METHOD FOR THE THERMO-HYDRAULIC ANALYSIS OF THE TEST FACILITY FOR THE PBMR RESERVE SHUTDOWN SYSTEM

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ABSTRACT

The Pebble Bed Modular Reactor (PBMR) is a revolutionary small, compact and safe nuclear power plant. It operates on a direct closed Brayton cycle. One of the unique features of this concept is its load following capability enabled by extracting or injecting of the working fluid (in the PBMR's case Helium) from or to the system during operation.

The Reserve Shutdown System (RSS) is one of the essential subsystems of the PBMR. The RSS is used as a maintenance and secondary shutdown system for the PBMR. Small Absorber Spheres (SAS) containing boron are used to perform the shutdown. When shutdown is required, the spheres flow into eight borings in the centre reflector of the reactor core. To continue the reactor operation, the spheres are removed from the borings in the centre reflector and transported back into the storage containers. As the RSS is a safety-related system, the functioning and components of the system must be tested in a non-nuclear environment, before the design can be finalized for the demonstration plant. A test set-up for the RSS was designed and forms part of the Helium Test Facility (HTF) for the PBMR.

A method had to be identified and a process developed which can be used to perform a thermo-hydraulic analysis and determine the specifications of the components in the test facility that will enable the test facility to perform all the required tests at the required conditions. This method also had to predict the performance of the test facility before the building of the actual plant. The method of simulation was identified as the most suitable method to perform the thermo-hydraulic analysis on the proposed test facility. The process developed included the set-up of a thermal fluid network with the use of Flownex Nuclear, a thermal fluid software package. With the method that was used for the thermo-hydraulic analysis of the RSS test facility, it was possible to obtain the process data for the components and to predict the functioning and performance of the proposed test facility. This method and process can be used widely in the industry for the design and performance prediction of large industrial plants and testing facilities. It can also be used in the design process of plants to optimize the layout and performance of the plants and processes.

SAMEVATTING

Die Korrelbedkernreaktor (KKR) is `n revolusionêre klein, kompakte en veilige kernaanleg. Dit word bedryf deur middel van `n direkte geslote Braytonsiklus. Een van die unieke kenmerke van hierdie konsep is die vermoë om kraglewering te reguleer soos wat die elektriesiteitsaanvraag varieer gedurende bedryfstoestande.

Die Reserveafskakelstelsel (RAS) is een van die belangrikste sub-stelsels van die KKR. Die RAS word gebruik as `n onderhoud en sekondêre afskakel stelsel in die KKR. Klein Absorbeerdersfere (KAS) wat boron bevat word gebruik om die reaktor af te skakel. Wanneer afskakeling vereis word, vloei die sfere in agt holtes in die sentrale reflekteerder van die reaktor kern. Die sfere word dan verwyder uit hierdie holtes en terug vervoer na die stoor houers sodat die reaktor weer in bedryf gestel kan word. Aangesien die RAS `n veiligheidsverwante stelsel is, word daar vereis dat die funktioneering en komponente van die stelsel getoets word in `n nie-kern omgewing, alvorens die ontwerp gefinaliseer kan word. `n Toets-opstelling van die RAS was ontwerp en vorm deel van die Helium Toetsfasiliteit.

Die behoefte het bestaan vir die identifisering van `n metode en ontwikkeling van `n proses waarmee `n termo-hidroliese analisese gedoen kon word en die spesifikasies van die komponente in die toetsfasiliteit bepaal kon word wat dit in staat sou stel om al die nodige toetse onder al die veskillende toestande te kon verrig. Hierdie metode moes ook die werkverrigting van die toets fasiliteit voorspel voordat die werklike aanleg gebou sou word. Die metode van simulasie was geïdentifiseer as die beste metode om die termohidroliese analiese te doen op die voorgestelde toetsfasiliteit. Die ontwikkelde proses behels die opstel van `n termo-vloeier netwerk deur gebruik te maak van Flownex Nuclear, `n termo-vloeier sagtewarepakket. Met die metode wat gebruik was vir die termohidroliese analiese van die RAS toets fasiliteit, was dit moontlik om die prosesdata vir die komponente te verkry en om die funksionering en werkverrigting te voorspel. Hierdie metode en proses kan algemeen in die industrie gebruik word vir die ontwerp en werkverrigtingvoorspelling van groot industriële aanlegte en toetsfasiliteite. Dit kan ook gebruik word in die ontwerpsproses van aanlegte vir die optimering van die uitleg en werkverrigting.

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LIST OF ABBREVIATIONS

AVR	Arbeidtsgemeinschatf Versuchsreaktor
CFD	Computational Fluid Dynamics
dP	Pressure Differential
GUI	Graphical User Interface
HTF	Helium Test Facility
MIT	Massachusetts Institute of Technology
NNR	National Nuclear Regulator
NRG	Nuclear Research and consultancy Group
PBMR	Pebble Bed Modular Reactor
PU for CHE	Potchefstroom University for Christian Higher Education
PWR	Pressurised Water Reactor
RSS	Reserve Shutdown System
SAS	Small Absorber Spheres
SUD	Software Under Development
V&V	Validation and Verification

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1. INTRODUCTION

1.1 BACKGROUND

1.1.1 Demand for Energy in the World

The worldwide increasing demand for energy led to the creation of a large field of research aimed at finding economical ways to convert energy into electricity. Although questions regarding the safety of nuclear power are always raised along with this concept, nuclear power has always been considered as a potential solution to the problem.

The main features of the Pebble Bed Modular Reactor (PBMR) are its small physical size, and that it is safe, clean, cost-effective and adaptable. South Africa's power utility giant, Eskom, has committed itself to the development of the PBMR so that it can be part of the future energy provision network of the world.

1.1.2 The PBMR as a Solution for the Energy Crisis

The nuclear technology of the PBMR is based on a concept that was developed in Germany by Prof. Dr Schulton. Silicon carbide-coated uranium granules are compacted into hard billiard-ball-like spheres (Figure 1) to be used as fuel for a high-temperature, Helium-cooled gas reactor [1].

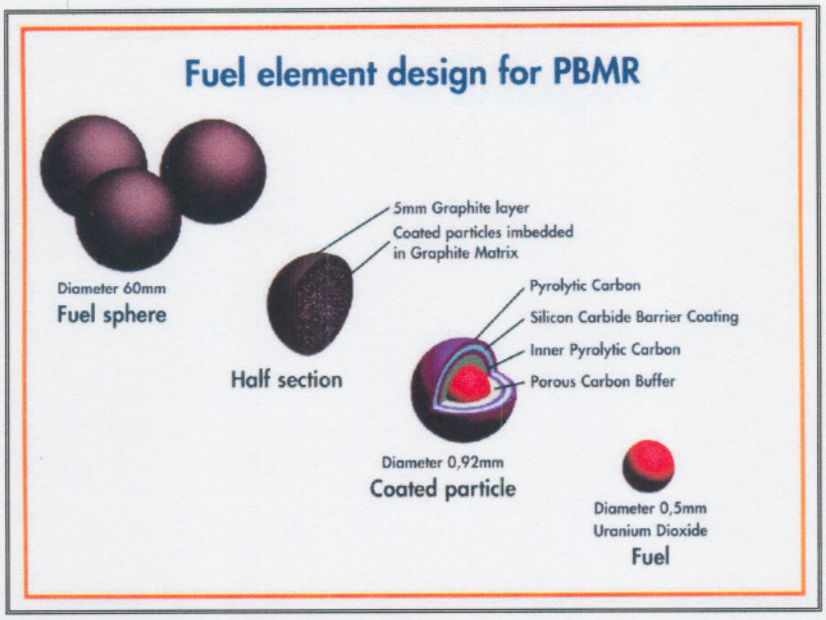


Figure 1: Illustration of the Pebble Fuel Design.

This concept was transformed into a design that resulted in the AVR ('Arbeidsgemeinschaft Versuchsreaktor'), a 15 MW (megawatt) demonstration pebble bed reactor, built in Germany. It operated successfully for 21 years, but the intense wave of post-Chernobyl anti-nuclear sentiment that swept Europe brought an early end to this reactor [1].

Eskom started with feasibility studies regarding the possibility of building a PBMR in South Africa in 1994. The design and costing studies showed that the PBMR has a number of advantages over other potential power sources [2]. These studies also showed that the electricity generated by a PBMR is highly competitive with that generated by other means.

Most of South Africa's coal-fired power stations have to be built near the pitheads of coal-producing areas. This requires long power lines from coal-rich areas, where the pitheads are situated, to the load centres. This implies high capital costs and transmission losses. The alternative option of transporting coal to distant power stations is unfeasible.

There are limited opportunities in South Africa for producing hydro-electric power, or power from natural gas. Large thermal, nuclear or hydro-electric power stations also require lead times of up to eight years, and could result in the installation of surplus capacity if economic growth is not as high as expected [2].

Eskom experiences short, sharp, demand peaks during winter. These are difficult to accommodate with the slow ramping characteristics of the existing large power stations. Every modern utility will pay a premium for plants with load following capability. Not only do they provide the utility with the ability to meet all power demands (base and peak load) with the same plant, but there are also hefty premiums attached to peak load supply [1].

These factors have created the need for small electricity generation units situated near the points of demand. The PBMR concept has a relatively short construction lead time, low operating cost, and fast load following characteristics. It is therefore considered as an option for the requirements as stated. Another advantage is that the pebble fuel used in this concept has inherently safe characteristics.

1.1.3 The Functioning of the PBMR

Research showed that a closed loop Brayton cycle layout with a three-shaft configuration would provide the optimal thermal efficiency for the PBMR. Figure 2 shows a simplified schematic diagram of the working of a Brayton cycle; the working of the cycle is stepwise described in the following paragraphs [3].

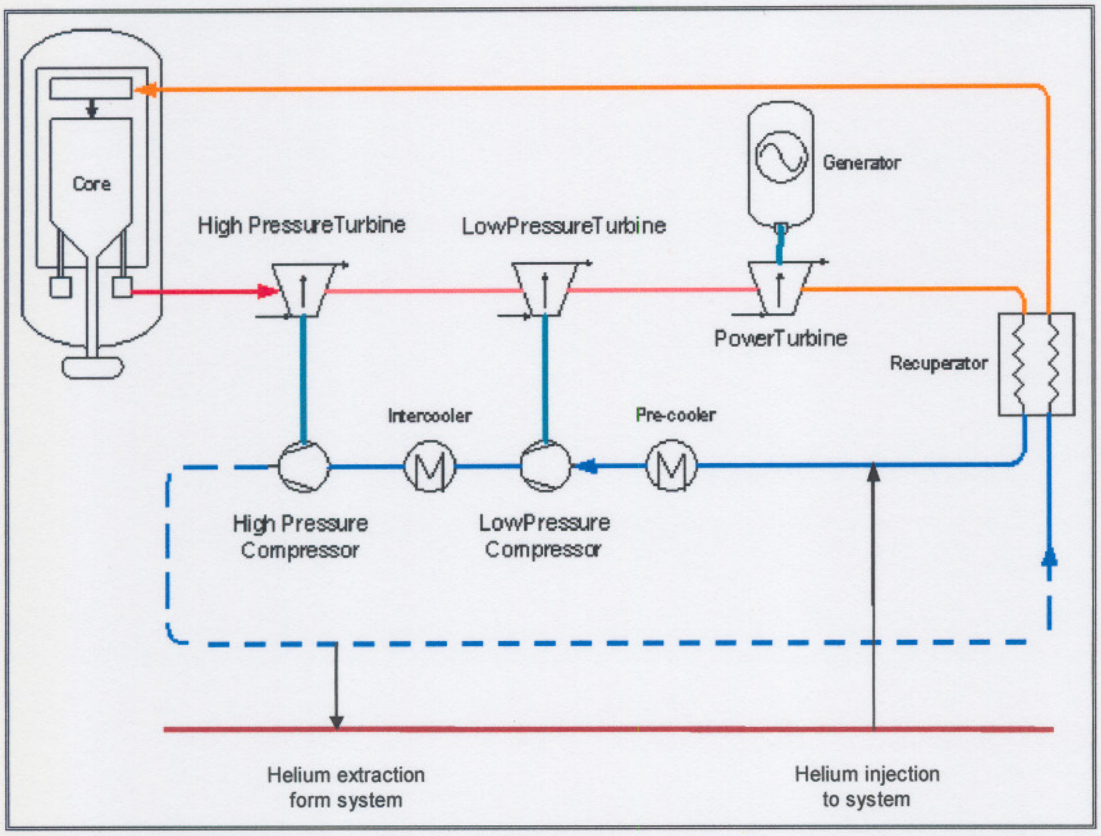


Figure 2: Simplified Diagram of a Direct Brayton Cycle Nuclear Power Conversion System

Helium enters the reactor at a temperature of about 500 °C and a pressure of 8.6 MPa [4]. It is conveyed to the top of the reactor via annular riser channels. The gas then moves downwards through the fuel spheres. During this process Helium absorbs heat from the fuel spheres, which were heated by the nuclear reaction. The heated gas leaves the reactor at a temperature of about 900 °C.

The reactor outlet is connected to the high-pressure turbine, which forms part of the high-pressure turbo unit. The high-pressure turbine drives the high-pressure compressor.

Next, the Helium flows through the low-pressure turbine, which drives the low-pressure compressor; this unit is known as the low-pressure turbo unit. The low-pressure turbine outlet is connected to the power turbine. This turbine drives the generator.

After the Helium exits the power turbine, it is still at a high temperature. During the next step of the cycle, the gas flows through the primary side of the recuperator where its heat is recuperated to the Helium entering the reactor (refer also to the last step of the process).

After the gas exits the recuperator, it is further cooled by the pre-cooler before passing through the low-pressure compressor. If the gas is cooled before the compression process, the increase in density results in a more efficient compression process.

The outlet of the low-pressure compressor is connected to an intercooler, where the gas is cooled before entering the high-pressure compressor. This compressor compresses the Helium to 8.7 MPa. The cold (±100 °C), high-pressure Helium then flows through the recuperator, where it is pre-heated before it returns to the reactor.

A three-shaft recuperative Brayton cycle had never been physically tested before, and there was much scepticism surrounding this concept. It was labelled as an unstable cycle that would not be self-sustaining or controllable. In order to address the scepticism, a test rig operating on this cycle was built at then Potchefstroom University for Christian Higher Education (PU for CHE) in 2002 (Figure 3). The project was a success and proved that this concept is feasible because the cycle bootstrapped and could be controlled [5].

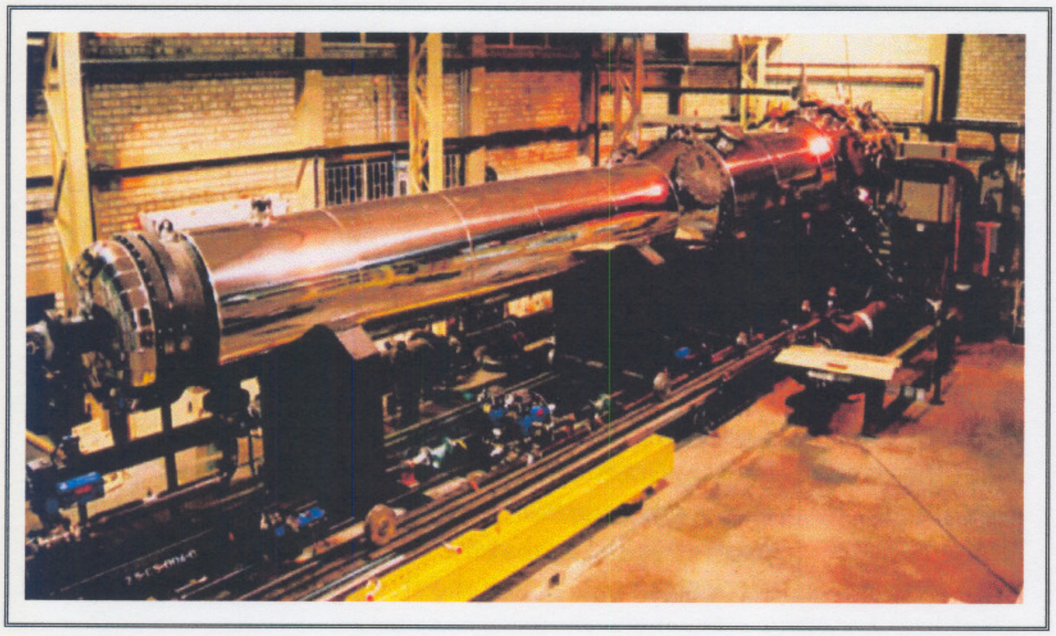


Figure 3: The Test Rig Built at the PU for CHE

1.1.4 The Reserve Shutdown System

One of the essential subsystems of the PBMR is the Reserve Shutdown System (RSS). The RSS is used as a maintenance and secondary shutdown system for the PBMR high-temperature gas-cooled reactor [6].

Small Absorber Spheres (SAS) containing boron are used to perform the shutdown. The spheres are stored in eight storage containers above the core internals of the reactor (all inside the reactor – refer to Figure 4). When shutdown is required, the valves of the storage containers are opened and the spheres flow into eight borings (each storage container serves a boring) in the centre column of the core of the reactor.

To put the reactor back into operation, the spheres are removed from the borings in the centre reflector and transported back into the storage container A pneumatic suction transport system, which operates at pressures between 2 MPa and 9.0 MPa, and temperatures between 50 °C and 350 °C, is used to transport the spheres from the core back into the storage containers.

The RSS has the following mechanical functions [7]:

- To assure shutdown to maintenance conditions of 100 °C by dropping the SAS into the eight borings inside the central reflector of the core structures.
- To remove the SAS from the central reflector and to transport them back to the feeder bin from where they are distributed to the eight storage containers of the SAS units.
- To store the SAS.

The maximum core temperature at which one full boring of spheres (column of spheres) will be removed and transported back to the container assembly will be 750 °C. The SAS are transported from the borings in the centre column via a discharge vessel. The discharge vessel (one vessel) is connected to the borings in the centre column (refer to Figure 4). The gas transport system is used to supply the transport medium to transport the spheres from the borings back to the storage containers.

1.1.5 Requirement for Testing of the RSS

The insertion function of the RSS is safety related, and the insertion of spheres must be tested in the reactor on a regular basis. This is done by opening and closing the storage container valve for a few seconds. Insertion of spheres during the tests is verified by:

- Measuring of height of spheres in the discharge vessel.
- Detection of the valve position (open or closed).

As the RSS is a safety-related system, it is a requirement that the functioning and components of the system are first tested in a non-nuclear environment, before the design can be finalized for the demonstration plant. A test set-up of the RSS was designed and forms part of the Helium Test Facility (HTF) [8].

The RSS test set-up vessel is a full-scale test facility, representing one full RSS system (in the PBMR reactor unit). The objective of the test facility is to simulate the dimensions, environmental and postulated operational conditions of the RSS inside the PBMR reactor.

The main purpose of this test facility will be to:

- Verify and validate the insertion of the SAS into the core internal borings under all postulated conditions.
- Prove that the SAS can be removed from the boring and returned to the storage container (for the full transport range of SAS removal).

It will further be used to verify and validate the performance of the control and instrumentation components integrated into the RSS at all defined operating conditions. It is therefore necessary to determine the specification of the components in the test facility for the complete operating range.

The test set-up must be able to simulate the PBMR equivalent RSS conditions as well as localized isolated component conditions. These conditions will be supplied by the HTF main loop, consisting of blowers, heaters, heat-exchangers and mixing devices [9]. The HTF will be used to create the required conditions in the RSS test set-up for the PBMR operational range of insertion and transport of spheres.

A schematic diagram of the RSS is shown in Figure 4.

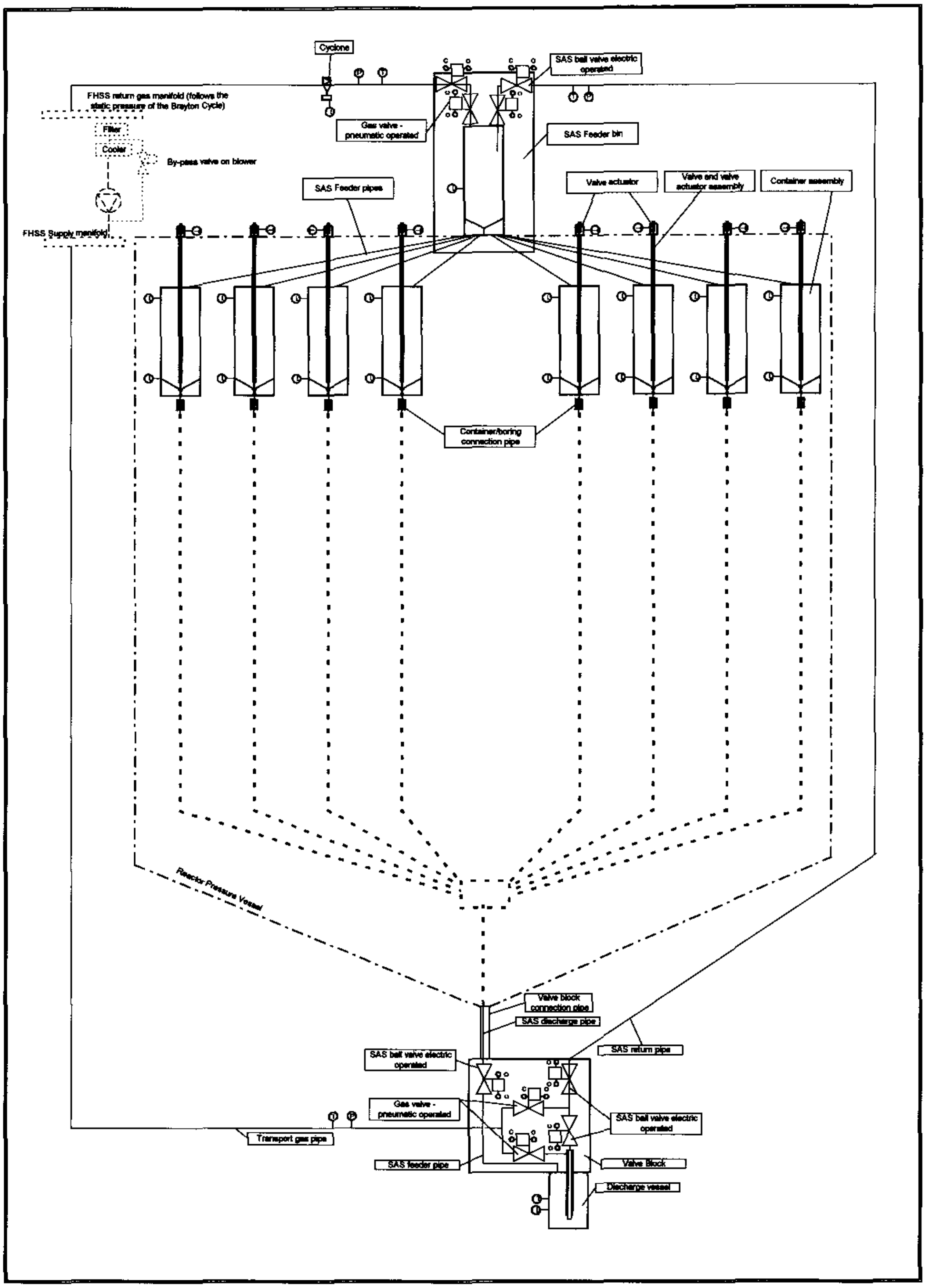


Figure 4: RSS Schematic Diagram

1.2 NEED FOR THE STUDY

1.2.1 Problem Statement

A test facility that will be able to perform all the identified tests must be designed and built. To ensure that the proposed test facility complies with all these requirements, it is firstly necessary to determine the specifications of the components within the test facility. The control and instrumentation components form a very important part of any testing facility. The accurate functioning of these components will determine the accuracy of the results obtained from the tests conducted.

It was therefore necessary to determine the full operating range of all control and instrumentation equipment in the proposed test set-up. With this information obtained, the specifications for these components can be determined, and will in turn be used to select the required components from the suppliers. It was required to identify a suitable method and develop a process for determining the specifications of the components in a test facility that will enable the test facility to perform all the required tests at the required conditions. With the use of this method, it also had to be possible to predict the performance of the test facility before the actual plant was built. A method had to be chosen and a process developed which could be used to perform a complete thermo-hydraulic analysis of a thermal fluid system such as the RSS test set-up.

1.2.2 Literature Survey on Possible Methods for Analysis

A method that could possibly be used for performing a thermo-hydraulic analysis was that of first order calculations [10]. This would have been a tedious process to follow, considering all the different test conditions that had to be evaluated and the number of components in the test set-up.

The ability to determine the fluid flow and heat transfer in complex networks was an important prerequisite in the design process of thermal-fluid networks. Complex flows could be solved using a Computational Fluid Dynamics (CFD) code, which required complex meshing in three dimensions to resolve the flow and temperature fields [11].

To obtain a solution using a CFD code for a simple pipe in three dimensions would have required many hundreds or even thousands of cells to ensure an accurate solution. This was simply not practical for large network simulations consisting of a large number of different and complex components, especially when dynamic simulations were performed which would have required excessive computational resources, and could have taken many hours to solve.

A CFD analysis required the generation of meshes, which would have to be altered and updated as the design progresses. Mesh generation in CFD is a complex process requiring a great deal of time and user expertise.

1.2.3 Selected Method for the Analysis

Simulation modelling overcame the difficulty associated with traditional CFD simulations, by employing a one-dimensional modelling methodology. This simplified the problem considerably by using average flow conditions across the flow area. This implied that the flow velocity, pressure and fluid properties across the flow area were equal to the average values for the cross-sectional area and that they varied only in the direction of flow.

This assumption greatly simplified the solution procedure and eliminated the need for complex computational meshes. The downside of using such a one-dimensional simulation methodology was that the detail flow fields within a component could not be resolved, but this was within the accuracy required for this study.

This process involved the setting up of a thermal-fluid network, which was a network consisting of thermal-fluid components connected in an unstructured manner. Thermal-fluid networks could therefore vary in complexity from just a few different components in a network to hundreds and even thousands of components in a single network.

Flownex provides the means to design and analyse very complex unstructured thermal fluid networks [12] and was the software used for the analysis. The objective of a thermal-fluid network analysis was to determine the flow rates, pressures, temperatures and heat transfer rates for the components in the network. Every thermal-fluid component in the network had to comply with the system specifications and the individual components had to function correctly as part of the integrated system.

When designing a thermal-fluid network, it is essential to accurately predict the flow rates through the components, as well as the temperature distributions and heat transfer rates throughout the network. Flownex can be used to assess the performance and operating conditions of the thermal-fluid components in complex unstructured thermal-fluid networks [12].

1.2.4 Requirement for the Simulation of a Test Set-up

Thermal system design involved the consideration of the technical details of the basic concept and the creation of a new or improved system for the specified task. It was important to distinguish between thermal-fluid *Design* and thermal-fluid *Simulation.*

Design refers to a situation where the characteristics of a system have to be specified so that it will enable the execution of specific functions at an acceptable level of performance. *Simulation,* on the other hand, generally refers to a situation where the characteristics of the system are known, and models have to be set up to predict its functionality and performance level. Simulation therefore formes an integral part of the design process, as a new design had to be analysed and evaluated to ensure that the design criteria are satisfied.

Simulation was used to predict the functionality and performance of the proposed test set-up. It also provided the specifications for the components in the test set-up. This data was then be used for the design of the test facility. The tool that was chosen to perform the simulation was Flownex.

It was required to perform tests on a critical subsystem, such as the RSS, for development and qualification purposes. A test set-up was therefore required to provide a facility for testing components and sub-assemblies in a high-temperature high-pressure Helium environment under conditions simulating the PBMR plant [13].

1.3 OVERVIEW OF REPORT

The first chapter of the report elaborated on the background of the PBMR plant as well as one of its essential subsystems. The need for testing of this subsystem was identified and a literature survey was conducted to identify possible methods for thermo-hydraulic analysis of the test facility to obtain process data of the components.

Chapter 2 discusses the selected approach for analysing the test facility in detail, and Chapter 3 gives a description of the method that was developed to set up the simulation model for the analysis. The modelling of each component is also described.

Chapter 4 discusses the results and interpretation thereof.

Chapter 5 contains the conclusions that were made from the study.

2. PROCESS USED FOR ANALYSIS

2.1 PREAMBLE

A subsystem as critical as the RSS needs to be tested before the proposed concept can be implemented in a full-scale nuclear reactor. Building an experimental set-up and testing the concept is necessary to provide reliable answers. The time and costs involved in such an experiment are substantial. To minimize this, it was necessary to verify the requirements and specifications of the components in such a test set-up before the RSS was constructed.

It was firstly necessary to be familiar with the layout of the complete testing facility. This test facility would provide the appropriate environment in which the required tests could be performed. Next, it had to be ensured that the test set-up itself represented the system as accurately as possible. A detailed layout of the RSS, which would form part of the demonstration plant, was required to accomplish this.

An appropriate software package was selected and used to build the simulation model and perform the simulations. This software had to be able to give the required result as accurately as possible. Flownex was selected as the most suitable software to accomplish this requirement. The procedure for setting up such a simulation model had to be understood fully in order to create a simulation model that would reflect the actual proposed hardware. A detailed description was given for the set-up of a model in Flownex.

Since the PBMR is a nuclear power plant, it has to be designed according to strict rules and regulations. It has to comply with safety standards and quality assurance codes given by the National Nuclear Regulator (NNR) in order to obtain an operating licence in South Africa. A detailed Verification and Validation (V&V) process needs to be performed on all software used as part of the design. The V&V process that was performed on Flownex is described in this section.

2.2 DESCRIPTION OF THE HELIUM TEST FACILITY

The proposed Helium Test Facility (HTF) provides a facility for development, verification and non-nuclear environment qualification testing of critical components and sub-assemblies of the PBMR main power and support systems, under conditions simulating the PBMR plant [14].

The HTF will consist of a main facility coupled to various system test set-ups (experiments) using different test configurations. This will require different quantities of helium at different operating conditions, as multiple cycles of varying temperatures and pressures will be applied by the facility in order to accommodate all the various tests.

The operating pressure will be 9.5 MPa maximum, except for the make-up and storage section, where the supply will be 20 MPa, and the storage vessel, where the supply will be 14 MPa. The experimental operating temperature will vary from 50 °C to 600 °C maximum. A diagram of the main facility is shown in Figure 5.

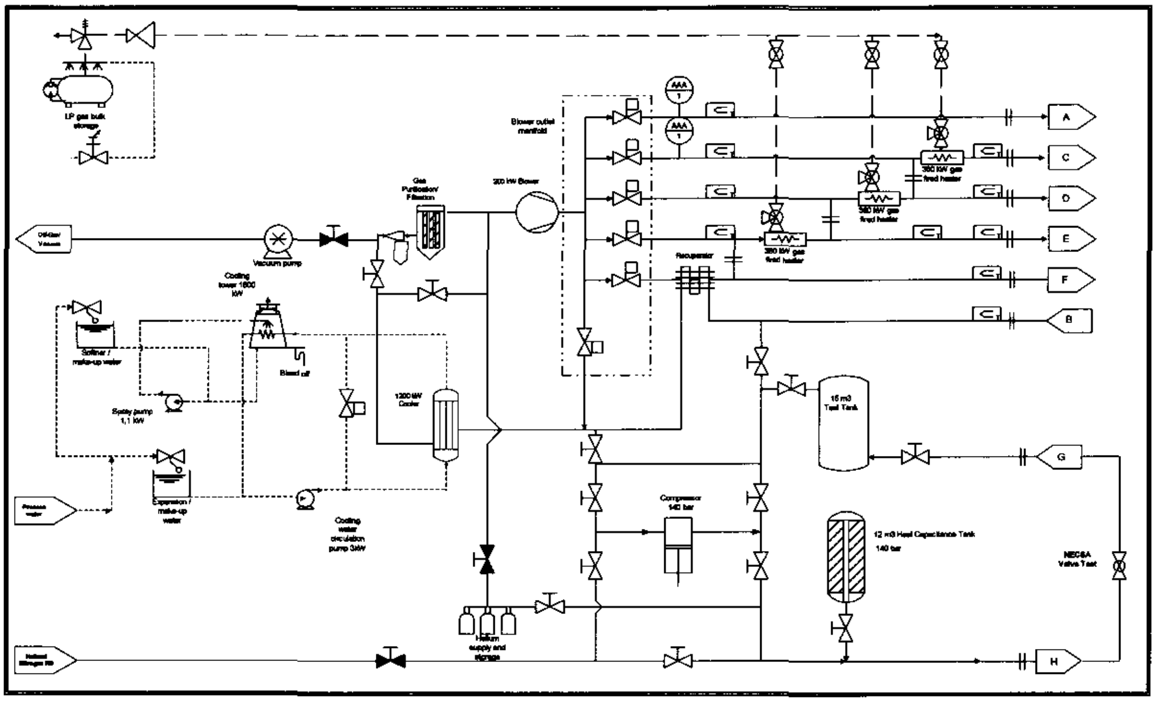


Figure 5: Diagram of Main Facility

One of the test set-ups that will be coupled to the Main Facility is the RSS. In this system, Small Absorber Spheres (SAS) containing B_4C are used to perform the cold shutdown. The spheres are stored in eight storage containers above the core internals of the reactor. When shutdown is required, the valves of the storage containers are opened and the spheres flow into eight borings in the graphite reflector housing of the reactor core. The spheres are pneumatically removed (one channel at a time) from the borings in the side reflector and transported back into the storage container before the reactor can restart.

The RSS test set-up vessel in the HTF will be a full-scale test facility, representing one full RSS system of the planned eight absorber sphere units of the PBMR reactor unit. The aim of the HTF main loop for the RSS test set-up will be to simulate the dimensions, environmental and postulated operational conditions of the RSS inside the PBMR reactor.

The main purpose of the RSS test set-up will be to:

- Verify and validate the insertion of the SAS into the core internal borings under all postulate conditions.
- Prove that the SAS can be removed from the boring and returned to the storage container.

The RSS test set-up will further be utilized to verify the performance of subsystems and components integrated into the RSS, at their defined operating conditions. The HTF main loop will create the required conditions in the RSS test set-up for the PBMR operational range of insertion and transport of spheres. Each of the respective supply lines from the main loop will be utilized in a specific part of the RSS set-up to simulate a different condition.

As the spheres will be removed one boring at a time, it is only required to test one set-up with a storage container, boring, discharge vessel and sphere return pipe [15]. This test set-up, that will form part of the HTF, needed to be analysed to determine the specification of the components in the test set-up. Figure 6 shows a diagram of the RSS test set-up.

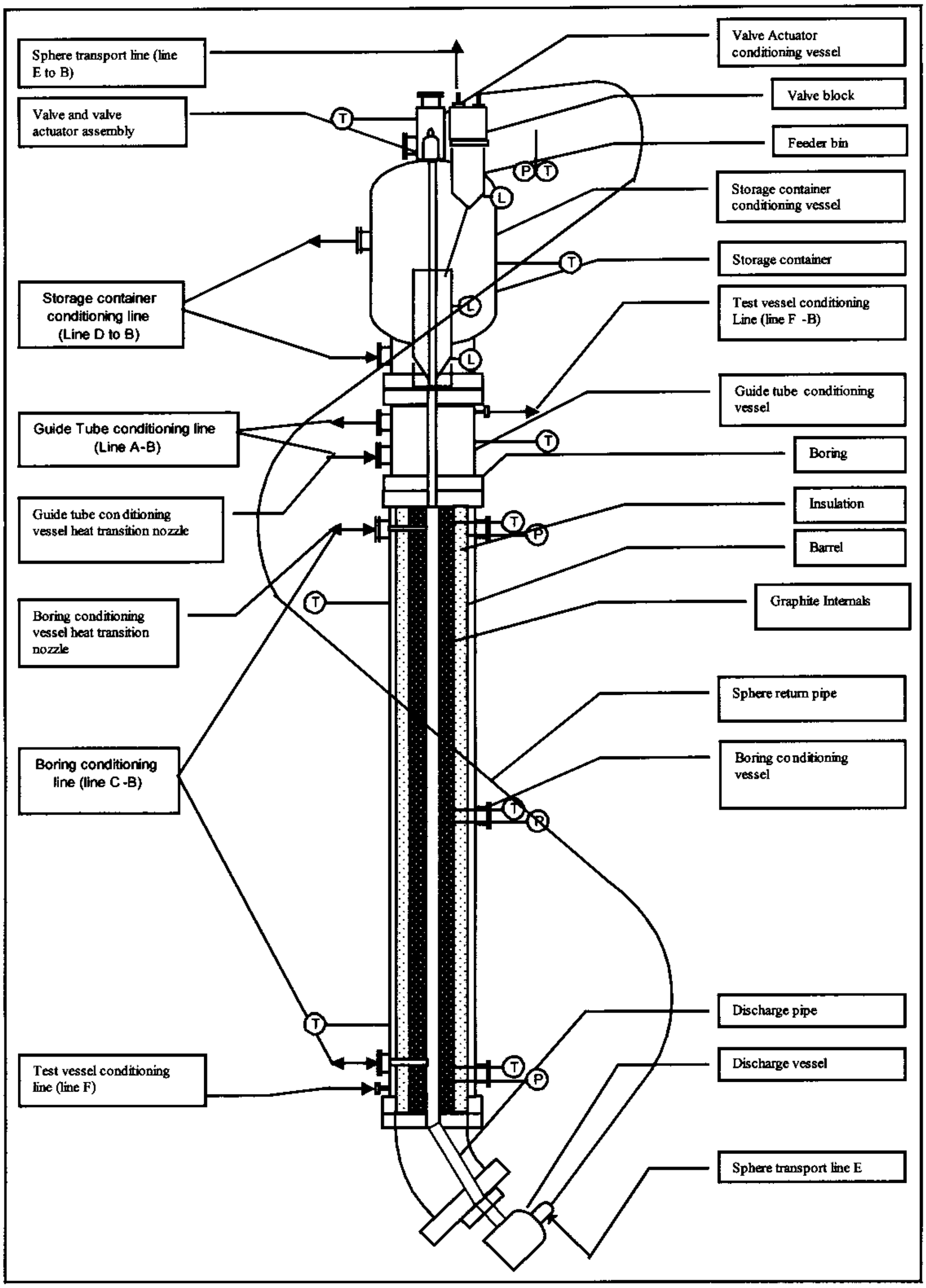


Figure 6: Diagram of RSS Test Set-up

The connection of the RSS test set-up with the Main Facility is illustrated in Figure 7.

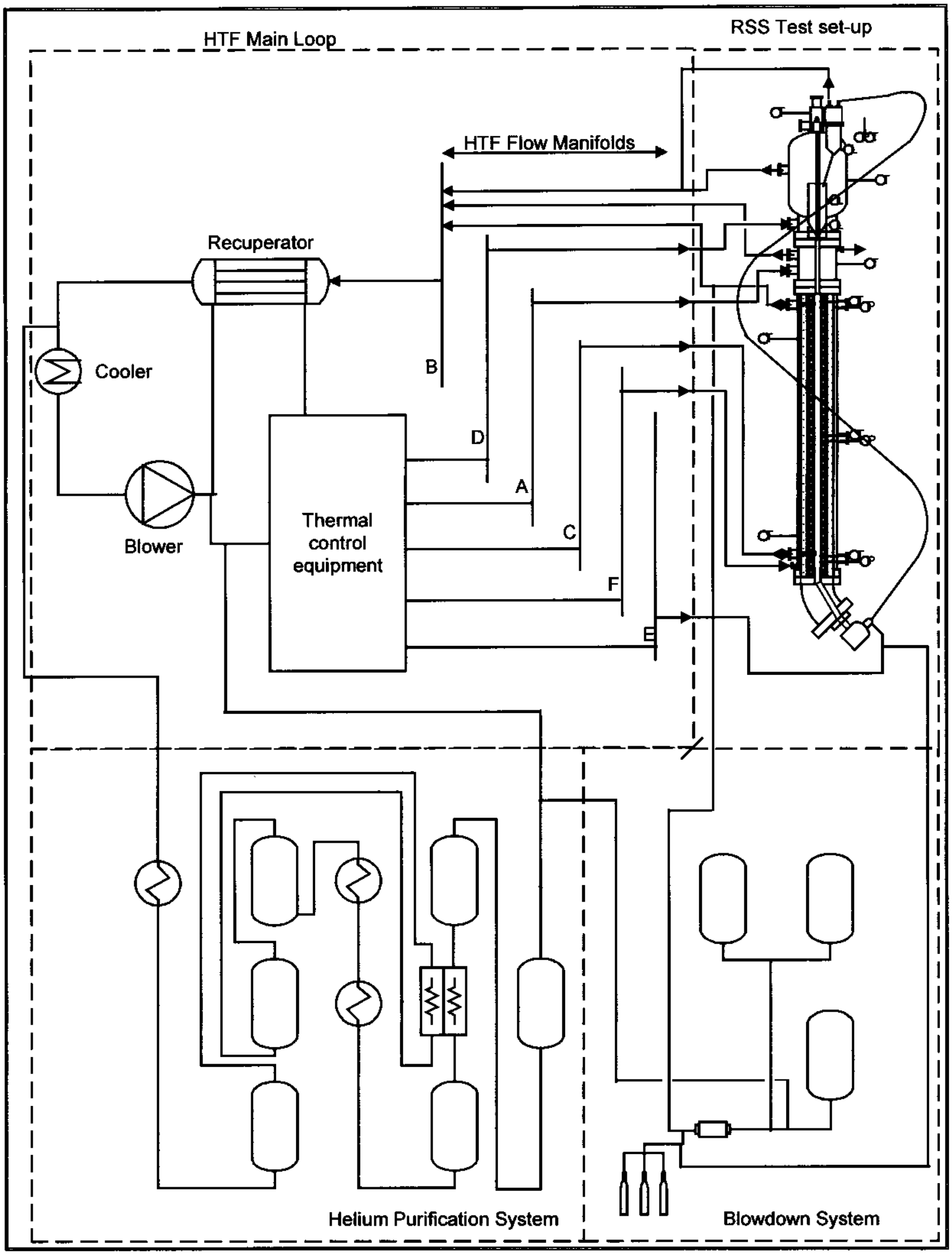


Figure 7: RSS Connected to Main Facility (Simplified Diagram)

2.3 LITERATURE SURVEY ON FLOWNEX

The software tool chosen for the analysis was Flownex. A literature survey was conducted on the development of Flownex and to determine the fields in which the software has been used. This was done to determine whether Flownex was an acceptable tool for the required analysis.

2.3.1 The Development of Flownex

Flownex is a general-systems Computational Fluid Dynamics (CFD) code that finds wide application in the industry. The code was developed over the past 15 years by M-Tech Industrial, in collaboration with the Faculty of Engineering at the then PU for CHE [16] (now the North West University).

The PBMR project has boosted the development of Flownex as a commercial product, and users include companies and universities such as Rolls Royce, Mitsubishi Heavy Industries, Kobe Steel, Concepts NREC, Eskom, Sasol, CSIR Miningtek, Iscor, MIT, Cranfield University, and Stuttgart University.

2.3.2 Use of Flownex in the Industry

Flownex is used in the industry by Rolls Royce [17] for the modelling and simulation of aircraft combustion chambers. Clients such as PCA Engineers (USA) [18], Concepts NREC (USA) [19] and Mitsubishi Heavy Industries [20] use Flownex for the modelling of turbo machines.

Mitsubishi Heavy Industries, Ltd (MHI) is one of the world's leading manufacturers of heavy machinery. With a vast amount of practical experience and a high level of technological capability, Mitsubishi has been active in the nuclear industry for more than three decades. Since commencing research into and developing of nuclear power generation in the 1950s, Mitsubishi has taken part in the design, manufacture and construction of a large number of very successful Pressurized Water Reactor (PWR) power plants [20].

Mitsubishi is the only organization to produce such a large range of supplies for nuclear power generation. These supplies include Architectural Engineering, Nuclear Steam Supply System, Turbine Generator Systems, Electrical Systems, I & C Systems, Nuclear Fuel, and also the Balance of Plant.

Kobe Steel Ltd (Japan) uses the software for the simulation of air chilling units [21]. From comprehensive power generation plants to individual machines, Plant Engineering Sector of Kobe Steel`s Plant Engineering Company has the capability to fulfil a vast range of needs in such industries as iron and steel making, cement, energy and chemical-related fields.

Integrating excellent manufacturing and plant engineering capabilities, they are expanding their operations into a variety of business fields. In addition to their ability to produce the world`s largest desulphurization reactors and oxygen generation plants for oil refining and petrochemical plants, they offer a wide ride range of power generation and gas supply facilities, nuclear equipment, and district heating and cooling systems [21].

Flownex is also used by a number of academic institutions. Massachusetts Institute of Technology (MIT) uses Flownex for design of the Breyton cycle [22] and Cranfield University uses it for the simulation of compressor units [23].

It was shown that Flownex is widely used in the industry and academics for the modelling and simulation of various thermal-fluid systems and networks. All the mentioned users of Flownex are well known in industry and academic fields. They have delivered reliable products and education. It can therefore be accepted that Flownex will be a reliable tool for the analysis of this particular thermal-fluid network.

2.4 PROCESS DEVELOPED FOR THE ANALYSIS

2.4.1 Setting Up of the Thermal-fluid Network

Flownex was used as the simulation tool to set up a thermal-fluid network for performing the analysis. Thermal-fluid networks were presented in Flownex by a combination of Nodes and Elements. In the Flownex Graphical User Interface (GUI), nodes were indicated with a square box symbol while elements were indicated with a circle.

A network was created by placing and connecting elements and nodes in any unstructured fashion. Flownex caters for any number of nodes and elements per network, limited only by the available computer memory. It was therefore possible to create very complex thermal-fluid networks using Flownex.

Nodes were used to connect elements together and to represent boundaries for a network. Nodes could also have special functions, for example reservoirs and tanks could be modelled with nodes. Junction losses could also be modelled where elements meet at a common node.

2.4.2 Solving of the Thermal-fluid Network

Flownex solves networks quickly and accurately by employing a very fast and stable implicit solver [12]. This eliminates the excessive time step restriction imposed on explicit codes. Flownex uses dynamic memory allocation, which means that very large and small networks can be solved on a personal computer without re-dimensioning the code each time.

Flownex provides extensive error and warning messages. Although nodes are the endpoints of elements, a node can have a volume. Flownex can also deal with heat transfer to and from nodes. Long pipes can be subdivided into a number of smaller increments. This increased accuracy enables the user to investigate how the pressure or temperature varies over the length of the pipe. Different pipe loss coefficients can also be specified in the forward and reverse flow directions.

2.4.3 Process for Creating a Flownex Network

Flownex is run from within the Windows environment. Elements and nodes define a network and form the basic building blocks to simulate a network.

An element is a component which causes a pressure drop or increase, such as a length of pipe or a duct, an orifice, a fan, a pump, a compressor, a turbine or a heat exchanger. An element can also be a combination component, such as a length of pipe, which include a number of secondary pressure loss components and orifices. In the case of a combined element, the diameter of the pipe has to be constant.

Nodes are the endpoints of elements. A network is defined by joining elements at common nodes as shown in Figure 8.

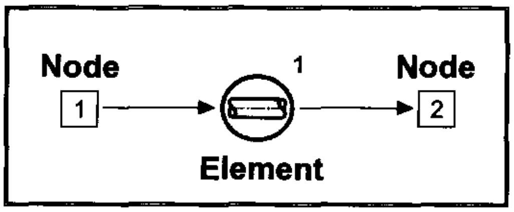


Figure 8: Basic Building Blocks of a Network

It is possible to distinguish between the following three types of nodes:

- *Boundary nodes.* A node associated with only one element is called a boundary node.

- *Fixed pressure node.* When defining a network, the pressure on any node, even that of boundary nodes, could have been fixed. Such nodes are called fixed pressure nodes. A node can therefore be both a boundary node and a fixed pressure node.
- *Internal nodes.* Nodes that are neither boundary nodes nor fixed pressure nodes were called internal nodes.

It is also possible to distinguish between the following two types of elements:

- *Boundary elements.* A boundary element is an element associated with a boundary node or a fixed pressure node.
- *Internal elements.* Internal elements are all elements that were not boundary elements.

In specifying a network, one has to adhere to the following simple rules:

- For boundary node/element pairs, one normally has to specify at least the node pressure, the node mass source or the element mass flow.
- The pressure of any node may have been fixed. Generally, if the pressure of an internal node is fixed, continuity would not have been satisfied at the node for the network specified by the user. It is important to remember that if the pressure of a node is fixed, Flownex will generate a mass source or sink at that node, which will cause continuity to be satisfied.
- The mass flow of any pipe element may have been fixed. If the mass flow of an internal element is fixed, generally the relationship between mass flow and pressure drop for that specific element will not be satisfied. An additional pressure difference will be generated in the element with the specified mass flow. If the mass flow of a boundary element as well as the pressure of the associated boundary node is fixed, the pressure of the boundary node will be ignored. If the mass flow, and not the pressure, were specified at a boundary, Flownex will calculate the pressure of the boundary node.

- Mass flows may not be fixed for all boundary elements. For at least one boundary element-node pair, the pressure and not the flow should be fixed. If two networks are connected together through a single fixed flow element, the pressure of at least one boundary node in each of the two networks should be fixed.
- Either the mass flow in a boundary element or the pressure of its associated boundary node must be fixed.
- If neither the node pressure nor the node mass source of a boundary node are specified, the flow in the associated boundary element will be zero.
- It is not allowed to specify both the pressure and mass source at the same node.

The convergence parameters specified for the project were subdivided into two groups. The first group was where the convergence criteria and the number of iterations for each solver were specified. The second group was where the relaxation parameters were specified to ensure a stable solution. For the solution to have been considered as converged, the conservation of mass, momentum and energy needed to be satisfied. To check if continuity was satisfied (conservation of mass) at each node, the sum of the continuity errors at all the nodes divided by the mean of all the element mass flows (absolute values) was calculated.

2.5 VERIFICATION AND VALIDATION (V&V) OF THE CODE

Since the PBMR is a nuclear power plant, it has to be designed under strict rules and regulations. It has to comply with safety standards and quality assurance codes given by the National Nuclear Regulator (NNR) in order to obtain an operating licence in South Africa.

One regulatory requirement is that all applicable software codes used for the design of the PBMR must be verified and validated. It is a lengthy process to verify and validate these codes. In order to meet this requirement, PBMR has a dedicated section that is responsible for this task.

The Software V&V process for Flownex was captured in the Verification and Validation of software [24]. This document, in conjunction with the procedure for Project Management for the Design, Development and Maintenance of Software [25] and Configuration Management Process Definition for Software [26], dictated the Software V&V process.

Flownex Nuclear is Software Under Development (SUD). It is being developed to perform thermal-fluid analyses on a high-temperature gas-cooled reactor coupled to a direct, recuperated Brayton cycle in an implicit way. As it is the first software product of its kind, a diverse number of verification and validation methods, from diverse sources, are used to qualify the software.

It should be stressed that Flownex Nuclear is the first software product of its kind, as it impacts on the availability of codes that can be used for independent V&V activities. In order to ensure that all phenomena for each component in Flownex Nuclear are validated for the various extremities, an extensive V&V exercise needs to be done.

Verification forms part of the overall Flownex Nuclear development process and includes the verification activities that form part of the software engineering process, as well as all related verification that is done as part of the derivation of the theory for component models or model enhancements. Validation of Flownex Nuclear is performed by comparing the results of the implemented theoretical models in Flownex Nuclear with benchmark data obtained using appropriate methods [27].

The Nuclear Research and consultancy Group (NRG) in Petten, the Netherlands, performs Independent Software V & V on the Flownex Nuclear software. The NRG is operating technically, managerially and financially independent of PBMR and M-Tech. This V&V is managed by PBMR and data obtained is accessible to M-Tech for V&V activities.

3. SIMULATION MODEL

3.1 PREAMBLE

This chapter will elaborate in detail on how the model was incorporated into the code and what is required to simulate all the defined test conditions.

A complete description is given of the simulation model set-up. The RSS test set-up is firstly described to fully understand what needs to be simulated. The method used for the modelling of the components such as the valves and heater is described and incorporated into the simulation model.

A summary is given of all the main elements and nodes in the Flownex model, and a diagram is given to show the layout of the Flownex model that will be used for the analysis. The source for material properties used in the model is also given.

The required test modes are described in order to define the inputs for the conditions to be simulated. All the tests that will be conducted in the test facility are described. These tests will be simulated in the analysis to obtain the process data for all the components in the test facility.

3.2 SIMULATION MODEL SET-UP

3.2.1 Description of the RSS Test Set-up

The test set-up must be able to simulate the required reactor conditions. This will be done in conjunction with the high temperature and pressure Helium Test Facility (HTF) [8]. The HTF will be used to simulate the reactor conditions in the RSS Test vessel set-up for the range of insertion and transport of spheres.

The RSS test set-up vessel is a full-scale test facility, representing one full RSS system (in the PBMR reactor unit). The purpose (or function) of the test facility is to simulate the dimensions, environmental and postulated operational conditions of the RSS inside the PBMR reactor. A diagram of the test vessel is shown in Figure 9.

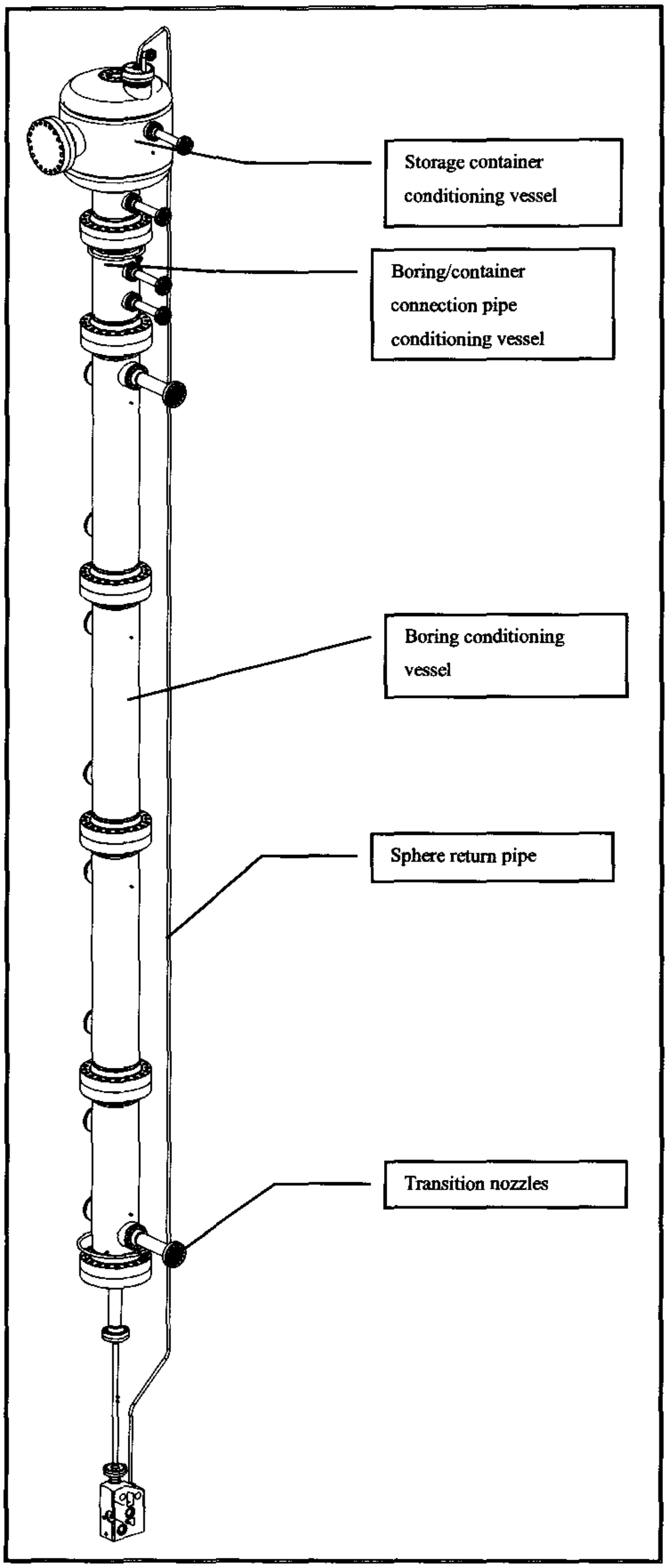


Figure 9: RSS Test Set-up

The process for setting up the simulation model was described in Chapter 2. Piping and Instrumentation diagrams [28] of the system were provided for the intended layout of the test set-up to be built. This indicated the position of conditioning vessels, valves and instrumentation. Pipe lengths, diameters and layout of the piping were obtained from pipe isometric drawings for each line [29], [30], [31], [32], [33], [34], [35], [36].

3.2.2 Modelling of Valves

Valves for the HTF were modelled in Flownex as a valve with loss coefficient element. This element required a curve giving a loss coefficient for different valve openings. The valve selection for the HTF was described in [37]. Final selection of the control valve characteristics will only be done once the process requirements have been confirmed and specified.

Supplier information on potential valves was available, and this is given in the Appendices. The supplier data only gave a rated (valve 100% open) valve flow coefficient (Cv) for the various valve types and sizes. A Microsoft Excel spreadsheet [38] was used to generate valve Cv curves for the various valves. The spreadsheet used the Cv values at 0% (Cv = 0.00001 assumed) and 100% valve openings, and the valve rangeability in the case of an equal percentage valve, to determine the Cv curves.

For equal percentage valves the Cv-curve was determined by

$$Cv = Cvm * R^{(\frac{y}{ym}-1)}$$

With

Cv = Valve flow coefficient

Cvm = Rated valve flow coefficient

R = Rangeability

y = Valve travel

ym = Rated valve travel

This equation calculated a larger than required Cv for small valve openings. Therefore this equation was only used to calculate the Cv values from 10% to 100% valve openings. For a 5% valve opening, the average was taken between the Cv calculated for 10% opening and that chosen for a 0% valve opening.

In the spreadsheet, the Cv curves was converted to a loss coefficient curve as required by Flownex. The conversion was done by using the following equation as described in [39].

$$K = \frac{N_2 d^4}{Cv^2}$$

With

K = Secondary loss coefficient

Cv = Valve flow coefficient [US gallons per minute/psi$^{1/2}$]

d = Valve inlet diameter in inches

N_2 = 890

The nominal valve size (in inches) was used as the valve inlet diameter. Note that this valve diameter had to be used as the Flownex element valve diameter, as a loss coefficient was associated with a specific velocity, and thus valve diameter. The valve diameters to be used in Flownex are given in Table 1.

Table 1: Valve Diameters for Use in Flownex

Size	0.5	1	1.5	2	2.5	3	4	6	8
Diameter [m]	0.0127	0.0254	0.0381	0.0508	0.0635	0.0762	0.1016	0.1524	0.2032

For all the valves, a pressure drop ratio factor (x_T) of 0.7 was assumed for the forward and backward directions. This was based on a brochure of Samson (T 8000-1) distributed by Necsa and used as a guideline. A scanned image of a part of this brochure is shown in the Appendices in Figure 12.

With the process described above, Cv-curves and loss coefficient curves were obtained for the various valves. A Flownex vl2 file was generated for each loss coefficient curve using the Microsoft Excel spreadsheet as described in [40]. The data obtained for each type of valve used in the test set-up, is given in the following sections.

3.2.3 Linear Globe Valve

Refer to Figure 13 in the Appendices for the supplier information. The rated Cv values were taken for the simple range trims on top of the figure. Where two Cv values were given for the same nominal size valve, the smaller value was used. Cv and K values were determined for valve sizes from 1" to 8". Only the Cv values and K values for openings of 5%, 50% and 100% are shown in Table 2 and Table 3. The full range of values is given in the Appendices.

Table 2: Cv Values for Linear Globe Valves

Valve Opening	Nominal size [“]						
	1	1.5	2	3	4	6	8
5 %	0.2	0.7	1.3	3.4	5.2	8.3	22.8
50 %	2.0	6.8	13.3	34.0	52.0	82.5	227.5
100 %	4.0	13.5	26.5	68.0	104.0	165.0	455.0

Table 3: K Values for Linear Globe Valves

Valve Opening	Nominal Size [“]						
	1	1.5	2	3	4	6	8
5 %	2 2247.9	9 888.6	8 111.0	6 236.1	8 426.0	1 6946.7	7 043.5
50 %	222.5	98.9	81.1	62.4	84.3	169.5	70.4
100 %	55.6	24.7	20.3	15.6	21.1	42.4	17.6
File.vl2	GV1Lin_1	GV1_5Lin_1	GV2Lin_1	GV3Lin_1	GV4Lin_1	GV6Lin_1	GV8Lin_1

3.2.4 Equal Percentage Globe Valve

Refer to Figure 13 for the supplier information. The same rated Cv values as for the linear globe valves were used. For the equal percentage globe valve curves, a rangeability of 50 (using Figure 12 in the Appendices as a guideline) was assumed for valves 2” and smaller, and 30 for larger valves. Cv and K values were determined for valve sizes from 1” to 8”. Only the Cv values and K values for openings of 5%, 50% and 100% are shown in Table 4 and Table 5. The full range of values is given in the Appendices.

Table 4: Cv Values for Equal Percentage Globe Valves

Valve Opening	Nominal Size [“]						
	1	1.5	2	3	4	6	8
5 %	0.06	0.20	0.39	1.59	2.44	3.86	10.66
50 %	0.57	1.91	3.75	12.4	19.0	30.1	83.1
100 %	4.00	13.50	26.50	68.0	104.0	165.0	455.0

Table 5: K Values for Equal Percentage Globe Valves

Valve Opening	Nominal Size [“]						
	1	1.5	2	3	4	6	8
5 %	25 4375.9	11 3056.0	92 730.8	28 427.3	38 409.8	77 251.2	32 107.4

Valve Opening	Nominal Size [“]						
	1	1.5	2	3	4	6	8
50 %	2 781.3	1 236.1	1 013.9	4 67.7	6 32.0	1 271.0	528.3
100 %	55.6	24.7	20.3	15.6	21.1	42.4	17.6
File.vl2	GV1EP_1	GV1_5EP_1	GV2EP_1	GV3EP_1	GV4EP_1	GV6EP_1	GV8EP_1

3.2.5 Y-Pattern Globe Valve

A linear characteristic was assumed for these valves. The supplier information is given in Figure 14 in the Appendices. The Cv values of a class 1690 valve were selected for the Y-pattern globe valves. Cv and K values were determined for valve sizes from 1” to 8”. Only the Cv values and K values for openings of 5%, 50% and 100% are shown in Table 6 and Table 7. The full range of values is given in the Appendices.

Table 6: Cv Values for Y-pattern Globe Valves

Valve Opening	Nominal Size [“]						
	0.5	1	1.5	2	2.5	3	4
5 %	0.4	0.6	1.3	3.0	3.0	3.0	3.0
50 %	3.5	6.0	12.5	30.0	30.0	30.0	30.0
100 %	7.0	12.0	25.0	60.0	60.0	60.0	60.0

Table 7: K Values for Y-pattern Globe Valves

Valve Opening	Nominal Size [“]						
	0.5	1	1.5	2	2.5	3	4
5 %	454.1	2472.1	2883.6	1582.2	3862.8	8009.9	25315.4
50 %	4.5	24.7	28.8	15.8	38.6	80.1	253.2
100 %	1.1	6.2	7.2	4.0	9.7	20.0	63.3
File.vl2	YGV0_5_1	YGV1_1	YGV1_5_1	YGV2_1	YGV2_5_1	YGV3_1	YGV4_1

3.2.6 Ball Valve

An equal percentage valve characteristic with a rangeability of 50 was assumed (using Figure 12 as a guideline) for these valves. The supplier information is given in Figure 15 in the Appendices. The Cv values of class 900 to 2800 valves were selected for the ball valves. Cv and K values were determined for valve sizes from 1” to 8”. Only the Cv values and K values for openings of 5%, 50% and 100% are shown in Table 8 and Table 9. The full range of values is given in the Appendices.

Table 8: Cv Values for Ball Valves

Valve Opening	Nominal Size [“]						
	0.5	1	1.5	2	2.5	3	4
5 %	0.13	0.15	0.27	0.75	1.26	1.54	1.38
50 %	1.3	1.4	2.5	7.2	12.0	14.7	13.2
100 %	9.0	10.0	18.0	51.0	85.0	104.0	93.0

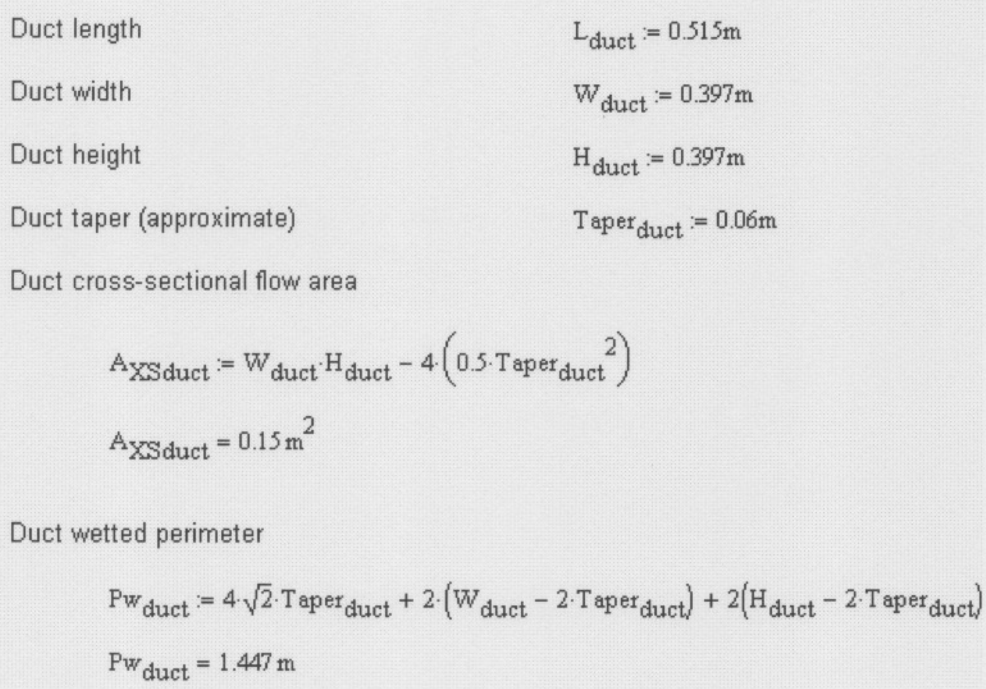
Table 9: K Values for Ball Valves

Valve Opening	Nominal Size [“]						
	0.5	1	1.5	2	2.5	3	4
5 %	3 140.4	40 700.1	63 594.0	25 036.6	22 004.8	30 480.0	12 0467.5
50 %	34.3	445.0	695.3	273.7	240.6	333.3	1317.1
100 %	0.7	8.9	13.9	5.5	4.8	6.7	26.3
File.vl2	BV0_5EP_1	BV1EP_1	BV1_5EP_1	BV2EP_1	BV2_5EP_1	BV3EP_1	BV4EP_1

3.2.7 Description of Heater

The proposed heater unit that will be used in the RSS test set-up is a hi-tech design. This paragraph contains a description of the heater unit, and some calculations that were used to determine the flow area, wetted perimeter and a loss coefficient to represent the flow restriction caused by the heater candles.

The heater unit has an octagonal shaped duct. The duct flow area and the wetted perimeter were calculated as follows:



Duct length	$L_{duct} := 0.515m$
Duct width	$W_{duct} := 0.397m$
Duct height	$H_{duct} := 0.397m$
Duct taper (approximate)	$Taper_{duct} := 0.06m$

Duct cross-sectional flow area

$$A_{XSduct} := W_{duct} \cdot H_{duct} - 4 \cdot \left(0.5 \cdot Taper_{duct}{}^{2}\right)$$

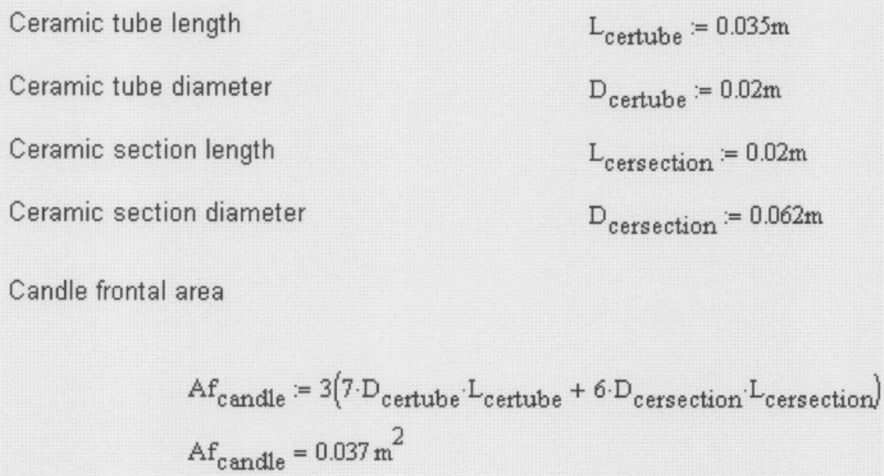
$$A_{XSduct} = 0.15\,m^{2}$$

Duct wetted perimeter

$$Pw_{duct} := 4 \cdot \sqrt{2} \cdot Taper_{duct} + 2 \cdot \left(W_{duct} - 2 \cdot Taper_{duct}\right) + 2\left(H_{duct} - 2 \cdot Taper_{duct}\right)$$

$$Pw_{duct} = 1.447\,m$$

Each heater unit has 18 candle elements arranged in sets of three. The frontal area of a set of three candles (one row) was calculated as follows:



Ceramic tube length	$L_{certube} := 0.035m$
Ceramic tube diameter	$D_{certube} := 0.02m$
Ceramic section length	$L_{cersection} := 0.02m$
Ceramic section diameter	$D_{cersection} := 0.062m$

Candle frontal area

$$Af_{candle} := 3\left(7 \cdot D_{certube} \cdot L_{certube} + 6 \cdot D_{cersection} \cdot L_{cersection}\right)$$

$$Af_{candle} = 0.037\,m^{2}$$

The candles cause a flow restriction, which was represented by a secondary loss coefficient. The loss coefficient was determined as a function of the reduced flow area and the duct flow area ratio. The assumption was made that each set of candles had a sudden contraction and a sudden enlargement loss coefficient. The equations used were obtained from [41]. The calculated loss coefficient was based on the duct velocity in the full duct area.

Loss for sudden enlargement

$$K_{enl} := \left(1 - \frac{A_{XSduct}}{A_{XSduct} - Af_{candle}}\right)^2$$

$$K_{enl} = 0.107$$

Loss for sudden contraction

$$K_{cont} := 0.5\,\frac{\left[1 - \frac{\left(A_{XSduct} - Af_{candle}\right)}{A_{XSduct}}\right]}{\left[\frac{\left(A_{XSduct} - Af_{candle}\right)}{A_{XSduct}}\right]^2}$$

$$K_{cont} = 0.217$$

The total loss coefficient of the heater unit was then calculated as follows:

Total loss per 50kW unit

$$K_{tot} := 6\left(K_{cont} + K_{enl}\right)$$

$$K_{tot} = 1.939$$

In the above calculations, the flow resistance caused by the heating wires was ignored.

3.2.8 Description of Flownex Model for Heater

The heater was modelled in Flownex as three pipe elements in series. The first element represented the heater inlet pipe, the second the heating elements as described above, and the third the heater outlet pipe. No heat transfer characteristics of the heaters were modelled. The heater duty was to be calculated by specifying the required outlet temperature on the heater outlet element node in Flownex.

For the inlet and outlet piping, secondary loss factors of 0.5 were assumed for pipe bends, and 0.5 and 1 for reducer and diffuser losses respectively. These were more conservative values than those suggested in [39]. The reasoning was that the loss factors are Reynolds number dependent, and in order not to determine a loss factor for every analysis performed, a more conservative value was rather used. A pipe roughness of 40 μm was used as suggested in [39].

The inputs used in Flownex for the heater inlet pipe are given in Table 10.

Table 10: Flownex Inputs for Heater Inlet Pipe

Item	Number	Description	Parameter	Flownex Input
Element (DW pipe)	1301	Heater H5 inlet pipe	Diameter (m)	0.04282
			Length (m)	2.7
			Num Inc	1
			Num Parallel	1
			K loss	1.5 *
			Roughness (μm)	40

* Exit loss + bend loss

The inputs used in Flownex for the heater element are given in Table 11.

Table 11: Flownex Inputs for Heater Element

Item	Number	Description	Parameter	Flownex Input
Element (DW pipe)	1303	Heater H5 element	Circumference (m)	1.447
			Area (m^2)	0.15
			Length (m)	1.545 *
			Num Inc	1
			Num Parallel	1
			K loss	5.82 **
			Roughness (m)	40

* L = 0.515 m x 3

** K = 1.94 x 3

The inputs used in Flownex for the heater outlet pipe are given in Table 12.

Table 12: Flownex Inputs for Heater Outlet Pipe

Item	Number	Description	Parameter	Flownex input
Element (DW pipe)	1305	Heater H5 outlet pipe	Diameter (m)	0.04282
			Length (m)	1.2
			Num Inc	1
			Num Parallel	1
			K loss	1 *
			Roughness (μm)	40

* Entry loss + bend loss

In the Flownex model of the heater, the flow resistance of heating wires were not modelled. The inlet and outlet pipe lengths were approximated. The volumes of the inlet diffusers and outlet reducers were not included in the model. No heat transfer characteristics were modelled for the heater, only flow resistance was considered. It was assumed that each set (row) of candles had a sudden contraction and sudden enlargement loss coefficient.

3.2.9 Summary of Elements and Nodes

The inputs for the valves and heater in the Flownex model were as described in the previous sections. Flow instruments were modelled as British Standard orifices and pipes as Darcy-Weishbach elements [15]. Conditioning vessels and the Mixing box were modelled as nodes with volumes. A summary of the main elements in the Flownex model is given in Table 13.

Table 13: Summary of Flownex Elements and Nodes

Flownex Number	Component Type E - Element N - Node	Description	Type [1]
1318	Node	Container Conditioning vessel	VN
1301	Element	Heater 5 inlet	DW
1303	Element	Heater 5	DW
1305	Element	Heater 5 outlet	DW
1417	Element	RSS-core boring #1	DW
1419	Element	RSS-core boring #2	DW
1421	Element	RSS-core boring #3	DW
1335	Node	Mixing box 5	VN
1422	Element	Graphite + insulation #1	CHT
1423	Element	Graphite + insulation #2	CHT
1424	Element	Graphite + insulation #3	CHT
1425	Element	RSS-jacket #1	CHT
1429	Element	RSS-jacket #2	CHT
1433	Element	RSS-jacket #3	CHT
1324	Element	Connection pipe conditioning	DW
1404	Node	RSS fluidizing bed	CN
1436	Element	RSS shell #1	CHT
1437	Element	RSS shell #2	CHT
1438	Element	RSS shell #3	CHT

NOTE: Connection nodes were nodes with no specified properties. However, the node numbers still had to be unique.

[1]DW -	Darcy-Weishbach pipe
BSO -	British Standard Orifice
CVLC -	Control Valve with Loss Coefficient
CHT -	Conductive Heat Transfer element
CN -	Connection node
VN -	Volume Node

A diagram of the Flownex network is shown in Figure 10.

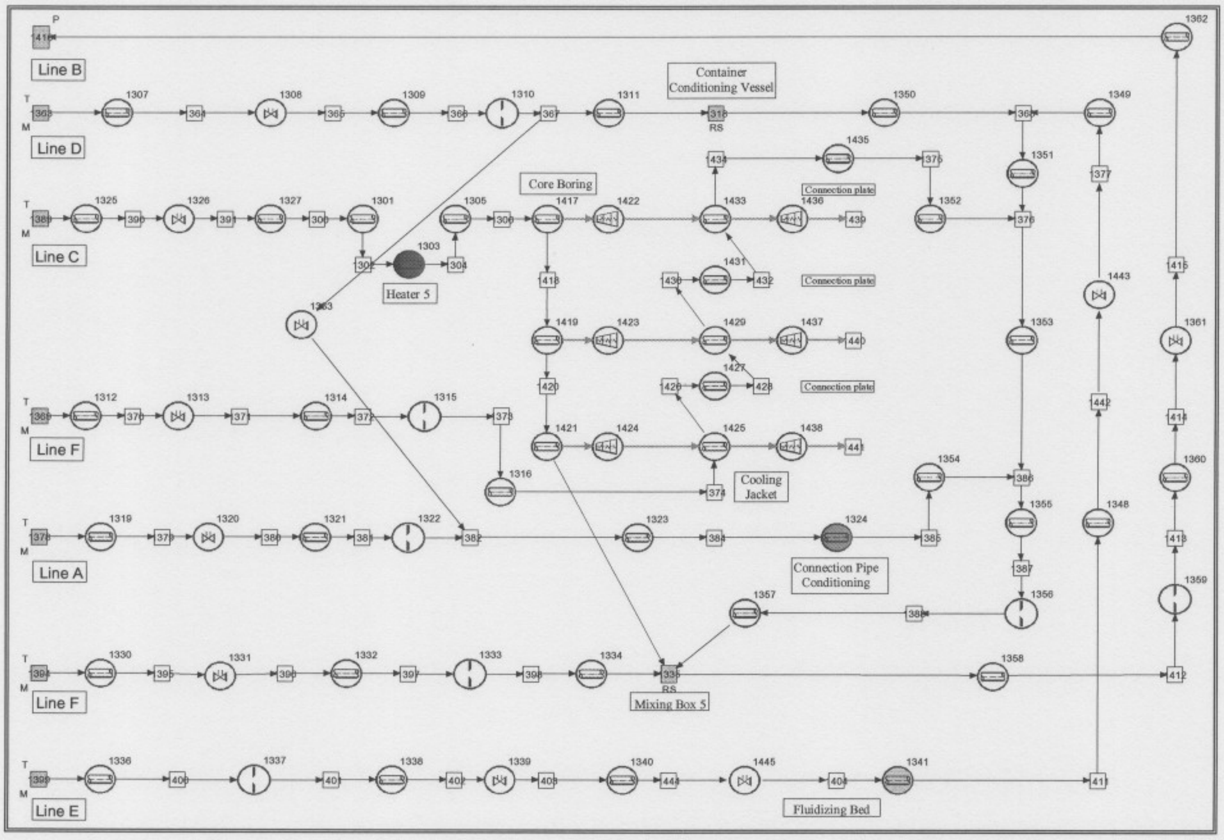


Figure 10: Flownex Model

3.2.10 Material Properties

PBMR has a database that contains the thermo physical properties of all the materials used in the PBMR design [42]. These properties are validated against various sources to ensure that they give an accurate mathematical representation of the actual behaviour of the materials. Helium, and the materials for the vessel, are characterized according to the corresponding properties in the database.

3.3 REQUIRED TEST MODES FOR EXPERIMENTS

3.3.1 RSS Commissioning

The RSS will be commissioned at a number of identified PBMR reactor conditions. The RSS test set-up combined with the HTF Main loop, must simulate the commissioning conditions of the RSS in the PBMR reactor. These conditions have to be simulated to determine the requirements of the components in the test set-up. The commissioning conditions under which the test set-up must be able to operate are given in Table 14.

Table 14: Commissioning Conditions for RSS in the Reactor

Description	Reactor Condition Applicable To Test
Insert SAS	Core temperature = 50 °C, Reactor pressure = 2.2 MPa Sphere temperature = 50 °C
Remove SAS	Core temperature = 50 °C, Reactor pressure = 2.2 MPa Sphere temperature = 50 °C

The required conditions were given for the beginning and the end of each test. Where the values at the beginning and end of the test were the same, it indicated that the conditions in the vessel should be kept constant for the duration of the test.

The RSS Test Set-up conditions that were required to simulate the reactor conditions for insertion of the SAS [9] are shown in Table 15.

Table 15: RSS Test Set-up Conditions to Simulate Insertion of SAS During Commissioning

Description	Beginning of Test	End of Test
Sphere transport line requirements (gas line E)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	50	50
Mass flow (kg/s)	n/a	n/a
Core boring conditioning line (gas line C)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	50	50
Mass flow (kg/s)	n/a	n/a
Storage container condition (gas line D)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	50	50
Mass flow (kg/s)	n/a	n/a
Boring/container connection pipe conditioning (gas line A)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	50	50
Mass flow (kg/s)	n/a	n/a
Test vessel conditioning (gas line F)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	50	50
Mass flow (kg/s)	n/a	n/a
Valve actuator conditioning		
Pressure (MPa) (gauge)	Atmospheric (air)	Atmospheric (air)
Temperature (°C)	20 to 50	20 to 50
Mass flow (kg/s)	n/a	n/a

The RSS Test Set-up modes that were required to simulate the reactor conditions for removal of the SAS [9] are shown in Table 16.

Table 16: RSS Test Set-up Conditions to Simulate Removal of SAS During Commissioning

Description	Beginning of Test	End of Test
Sphere transport line requirements (gas line E)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	50	50
Mass flow (kg/s)	n/a	0.10
Pressure drop (transport of spheres) (kPa)	n/a	33.1
Core boring conditioning line (gas line C)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	50	50
Mass flow (kg/s)	n/a	n/a
Storage container condition (gas line D)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	50	50
Mass flow (kg/s)	n/a	n/a
Boring/container connection pipe conditioning		
(gas line A)	2.2	2.2
Pressure (MPa) (gauge)	50	50
Temperature (°C)	n/a	n/a
Mass flow (kg/s)		
Test vessel conditioning (gas line F)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	50	50
Mass flow (kg/s)	n/a	n/a
Valve actuator conditioning		
Pressure (MPa) (gauge)	Atmospheric (air)	Atmospheric (air)
Temperature (°C)	20 to 50	20 to 50
Mass flow (kg/s)	n/a	n/a

3.3.2 RSS Plant Normal Operational Conditions

The SAS will be inserted and removed during different PBMR reactor conditions. The RSS test set-up, combined with the HTF Main loop, must simulate these conditions of the RSS in the PBMR reactor during normal plant conditions. The required conditions are shown in Table 17.

Table 17: RSS Normal Operational Conditions in Reactor

Description	Reactor Condition Applicable to Test
Insertion of spheres during cold plant conditions	Core temperature = 250-500 °C, Reactor pressure = 2.2 to 6.5 MPa Sphere temperature = 50 to 150 °C
Removal of spheres during plant start-up conditions	Core temperature = 250 to 500 °C, Reactor pressure = 2.2 to 6.5 MPa Sphere temperature = 50 to 150 °C
Removal of spheres after dosing during hot plant conditions (approximate 5 kg)	Core temperature = 900 °C, Reactor pressure = 9.0 MPa) Sphere temperature = 350 °C,
Insertion of spheres during hot plant conditions	Core temperature = 900 °C, Reactor pressure = 9.0 MPa) Sphere temperature = 350 °C,

The required conditions were given for the beginning of the test and at the end of each test. Where the values at the beginning and end of the test are the same, this indicates that the conditions in the vessel should be kept constant for the duration of the test.

The RSS Test Set-up modes to simulate insertion of spheres during cold plant conditions are shown in Table 18 [9].

Table 18: RSS Test Set-up Conditions to Simulate Insertion of SAS during Cold Start-up of the Reactor

Description	Beginning of Test	During Test
Sphere transport line requirements (gas line E)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	100	100
Mass flow (kg/s)	0	0
Core boring conditioning line (gas line C)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	250	250
Mass flow (kg/s)	0.02 to 0.05	0.05
Storage container condition (gas line D)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	60	60
Mass flow (kg/s)	0.05	0.05
Boring/container connection pipe conditioning (gas line A)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	60	60
Mass flow (kg/s)	0.05	0.05
Test vessel conditioning (gas line F)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	50	50
Mass flow (kg/s)	0.05	0.05
Valve actuator conditioning		
Pressure (MPa) (gauge)	Atmospheric (air)	Atmospheric (air)
Temperature (°C)	20 to 50	20 to 50
Mass flow (kg/s)	TBD	TBD

The RSS Test Set-up modes to simulate removal of spheres during plant start-up conditions are shown in Table 19 [9].

Table 19: RSS Test Set-up Conditions to Simulate Removal of Spheres during Plant Start-up

Description	Beginning of Test	During Test
Sphere transport line requirements (gas line E)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	100	100
Mass flow (kg/s)	0	0.1
Pressure drop (transport of spheres) (kPa)	n/a	37.9
Core boring conditioning line (gas line C)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	250	250
Mass flow (kg/s)	0.02 to 0.05	0.05
Storage container condition (gas line D)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	60	60
Mass flow (kg/s)	0.05	0.05
Boring/container connection pipe conditioning (gas line A)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	60	60
Mass flow (kg/s)	0.05	0.05
Test vessel conditioning (gas line F)		
Pressure (MPa) (gauge)	2.2	2.2
Temperature (°C)	50	50
Mass flow (kg/s)	0.05	0.05
Valve actuator conditioning		
Pressure (MPa) (gauge)	Atmospheric (air)	Atmospheric (air)
Temperature (°C)	20 to 50	20 to 50
Mass flow (kg/s)	TBD	TBD

The RSS Test Set-up modes to simulate removal of spheres after dosing during hot plant conditions are shown in Table 20 [9].

Table 20: RSS Test Set-up Conditions to Simulate Removal of Spheres after Dosing during Hot Plant Conditions

Description	Beginning of Test	During Test
Sphere transport line requirements (gas line E)		
Pressure (MPa) (gauge)	9.0	9.0
Temperature (°C)	100	100
Mass flow (kg/s)	0	0.3
Pressure drop (transport of spheres) (kPa)	n/a	70
Core boring conditioning line (gas line C)		
Pressure (MPa) (gauge)	9.0	9.0
Temperature (°C)	750	750
Mass flow (kg/s)	0.02 to 0.05	0.05
Storage container condition (gas line D)		
Pressure (MPa) (gauge)	9.0	9.0
Temperature (°C)	280	280
Mass flow (kg/s)	0.05	0.05
Boring/container connection pipe conditioning (gas line A)		
Pressure (MPa) (gauge)	9.0	9.0
Temperature (°C)	280	280
Mass flow (kg/s)	0.05	0.05
Test vessel conditioning (gas line F)		
Pressure (MPa) (gauge)	9.0	9.0
Temperature (°C)	50	50
Mass flow (kg/s)	0.05	0.05
Valve actuator conditioning		
Pressure (MPa) (gauge)	Atmospheric (air)	Atmospheric (air)
Temperature (°C)	60	60
Mass flow (kg/s)	TBD	TBD

The RSS Test Set-up modes to simulate insertion of spheres during hot plant conditions are shown in Table 21 [9].

Table 21: RSS Test Set-up Conditions to Simulate Insertion of Spheres during Hot Plant Conditions

Description	Beginning of Test	During Test
Sphere transport line requirements (gas line E)		
Pressure (MPa) (gauge)	9.0	9.0
Temperature (°C)	100	100
Mass flow (kg/s)	0	0
Core boring conditioning line (gas line C)		
Pressure (MPa) (gauge)	9.0	9.0
Temperature (°C)	750	750
Mass flow (kg/s)	0.02 to 0.05	0.05
Storage container condition (gas line D)		
Pressure (MPa) (gauge)	9.0	9.0
Temperature (°C)	280	280
Mass flow (kg/s)	0.05	0.05
Boring/container connection pipe conditioning (gas line A)		
Pressure (MPa) (gauge)	9.0	9.0
Temperature (°C)	280	280
Mass flow (kg/s)	0.05	0.05
Test vessel conditioning (gas line F)		
Pressure (MPa) (gauge)	9.0	9.0
Temperature (°C)	50	50
Mass flow (kg/s)	0.05	0.05
Valve actuator conditioning		
Pressure (MPa) (gauge)	Atmospheric (air)	Atmospheric (air)
Temperature (°C)	60	60
Mass flow (kg/s)	TBD	TBD

The test conditions given in tables 18 to 21 defined the operating range that must be achieved by the RSS test set-up. Where conditions were specified as the same at the beginning and end of a test, those conditions should be kept constant throughout the test.

3.4 TEST DESCRIPTIONS

3.4.1 RSS Test Preparation

Before tests can be performed in the RSS test set-up, the RSS test set-up and the HTF main loop must be prepared for the tests. This means that the HTF main loop and the RSS test set-up must be set to similar conditions so that they can be connected.

The RSS test preparation is divided into 4 main steps:

- Filling of the RSS test set-up with Helium.
- Purification of the RSS test set-up Helium to the correct purity, and conditioning of the RSS test set-up to be ready for connection to the HTF main loop and conditioning of the HTF main loop to be ready for connection to the RSS test set-up.
- Connection of the RSS test set-up to the HTF main loop and setting the RSS test set-up to the required mode for a test or a test combination.
- Conditioning of the RSS test set-up to the required test mode

For the simulation process followed, it was assumed that the test set-up was already filled with Helium, connected to the main loop, and that steady state conditions had been achieved in each of the conditioning vessels in the test set-up.

3.4.2 RSS Tests to be Simulated

The tests that will be performed in the RSS test set-up are given in Table 22. These tests had to be simulated with the Flownex model to determine the thermo-hydraulic requirements of the test set-up.

Table 22: Reserve Shutdown System Tests

Test Identification Number	Test Description
Tests to simulate RSS commissioning conditions in the reactor	
RSS-A1	To validate the insertion of SAS during the commissioning of the RSS in the reactor.
RSS-A2	To validate the removal of SAS during the commissioning of the RSS in the reactor.
Tests to simulate RSS normal operational conditions in the reactor	
RSS-B1	To validate the insertion of SAS during cold plant start-up conditions.
RSS-B2	To validate the insertion of SAS during hot plant start-up conditions.
RSS-B3	To validate the removal of SAS during cold plant start-up conditions.
RSS-B4	To validate the removal of SAS during hot plant start-up conditions.
RSS-B5	To validate the insertion and removal SAS after testing of a valve actuator (dosing and removal of approximate 5 kg spheres).
RSS-B6	To validate the insertion of SAS during plant full power conditions.
Tests to simulate RSS abnormal operational conditions in the reactor	
RSS-C1	To validate the removal of SAS after an accidental insertion of SAS into the boring of the reactor.
RSS-C2	To determine if SAS can be removed with a storage container valve that leaks.
RSS-C3	To prove that the valve actuator will open and close during maximum plant conditions (temperature and pressure).
RSS-C4	To prove that the electrical penetration assemblies will not leak during maximum plant conditions (temperature and pressure).
RSS-C5	To validate that electrical components inside the reactor pressure boundary will survive and perform their functions during maximum plant conditions (temperature and pressure).
Tests to simulate RSS component qualification during normal operational conditions	
RSS-D1	To prove that the valve actuator will open and close under normal plant conditions (temperature and pressure).
RSS-D2	To prove that the sphere and gas isolation valves will open and close during normal plant conditions (temperature and pressure).
RSS-D3	To validate that the electrical penetration assemblies will not leak during normal plant conditions (temperature and pressure).
RSS-D4	To validate that the electrical components inside the reactor pressure boundary will survive and perform their functions during all plant operational conditions.

Test Identification Number	Test Description
RSS-D5	To qualify the welding (full penetration) of the sphere return pipe. The aim is to develop a pipe with minimum weld penetration inside the pipe. This is required to prevent damage to SAS during transport.
RSS-D6	To qualify the SAS.

The requirements for the steady state thermo-hydraulic modelling of each of these defined tests are given in the Appendices in Table 28.

4. INTERPRETATION OF RESULTS

4.1 PREAMBLE

This chapter describes the interpretation of the simulation results obtained. The process that was followed for the analysis as well as the experimental modes, will be described.

A number of assumptions were made during the analysis. These assumptions are given and motivated to verify that valid results were obtained. The convergence criteria and relaxation parameters that were selected are given and verified to be acceptable.

The detailed results that were obtained are also given and discussed in this chapter.

4.2 DETAILED ANALYSIS

The method of simulation, as described in the previous chapters, was chosen to perform the steady state analysis on the RSS test set-up.

4.2.1 Analysis Process

The Helium Test Facility (HTF) consists of components that supply Helium at a required flow rate, pressure and temperature to various subsystems. These subsystems are connected to the HTF main open loop, forming a closed loop system, and are representations of systems to be used in the PBMR plant.

The following results were expected:

- Mass and energy balance for tests defined.
- Required pressure differentials.
- Required duty of heater H5.
- Heat loss in test set-up.

The simulations required for this analysis were given in [43]. Each simulation, as listed in [43], represented a test condition in the HTF, with the required mass flow rate, temperature and system pressure in the test set-up.

Flownex was used as the simulation software for the analysis. The simulation model built for the analysis was described in the previous chapter, and is shown in Figure 10. During the analysis, a number of changes were made to the initial model in order to obtain feasible results. These changes will also be incorporated into the design of the RSS test set-up to ensure that the physical test set-up functions as required.

The changes required in the test set-up were as follows:

- The 4" Y-pattern globe valve (hand valve, element number 1361) in line RS-B011 (return line to Manifold B) was changed to a 3" ball valve. This was done because the Y-pattern valve cause a high-pressure loss.
- Valve AA203 (element number 1445) was added to line E before the fluidizing bed (node 1404).
- Valve AA511 (element number 1443) was added to the outlet of the SAS transport line (Line E), after the feeder bin (node 1411).
- The following valves were changed from 2" to 1": AA503 (element number 1320), AA504 (element number 1308), AA505 (element number 1326) and AA001 (element number 1313) to achieve the required pressure drops for control purposes.

The pressure drop in the SAS transport line, caused by the flow of the SAS, was obtained from [44] for each condition of transport. The pressure drops in the SAS transport line were calculated with the use of the MathCAD model in [44]. The transport conditions in the SAS transport line (RS-E004a) are given in Table 25, and were used as inputs to the model in [44] to determine the pressure drop in line RS-E004a. Line RS-E004a was used to transport the SAS spheres from the fluidizing bed to the feeder bin. The specified pressure drop in the line was achieved in the simulations by optimizing for a secondary loss factor (k-value).

The valve in line RS-E004 was a full bore ball valve and would only be used to isolate the transport line and not for control. In the full open position (during SAS transport), the valve was considered to have no resistance to the flow, and would therefore not contribute to the pressure drop.

For each simulation, the pressure at Manifold B was fixed and the mass flows and temperatures were specified at the inlet manifolds. The pressure drop required in each line of the test set-up was obtained from [45]. These required pressure drops in each line were achieved by adjusting the valves in each line to give the required inlet pressure at the inlet manifolds.

4.2.2 Experimental Modes Analysed

Each experimental mode represented the conditions for a specific test, or group of tests requiring similar conditions. The temperature at manifold B was calculated assuming no heat loss, and used with the temperature considering heat loss to determine the total heat loss to atmosphere for each line. For all of the experimental modes, the valve in line RS-F005 was considered fully closed, as no cooling flow was required to mixing box 5.

The following modes were analysed:

- Mode RSS-M3(a) simulated the conditions for tests RSS-A1 and RSS-A2 in Table 22.
- Mode RSS-M(b) simulated the conditions for tests RSS-B1, RSS-B3 and RSS-C2 in Table 22.
- Mode RSS-M(c) simulated the conditions for tests RSS-B2 and RSS-B4.
- Mode RSS-M(d) simulated the conditions for tests RSS-B5, RSS-B6, RSS-C1, RSS-D1, RSS-D2, RSS-D3, RSS-D4, RSS-D5 and RSS-D6. For this experiment, the required temperature for the flow in Line A in the test set-up could not be

achieved from Line A in the Main Facility. The combined flows for Line A and D were supplied to the test set-up via Line D. The required flow was then diverted to Line A in the test set-up by means of Valve AA509. For this experiment, Valve AA509 was used and Valve AA503 was fully closed.

The maximum Helium temperature from the main facility was at 580 °C For this test, the maximum Helium temperature in the boring was required to be 750 °C. Heater H5 was used to heat up the Helium to the required temperature. The required duty of heater H5 to allow a maximum Helium temperature of 750 °C in the boring was determined as 47 kW.

Mode RSS-M(e) simulated the conditions for tests RSS-C3, RSS-C4 and RSS-C5. The maximum Helium temperature from the main facility was at 580°C For this test the maximum Helium temperature in the boring was required to be 750°C. Heater H5 was used to heat up the Helium to the required temperature. The required duty of Heater H5 to allow a maximum Helium temperature of 750°C in the boring was determined as 47kW.

Mode RSS-M(e) Combo was the same test as in Mode RSS-M(e), but was performed in parallel with two of the tests in the Reactivity Control System, experiments RCS-M3 (a) and (b).

4.2.3 Assumptions Made for Analysis

For simplification of the simulation model and where details of the test set-up had not yet been finalized, some assumptions were made for this analysis. The results of this study will also be used to verify these assumptions and to identify further work required.

Line F005 supplied cooling flow to mixing box 5. This was to ensure that the Helium temperature in return line B did not exceed 480 °C. From the analysis it was found that in none of the identified experimental modes did the temperature in line B exceed 450 °C. It was therefore assumed that the valve in line F005 was fully closed in all of the experimental modes.

From the analysis, the approximated duty of heater 5 was determined. The required duty was determined to achieve a maximum Helium temperature of 750 °C in the boring. This maximum gas temperature was assumed at the inlet of the boring. No heat loss was assumed in the heater, and an efficiency of 100% was assumed for the heater. This assumption was acceptable for obtaining first order process data that would be used in the detail design of the heater.

The characteristics for the valve in the SAS transport line, line RS-004, have not yet been determined. As this valve should be able to allow the SAS to flow through without restriction, it was assumed that this valve was a full bore ball valve with negligible resistance to flow.

4.2.4 Flownex Convergence Criterion and Relaxation Parameters

The convergence and relaxation parameters, listed in Table 23 were used in the RSS Flownex Model for this analysis.

Table 23: Convergence Criteria

Parameter	Value
Number iterations main	500
Number iterations	200
Number iterations Temp.1	10
Number iterations Temp. 2	3
Convergence Criteria	1e-6
Relax Pressure	0.7
Relax Density	-
Relax Mass	0.7
Relax OR	1
Relax. Negative Pressure Coefficient	1
Relax CAU	1
Relax Optimizer	0.9
Relax Junction	0.9
Relax Temp. solver	0.985

The convergence criteria used should be sufficient to ensure accurate results. The choice of convergence criteria was evaluated in a steady state analysis and the results are shown in Table 24. It can be seen that the convergence requirement of 1e-5 was sufficient.

Table 24: Convergence Criteria Comparison

Parameter	Convergence Criteria: 1e-6	Convergence Criteria: 1e-5 (Default Value)	Difference [%]
Manifold B temperature	365.6376	365.6376	0
Manifold B pressure	8 899.9449	8 899.9448	0

4.3 DETAILED RESULTS

The mass flow rates and temperatures in each line are given in Table 25. These were the specified test conditions. The results for the pressure drop over each line are also given in Table 25. The assumed pressures for Manifold B and calculated pressures of the inlet manifolds are given in Table 26.

Table 25: Inlet Conditions and dP for Each Line

Experimental Mode	*P (Mpa)	Line A			Line C				Line D			Line E			Line F		
		m	T	dP	m	T	dP	Q	m	T	dP	M	T	dP	m	T	dP
		(kg/s)	(°C)	(kPa)	(kg/s)	(°C)	(kPa)	(kW)	(kg/s)	(°C)	(kPa)	(kg/s)	(°C)	(kPa)	(kg/s)	(°C)	(kPa)
RSS-M3(a)	2.2	0	50	4	0	50	2	0	0	50	4	0.15	50	61	0	50	4
RSS-M3(b)	2.2	0.05	60	77	0.05	250	77	0	0.05	60	77	0.15	100	76	0.05	50	114
RSS-M3(c)	6.5	0.05	100	82	0.05	500	82	0	0.05	100	82	0.3	100	83	0.05	50	124
RSS-M3(d)	9	0.05	280	90	0.05	580	92	47	0.05	280	90	0.4	100	90	0.05	50	136
RSS-M3(e)	9	0	280	2	0.05	580	41	47	0.1	350	42	0	100	2	0.05	50	68
RSS-M3(e) Combo	9	0	280	2	0.05	580	35	47	0.1	350	25	0	100	2	0.05	50	76

*Refers to the system pressure in the Main Facility.

Table 26: Manifold Pressures

Experimental Mode	**Line A**	**Line C**	**Line D**	**Line E**	**Line F**	**Line B**
	Manifold Pressure (kPa)					
RSS-M3(a)	2 154	2 152	2 154	2 211	2 154	2 150
RSS-M3(b)	2 227	2 227	2 227	2 226	2 264	2 150
RSS-M3(c)	6 482	6 482	6 482	6 483	6 524	6 400
RSS-M3(d)	8 990	8 992	8 990	8 990	9 036	8 900
RSS-M3(e)	8 902	8 941	8 942	8 902	8 968	8 900
RSS-M3(e)Combo	8 902	8 935	8 925	8 902	8 976	8 900

The pressure was fixed at the outlet of line B and the pressures at the inlet of each line were calculated in the simulations. These are the pressures displayed in Table 26.

4.3.1 Valve Specifications

Valves that could provide sufficient control over the full operating range needed to be selected in order to be able to control the conditions in the test set-up sufficiently. For a control valve to be able to control flow sufficiently, a minimum of 30% of the total pressure drop in that particular line was required to occur over the valve.

As part of the valve selection process, it was required to determine the specifications of each valve. This included the operating pressure, temperature, mass flow and pressure differential for the complete operating range of the valve. From this data, a Cv value was calculated which will be used to select the valve from the supplier. The process data for each valve was determined for all the experimental modes, and from this, a range of Cv values was calculated. These results and calculated Cv values are given in Appendix A.1. The maximum and minimum Cv values for each valve specified the Cv range for the valve and gave sufficient information for the selection of the valves from suppliers.

4.3.2 Instrumentation Specifications

Accurate instrumentation was required to be able to monitor conditions in the test set-up. Only instrumentation that has an effect on the system pressure drop (flow measuring) was evaluated in this analysis. The flow transmitters that will be used for flow measurement were modelled as flow orifices.

The data required to select the flow orifices were operating pressure, temperature, mass flow and gas density. The results for each flow orifice are given in the Appendices. This data gave sufficient information to the Control and Instrumentation team to select the required equipment for flow measurement in the test set-up.

4.3.3 Heater Specifications

The heater in line C was required to heat up the Helium supplied from the Main Facility from approximately 570 °C to 750 °C. From the analysis, the process data was determined for the heater at all operating points. The heater manufacturers required this process data for the design of the heater. The data that was obtained included pressure, flow and inlet and outlet temperature. From this data the required conductivity would be determined.

These results will be used by the heater manufacturer for the detail design of the heater and are included in Table 41 in the Appendices.

4.3.4 Heat Loss to Atmosphere

To determine the heat loss for each experimental mode, the outlet temperature (temperature at Manifold B) was calculated from conservation of mass and energy. T_calc was the calculated temperature at Manifold B from conservation of energy, assuming no heat loss to atmosphere. T_act was the temperature at Manifold B obtained from the simulation model with heat loss to atmosphere included. The difference between this calculated temperature and the outlet temperature obtained from the simulations was used to determine the heat loss over the test set-up. The calculations are as follows:

T_calc was calculated by:

$$T\_calc = (m_A T_A + m_C T_C + m_D T_D + m_E T_E + m_F T_F + Q_{H5}/C_P) / m_B$$

Total Heat loss (Q) was calculated by:

$$Q = m_B C_p(T_{calc} - T_{act})$$

With

$C_p = 5.195$ kJ/kg.K for Helium

These results are given in Table 27.

Table 27: Total heat loss to atmosphere in the test set-up

Experimental Mode	Press (Mpa)	Line B			Total Q_loss
		m	T_act	T_calc	Q
		kg/s	°C	°C	kW
RSS-M3(a)	2.2	0.15	48.89	50.00	0.86
RSS-M3(b)	2.2	0.35	98.91	102.86	7.18
RSS-M3(c)	6.5	0.50	131.48	135.00	9.14
RSS-M3(d)	9.0	0.60	176.86	180.91	12.63
RSS-M3(e)	9.0	0.20	365.64	377.74	12.57
RSS-M3(e)Combo	9.0	0.20	365.64	377.74	12.57

The available heat input of the system was sufficient to overcome this heat loss to atmosphere for the current layout.

4.3.5 Verification and Validation of Results

The process developed to perform the thermo-hydraulic analysis in this study was based on the Flownex Nuclear software. Verification forms part of the overall Flownex Nuclear development process, and includes the verification activities that form part of the software engineering process, as well as all related verification that was done as part of the derivation of the theory for component models or model enhancements. Validation of Flownex Nuclear was performed by comparing the results of the implemented theoretical models in Flownex Nuclear with benchmark data obtained using appropriate methods [27].

The V&V of Flownex was managed by PBMR and data obtained was accessible to M-Tech for V&V activities. As this verification has been done, the results of this study can be considered to be accurate and reliable.

5. CONCLUSION AND RECOMMENDATIONS

The objective of this study was to identify a suitable method, and then to develop a process, for conducting a thermo-hydraulic analysis on a proposed test facility before the actual facility was designed and built. The method of simulation was chosen to perform the thermo-hydraulic analysis on the proposed test facility. A thermal fluid network was set up with the use of Flownex Nuclear, a thermal fluid software package developed by M-Tech Industrial. M-Tech Industrial is a company that works in collaboration with the Faculty of Engineering at Potchefstroom University for Christian Higher Education (now North-West University).

The thermal-fluid network was set up according to the specifications and proposed layout of the test facility by making use of the developed process. All the conditions for the proposed tests that have to be performed in the test facility were identified and used to set up the experimental modes. The different experimental modes were simulated and the process data was captured for each of the components in the test facility.

The process data for the components defined the operating range for each component and will be used to select the components from suppliers. This process data will also be used for the design of components whose operating ranges are not satisfied by off-the-shelf parts.

With the method chosen and process developed for the thermo-hydraulic analysis of the RSS test facility, it was possible to obtain the process data for the components and to predict the functioning and performance of the test set-up that has to be designed and built.

This process for setting up a simulation model can be used widely in the industry for the design and performance prediction of large industrial plants and testing facilities. It can also be used in the design process of plants to optimize the layout and performance of the plants and processes. The software used for this thermo-hydraulic analysis has been properly verified and validated to be reliable for such analysis, and the results can be considered to be accurate.

With this process developed to set up a simulation model for conducting a thermo-hydraulic analysis of the RSS test facility, it was possible to obtain the process data for the components and to predict the functioning and performance of the proposed test set-up.

A schematic layout of the process developed for the thermo-hydraulic analysis of a thermal-fluid system is given in Figure 11. From this diagram it can be seen that a structured process was obtained, which can be followed to conduct a thermo-hydraulic analysis on any thermal-fluid system.

The objective of this study to identify a suitable method and develop a process to carry out a thermo-hydraulic analysis on a test facility before the actual facility was built, has therefore been accomplished.

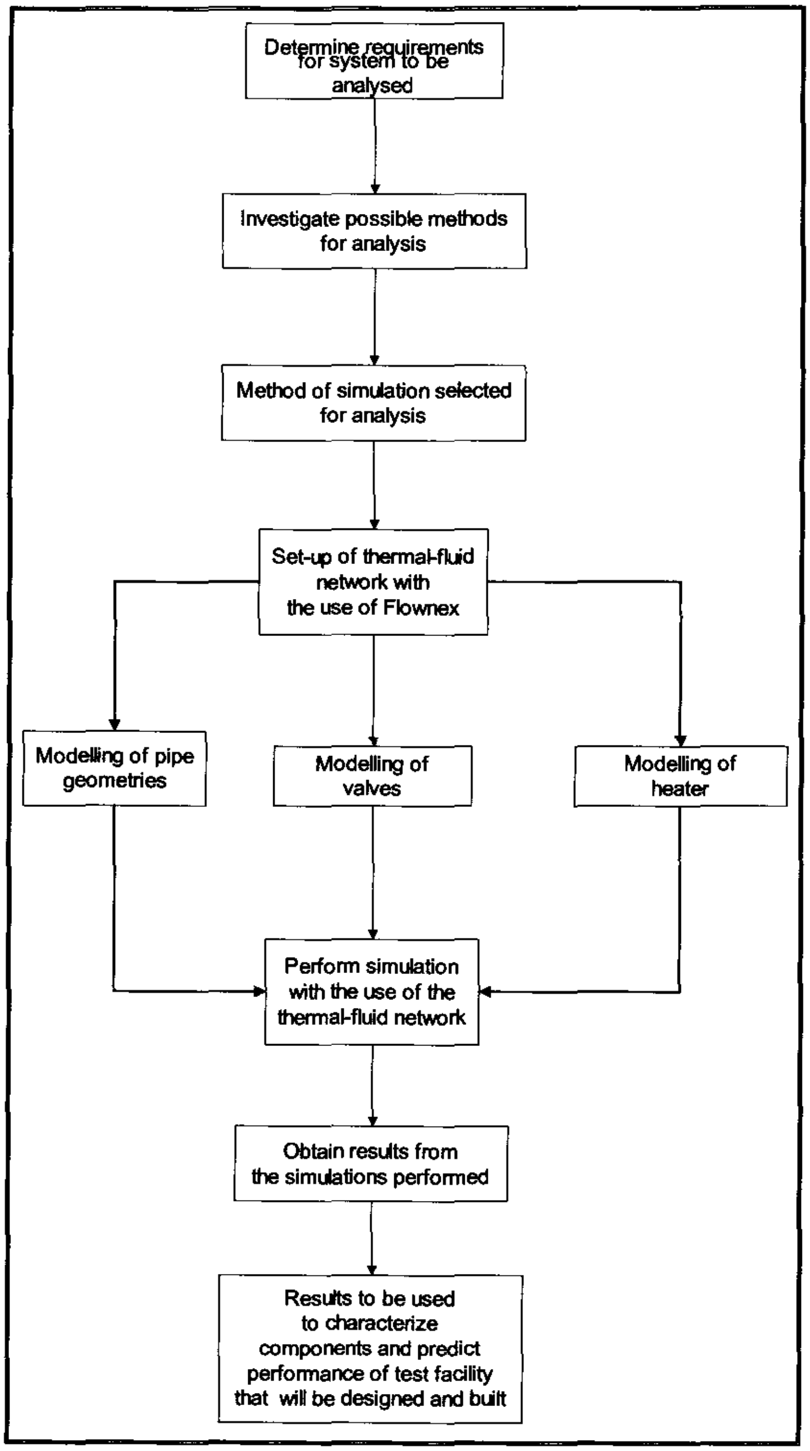


Figure 11: Process for the Thermo-hydraulic Analysis of a Thermal-fluid System

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A. APPENDICES

A.1 SUPPLIER INFORMATION FOR VALVES

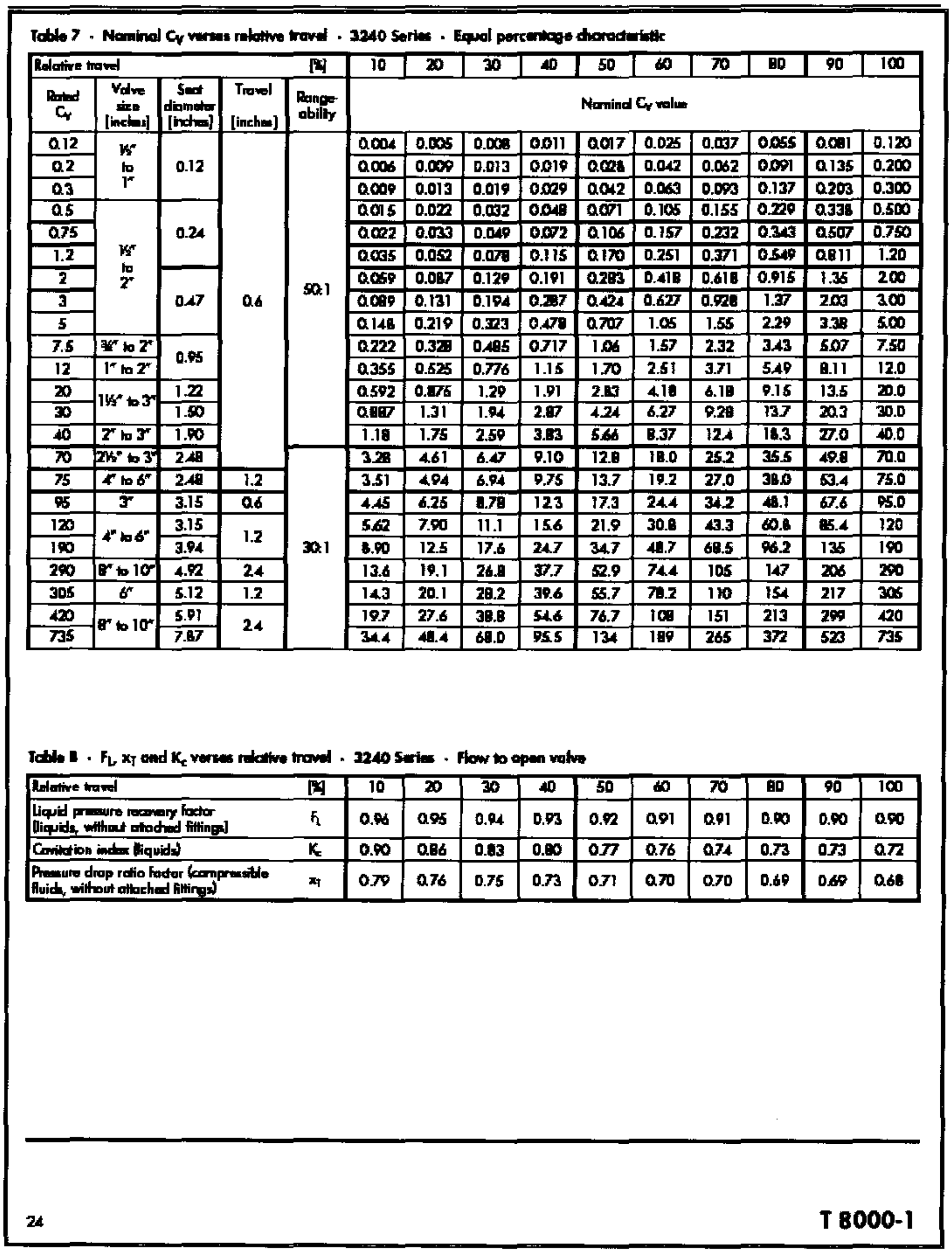

Table 7 · Nominal C_V verses relative travel · 3240 Series · Equal percentage characteristic

Relative travel				[%]	10	20	30	40	50	60	70	80	90	100
Rated C_V	Valve size [inches]	Seat diameter [inches]	Travel [inches]	Rangeability	Nominal C_V value									
0.12	½" to 1"	0.12	0.6	50:1	0.004	0.005	0.008	0.011	0.017	0.025	0.037	0.055	0.081	0.120
0.2					0.006	0.009	0.013	0.019	0.028	0.042	0.062	0.091	0.135	0.200
0.3					0.009	0.013	0.019	0.029	0.042	0.063	0.093	0.137	0.203	0.300
0.5	½" to 2"	0.24			0.015	0.022	0.032	0.048	0.071	0.105	0.155	0.229	0.338	0.500
0.75					0.022	0.033	0.049	0.072	0.106	0.157	0.232	0.343	0.507	0.750
1.2					0.035	0.052	0.078	0.115	0.170	0.251	0.371	0.549	0.811	1.20
2		0.47			0.059	0.087	0.129	0.191	0.283	0.418	0.618	0.915	1.35	2.00
3					0.089	0.131	0.194	0.287	0.424	0.627	0.928	1.37	2.03	3.00
5					0.148	0.219	0.323	0.478	0.707	1.05	1.55	2.29	3.38	5.00
7.5	¾" to 2"	0.95			0.222	0.328	0.485	0.717	1.06	1.57	2.32	3.43	5.07	7.50
12	1" to 2"				0.355	0.525	0.776	1.15	1.70	2.51	3.71	5.49	8.11	12.0
20	1½" to 3"	1.22			0.592	0.876	1.29	1.91	2.83	4.18	6.18	9.16	13.5	20.0
30		1.50			0.887	1.31	1.94	2.87	4.24	6.27	9.28	13.7	20.3	30.0
40	2" to 3"	1.90			1.18	1.75	2.59	3.83	5.66	8.37	12.4	18.3	27.0	40.0
70	2½" to 3"	2.48		30:1	3.28	4.61	6.47	9.10	12.8	18.0	25.2	35.5	49.8	70.0
75	4" to 6"	2.48	1.2		3.51	4.94	6.94	9.75	13.7	19.2	27.0	38.0	53.4	75.0
95	3"	3.15	0.6		4.45	6.25	8.78	12.3	17.3	24.4	34.2	48.1	67.6	95.0
120	4" to 6"	3.15	1.2		5.62	7.90	11.1	15.6	21.9	30.8	43.3	60.8	85.4	120
190		3.94			8.90	12.5	17.6	24.7	34.7	48.7	68.5	96.2	135	190
290	8" to 10"	4.92	2.4		13.6	19.1	26.8	37.7	52.9	74.4	105	147	206	290
305	6"	5.12	1.2		14.3	20.1	28.2	39.6	55.7	78.2	110	154	217	305
420	8" to 10"	5.91	2.4		19.7	27.6	38.8	54.6	76.7	108	151	213	299	420
735		7.87			34.4	48.4	68.0	95.5	134	189	265	372	523	735

Table 8 · F_L, x_T and K_c verses relative travel · 3240 Series · Flow to open valve

Relative travel	[%]	10	20	30	40	50	60	70	80	90	100
Liquid pressure recovery factor (liquids, without attached fittings)	F_L	0.96	0.95	0.94	0.93	0.92	0.91	0.91	0.90	0.90	0.90
Cavitation index (liquids)	K_c	0.90	0.86	0.83	0.80	0.77	0.76	0.74	0.73	0.73	0.72
Pressure drop ratio factor (compressible fluids, without attached fittings)	x_T	0.79	0.76	0.75	0.73	0.71	0.70	0.70	0.69	0.69	0.68

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T 8000-1

Figure 12: Samson Brochure used as Guideline

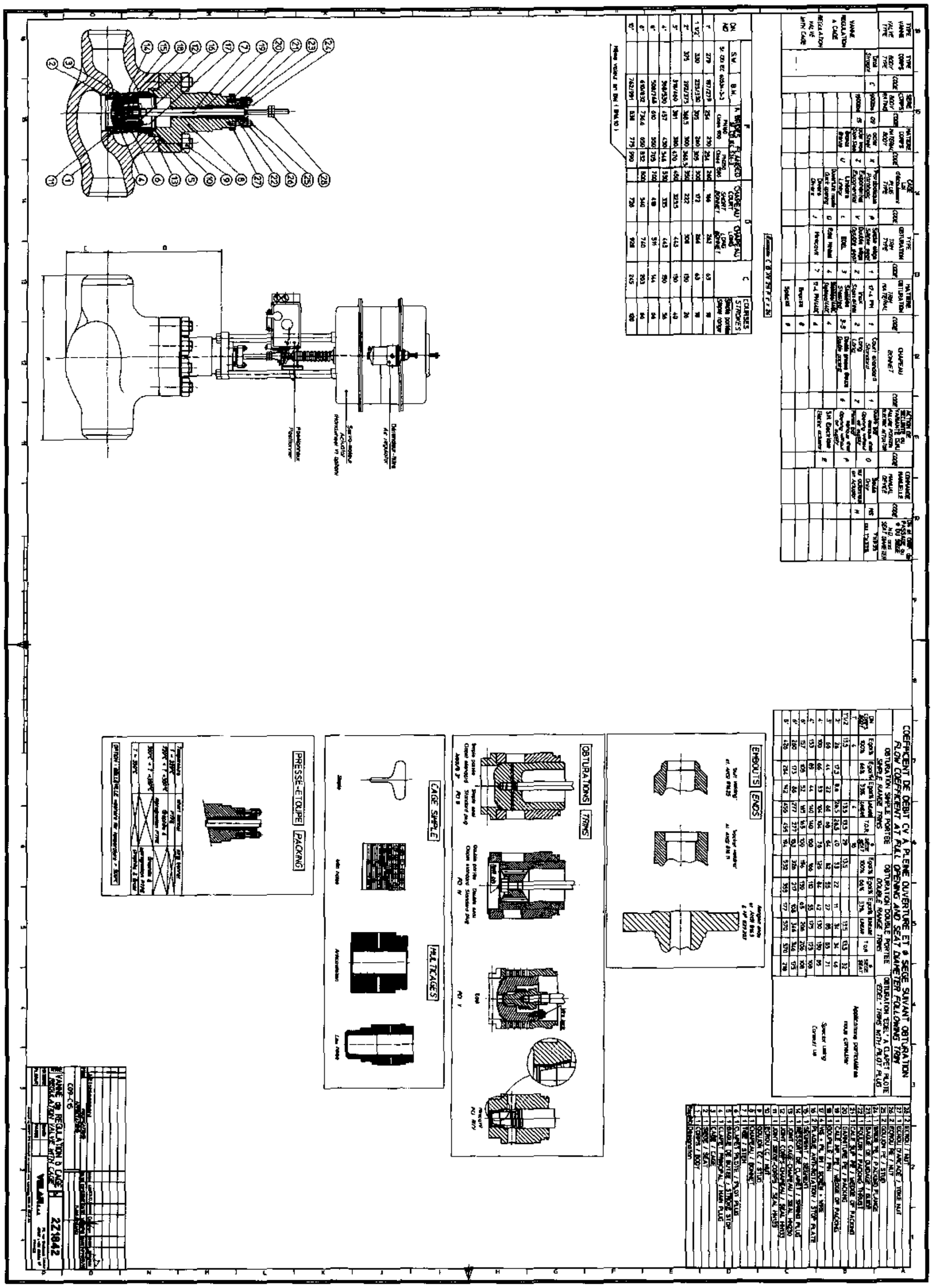
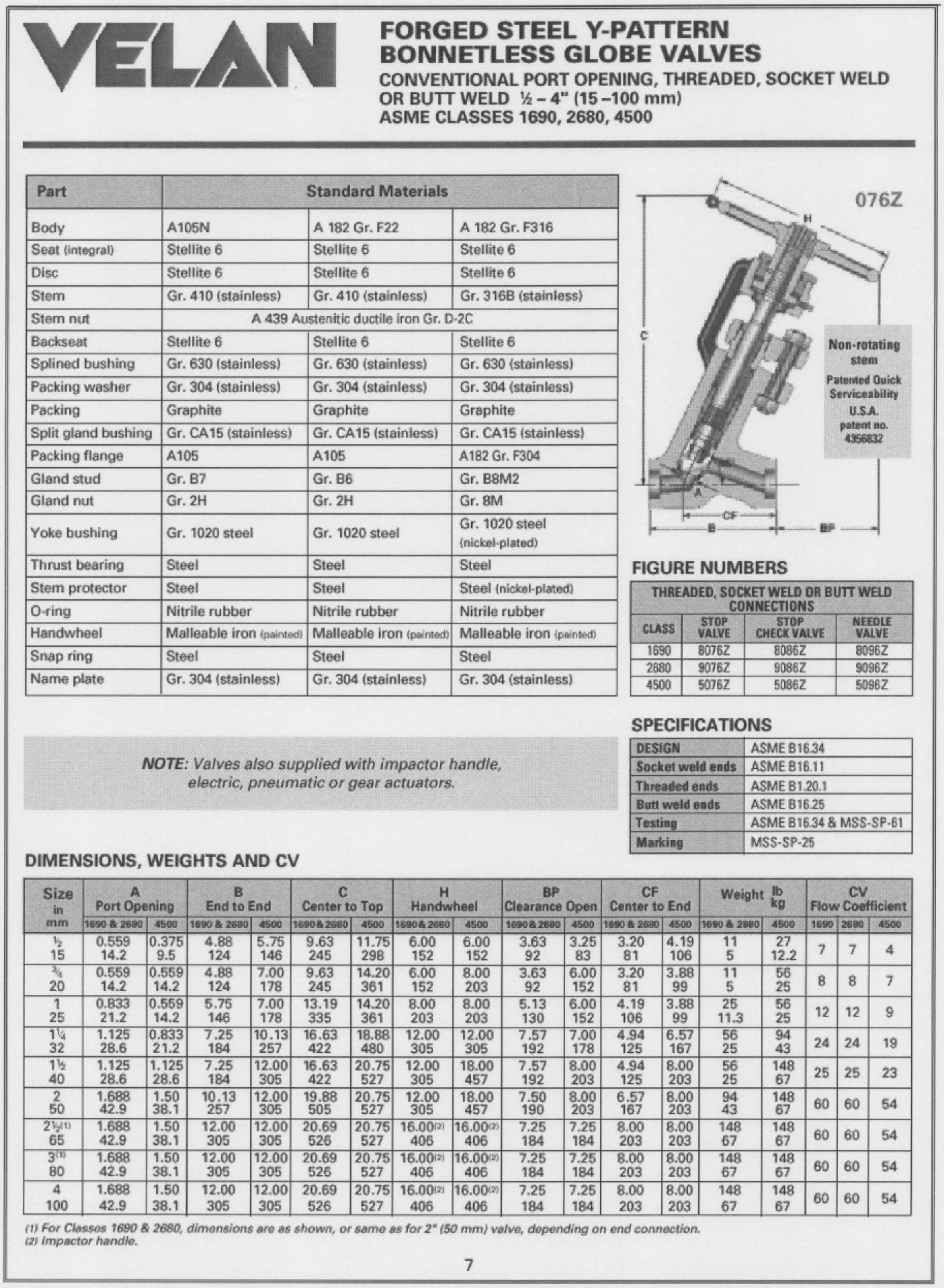


Figure 13: Globe Valves Supplier Information



VELAN

FORGED STEEL Y-PATTERN BONNETLESS GLOBE VALVES

CONVENTIONAL PORT OPENING, THREADED, SOCKET WELD OR BUTT WELD ½ – 4" (15 –100 mm)
ASME CLASSES 1690, 2680, 4500

Part	Standard Materials		
Body	A105N	A 182 Gr. F22	A 182 Gr. F316
Seat (integral)	Stellite 6	Stellite 6	Stellite 6
Disc	Stellite 6	Stellite 6	Stellite 6
Stem	Gr. 410 (stainless)	Gr. 410 (stainless)	Gr. 316B (stainless)
Stem nut	A 439 Austenitic ductile iron Gr. D-2C		
Backseat	Stellite 6	Stellite 6	Stellite 6
Splined bushing	Gr. 630 (stainless)	Gr. 630 (stainless)	Gr. 630 (stainless)
Packing washer	Gr. 304 (stainless)	Gr. 304 (stainless)	Gr. 304 (stainless)
Packing	Graphite	Graphite	Graphite
Split gland bushing	Gr. CA15 (stainless)	Gr. CA15 (stainless)	Gr. CA15 (stainless)
Packing flange	A105	A105	A182 Gr. F304
Gland stud	Gr. B7	Gr. B6	Gr. B8M2
Gland nut	Gr. 2H	Gr. 2H	Gr. 8M
Yoke bushing	Gr. 1020 steel	Gr. 1020 steel	Gr. 1020 steel (nickel-plated)
Thrust bearing	Steel	Steel	Steel
Stem protector	Steel	Steel	Steel (nickel-plated)
O-ring	Nitrile rubber	Nitrile rubber	Nitrile rubber
Handwheel	Malleable iron (painted)	Malleable iron (painted)	Malleable iron (painted)
Snap ring	Steel	Steel	Steel
Name plate	Gr. 304 (stainless)	Gr. 304 (stainless)	Gr. 304 (stainless)

Non-rotating stem
Patented Quick Serviceability
U.S.A. patent no. 4356832

FIGURE NUMBERS

THREADED, SOCKET WELD OR BUTT WELD CONNECTIONS			
CLASS	STOP VALVE	STOP CHECK VALVE	NEEDLE VALVE
1690	8076Z	8086Z	8096Z
2680	9076Z	9086Z	9096Z
4500	5076Z	5086Z	5096Z

SPECIFICATIONS

DESIGN	ASME B16.34
Socket weld ends	ASME B16.11
Threaded ends	ASME B1.20.1
Butt weld ends	ASME B16.25
Testing	ASME B16.34 & MSS-SP-61
Marking	MSS-SP-25

***NOTE:** Valves also supplied with impactor handle, electric, pneumatic or gear actuators.*

DIMENSIONS, WEIGHTS AND CV

Size in mm	A Port Opening		B End to End		C Center to Top		H Handwheel		BP Clearance Open		CF Center to End		Weight lb kg		CV Flow Coefficient		
	1690 & 2680	4500	1690 & 2680	4500	1690 & 2680	4500	1690 & 2680	4500	1690 & 2680	4500	1690 & 2680	4500	1690 & 2680	4500	1690	2680	4500
½ 15	0.559 14.2	0.375 9.5	4.88 124	5.75 146	9.63 245	11.75 298	6.00 152	6.00 152	3.63 92	3.25 83	3.20 81	4.19 106	11 5	27 12.2	7	7	4
¾ 20	0.559 14.2	0.559 14.2	4.88 124	7.00 178	9.63 245	14.20 361	6.00 152	8.00 203	3.63 92	6.00 152	3.20 81	3.88 99	11 5	56 25	8	8	7
1 25	0.833 21.2	0.559 14.2	5.75 146	7.00 178	13.19 335	14.20 361	8.00 203	8.00 203	5.13 130	6.00 152	4.19 106	3.88 99	25 11.3	56 25	12	12	9
1¼ 32	1.125 28.6	0.833 21.2	7.25 184	10.13 257	16.63 422	18.88 480	12.00 305	12.00 305	7.57 192	7.00 178	4.94 125	6.57 167	56 25	94 43	24	24	19
1½ 40	1.125 28.6	1.125 28.6	7.25 184	12.00 305	16.63 422	20.75 527	12.00 305	18.00 457	7.57 192	8.00 203	4.94 125	8.00 203	56 25	148 67	25	25	23
2 50	1.688 42.9	1.50 38.1	10.13 257	12.00 305	19.88 505	20.75 527	12.00 305	18.00 457	7.50 190	8.00 203	6.57 167	8.00 203	94 43	148 67	60	60	54
2½(1) 65	1.688 42.9	1.50 38.1	12.00 305	12.00 305	20.69 526	20.75 527	16.00(2) 406	16.00(2) 406	7.25 184	7.25 184	8.00 203	8.00 203	148 67	148 67	60	60	54
3(1) 80	1.688 42.9	1.50 38.1	12.00 305	12.00 305	20.69 526	20.75 527	16.00(2) 406	16.00(2) 406	7.25 184	7.25 184	8.00 203	8.00 203	148 67	148 67	60	60	54
4 100	1.688 42.9	1.50 38.1	12.00 305	12.00 305	20.69 526	20.75 527	16.00(2) 406	16.00(2) 406	7.25 184	7.25 184	8.00 203	8.00 203	148 67	148 67	60	60	54

(1) For Classes 1690 & 2680, dimensions are as shown, or same as for 2" (50 mm) valve, depending on end connection.
(2) Impactor handle.

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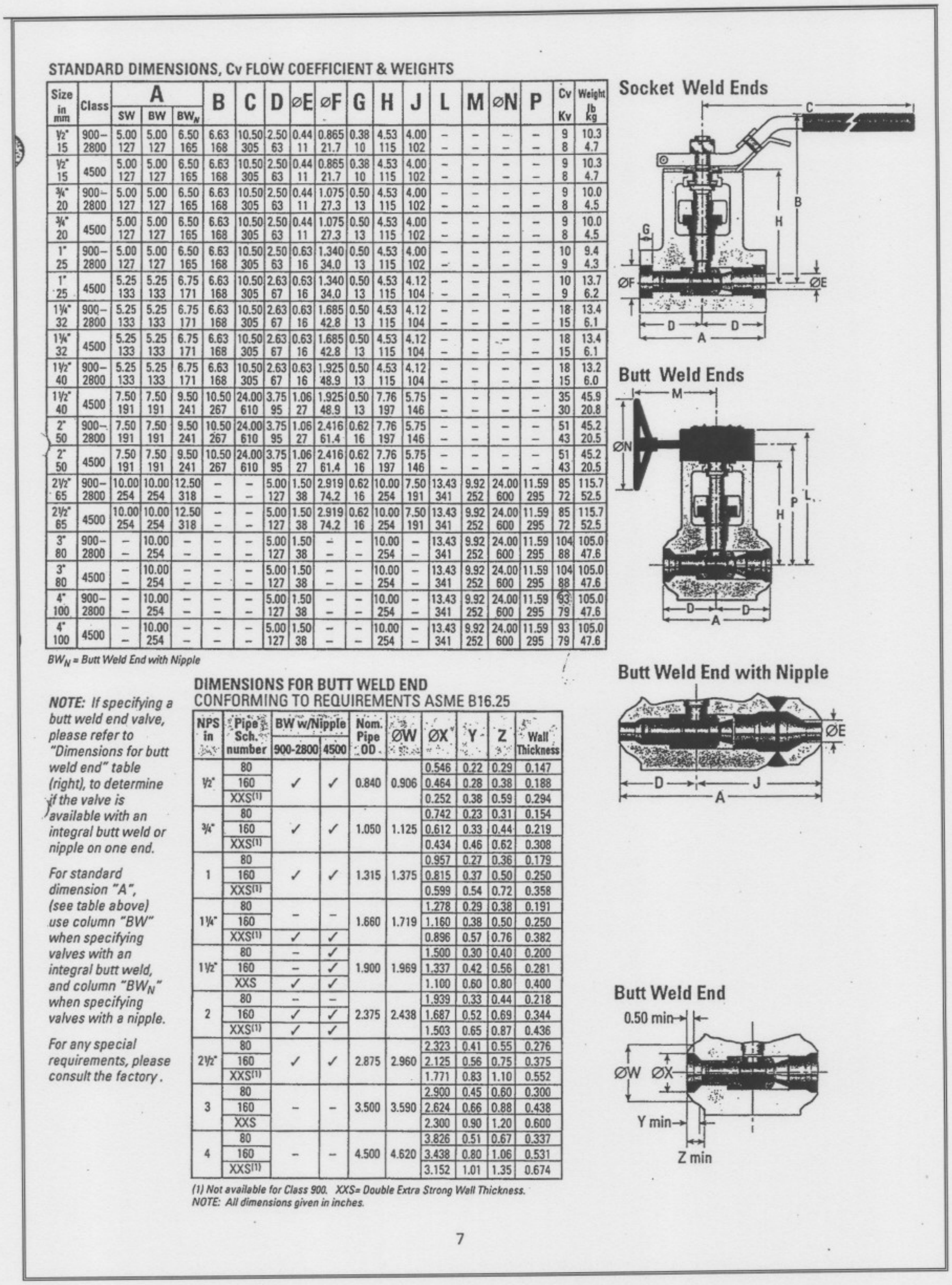
Figure 14: Y-pattern Globe Valves Supplier Information



STANDARD DIMENSIONS, Cv FLOW COEFFICIENT & WEIGHTS

Size in mm	Class	A			B	C	D	ØE	ØF	G	H	J	L	M	ØN	P	Cv Kv	Weight lb kg
		SW	BW	BW$_N$														
½" 15	900– 2800	5.00 127	5.00 127	6.50 165	6.63 168	10.50 305	2.50 63	0.44 11	0.865 21.7	0.38 10	4.53 115	4.00 102	– –	– –	– –	– –	9 8	10.3 4.7
½" 15	4500	5.00 127	5.00 127	6.50 165	6.63 168	10.50 305	2.50 63	0.44 11	0.865 21.7	0.38 10	4.53 115	4.00 102	– –	– –	– –	– –	9 8	10.3 4.7
¾" 20	900– 2800	5.00 127	5.00 127	6.50 165	6.63 168	10.50 305	2.50 63	0.44 11	1.075 27.3	0.50 13	4.53 115	4.00 102	– –	– –	– –	– –	9 8	10.0 4.5
¾" 20	4500	5.00 127	5.00 127	6.50 165	6.63 168	10.50 305	2.50 63	0.44 11	1.075 27.3	0.50 13	4.53 115	4.00 102	– –	– –	– –	– –	9 8	10.0 4.5
1" 25	900– 2800	5.00 127	5.00 127	6.50 165	6.63 168	10.50 305	2.50 63	0.63 16	1.340 34.0	0.50 13	4.53 115	4.00 102	– –	– –	– –	– –	10 9	9.4 4.3
1" 25	4500	5.25 133	5.25 133	6.75 171	6.63 168	10.50 305	2.63 67	0.63 16	1.340 34.0	0.50 13	4.53 115	4.12 104	– –	– –	– –	– –	10 9	13.7 6.2
1¼" 32	900– 2800	5.25 133	5.25 133	6.75 171	6.63 168	10.50 305	2.63 67	0.63 16	1.685 42.8	0.50 13	4.53 115	4.12 104	– –	– –	– –	– –	18 15	13.4 6.1
1¼" 32	4500	5.25 133	5.25 133	6.75 171	6.63 168	10.50 305	2.63 67	0.63 16	1.685 42.8	0.50 13	4.53 115	4.12 104	– –	– –	– –	– –	18 15	13.4 6.1
1½" 40	900– 2800	5.25 133	5.25 133	6.75 171	6.63 168	10.50 305	2.63 67	0.63 16	1.925 48.9	0.50 13	4.53 115	4.12 104	– –	– –	– –	– –	18 15	13.2 6.0
1½" 40	4500	7.50 191	7.50 191	9.50 241	10.50 267	24.00 610	3.75 95	1.06 27	1.925 48.9	0.50 13	7.76 197	5.75 146	– –	– –	– –	– –	35 30	45.9 20.8
2" 50	900– 2800	7.50 191	7.50 191	9.50 241	10.50 267	24.00 610	3.75 95	1.06 27	2.416 61.4	0.62 16	7.76 197	5.75 146	– –	– –	– –	– –	51 43	45.2 20.5
2" 50	4500	7.50 191	7.50 191	9.50 241	10.50 267	24.00 610	3.75 95	1.06 27	2.416 61.4	0.62 16	7.76 197	5.75 146	– –	– –	– –	– –	51 43	45.2 20.5
2½" 65	900– 2800	10.00 254	10.00 254	12.50 318	– –	– –	5.00 127	1.50 38	2.919 74.2	0.62 16	10.00 254	7.50 191	13.43 341	9.92 252	24.00 600	11.59 295	85 72	115.7 52.5
2½" 65	4500	10.00 254	10.00 254	12.50 318	– –	– –	5.00 127	1.50 38	2.919 74.2	0.62 16	10.00 254	7.50 191	13.43 341	9.92 252	24.00 600	11.59 295	85 72	115.7 52.5
3" 80	900– 2800	– –	10.00 254	– –	– –	– –	5.00 127	1.50 38	– –	– –	10.00 254	– –	13.43 341	9.92 252	24.00 600	11.59 295	104 88	105.0 47.6
3" 80	4500	– –	10.00 254	– –	– –	– –	5.00 127	1.50 38	– –	– –	10.00 254	– –	13.43 341	9.92 252	24.00 600	11.59 295	104 88	105.0 47.6
4" 100	900– 2800	– –	10.00 254	– –	– –	– –	5.00 127	1.50 38	– –	– –	10.00 254	– –	13.43 341	9.92 252	24.00 600	11.59 295	93 79	105.0 47.6
4" 100	4500	– –	10.00 254	– –	– –	– –	5.00 127	1.50 38	– –	– –	10.00 254	– –	13.43 341	9.92 252	24.00 600	11.59 295	93 79	105.0 47.6

BW$_N$ = Butt Weld End with Nipple

Socket Weld Ends

Butt Weld Ends

Butt Weld End with Nipple

***NOTE:** If specifying a butt weld end valve, please refer to "Dimensions for butt weld end" table (right), to determine if the valve is available with an integral butt weld or nipple on one end.*

For standard dimension "A", (see table above) use column "BW" when specifying valves with an integral butt weld, and column "BW$_N$" when specifying valves with a nipple.

For any special requirements, please consult the factory.

DIMENSIONS FOR BUTT WELD END
CONFORMING TO REQUIREMENTS ASME B16.25

NPS in	Pipe Sch. number	BW w/Nipple		Nom. Pipe OD	ØW	ØX	Y	Z	Wall Thickness
		900-2800	4500						
½"	80	✓	✓	0.840	0.906	0.546	0.22	0.29	0.147
	160					0.464	0.28	0.38	0.188
	XXS(1)					0.252	0.38	0.59	0.294
¾"	80	✓	✓	1.050	1.125	0.742	0.23	0.31	0.154
	160					0.612	0.33	0.44	0.219
	XXS(1)					0.434	0.46	0.62	0.308
1	80	✓	✓	1.315	1.375	0.957	0.27	0.36	0.179
	160					0.815	0.37	0.50	0.250
	XXS(1)					0.599	0.54	0.72	0.358
1¼"	80	–	–	1.660	1.719	1.278	0.29	0.38	0.191
	160					1.160	0.38	0.50	0.250
	XXS(1)	✓	✓			0.896	0.57	0.76	0.382
1½"	80	–	✓	1.900	1.969	1.500	0.30	0.40	0.200
	160	–	✓			1.337	0.42	0.56	0.281
	XXS	✓	✓			1.100	0.60	0.80	0.400
2	80	–	–	2.375	2.438	1.939	0.33	0.44	0.218
	160	✓	✓			1.687	0.52	0.69	0.344
	XXS(1)	✓	✓			1.503	0.65	0.87	0.436
2½"	80	✓	✓	2.875	2.960	2.323	0.41	0.55	0.276
	160					2.125	0.56	0.75	0.375
	XXS(1)					1.771	0.83	1.10	0.552
3	80	–	–	3.500	3.590	2.900	0.45	0.60	0.300
	160					2.624	0.66	0.88	0.438
	XXS					2.300	0.90	1.20	0.600
4	80	–	–	4.500	4.620	3.826	0.51	0.67	0.337
	160					3.438	0.80	1.06	0.531
	XXS(1)					3.152	1.01	1.35	0.674

(1) Not available for Class 900. XXS= Double Extra Strong Wall Thickness.
NOTE: All dimensions given in inches.

Butt Weld End

7

Figure 15: Ball Valves Supplier Information

A.2 HTF REQUIREMENTS FOR STEADY STATE THERMO-HYDRAULIC MODELLING

Table 28: HTF Requirements for Steady State Thermo-hydraulic Modelling

Experimental Mode (Tests)	Sim No.	Press (MPa)	Line A		Line C				Line D		Line E			Line F	
			m (kg/s)	T (°C)	m_{min} (kg/s)	m_{max} (kg/s)	T (°C)	Q_{max} (kW)	m (kg/s)	T (°C)	m (kg/s)	T (°C)	SAS Load Line dP (kPa)	m (kg/s)	T (°C)
RSS-M3(a) (RSS-A1, A2)	1	2.2	0.00	50	0.00	0.00	50	-	0.00	50	0.10	50	33.1	0.00	50
RSS-M3(b) (RSS–B1, B3, C2)	2	2.2	0.05	60	0.02	0.05	250	-	0.05	60	0.10	100	37.9	0.05	50
RSS-M3(c) (RSS-B2, B4)	3	6.5	0.05	100	0.02	0.05	500	-	0.05	100	0.20	100	46.9	0.05	50
RSS-M3(d) (RSS-B5, B6, C1, D1, D2, D3, D4, D5, D6)	4	9.0	0.05	280	0.02	0.05	580	Note$^{(1)}$	0.05	280	0.30	100	70	0.05+note$^{(2)}$	50
RSS-M3(e) (RSS-C3, C4, C5)	5	9.0	0.00	280	0.02	0.05	580	Note$^{(1)}$	0.10	350	0.00	100		0.05+note$^{(2)}$	50

Notes:

1. Heater H5 duty to be determined to allow RSS boring maximum Helium inlet temperature of 750 °C.
2. Additional 50 °C Helium flow from Line F to be determined to control the combined Helium return stream temperature from mixing chamber M5 at a maximum of 500 °C.

A.3 PROCESS DATA FOR VALVES

Table 29: RSS Valve Z ALGC20 AA503

Test	P	dPblower	T	Flow	dPvalve	Volume Flow		Cv	Density	Viscosity	z
	(kPa)	(kPa)	(°C)	(kg/s)	(kPa)	(m^3/h)	(Nm^3/h)		(kg/m^3)	(cp)	
RSS-M3a	2 200	100	-	0	0	-	-	-	-	-	-
RSS-M3b	2 200	130	59.8	0.05	55.07	57.11	1 017	5.0	3.15	0.0214	1.009195
RSS-M3c	6 500	140	99.54	0.05	66.03	21.95	1 032	2.8	8.20	0.0232	1.023729
RSS-M3d	9 000	150	-	0	0	-	-	-	-	-	-
RSS-M3e	9 000	75	-	0	0	-	-	-	-	-	-
RSS-M3e & RCS-M3a	9 000	90	-	0	0	-	-	-	-	-	-
RSS-M3e & RCS-M3b	9 000	90	-	0	0	-	-	-	-	-	-

Table 30: RSS Valve Z ALGC20 AA509

Test	P	dPblower	T	Flow	dPvalve	Volume Flow		Cv	Density	Viscosity	z
	(kPa)	(kPa)	(°C)	(kg/s)	(kPa)	(m^3/h)	(Nm^3/h)		(kg/m^3)	(cp)	
RSS-M3a	2 200	100	-	0	0	-	-	-	-	-	-
RSS-M3b	2 200	130	-	0	0	-	-	-	-	-	-
RSS-M3c	6 500	140	-	0	0	-	-	-	-	-	-
RSS-M3d	9 000	150	278.76	0.045	0.17	21.06	926	51.8	7.69	0.0305	1.020511
RSS-M3e	9 000	75	-	0	0	-	-	-	-	-	-
RSS-M3e & RCS-M3a	9 000	90	-	0	0	-	-	-	-	-	-
RSS-M3e & RCS-M3b	9 000	90	-	0	0	-	-	-	-	-	-

Table 31: RSS Valve Z ALGC20 AA505

Test	P	dPblower	T	Flow	dPvalve	Volume Flow		Cv	Density	Viscosity	z
	(kPa)	(kPa)	(°C)	(kg/s)	(kPa)	(m^3/h)	(Nm^3/h)		(kg/m^3)	(cp)	
RSS-M3a	2 200	100	-	0	0	-	-	-	-	-	-
RSS-M3b	2 200	130	249	0.05	60.2	89.19	1 013	6.0	2.02	0.0293	1.0054
RSS-M3c	6 500	140	498	0.05	70.78	44.77	1 018	3.9	4.02	0.0385	1.0099
RSS-M3d	9 000	150	577	0.05	78.74	35.75	1 020	3.3	5.03	0.0413	1.0122
RSS-M3e	9 000	75	577	0.05	37.7	35.75	1 020	4.8	5.03	0.0413	1.0122
RSS-M3e & RCS-M3a	9 000	90	577	0.05	32.17	35.75	1 020	5.2	5.03	0.0413	1.0122
RSS-M3e & RCS-M3b	9 000	90	577	0.05	32.17	35.75	1 020	5.2	5.03	0.0413	1.0122

Table 32: RSS Valve Z ALGC20 AA504

Test	P	dPblower	T	Flow	dPvalve	Volume Flow		Cv	Density	Viscosity	z
	(kPa)	(kPa)	(°C)	(kg/s)	(kPa)	(m^3/h)	(Nm^3/h)		(kg/m^3)	(cp)	
RSS-M3a	2 200	100	-	0	0	-	-	-	-	-	-
RSS-M3b	2 200	130	60	0.05	55.07	57.11	1 017	5.0	3.15	0.0214	1.009195
RSS-M3c	6 500	140	100	0.05	66.03	21.95	1 032	2.8	8.20	0.0232	1.023727
RSS-M3d	9 000	150	280	0.1	68.98	46.84	2 057	5.7	7.69	0.0305	1.020487
RSS-M3e	9 000	75	349	0.1	35.3	52.61	2 052	8.5	6.84	0.0332	1.017764
RSS-M3e & RCS-M3a	9 000	90	349	0.1	18.5	52.62	2 052	11.7	6.84	0.0332	1.017762
RSS-M3e & RCS-M3b	9 000	90	349	0.1	18.5	52.62	2 052	11.7	6.84	0.0332	1.017762

Table 33: RSS Valve Z ALGC20 AA007

Test	P	dPblower	T	Flow	dPvalve	Volume Flow		Cv	Density	Viscosity	z
	(kPa)	(kPa)	(°C)	(kg/s)	(kPa)	(m^3/h)	(Nm^3/h)		(kg/m^3)	(cp)	
RSS-M3a	2 200	100	50	0.15	23.36	166.29	3 053	22.7	3.25	0.0210	1.009534
RSS-M3b	2 200	130	100	0.15	17.59	191.68	3 048	28.0	2.82	0.0232	1.008025
RSS-M3c	6 500	140	100	0.3	17.47	131.81	6 191	33.0	8.19	0.0232	1.023701
RSS-M3d	9 000	150	100	0.4	10.56	128.06	8 328	48.3	11.24	0.0232	1.032817
RSS-M3e	9 000	75	-	0	0	-	-	-	-	-	-
RSS-M3e & RCS-M3a	9 000	90	-	0	0	-	-	-	-	-	-
RSS-M3e & RCS-M3b	9 000	90	-	0	0	-	-	-	-	-	-

Table 34: RSS Valve Z ALGC20 AA203

Test	P	dPblower	T	Flow	dPvalve	Volume Flow		Cv	Density	Viscosity	z
	(kPa)	(kPa)	(°C)	(kg/s)	(kPa)	(m^3/h)	(Nm^3/h)		(kg/m^3)	(cp)	
RSS-M3a	2 200	100	50	0.15	3.36	166.23	3 053	59.8	3.25	0.0210	1.009538
RSS-M3b	2 200	130	100	0.15	3.83	191.58	3 048	60.1	2.82	0.0232	1.00803
RSS-M3c	6 500	140	100	0.3	5.31	131.77	6 191	59.8	8.20	0.0232	1.023709
RSS-M3d	9 000	150	100	0.4	6.86	128.06	8 328	59.9	11.24	0.0232	1.032817
RSS-M3e	9 000	75	-	0	0	-	-	-	-	-	-
RSS-M3e & RCS-M3a	9 000	90	-	0	0	-	-	-	-	-	-
RSS-M3e & RCS-M3b	9 000	90	-	0	0	-	-	-	-	-	-

Table 35: RSS Valve Z ALGC20 AA001

Test	P	dPblower	T	Flow	dPvalve	Volume Flow		Cv	Density	Viscosity	z
	(kPa)	(kPa)	(°C)	(kg/s)	(kPa)	(m^3/h)	(Nm^3/h)		(kg/m^3)	(cp)	
RSS-M3a	2 200	100	-	0	0	-	-	-	-	-	-
RSS-M3b	2 200	130	49	0.05	92.62	55.32	1 018	3.8	3.25	0.0209	1.009557
RSS-M3c	6 500	140	49	0.05	107.84	19.07	1 036	2.1	9.44	0.0209	1.028236
RSS-M3d	9 000	150	49	0.05	117.92	13.92	1 047	1.7	12.93	0.0209	1.03909
RSS-M3e	9 000	75	49	0.05	56.97	13.92	1 047	2.4	12.93	0.0209	1.039105
RSS-M3e & RCS-M3a	9 000	90	49	0.05	72.79	13.92	1 047	2.1	12.93	0.0209	1.039099
RSS-M3e & RCS-M3b	9 000	90	49	0.05	72.79	13.92	1 047	2.1	12.93	0.0209	1.039099

Table 36: RSS Valve Z ALGC20 AA502

Test	P	dPblower	T	Flow	dPvalve	Volume Flow		Cv	Density	Viscosity	z
	(kPa)	(kPa)	(°C)	(kg/s)	(kPa)	(m^3/h)	(Nm^3/h)		(kg/m^3)	(cp)	
RSS-M3a	2 200	100	49	0.15	1.14	165.78	3 053	102.4	3.26	0.0209	1.00957
RSS-M3b	2 200	130	99	0.35	7.15	446.19	7 113	102.5	2.82	0.0232	1.008048
RSS-M3c	6 500	140	132	0.5	5.4	237.78	10 296	102.9	7.57	0.0246	1.021498
RSS-M3d	9 000	150	177	0.6	6.25	230.25	12 413	103.1	9.38	0.0265	1.0262
RSS-M3e	9 000	75	366	0.2	0.98	108.01	4 101	103.0	6.67	0.0338	1.017206
RSS-M3e & RCS-M3a	9 000	90	366	0.2	0.98	108.01	4 101	103.0	6.67	0.0338	1.017205
RSS-M3e & RCS-M3b	9 000	90	366	0.2	0.98	108.01	4 101	103.0	6.67	0.0338	1.017205

A.4 PROCESS DATA FOR FLOW INSTRUMENTATION

Table 37: RSS Orifice Z ALGC20 KA001 (Line E)

Test	P	T	Flow	Volume Flow		Density	Viscosity	z
	(kPa)	(°C)	(kg/s)	(m^3/h)	(Nm^3/h)	(kg/m^3)	(cp)	
RSS-M3a	2 200	50	0.15	165.58	3 053	3.26	0.0210	1.009575
RSS-M3b	2 200	100	0.15	189.63	3 048	2.85	0.0232	1.008112
RSS-M3c	6 500	100	0.3	132.20	6 191	8.17	0.0232	1.023628
RSS-M3d	9 000	100	0.4	128.24	8 328	11.23	0.0232	1.032767
RSS-M3e	9 000	-	0	-	-	-	-	-
RSS-M3e & RCS-M3a	9 000	-	0	-	-	-	-	-
RSS-M3e & RCS-M3b	9 000	-	0	-	-	-	-	-

Table 38: RSS Orifice Z ALGC20 KA015 (Line F)

Test	P	T	Flow	Volume Flow		Density	Viscosity	z
	(kPa)	(°C)	(kg/s)	(m^3/h)	(Nm^3/h)	(kg/m^3)	(cp)	
RSS-M3a	2 200	-	0	-	-	-	-	-
RSS-M3b	2 200	49	0.05	56.00	1 017	3.21	0.0209	1.009442
RSS-M3c	6 500	49	0.05	19.30	1 036	9.33	0.0209	1.027902
RSS-M3d	9 000	49	0.05	14.03	1 047	12.83	0.0209	1.038785
RSS-M3e	9 000	49	0.05	14.05	1 047	12.81	0.0209	1.038724
RSS-M3e & RCS-M3a	9 000	49	0.05	14.05	1 047	12.81	0.0209	1.038723
RSS-M3e & RCS-M3b	9 000	49	0.05	14.05	1 047	12.81	0.0209	1.038723

Table 39: RSS Orifice Z ALGC20 KA017 (Line B011)

Test	P	T	Flow	Volume Flow		Density	Viscosity	z
	(kPa)	(°C)	(kg/s)	(m^3/h)	(Nm^3/h)	(kg/m^3)	(cp)	
RSS-M3a	2 200	49	0.15	169.49	3 052	3.19	0.0209	1.009358
RSS-M3b	2 200	99	0.35	454.41	7 112	2.77	0.0232	1.007901
RSS-M3c	6 500	132	0.5	241.15	10 293	7.46	0.0246	1.021191
RSS-M3d	9 000	177	0.6	232.55	12 409	9.29	0.0265	1.025934
RSS-M3e	9 000	366	0.2	109.23	4 100	6.59	0.0338	1.017009
RSS-M3e & RCS-M3a	9 000	366	0.2	109.23	4 100	6.59	0.0338	1.017009
RSS-M3e & RCS-M3b	9 000	366	0.2	109.23	4 100	6.59	0.0338	1.017009

Table 40: RSS Orifice Z ALGC20 KA020 (Line B025)

Test	P	T	Flow	Volume Flow		Density	Viscosity	z
	(kPa)	(°C)	(kg/s)	(m^3/h)	(Nm^3/h)	(kg/m^3)	(cp)	
RSS-M3a	2 200	49	0.15	169.61	3 052	3.18	0.0209	1.009349
RSS-M3b	2 200	76	0.3	364.28	6 100	2.96	0.0221	1.008562
RSS-M3c	6 500	93	0.45	196.93	9 288	8.23	0.0229	1.023883
RSS-M3d	9 000	128	0.55	190.38	11 419	10.40	0.0244	1.029835
RSS-M3e	9 000	250	0.15	67.29	3 089	8.02	0.0294	1.021654
RSS-M3e & RCS-M3a	9 000	250	0.15	67.29	3 089	8.02	0.0294	1.021654
RSS-M3e & RCS-M3b	9 000	250	0.15	67.29	3 089	8.02	0.0294	1.021654

A.5 PROCESS DATA FOR HEATER

Table 41: Process Data for Heater

Test	P	Flow		Duty	Tin	Tout	Density *	Conductivity *	Viscosity *	z *
	(kPa)	(kg/s)	(kg/h)	(kW)	(°C)	(°C)	(kg/m^3)	(W/mK)	(cp)	
RSS-M3a	2 200	0	0	0	-	-	-	-	-	-
RSS-M3b	2 200	0.05	180	0	248	248	2.02	0.2290	0.0293	1.0054
RSS-M3c	6 500	0.05	180	0	496	496	4.03	0.3032	0.0385	1.0099
RSS-M3d	9 000	0.05	180	46	576	753	5.04	0.3255	0.0412	1.0122
RSS-M3e	9 000	0.05	180	46	576	753	5.04	0.3255	0.0412	1.0122
RSS-M3e & RCS-M3a	9 000	0.05	180	46	576	753	5.04	0.3255	0.0412	1.0122
RSS-M3e & RCS-M3b	9 000	0.05	180	46	576	753	5.04	0.3255	0.0412	1.0122

* Gas properties are based on the inlet temperature