing the respective pressure drop.

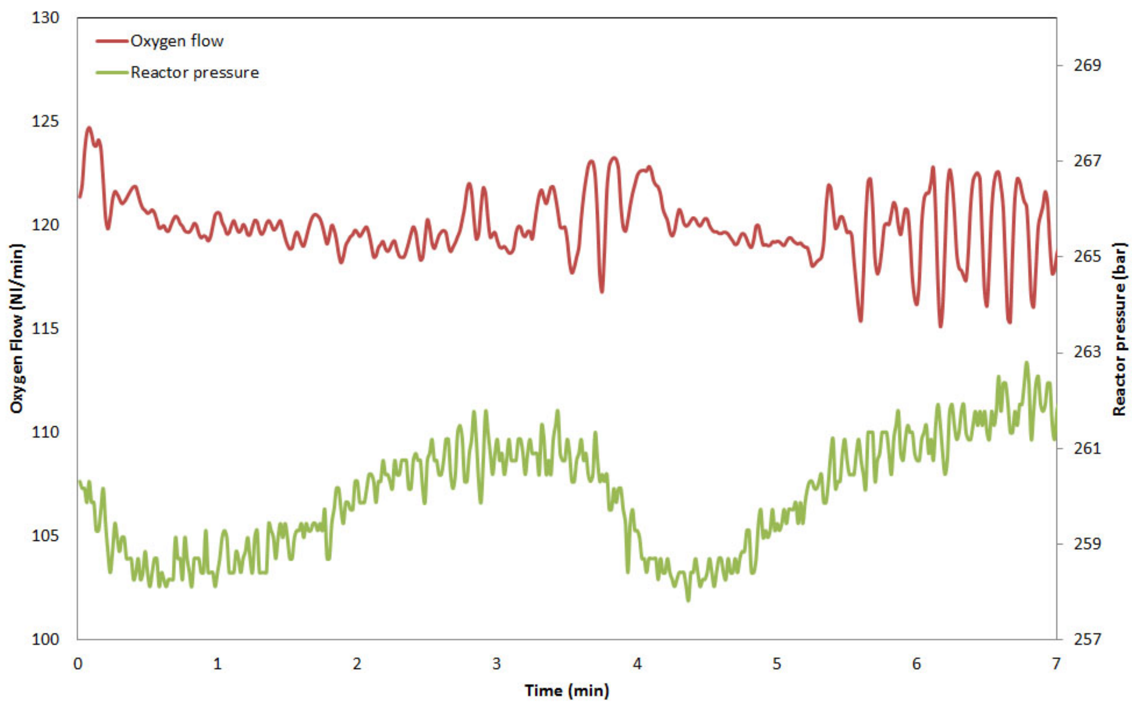

Figure 6.8: Oxygen flow fluctuations at reactor set pressure 260 bar and set point for the oxygen flow 120 Nl/min.

The flow controller is a "black box" controller constructed from the company Bronkhorst, and its settings are fixed. As already shown, the initial set-up of the pressure controller led to pressure fluctuations of $\pm$2% and consequently oxygen flow rate fluctuations. The induced fluctuations can be seen on Fig.6.8, where a $\pm$4% fluctuation on the set flow rate can be observed. Because the oxygen flow controller is a needle valve there is a limitation in its opening and closing speed to avoid ignition of the materials from the oxygen flowing in the line.
After adjusting the pressure control of the reactor, these fluctuations vanished and the control was stable.

Chapter 7

Assessment of the project results

The project results assessment is deemed to be incomplete in the current time, since no relevant experiments have been carried out for the feasibility of spallation drilling. Nevertheless, according to the project plan, the relevant tasks were carried out in a timely and efficient manner and the plant provides a stable and robust infrastructure for the intended investigations.
Taking the previous experience of our research group as a starting point and considering the challenge of the accomplished task, the plant design phase was successfully completed. Additionally the following commissioning of the plant showed that only minor mistakes in the initial planning were made and the corresponding adaptations were carried through in a very efficient and fast way.
The plant construction phase needed certain practical project management skills, to ensure a smooth project run and avoid big delays. Although the reactor delivery delayed the construction for some months, it was carried through in an efficient way and the experience gained will be valuable for us in the future. As the plant did not have any structural problems and each part of it accomplished its goal during the commissioning phase, this phase of the project is also considered successful.
The commissioning phase of each industrial scale plant is the time where the preceding planning and construction phases are judged and all the necessary corrections are done. The control system installed for the plant and the preceding HAZOP study proved to be very important tools for the correct setting of all the parameters of the process. The start-up and emergency procedures are programmed in a way, that allows for their flexible adaptation in case needed. The

developed control concepts proved to be correct and apart from the pressure control valve no hardware change was necessary. As the commissioning of the plant was finished with minor hardware adaptations this project phase is also considered successful.

In parallel to the tasks presented relevant to the construction and the commissioning of the plant great effort was made for the development of a new sensor design and for the optimization of the one developed in the preceding project. A focus project running over a year and occupying three students and an additional bachelor thesis were launched in search for alternative concepts and an optimization of the sensor construction. The result of this combined effort was the design and construction of four different sensors, two of which were also functional and the third needed minor revisions. As each custom-built sensor needs a calibration to provide trustworthy and reliable measurements, a calibration facility has been built, simulating as far as possible the conditions expected in the reactor flames and the first generation of sensors was calibrated successfully. Additionally a publication on the calibration methodology and the plant was peer reviewed and accepted from experimental heat transfer Journal.

Chapter 8

Outlook

The successful building and commissioning of the spallation drilling pilot plant after two years of strenuous endeavors is a first step towards the demonstration of the feasibility of the technique. In this ongoing commitment we will strive to produce reliable and reproducible data, which are indispensable for the future development of a respective industrial application. The most important sub-projects towards this aim are:

- **The ignition project / April 2011 - October 2011**. The ignition problem can be blamed for many delays in the previous projects, since no reliable solution for it could be found. All the predecessors depended on the self-ignition of the combustible mixture and even when very high pre-heating temperatures were used, an ignition did not always occur, putting the projects off-schedule. At the same time the safety of the plants was compromised, because temperatures exceeding the self ignition of the fuel in atmospheric pressure were produced and could lead to accidents in case of a leakage. As five times higher fuel power is used in the new plant, it is necessary to solve this problem, prior to the scheduled drilling experiments.

- **The heat transfer project / October 2011 - April 2012**. Once the ignition project is completed different burners will have to be characterized. This characterization consists of the heat transfer measurements for different burner-injector geometries. The heat transfer project has been already initiated with the design of special heat flux sensors in addition to the ones already constructed during previous projects. The design of the sensors is quite advanced, with few details remaining to be resolved prior to their implementation.

- **The drilling project / April 2012 - December 2012**.The actual rock experiments are the final subproject, where different rock probes will be inserted in the reactor thermal and spallation will be investigated.

References

[1] Chad R. Augustine. *Hydrothermal Spallation Drilling and Advanced Energy Conversion Technologies for Engineered Geothermal Systems*. PhD thesis, Massachusetts Institute of Technology, 2009.

[2] Rick M. Rauenzahn. *Analysis of rock mechanics and gas dynamics of flame - jet thermal spallation*. Doctoral thesis, MIT, 1986.

[3] Mark Wilkinson. *Computational modeling of the gas phase transport phenomena and experimental investigation of surface temperatures during flame jet thermal spallation drilling*. PhD thesis, Massachusetts institute of technolgy, 1989.

[4] Rodrigues. Analysis of the performance of a thermal spallation device for rock drilling. 2006.

[5] Tobias Rothenfluh, Martin J. Schuler, and Philipp Rudolf von Rohr. Penetration length studies of supercritical water jets submerged in a subcritical water environment using a novel optical schlieren method. *The Journal of Supercritical Fluids*, 57(2):175 – 182, 2011.

[6] Beat Wellig. *Traspiring wall reactor for supercritical water oxidation*. PhD thesis, ETH Zurich, 2003.

[7] Markus Weber. *Apparate einer SCWO Anlage und deren Leistungsfaehigkeit*. Phd thesis, 1997.

[8] Hans Lukas LaRoche. *Wandgekuehlter Hydrothermalbrenner fuer die Ueberkritische Nassoxidation*. PhD thesis, ETH Zurich, 1996.

[9] Karol Prikopsky. *Characterization of continuous diffusion flames in supercritical water*. PhD thesis, ETH Zurich, 2007.

[10] F. W. PRESTON and H. E. WHITE. Observations on spalling*. *Journal of the American Ceramic Society*, 17(1-12):137–144, 1934.

[11] Sukanta Roy Harsch Gupta. *Geothermal energy: an alternative source for the 21st century*. Elsevier, 2007.

[12] Laflamme Poirier, Fecteau. Thermal rock fragmentation - applications in narrow vein extraction. *Canadian Institute of Mining - Bulletin*, -(96):–, 2003.

[13] J. G. Ziegler and N. B. Nichols. Optimum settings for automatic controllers. *Journal of Dynamic Systems, Measurement, and Control*, 115(2B):220–222, 1993.

Appendix A

Communication - Publications

In the course of these two years different communication efforts were made, not only in the scientific community but also in the press and through contacts with various companies. The following list summarizes the communication efforts for the project.

Scientific publications.

The scientific publications for the project were in peer reviewed journals and in conferences, relevant with the corresponding topic of the presented results.

Scientific Journals Publications.

- Tobias Rothenfluh, Martin J. Schuler, and Philipp Rudolf von Rohr. Penetration length studies of supercritical water jets submerged in a subcritical water environment using a novel optical schlieren method. The Journal of Supercritical Fluids, 57(2),175-182, 2011.
- Panagiotis Stathopoulos, Florian Hofmann, Tobias Rothenfluh and Philipp Rudolf von Rohr. Calibration of a Gardon sensor in a high temperature - high heat flux stagnation facility. Experimental Heat transfer Journal, (copy editing and typesetting phase not yet in press), 2011.

Scientific Conferences.

- Tobias Rothenfluh, Martin Schuler, Philipp Rudolf von Rohr. Experimental and numerical heat transfer study of supercritical water jets penetrating subcritical water. 12th European Meeting on Supercritical Fluids, Graz, Austria, May 2010.
- Martin Schuler,Tobias Rothenfluh,Panagiotis Stathopoulos,Philipp Rudolf von Rohr.Heat Transfer of a Hydrothermal Flame in Supercritical Water towards Rock used for Contact Free Drilling. R09 Twin World Congress and World Resources Forum Davos, Switzerland, September 2009.

General publications.

- Dr. Keith Evans, Dr. Thomas Driesner, Prof. Dr. Stefan Wiemer, Prof. Dr. Philipp Rudolf von Rohr. Drei Forschungsgebiete im Fokus. Geothermie.ch Nr47, September 2009.
- Martin Schuler,Tobias Rothenfluh,Panagiotis Stathopoulos,Philipp Rudolf von Rohr. Neuartiges Bohrverfahren. Geothermie.ch Nr50, März 2011.
- Panagiotis Stathopoulos, Martin Schuler, Tobias Rothenfluh, Philipp Rudolf von Rohr. Geothermal energy: Renewable energy for heat and power. Newsletter of the Energy Science Center at ETH Zürich, No.1, March 2010.

Communication - Focus project

As a part of the focus project carried out in the academic year 2010-2011, several cooperations with different companies specializing in sensor construction were developed, with the one with the company Oxsensis being the most important. The result of this cooperation was the development of a novel heat flux measurement concept, based on two temperature measurements by means of a sapphire optical fiber. The sensor has been tested and further cooperation with the company is pending for the optimization of the developed sensor.
Additionally several press releases through the ETH press communication were

carried for the focus project in forming companies like ALSTOM about our efforts for the development of high temperature heat flux sensors.