To the Graduate Council:

I am submitting herewith a thesis written by Wesley Charles Williams entitled "Conceptual Design and Layout of the Balance of Plant for a Generation IV Nuclear Power Plant Using the Westinghouse International Reactor, Innovative & Secure (IRIS)." I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Nuclear Engineering.

Dr. Lawrence Townsend, Major Professor

We have read this thesis
and recommend its acceptance:

Dr. Laurence Miller

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Accepted for the Council:

Vice Provost and Dean of Graduate Studies

# CONCEPTUAL DESIGN AND LAYOUT OF THE BALANCE OF PLANT FOR A GENERATION IV NUCLEAR POWER PLANT USING THE WESTINGHOUSE INTERNATIONAL REACTOR, INNOVATIVE & SECURE (IRIS)

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Wesley Charles Williams
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*"A book of 200 pages may contain nothing of any value at all. Another may contain as little as one hint, one fact, which is of supreme importance to readers."*

- Idries Shah.

# DEDICATION

I dedicate this to my wife, Gabriela, for her loving rebuttal of my daily self-skepticism and for giving me a reason to persevere. Thank you for believing in me. ¡Te amo!

# ACKNOWLEDGEMENTS

I wish to thank everyone who helped me during the creation of this thesis. I give highest acknowledgement to Dr. Larry Townsend for the sharing of his encompassing knowledge as well as his prompt and courteous help. I also want to acknowledge Dr. Miller, Dr. Mynatt, Dr. Dodds, and the rest of the University of Tennessee Nuclear Engineering Department for giving me an exemplary academic environment to work and also for their technical assistance. I acknowledge the people of Westinghouse, Dr. Carelli, Dr. Conway, as well as Fabio Famiani, for helping me in acquiring the information pertaining to IRIS and allowing me to be a part of their research effort. Finally I give acknowledgement to the US Department of Energy and the NERI program for their funding of this research effort.

# ABSTRACT

The purpose of this research is to develop a conceptual design and layout of a balance of plant for a Generator IV nuclear power plant using the Westinghouse International Reactor, Innovative & Secure (IRIS). This encompasses the background research of the nuclear primary system, selection of important components, mathematical modeling of the system and components, solid modeling of the components, layout of the system, and visualization.

The system is 1000 MW thermal and 360 MW electric. It has six feed water heaters and dual reheat with one high pressure and one low-pressure tandem compound turbo-generator unit. The sizes and the weights of these components along with the piping involved with the layout are determined. The final layout of the plant is 100 meters long by 40 meters wide with an approximate weight of 7400 tons. Drawings of the layouts and the components are created along with the solid models. With these results the further development of the system as well as the fabrication and modularization studies can be pursued. The study also can be used to find areas in the plant design that warrant further development.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Statement of Problem and Objectives

The objective of this work is to develop a conceptual design and layout of the balance of plant for a Generation IV nuclear power plant using the Westinghouse International Reactor, Innovative & Secure (IRIS) as the primary component. The motivation to develop the concept is to create a layout for use in modularity and manufacturing studies. In order to determine the layout, various requirements must be taken into account, for example, standard design specifications. The research focuses on two aspects: conceptual design of the supporting systems to the IRIS reactor and layout of the design concept in a 3-D Computer Aided Design (CAD) package. This gives the information needed to carry out modularity and manufacturing simulations and design specifications of the nuclear power plant.

## 1.2 Organization of Thesis

This thesis consists of three foci organized into eight chapters. Chapter 2 covers the first phase of the project involving an extensive review of the previous work in the field. The next five chapters are the results of the second and third phases of the project involving the conceptual design and layout of the power plant. This involves component selection, mathematical modeling, solid modeling and layout. The thesis concludes with a retrospective of the work done and recommendations for the future work.

# CHAPTER 2

# REVIEW OF PRIOR WORK

## 2.1 Description of NERI Project

The US Department of Energy (DOE) is currently sponsoring a three-year research project with the University of Tennessee under the DOE's Nuclear Energy Research Initiative (NERI)[1]. The thrust of the research is to investigate modularization of Generation IV nuclear reactor plant concepts (Mynatt, 2000). Of the three designs being considered, one is an advanced pressurized water reactor (APWR) concept. The Westinghouse IRIS design is chosen as the centerpiece of the (APWR) design concept under consideration since it appears to be a serious candidate for future construction.

The research project involves seven phases over the course of three years. The first two years involve four of the phases that are concerned with the design and layout of the nuclear reactors. The third year involves the other three phases concerning manufacturing simulation. The first three phases are the major focus here and they involve: (1) review of previous work, (2) preliminary design and layout, and (3) initial revision of the concept. The desired outcome is a modular reactor plant concept that can be effectively modeled by the industrial engineering partners in a manufacturing simulation.

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[1] DOE Solicitation No. DE-PS03-00SF22016

## 2.2 Generation IV Nuclear Reactors

The design of Generation IV nuclear reactors is a major focus of many institutes concerned with nuclear energy technologies as well as the nuclear power industry. The requirement for cleaner, cheaper and more reliable large power sources is extremely important in both the US and world economies. The idea behind Generation IV nuclear reactors is to provide this power source in a safer and more manageable system than previously-produced nuclear reactors. In order to achieve the manageability and safety requirements it is desired to create a new modular nuclear reactor concept capable of accomplishing both. Generation IV has four main objectives: proliferation resistance, enhanced safety, improved economics, and reduced waste (Carelli, 2000). Some of these objectives must also be considered in the development of the balance of plant design.

## 2.3 US Government

In the 1950's (or perhaps earlier), the US government first considered the idea of modularity in nuclear power plants for military uses. A small transportable integral plant can be deployed to difficult to reach sites, like Greenland or other arctic regions, where the delivery of oil or coal is virtually impossible most of the year. Of the major concerns cost, reliability, portability and safety were singled out as well as speedy deployment (Corliss, June 1964), not unlike Generation IV reactor requirements. Several reactors were designed and deployed by the US Army Corps of Engineers but these are relatively small (< 10 Megawatts (MW) electric) and not prototypical of the demands of the modern commercial power plant.

## 2.4 Westinghouse AP600

Westinghouse has previously employed the idea of modularity in nuclear reactor construction with the design of the AP600 and AP1000 plants. The objective of both is to reduce onsite costs and improve the quality and safety for the units. The Nuclear Regulatory Commission (NRC) granted design certification to the AP600, making it the only passively safe reactor licensed in the world to date (Winters, 2000). The concept of passive safety is new to the Generation III reactors and is carried over to Generation IV concepts.

Passive safety is the reduction of moving or manually controlled parts in the safety systems. The AP600 is innovative in the use of passive heat removal and containment cooling systems. This is accomplished by residual heat removal without operator action through a steam generator-like apparatus, which boils water that can condense inside the steel reactor containment vessel. Then the heat is removed through natural circulation of air over the containment vessel outside. This is one of the many passive safety features. However, more important to this study, is the modularization of the plant.

It is believed that through the reduction of construction costs nuclear power becomes a much more lucrative investment (Winters, 2000). This reduction in cost can be achieved by reducing skilled labor needs for onsite construction. It was determined by Westinghouse that shop labor costs are far less than field labor costs (Winters, 2000). It is therefore desirable to construct as much of the power plant in a manufacturing facility. The quality of shop work such as welding is higher when performed in a facility as compared to fieldwork (Winters, 2000). This would improve safety as well as reducing costs. Reduction and elimination of components along with standardization of modules also helps to reduce costs.

The Westinghouse AP600 team compiled four comprehensive documents on the layout standards and guidelines for nuclear plant modules (Westinghouse, 2000). In the first of the documents a description of layout standards and inviolate rules are laid out which have proven to be cost effective. The second gives layout guidelines that maximize modularization. The third presents module design standards for detail analysis and acceptance of modules for structural and equipment purposes. The fourth and final document gives lessons learned from the AP600 studies concerning effective fabrication and module assembly. These four documents are observed throughout the design process herein described.

## 2.5 Westinghouse AP1000

The Westinghouse AP1000 conceptual design is a continuation of the AP600 design. The objective was simply to scale up an AP600 design from 600 MW thermal (MWt) power to 1000 MWt power. Information pertaining to the AP1000 is not as readily available due to the fact it is still under development. The important aspect is the necessity of a power output increase in order to take advantage of economy of scale. The same guidelines used for the AP600 are utilized for the AP1000 thus making further investigation into the AP1000 not particularly worthwhile for this study.

## 2.6 Westinghouse IRIS

The Westinghouse International Reactor Innovative and Secure (IRIS) began in 1999 and is the current design trying to conform to the four ideas of Generation IV nuclear reactor technology as defined by the DOE. The design is the undertaking of an international consortium of researchers and engineers. The original design was a reactor of 300 MW thermal output. Due to economy of scale the output was increased to 1000 MW thermal. This plant would be capable of producing over 300 MW of electricity. The key difference between the IRIS and other pressurized water reactors (PWRs) is its integral, pool-type design. This means that the reactor core and the steam generators are contained in the same pressure vessel. It is the goal of the IRIS project to deploy a first-of-a-kind plant by 2010 (Carelli, 2000).

In order to satisfy proliferation resistance the IRIS is designed to have a long life core (8 years) without shuffling or refueling. This renders all or most of the core fuel material inaccessible to the user in the field. The fuel would be managed by the consortium and could be maintained as one large piece for storage and accounting purposes. The aim of IRIS is to have 8 years of operation between shutdowns. In order to accomplish this, on line maintenance and diagnostics must be innovative. The reactor is also designed to burn mixed oxide fuel (MOX). This will help to reduce the worlds' plutonium stock. The current design can burn MOX fabricated in SMP, Sellafield (Carelli, 2000).

Eliminating accidents by design methods rather than coping with them using passive means, i.e. Generation III reactors, creates enhanced safety. The IRIS vessel contains the steam generators. This takes away the primary loop piping, thus removing the possibility of loss of coolant accidents (LOCAs) in the primary loop. IRIS has a tall vessel in order to locate the steam generators and internal control rod drives. This eliminates loss of flow accidents (LOFAs) along with control rod ejection accidents. The tall vessel permits the possibility of maintaining natural circulation in the core. Due to the pool-type design, there is a large inventory of water inside the vessel. This slows down the transient evolution and maintains essential core coverage. The innovative containment is much smaller and round in shape thus allowing for much higher containment pressures. This also lengthens transient evolution in case of a LOCA. Finally the long life of the core reduces the opportunity for refueling accidents.

Economics are also improved. Design features, simplification, and modularization reduce capital costs, while operation and maintenance costs are reduced by other means. The integral design eliminates the external pressurizer and various primary pipes and valves. The refueling system is simplified. There is no soluble neutron absorber system. Modularization is achieved with factory fabrication, shorter construction times and mass deployment. Finally the long-life core gives less shutdown time and maintenance time, thus reducing cost and personnel. It is estimated that the cost will be 3 to 4 cents per kilowatt-hour.

Finally, waste will be reduced since there is less spent fuel and fewer structures in the system. The IRIS consortium manages the fuel and reactor. Therefore, there is no decommissioning of the reactor. It is the goal of the IRIS project to have an international repository for the waste produced by IRIS thus enabling smaller third world countries to consider nuclear power as an option.

# CHAPTER 3

# METHODOLOGY

## 3.1 Initial Component Selection

A list of components needed in the power plant is compiled through a review of various materials concerning plant design. The components needed to perform substantial thermodynamic modeling of the system are therefore shown. The components are selected to best complement the design and modularization process. This involves finding the cycle to be used and the selection of components that best realize this cycle. A description of the components and their functions is completed and the typical operational parameters of the components are also found. The result is enough information to begin the mathematical modeling and optimization process.

## 3.2 Mathematical Modeling

Mathematical modeling of the system involves determining appropriate methods of modeling the system and the implementation of these methods. A few codes are used in this process. The two most important are a modified ORCENT2 code from Oak Ridge National Laboratory (ORNL, 2000) and CyclePad v2 for 32-bit Windows© 1995 Kenneth D. Forbus & Peter B. Whalley of Northwestern University (Forbus, 1995). Both systems analyze thermodynamic systems.

CyclePad is used for basic thermodynamic modeling and can be used to do various optimization calculations. It also provides simple graphic interface and visualization capabilities. CyclePad is used to find initial system output using the design information from the IRIS steam generator outputs. The effects of variation of certain parameters can be investigated in order to visualize design effects. Furthermore CyclePad can be used to obtain approximate heat exchanger sizing.

The ORCENT2 digital computer program performs calculations at valves-wide-open design conditions, maximum guaranteed rating conditions, and an approximation of part-load conditions for steam turbine cycles supplied with throttle steam characteristic of contemporary light-water reactors. Turbine performance calculations are based on a method published by the General Electric Company. The output includes all information normally presented on a turbine-cycle heat balance diagram. The program was written in FORTRAN IV for the IBM System 360 digital computers at the Oak Ridge National Laboratory (ORNL, 2000). The program has been updated from FORTRAN IV to a more compatible FORTRAN 77 language, while maintaining the original functionality. In this work it is used to determine the final design concept of the balance of plant system and give the design parameters needed to further specify components.

The generalized heat balance of ORCENT2 follows a standard procedure. First, the turbine inlet conditions, internal efficiency, extraction and condenser pressures are used to determine the turbine expansion line. Second, pressure drops in the reheat and extraction lines and the terminal temperature difference and drain cooler approach of feed water heaters are used to determine steam properties at the various locations. Third, the determination of extraction steam flow rates is made starting with the feed water heater closest to the steam generator and solving for each concurrent heater until the condenser is reached. Fourth, the outputs of all of the turbine cylinders are determined. The sum of the turbine outputs is the gross output of the steam turbine. It is then multiplied by the mechanical efficiency and generator efficiency in order to determine the turbo-generator net output. Finally, the power consumed by feed water pumps and the heat inputs supplied to the turbine-cycle system is used to determine an estimated net heat rate.

In our case the steam turbine output is initially estimated and then a trial-and-error approach is taken. The steam flow rate at the turbine inlet is estimated in order to determine the turbo-generator net output. If the calculated value does not match the input a new turbine output is estimated and another heat balance is performed. This iterative process is repeated until it converges within the desired tolerance.

## 3.3 Solid Modeling of Components

The final components are approximated by virtual components in a SolidWorks® 2001 environment. The SolidWorks® 2001 environment allows for as much or as little detail as desired to be input by the user. It is common practice to approximate the external geometric features that will be needed for the study. The virtual components contain the most important geometrical features of the components to scale in order to best arrange the components in the layout. These components however are not intended to be fully detailed to the point of use as finalized components.

## 3.4 Plant Layout

Plant layout is achieved through various levels of design. Primarily the components are arranged for functionality, as they would be in a conventional manner. Secondly details of the modularization process are considered. Finally considerations of increasing accessibility and ease of construction may be considered. These various levels are then compiled into a final layout design, which can be used for further design and economic study. The layouts are also achieved in the virtual model environment SolidWorks® 2001. This permits for visualization and assembly analysis. It also allows for ease in layout modification.

# CHAPTER 4

# COMPONENT SELECTION

## 4.1 Westinghouse IRIS

The Westinghouse IRIS as reviewed in the initial document search is selected as the primary side component. The selection of the IRIS is due to its innovative nature and compliance with the Generation IV goals. Although the IRIS is still undergoing design changes and modifications, the main design concept is stable enough to create a power plant design. The design parameters used in the design of the balance of plant are taken from the published IRIS design as of April of 2001 (Carelli & Oriani, 2001). Though the exact values are subject to change it is believed that the parameters are close enough to the final parameters to accomplish this study. A schematic of the IRIS design can be seen in Figure 4-1 (Carelli & Oriani, 2001). The IRIS primary system contains internally the steam generators and primary loop. Therefore it can be used as the entire primary component of the power plant. The current design also reduced the number of steam generators from 12 to 8. However the general look remains the same.

The parameters of the IRIS primary system are for 1000 MW of thermal power output. The parameters of most importance here are the steam generator entrance and exit conditions. The balance of plant (BOP) components are then determined with these parameters and considering the IRIS primary system as a black box. The parameters are for steady state operation of the primary plant. The IRIS parameters are tabulated in Table 4-1 (Carelli & Oriani, 2001).

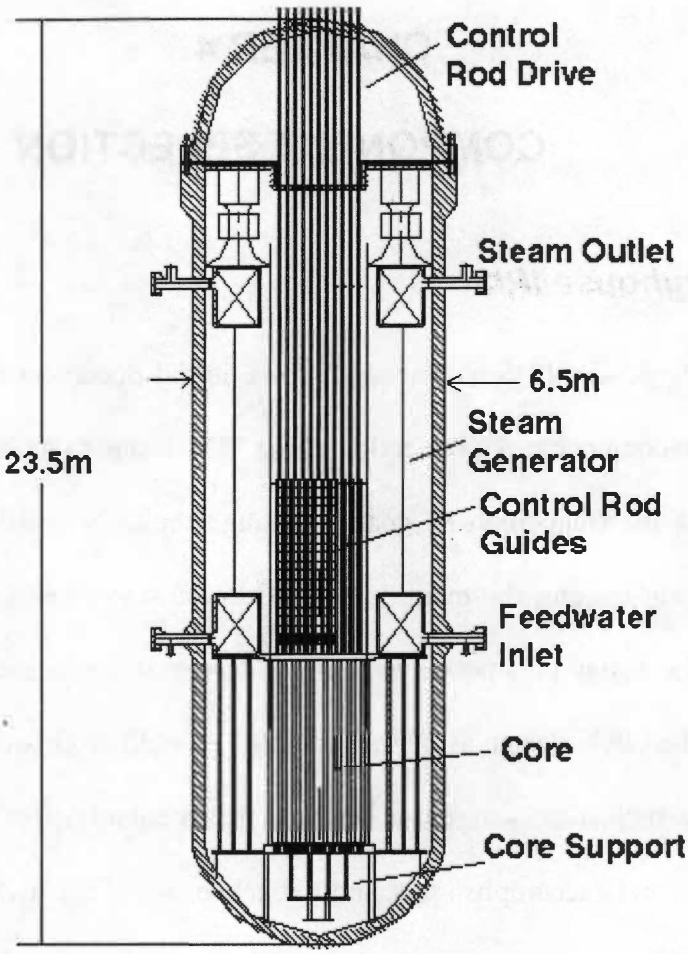



**Figure 4-1: Schematic of IRIS Primary System (*Source: Carelli & Oriani, 2001*)**

## 4.2 Steam Turbines

The steam turbine is the heat (thermal) engine that uses steam as a working fluid and its potential thermal energy is transformed into kinetic energy by means of expansion through the turbine nozzles. The resulting steam jets are converted into mechanical energy. This mechanical energy does work on the rotating blades (buckets). This mechanical energy is used to drive the generator and thus produce electricity. Some of the standard specifications are that the turbine set rotates at 1800 or 3600 rpm in order to generate at 60 Hz or at 1500 or 3000 rpm for generating at 50 Hz. In this study we choose the typical value of 1800 rpm for US nuclear power applications, although currently there are some plants using 3600-rpm sets.

### 4.2.1 Condensing vs. Non-Condensing

There are various turbine types and selections that must be determined before further analysis can proceed. There are two main types of turbines: condensing which has exhaust steam at less than atmospheric pressure and non-condensing which has exhaust back pressure higher than atmospheric pressure. Condensing turbines are most often found in central stations and are usually multistage and capable of handling large amounts of steam. The cost of the condensing turbine is higher, but the efficiency is much higher also. A vacuum in the condenser maintains sub-atmospheric pressure.

### 4.2.2 Four Flow Patterns

Steam flow patterns must also be determined in order to design the turbine set.

**Table 4-1: IRIS Design Parameters (*Source: Carelli & Oriani, 2001*)**

| Parameter | Metric Units | English Units |
|---|---|---|
| Reactor Vessel Inner Diameter | 6.1 meters | 20.01 feet |
| Number of Steam Generators | 8 | 8 |
| Thermal Power per Steam Generator | 125 MW | 125 MW |
| Secondary Side Inlet Temperature | 485.15 K | 413.6 °F |
| Secondary Side Outlet Temperature | 590.15 K | 602.6 °F |
| Steam Outlet Pressure | 7.0 MPa | 1015.28 psia |
| Secondary Side Mass Flow Rate per SG | 62.54 kg/s | 3,970,794 lbm/hr |
| Condensation Temperature | 305.75 K | 90.68 °F |

There are four main types of steam flows: straight flow, reheat, extraction and induction. Straight flow is used in simple applications with full throttle steam flow from inlet to exhaust. Reheat is almost always utilized in power plants. Reheat involves removing exhaust steam flow from the unit at one (single-reheat) or two (double-reheat) intermediate stages. This steam temperature is raised by passing through the boiler again or in our case a heat exchanger with part of the initial steam flow that is diverted. Then the steam is returned to the same position to continue expansion through the consequent lower stages. Extraction turbines are also common in utility power plants. There is automatic extraction and non-automatic extraction. Automatic extraction removes steam at various points only with specific pressures and flow rates in order to meet demand of the process. The non-automatic extraction, as used in power plants, occurs at approximate pressures depending on the turbine load variations. This is used to heat the feed water as it is being returned to the steam generator. Induction turbines are the opposite of extraction turbines and are not viable for power production except in the case of combined cycle generation. Even though the straight flow turbine is the cheapest to manufacture, non-automatic extraction, reheat turbines are most commonly used in power plants for energy production. This is because efficiency over the lifetime can far outweigh initial capital costs of the extra features. Therefore this is the type of turbine that is chosen for this work.

### 4.2.3 Tandem and Cross Compounding

After passing the 40 MW electric (MWe) range single casing turbines are no longer feasible. Due to the separate casings of the various pressure stages of the turbines they must be combined on either one or multiple shafts. This means that the turbines must be either tandem compound or cross compound. If all of the turbines are combined on one shaft and drive one generator this is tandem compounding. On the other hand, if the turbines are combined on two or more shafts utilizing two or more generators this is cross compounding. For large units cross compounding is used in order to create two smaller turbine sets as one. However, tandem compounding is most often used even in excess of 1.5 gigawatt electric systems. Thus due to the availability of tandem compound units this is the standard selection for this concept. Nuclear turbine sets usually consist of tandem compounded high pressure (HP) and low-pressure (LP) turbines. There is most often a high-pressure unit followed by one to three low-pressure units. The ranges of operation are most often, but not exclusively, one or two low-pressure unit for up to 500 MWe and three low-pressure units beyond approximately 500 MWe. Therefore the turbine set used in this concept is around 350 MWe and thus is one low-pressure unit. This tandem compound unit may appear as shown in Figure 4-2 without the extra two LP units. It also shows the moisture separator reheaters on the sides.

### 4.2.4 High Pressure

The high-pressure (HP) turbine operates from the highest-pressure ranges 7 MPa (1015.2 psia) to pressures around 2 to 4.8 MPa (300 to 700 psia) depending on the system. The high-pressure turbines with reheat often have intermediate stages in the same casing unit in order to cope with the wet steam conditions of nuclear power plants. It is usually desirable to maintain the quality of the steam in the high-pressure turbine to less than 3 or 4% in order to protect the blades. Therefore one or two reheat stages are used to

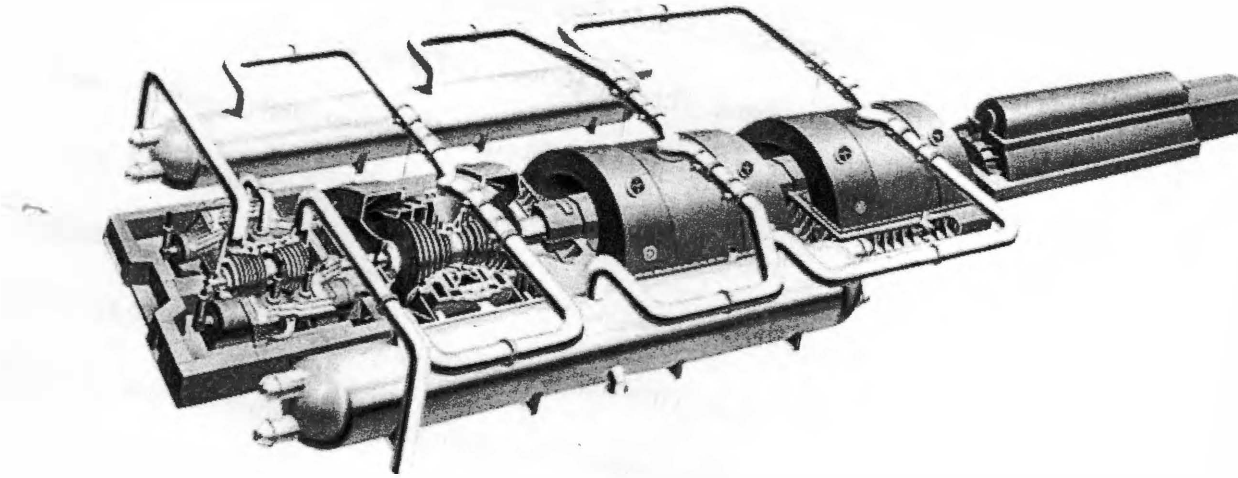


**Figure 4-2: Typical Tandem Compound Turbine**

***(Source: http://www.mhi.co.jp/atom/hq/atome_e/03/image/a36.jpg)***

help with this problem. For nuclear power units of around 800 MWt the HP turbine has two reheat sections and double flow. Double flow means that the steam is equally split into two directions in order to expand. This can be seen in Figure 4-3.

The HP turbine supplies a large part of the overall power and is usually more efficient than the LP stages. This is due to the higher pressures, temperatures and quality of the steam passing through the stages. These parameters make the turbine smaller also because the blades do not need to withstand the corrosive power of the moisture in the steam. This also makes for smaller cylinders to contain the apparatus. A cross sectional view of a typical HP turbine is shown in Figure 4-4.

### 4.2.5 Low Pressure

The low-pressure (LP) turbines usually expand the main steam from the HP exhaust pressure and temperature after moisture separation down to the condenser pressure. This is usually from around 2 to 4.8 MPa (300 to 700 psia) down to 6.9 to 69 kPa (1 to 10 psia) in the condenser. The LP turbines therefore must be much larger than the HP turbine. The blades or buckets are much larger in order to withstand the moist steam conditions, which can be around 10% wet in quality. The cylinder is larger in order to keep the expanded steam flowing. The LP cylinders are almost always double flow

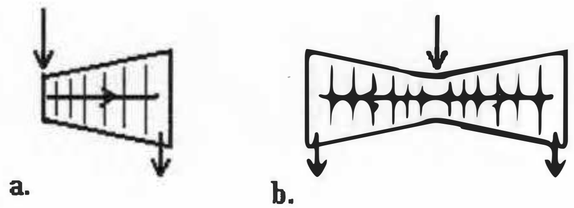



**Figure 4-3: HP Turbines – a. Single Flow b. Double Flow**

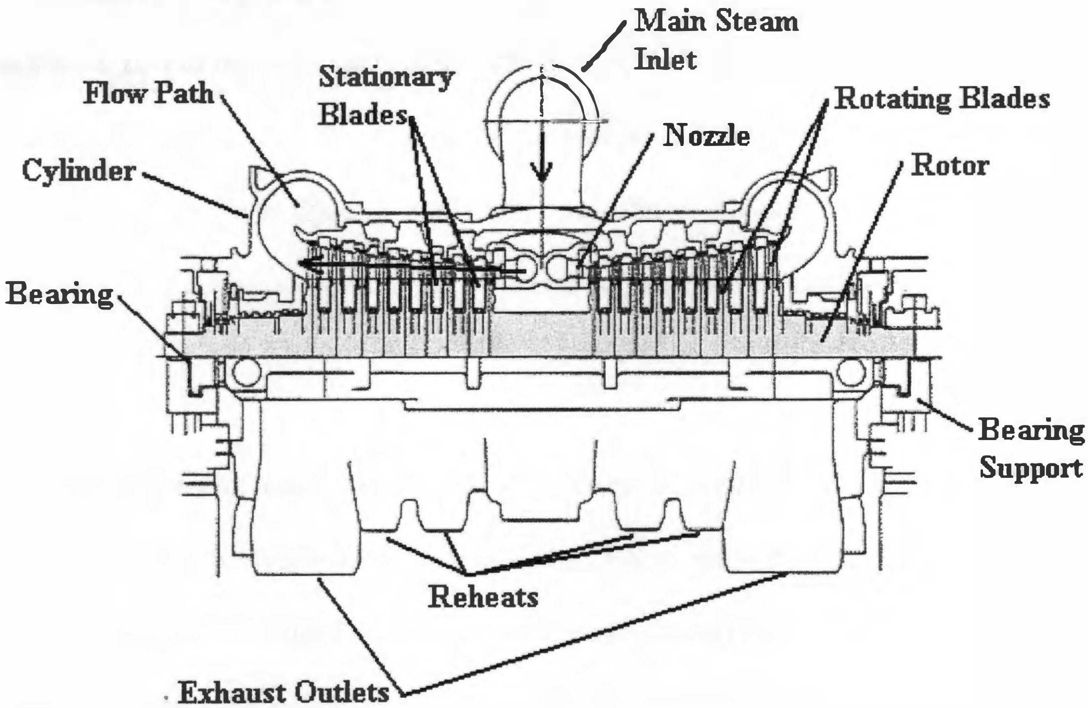



**Figure 4-4: Sectional View of Double Flow, Dual Reheat HP Turbine**

**(*Source: http://www.mhi.co.jp/power/e_power/product/turbine/steam/index.htm*)**

with extraction points for feed water heating. These extraction point pressures are determined by trial and error. The LP turbines are slightly less efficient due to the steam properties and to the increased seal leakages. Unlike the HP turbine the LP turbines usually exhaust directly into the condenser rather than through a piping system. The schematic of the LP turbine can be seen in Figure 4-5.

## 4.3 Heaters

There are two different kinds of heaters that are used in typical power plant turbine generator sets. They are feed water heaters and reheater. The difference between the two is their location in the thermodynamic cycle. The feed water heater is on the condensed side of the cycle and heats compressed liquid back to saturated liquid in order to obtain higher thermal efficiency. The reheater is on the steam side before being fully used by the turbines. The reheater also improves the thermal economy by reheating previously superheated steam to saturated steam once again before returning to the turbines. In our case there are two stages of reheat and six feed water heaters. This corresponds to the dual reheat of the HP turbine and the five extraction points of the LP turbines, respectively. The first feed water heater utilizes the moisture and some of the steam from the HP turbine exhaust and reheat extraction points.

### 4.3.1 Reheater

The reheater is simply a counter flow heat exchanger, which uses a fraction of the initial main steam flow in order to reheat the steam back to saturation or superheated steam after it has expanded through the HP turbine. It is non-mixing and the hot side

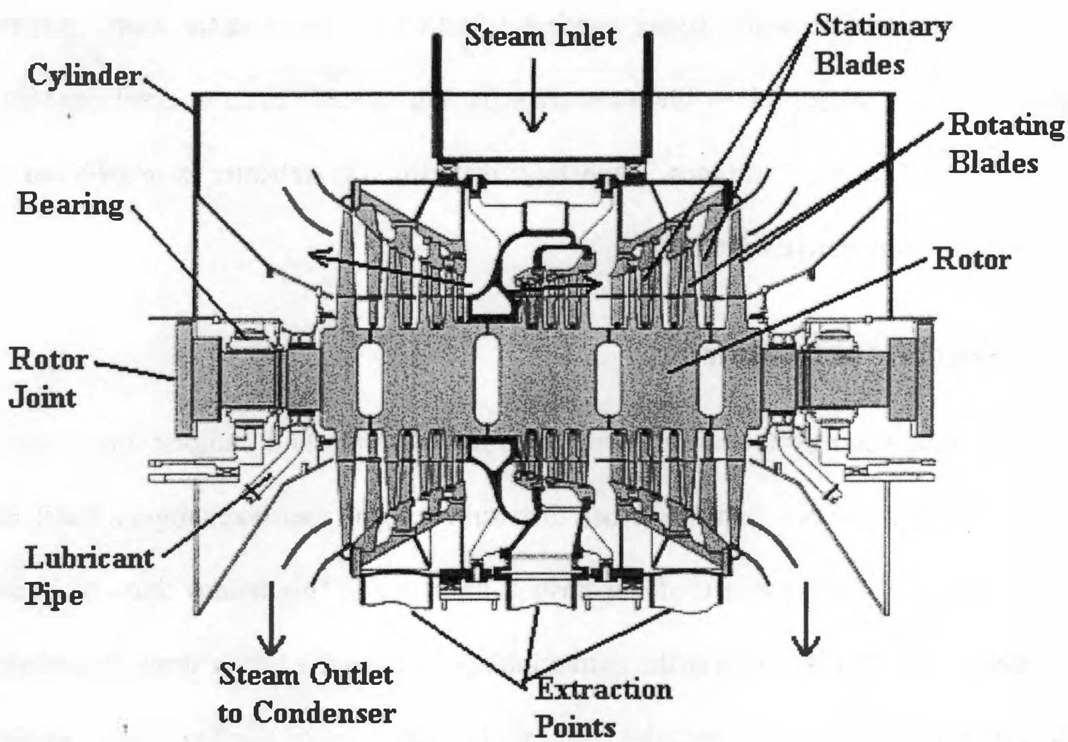



**Figure 4-5: Sectional View of Double Flow, Five Extraction LP Turbine**

**(*Source: http://www.mhi.co.jp/power/e_power/product/turbine/steam/index.htm*)**

contents return to feed water heater number 1, which is closest to the steam generator. These two reheat stages follow the moisture separator (usually in an integral unit) and lie between the HP and LP turbines in the flow diagram. The reheater is usually stainless steel and uses conductive heat transfer.

### 4.3.2 Feed Water Heater

The feed water heaters are of two types: flashed drain and pumped drain. None of them are mixing and are therefore cross flow tube-in-shell heat exchangers. Feed water heaters numbers 1 and 3-6 are of the flashed drain type. This means that after having been used for the thermal power the extraction steam from the heater drain flashes down to the previous heater. This cascades through the heaters until the final one, number 6. The feed water heater number 6 or the one closest to the condenser in the thermodynamic loop flashes to the condenser. In this way all of the potential heat is used effectively. Feed water heater number 2 is of the pumped drain type. The moisture separation liquid from the HP turbine exhaust heats the feed water in this heater. Then the cooled extraction moisture is pumped up to the feed water pressure and combined with it before it enters the main feed water pump.

## *4.4 Moisture Separators*

The moisture separators are used in order to remove as much excessive wetness as possible from the steam. Due to the relatively low temperature and pressures of the nuclear system in comparison to the standard fossil fuel plant, it is very important. It prevents problems that occur with turbine blade corrosion and lubrication removal. The moisture separator lies between the HP and LP sections of the turbine, before the reheater (usually an integral unit). As stated above the removed moisture is used to heat the feed water in the feed water heater number 2. A typical moisture separator reheater for three LP units is shown in Figure 4-6. The moisture is usually separated using a vortex along with condensation.

### 4.5 Condenser

The condenser is the component of the plant where the latent heat of the system, which is not used by the turbines, is removed. The heat is transferred to cooling water and finally ends up in the atmosphere. The condenser dictates the overall system efficiency by the pressure that is maintained in it. The determining factor in the condenser is the cooling water temperature. There are three types of condensers: water-cooled surface condensers, water-cooled contact condensers and air-cooled surface condensers. The one used in this concept is a water-cooled surface condenser, which is the most commonly used. It is a tube in shell type heat exchanging devices using cross-flow. The basic design is a shell with two water boxes on each end separated by tube sheets. The water flows through tubes between the two boxes from side to side, while the steam condenses on the outside of the tubes, thus removing the latent heat. This condensed steam then drips into the hot well where as a liquid it is pumped into the feed water pipes. The cooling water is supplied by any large water mass that can accept the latent heat and thus evaporate it into the atmosphere. Usually this is a lake, river or the ocean. Special intakes are designed to pump in this cooling water. The schematic of a surface condenser can be seen in Figure 4-7. This is usually connected to the LP turbine by an expansion joint.

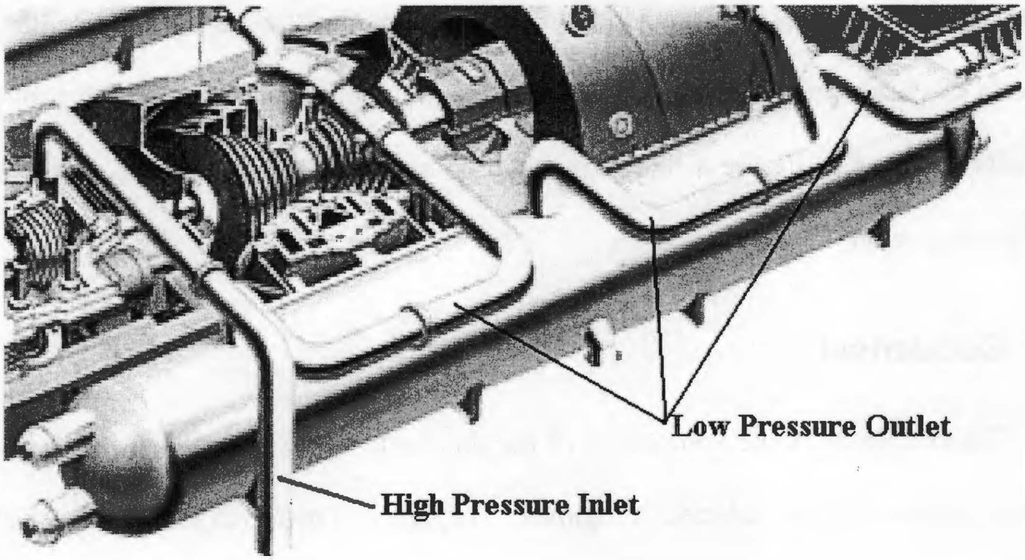
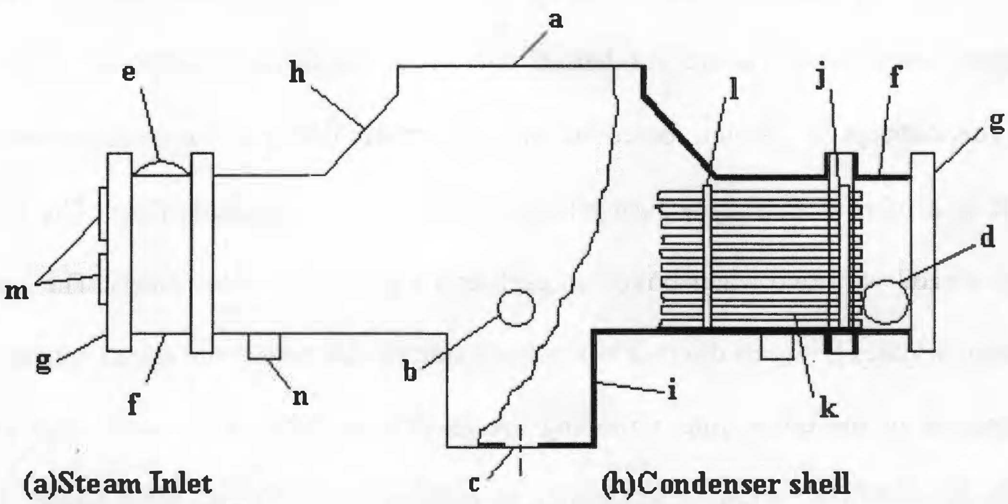



**Figure 4-6: Moisture Separator Reheater**

**(*Source: http://www.mhi.co.jp/atom/hq/atome_e/03/image/a36.jpg*)**




**(a)Steam Inlet**
**(b)Air-vapor outlet**
**(c)Condensate outlet**
**(d)Circulating (cold-water) inlet**
**(e)Circulating (discharge) outlet**
**(f)Water box**
**(g)Water box cover**
**(h)Condenser shell**
**(i)Hotwell**
**(j)Tube sheet**
**(k)Tubes**
**(l)Tube-support plate**
**(m)Handholes or manholes**
**(n)Condenser-support bracket**

**Figure 4-7: Surface Condenser Schematic (*Source: Li, 1985*)**

## 4.6 Pumps

There are three uses of pumps in the main thermodynamic power plant cycle. They are as follows: feed water pump, condensate pump and feed water heater drain pump. A turbine drives the feed water pump due to the large amount of feed water flow. The feed water pump is situated between the feed water heaters number 1 and 2. It raises the pressure up to the steam generator inlet design pressure. The condensate pump is situated between the condenser outlet and the feed water heater number 6. It raises the pressure of the flow from the condenser pressure back up to the extraction point pressure of the last feed water heater. Finally, the feed water heater drain pump is situated between the drain on feed water heater number 2 and the main feed water line. It provides the work to raise the pressure of the extraction steam condensate to the feed water pressure going into the feed water pump. Also there are the primary pumps, however they are part of the integral design of the primary system. Therefore our only concern with the primary pumps will be supplying the necessary electricity to run them. This may seem arbitrary, but it will greatly influence the overall efficiency of the power plant and therefore must be considered.

## 4.7 Electric Generator and Exciter

The electric generator is the rotating machine that converts mechanical energy into electrical energy. The most common are the synchronous generator. It has a stationary stator that is surrounded by output windings. Inside of this is the turbine driven rotor that has the dc windings acting as electromagnets. The exciter feeds the DC windings and while they spin they create electric voltage or potential in the system. A typical arrangement of the turbo-generator set with the exciter is shown in Figure 4-8. In the large generators cooling is provided by hydrogen. This allows for more current to be carried in the windings and therefore higher production capability. There is great experience in custom building of generators for various power production applications therefore the details of generator design will not be pursued here. The most important factors are typical values of power factors and efficiencies for these generators in order to better the estimate of power plant output and efficiency. It is also important to know the size and the weight of the typical generator in order to better design modules in the future.

## 4.8 Piping

In a typical nuclear power plant there are various runs of piping to be considered. Of course the most important are the main steam and feed water lines, but the reheat and feed water heater extraction lines must also be considered. It is desirable to find the broad

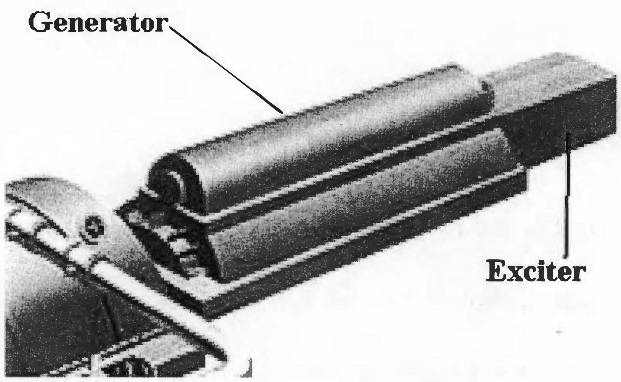



**Figure 4-8: Turbo-Generator Set with Exciter**

***(Source: http://www.mhi.co.jp/atom/hq/atome_e/03/image/a36.jpg)***

sizes of the piping needed to complete the layout in order to minimize the use and need of excessive piping. Due to flow and pressure needs various piping runs are quite large and contribute weight and volume to the design. Of these the reheated steam line, which enters the LP turbine, and the LP turbine extractions are usually the largest pipes in the system. There will be an excess of 30 pipes just for the steam cycle. This does not include the piping needed for lubrication, chemical and volume control and sampling extraction lines. It is easy to see why piping can take up most of the volume of a power plant design layout.

## 4.9 Valves and Control

Various valves are needed to control the thermodynamic process. Of these it is important to note the throttling stop and control valve chest, which controls the overall turbine performance. In nuclear plants there are also intercept valves. These gates are used to quickly divert steam completely from the turbines in the event of an emergency. These are arranged with interconnecting cross over pipes before entering the first turbine. Other valves are used to tap steam for chemical processing and checking. Valves and control will not be specifically found in this research.

# CHAPTER 5

# MATHEMATICAL MODELING AND OPTIMIZATION

## 5.1 Basic Thermodynamics

In order to determine the general BOP performance, a model of the IRIS plant is created in CyclePad. The system is modeled as a Rankine cycle. This is a simple model with only one turbine that is set at 90% efficiency. The steam generator flow and temperature parameters are entered into the program in order to generate the results. Several other assumptions must be made for the cycle. The assumptions made can be seen in Table 5-1. This is in reference to the diagram of Figure 5-1. The program can be used to produce a temperature-entropy (T-s) diagram along with various other parameters. The maximum or Carnot efficiency of the plant is 48.19% and the thermal efficiency (without reheat or feed water heat) is 38.14%. This produces 383.2 MW of net electrical power. This calculation gives an estimate of what the power plant performance could be. Figure 5-1 and Figure 5-2 show the results of the preliminary calculations. These values can then be referred to when calculations with ORCENT2 are performed.

## 5.2 Turbine-Cycle Heat Balance Modeling

It is common practice to perform a turbine-cycle heat balance in order to predict performance of the various components of the plant and to obtain the gross heat rate performance of the cycle and turbine. This heat balance model considers the feed water

**Table 5-1: Assumptions Made in Cycle Pad**

| | |
|---|---|
| Cycle is a heat engine | Condenser does not work isochorically |
| Environmental temperatures are neglected | Condenser does not work isobarically |
| Isentropic processes are treated as ideal | IRIS SG works isobarically |
| The working fluid is water | Pump works isentropically |
| Turbine set works adiabatically | P(S1) = 7.0 MPa (1015.2 psia) |
| Turbine set does not work isentropically | T(S1) = 317.0°C (602.6°F) |
| Turbine set does not work isothermally | P(S2) = 0.0049 MPa (0.71 psia) |
| Turbine set has an efficiency of 90% | T(S3) = 32.60°C (90.68°F) |
| The working fluid at S3 is saturated | T(S4) = 212.0°C (413.6°F) |
| The working fluid at S1 is superheated vapor | Flow rate = 500.3 kg/s (3,971 kip/hr) |

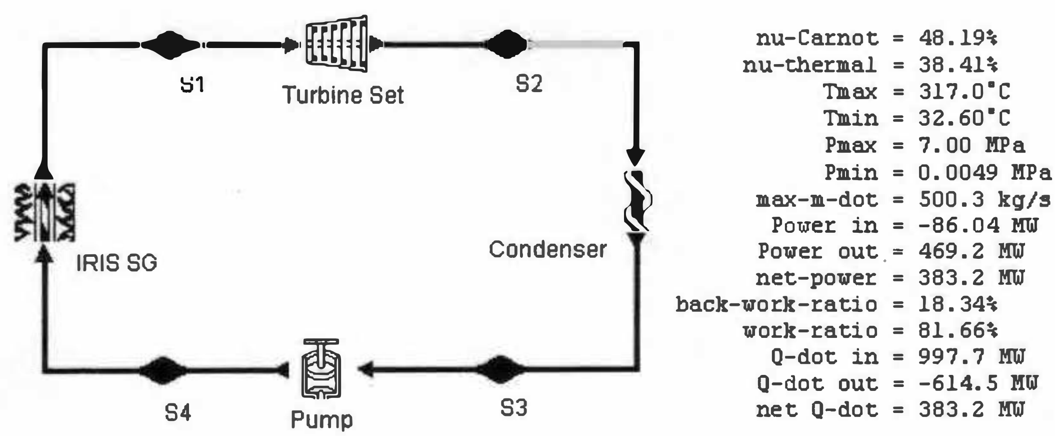



**Figure 5-1: Thermodynamic Analysis of Simplified IRIS**

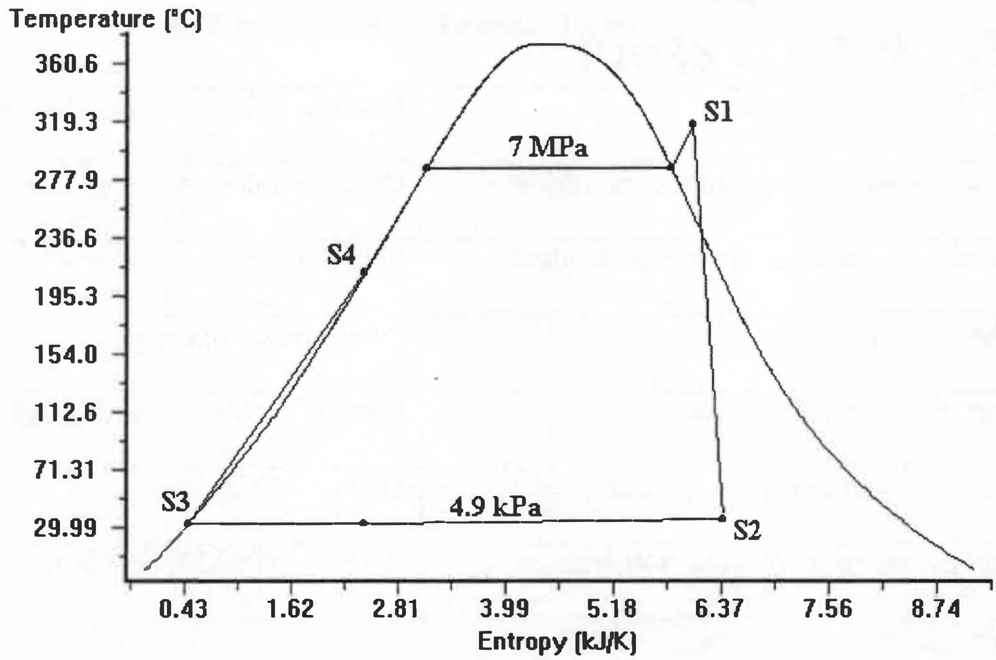



**Figure 5-2: Temperature – Entropy (T-s) Diagram of Simplified IRIS BOP**

heaters and extractions along with the inter-stage reheat and moisture separation. The following definitions are used for the gross heat rate (GHR) and net heat rate (NHR). It is important to note that the heat input is in Btu/hr and the outputs are in kW.

$$GHR = \frac{heat\ input}{generator\ output + auxiliary\ turbine\ output} \quad (5.1)$$

$$NHR = \frac{heat\ input}{generator\ output} \quad (5.2)$$

The system is modeled in ORCENT2 (ORNL, 2000), an advanced generalized heat balance program. This program is designed for general-purpose study of power plants using steam cycles larger than 100 MWe in output. The program generates a complete heat and mass balance. The process flow of the program can be seen in Figure 5-3. It is designed to determine the effects due to the variation of the following parameters:

- Main steam pressure and temperature
- Reheat steam pressure and temperature
- Steam generator and reheater pressure drops
- Condenser pressure
- Number of feed water heaters
- Type of feed water heaters
- Method of heater drain disposal
- Drain cooler approach
- Feed water heater terminal temperature difference

- Steam extraction for the auxiliary steam turbine
- Steam extraction for an industrial usage (n/a)
- Turbine exhaust end loss
- Steam extraction pressures
- Different drive mechanisms for the feed water pump
- Part-load performance calculation

### 5.2.1 Turbine Expansion Lines

Internal efficiency of the turbine is used to determine the turbine expansion line. The equation is displayed in 5.3. This is calculated for both the HP and LP units. The efficiencies found are typical for steam turbines. A complete table of the expansion line calculation results is in Appendix A - Table II.

$$\eta_i = \frac{h_i - h_e}{h_i - h_{es}} \qquad (5.3)$$

$h_i$ = *enthalpy at the turbine inlet*

$h_e$ = *enthalpy at the turbine outlet*

$h_{es}$ = *enthalpy at the isentropic turbine outlet*

Internal Efficiency for HP turbine $\eta_i = \frac{1249.8 - 1122}{1249.8 - 1103.15} = 0.87$

Internal Efficiency for LP turbine $\eta_i = \frac{1283.8 - 978}{1283.8 - 915.01} = 0.83$

Figure 5-4 shows the results of the calculation of the turbine expansion line by ORCENT2. In this figure the entropy values at each of the extraction points can be seen. The values with H and P are the enthalpy and pressure in Btu/lb and psia respectively. The lowest value of each turbine's curve is the one associated with the expansion line-

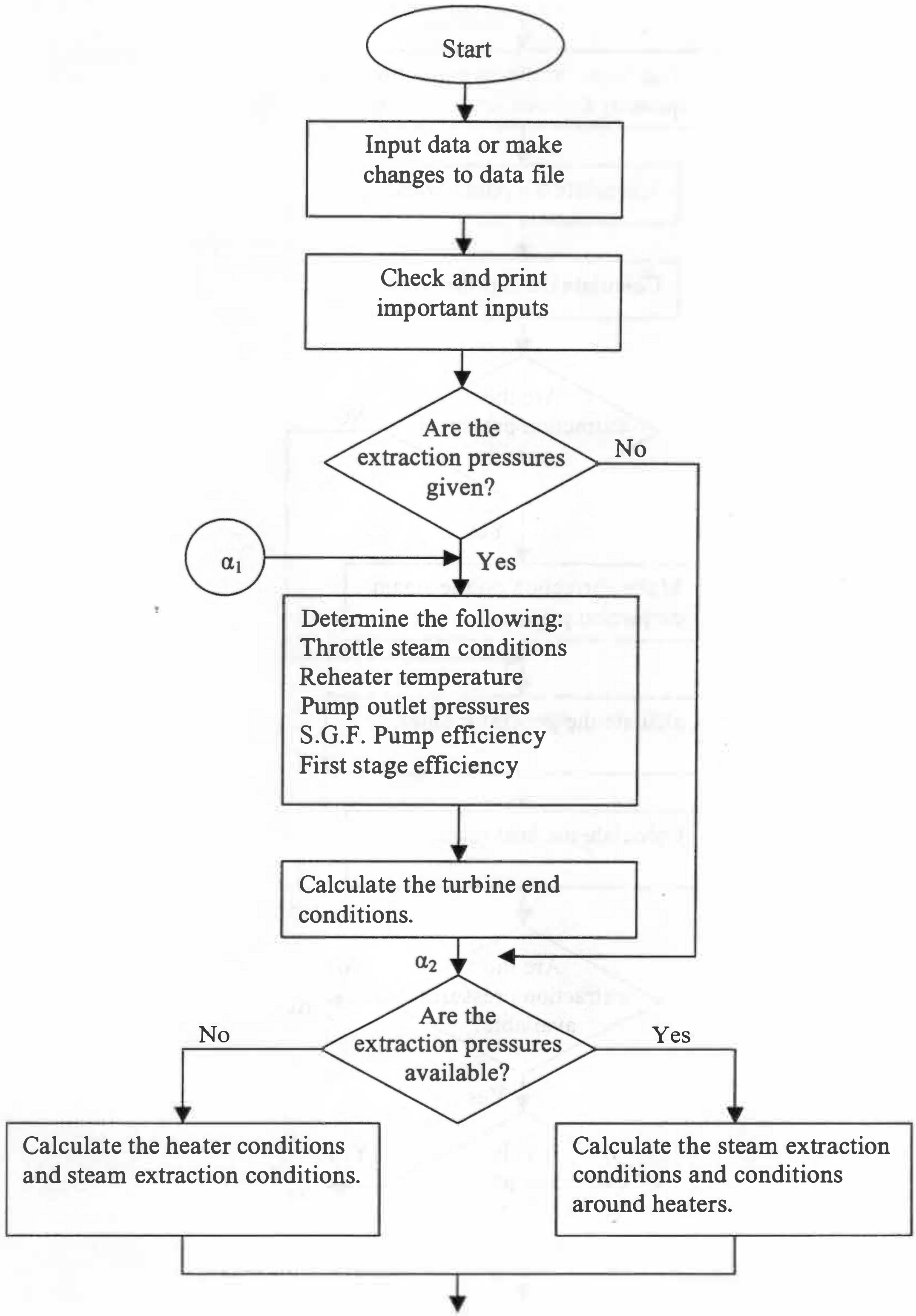



**Figure 5-3: Flowchart of ORCENT2 Program (*Source: Li, 1985*)**

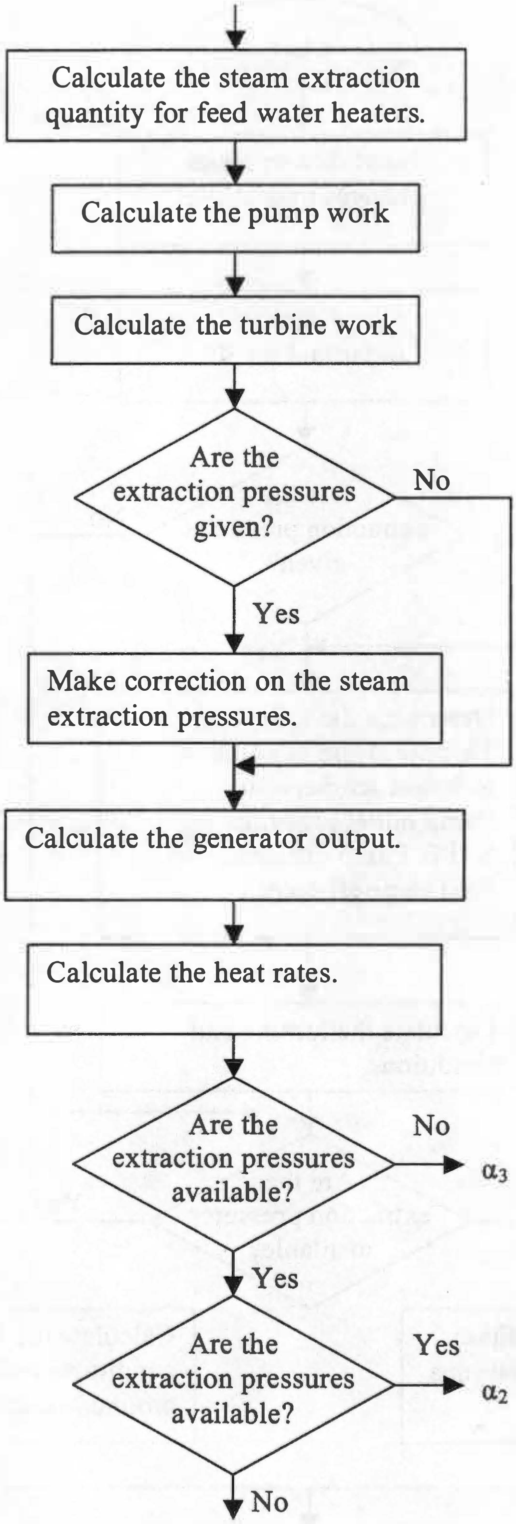



**Figure 5-3: Flowchart of ORCENT2 Program (cont.)**

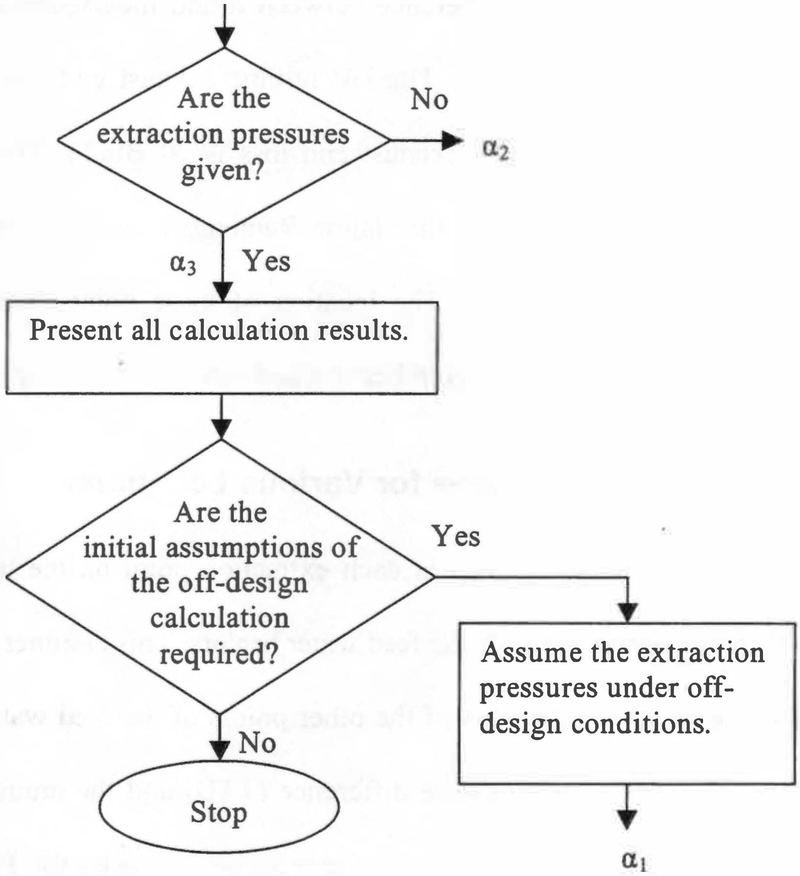



**Figure 5-3: Flowchart of ORCENT2 Program (cont.)**

end point (ELEP). The difference between it and the used-energy-end point (UEEP) is called the exhaust end loss. The HP turbine exhaust end loss is determined to be 1.5 Btu/lb and the LP turbine exhaust end loss is 20 Btu/lb. The extraction points of the turbines can also be seen in the figure. Remember the HP unit has one extraction point and the LP unit has three. The location of these points can be manipulated to help improve performance through reheating and feed water heating.

### 5.2.2 Steam Conditions for Various Locations

The conditions taken at each extraction point on the turbine expansion line are used as inlet conditions for the feed water heaters. This assumes there are no losses due to piping runs. The conditions of the other points of the feed water heaters are determined using the terminal temperature difference (TTD) and the drain cooler approach (DCA). Equation 5.4 and 5.5 show the two approaches respectively. Pressure drop is neglected across the heater for the heat balance calculation. Utilizing this, the states surrounding the feed water heaters can be determined. The results are in Appendix A - Table VII.

$$
\begin{aligned}
&T_e = T_s - TTD \\
&T_e = feedwater\ exit\ temperature \\
&T_s = extraction\ steam\ saturation\ temperature
\end{aligned} \tag{5.4}
$$

$$
\begin{aligned}
&T_d = T_i - DCA \\
&T_d = feedwater\ drain\ exit\ temperature \\
&T_i = temperature\ of\ entering\ feedwater
\end{aligned} \tag{5.5}
$$

### 5.2.3 Extraction Flow Rates

Calculation of the extraction flow rates begins with the highest-pressure heater and

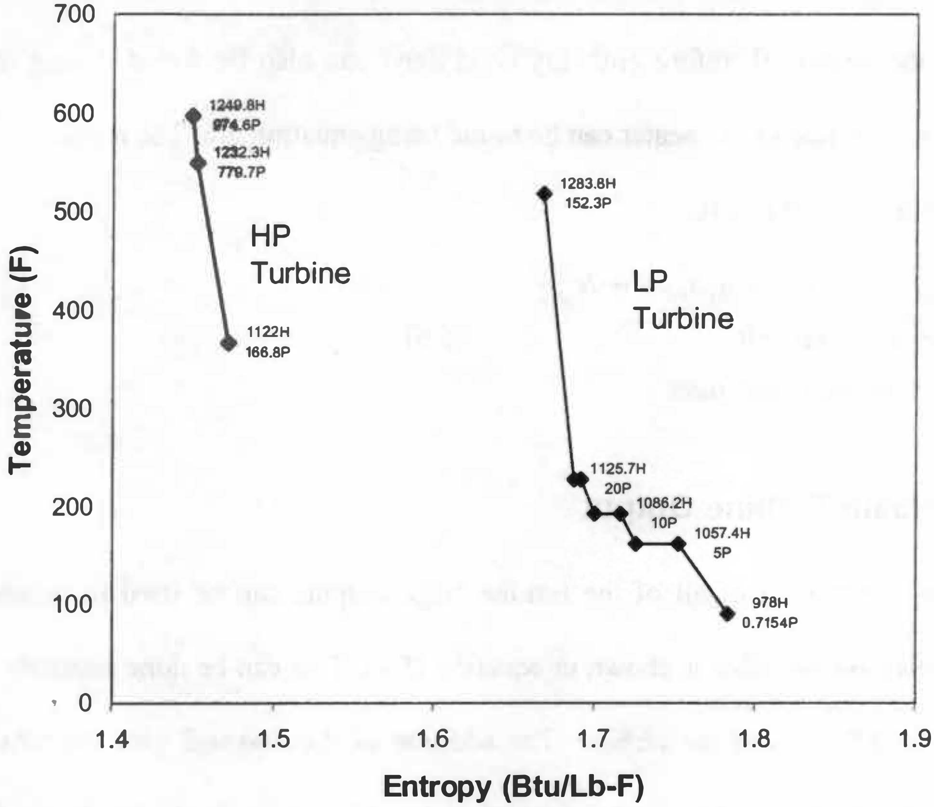



**Figure 5-4: Turbine Expansion Line**

flows down to the condenser. The temperature and pressure conditions are known around each of the heaters therefore enthalpy conditions can also be found. Using these, the extraction flow rate of the heater can be found using equation 5.6. The results can be seen in Appendix B - Table VII.

$$\dot{m}_h h_{h,i} + \dot{m}_c h_{c,i} = \dot{m}_h h_{h,e} + \dot{m}_c h_{c,e} \quad (5.6)$$

$_{i,e}$ = *inlet and exit*

$_{h,c}$ = *hot and cold sides*

### 5.2.4 Steam Turbine Output

The summation of all of the turbine stage outputs can be used to determine the turbine work output. This is shown in equation (5.7). This can be done similarly for both the HP and LP units of the turbine. The addition of the two will give the total turbine output as in equation (5.8). The turbine exhaust end loss can also be used with the gross output, mechanical coupling efficiency and generator efficiency in order to determine the net turbo generator output as shown in equation (5.9). The results can be seen in Appendix B - Table I.

$$\dot{W}_t = \sum \dot{m}_i h_i - \sum \dot{m}_e h_e \quad (5.7)$$

$$\dot{W}_t = \dot{W}_{HP} + \dot{W}_{HP} \quad (5.8)$$

$$\dot{W}_{net} = \eta_{coupling} \eta_{generator} (\dot{W}_t - loss_{exhaust}) \quad (5.9)$$

### 5.2.5 Turbine System Net Heat Rate

Using the heat supplied to the system from the primary system the turbine net heat rate (NHR) can be calculated. This takes into account the amount of heat supplied in the steam generator (SG), and the two reheat stages (RH1 and RH2). Equation 5.10 shows the heat input calculation and equation 5.11 is the calculation of the NHR. The results can be seen in Appendix B - Table I.

$$\dot{Q} = \dot{m}_{SG}(h_{SG,e} - h_{SG,i}) + \dot{m}_{RH1}(h_{RH1,e} - h_{RH1,i}) + \dot{m}_{RH2}(h_{RH2,e} - h_{RH2,i}) \qquad (5.10)$$

$$NHR = \frac{Heat\ input}{turbo-generator\ net\ output} \qquad (5.11)$$

## 5.3 Heat Exchanger Calculation

Heat exchanger analysis is performed using one of two typical procedures. These are the log mean temperature difference (LMTD) method and the number of transfer units (NTU) effectiveness approach. For solving problems involving predetermined hot and cold inlet and outlet temperatures the LMTD method is most effective. These problems are called heat exchanger design problems because the LMTD is determined. This is opposed to the NTU method, which is known as a heat exchanger performance calculation. For the cases in this research the LMTD method is appropriate because inlet and outlet temperatures are known along with the mass flow rates. These values have been determined in the heat balance calculation by ORCENT2. Thus only the heat exchanger type and heat transfer surface area are all that is left to be determined. The desired effect is to make the cold leg outlet temperature the desired value. This involves an iterative method and is therefore calculated in a spreadsheet for easy manipulation. A key aspect to all of the heat exchanger designs is the fact they are condensing heat exchangers.

Condensation occurs in all of the feed water heaters, the reheater and, of course, the condenser. This gives the extra problem of determining the average convection coefficient. Due to the phase change of the working fluid, latent heat effects are significant and must be incorporated into the design. Not only are there latent heat effects but liquid interface and density issues also increase the heat transfer rates over normal convection. This is due to surface tension and buoyancy forces that improve flow characteristics of the coolant. Condensation occurs when the temperature of a vapor is reduced below its saturation temperature. In our case this results from the hot steam vapor making contact with the cooler surface of the tubes in the tube-in-shell heat exchangers. The vapor releases its latent heat, this heat is transferred to the surface (and to the coolant liquid inside the tubes) and condensate is formed. This is done in order to regain energy input during boiling and therefore increase efficiency of the system. Also in the case of the IRIS plant, the feed water inlet temperature of the steam generator must be strictly maintained for safety purposes. The condensation occurs in two forms, film and drop wise, on smooth and rough surfaces respectively. For these cases the condensation is assumed to be film condensation because it is occurring over the outside of smooth, clean tubes. Of course over time the cleanliness might change thus slightly affecting the condensation type. In film condensation the liquid covers the entire condensing surface and flows with gravity continuously from one tube to the next. This is illustrated in Figure 5-5. Equation 5.12 governs the average convection coefficient of a horizontal tube bank with continuous condensate. This equation is often used in condenser design. It is assumed that heat transfer to the sheet between the tubes and the

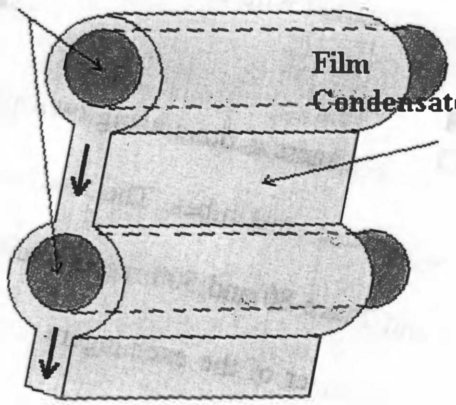



**Figure 5-5: Vertical Tier of Horizontal Tubes with Continuous Condensate Sheet**

***(Source: Incropera, 1996)***

$$\overline{h}_{D,N} = 0.729\left[\frac{g\rho_l(\rho_l-\rho_v)k_l^3 h'_{fg}}{N\mu_l(T_{sat}-T_s)D}\right]^{1/4}$$

$$\begin{aligned}
&\rho = Density\ (l - liquid, v - vapor)\\
&N = Number\ of\ tube\ rows\\
&h'_{fg} = Heat\ of\ vaporization\\
&\mu_l = Viscosity\\
&D = Diameter\ of\ tube\\
&k = Thermal\ conductivity\\
&T_{sat} = Saturation\ temperature\\
&T_s = Tube\ temperature
\end{aligned} \qquad (5.12)$$

momentum gain of the falling condensate are both negligible. It is also assumed here that the tube temperature is an average temperature value across the heat exchanger and does not vary from top to bottom. The tube bank is assumed to be zigzag design therefore the rows in the tube bank would be counted by skipping every other row. With this in mind the calculation can be done for each of the heat exchangers inside of the heat exchanger calculation. The value must be iterated with the design due the changing size of the heat exchanger.

The design of the heat exchangers is done using two-pass tube-in-shell design with 1" OD 18 (BWG), ferritic stainless steel tubes. The feed water heaters have 5000 tubes each, the reheat stages 1 and 2 have 80 and 500 respectively, and the condenser has 4000 tubes. This determines the diameter of the exchangers and leaves only the lengths to be determined. The diameter of the unit can be determined from the curve fit plot in Figure 5-6. As stated previously the design calculation is done using a spreadsheet. Figure 5-7 shows the known properties of the fluid entering and exiting the heat exchanger. The cold exit temperature is known and is used as the point of iteration. After these properties are entered for each exchanger, the iterations on cold exit temperature can be made by variation of the heat exchanger length. This is done until the desired cold exit temperature is achieved. The equations that are used in order to do this are 5.13 through 5.21. Figure 5-8 shows the correction factor to be used in equation 5.21 after the determination of P and R from equations 5.19 and 5.20 respectively.

$$T_{c,o} = T_{c,i} + \frac{q}{\dot{m}_c c_{p,c}} \tag{5.13}$$

$$U = \frac{1}{(1/h_i) + (1/h_o)} \tag{5.14}$$

$$\mathrm{Re}_D = \frac{4\dot{m}}{\pi D \mu} \tag{5.15}$$

$$\begin{aligned} Nu_D &= 0.023\,\mathrm{Re}_D^{4/5}\,\mathrm{Pr}^{0.4} \ \textit{(turbulent flow)} \\ Nu_D &= 4.36 \ \textit{(laminar flow)} \end{aligned} \tag{5.16}$$

$$\mathrm{h_i} = Nu_D \frac{k}{D} \tag{5.17}$$

$$\Delta T_{lm,CF} = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln[(T_{h,i} - T_{c,o})/(T_{h,o} - T_{c,i})]} \quad (5.18)$$

$$P = \frac{T_{c,o} - T_{c,i}}{T_{h,i} - T_{c,i}} \quad \textit{(Used to find F from Fig. 5-8)} \quad (5.19)$$

$$R = \frac{T_{h,i} - T_{h,o}}{T_{c,o} - T_{c,i}} \quad \textit{(Used to find F from Fig. 5-8)} \quad (5.20)$$

$$\mathrm{L} = \frac{q}{\mathrm{U(N2\pi D)F}\Delta T_{lm,CF}} \quad (5.21)$$

$T_{c,o}$ = *Cold outlet temperature*

$T_{c,i}$ = *Cold inlet temperature*

$T_{h,o}$ = *Hot outlet temperature*

$T_{c,i}$ = *Hot inlet temperature*

$\Delta T_{lm,CF}$ = *Log mean temperature difference*

$q$ = *Heat transfer rate*

$\dot{m}_c$ = *Mass flow rate of cold side*

$c_{p,c}$ = *Specific heat of cold side*

$D$ = *Diameter of tubes*

$\mu$ = *Dynamic viscocity*

$\mathrm{Re}_D$ = *Reynolds number*

$Nu_D$ = *Nusselt number*

$Pr$ = *Prandle number*

$P, R, F$ = *Correction factor coefficients*

$k$ = *Thermal conductivity*

$h$ = *Enthalpy in and out*

$U$ = *Overall heat transfer coefficient*

$N$ = *Number of tubes*

The results of the heat exchanger calculations give not only the sizes but also approximate weights of the units. Each unit's weight is approximated as the total weight of the combined tubes in addition to the weight of a pressure vessel to hold them. The pressure vessel is assumed to be a 1" thick hollow steel vessel. The moisture separator

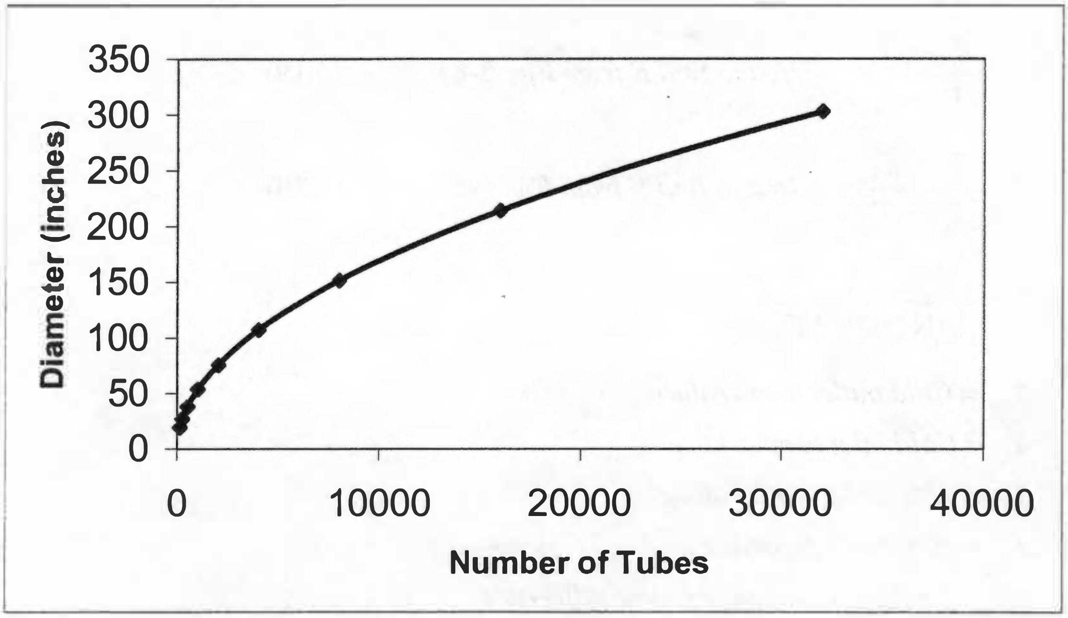



**Figure 5-6: Heat Exchanger Diameter as a Function of Tubes**

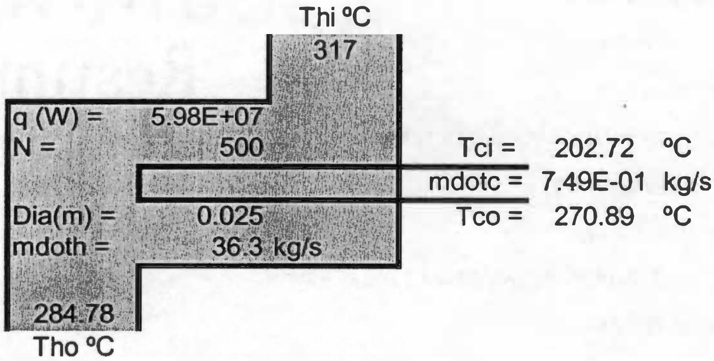



**Figure 5-7: Heat Exchanger with Known Parameters**

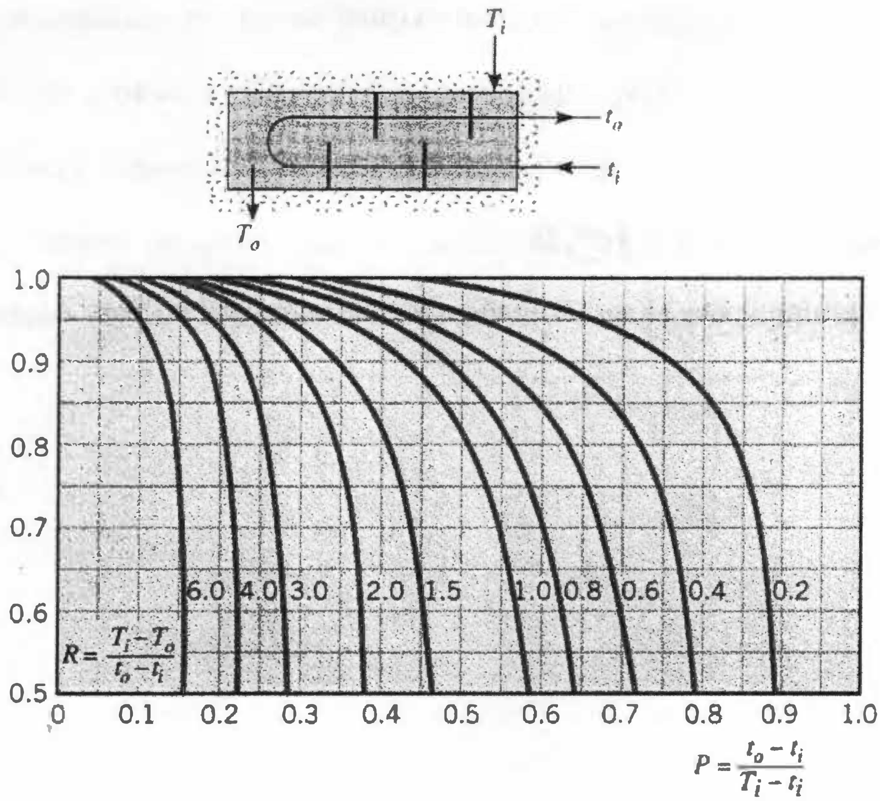



**Figure 5-8: Correction Factor for a Shell-and-Tube Heat Exchanger w/2 Tube Passes**

**(*Source: Incropera, 1996*)**

reheater (MSR) size is approximated from existing designs in combination with the calculations. Sizing of the MSR is dependent on the moisture separation and drain tank reserve size, which the design of is beyond the scope of this project. These sizes are useful for determining the transportation and layout issues in the later chapters. Table 5-2 gives the results of the calculations. With these results, models of the plant can be made.

**Table 5-2: Heat Exchanger Sizes and Weights**

| Name | Length (m) | Diameter (m) | Weight (tons) |
|---|---|---|---|
| Feed water #1 | 16.61 | 3.05 | 107 |
| Feed water #2 | 4.38 | 3.05 | 31 |
| Feed water #3 | 8.55 | 3.05 | 57 |
| Feed water #4 | 21.08 | 3.05 | 135 |
| Feed water #5 | 19.88 | 3.05 | 128 |
| Feed water #6 | 29.37 | 3.05 | 187 |
| Reheater Stage 1 | 5.25 | 0.40 | 2 |
| Reheater Stage 2 | 5.25 | 1.0 | 6 |
| MSR unit | 6.00 | 3.00 | 16 |
| Condenser | 7.00 | 4.30 | 85 |

# CHAPTER 6

# SOLID MODELING OF COMPONENTS

## 6.1 Description of Work and Software Used

Solid modeling is the creation of three-dimensional virtual components in a computer aided drafting/design (CAD) environment. The virtual components approximate the geometries of the actual design components. These models reflect the major geometries of the design and are excellent for use in finding mass properties, interference, conflicting geometries and layout. SolidWorks® 2001 is a well-known commercial CAD software package. It has the capability of parametric equation implementation into the models in order to constrain one feature with another in the model or assembly. Piping modules along with surface rendering modules are also used from the SolidWorks® Add-ins. Parts are created for each component in the system and then these can be arranged in various layout configurations and then connected with piping. This chapter shows the component feature models and some of the references of the features. The following chapter will cover layout and piping creation.

## 6.2 Component Feature Modeling

In order to create useful yet accurate solid models selective features are chosen as of most importance for this study. Key features of the models are general volumetric sizing in order to determine layout size, approximate connection points for piping which are reasonable to actual practice and reference to conventional design practice. Most components can be approximated using cylindrical shapes with pipe connections or otherwise parallelepipeds. Specifics of each solid model are given in the following sections. This should help the understanding that is inherent into each component. Dimensioned drawings can be seen in Appendix D for all of the component models.

### 6.2.1 Primary System Components

The IRIS model contains the major external cylindrical geometry of the reactor vessel. The dimensions are taken from preliminary schematics in AutoCAD format acquired from Westinghouse (Conway, 2001). The internals of the reactor are of no importance to this study and are therefore neglected in order to save time and file space. It is important to use the vessel geometry in order to achieve proper elevations of primary to secondary components in the final layout. Of more importance is the geometry of the containment. It is recreated somewhat more accurately in order to determine an approximate weight of the primary unit. Other than these two essential components the remainder of the primary systems, i.e. passive cooling and refueling systems, are neglected. However the main steam and main feed water-piping runs are preserved. Figure 6-1 shows a perspective view of the reactor vessel and the containment structure inside the reactor building.

### 6.2.2 Steam Turbine and Generator

Correct sizing of the turbine and generator are very important in order to determine proper layout. However, without a complete turbine design for this very specific application, exact sizing of the components must be made from referencing other designs.

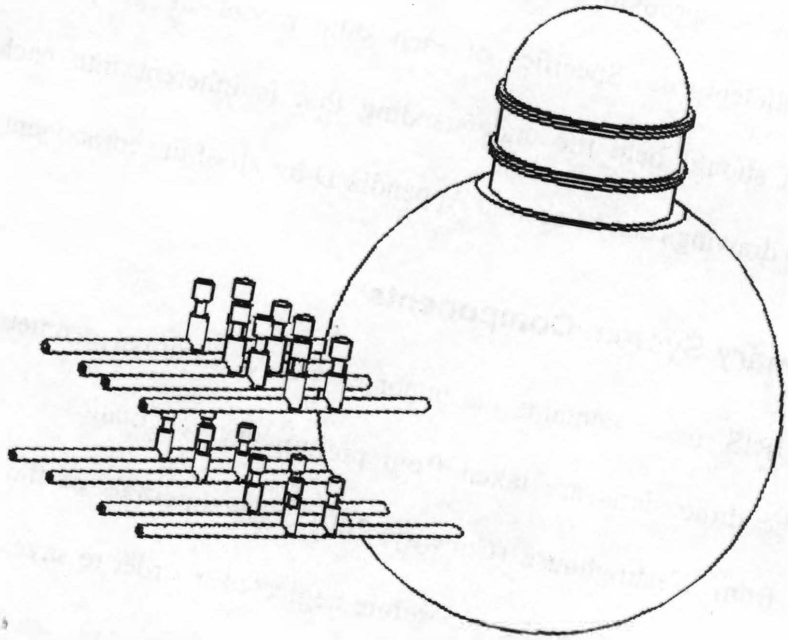


**Figure 6-1: IRIS Reactor Containment Structure Perspective (*Source: Conway, 2001*)**

Various steam turbine designs have been reviewed in order to find the sizes and weights of the steam turbine and generator. The final weight results are most likely within a 10% error of what the actual unit would weigh. The approximated weight of the unit is 1600 tons (1.5 Gg). The weight is taken as 30% of the volume as solid stainless steel. This value was referenced to various other turbine systems and would appear to be a fair estimation of the actual weight. A perspective view of the steam turbine model can be seen in Figure 6-2. It is important to note that the various steam extraction points are not exact in location, however they have been placed in a similar fashion to existing technology.

### 6.2.3 Feed water heaters

The feed water heater models are quite simplistic. They only show the five connection points of the two hot and two cold legs along with the drain cooler inlet from the above feed water heater. In actual design practice pipe connections are variable in placement but are typically placed as shown in the models. One of the six feed water heaters can be seen in Figure 6-3.

### 6.2.4 Moisture Separator Reheater

The MSR unit has various connection points due to the integral unit. There are four hot leg connections, one for each stage, along with the two cold leg connections and the drain cooler connection. The unit is otherwise cylindrical in shape like the feed heaters. Figure 6-4 shows a perspective view of the unit.

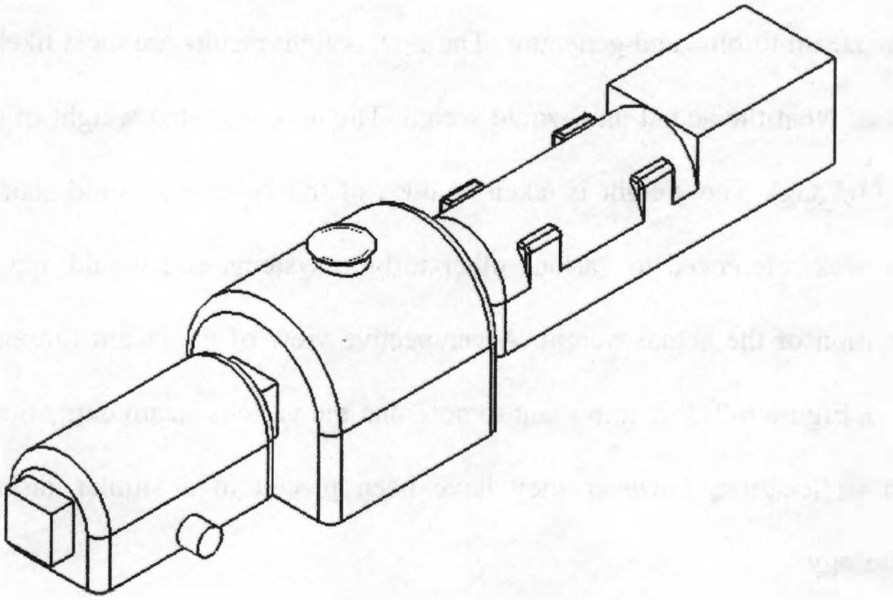


**Figure 6-2: Steam Turbine Generator Perspective**

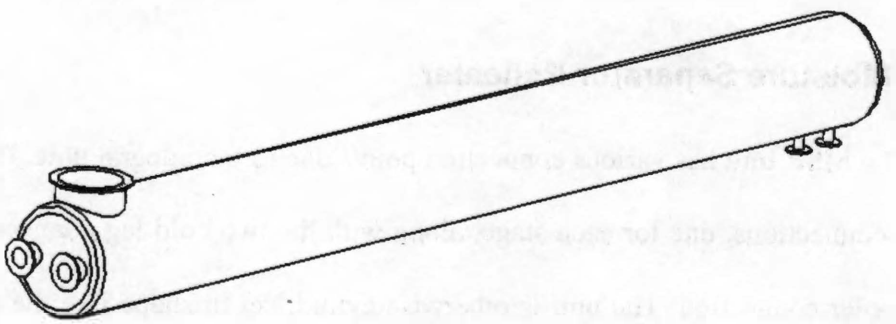


**Figure 6-3: Feed Water Heater Perspective**

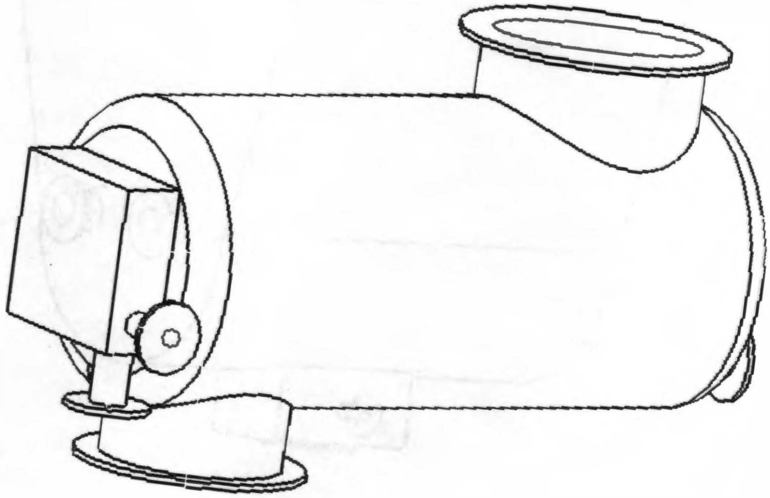


**Figure 6-4: MSR Unit Perspective**

## 6.2.5 Condenser

The condenser unit is cylindrical in shape at the bottom with a louver or expansion joint that connects it to the bottom of the LP turbine unit. There are three other connections the cold water inlet and outlet, along with the condensate drain pump connection. The perspective view of the condenser can be seen in Figure 6-5.

## 6.2.6 Pipes

Piping runs are considered in the assembly layout modeling. It is important to know the piping runs because they contribute to the total space and weight of the system. In our case there are 30 piping runs in the balance of plant system. Each piping run is unique to

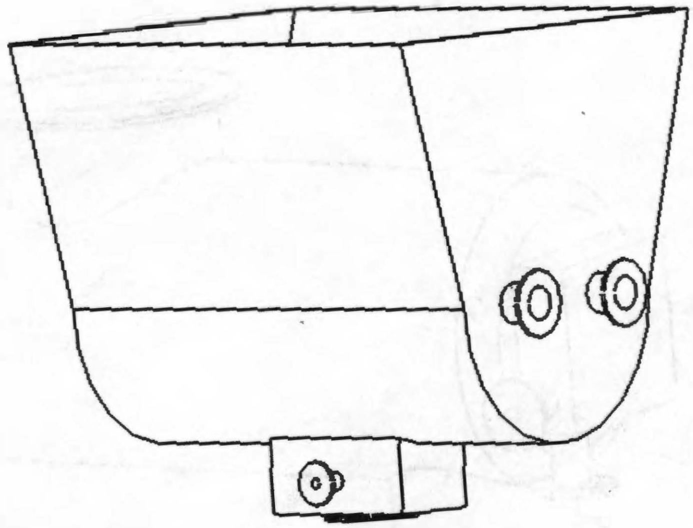


**Figure 6-5: Condenser Perspective**

its equipment and therefore an example figure is not shown. However a complete listing of the piping components can be seen in Appendix D.

### 6.2.7 Other components

Some of the other components are pumps and valves. These components do not contribute to the weight or space requirements as much as the previous components. However they are included in the instances where they deem most needed. The condensate and feed water pump are sized to approximate specifications. The valves are more of an aesthetic addition to the layout and are drawn with minimal detail. These components can be seen in the final layout drawings.

# CHAPTER 7

# PLANT LAYOUT

## *7.1 Assembly Solid Modeling*

There are two main sub assemblies: the reactor building assembly and the balance of plant assembly. Each are created separately and the combined into the final layout assembly. Of key importance during the layout of the plant is the prevention of interferences of the geometries involved and proper spacing of the components. Also correct usage of piping runs in order to prevent tight turning radii. The final result of the assembly process should be a layout of the balance of plant in respect to the primary system. This will give a projected weight of the plant. Another goal of the assembly model is the determination of the footprint of the plant. Here the footprint is defined as the surface space occupied by the plant structure. This area can be used to determine the situation and modularization restrictions of the plant. This can then be used to do further design and plant modularization. Assembly model files can be found in on the accompanying CD-ROM in the SolidWorks® 2001 format.

### 7.1.1 Reactor Building

The reactor building and containment structure is created first. Westinghouse has designed this for the IRIS primary plant. The building is roughly 40m x 50m (132' x 164') rectangular. This structure contains a reactor vessel, a spherical containment and the main steam and feed water return piping. There are four main steam lines and four feed water returns (one for every two steam generators). The building assembly also houses the main steam valves along with the refueling apparatus. These can be seen in Figure 7-1 and Figure 7-2.

### 7.1.2 Balance of Plant

The balance of plant model is the more important of the two sub assemblies. It contains many more parts and has many more piping runs than the primary system. The initial concept is to place the turbo generator set axially in line with the primary component. The high-pressure turbine is facing the primary component in order to assist with the connection of the steam lines. It is important to note that this setup prevents rupture of the containment due to turbine blade failure. This is an important safety feature. The reheater is offset arbitrarily to one side of the HP unit in order to facilitate connections of the main steam line. The feed water heaters are aligned in descending order clockwise under the bottom of the turbine. This is in order to facilitate the connection of the extraction steam lines. The condenser is placed under the LP turbine, as is convention with the coolant intake facing away from the containment. In Figure 7-3 the general layout of the balance of plant can be seen.

Now that the balance of plant layout is complete, the piping runs can be measured in order to determine the weights and lengths. It is also important to calculate the number of 90° elbows and flanges involve in the assembly, because they too will contribute to the total weight. Also there are 7 'tee' connectors in the assembly. These are the connections involving three pipe ends. The total volume of each piping run is determined

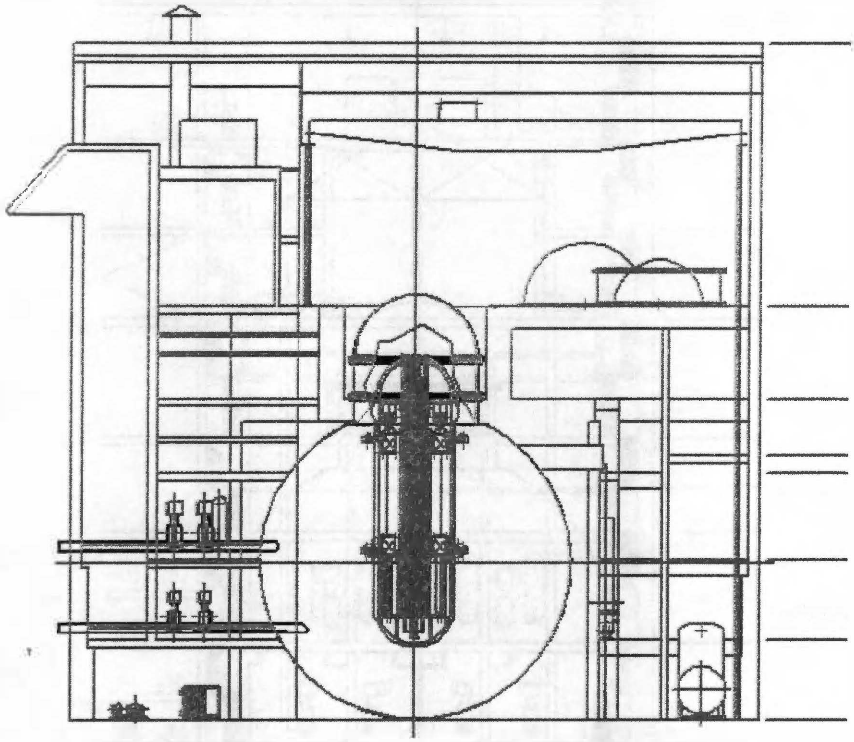


**Figure 7-1: IRIS Reactor Vessel and Containment Structure Detail (Front) (*Source: Conway, 2001*)**

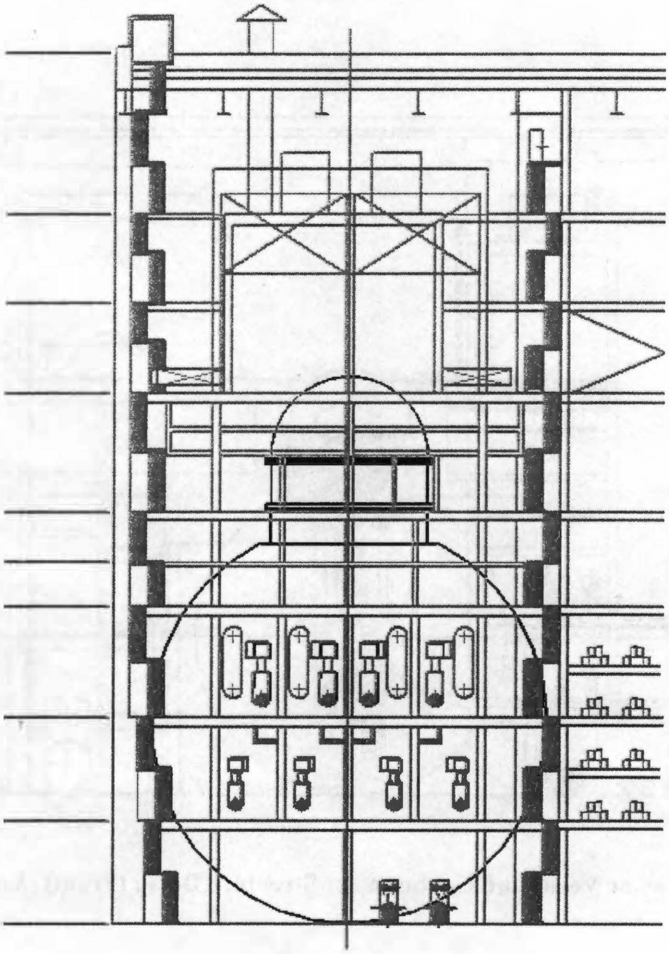


**Figure 7-2: IRIS Reactor Vessel and Containment Structure Detail (Left) (*Source: Conway, 2001*)**

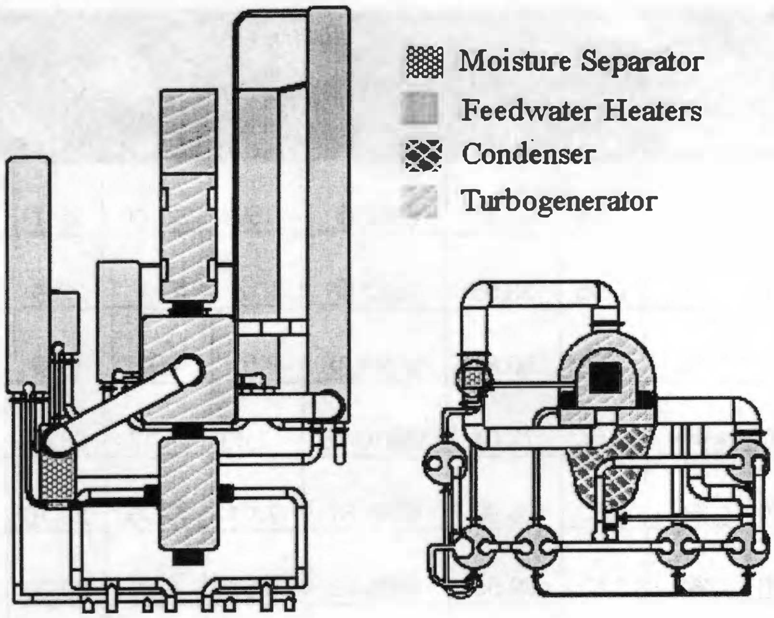



**Figure 7-3: Balance of Plant Layout**

from the solid models and multiplied by the density of stainless steel in order to determine the weight. Table 7-1 shows the results of the piping run calculations. The table includes: the pipe diameters, the volume, the weight, the length and the numbers of elbows and flanges. These weight values are useful for the determination of the total weight of the balance of plant in the following subsection. The other values could prove useful in the fabrication and modularization to be done in future work.

### 7.1.3 Footprint and Weight of Balance of Plant

One of the main goals of the research is the determination of the total plant footprint and weight. The footprint of the plant can be taken from a projection of the solid model layout. It is important to note that the reactor building size was predetermined from the Westinghouse design. It was a rectangular building of 40m x 56m (132' x 184').

**Table 7-1: Piping Runs in Assembly Model**

| Diameter | | Volume | | Weight | | Length | | Elbow | Flanges |
|---|---|---|---|---|---|---|---|---|---|
| mm | inches | m^3 | ft^3 | kg | ton | m | ft | # | # |
| 600 | 24 | 0.89 | 31.43 | 6897.83 | 7.60 | 12.00 | 39.37 | 2 | 2 |
| 600 | 24 | 0.95 | 33.55 | 7362.85 | 8.12 | 6.90 | 22.64 | 2 | 2 |
| 1800 | 72 | 2.29 | 80.87 | 17748.35 | 19.57 | 6.00 | 19.69 | 1 | 2 |
| 1000 | 40 | 2.04 | 72.04 | 15810.76 | 17.43 | 8.12 | 26.64 | 3 | 2 |
| 600 | 24 | 0.82 | 28.96 | 6355.31 | 7.01 | 7.06 | 23.16 | 1 | 2 |
| 600 | 24 | 1.12 | 39.55 | 8680.42 | 9.57 | 8.90 | 29.20 | 2 | 2 |
| 600 | 24 | 0.76 | 26.84 | 5890.28 | 6.49 | 4.80 | 15.75 | 2 | 2 |
| 600 | 24 | 1.89 | 66.74 | 14648.20 | 16.15 | 16.21 | 53.18 | 3 | 2 |
| 600 | 24 | 0.52 | 18.36 | 4030.19 | 4.44 | 3.70 | 12.14 | 0 | 2 |
| 600 | 24 | 0.72 | 25.43 | 5580.27 | 6.15 | 5.90 | 19.36 | 1 | 2 |
| 400 | 16 | 0.53 | 18.72 | 4107.70 | 4.53 | 7.02 | 23.03 | 1 | 2 |
| 350 | 14 | 0.68 | 24.01 | 5270.25 | 5.81 | 11.76 | 38.58 | 1 | 2 |
| 300 | 12 | 0.53 | 18.72 | 4107.70 | 4.53 | 7.59 | 24.90 | 3 | 2 |
| 250 | 10 | 1.12 | 39.55 | 8680.42 | 9.57 | 29.62 | 97.18 | 3 | 2 |
| 250 | 10 | 0.35 | 12.36 | 2712.63 | 2.99 | 6.87 | 22.54 | 2 | 2 |
| 200 | 8 | 0.19 | 6.71 | 1472.57 | 1.62 | 3.63 | 11.91 | 2 | 2 |
| 200 | 8 | 0.55 | 19.42 | 4262.70 | 4.70 | 17.38 | 57.02 | 3 | 2 |
| 350 | 14 | 0.58 | 20.48 | 4495.22 | 4.96 | 7.09 | 23.26 | 3 | 1 |
| 250 | 10 | 0.65 | 22.95 | 5037.74 | 5.55 | 13.16 | 43.18 | 4 | 2 |

Table 7-1: Piping Runs in Assembly Model (cont.)

| Diameter | | Volume | | Weight | | Length | | Elbow | Flanges |
|---|---|---|---|---|---|---|---|---|---|
| mm | inches | m^3 | ft^3 | kg | ton | m | ft | # | # |
| 200 | 8 | 0.17 | 6.00 | 1317.56 | 1.45 | 5.76 | 18.90 | 0 | 2 |
| 1500 | 60 | 3.12 | 110.18 | 24181.16 | 26.66 | 9.75 | 31.99 | 2 | 2 |
| 1800 | 72 | 4.58 | 161.74 | 35496.70 | 39.13 | 12.75 | 41.83 | 2 | 2 |
| 600 | 24 | 2.12 | 74.87 | 16430.79 | 18.11 | 20.95 | 68.73 | 2 | 1 |
| 700 | 28 | 2.62 | 92.52 | 20305.97 | 22.39 | 16.44 | 53.94 | 4 | 1 |
| 700 | 28 | 2.62 | 92.52 | 20305.97 | 22.39 | 16.44 | 53.94 | 4 | 1 |
| 600. | 24 | 3.86 | 136.31 | 29916.44 | 32.98 | 15.00 | 49.21 | 0 | 0 |
| | | | | | | | | | |
| | Totals | 36.27 | 1280.86 | 281105.99 | 309.89 | 280.80 | 921.26 | 53 | 46 |

The final layout of the balance of plant is the same width 40m (132') and is 44m (144'). This gives a total footprint of 40m x 100m (132' x 328') roughly the size of a football field. The footprint can be seen in Figure 7-4.

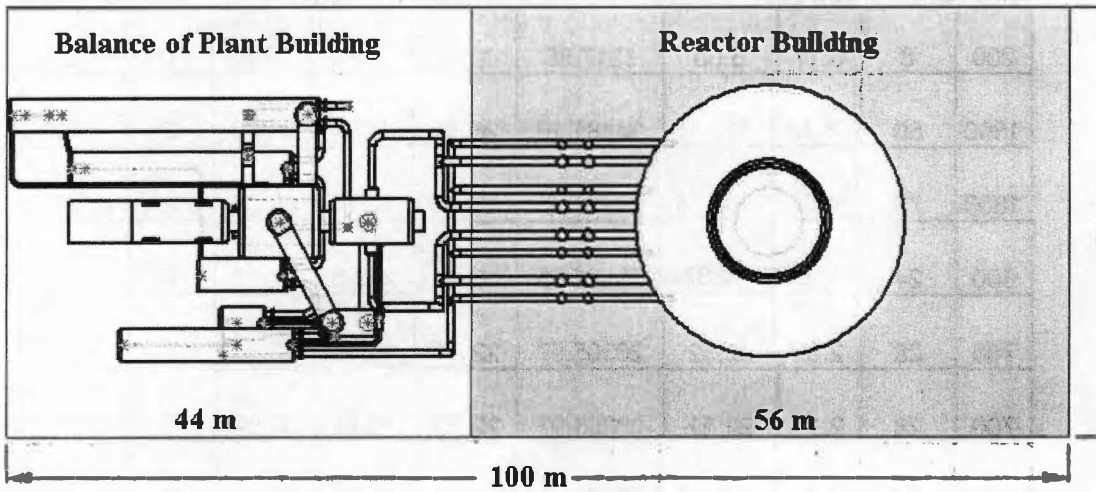



**Figure 7-4: Footprint of IRIS Plant Layout**

The rough weight estimate of the balance of plant is taken as the summation of the pipes and other components in this analysis. Of course many of the subsystems have been neglected, but the major weight is through the contribution of these main components. The contribution of the heat exchanging equipment is 746 tons. The turbo-generator contributes 1600 tons. The piping contributes 310 tons. The estimated weight total is 2656 tons. The containment structure contributes around 3100 tons and the reactor vessel approximately 1600 tons. This gives a rough total of around 7356 tons for the major plant components.

### 7.1.4 Concept Drawings and Visualization

The final result of the assembly modeling is the production of drawings and visualizations of the plant in order to gain both the engineering 'feel' for the components sizes along with the idea of how the plant will take shape. The visualizations can be used to help promote further development and interest in the design. The drawings contain the important information regarding dimensions and locations of the components. A photo rendering of the balance of plant can be seen in Figure 7-5. Photo rendering of the solid model gives a 'lifelike' appearance to the objects using lighting and shadow effects. The component and assembly drawings can be found in Appendix D.

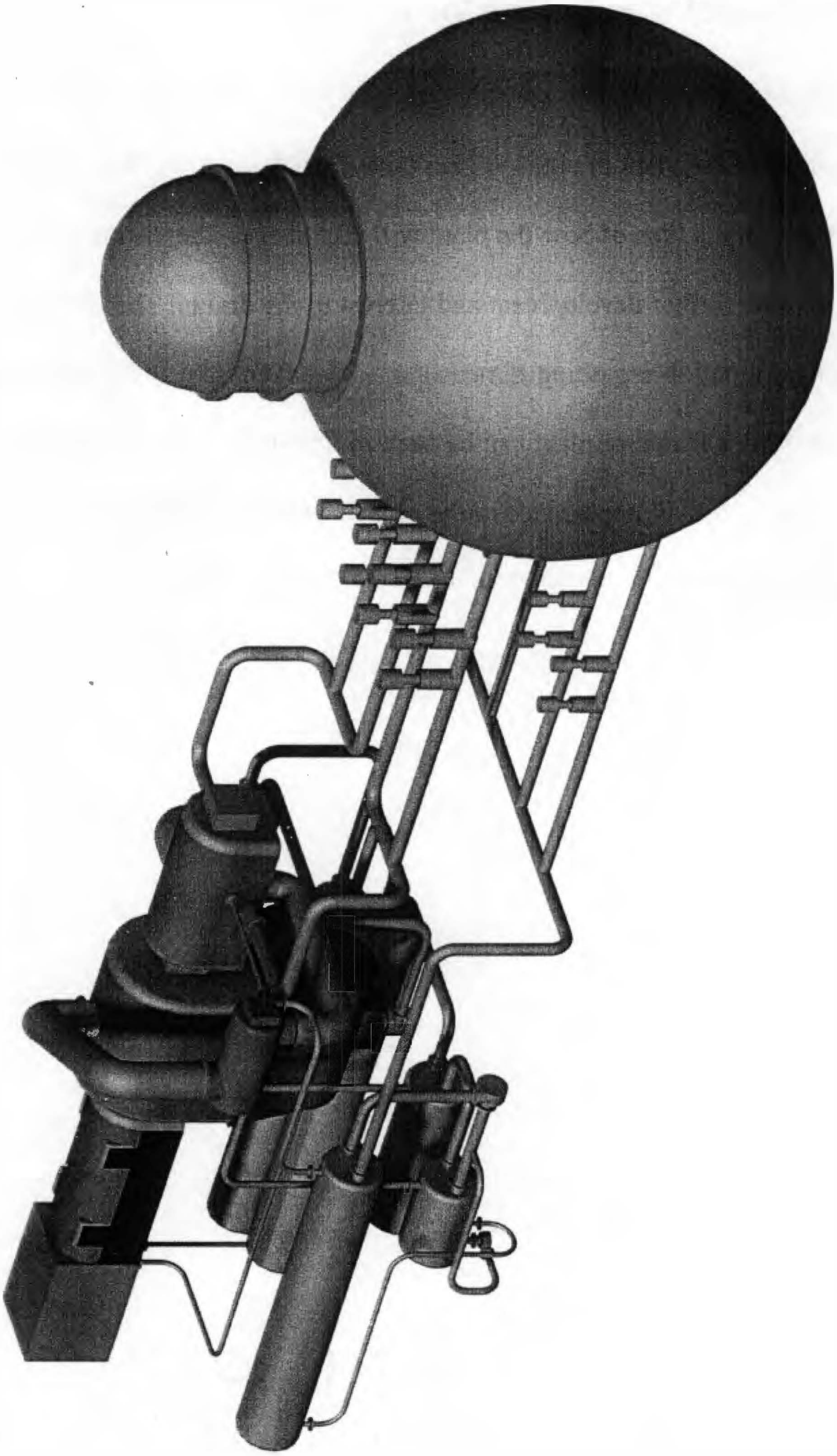


**Figure 7-5: Rendering of Balance of Plant with Primary System**

# CHAPTER 8

# CONCLUSIONS AND FUTURE WORK

## 8.1 Conclusions

This work completes the conceptual design and layout of the balance of plant system for the Westinghouse IRIS. The important major components to be studied have been found. Thermodynamic modeling of the plant has been completed, including a total heat balance calculation. The major components of the balance of plant now have preliminary designs and have been modeled in a CAD environment. The components have been assembled into a preliminary layout of the plant and the sizes and weights found. Piping runs were created to attach the balance of plant to itself and to the primary system. It is believed that these results are substantially enough information to pursue the modularization and fabrication studies needed in the next step of the Westinghouse IRIS power plant design.

## 8.2 Future Work

It is important to note the features not covered in this conceptual design. Some of the items are more important to the system then others, however all would be needed in a complete reactor design. These will be left for future work. Some of those systems are listed as follows: radioactive waste (solid, liquid, and gaseous), spent fuel storage, containment pressure control, auxiliary feed water, emergency core cooling, closed cooling water, service water, circulating water, cooling tower(s), electrical, control, valve, lubrication, air addition/removal, and the substation. Along with this is the design of the structural support and building facilities. The design of these items is beyond the scope of the immediate project and is deemed future work. It is also important to note that further optimization of the thermodynamics cycle can be performed. In order to do this the economics of various designs must be balanced in order to determine the needs of the utility or power provider. The layout of the plant could also be further optimized in order to achieve a higher level of accessibility and modularity. These are just a few of the design tasks involved in the development of a complete nuclear reactor. Nevertheless, the results as shown above for the conceptual design must first be completed in order to view the overall possibility of the power plant concept. It is hoped that this study can be useful in the promising possibility of development and construction of the Generation IV nuclear power plant using the Westinghouse IRIS.

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# APPENDICES

# APPENDIX A

**ORCENT2 input deck**

INPUT DATA

THROTTLE STEAM TEMPERATURE = 602.6 F

THROTTLE STEAM PRESSURE = 1015.2 PSIA

THROTTLE STEAM MOISTURE = 0 PER CENT

ESTIMATED THROTTLE STEAM FLOW = 3800000 LB/HR

FW MAKE-UP RATE (TO CONDENSER HOTWELL) = 0 = PER CENT

CONDENSATE BY-PASSED TO STEAM GENERATOR = 0 LB/HR

THROTTLE FLOW RATIO = 1

REQUIRED STEAM GENERATOR OUTLET FLOW = 3970794 LB/HR

REQUIRED ELECTRICAL OUTPUT = 300 MWE

GENERATOR RATED CAPABILITY = 333.333 MVA

GENERATOR POWER FACTOR = 0.9

GENERATOR OPERATION AT RATED HYDROGEN PRESSURE, IH2 = 0

ROTATIONAL SPEED OF TURBINE-GENERATOR = 1800 RPM

FEEDWATER PUMP ISENTROPIC EFFICIENCY = 0.878

FEEDWATER PUMP TURBINE EFFICIENCY = 0.77

PRESSURE OF FWP INLET ABOVE COND. PRESSURE = 220 PSIA

RATIO OF FWP DISCHARGE PRESSURE TO H-P THROTTLE = 1.31

PITCH DIAMETER OF GOVERNING STAGE = 65 IN.

NUMBER OF PARALLEL H-P SECTIONS = 2

NUMBER OF PARALLEL L-P SECTIONS = 4

BOWL PRESSURE L-P SECTION = 152.3 PSIA

EXHAUST PRESSURE L-P SECTION =0.7154 = PSIA = 1.46 IN. HGA

CONDENSER PRESSURE = 0.7154 PSIA = 1.46 IN. HGA

PITCH DIAMETER OF LAST STAGE L-P SECTION = 132 IN.

LENGTH OF LAST STAGE BUCKETS L-P SECTION = 43 IN.

# OF MOISTURE REMOVAL STAGES LP SECTION = 3

MOISTURE REMOVAL STAGE # 1

MOISTURE REMOVAL STAGE PRESSURE = 20 PSIA

MOISTURE REMOVAL STAGE # 2

MOISTURE REMOVAL STAGE PRESSURE = 10 PSIA

MOISTURE REMOVAL STAGE # 3

MOISTURE REMOVAL STAGE PRESSURE = 5 PSIA

EXTERNAL MOISTURE SEPARATOR DRAINS TO FW HEATER 2, MS = 2

MOISTURE SEPARATOR EFFECTIVENESS = 100 PER CENT

NUMBER OF STAGES OF REHEAT = 2

ESTIMATED STEAM FLOW TO 1ST STAGE REHEATER = 30 LB/HR

TERMINAL TEMPERATURE DIFFERENCE 1ST STAGE REHEATER = 25 F

1ST STAGE REHEATER DRAINS TO FW HEATER # 1, NDRH = 1

ESTIMATED STEAM FLOW TO 2ND STAGE REHEATER = 81 LB/HR

TERMINAL TEMPERATURE DIFFERENCE 2ND STAGE REHEATE = 25 F

2ND STAGE REHEATER DRAINS TO FW HEATER # 1

TOTAL # OF FW HEATERS = 6

# OF FW HEATERS HP SECTION = 2

# OF FW HEATERS LP SECTION = 4

FW HEATER # 1

EXTRACTION STAGE PRESSURE = 330 PSIA

TERMINAL TEMPERATURE DIFFERENCE = 5 F

DRAIN IS FLASHED, ND (1) = 0

THERE IS A DRAIN COOLER SECTION, NDC (1) = 1

DRAIN COOLER APPROACH TEMPERATURE DIFFERENCE = 10 F

FW HEATER # 2

EXTRACTION STEAM FROM MOISTURE SEPARATOR VESSEL

TERMINAL TEMPERATURE DIFFERENCE 5 F

DRAIN IS PUMPED, ND(2) = 1

THERE IS NO DRAIN COOLER SECTION, NDC (2) = 0

FW HEATER # 3

EXTRACTION STAGE PRESSURE = 100 PSIA

TERMINAL TEMPERATURE DIFFERENCE = 5 F

DRAIN IS FLASHED, ND (3) = 0

THERE IS A DRAIN COOLER SECTION, NDC (3) = 1

DRAIN COOLER APPROACH TEMPERATURE DIFFERENCE = 10 F

FW HEATER # 4

EXTRACTION STAGE PRESSURE = 64 PSIA

TERMINAL TEMPERATURE DIFFERENCE = 5 F

DRAIN IS FLASHED, ND (4) = 0

THERE IS A DRAIN COOLER SECTION, NDC (4) = 1

DRAIN COOLER APPROACH TEMPERATURE DIFFERENCE = 10 F

FW HEATER # 5

EXTRACTION STAGE PRESSURE = 20 PSIA

TERMINAL TEMPERATURE DIFFERENCE = 5 F

DRAIN IS FLASHED, ND (5) = 0

THERE IS A DRAIN COOLER SECTION, NDC (5) = 1

DRAIN COOLER APPROACH TEMPERATURE DIFFERENCE = 10 F

FW HEATER # 6

EXTRACTION STAGE PRESSURE = 6 PSIA

TERMINAL TEMPERATURE DIFFERENCE = 5 F

DRAIN IS FLASHED, ND (6) = 0

THERE IS A DRAIN COOLER SECTION, NDC (6) = 1

DRAIN COOLER APPROACH TEMPERATURE DIFFERENCE = 10 F

FW PUMP IS LOCATED BEFORE FW HEATER # 1, IP = 1

FW PUMP IS TURBINE DRIVEN, IFPT = 1

STEAM FLOW TO FW PUMP TURBINE WILL BE CALCULATED

STEAM FLOW TO STEAM JET AIR EJECTOR = 1500 LB/HR

VALVE STEM AND PACKING LEAKAGES WILL BE CALCULATED LK=1

# APPENDIX B

**TABLE B-I: OVERALL PERFORMANCE**

| | |
|---|---|
| NET TURBINE CYCLE HEAT RATE, BTU/KW-HR | 9463 |
| NET TURBINE CYCLE EFFICIENCY, PER CENT | 36.06 |
| | |
| GROSS TURBINE CYCLE HEAT RATE, BTU/KW-HR | 9333 |
| GROSS TURBINE CYCLE EFFICIENCY, PER CENT | 36.56 |
| | |
| GENERATOR OUTPUT, MWE | 360.504 |

**TABLE B-II: TURBINE EXPANSION LINE**

| | STEAM FLOW | PRESS. | TEMP. | MOISTURE | ENTHALPY | ENTROPY |
|---|---|---|---|---|---|---|
| | LB/HR | PSIA | F | PER CENT | BTU/LB | BTU/LB-F |
| | | | | | | |
| TURBINE THROTTLE | 3681205 | 1015.2 | 602.6 | 0 | 1249.9 | |
| GOVERNING STAGE BOWL | 3677524 | 974.6 | 597.2 | 0 | 1249.8 | 1.4485 |
| GOVERNING STAGE SHELL | 3677524 | 779.7 | 549.3 | 0 | 1232.3 | 1.4517 |
| HP SECTION ELEP | 3402599 | 166.8 | 366.9 | 8.61 | 1122 | 1.4715 |
| HP SECTION UEEP | | 166.8 | | | 1123.5 | |
| EXTERNAL MOISTURE SEPARATOR INLET | 3390334 | 165.6 | | | 1123.5 | |
| EXTERNAL MOISTURE SEPARATOR OUTLET | 3105851 | 163.8 | 365.4 | 0 | 1195.4 | |
| 1ST STAGE REHEATER INLET | 2973357 | 163.8 | | | 1195.4 | |
| 1ST STAGE REHEATER OUTLET | 2973357 | 161.7 | 396.9 | | 1215.2 | |
| 2ND STAGE REHEATER INLET | 2973357 | 161.7 | | | 1215.2 | |
| 2ND STAGE REHEATER OUTLET | 2973357 | 159.2 | 519.6 | | 1283.8 | |
| LP SECTION BOWL | 2910269 | 152.3 | 518.4 | 0 | 1283.8 | 1.6683 |
| BEFORE MOISTURE REMOVAL NO. 1 | | 20 | 228 | 3.19 | 1125.7 | 1.6875 |
| AFTER MOISTURE REMOVAL NO. 1 | | 20 | 228 | 2.87 | 1128.7 | 1.6919 |
| BEFORE MOISTURE REMOVAL NO. 2 | | 10 | 193.2 | 5.82 | 1086.2 | 1.7003 |
| AFTER MOISTURE REMOVAL NO. 2 | | 10 | 193.2 | 4.77 | 1096.5 | 1.7161 |
| BEFORE MOISTURE REMOVAL NO. 3 | | 5 | 162.2 | 7.36 | 1057.4 | 1.7257 |
| AFTER MOISTURE REMOVAL NO. 3 | | 5 | 162.2 | 5.73 | 1073.8 | 1.7521 |
| LP SECTION ELEP | 2221131 | 0.7154 | 90.8 | 11.81 | 978 | 1.7828 |
| LP SECTION UEEP | | 0.7154 | | | 998 | |

**TABLE B-III: STEAM JET AIR EJECTOR**

| | |
|---|---|
| STEAM FLOW, LB/HR | 1500 |
| STEAM ENTHALPY IN, BTU/LB | 1249.9 |
| STEAM ENTHALPY OUT, BTU/LB | 180.2 |

**TABLE B-IV: EXTERNAL MOISTURE SEPARATOR DRAINS TO FW HEATER**

| | |
|---|---|
| DRAIN FLOW, LB/HR | 284483 |
| DRAIN PRESSURE, PSIA | 163.8 |
| DRAIN TEMPERATURE, F | 365.4 |
| DRAIN ENTHALPY, BTU/LB | 338.1 |

**TABLE B-V: LIVE STEAM REHEATER**

| | |
|---|---|
| 1ST STAGE DRAINS TO FW HEATER NO. 1 | |
| 1ST STAGE STEAM FLOW, LB/HR | 76652 |
| 1ST STAGE STEAM ENTHALPY, BTU/LB | 1166.7 |
| 1ST STAGE PRESSURE, PSIA | 315.3 |
| 1ST STAGE DRAIN TEMPERATURE, F | 421.9 |
| 1ST STAGE DRAIN ENTHALPY, BTU/LB | 399 |
| | |
| 2ND STAGE DRAINS TO FW HEATER NO. 1 | |
| 2ND STAGE STEAM FLOW, LB/HR | 288089 |
| 2ND STAGE STEAM ENTHALPY, BTU/LB | 1249.9 |
| 2ND STAGE PRESSURE, PSIA | 1000.1 |
| 2ND STAGE DRAIN TEMPERATURE, F | 544.6 |

**TABLE B-VI: MOISTURE REMOVAL STAGES**

| MOISTURE REMOVAL STAGE NO. | 1 | 2 | 3 |
|---|---|---|---|
| DRAINS TO FW HEATER NO. | 5 | 6 | 6 |
| STAGE PRESSURE, PSIA | 20 | 10 | 5 |
| TEMPERATURE, F | 228 | 193.2 | 162.2 |
| WATER REMOVED, LB/HR | 8491 | 27191 | 41929 |
| WATER ENTHALPY, BTU/LB | 196.3 | 161.3 | 130.2 |
| STEAM REMOVED, LB/HR | 0 | 12275 | 0 |
| STEAM ENTHALPY, BTU/LB | 0 | 1096.5 | 0 |

**TABLE B-VII: FW HEATERS**

| FW HEATER NO. | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| FW FLOW, LB/HR | 3970794 | 2987715 | 2987715 | 2987715 | 2987715 | 2987715 |
| FW TEMPERATURE OUT, F | 413.4 | 356.3 | 316.8 | 286.5 | 218.6 | 161.5 |
| FW ENTHALPY OUT, BTU/LB | 390.8 | 328.4 | 287.1 | 255.8 | 186.8 | 129.4 |
| FW TEMPERATURE IN, F | 360 | 316.8 | 286.5 | 218.6 | 161.5 | 92 |
| FW ENTHALPY IN, BTU/LB | 334.1 | 287.1 | 255.8 | 186.8 | 129.4 | 60.1 |
| EXTRACTION STAGE PRESSURE, PSIA | 330 | 163.8 | 100 | 64 | 20 | 6 |
| EXTRACTION STEAM FLOW, LB/HR | 198273 | 132495 | 93468 | 197502 | 155720 | 152561 |
| EXTRACTION STEAM ENTHALPY, BTU/LB | 1166.7 | 1195.4 | 1244.7 | 1207.7 | 1128.7 | 1073.8 |
| SHELL PRESSURE, PSIA | 303.6 | 155.6 | 92 | 58.9 | 18.4 | 5.5 |
| SHELL TEMPERATURE, F | 418.4 | 361.3 | 321.8 | 291.5 | 223.6 | 166.5 |
| SHELL DRAIN FLOW, LB/HR | 563014 | 983079 | 95873 | 293375 | 457586 | 695996 |
| SHELL DRAIN TEMPERATURE, F | 370 | 361.3 | 296.5 | 228.6 | 171.5 | 102 |
| SHELL DRAIN ENTHALPY, BTU/LB | 342.9 | 333.7 | 266.1 | 196.9 | 139.4 | 70 |

**TABLE B-VIII: CONDENSER**

| | |
|---|---|
| CONDENSER PRESSURE, PSIA | 0.7154 |
| CONDENSATE FLOW, LB/HR | 2987715 |
| CONDENSATE TEMPERATURE, F | 90.8 |
| CONDENSATE ENTHALPY, BTU/LB | 58.8 |

**TABLE B-IX: CONDENSATE AND FEEDWATER**

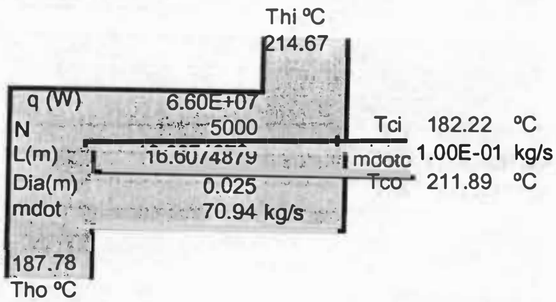
| | |
|---|---|
| FW FLOW TO FW PUMP, LB/HR | 3970794 |
| FW TEMPERATURE TO FW PUMP, F | 357.6 |
| FW ENTHALPY TO FW PUMP, BTU/LB | 329.7 |
| FW ENTHALPY RISE ACROSS FW PUMP, BTU/LB | 4.3 |
| FW PRESSURE INCREASE ACROSS FW PUMP, PSI | 1109 |
| | |
| FW FLOW TO STEAM GENERATOR, LB/HR | 3970794 |
| FW TEMPERATURE TO STEAM GENERATOR, F | 413.4 |
| FW ENTHALPY TO STEAM GENERATOR, BTU/LB | 390.8 |
| | |
| MAKE-UP TO CONDENSER HOTWELL, LB/HR | 0 |
| | |
| STEAM FLOW FROM STEAM GENERATOR, LB/HR | 3970794 |
| STEAM ENTHALPY FROM STEAM GENERATOR, BTU/LB | 1249.9 |
| | |
| THROTTLE STEAM FLOW FW PUMP TURBINE, LB/HR | 63088 |
| THROTTLE PRESSURE FW PUMP TURBINE, PSIA | 151.2 |
| THROTTLE ENTHALPY FW PUMP TURBINE, BTU/LB | 1283.8 |
| EXHAUST PRESSURE FW PUMP TURBINE, PSIA | 0.96098 |
| EXHAUST ENTHALPY FW PUMP TURBINE, BTU/LB | 1011.6 |

**TABLE B-X: VALVE STEM AND SHAFT LEAKAGES**

| | |
|---|---|
| STEAM SEAL REGULATOR | |
| FLOW TO SSR, LB/HR | 10453 |
| ENTHALPY AT SSR, BTU/LB | 1130.7 |
| FLOW FROM SSR TO MAIN CONDENSER, LB/HR | 3600 |
| FLOW FROM SSR TO STEAM PACKING EXHAUSTER, LB/HR | 2400 |
| FLOW FROM SSR TO FW HEATER NO. 6, LB/HR | 4453 |
| MAKE-UP FROM THROTTLE STEAM, LB/HR | 0 |
| ENTHALPY OF MAKE-UP STEAM, BTU/LB | 0 |
| | |
| THROTTLE VALVE STEM | |
| LEAK NO. 1 (DRAINS TO FW HEATER NO. 2), LB/HR | 3087 |
| ENTHALPY LEAK NO. 1, BTU/LB | 1249.9 |
| LEAK NO. 2 (DRAINS TO SSR), LB/HR | 594 |
| ENTHALPY LEAK NO. 2, BTU/LB | 1249.9 |
| | |
| GOVERNING STAGE SECTION | |
| LEAK NO. 3 (DRAINS TO FW HEATER NO. 0), LB/HR | 0 |
| ENTHALPY LEAK NO. 3, BTU/LB | 0 |
| LEAK NO. 4 (DRAINS TO SSR), LB/HR | 0 |
| ENTHALPY LEAK NO. 4, BTU/LB | 0 |
| | |
| HP TURBINE SECTION | |
| TOTAL LEAK NO. 5 (DRAINS TO FW HEATER NO. 3), LB/HR | 2405 |
| ENTHALPY LEAK NO. 5, BTU/LB | 1123.5 |
| TOTAL LEAK NO. 6 (DRAINS TO SSR), LB/HR | 9859 |
| ENTHALPY LEAK NO. 6, BTU/LB | 1123.5 |

# APPENDIX C

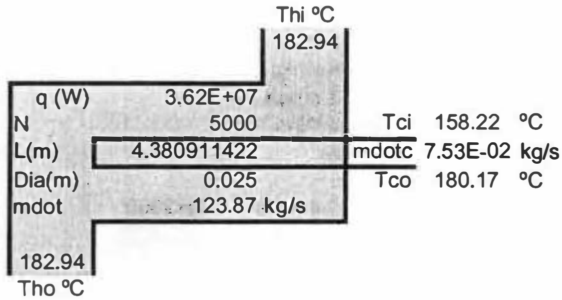
**Table C-I: Spreadsheet Calculation for Feedwater Heater #1**




| Feedwater Properties | | | | | | |
|---|---|---|---|---|---|---|
| Tavg | 197.055 | °C | | | | |
| cp | 4.479422294 | kJ/kg.°C | | | | |
| mu | 0.013644648 | c(kg/s.m) | | | | |
| k | 0.665281288 | W/m.°C | | | | |
| Pr | 0.918711234 | | | | | |
| Re | 37348.82649 | | | | | |
| Nu | 4.36 | laminar | Re<2300 | | | |
| Nu | 101.116264 | turb | Re>2300 | | | |
| hi | 2690.830337 | W/m2.°C | | | | |
| Tinit | 214.67 | °C | | | | |
| P | 20.93 | bars | | | | |
| cp | 4.576306215 | kJ/kg.°C | | TUBES | h/w | 1 |
| mu | 0.012469832 | c(kg/s.m) | | | h | 70.71067812 |
| k | 0.652622487 | W/m.°C | | | w | 70.71067812 |
| vl | 0.001180692 | m^3/kg | | | | |
| vg | 0.095290008 | m^3/kg | | | | |
| hg | 2799.286389 | KJ/kg | | | | |
| hf | 919.0938855 | KJ/kg | | | | |
| hfg | 1880.192503 | KJ/kg | Ja | 0.042933696 | Must be < 0.1 | |
| ho | 5699.569635 | W/m2.°C | | DIVby4 for Circular zigzag Exchanger | | |
| U | 1827.871726 | W/m2.°C | | | | |
| Tco | 211.66 | °C | | | | |
| delTlm | 4.010692214 | °C | | | | |
| P | 0.914329738 | Not Important Phase Change | | | | |
| R | 0.906302663 | Not Important Phase Change | | | | |
| F | 0.69 | Chart 11.10 | | | | |
| L | 16.6074879 | meters | 54.47256 feet | | | |
| Diameter | 3.046449236 | meters | 9.992353 feet | | | |

| | |
|---|---|
| Tube weight | |
| 138298.8555 | lb |
| 69.14942775 | ton |
| Shell estimate w | |
| 69522.09405 | lb |
| 34.76104703 | ton |
| End Caps | |
| 6536.481628 | lb |
| 3.268240814 | ton |
| Total | |
| 214357.4312 | lb |
| 107.1787156 | ton |

**Table C-II: Spreadsheet Calculation for Feedwater Heater #2**




Feedwater Properties

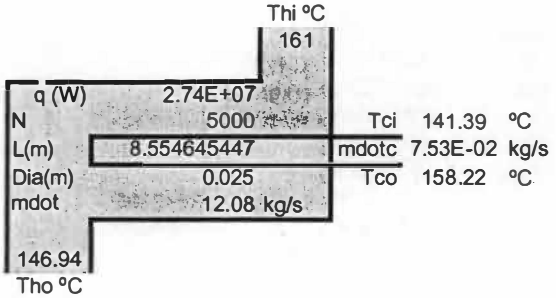
| | | | | |
|---|---|---|---|---|
| Tavg | 169.195 | °C | | |
| cp | 4.366799673 | kJ/kg.°C | | |
| mu | 0.016038112 | c(kg/s.m) | | |
| k | 0.678995019 | W/m.°C | | |
| Pr | 1.031454158 | | | |
| Re | 23908.60059 | | | |
| Nu | 4.36 | laminar | Re<2300 | |
| Nu | 74.1226835 | turb | Re>2300 | |
| hi | 2013.157316 | W/m2.°C | | |
| Tinit | 182.94 | °C | | |
| P | 10.73 | bars | | |
| cp | 4.417102068 | kJ/kg.°C | | |
| mu | 0.01475946 | c(kg/s.m) | | |
| k | 0.67319988 | W/m.°C | | |
| vl | 0.001131421 | m^3/kg | | |
| vg | 0.181822601 | m^3/kg | | |
| hg | 2779.730997 | KJ/kg | | |
| hf | 776.1917621 | KJ/kg | | |
| hfg | 2003.539235 | KJ/kg | Ja | 0.030370136 Must be < 0.1 |
| ho | 6184.816022 | W/m2.°C | DIVby4 for Circular zigzag Exchanger | |
| U | 1518.790939 | W/m2.°C | | |
| Tco | 180.22 | °C | | |
| delTlm | 10.02848495 | °C | | |
| P | 0.887944984 | Not Important Phase Change | | |
| R | 0 | Not Important Phase Change | | |
| F | 0.69 | Chart 11.10 | | |
| L | 4.380911422 | meters | 14.36939 | feet |
| Diameter | 3.046449236 | meters | 9.992353 | feet |

TUBES

| | | |
|---|---|---|
| h/w | 1 | |
| h | 70.71067812 | |
| w | 70.71067812 | |

| | | |
|---|---|---|
| Tube weight | | |
| | 36482.03986 | lb |
| | 18.24101993 | ton |
| Shell estimate w | | |
| | 18339.32607 | lb |
| | 9.169663036 | ton |
| End Caps | | |
| | 6536.481628 | lb |
| | 3.268240814 | ton |
| Total | | |
| | 61357.84756 | lb |
| | 30.67892378 | ton |

**Table C-III: Spreadsheet Calculation for Feedwater Heater #3**




| | | | | | | |
|---|---|---|---|---|---|---|
| Feedwater Properties | | | | | | |
| Tavg | 149.805 | °C | | | | |
| cp | 4.309766406 | kJ/kg.°C | | | | |
| mu | 0.018274152 | c(kg/s.m) | | | | |
| k | 0.683892443 | W/m.°C | | | | |
| Pr | 1.151604 | | | | | |
| Re | 20983.12506 | | | | | |
| Nu | 4.36 | laminar | Re<2300 | | | |
| Nu | 69.78229318 | turb | Re>2300 | | | |
| hi | 1908.94332 | W/m2.°C | | | | |
| Tinit | 161 | °C | | | | |
| P | 6.3431 | bars | | | | |
| cp | 4.340902115 | kJ/kg.°C | | TUBES | h/w | 1 |
| mu | 0.016912799 | c(kg/s.m) | | | h | 70.71067812 |
| k | 0.681538524 | W/m.°C | | | w | 70.71067812 |
| vl | 0.001103179 | m^3/kg | | | | |
| vg | 0.299549261 | m^3/kg | | | | |
| hg | 2758.525438 | KJ/kg | | | | |
| hf | 679.9233212 | KJ/kg | | | | |
| hfg | 2078.602117 | KJ/kg | Ja | 0.023417133 | Must be < 0.1 | |
| ho | 6496.139919 | W/m2.°C | | DIVby4 for Circular zigzag Exchanger | | |
| U | 1475.38847 | W/m2.°C | | | | |
| Tco | 158.28 | °C | | | | |
| delTlm | 4.006671035 | °C | | | | |
| P | 0.858235594 | Not Important Phase Change | | | | |
| R | 0.835412953 | Not Important Phase Change | | | | |
| F | 0.69 | Chart 11.10 | | | | |
| L | 8.554645447 | meters | 28.05924 | feet | | |
| Diameter | 3.046449236 | meters | 9.992353 | feet | | |

| | | |
|---|---|---|
| Tube weight | | |
| | 71238.80996 | lb |
| | 35.61940498 | ton |
| Shell estimate w | | |
| | 35811.36827 | lb |
| | 17.90568414 | ton |
| End Caps | | |
| | 6536.481628 | lb |
| | 3.268240814 | ton |
| Total | | |
| | 113586.6599 | lb |
| | 56.79332993 | ton |

**Table C-IV: Spreadsheet Calculation for Feedwater Heater #4**

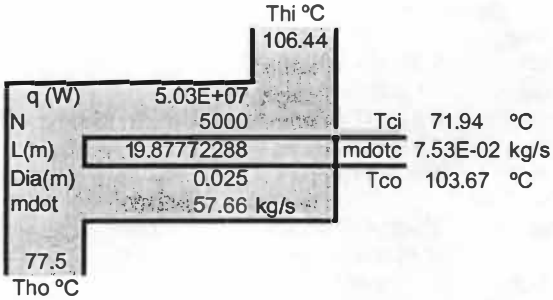
| | | | |
|---|---|---|---|
| Thi °C | 144.17 | | |
| q (W) | 6.04E+07 | | |
| N | 5000 | Tci | 103.67 °C |
| L(m) | 21.08435624 | mdotc | 7.53E-02 kg/s |
| Dia(m) | 0.025 | Tco | 141.39 °C |
| mdot | 36.96 kg/s | | |
| Tho °C | 109.22 | | |

| Feedwater Properties | | | | |
|---|---|---|---|---|
| Tavg | 122.53 | °C | | |
| cp | 4.250803211 | kJ/kg.°C | | |
| mu | 0.02269473 | c(kg/s.m) | | |
| k | 0.684017039 | W/m.°C | | |
| Pr | 1.410357113 | | | |
| Re | 16895.94136 | | | |
| Nu | 4.36 | laminar | Re<2300 | |
| Nu | 63.63343803 | turb | Re>2300 | |
| hi | 1741.054235 | W/m2.°C | | |
| Tinit | 144.17 | °C | | |
| P | 4.0609 | bars | | |
| cp | 4.295754632 | kJ/kg.°C | | |
| mu | 0.019044715 | c(kg/s.m) | | |
| k | 0.684579278 | W/m.°C | | |
| vl | 0.001084153 | m^3/kg | | |
| vg | 0.455728281 | m^3/kg | | |
| hg | 2738.757938 | KJ/kg | | |
| hf | 607.1218035 | KJ/kg | | |
| hfg | 2131.636134 | KJ/kg | Ja | 0.04358571 Must be < 0.1 |
| ho | 5451.896255 | W/m2.°C | DIVby4 for Circular zigzag Exchanger | |
| U | 1319.631919 | W/m2.°C | | |
| Tco | 141.42 | °C | | |
| delTlm | 4.006671035 | °C | | |
| P | 0.931358025 | Not Important Phase Change | | |
| R | 0.926564157 | Not Important Phase Change | | |
| F | 0.69 | Chart 11.10 | | |
| L | 21.08435624 | meters | 69.15669 | feet |
| Diameter | 3.046449236 | meters | 9.992353 | feet |

| TUBES | | |
|---|---|---|
| h/w | 1 | |
| h | 70.71067812 | |
| w | 70.71067812 | |

| | |
|---|---|
| Tube weight | |
| 175579.9766 | lb |
| 87.78998828 | ton |
| Shell estimate w | |
| 88263.11396 | lb |
| 44.13155698 | ton |
| End Caps | |
| 6536.481628 | lb |
| 3.268240814 | ton |
| Total | |
| 270379.5722 | lb |
| 135.1897861 | ton |

**Table C-V: Spreadsheet Calculation for Feedwater Heater #5**




| | | | | | |
|---|---|---|---|---|---|
| Feedwater Properties | | | | | |
| Tavg | 87.805 | °C | | | |
| cp | 4.202837218 | kJ/kg.°C | | | |
| mu | 0.032256128 | c(kg/s.m) | | | |
| k | 0.671788637 | W/m.°C | | | |
| Pr | 2.01800457 | | | | |
| Re | 11887.62722 | | | | |
| Nu | 4.36 | laminar | Re<2300 | | |
| Nu | 55.43356843 | turb | Re>2300 | | |
| hi | 1489.585655 | W/m2.°C | | | |
| Tinit | 106.44 | °C | | | |
| P | 1.2686 | bars | | | |
| cp | 4.225225578 | kJ/kg.°C | TUBES | h/w | 1 |
| mu | 0.026382549 | c(kg/s.m) | | h | 70.71067812 |
| k | 0.680163104 | W/m.°C | | w | 70.71067812 |
| vl | 0.001048617 | m^3/kg | | | |
| vg | 1.354138264 | m^3/kg | | | |
| hg | 2685.619003 | KJ/kg | | | |
| hf | 446.3005455 | KJ/kg | | | |
| hfg | 2239.318458 | KJ/kg | Ja | 0.035077348 | Must be < 0.1 |
| ho | 5348.688492 | W/m2.°C | DIVby4 for Circular zigzag Exchanger | | |
| U | 1165.108254 | W/m2.°C | | | |
| Tco | 103.70 | °C | | | |
| delTlm | 4.004301176 | °C | | | |
| P | 0.919710145 | Not Important Phase Change | | | |
| R | 0.912070596 | Not Important Phase Change | | | |
| F | 0.69 | Chart 11.10 | | | |
| L | 19.87772288 | meters | 65.19893 | feet | |
| Diameter | 3.046449236 | meters | 9.992353 | feet | |

| | |
|---|---|
| Tube weight | |
| 165531.7373 | lb |
| 82.76586864 | ton |
| Shell estimate w | |
| 83211.91788 | lb |
| 41.60595894 | ton |
| End Caps | |
| 6536.481628 | lb |
| 3.268240814 | ton |
| Total | |
| 255280.1368 | lb |
| 127.6400684 | ton |

**Table C-VI: Spreadsheet Calculation for Feedwater Heater #6**

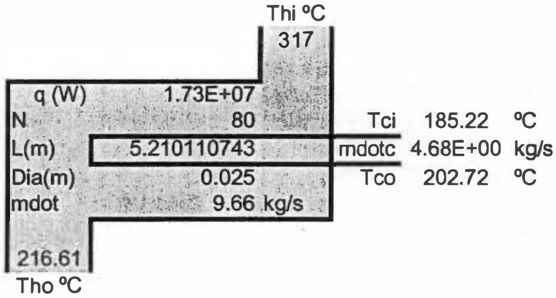
| | | | | |
|---|---|---|---|---|
| Feedwater Properties | | | | |
| Tavg | 52.637 | °C | | |
| cp | 4.180390726 | kJ/kg.°C | | |
| mu | 0.052369347 | c(kg/m.s) | | |
| k | 0.643328126 | W/m.°C | | |
| Pr | 3.402996434 | | | |
| Re | 7322.008854 | | | |
| Nu | 4.36 | laminar | Re<2300 | |
| Nu | 46.36354481 | turb | Re>2300 | |
| hi | 1193.078896 | W/m2.°C | | |
| Tinit | 74.72 | °C | | |
| P | 0.3792 | bars | | |
| cp | 4.191476459 | kJ/kg.°C | | |
| mu | 0.03792284 | c(kg/m.s) | | |
| k | 0.663230828 | W/m.°C | | |
| vl | 0.001025645 | m^3/kg | | |
| vg | 4.174685537 | m^3/kg | | |
| hg | 2634.128754 | KJ/kg | | |
| hf | 312.7995487 | KJ/kg | | |
| hfg | 2321.329206 | KJ/kg | Ja | 0.039618631 Must be < 0.1 |
| ho | 4692.652927 | W/m2.°C | DIVby4 for Circular zigzag Exchanger | |
| U | 951.2334817 | W/m2.°C | | |
| Tco | 71.89 | °C | | |
| delTlm | 4.008136831 | °C | | |
| P | 0.93293066 | Not Important Phase Change | | |
| R | 0.927901797 | Not Important Phase Change | | |
| F | 0.69 | Chart 11.10 | | |
| L | 29.36644101 | meters | 96.32193 | feet |
| Diameter | 3.046449236 | meters | 9.992353 | feet |

| | | | | | |
|---|---|---|---|---|---|
| | Thi °C 74.72 | | | | |
| q (W) | 6.07E+07 | | | | |
| N | 5000 | | Tci | 33.33 | °C |
| L(m) | 29.36644101 | | mdotc | 7.53E-02 | kg/s |
| Dia(m) | 0.025 | | Tco | 71.94 | °C |
| mdot | 87.7 | kg/s | | | |
| 38.89 Tho °C | | | | | |

| TUBES | | |
|---|---|---|
| | h/w | 1 |
| | h | 70.71067812 |
| | w | 70.71067812 |

| | | |
|---|---|---|
| Tube weight | | |
| | 244549.0375 | lb |
| | 122.2745187 | ton |
| Shell estimate w | | |
| | 122933.4915 | lb |
| | 61.46674577 | ton |
| End Caps | | |
| | 6536.481628 | lb |
| | 3.268240814 | ton |
| Total | | |
| | 374019.0107 | lb |
| | 187.0095053 | ton |

**Table C-VII: Spreadsheet Calculation for Reheater Stage #1**




| Feedwater Properties | | | | | |
|---|---|---|---|---|---|
| Tavg | 193.97 | °C | | | |
| cp | 4.464760726 | kJ/kg.°C | | | |
| mu | 0.013873527 | c(kg/s.m) | | | |
| k | 0.667181218 | W/m.°C | | | |
| Pr | 0.928413133 | | | | |
| Re | 1719124.66 | | | | |
| Nu | 4.36 | laminar | Re<2300 | | |
| Nu | 2173.052617 | turb | Re>2300 | | |
| hi | 57992.79564 | W/m2.°C | | | |
| Tinit | 317 | °C | | | |
| P | 21.74 | bars | | | |
| cp | 6.389807109 | kJ/kg.°C | TUBES | h/w | 1 |
| mu | 0.007954145 | c(kg/s.m) | | h | 8.94427191 |
| k | 0.512627534 | W/m.°C | | w | 8.94427191 |
| vl | 0.001482777 | m^3/kg | | | |
| vg | 0.016292019 | m^3/kg | | | |
| hg | 2709.511635 | KJ/kg | | | |
| hf | 1443.699112 | KJ/kg | | | |
| hfg | 1265.812523 | KJ/kg | Ja | 0.114450154 | Must be < 0.1 |
| ho | 6634.542804 | W/m2.°C | | DIVby4 for Circular zigzag Exchanger | |
| U | 5953.450881 | W/m2.°C | | | |
| Tco | 195.53 | °C | | | |
| delTlm | 64.14829313 | °C | | | |
| P | 0.132797086 | Not Important Phase Change | | | |
| R | 5.736571429 | Not Important Phase Change | | | |
| F | 0.69 | Chart 11.10 | | | |
| L | 5.210110743 | meters | 17.08916 | feet | |
| Diameter | 0.387586078 | meters | 1.271282 | feet | |

| | | |
|---|---|---|
| Tube weight | | |
| | 694.1951554 | lb |
| | 0.347097578 | ton |
| Shell estimate w | | |
| | 2932.292499 | lb |
| | 1.466146249 | ton |
| End Caps | | |
| | 130.9565932 | lb |
| | 0.065478297 | ton |
| Total | | |
| | 3757.444248 | lb |
| | 1.878722124 | ton |

**Table C-VIII: Spreadsheet Calculation for Reheater Stage #2**

| Feedwater Properties | | | |
|---|---|---|---|
| Tavg | 236.805 | °C | |
| cp | 4.738619715 | kJ/kg.°C | |
| mu | 0.011244504 | c(kg/s.m) | |
| k | 0.632310598 | W/m.°C | |
| Pr | 0.842678116 | | |
| Re | 339370.3771 | | |
| Nu | 4.36 | laminar | Re<2300 |
| Nu | 570.8626996 | turb | Re>2300 |
| hi | 14438.5014 | W/m2.°C | |
| Tinit | 317 | °C | |
| P | 68.95 | bars | |
| cp | 6.389807109 | kJ/kg.°C | |
| mu | 0.007954145 | c(kg/s.m) | |
| k | 0.512627534 | W/m.°C | |
| vl | 0.001482777 | m^3/kg | |
| vg | 0.016292019 | m^3/kg | |
| hg | 2709.511635 | KJ/kg | |
| hf | 1443.699112 | KJ/kg | |
| hfg | 1265.812523 | KJ/kg | |
| ho | 4374.020831 | W/m2.°C | |
| U | 3357.035549 | W/m2.°C | |
| Tco | 236.39 | °C | |
| delTlm | 62.36762701 | °C | |
| P | 0.596517326 | Not Important Phase Change | |
| R | 0.472641925 | Not Important Phase Change | |
| F | 0.69 | Chart 11.10 | |
| L | 5.268228398 | meters | 17.27979 feet |
| Diameter | 0.966482391 | meters | 3.170062 feet |

| | | |
|---|---|---|
| Thi °C | 317 | |
| q (W) | 5.98E+07 | |
| N | 500 | |
| L(m) | 5.268228398 | |
| Dia(m) | 0.025 | |
| mdot | 36.3 | kg/s |
| Tho °C | 284.78 | |
| Tci | 202.72 | °C |
| mdotc | 7.49E-01 | kg/s |
| Tco | 270.89 | °C |

TUBES

| | |
|---|---|
| h/w | 1 |
| h | 22.36067977 |
| w | 22.36067977 |

| | | |
|---|---|---|
| Ja | 0.242324312 | Must be < 0.1 |

DIVby4 for Circular zigzag Exchanger

| | | |
|---|---|---|
| Tube weight | | |
| | 4387.117198 | lb |
| | 2.193558599 | ton |
| Shell estimate w | | |
| | 7121.077406 | lb |
| | 3.560538703 | ton |
| End Caps | | |
| | 705.1511988 | lb |
| | 0.352575599 | ton |
| Total | | |
| | 12213.3458 | lb |
| | 6.106672902 | ton |

**Table C-IX: Spreadsheet Calculation for Condenser**

| | | | | | |
|---|---|---|---|---|---|
| Feedwater Properties | | | | | |
| Tavg | 25 | °C | | | |
| cp | 4.18217991 | kJ/kg.°C | | | |
| mu | 0.089051909 | c(kg/m.s) | | | |
| k | 0.607458162 | W/m.°C | | | |
| Pr | 6.13097538 | | | | |
| Re | 7034.479839 | | | | |
| Nu | 4.36 | laminar | Re<2300 | | |
| Nu | 56.82314359 | turb | Re>2300 | | |
| hi | 1380.707294 | W/m2.°C | | | |
| Tinit | 32.66 | °C | | | |
| P | 0.049325 | bars | | | |
| cp | 4.179612979 | kJ/kg.°C | | TUBES | |
| mu | 0.075454118 | c(kg/m.s) | | | |
| k | 0.618747484 | W/m.°C | | | |
| vl | 0.00100525 | m^3/kg | | | |
| vg | 28.51030152 | m^3/kg | | | |
| hg | 2560.377273 | KJ/kg | | | |
| hf | 136.8644066 | KJ/kg | | | |
| hfg | 2423.512867 | KJ/kg | Ja | 0.013165297 | Must be < 0.1 |
| ho | 4572.718906 | W/m2.°C | | DIVby4 for Circular zigzag Exchanger | |
| U | 1060.496281 | W/m2.°C | | | |
| Tco | 30.01 | °C | | | |
| delTlm | 6.409758035 | °C | | | |
| P | 0.789889415 | Not Important Phase Change | | | |
| R | 0 | Not Important Phase Change | | | |
| F | 0.69 | Chart 11.10 | | | |
| L | 6.990165783 | meters | 22.92774 | feet | |
| Diameter | 4.304151025 | meters | 14.11762 | feet | |

| | | |
|---|---|---|
| Thi °C | 32.66 | |
| q (W) | 5.15E+07 | |
| N | 10000 | |
| L(m) | 6.990165783 | |
| Dia(m) | 0.025 | |
| mdot | 376.45 | kg/s |
| Tho °C | 32.66 | |
| Tci | 20 | °C |
| mdotc | 1.23E-01 | kg/s |
| Tco | 30.00 | °C |

| | |
|---|---|
| h/w | 1 |
| h | 100 |
| w | 100 |

| | | |
|---|---|---|
| Tube weight | | |
| | 116421.2111 | lb |
| | 58.21060556 | ton |
| Shell estimate w | | |
| | 41242.88851 | lb |
| | 20.62144425 | ton |
| End Caps | | |
| | 12922.81815 | lb |
| | 6.461409077 | ton |
| Total | | |
| | 170586.9178 | lb |
| | 85.29345889 | ton |

# APPENDIX D

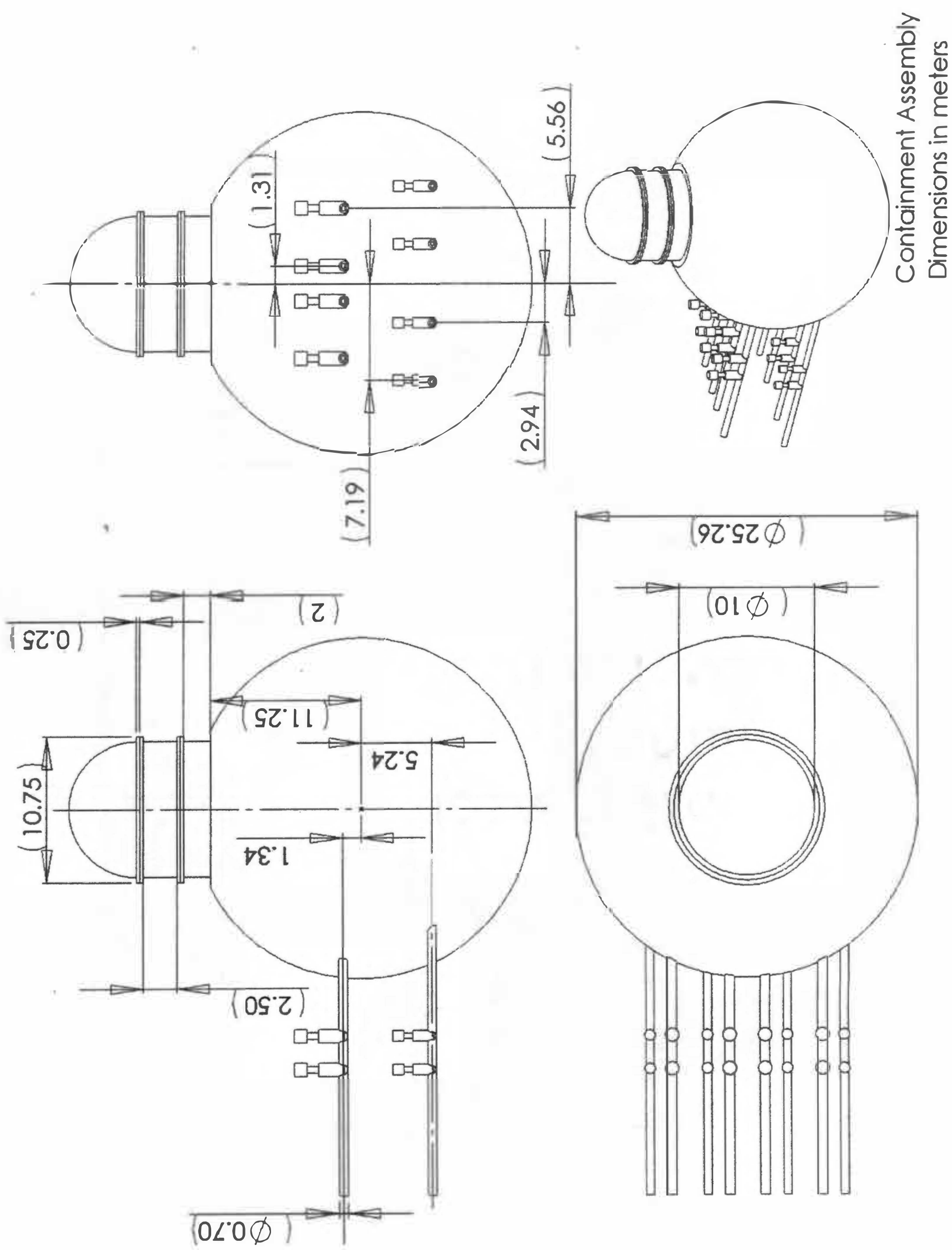



**Figure D-1: Containment Assembly**

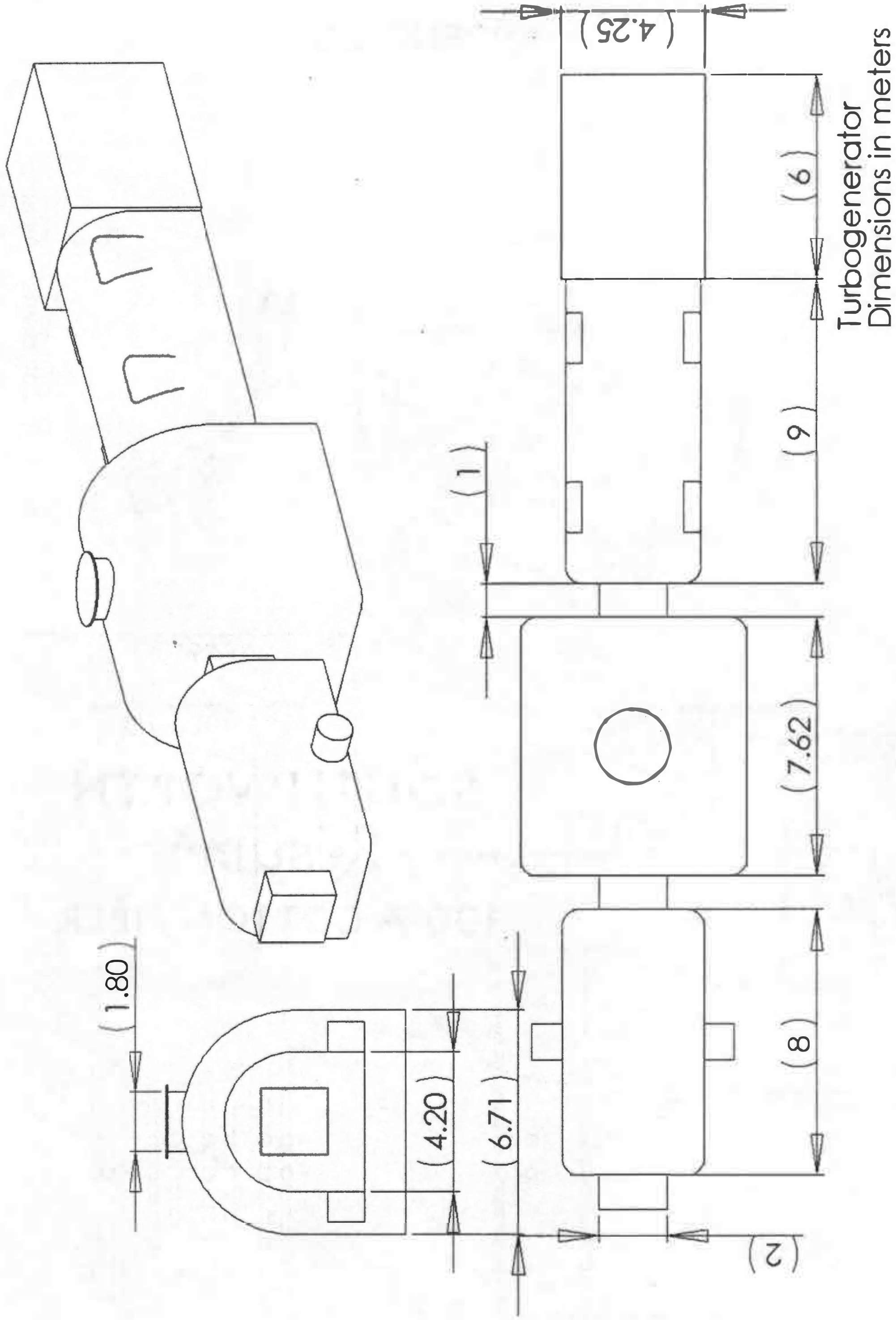



**Figure D-2: Turbo-generator Unit**

| In Meters | Length | DHotIn | HotInOS | DHotOut | DHotOutF | HotOutOS |
|---|---|---|---|---|---|---|
| FWH1 | 16.61 | 0.3 | 0.7 | 0.25 | 0.375 | 0.65 |
| FWH2 | 4.38 | 0.35 | 0.75 | 0.35 | 0.425 | 0.75 |
| FWH3 | 8.55 | 0.4 | 0.8 | 0.2 | 0.35 | 0.6 |
| FWH4 | 21.08 | 0.6 | 1 | 0.2 | 0.35 | 0.6 |
| FWH5 | 19.88 | 1 | 1.4 | 0.25 | 0.375 | 0.65 |
| FWH6 | 29.37 | 1.8 | 2.2 | 0.25 | 0.375 | 0.65 |

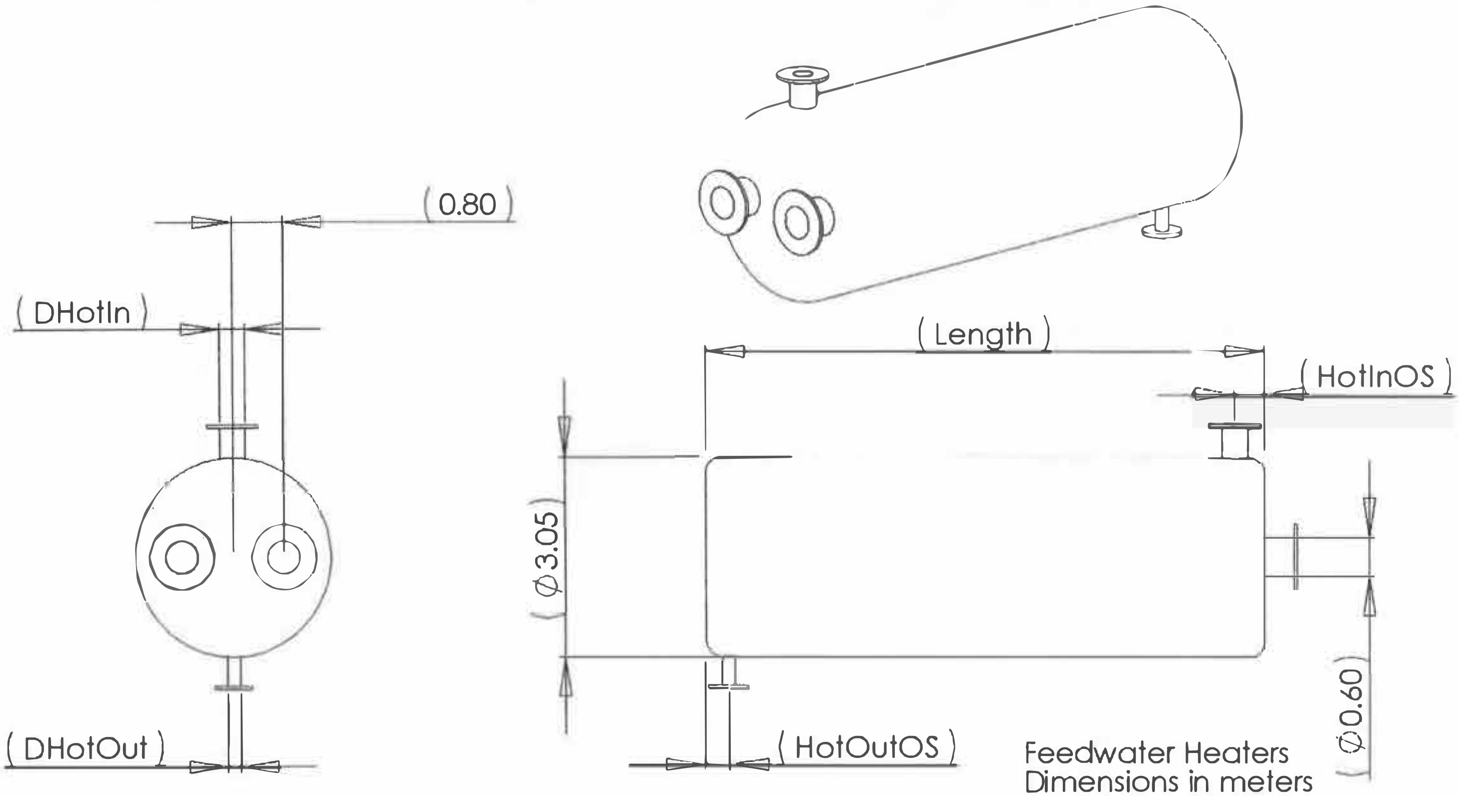



Figure D-3: Feed Water Heaters

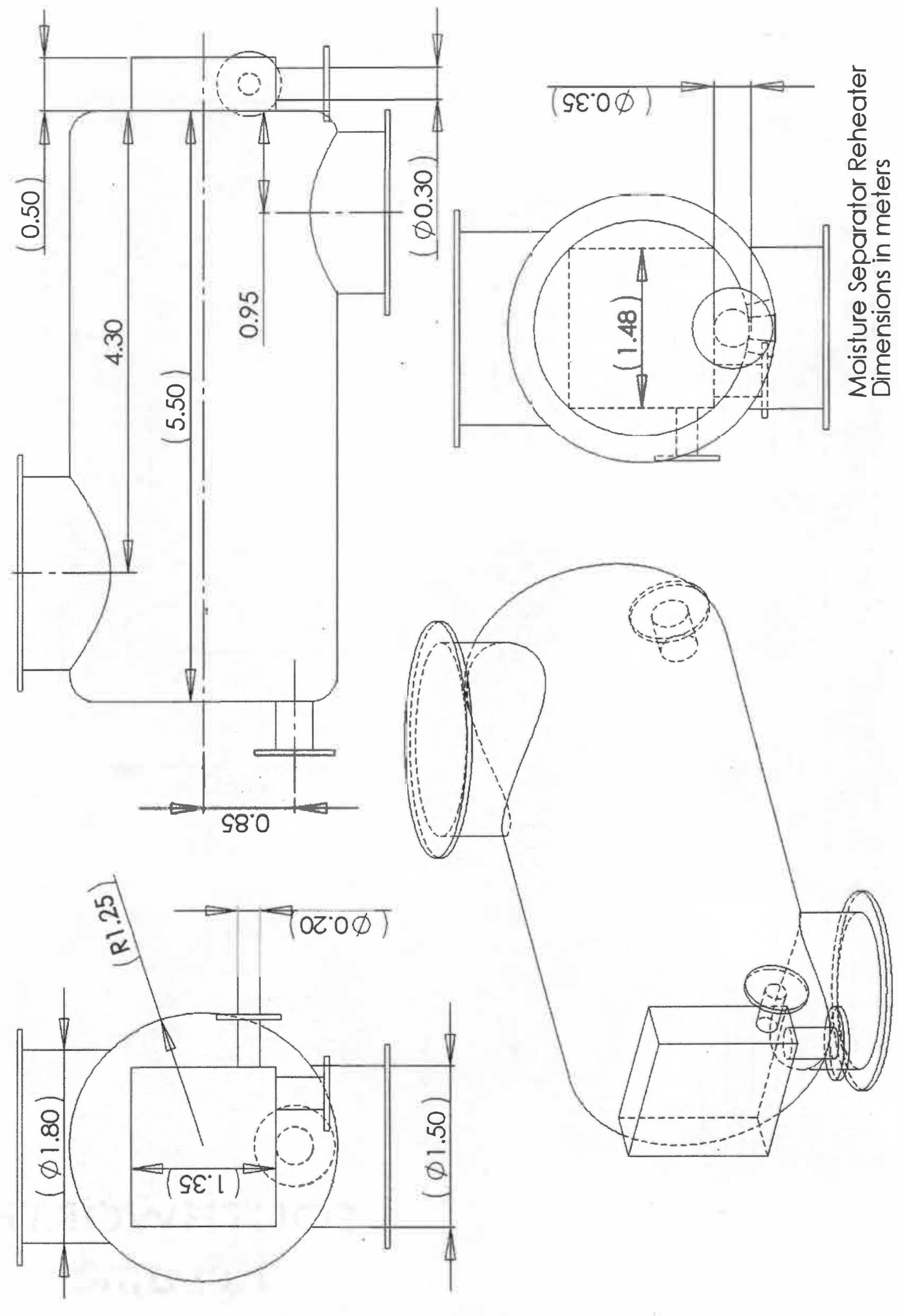



**Figure D-4: Reheater**

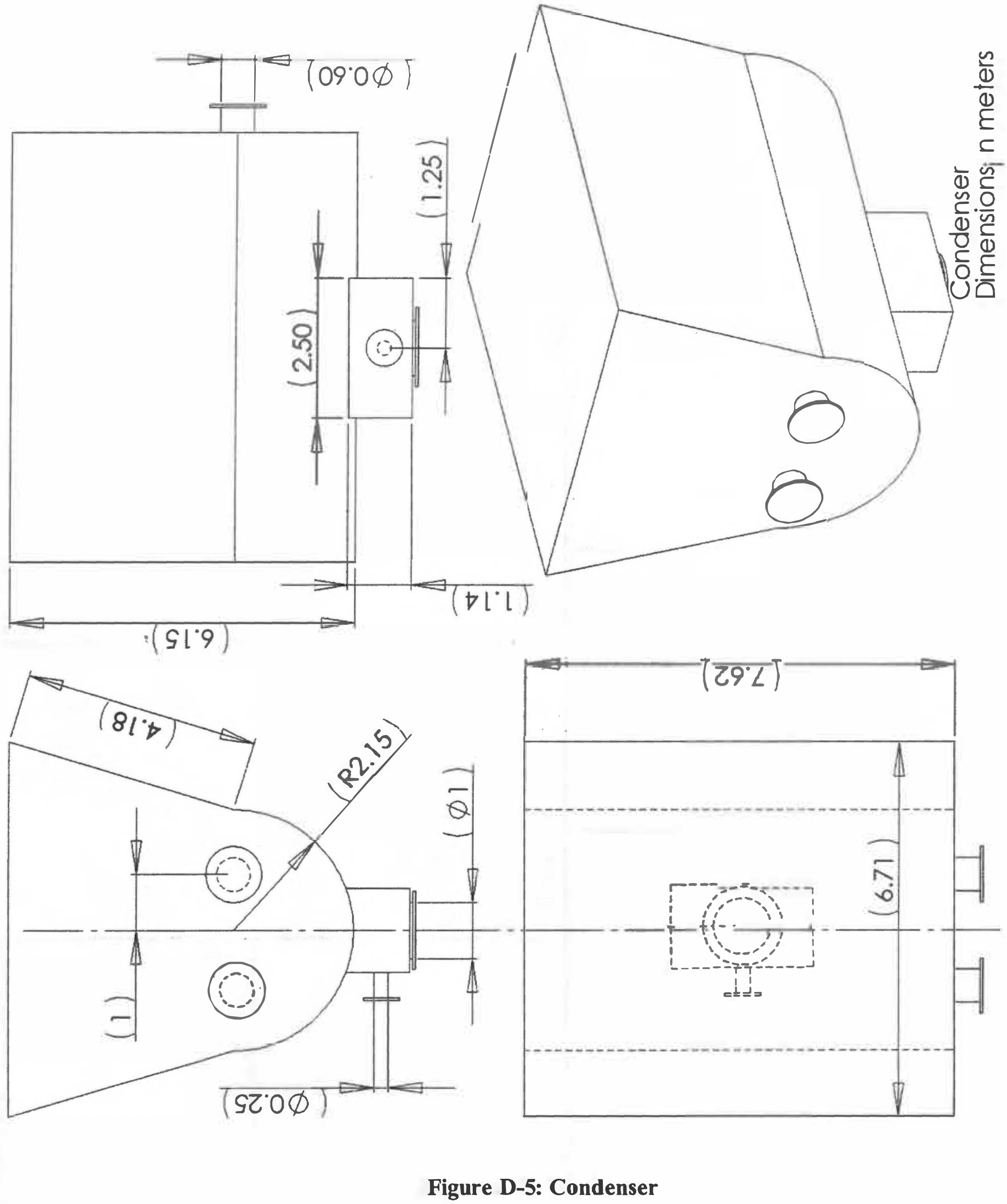



**Figure D-5: Condenser**

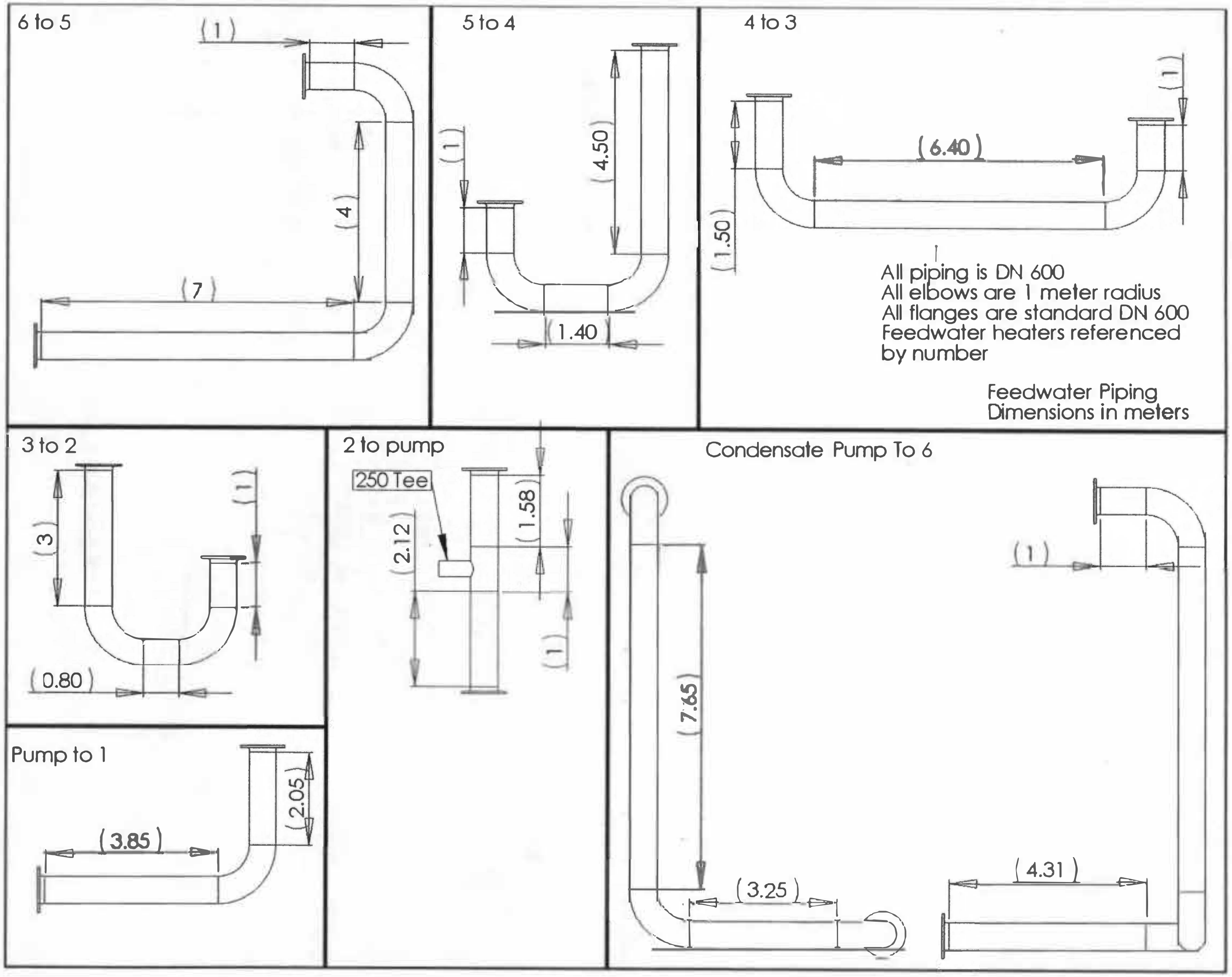



Figure D-6: Feed Water Piping

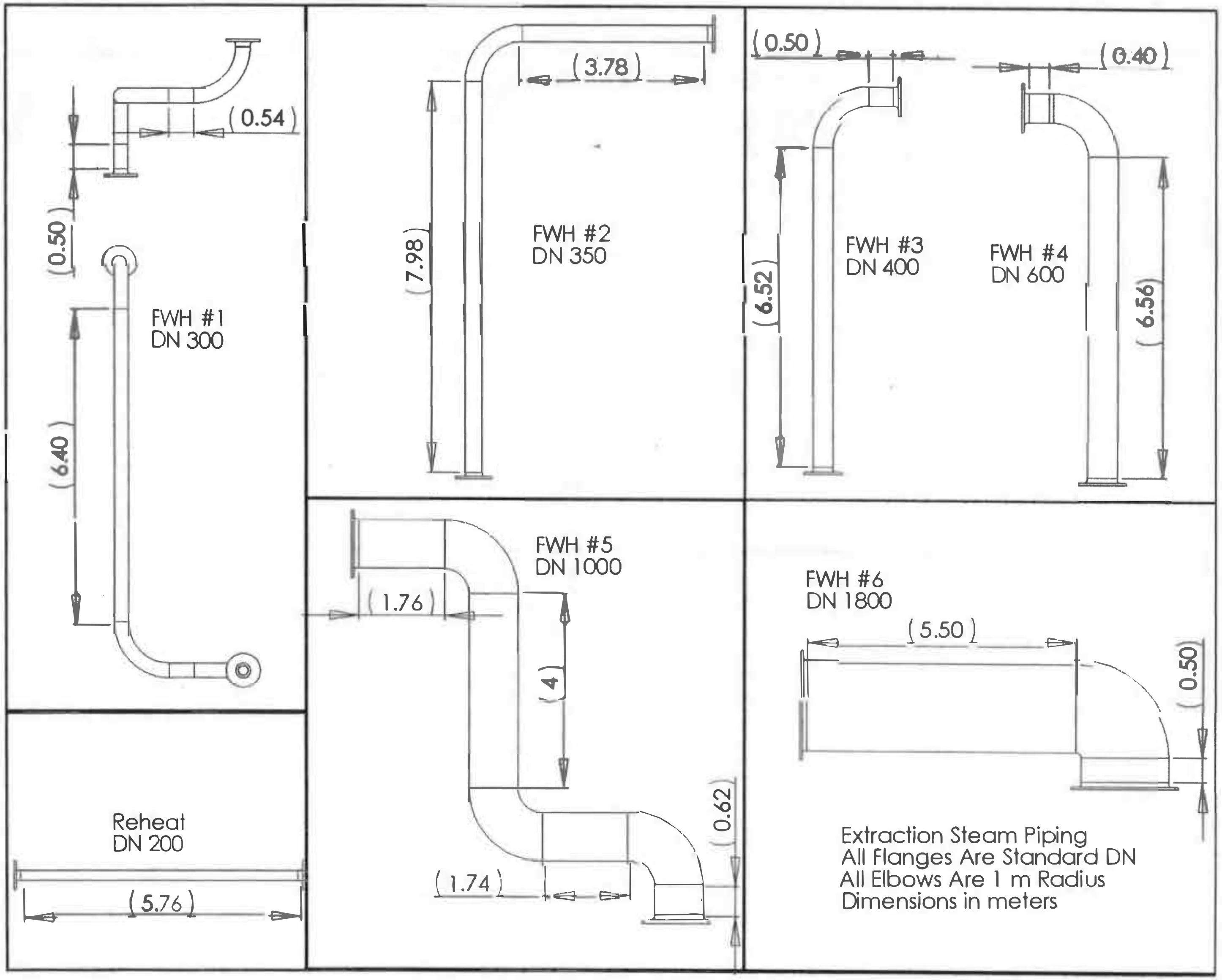



Figure D-7: Extraction Steam Piping

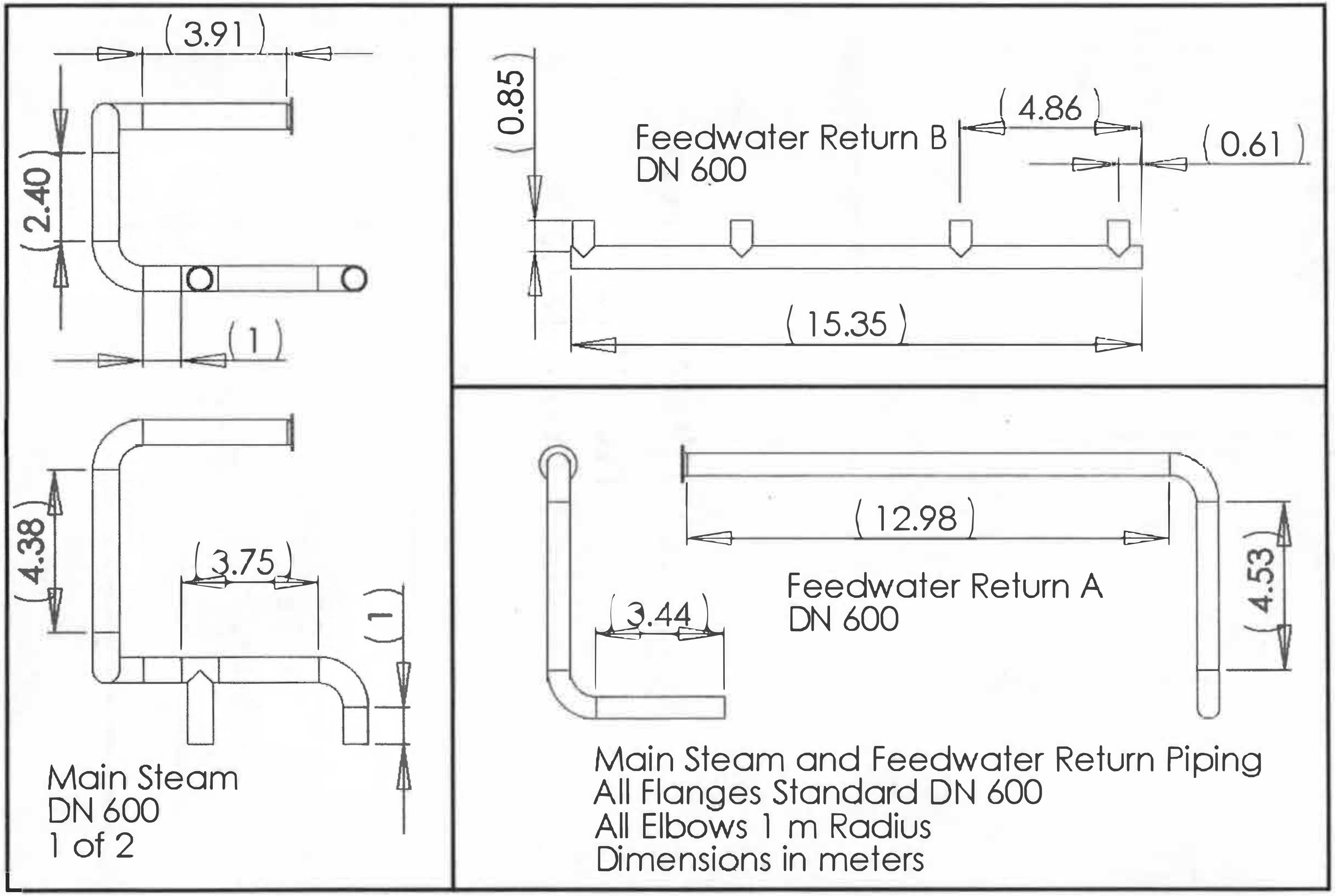



**Figure D-8: Feed Water and Main Steam Piping**

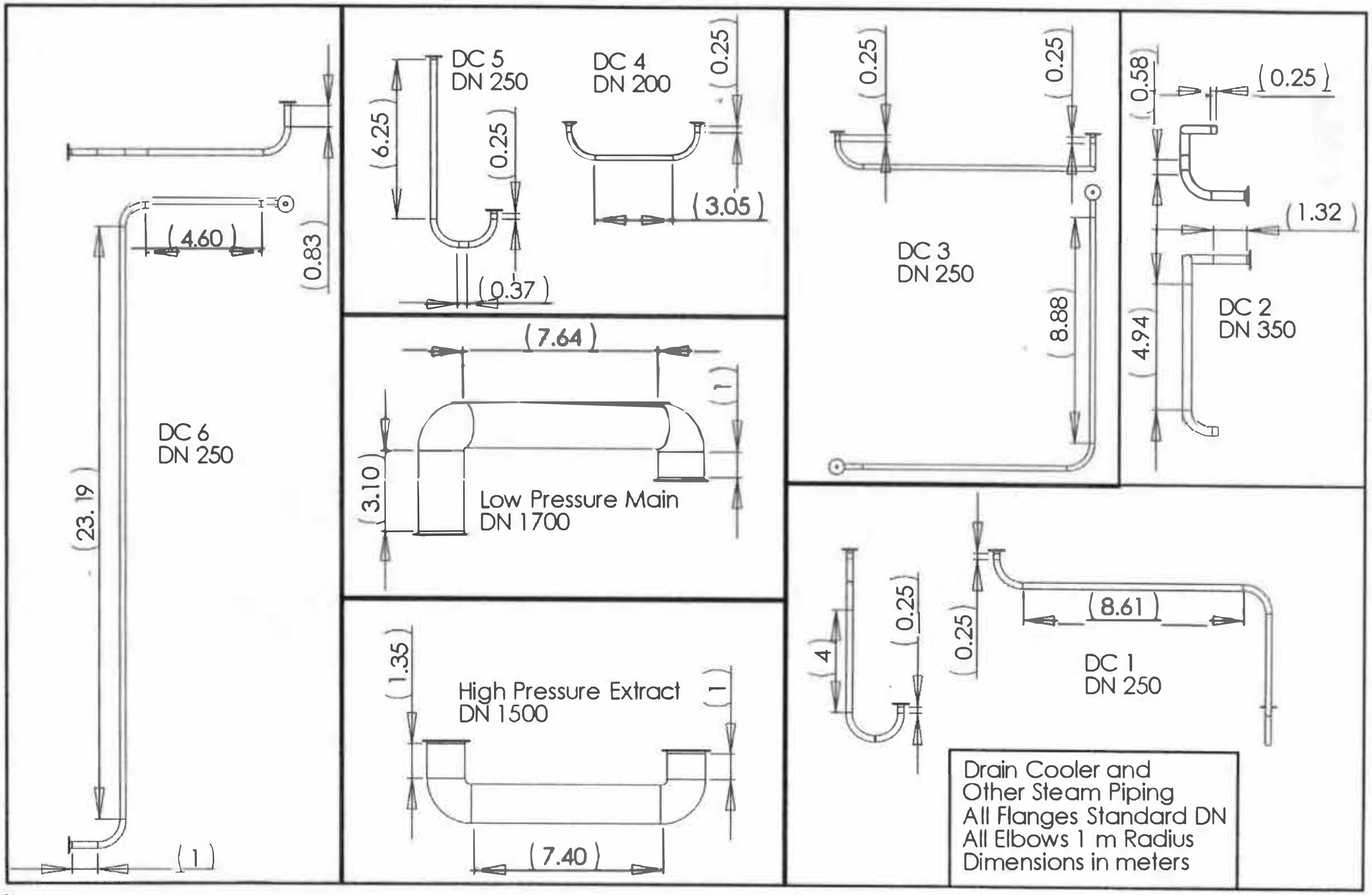



Figure D 9: Drain Cooler and Other Piping

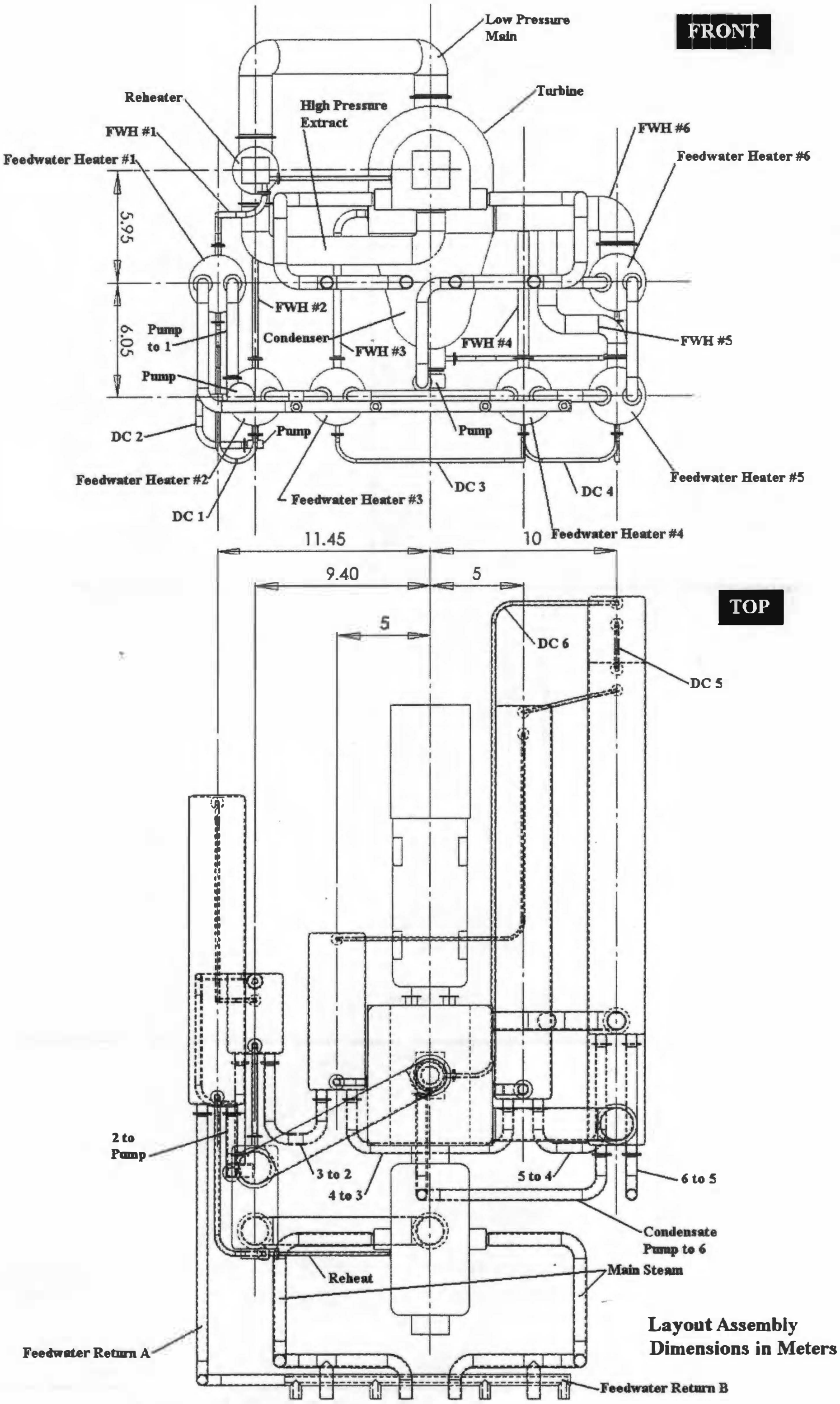



Figure D-10: Layout Assembly

# VITA

Wesley Charles Williams is a native of Knoxville, Tennessee. Born July 16, 1976, it seemed that it was his destiny to become an engineer. He comes from a family of local land surveyors and civil engineers. He graduated with honors from Central High School of Knoxville. He pursued his undergraduate studies at the University of Tennessee where he worked as a land surveyor in the family business as well as performing classical guitar. In the middle of his undergraduate studies he spent nine months in Costa Rica studying Spanish along with guitar. After his return to the states, he graduated with a Bachelor of Science in Mechanical Engineering in May of 2000. He then continued graduate study in Nuclear Engineering at UTK, where he was awarded a Master of Science degree in May of 2002.