Condition monitoring for a neutral beam heating system

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Condition Monitoring
for a
Neutral Beam Heating System

NICK WRIGHT

DECEMBER 2013

A DOCTORAL THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE AWARD OF DOCTOR OF PHILOSOPHY OF LOUGHBOROUGH UNIVERSITY

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Abstract

This thesis presents the design of a condition monitoring scheme for the neutral beam cryogenic pumping system deployed in the Joint European Torus. The performance of the scheme is demonstrated by analysing its response to a range of fault scenarios.

Condition monitoring has been successfully used in a diverse range of industries, from rail transport, to commercial power generation, to semiconductor manufacturing, among others. The application of model based condition monitoring to fusion applications has, however, been very limited. Given the importance of improving the availability of fusion devices, it was hypothesised that model based condition monitoring techniques could be used to good effect for this application. This provided the motivation for this research, which had the ultimate objective of demonstrating the usefulness of model based condition monitoring for fusion devices.

The cryogenic pumping system used in the neutral beam heating devices operated by the project sponsor, the Culham Centre for Fusion Energy, was selected as the target for a demonstration condition monitoring scheme. This choice of target system was made and justified by the author through an analysis of its role in the neutral beam devices.

The relative merits of several model based approaches were investigated. An observer based residual generation scheme, utilising a Kalman filter bank and residual thresholding arrangement was determined to be most suitable. A novel, accurate non-linear simulation model of the cryogenic pumping system was developed to act as a surrogate plant during the research, to facilitate the design and test procedure. This model was validated using historical process data. Two system identification techniques were used to obtain a set of linear models of the system for use in the Kalman filter bank.

The scheme was tested by using the non-linear model to simulate ten different faults, all with unique failure modes. Two residual thresholding arrangements were tested and their performance was analysed to find the arrangement with the best performance.

It was found that both variations of the scheme could detect all ten faults. The scheme using dual thresholds to check both the direction and magnitude of the residual signals was, however, better at isolating specific faults.

The non-linear simulation model developed during the research was proven to be a genuine representation of the plant, by validating its response using historical process data. As such, it could be used in the future as the basis for a model based control system design procedure.

The effectiveness of the scheme at detecting a range of faults which can arise in neutral beam heating systems supports the case for the future use of model based condition monitoring in nuclear fusion research.
Acknowledgements

Writing a thesis is hard work, not only for the person writing it, but also for everyone who supports them. These supporting people are the foundations on which research is built, and as engineers, we know how important solid foundations are. Their contribution should be recognised.

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Big fleas have little fleas,
Upon their backs to bite ’em,
And little fleas have lesser fleas,
    and so, ad infinitum.

And the great fleas, themselves, in turn
    Have greater fleas to go on;
While these again have greater still,
    And greater still, and so on.

    - The Siphonaptera
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1. Introduction

1.1. Nuclear Fusion Research

Commercial nuclear fusion power has, for several decades, been seen as a panacea to many of the problems associated with energy production. The prospect of harnessing this means of energy production is an enticing one, as it would potentially allow abundant, cheap energy to be produced with a relatively minor environmental impact[1].

Nuclear fusion as a process was first recognised in 1920 by Sir Arthur Eddington, building on the experimental work of Francis William Aston on measuring the mass of helium and hydrogen nuclei. Eddington theorised that the mass difference between four hydrogen atoms and a helium atom (the so called “mass defect”) was the key to energy generation in stars. Early experiments with fusion plasmas took place in the following decades (most notably at Cavendish laboratory), but it was only after the Second World War that wider interest in harnessing nuclear fusion for energy production began. In 1946 Thomson and Blackman filed the first patent for a nuclear fusion reactor, and by the end of the 1950s experimental reactors were being operated in the United States, the Soviet Union, France, Germany, the UK and Japan[2]. Given the context of the Cold War, much of this early research had been conducted in secret. However, in 1958 at the “Atoms for Peace” conference in Geneva (named for Dwight Eisenhower’s famous speech as part of Operation Candor), many countries disclosed their research activities, including the United States and Soviet Union. Recognising the difficulties in fusion research highlighted at the conference, the following years saw the establishment of a series of international fusion research organisations. The first of these was the European Atomic Energy Community (EURATOM-CEA), the European organisation, which is the predecessor of the current European Fusion Development Agreement (EFDA) and ITER organisations. In 1968 Soviet scientists announced their success with a type of magnetic confinement reactor called a Tokamak (an acronym of toroidal’naya kamera s aksial’nym magnitnym polem - toroidal chamber with magnetic coils), developed by Soviet physicists Igor Tamm and Andrei Sakharov in the 1950s[3]. Their success led to the widespread use of Tokamak devices in fusion research. In the 1970s and 80s several
large Tokamaks were constructed, including the Joint European Torus (JET) experiment at Culham on which the research presented here is based. At the end of 1999, the United Kingdom Atomic Energy Authority took over the management of the facility, the research effort being coordinated by the European Fusion Development Agency[4]. Fusion research using other magnetic confinement devices (primarily with stellarator and reversed field pinch devices) has continued, albeit to a lesser extent. In parallel to experiments using magnetic confinement devices, research into inertial confinement fusion has been conducted since the mid 1960s, most notably at the National Ignition Facility (NIF) in the US, and with the French Laser Mégajoule experiment. Much of the research into inertial confinement fusion has, however, been related to weapon development.

![Soviet T1 Tokomak](a)  ![The Joint European Torus in 1991](b)

Figure 1.1.: Past and Present Tokomaks

Table 1.1 is a list of magnetic confinement fusion devices that are currently operational or under construction. Arguably, the most important contemporary European experiment in magnetic confinement fusion is the ITER experiment, which is currently being designed. The aim of this experiment is to build a reactor with a performance significantly exceeding the current generation of fusion reactors, and to develop technology that can be eventually be used in an operational, electricity generating reactor.

<table>
<thead>
<tr>
<th>Experiment Name</th>
<th>Location</th>
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<tbody>
<tr>
<td>DIII-D</td>
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<td>Tokamak</td>
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<td>United States</td>
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<td>Alcator C-Mod</td>
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<td>Pegasus</td>
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<td>Experiment Name</td>
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<tr>
<td>UCLA ET</td>
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<tr>
<td>STOR-M</td>
<td>Canada</td>
<td>Tokamak</td>
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<tr>
<td>EAST</td>
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<td>Switzerland</td>
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<td>Czech Republic</td>
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<td>ITER</td>
<td>France</td>
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<tr>
<td>H-1NF</td>
<td>Australia</td>
<td>Stellarator</td>
</tr>
<tr>
<td>Wendelstein 7-X</td>
<td>Germany</td>
<td>Stellarator</td>
</tr>
<tr>
<td>Large Helical Device</td>
<td>Japan</td>
<td>Stellarator</td>
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<tr>
<td>HSX</td>
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<tr>
<td>TJ-II</td>
<td>Spain</td>
<td>Stellarator</td>
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<td>MST</td>
<td>United States</td>
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<tr>
<td>RFX</td>
<td>Italy</td>
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<tr>
<td>TPE-RX</td>
<td>Japan</td>
<td>Reversed Field Pinch</td>
</tr>
<tr>
<td>EXTRAP T2R</td>
<td>Sweden</td>
<td>Reversed Field Pinch</td>
</tr>
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Table 1.1.: A list of current magnetic confinement fusion experiments

A great deal of research has been conducted on the theoretical and physical aspects of fusion power generation; the nuclear process is well understood and numerous methods of exploiting it have been proposed. However, the engineering knowledge required to use this knowledge practically is less well developed[5][6][7][8]. There remains a lot of
work to be done in this area before nuclear fusion could be considered a viable means of power generation. One of the major activities being carried out at by Culham Centre for Fusion Energy (CCFE) staff is developing new engineering techniques and designs for use in future nuclear fusion experiments, such as the upcoming ITER experiment in France[9][10]. The research presented in this thesis is one such activity that has been funded by the UK Engineering and Physical Sciences Research Council (EPSRC) and the Culham Centre for Fusion Energy (CCFE) via a Case Award studentship.

1.2. Nuclear Fusion Fundamentals

Nuclear fusion reactions occur when two or more atomic nuclei collide at high velocity. A high velocity collision causes the nuclei to fuse, creating a single nucleus of a different total mass. For nuclei with an atomic mass lower than iron, a fusion reaction results in a release of energy, because the resultant nucleus has a lower total mass. For this reason, hydrogen and its isotopes, deuterium and tritium, are the fuels used almost exclusively in contemporary fusion research.

The industrial sponsor of this research, CCFE, is responsible for running and maintaining JET. As noted in the first section, JET is a magnetic confinement fusion device. The purpose of magnetic confinement fusion devices is to create and maintain a high temperature plasma of fusion capable fuel, in order to produce the conditions necessary for a nuclear fusion reaction to occur. Their primary defining characteristic is that the fusion capable plasmas are constrained by magnetic fields.

At JET, the fusion plasma is shaped into a toroid by a series of magnetic fields and is contained in an evacuated toroidal vacuum chamber. The ultra high vacuum is maintained, because even a small amount of trace atmospheric gas coming into contact with the plasma will hamper the operation of the device. Similarly, the plasma cannot come into contact with any of the vessel surfaces, as this would result in a rapid reduction in the plasma temperature, ending the fusion reaction.

Three mechanisms are used to heat the plasma inside this chamber: ohmic heating, radio frequency (RF) heating, and neutral beam heating. The first of these methods, ohmic heating, involves passing a large electric current through the plasma (millions of Amperes at JET). The impedance of the plasma causes this current to generate heat. At high temperatures, however, the impedance of the plasma is too low for this heating technique alone to be effective. RF heating is the second heating technique. An antenna directed
at the fusion plasma is used to generate electromagnetic radiation which is subsequently absorbed by the plasma. The frequency of the radiation is automatically controlled and matched to the plasma condition in order to maximise the level of absorption. The final (and most important) heating technique is neutral beam heating. Here a beam of neutrally charged particles is created and sent at high velocity into the plasma. The heating is caused by the transfer of kinetic energy between the beam particles and the plasma. At JET, approximately one megawatt of heating power is from ohmic heating, twenty megawatts are provided by RF heating, and thirty-five megawatts are provided by neutral beam heating.

The three heating techniques are illustrated graphically in Fig. 1.2.

![Figure 1.2.: An illustration of the JET heating mechanisms [11]](image)

Conceptually, the operation of JET and other magnetic confinement devices is straightforward. The engineering reality, however, is considerably more involved.
1.3. RESEARCH OBJECTIVES

1.3. Research Objectives

1.3.1. Motivation

As already noted, one of the main research activities at CCFE is investigation into engineering technology applicable to ITER\(^9\)[10]. In particular, there is an interest in Neutral Beam Heating System (NBHS) technology, because CCFE are responsible for the ITER NBHS.

Over the years, one of the main engineering challenges at CCFE has been to improve the reliability of the JET experiment as a whole, and an important part of that process has been to improve the reliability of the NBHS. Great progress has been made on this front, as evidenced by the much reduced failure rate of the device since it started operating in the late 1980s\(^{12}\). Nonetheless, failures and unplanned maintenance activities remain difficult to deal with, even with their reduced frequency, owing to both the complexity of the device and the practicality of carrying out repair work as physical access to the device is often restricted. The latter of these factors is set to be an even more significant consideration when ITER begins to operate, because it is expected that maintenance work will be conducted entirely by remote\(^{13}\), with the hot-cell containing the device being entirely inaccessible to human personnel.

A high degree of instrumentation is common both to JET and to the design for ITER, as would be expected given their experimental status. An important (currently unexploited) opportunity afforded by this situation is the use of process data for real-time condition monitoring and fault detection, which goes beyond the standard safety interlock/alarm threshold approach. This high level of instrumentation and the successful use of condition monitoring in several other industries (including the nuclear fission industry\(^{14}\)) implies that it could also be used for nuclear fusion applications to good effect. CCFE wished to explore this possibility, ideally by means of a demonstration focused on the JET NBHS, and thereby provide a case for the inclusion of condition monitoring technology to the ITER NBHS design and to JET, should the demonstration prove successful. This provided the motivation for the research presented in this thesis.
1.3.2. Preliminary Work

The first phase of the research was to identify what would constitute a good demonstration of condition monitoring in a fusion application. It was also necessary to define some specific research objectives consistent with that aim. To this end, a preliminary investigation was conducted to find out what parts of the NBHS were historically failure prone and where better diagnostic information would be most useful.

A number of options were investigated, four of which are discussed here.

Neutral Beam Duct Heat Load

The neutral injection boxes (NIBs) both generate a beam of high velocity, neutrally charged particles\(^1\). The beam passes from the NIB into the magnetic confinement chamber (the torus) via a copper lined duct. Owing to the magnetic field around the torus, any beam particles that are ionised during their journey are deflected. The deflected particles then collide with the duct lining, resulting in a high thermal load. Over time this can result in the duct lining being eroded and deformed.

\[\text{Figure 1.3.: Horizontal Beam Deflection [15]}\]

\(^1\)The neutral beam injection system is fully described in Section 2.2.1.
1.3. RESEARCH OBJECTIVES

CHAPTER 1. INTRODUCTION

The current practice at CCFE is to estimate this heat load on the duct in advance, to ensure its acceptability. Figure 1.3 is an illustration of one such estimate. The diagram shows the horizontal path of the ionised portion of a deuterium beam for three different experiment conditions. The opportunity exists, however, for the real-time estimation of duct heat load using data collected by several thermocouples embedded within the duct wall.

**Electron Back-streaming**

The re-ionisation of the neutral beam results not only in beam particle deflection, it also results in an effect known as electron back-streaming: electrons stripped from the re-ionised portion of the beam are accelerated to the rear of the NBHS by the Positive Ion Neutral Injector (PINI) devices (described in Section 2.2.1). Electron back-streaming can, over time, cause water leaks into the NIBs by the erosion of water cooled components within the PINIs. Currently, the effect of electron back-streaming is mitigated by periodic inspection and maintenance of the PINIs. It may, however, be possible to reduce the occurrence or severity of electron back-streaming by estimating the magnitude of the effect in real-time. To this end, monitoring the operational state of the PINI devices may provide an indication of the current level of electron back-streaming.

**Vacuum Leaks**

Leaks into the NBHS are problematic. Water and air leaks compromise the vacuum maintained within the NIBs, preventing the operation of the NBHS, and ultimately the experiment as a whole. The presence of multiple water cooled components within the NIBs mean that there are many potential places where a leak can arise, making both their prevention and timely maintenance difficult. This failure mode is perceived to be one of the most challenging to deal with by the operational staff at JET. To illustrate the difficulty of isolating the cause and location of leak, the detection and isolation procedure is shown in Fig. 1.4 and Fig. 1.5, respectively.

**Vacuum Pumping**

The maintenance of a NIB vacuum is an essential precondition for the operation of the JET experiment. Of all the failure modes identified during the initial phase of the research, failure modes resulting in a compromised NIB vacuum were most serious in terms
1.3. RESEARCH OBJECTIVES

CHAPTER 1. INTRODUCTION

Base Pressure Alarm

Review 7 day base pressure trend

Look for evidence of water using residual gas analyser (mass 18 or 28/32)

Abnormal PINI behavior?

Yes

Inform lead maintenance engineer

No

Perform one or more sync pulses to gather more data

Close rotary high vacuum valve

Set pumps to STANDBY

Do not turn off cryopumping system as low pressure is still required

Proceed to leak isolation

Experiments can only continue if one NIB is required

Allow DPIS to operate

Figure 1.4.: NIB leak detection procedure
Switch pumps to SHUTDOWN and wait for 10 minutes

Base pressure rise?

Yes

Water leak most likely on PINI loop

Clamp water hoses ASAP

Clamp all PINI water supplies

Unclamp PINI water supplies one by one until a pressure rise is observed

Base pressure rise?

No

Confirm the last unclamped PINI as faulty

Water leak most likely on NIB loop

Set pumps to FULLDOWN

Base pressure rise?

No

Leak confirmed most likely in NIB

Compare base pressure trends between pumps on STANDBY and FULLON

Significant change?

Yes

Leak probably large

Leak probably small

Leak most likely not close to gauges

Yes

Use residual gas analyser to confirm if the leak is air or water

Consider actuating calorimeter door to determine on which side the leak is located

No

Vacuum gauge measurements similar?

Yes

Leak possibly close the the vacuum gauge indicating the higher pressure

In the case of an air leak, turn off the LHe cryopump loop, as this removes oxygen and nitrogen from the vacuum, masking all but the largest air leaks

No

Figure 1.5.: NIB leak isolation procedure
of overall lost experimental time. This NBHS cannot operate with reduced performance with this type of failure, nor can it be reconfigured to operate in any secondary mode which can support the experiment; these failure modes completely prevents the operation of the NBHS. Leak faults are an important subset of the causes of these failure modes, together with faults that affect the operation of the system responsible for creating and maintaining the vacuum.

The NBHS vacuum system uses three vacuum pumping techniques: rough pumping, turbo-molecular pumping, and cryogenic pumping (commonly referred to as cryopumping). Of these, the cryogenic pumping system is relied upon for the greatest length of time, as it is required to operate continuously for extended periods (months) during an experimental campaign. Any failure that disrupts the operation of the cryopump can result in the NBHS vacuum being compromised, and consequently disrupt an ongoing experimental campaign in general.

A condition monitoring scheme applied to the cryopumping system could be used to detect and isolate faults affecting the pump performance and the state of the vacuum. This information could be used to assist in maintenance and to inform other supervisory activities, to ultimately improve the availability of the NBHS. The cryogenic pumping system and the supporting plant are highly instrumented. Many process variables are already measured and recorded in real-time. This existing source of information can be leveraged and reused in a condition monitoring scheme, reducing or eliminating the need for additional sensor hardware. Furthermore, the historical process data can be used during the design of a condition monitoring scheme. Finally, the JET NBHS cryopumping system has several similarities with the proposed ITER cryopumping system[16]. This suggests that the development of a scheme for JET could be used to inform the development of a similar scheme for ITER.

The main alternative vacuum related scheme would be one applied to those components prone to leak failures. It was felt, however, that such a scheme would have to cover a disparate collection of devices within the NIB. This would make the scheme dependant on the particular configuration of several NBHS subsystems, all of which are subject to change, and which do not have the same degree of similarity to the ITER design. These subsystems (including, crucially, several water cooling loops) are also not as highly instrumented, and could require the addition of additional sensor hardware for a condition monitoring scheme to be effective.

For these reasons, it was felt that a condition monitoring scheme based on the JET NBHS
cryogenic pumping system would provide a good demonstration of condition monitoring techniques in a fusion application.

1.3.3. Objectives

With the JET NBHS cryopumping system identified as a target platform for a demonstration condition monitoring system, the following research objectives were defined:

- Build and validate a simulation model of the JET NBHS cryopumping system that can be used in the design process, in order to minimise the impact of the research on the operation of JET.
- Design a condition monitoring scheme for the JET NBHS cryopumping system
- Demonstrate the utility of the scheme by testing it in simulation with a range of realistic faults
- Develop a suitable design procedure that could be used to develop future condition monitoring schemes at CCFE
- Use pre-existing sensors to good effect, in order to minimise or eliminate the need for additional hardware

1.4. Contributions

The main novel contributions of this thesis are as follows:

- A novel dynamic model of a large-scale cryopumping system. There are no models of large scale cryopumping systems reported in the literature. Therefore, this novel model is the first of its kind. It has been validated using historical process data collected from JET. In this research the model has been used as a surrogate plant for testing the condition monitoring scheme, but it could find further utility for model-based control design. It could also be adapted to represent the cryogenic pumping systems on several other fusion experiments. The model is presented in Chapter 4.
• The first design of a real-time model-based condition monitoring scheme to a cryogenic pumping system. This is the first design of its kind, and more generally, it is the first design of any model-based condition monitoring scheme to the neutral beam heating system at JET. Its effectiveness has been tested by simulating its response to a range of realistic faults. The design of the scheme is presented in Chapter 5.

• A comparison between using a single and dual threshold arrangement for detecting faults. The condition monitoring scheme presented in Chapter 5 uses a bank of Kalman filters to estimate the state of the plant in a fault free state. The residual signals from the Kalman filter bank are used to diagnose faults by comparing them to a threshold. The relative utility of using a single threshold and a dual threshold arrangement has been investigated and tested in simulation. The simulation results and comparison is presented in Chapter 6.

1.5. Publications

The research presented here has resulted in two conference presentations and one journal publication. The novel non-linear simulation model of the JET cryopumping system was presented at the 2012 UKACC Control conference in Cardiff[17]. The design of the condition monitoring scheme itself was presented in 2012, at the 27th Symposium on Fusion Technology in Liege (the poster presentation is available on the SOFT website), which was followed by a journal publication in Fusion Engineering and Design[18].

One further paper has been submitted to the International Federation of Automatic Control (IFAC) 19th World Congress, 2014, concerning the simulation and performance of the condition monitoring scheme. A technical report for the engineering staff at CCFE is also in preparation.

1.6. Thesis Layout

The order of this thesis was selected to allow the reader to easily follow (and reproduce or adapt) each stage of the research. This order also closely corresponds to the chronological order of the research activities.

This thesis covers the following topics:
• **Chapter One - Introduction.** This chapter introduces the context and motivation for the research. This is followed by a summary of the preliminary investigation which informed the research objectives. Finally, the novel research contributions and publications are listed, followed by this summary of the thesis contents.

• **Chapter Two - Literature Review.** The literature review is an assessment of the current state of the art relating to this research. The two main topics are fusion engineering and fault detection. The former covers neutral beam heating, including a description of how neutral beams work, their main components, a discussion of their reliability, cryogenic pumps, and control engineering practice in the fusion sector. There is a particular focus on JET and ITER. The latter is a review of fault detection and condition monitoring techniques. The purpose of this chapter is to show the gap in knowledge this research addresses (i.e. modelling and fault detection for cryogenic pumps) and to justify the choice of techniques used to design the condition monitoring scheme.

• **Chapter Three - The Cryopumping System.** In Chapter Three the purpose, design and operation of the cryopumping scheme are presented, followed by an analysis of its failure modes. A simplified FMECA was conducted to investigate these in an analytical manner. The purpose of this chapter is to explain how the cryopump works, to provide information for the modelling procedure in the next chapter, and to present the work done to identify a set of candidate faults for testing the condition monitoring scheme, in accordance with the second objective listed in Section 1.3.3.

• **Chapter Four - Modelling The Cryopumping System.** This chapter presents the development of the non-linear simulation model of the JET cryopump. The concept and structure of the model is presented, followed by a full mathematical description of the plant, derived from a first principles physical analysis. The model is validated against two sets of historical process data, to demonstrate its effectiveness at representing the physical plant and support its use as a surrogate in Chapter 5 and Chapter 6.

• **Chapter Five - Design of the Condition Monitoring System.** The design of the condition monitoring scheme is presented in this chapter. The scheme is based on an analytical residual generation approach, which uses Kalman filtering. The design procedure is explained, followed by a detailed description of the main
design steps. The outcome of the design is summarised and the full set of design results is presented in appendices D, E, and F owing to their length. This chapter provides all the information needed to reproduce the design procedure for this or a similar plant.

- **Chapter Six - Simulation and Verification of the Condition Monitoring Scheme.** This chapter describes and presents the results of the procedure used to test the condition monitoring scheme. The non-linear simulation model was adapted to simulate the effect of a selection of realistic faults. The effectiveness of the scheme at detecting these faults was tested. Two variations of the scheme using different fault isolation methods were simulated and their performance was evaluated. The results of these tests are shown in this chapter. The chapter finishes with a discussion of the results.

- **Chapter Seven - Conclusions and Future Research.** The final chapter is a summary of the research, which includes some suggestions for future research activities. The main outcomes of the research are discussed together with some commentary on the extent to which the research objectives were achieved. The research highlighted some future areas of investigation. Some of these suggestions relate to JET specific implementation issues, while the others have more applicability to fault detection and condition monitoring in general.

### 1.7. Summary

This chapter has presented the context, motivation, objectives and contributions of the research presented in this thesis. The final section provides a description of the content of each chapter, and can be used as a guide to the content to be found in the following chapters. The next chapter is a literature survey which provides a review of the published research relating to the subject of this thesis.
2. Literature Review

2.1. Literature Overview

In the previous chapter, the present direction of fusion research was briefly discussed. The objectives of the research presented in this thesis were justified within that context. With those objectives in mind, it is necessary to review what previous related work has been done. This is to ensure a gap in knowledge is addressed and the utility of this research is maximised. There are two groups of topics covered in this chapter: Fusion engineering and fault detection.

2.2. Fusion Engineering

The journal *Fusion Engineering and Design* and its imprints are an important source focusing specifically on nuclear fusion engineering research. Issues are frequently published, and it contains one of the larger collections of research, along with the IAEA journal *Nuclear Fusion*. Other important publications for nuclear fusion researchers include *Nuclear Instruments and Methods in Physics Research, Journal of Nuclear Materials, Journal of Applied Physics, Plasma Physics and Controlled Fusion*, and *Fusion Science and Technology*. Fusion related articles also occasionally appear in non-fusion field specific publications such as *Vacuum* and *Cryogenics*. Finally, fusion research organisations (such as CCFE) occasionally self publish material of interest to the fusion researcher. Typically these take the form of technical or administrative reports.

2.2.1. Neutral Beam Heating

Neutral beam heating is central to the JET experiment. It is one of the three main mechanisms for plasma heating. In the introductory sections, it was noted that the neutral beam heating system was, in part, selected as a platform for this research because of the role CCFE is taking in the design of the ITER beamlines. As such it is useful
2.2. FUSION ENGINEERING CHAPTER 2. LITERATURE REVIEW

to review the operation of these devices. In [19] Speth describes the fundamentals of neutral beam heating, and she specifically notes the paper is aimed at readers who are not plasma physicists by training. As such, it is a useful introductory text in particular for engineers. Duesing et al published an important paper in 1987[20], which is one of the fundamental papers on the neutral beam heating system at JET. In the first part of the paper the parameters and layout of the device are detailed, and presented together with a summary of the physics calculations relating to the design. While the device has been updated since the time this paper was written, the fundamentals of the device remain the same. Based on these two papers, the basic operation of the device can be summarised.

Neutral Beam Fundamentals

During the operation of the JET device, a high temperature plasma is contained in a toroidal vessel using a strong magnetic field. A neutral beam heating device provides heating to this plasma by injecting particles of neutral charge into it at a high velocity, causing a transfer of kinetic energy from the beam particles to the plasma.

Figure 2.1.: A simplified diagram of a neutral beam heating system [11]

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2.2. FUSION ENGINEERING CHAPTER 2. LITERATURE REVIEW

Figure 2.1 is a simplified illustration of the neutral beam heating devices at JET. This image, together with the two following illustrations, were produced by CCFE staff for use during in-house training sessions[21]. Figure 2.1 shows the generation and life of the beam, prior to it passing into the toroidal chamber. Figure 2.2 is a plan view illustration of the device. At JET, two neutral beam heating devices are used. The configuration of these devices is illustrated in Fig. 2.3.

The beam begins its journey as source gas (typically a hydrogen or helium isotope), shown in blue on the left of the illustration (Fig. 2.2). The gas is fed into a Positive Ion Neutral Injector (PINI), a cylindrical device designed to ionise and accelerate the source gas to a high velocity. The PINI contains several tungsten filaments. These filaments are connected to a high voltage power supply, which during the operation of the beam runs at 130kV. This creates an electrical arc between the filaments and the PINI walls, through the source gas. The arc ionises the gas, stripping it of electrons. The gas, now positively charged, is accelerated through a series of metallic accelerator grids, which are held at a high voltage.

The kinetic energy of the beam must be sufficiently high if it is to reach the centre of the plasma. This is necessary to ensure the beam particles are not ionised at the plasma edge and potentially prematurely removed via the divertor ring. At JET, the beam particles are accelerated to 80keV, using older accelerator equipment, 140keV when the newer accelerator equipment is used. In the case of a Deuterium beam, this corresponds to a mean particle velocity of 2800 km/s in the former scenario, 3600 km/s in the latter.
This is approximately five times the mean ion velocity inside the plasma. The neutral beam systems can reliably provide 20MW of heating power to the plasma, although a higher power is theoretically achievable. At JET, there are eight PINIs in each Neutral Beam Injector (NBI).

Upon passing through the accelerator grids, the gas, now a beam, is travelling at high velocity and is consequently of high kinetic energy. The beam travels through a neutraliser box, containing neutraliser gas, typically the same material as the source gas. A proportion of the beam ions pick up electrons, restoring a neutral charge. Only around 20% to 25% of the particles leave the neutraliser gas cloud with a neutral charge, according to the efficiency of the neutraliser. As the beam leaves the gas cloud, it passes by a subsystem known as the deflection (or bending) magnet. The magnet deflects the charged portion of the beam into a “vee-shaped” water cooled copper collectors, known as ion dumps. These absorb the energy of the deflected portion of the beam. The ion dumps are split into two categories; Full and Fractional Energy Ion Dumps (FEIDs), their locations being predetermined according to the predicated momentum of the beam particles and thus their associated paths. Once the remainder of the beam is of neutral charge, it passes through the Rotary High Vacuum Valve (RHVV), which can be closed to seal the neutral beam from the torus when the beam is inactive. Finally, it passes through a water cooled copper scraper, with an aperture which refines the profile of the beam. Accordingly, the neutral charge of the beam allows it to pass through the magnetic fields around the torus and collide with the plasma within, transferring kinetic energy to provide heating power.

At JET, the NBI systems do not normally operate continuously during an experiment. Rather, heating power is provided in short bursts known as pulses. Between pulses, the NBI system is kept on standby. The vacuum is maintained and the other support systems remain enabled, ready for subsequent pulses. The main factor that limits the duration of a pulse is the stability of the fusion plasma. The difficulty of controlling the shape of a plasma over long periods of time means that it cannot (currently) be maintained permanently. Running the NBI system without a plasma present would damage the torus.

The neutral beam heating systems can operate in several modes, the most important (and commonly used) modes being known a synchronous (SYNC) and asynchronous (ASYNC). In SYNC mode, the NBI works in time with plasmas within the torus, providing heating power in pulses of up to eight seconds. The timing is controlled by a central supervisory software agent. In ASYNC mode, the NBI can operate independently of
plasmas, providing shorter pulses of power. In Fig. 2.2 there is a component labelled calorimeter. This component is used to examine the profile of the beam in ASYNC. Calorimeter gates close in front of the RHVV, exposing a tiled surface, onto which the beam is shone. By examining the resultant power density on the calorimeter gates using an infra-red camera, the beam profile and strength can be determined, and if necessary, adjusted.

Power, coolant water and data connections to the NBI are all run through the central support column. The limited physical space, availability of data ports and other such practical considerations put a limit on the amount of support equipment used in the NBI.

In order to operate the beam, a vacuum must be maintained within the NBI. Atmospheric particles would disrupt, block or scatter the beam, making their presence undesirable. A vacuum system operates on a continuous cycle during JET operating campaigns to achieve this. The research presented here focuses on the vacuum system in particular, and as such, the next chapter provides a full description of it and the supporting plant.
2.2. FUSION ENGINEERING

Neutral Beam Operation and Engineering

In [22] and [23] Thompson and Jones (respectively) discuss the use of neutral beam heating at JET, with a focus on the use of tritium beams. Jones focuses on a period culminating in the deuterium-tritium operational campaign of 1997, and the neutral beam engineering upgrade carried out in preparation for it. The author makes clear the importance of neutral beam heating to the experiment, how the neutral beam device was of central importance to the progress of the entire fusion research programme at JET. In [24], Čirić, together with several other members of the CCFE engineering team, wrote in 2007 about the recent neutral beam enhancement project at JET. The purpose of this project was improve the neutral beam by increasing the total heating power and increasing the overall reliability. The performance of the upgraded beam was reported on in 2011, again by Čirić[25]. These papers, among others, demonstrate the reliance on the neutral beam heating system at JET, and the importance and effort spent on ensuring its availability.

Two historical reviews of the overall reliability and availability of the neutral beam heating systems have been published since they started operating in the late 1980s (not including a further paper on reliability modelling[26]). The first of these was by Challis et al in 1991[27], and the second by King et al in 2005[12].

In the first of these papers, reliability data relating to the period between 1988 to 1991 was reported on. The data was drawn from both automatically collected electronic logs and from logs kept by the operational team responsible for the devices. The author reports an average availability for the NBI of around 85% for the period. Regarding the failures that occurred during that period the author said:

“From 1989 onward virtually no loss of availability is attributable to problems with software and the NORD computer. The outstanding down time is caused by either power supply faults or mechanical system failures (e.g. loss of cryogenics, vacuum leaks, cooling circuit problems, failure of fast shutter or calorimeter positioning indicators etc.). The relatively poor hardware availability in 1990 was due to problems with the cooling and cryogenic systems early in the year. The cryogenic problems were partially related to the commissioning of helium operation. Individual hardware faults often result in significant loss of availability since they can render one or both injectors inoperable and frequently cannot be repaired immediately due to access restrictions. High voltage power supply faults on the other hand are much more numerous but
usually result in the temporary loss of only one or two beamlines from an injector. In this case often the Tokamak program is only slightly affected and remedial work can be carried out in parallel with operation.”

The author also notes that some other early failures were related to passive devices (e.g. the bellows in the beamline dumps), but these were largely resolved by 1988.

The second paper is a review of the performance and reliability of the neutral beams from 1994 to 2003. The author reports an availability of around 91% for the neutral beams in 2003. The paper then goes on to discuss the interruption of beam pulses before their completion. Forty-three percent of pulses carried out in support of the EFDA agreement in that period were interrupted. The majority of the interruptions were caused by one of the protection interlocks, and around 8% were directly attributable to high pressure events, according to the charts presented at the end of the paper.

There are several other papers which look at individual components in the neutral beam heating systems which, providing (in part) commentary on their reliability[28][29][30][31]. Here the components are the PINIs, power supply, deflection magnet, and ion dumps, respectively. In 2007, Pinna published a paper describing the initial results of a database cataloguing failures of components used in several different fusion devices[32]. At the time of publication the database contained a record of 832 component failures. Six hundred and ninety-seven of these were mechanical, 39 electrical and 96 related to instrumentation and controls. The author makes a comment specifically relating to JET, regarding several recorded failures relating to the vacuum systems:

“It is worthy to mention the recent addition of data from the Active Gas Handling System and Vacuum System of JET (more than 130 failure rates related to operating experience gained since 1983 up to 2001). The identified failures or malfunctions are related to valve failure to open/close, I&C erratic or no output, vacuum pump and blowers failure to run, transformer failure to operate, and leaks on bellows, electrical feedthroughs, flanges, valves, welds and optical windows.”

A more recent 2010 paper by Pinna[33] examines the operating experiences of several current fusion experiments, including JET, drawing conclusions on reliability for the upcoming ITER experiment. The author identifies 670 vacuum leaks at JET between 1983-2007 and 100 failures in neutral beam mechanical components between 1985 and
2004. The author also notes that the Tore Supra experiment had failures with the cryogenic system that had a “definite impact” on the ability to produce plasma.

Taken together these papers show that there has been a continual improvement in the reliability of the JET NBHS over the years, although a variety of failures still occur, several relating to the vacuum and cryogenic systems. Those failures resulting in the loss of vacuum in the NBHS or where mechanical repairs are required are particularly disruptive.

2.2.2. Control and Monitoring in Fusion

The research presented in this thesis regards the development of a condition monitoring system for deployment on the JET NBHS. It is therefore instructive to review the current control engineering practice at JET and the development of condition monitoring schemes on other fusion devices, particularly where they involve cryogenic systems.

Current Practice

In 1999 Krom described the work on upgrading Control and Data Acquisition System (CODAS), starting with the original implementation from when JET was constructed (1979 to 1982), through the 90s[34]. Of particular note to this research is the hierarchical control architecture, which has been maintained consistently from the outset. Core control of the experiment has been centralised, but individual departments have been responsible for their own front-end control equipment.

In 2012, Hennig published a paper in which a comparison is made between the usage of Programmable Logic Controllers (PLCs) at JET and Wendelstein 7-X[35]. An important point made by this paper is that at JET there is no unified control architecture encompassing the entire experiment. The CODAS arrangement is an in-house solution for controlling the main part of the experiment (e.g. the torus itself), but in addition and separate to this, off-the-shelf PLC hardware is frequently used for supporting plant (e.g. the cryogenics plant). Furthermore, each department at JET uses its own preferred PLC hardware, meaning that across the site a range of devices from different manufacturers can be found. This has obvious implications for site-wide commissioning of new control systems techniques. Currently, the interface between control software at CCFE is facilitated by a bespoke HTTP software system referred to as “black box”, which is functionally described in [36].
In 2009 Vega et al wrote about diagnostics, control and data acquisition at JET, in the context of preparing for the ITER experiment[37]. Aside from the technical discussion, a key point made here is that the amount of data collected has continually increased over time. This is supported by Blackler in [38], who notes that overnight batch processing is used to alleviate some of the computing load. Year on year the amount of collected data at JET roughly doubles, as per Moore’s Law. A second key point is that, at ITER in particular, this trend is likely to accelerate. This, combined with the higher availability requirement and longer sustained operation of the ITER machine, present several technical challenges. As a consequence tools for data processing and interpretation, such as condition monitoring tools, will become increasingly important in the future.

Only two applications of condition monitoring for fusion cryogenic systems can be found in the literature. In [39] the recent cryogenic plant controls upgrade on Tore Supra is described. The cryogenics plant at Tore Supra is similar to the one supporting JET and the control system has been developed in a similar way. Ladder logic has been used to define the PLC operation and this is supported by a number of small subroutines for various tasks (e.g. PID, alarms, interlocks etc.). Of particular interest is the short description of the fault detection arrangement, which was carried out in the traditional manner with thresholds defining alarm conditions. In 2009, Guillerminet published a paper which describes a new data acquisition scheme, again at Tore Supra[40]. The scheme is used to support the main part of the experiment, rather than the cryogenic plant as above. The author reports success in using an expert system based fault detection scheme, as part of the data acquisition scheme.

Also of note are three papers on the development of the control systems for the KSTAR experiment, including one for the cryogenic vacuum system[41][42][43]. The KSTAR engineering team have adopted the open source Experimental Physics and Industrial Control System (EPICS) framework to develop their distributed control scheme. This has allowed them to bypass some of the difficulties with separation between plant and experiment control described in [35]. Regarding fault detection and monitoring, KSTAR is utilising a traditional approach with pre-defined thresholds for key process variables and alarm conditions, as with the Tore Supra and JET cryogenic plant.

Recent research by published by Zhou[44] at the end of 2012 details the design of an expert system fault detection scheme for the EAST cryogenic plant. This is an addition to the control system described in [45]. The system uses a knowledge base of faults to detect and diagnose faults. The knowledge base is a set of rules and conditions which have been derived from a set of fault trees. Fault logs collected from the cryogenic plant
are tested using these rules, and if the data matches a set of conditions corresponding to a fault in the rule base, a fault is flagged. At the time the paper was written, the system was not yet commissioned, but the author does report success with their preliminary simulations.

In summary, the application of condition monitoring to fusion cryogenic plant is currently limited, with only one article relating to this appearing in the literature[44]. Where condition monitoring has been applied to a fusion application, expert systems have been used and some success has been reported. The available control hardware at JET would, however, allow several other types of scheme to be developed and deployed, including analytical/quantitative schemes. The application of these schemes at JET or for ITER has not yet been investigated, and there remains significant opportunity to prove the usefulness of such a scheme at JET, and for ITER in the future.

2.2.3. Cryogenic Pumping

For the purpose of the design and testing of the condition monitoring scheme, it was determined that obtaining a simulation model of the cryopumping system would be useful. Such a model facilitates the design process by allowing experiments to be conducted rapidly in simulation, without disrupting the operation of the physical plant, which would not normally be permitted. The development and validation of such a model is discussed in chapter 4, however it is useful to review what information already is present in the literature.

Cryopumps have seen extensive use in fusion applications, both at JET and elsewhere. Accordingly, several general descriptions of cryopumps appear in the literature, in addition to articles on individual designs. Two widely cited resources on cryopumping are Sedgley et. al. on fusion cryopumps specifically[46], and Bentley[47], on cryopumps more generally. There are also a number of general reference resources, such as [48], [49], and [50].

On modelling, several static models of cryopumps have been presented in the literature. In particular, the pumping speed and efficiency of cryopumps are of interest to fusion researchers, and the literature reflects this. Obert and Perinić developed a numerical Monte Carlo model of a JET cryopump in [51] in 1992. Similarly, Akiba et. al. developed a Monte Carlo model for an ITER type cryopump in [52] and [53] in 2012. Other static models can be found in the literature for other fusion cryopumps.
Dynamic models of the type of cryopump used in the JET NBHS could not be found at the time of writing. The closest that could be found was an article describing a model of the JET divertor cryopump, which was used to test its response to a set of fault conditions [54]. This cryopump, however, significantly differs from the NBHS cryopump in configuration, operating modes, conditions, and function. Specifically, it is a single phase, continuously supplied, unshielded pump in a horizontal ring configuration, as opposed to a two-phase, trickle fed, fully shielded, vertical pump, like the NBHS cryopump. As such, this model cannot be used to describe the cryopump of interest for this research. There is, therefore, a gap in knowledge that the model presented in chapter 4 addresses.

2.3. Fault Detection

For as long as people have been building machines, machines have failed. Fallibility of hardware and processes has been, and will be, a constant in the engineering domain, regardless of how advanced and sophisticated our techniques become. The fallibility of the machine is a mirror of the fallibility of the designer, unable to foresee or control every eventuality. Over time engineers have developed strategies to manage this reality. Starting with periodic inspection and maintenance, to the wide adoption of standard replaceable parts, to condition based maintenance and systems engineering tools, much progress has been made on improving the reliability of machinery. A significant contemporary contribution to this progress has been the development of automated condition monitoring and intelligent fault detection. In this section, a review of relevant research in this area is presented, together with some commentary on how it relates and contributes to the new research described later in this thesis.

2.3.1. Review and Ontology

A fault detection scheme is a tool which recognises abnormal behaviour in a process, plant or system. This process is also known as Fault Detection and Isolation (FDI), where specific information on the nature of the fault is generated. The techniques used in the development of these tools have roots in several areas, including control engineering, statistics and machine intelligence.

In the literature there is frequent use of field-specific terminology. In [55], Isermann suggested several definitions for some of this terminology, following a discussion by the
SAFEPROCESS Technical Committee. To maintain consistency, those definitions are assumed in this thesis. A summary of the most commonly used terminology from [55] is presented in Table 2.1.

<table>
<thead>
<tr>
<th>Terminology</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Fault</td>
<td>A permitted deviation of at least one characteristic property or parameter of the system from the acceptable / usual / standard condition.</td>
</tr>
<tr>
<td>Failure</td>
<td>A permanent interruption of a system’s ability to perform a required function under specified operating conditions.</td>
</tr>
<tr>
<td>Error</td>
<td>A deviation between a measured or computed value (of an output variable) and the true, specified or theoretically correct value.</td>
</tr>
<tr>
<td>Reliability</td>
<td>Probability that a system or equipment will operate satisfactorily and effectively at any point of time.</td>
</tr>
<tr>
<td>Disturbance</td>
<td>An unknown (and uncontrolled) input acting on a system.</td>
</tr>
<tr>
<td>Residual</td>
<td>A fault indicator, based on a deviation between measurements and model-equation-based computations.</td>
</tr>
<tr>
<td>Symptom</td>
<td>A change of an observable quantity from normal behaviour.</td>
</tr>
<tr>
<td>Fault detection</td>
<td>Determination of the faults present in a system and the time of detection.</td>
</tr>
<tr>
<td>Fault isolation</td>
<td>Determination of the kind, location and time of detection of a fault. Follows fault detection.</td>
</tr>
<tr>
<td>Fault identification</td>
<td>Determination of the size and time-variant behaviour of a fault. Follows fault isolation.</td>
</tr>
<tr>
<td>Fault diagnosis</td>
<td>Determination of the kind, size, location and time of detection of a fault. Follows fault detection. Includes fault isolation and identification.</td>
</tr>
</tbody>
</table>
2.3. FAULT DETECTION  

### Terminology Description

<table>
<thead>
<tr>
<th>Terminology</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Monitoring</td>
<td>A continuous real-time task of determining the conditions of a physical system, by recording information, recognising and indicating anomalies in the behaviour.</td>
</tr>
<tr>
<td>Supervision</td>
<td>Monitoring a physical system and taking appropriate actions to maintain the operation in the case of faults.</td>
</tr>
<tr>
<td>Reliability</td>
<td>Ability of a system to perform a required function under stated conditions, within a given scope, during a given period of time.</td>
</tr>
<tr>
<td>Availability</td>
<td>Probability that a system or equipment will operate satisfactorily and effectively at any point of time.</td>
</tr>
</tbody>
</table>

Table 2.1.: A table of commonly used terminology

In the most general sense, all FDI schemes use some representation of the plant or process to identify faults. These representations can take many different forms, with varying levels of abstraction. The levels of abstraction range from explicit mathematical models of individual physical components to the abstract information contained within the structure of a neural network or statistical data. As such, all FDI schemes can be classified according to the nature of this representation or how they are used.

In 2003 Venkatasubramanian wrote three papers reviewing FDI techniques[56][57][58]. The FDI techniques were classified along the lines described above, with three main categories of techniques being identified: Quantitative model based, qualitative model based and process history based. In [14], a review of FDI applications in nuclear power, Ma and Jiang used a similar classification. They identified three classes of technique: Model based, data based and signal driven, roughly corresponding to those defined by Venkatasubramanian. Many of the reviews cited in the following sections (which mostly address a single class of technique) also assume a similar division between these methods. As such, the ontology presented by Venkatasubramanian informs the structure of this review, and conforms to one of the logical classifications which could be generally recognised by practitioners within the FDI field. In the first of these papers by Venkatasubramanian, a diagram illustrating this ontology of the techniques was presented. This
is recreated below in Fig. 2.4, as the visual representation of the various techniques is instructive.

![Figure 2.4.: Venkatasubramanian’s classification of diagnostic techniques [56]](image)

In the first paper, [56], the desirable characteristics of a fault detection scheme are discussed. These are: Speed of detection and diagnosis, isolability, robustness, novel identifiability, classification error estimate, adaptability, explanation facility, modelling requirements, storage and computation requirements and multiple fault identifiability. The paper then discusses the transformation of information through a diagnostic scheme. This transformation is illustrated in Fig. 2.5, again reproduced from this first paper.

![Figure 2.5.: Venkatasubramanian’s illustration of information transformation [56]](image)

The diagnostic process is described as a series of transformations or mappings of process data. Measured process data is first delivered to the diagnostic scheme. From this data, a set of features is extracted via a processing function designed in advance using
knowledge of the problem. These features are then tested against an objective function to discriminate between them and produce a set of decision points. Finally, these decision points are classified, to index the failure class. In this way, diagnostic systems can deliver ergonomic information to the end user, providing a useful tool for managing process data.

2.3.2. Quantitative Model Based Methods

In the second half of [56], Venkatasubramanian examines quantitative model based schemes. Four of the most frequently used approaches are identified and introduced: parity relations, diagnostic observers, Kalman filtering, and parameter estimation. A number of other papers which review quantitative model based methods have also been written. These include [55], a review of FDI methods based on applications papers from 91 to 95 and the IFAC world congress of 1996, written by Isermann in 1997. Gertler also carried out a review of model based fault detection in 1988[59]. [60] is a review of (quantitative) model based FDI, written by the same author in 2005, which includes some examples illustrating their application. [61] is a 1990 review of quantitative FDI techniques, written by Frank. [62] is a recent review of model based FDI in aerospace applications, written in 2012 by Zolghadri. In addition to this, a large amount of research into applications of model based FDI has been published over time. A selection of the most recent applications papers is presented in a later section. Now, a summary of the most popular techniques from the reviews and applications literature is presented.

Parity Relations

In 1984, Chow and Willsky introduced the parity relations method in [63]. Traditionally, a common way of avoiding problems caused by failed sensors has been to include redundant sensors, on the basis that it is unlikely that several sensors will fail together (common mode failures aside). Where no physically redundant sensor is available experienced plant operators might, on seeing an unusual measurement from one sensor, check one or more other sensor. They could then see if the unusual measurement is consistent with the other available information, and better decide what actions to take. The parity relations technique replicates this common sense approach and gives it a quantitative grounding.
A mathematical relationship between two or more sensors is found while the plant is operating in a fault-free state. With this relationship established, the output of one sensor can be estimated from measurements taken from the other(s). A discrepancy (or residual) between the estimate and the measurement indicates that the plant has deviated from the fault-free state under which the relationship was established, implying a fault has occurred. This type of approach, where sensor redundancy is synthesised mathematically, is known as analytical redundancy.

**Diagnostic Observers and Kalman Filtering**

If a mathematical model of the plant can be determined, then a second approach to quantitative FDI approach is to use state or output observers. In this case, the nominal outputs of the plant are calculated and compared to the measured output of the plant to generate the residual signal. Faults are assumed to affect the state(s) of the plant. Luenberger observers[64] can be used in deterministic settings, and Kalman filters[65] can be used to reduce the effect of measurement noise or uncertainty in the plant model. Alternatively, output observers (also known as unknown input observers) can be used to decouple the residuals entirely from the plant inputs such that they only depend on faults, although this approach does require a highly accurate plant model to be effective. In [66], Frank surveys residual generation and evaluation in observer based FDI schemes, and provides two representative examples.

**Parameter Estimation**

There are several different ways in which faults can be classified. They can be classified by their duration, the time they take to manifest, the severity of their consequence, their likelihood, or by some other measure. In the context of using process models to detect
2.3. FAULT DETECTION

faults, it is useful to differentiate between additive and multiplicative faults. Faults which affect a state or measurement directly can be considered additive faults. Those which affect the parameters of a plant can be considered to be multiplicative faults. This is illustrated in Fig. 2.8, where $U$ is the input, $Y$ the nominal output, $f$ the fault, $P$ the plant, and $Y_f$ the output in the presence of a fault. Parity relations and observer based techniques work well in the case of additive faults, however, the parameter estimation method better accommodates multiplicative faults[56].

In 1984, Isermann discussed parameter estimation in [67]. More recently, the same author produced a review and tutorial in [68]. To summarise, in parameter estimation a linear plant model is assumed and the structure of the model is determined. The model structure could be determined from the properties of historical input/output data or by applying knowledge of the physical system itself, via so-called “grey box” modelling. When the scheme is run, the plant parameters are periodically re-determined and checked for consistency against a known set. A deviation in the plant parameters implies the occurrence of a fault.
Comparison of methods

The techniques presented above have the advantage of a transparent, repeatable and deterministic connection between plant faults and the output of the diagnostic system. In addition to this the computational requirements are not taxing for contemporary PC and PLC hardware, unless very high order models are used. However, this class of scheme does have some features that pose challenges for a successful implementation. As Venkatasubramanian points out in [56], the reliance on linear plant models, or a specific non-linear model, has implications when the plant itself displays non-linear characteristics. These implications will be familiar to many control engineers, and care must be taken at the design stage to ensure the robustness of the scheme to disturbances and uncertainty in the models. The observer based class of scheme which uses Kalman filters [65] does help mitigate this somewhat, although strong non-linearities will require special treatment.

2.3.3. Qualitative Model Based Methods

The second paper by Venkatasubramanian, [57], concerns qualitative model based techniques. Several techniques are introduced and their taxonomy is considered. In [69] and [70], Frank also reviews several qualitative model based techniques. Sahin reviews hybrid expert systems techniques in [71], covering published research from 1988 to 2010, with some examples of industrial applications. Qualitative simulation is one popular way in which qualitative models are used, and is well described in [72].

In contrast to quantitative model based techniques which use explicit numerical models of a plant to diagnose abnormal behaviour, qualitative techniques use symbolic or rule-based models for diagnosis in a manner closer to a human operator. These techniques have two important classifiers: the type of model they employ, and their diagnosis method. The most commonly used models and diagnosis methods (as identified in the reviews listed above) are introduced below.

Model Types

Digraphs are one way of representing cause-effect relationships. These graphs have two elements: nodes and arcs. A node represents a variable. An arc represents the relationships between nodes and has a positive or negative sign. For example, consider
a simplified DC motor model, relating the terminal voltage to rotational velocity. The voltage across the motor terminals induces an armature current. The current creates a torque to spin the motor, which has an opposing load torque. The rotating motor has a back emf that opposes the terminal voltage. These relationships allow the digraph in Fig. 2.9 to be defined. The digraph can be used to produce a rule-set for a diagnostic scheme, or used directly in a qualitative simulation, such as QSIM[72].

A second way of representing cause-effect relationships is to use qualitative physics. Here, physical phenomena are described in terms of relationships and structure. For fault detection, it can be used to derive qualitative expressions from known quantitative equations, and can be used to determine the relationships between process variables via precedence ordering.

Finally, an abstraction hierarchy is a form of model that can define the functional or structural relationship between the components of a system. Each component is considered on its own and a qualitative or quantitative description of its operation is defined. Decomposing the system in this manner allows each component to be classified according to whether it is functional or not, providing a base of knowledge on which a system-wide diagnosis can be made. The key feature of this type of model is that each component is considered in isolation, and not in relation to some other part of the system. The gross behaviour of the system is determined by inference from each component, rather than the other way around.
Diagnosis Methods

There are two classes of diagnostic method: topographic and symptomatic. Topographical diagnosis is an essentially inductive process. The nominal operation of a system is predefined by some qualitative model, and the actual operation of the plant is compared to this. As with the quantitative techniques described in the previous section, a difference between the observed and modelled behaviour implies a fault. The fault can be isolated via knowledge of the structure of the model, or via the functional grouping of its components. A symptomatic search, on the other hand, is a deductive process. Knowledge of a fault condition is used to determine a related set of symptoms, and the plant is periodically checked during operation to see if these conditions apply. The symptoms can be defined in advance using a look-up table, or at run time using a qualitative model. Of the two classes, a topographical diagnosis has the advantage of being able to capture a wider range of faults, including those which remain undefined, whereas a symptomatic search is limited to those which are included in the knowledge base, although it does have the potential for superior isolation.

Comparison of methods

This class of technique has several advantages, in particular the ability to capture and use high level information, be it from experienced plant operators, or deductive reasoning based on knowledge of the plant or physics behind it. This level of abstraction can be useful during the design process and to the end user. In addition, qualitative models do not require the kind of detailed information about a plant that a quantitative model would (for example, the exact dimensions of a plant component). However, the generation of spurious solutions is cited as a major downside to these techniques by Venkatasubramanian, who suggests there is still work left to be done regarding this.

2.3.4. Process History Based Methods

The final class of techniques are process history based methods. These methods are reviewed in [57], the third paper by Venkatasubramanian. These methods, as the name implies, rely on historical process measurements taken from a plant, rather than knowledge about its internal operation or dynamics. The process history is used as a knowledge base, on which the diagnostic schemes are developed. The schemes can be further
classified as either qualitative or quantitative. The most common of these methods are introduced below.

**Qualitative Process History Based Methods**

The two main qualitative methods are Qualitative Trend Analysis (QTA) and use of expert systems.

QTA and its application to FDI are well described by Yamashita’s 2011 paper[73]. The technique involves reducing time series data to a series of symbolic values. For example, the relationship between two time series data sets can be represented by plotting their trends symbolically, as in Fig. 2.10. Here (I) represents increasing, (S) steady, and (D) decreasing, with one index per variable. The data set is divided temporally into series of segments, and a symbol is assigned to each segment. The symbol can be determined via linear least squares, or a similar method. Once the appropriate symbols are determined, the segments are reassembled to give a qualitative representation that form the basis of a rule set for fault detection. As with the other methods, the operation of the plant is checked for consistency against the representation, and a difference implies a fault. It should be noted that there are many possible extensions to this technique, for example, taking the second derivative of the data sets or using a fuzzy-logic approach to the consistency checking procedure.

Figure 2.10.: A symbolic representation of trends in a two variable process for QTA
Expert systems have seen use in a number of areas of machine intelligence, including fault detection. Their application and methodology have recently been reviewed by Liao in [74]. Puppe provides a comprehensive introduction to expert systems, in particular diagnostics, in his 2011 book[75]. Fink and Lusth also provide a description of their use in electrical and mechanical systems in their 1984 paper[76]. In the context of fault detection, expert systems are used to mimic the application of knowledge by an expert operator. When diagnosing a fault, a human operator will use experiential knowledge as a short cut to diagnosis. For example, an HVAC technician diagnosing a fault in a dehumidifier unit might check the fluid reservoir for a blockage, because her experience suggests the symptoms are often connected to that fault. Further investigation might reveal other information that she can use to arrive at a rapid diagnosis, without recourse to in-depth investigation. An expert system replicates this knowledge by applying a set of conditional rules (determined in advance) to monitored process variables. There are a large number of approaches to determining the rule set, including systematic tools such as Failure Mode Effect and Criticality Analysis (FMECA).

### Quantitative Process History Based Methods

The second sub-class of process history based methods are quantitative methods. The most popular of these are statistical tools such as Principle Component Analysis (PCA) and neural network methods. In both cases the tools are used for pattern recognition. They are used to classify process data, such that abnormal behaviour can be identified and flagged.

PCA is a widely used statistical tool, described in many mathematical and statistical text books. One useful introduction is provided by Joliffe in [77]. PCA, along with the related Partial Least-Squares (PLS) technique, reduces large multivariate data sets to a smaller dimension without losing important information that can be used to characterise the data set.

It is common for process data taken from a plant to contain variables that are in some way correlated, either because they represent physical properties that are associated or because they are driven by the same plant dynamics. When used with a data set like this, PCA/PLS can produce a reduced data set which represents the current operation of the plant. Provided that a representation of the plant in a nominal, fault-free state is available, PCA/PLS can be used with process data to produce a residual for use in fault detection.
Neural networks (formally, Artificial Neural Networks) are an information processing tool inspired by biological nervous systems. What distinguishes the method is the use of a large number of simple parallel calculations to perform a complex operation. Research into neural networks is extensive and their applications numerous. [78] is a helpful introduction to their use and the various configurations they can take. Regarding their use in fault detection specifically, [79] and [80] provide a description of the basic methodology. Typically, neural networks are used to identify static or dynamic models for use in residual generation, though the identification methods and learning regime differ between applications. According to Sorsa[80], it is difficult to make a direct comparison between the various methods because all neural network architectures do not use the same information about a problem, however, there have been numerous successful applications in various classification problems[81].

Comparison of Methods

Neural networks have been proven useful in fault detection for non-linear and undetermined processes[80]. PCA/PLS is similarly suited and both have the advantage that they can be applied successfully to stochastic data sets without any special consideration; a useful feature considering the stochastic nature of many real world processes. These techniques show strong isolation capability and are robust to uncertainty as noted in [57], however, the author also points out that schemes which rely on training data sets are difficult to generalise. It is also of note that many of these schemes have a high computational requirement on traditional hardware using von Neumann architecture, which could be a burden at run-time.

Expert systems are effective at drawing from human experience and the QTA approach is similarly successful in reducing a complex data set, they have the disadvantage of limited isolation capability outside of the rule-set.

2.3.5. Residual Evaluation

In many of the techniques introduced above, a fault manifests itself on the output side of the scheme as a residual. Real world considerations mean, however, that several other things also manifest themselves as a residual (e.g. unmeasured disturbances, model uncertainties etc.), therefore the presence of a residual alone is not enough to declare the presence of a fault. Residual evaluation is required if false alarms are to be avoided.
Frank gives a good treatment of residual evaluation in his 1996 paper [70]. Frank identifies three classes of residual evaluation methods which, as with the detection classes above, fall into the three similar categories: quantitative, qualitative, and data driven.

![Diagram of faults mapping onto residuals](image)

Figure 2.11.: An illustration of faults mapping onto residuals

In many fault detection schemes, it is useful to produce more than one residual. Ideally, residuals will be selected such that faults will map on to a unique set of residuals to assist with isolation, although that is not always possible depending on the sensor configuration of the plant.

The most straightforward quantitative method for residual evaluation is to assign thresholds for each residual signal. Generally these are selected such that anticipated noise/disturbances will be ignored while gross deviations are recognised and flagged. Where one can be satisfied that the noise and disturbance can be properly anticipated, this approach is sufficient. A refinement of this method has, however, been suggested by Clark [82]. This method involves using an adaptive threshold, which scales according to the input to the plant. Other methods are also possible, including taking the root mean square of the residual or some other windowed average to reduce the effect of signal noise or plant disturbance. The utility of these depends on the anticipated fault magnitude relative to disturbances, and the duration of its manifestation in the residual signal.

Fuzzy logic is a popular tool in qualitative residual evaluation. In [83] Sneider discusses the use of fuzzy logic for residual evaluation in a robotic application, and includes a description of the basic methodology. The usual approach is to define fuzzy detection thresholds, rather than a traditional binary threshold. Residual signals can be classed
by their magnitude (and possibly direction), for example, splitting them into “large”, “medium” and “small” fuzzy sets. An inference engine (essentially a set of if-then conditional statements) is used to evaluate a set of fuzzified residual signals and map them on to a fault, or set of faults. It is possible to extend this method, as above, with dynamic fuzzy thresholds by altering the fuzzy membership function while the scheme operates. The main advantage of this fuzzy approach is that it better accommodates uncertainty in the residual signals and in the scheme that generates them.

Neural networks can also be applied to residual evaluation. As with the detection technique, a neural network can act as a classifier, mapping residuals to faults. As noted previously, neural networks are well suited to such pattern recognition tasks, but the difficulty in generalising the schemes and in ensuring the recognition of faults not present in the training data set poses challenges for their implementation.

2.4. Summary

In conclusion, the findings presented in the papers discussed in the first section support the outcome of the initial study presented in the first chapter: failures resulting in a compromised vacuum in the neutral injector boxes can severely disrupt the operation of the experiment as a whole and have, historically, been some of the more difficult failures to deal with. Given the requirement for the continual maintenance of an NBI vacuum at both JET and ITER, and the importance of the cryogenic pumping system in producing it, a fault detection scheme applied to this pumping system in particular would be a useful tool, which could help prevent the repetition of problems in the future. Furthermore, such a scheme could also act as proof-of-method for future fusion applications. Research into condition monitoring for fusion is limited, and there is significant scope to prove the efficacy of such a condition monitoring application.

A review of models of fusion cryopumps was conducted. At the time of writing, no dynamic model of a NBHS style cryopump could be found.

A survey of the literature relating to fault detection techniques has been presented in the second section, with a focus on describing the main classes of FDI schemes and their relative merits. Of the three classes of scheme, qualitative model based schemes have proven to be effective, provided detailed information about the plant is available. For this application detailed design information is available, and the relative advantages (i.e. short detection time, high sensitivity, repeatability) of this approach outweigh the
others. In particular the deterministic nature of the scheme, its adaptability, and the potential for high sensitivity to faults are attractive. A statistical tool (specifically, system identification) will also be used where applicable, as this will make good use of the large amount of process data that is available.
3. The Cryopumping System

3.1. Cryopumping Overview

In the previous chapter the importance of maintaining a vacuum within the neutral injection box was highlighted. It was also noted that the cryogenic pumping system (or cryopumping system) is important in the creation and maintenance of this vacuum. The neutral beam cryopumps are the only devices that can bring the pressure to the required level on which the experiment depends. Of all the vacuum devices in use, it is the most complex, requires the most supporting plant, and requires the most specialist knowledge to operate. For these reasons, and for the faults that have occurred in the past, the cryogenic pumping system was selected as a target platform for demonstrating a condition monitoring scheme. The other vacuum systems would not provide as good a demonstration owing to either their low complexity or inherent/historical greater reliability.

As will be explained further in the next chapter, a mathematical simulation model of the plant is useful, not least because it provides a platform for conducting (simulated) experiments which would not be viable to run otherwise, owing to the tight operational schedule of the experiment. In the literature, no mathematical dynamic models of a large scale cryopumping system similar to the one in use at the Joint European Torus (JET) could be found. It was necessary therefore to develop one. This novel derivation is detailed in the following chapter. However, prior to that, it is useful to review the operation of the pump.

3.2. The NBI Cryogenic System

3.2.1. The Pumps

If the neutral beam is to pass unhindered through the neutral injection box (NIB), a vacuum must be maintained, otherwise the beam ions collide with atmospheric particles.
3.2. **THE NBI CRYOGENIC SYSTEM**

In order to achieve a vacuum, the NIB itself is separated from the atmosphere by metal sheets, which are sealed shut by welding during periods where experiments are due to be performed. The vacuum maintained within the NIB during operational periods is similar to that maintained within the torus itself, that is, around $10^{-9}$ mbar in pressure. This low pressure is reached in three stages. Initially, the bulk of the gas inside the NIB is removed using standard roughing pumps, of the sort commonly used to remove gasses from a vessel. Once enough gas is removed from the NIB and the pressure is lowered to around $10^{-3}$ mbar, the flow regime of the remaining gas is altered. The mean free path of the gaseous molecules is large enough that the predominate gas flow mode is molecular rather than viscous. At this point the roughing pumps are turned off and molecular turbo-pumps take over. Turbo-pumps are designed specifically to pump gas with a molecular flow regime. A high velocity fan directs gas into a series of baffles that act as a molecular trap, taking advantage of the high mean free path and random molecule trajectory to ensure a mean unidirectional overall flow. The turbo-pumps are left on continuously while low pressure is maintained within the NIB, however, they alone cannot bring the pressure to the ultra low level that is required, the final pumping stage relies on cryopumping.

![Figure 3.1.: The NBI cryopump walls prior to assembly](image)

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Cryopumping is the process by which gas is condensed and adsorbed onto low temperature panels, removing the gas molecules from the vacuum vessel, lowering the pressure. Cryopumping can provide very high instantaneous pumping speed, but the build up of condensed gas means it is only a viable pumping solution where pressure is already very low. It’s effectiveness depends on the temperature of the panels and their surface area. At JET, each NIB contains twenty cryopumping systems, ten on each side wall, as can be seen in Fig. 2.2, in the previous chapter, and in Fig. 3.2, below.

The NIB cryopumps are designed to balance the two conflicting goals of increasing the surface area, thus incidence of particle collision, and reducing heat load upon the sections of lowest temperature[49]. As such, the cryopumps are a relatively complex shape, consisting of a series of chevrons designed to pre-cool gas prior to condensation.

As can be seen in Fig. 3.3 and Fig. 3.4, the chevrons consist of two panels: a forward, beam facing panel (in green) and a smaller panel inset behind (in pale blue). The forward facing panels, and the crescent shaped back panel, are cooled to liquid nitrogen (LN2) temperature, roughly 77K. The rear panels are cooled to liquid helium temperature (LHe), roughly 4.2K. The cooling is provided via several capillary tubes inset into the panels, which are filled with the corresponding fluid and are topped up by a trickle feed from the bottom. The trickle feed to each NIB is controlled by a flow valve, at the far end of a cryogenic transmission line. Each LHe panel is “protected” by one or more
LN2 panels; the shape is such that every molecule or ion, regardless of the direction of travel and origin, will come into contact with at least one LN2 panel before reaching an LHe panel. The shape of the panels were tested via Monte Carlo simulation of the incoming molecular gas flow by the manufacturer (although the results of this test are proprietary and non-public domain). The result of this is that molecules and stray beam ions are cooled before coming into contact with any LHe panels, thus the heat load upon them is reduced. Liquid nitrogen has a higher specific heat capacity and latent heat of vaporisation than liquid helium, which means that less of it is boiled per unit heat load. Therefore, in addition to pre-cooling gas molecules, a smaller quantity of nitrogen is sacrificially boiled to protect the helium. Considering the relative cost of replacing liquid nitrogen compared to replacing liquid helium, this has the advantage of lowering the operating cost of the pump. Finally, gasses and vapours of a relatively high atomic mass, for example water vapour and oxygen molecules, can be condensed onto the LN2 panels directly and need never come into contact with an LHe panel.
During periods of operation, the NIB vacuum is maintained constantly, until such time as the cryopumps are no longer able to work effectively, owing to a build up of condensed material upon their surfaces. At this point the pumping panels (or cryopanels) are put through a “regeneration” procedure. The capillaries are flushed with room temperature water, raising the panel temperatures to boil of the material condensed upon them. This gas is then removed via the roughing and turbo-pumps before the cryopumps are brought back down to their regular operating temperature.

3.2.2. Supporting Plant

The NIB cryopumping system is supported by a cryogenics facility which services cryogenics for the entire experiment. From the perspective of the NIB cryopumping system, there are five important supporting components: the LHe liquefier, the LHe tanks, the LN2 tanks, a valve box, and a transmission line. The purpose and operation of each of these components is described below.
3.2. THE NBI CRYOGENIC SYSTEM

CHAPTER 3. CRYOPUMPING

The Helium Tanks

The liquid helium used at the site is stored in two cryostats (specially insulated tanks), one with a 5000L capacity, the other with 1000L. Both NIBs are supplied from the 5K tank, although a cross-feed is available. In addition to supplying the two NIBs, the 5K also supplies a “sub-cooler” in a valve box. The tank is topped up periodically with liquid helium from one of two liquefiers. Normally, the refill valve is opened when the tank fluid level is at 70% of its maximum and closed at 85%, although the plant operator can change these parameters or start an immediate refill, if required. Both tanks have an electrical heater which can be used to raise the temperature of the tank and boil away the cryogenic fluid, should they need to be emptied. According to practical observations made by the engineer in charge of the cryogenic plant and according to the tank manufacturer, both tanks have a fluid loss rate of 1.5-2% per day, owing to heat transmitted to the fluid. In the 5K tank, that corresponds to around 100L a day. Gas evolved inside the tank is sent to the helium liquefier for reprocessing and is fed back to the tank. As an alternative the gas can be sent to a bank of balloons for collection via a warmed water bath, but this is usually avoided because the helium is not then recovered.

The Nitrogen Tanks

Similar to the helium, the liquid nitrogen used at the site is also stored in two tanks, one with a 50000L capacity, the other with 60000L. The nitrogen is pressurised to around 4BarG in these tanks. The NIBs can be supplied from either of these tanks. Both tanks can be vented to the atmosphere if required. The tanks are refilled periodically by a commercial tanker.

The Helium Liquefier

Helium evolved from the pumps is returned to a helium liquefier (designated TCF 200) so that it can be returned to the tanks and reused. The liquefier operates using a multi-stage compression-expansion regime, similar to many other refrigeration devices. For this research the relevant features of the liquefier are the inlet pressure (which is controlled) and the liquefaction capacity, which is sufficient for the full time operation of both pumps. The liquefier is also connected to a helium purifier which can remove trace contaminants and moisture from the helium, prior to returning it to the tanks or NIBs.
When the cryopumps are initially being brought online, they operate in a “cooldown” mode, to lower the temperature of the pump panels and components prior to normal operation. During this mode the liquefier provides a stream of high pressure helium to both NIBs. During normal operation the helium supply is held at a regular pressure (a tank pressure of 1.65BarA, seen as around 1.08BarA at the NIB after the valve boxes and transmission line).

The Helium Valve Box

The flow of helium to the experiment is mediated by two valve boxes. Valve box one routes the helium to and from the NIBs. Helium travelling to the NIBs from the helium tanks is “sub-cooled” prior to entering the main transmission line. The line carrying helium from the tank to the valves passes through a (relatively small) bath of liquid helium. The helium in the bath slowly evaporates, ensuring the steady, low temperature of the helium being delivered to the pumps. Helium retuning from the pumps is passed either to the TCF200 liquefier, or it is passed to a set of recovery balloons via a warm water bath if it is too warm to enter the liquefier. Ideally, the helium collection balloons are rarely used, as the gas that enters them is not recovered. The difficulty in measuring the exact temperature of the low temperature helium gas remains a challenge, however, because of the scaling and linearity of the currently used transducer devices.

The Transmission Line

The cryogenic fluid is carried to and from the NIBs by long low-loss transmission lines. The transmission lines have a concentric ring structure, in which successive rings carry fluids of decreasing temperature, together with a vacuum jacket. The transmission lines provide good thermal insulation, with a measured loss of \(\leq 10\) mW/m for the liquid helium section and \(\leq 150\) mW/m for the liquid nitrogen section\[85\]. An illustration of a transmission line segment is provided in Fig. 3.5, below.

3.2.3. Control and Data Acquisition

A large amount of process data is collected from the cryogenic plant and cryopumps. The data is used for both supervisory control and for evaluation of the state of the plant by the engineers in charge. Passive electronic components are primarily used to
Figure 3.5.: An illustration of a cryogenic transmission line segment

1. Liquid Helium
2. Vacuum
3. Gaseous Helium
4. Liquid Nitrogen
5. Gaseous Nitrogen
6. Vacuum
collect the data, because the strong magnetic fields in and around the NIB complicate the use of active electronics. Where possible, the electronics used to support the passive sensors are kept a distance away. The sensors are connected to an Allen Bradley I/O module, which is in turn supported by Allen Bradley PLC hardware (specifically, the Controllogix brand is used). Communication between these devices is over Ethernet with a proprietary Allen Bradley protocol. The interface to the PLCs is via PCs running the General Electric Proficy iFix HMI software or indirectly via the CODAS system. Each monitored variable is periodically logged. The cryogenic control and data acquisition architecture is illustrated in Fig. 3.6.

![Figure 3.6.: The cryogenic plant control architecture](image)

For each plant subsystem a graphical reporting interface (known as a mimic) has been developed by one of the engineers in charge. The interface runs on the Proficy iFix software and shows the scaled output of each sensor component. A copy of each of the relevant mimics is provided in Appendix B, and all of the monitored variables can be seen there.

Each NIB cryopump has four operational modes: full cooldown, warm up, regeneration, and LN2 only. In “full cooldown” mode, the pump temperature is brought down to
it’s operational level and maintained. Cryogenic fluid is trickle fed to the pump and the fluid levels within the pump is controlled via a PID loop which determines the inlet valve positions. The pressure in the gas return lines are controlled via another PID loop which determines the outlet valve positions. The pump is kept in this mode for extended periods of time during an operational campaign, including all times when the NIB is being actively used to support experiments. As such, the condition monitoring scheme presented in this thesis is designed to run while the pump is in this mode.

In the “warm up” mode the pumps are flushed with warm fluid, in order to bring them back up to room temperature. This is typically carried out at the end of an operational campaign or prior to maintenance work. The purpose of the “regeneration” mode is to temporarily raise the temperature of the pump so that material collected on the pump surfaces evaporates. The evaporated material is then removed from the vacuum space by one of the other pumps prior to the cryopump being brought back down to its operational temperature. Done periodically, this operation ensures the continued effectiveness of the pump, as a build up of material on the pumping surfaces reduces the pumping speed and capacity. The “LN2 only” mode, as the name would imply, sees only the nitrogen panels brought down to the operational temperature, and helium is not delivered to the pumps. Each of these modes can be selected by the cryogenic plant engineers via the Proficy iFix interface, or via the site CODAS system. A full set of diagrams showing the control logic for each of these modes is presented in Appendix G, and is up to date as of February 2013.

3.3. Faults

With the normal operation of the plant described, its failure modes remain to be considered, because the research presented in this thesis concerns their detection. As would be expected, a system of this complexity is potentially subject to a wide range of faults, of which only a small set have occurred historically. Therefore in order to identify any points of failure, it is necessary to use an analytical technique. Several tools are available, the most common of which are described in [86]. These include Failure Mode Effect and Criticality Analysis (FMECA), Event Tree Analysis (ETA), Fault Tree Analysis (FTA), Reliability Block Diagram (RBD) analysis, and Functional Failure Analysis (FFA).

For this research, a simplified FMECA was conducted, in collaboration with the senior engineers responsible for the NBHS. Typically, a FMECA is carried out during the design
stage of an engineering project, with the objective of identifying any points of failure so that they can be mitigated. The standard for a FMECA defined in the UK by the BSI (in BS 5760-5:1991) reflects this. The objective of the procedure carried out here, however, was to identify a range of faults, from which a subset can be drawn as test cases later in the research. As such, a limited selection of failure modes will be considered, because a fully comprehensive FMECA would not only be excessively time consuming, it would also not usefully contribute to the research objectives. The methodology that was employed is described in the next subsection.

3.3.1. FMECA Methodology

The first stage of the FMECA procedure was to define the boundaries and operating state of the system. For the purpose of this procedure, the cryopumping system was treated as six discrete components. Each component corresponds to physical assembly. Figure 3.7 is a graphical representation of the components, and it lists their primary functions and interactions. As has been previously noted, the operational mode of interest is the “Full Cooldown” mode, therefore the functions and failures associated with this mode in particular that were explored.

For each of the plant components, the following analytical steps were completed and encoded in a table:

1. The functions of each component were defined.
2. The failure modes of each component were defined, in terms of non-fulfilment of the functions defined in the previous step.
3. The potential causes of each failure mode were listed.
4. The probable effects of each failure were listed, both for this component and for the other system components.
5. The severity of the failure mode was estimated, according to the scale below.

The following definitions of fault severity were used:

Catastrophic - Any failure that prevents the cryopump from pumping the NBHS gas space, or that results in damage to other systems within the NBHS.

Critical - Any failure that impairs the cryopump performance to the extent that the NBHS vacuum pressure would likely increase.
3.3. FAULTS

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Figure 3.7.: A graphical representation of the system components, their functions, and interactions.
3.3. FAULTS

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Major - Any failure that impairs the cryopump performance, but would not likely result in an increase NBHS vacuum pressure before the next scheduled maintenance activity.

Minor - Any failure that does not impair the cryopump performance.

3.3.2. FMECA Results

All of the FMECA worksheets generated for the cryogenic pumping system are presented in Appendix C. In total, forty nine different failure modes were identified. A summary of the failure mode severity for each plant component is summarised below in Table 3.1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Catastrophic</th>
<th>Critical</th>
<th>Major</th>
<th>Minor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium Tanks</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Transmission Lines</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Cryopump (He)</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cryopump (N2)</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Valve Box</td>
<td>1</td>
<td>11</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Control &amp; Data Acquisition</td>
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<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Totals</td>
<td>11</td>
<td>23</td>
<td>11</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 3.1.: A summary of the failure mode classes

A significant proportion of the failure modes categorised as catastrophic are associated with leak events (both liquid and gas) and events that prevent the transmission of cryogenic fluid. The cryopump relies on an uninterrupted supply of cryogenic fluid to maintain a low temperature, and as such, events resulting in their delivery being prevented have a significant effect on its operation. The valve box component has a relatively higher number of critical failure modes, because owing to its multiple functions and many moving parts, it can fail in more ways than a purely passive component, such as the helium cooled pumping surfaces.

3.3.3. Faults of Interest

For the purpose of this research, it was useful to focus on a smaller subset of the faults presented in Appendix C. The objective was to select a set which could be simulated to test the condition monitoring scheme. To facilitate this, the result of the FMECA activity carried out collaboratively with the engineers responsible for the NBHS was examined, with the objective of identifying the most severe faults which affect the helium loop of the cryopumping system, together with their relative likelihood. The most severe
and hard to manage (i.e. those that result in the greatest loss of function and which are
difficult to repair) and the most likely faults were chosen to be simulated, because these
best demonstrate the scheme’s utility. In addition to these, any relevant faults which
have occurred recently (within the last five years) were also selected, as these were/are
of particular interest to the engineers responsible for the operation of the plant. These
recent faults were identified by consulting the engineers responsible for running the
plant.

The faults selected are detailed in Table 3.2.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Fault</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>Leak Fault</td>
<td>Cryogenic fluid leaking from the transmission line to atmosphere</td>
</tr>
<tr>
<td>Line Ice</td>
<td>Fault</td>
<td>Cryogenic fluid contamination or impurity resulting in ice formation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>in the transmission line</td>
</tr>
<tr>
<td>Insulation</td>
<td>Fault</td>
<td>Compromised vacuum jacket resulting in deteriorated thermal insulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>between the cryogenic fluid and atmosphere</td>
</tr>
<tr>
<td>Broken Valve</td>
<td>Stem</td>
<td>Mechanical damage of the inlet valve stem resulting in loss of valve</td>
</tr>
<tr>
<td></td>
<td></td>
<td>control and debris passing into the transmission line</td>
</tr>
<tr>
<td>Return Line</td>
<td>Worn Valve</td>
<td>Mechanical wear of return line valve resulting in loss of fine valve control</td>
</tr>
<tr>
<td>Leak Fault</td>
<td></td>
<td>Loss of helium gas to atmosphere or vacuum jacket from the return line</td>
</tr>
<tr>
<td>Insulation</td>
<td>Fault</td>
<td>Compromised vacuum jacket resulting in deteriorated thermal insulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>between the helium gas and atmosphere</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>Heat Fault</td>
<td>Unplanned heat load on pumping surface owing to reduced thermal insulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>or gas leak into NIB vacuum space</td>
</tr>
</tbody>
</table>
3.4. SUMMARY

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Fault</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Leak Fault</td>
<td>Cryogenic fluid leaking from the heat exchanger to atmosphere or NIB vacuum space</td>
</tr>
<tr>
<td></td>
<td>Manifold Blockage</td>
<td>Ice formation on the return manifold owing to cryogenic vapour impurity</td>
</tr>
</tbody>
</table>

Table 3.2.: Table of Selected Faults

Leak faults have been an occasional problem for the cryogenic plant operators, with a recent event occurring in 2010. Both gas and liquid leak faults are typically associated with junctions where one component meets another (e.g. where a transmission line is connected to a valve or downstream equipment), and can be caused by improper fitting, seal degradation and thermal cycling, among other causes. Insulation and thermal faults are of particular interest in a cryogenic application like this; they can result in continual lost cryogenic fluid inventory over time, loss of efficiency, and in extreme cases can be a safety hazard as leaking cryogenic gasses can displace oxygen in closed areas, potentially resulting in suffocation. In the transmission lines these faults are most likely where the vacuum jacket space is compromised. For the heat exchanger is most likely caused by degraded panel insulation, or where gas/fluid has leaked into the vacuum space. The blockage faults are relatively unique to cryogenic applications; these faults are caused by water vapour (typically) being caught in the cryogenic material and freezing solid onto cryogenic surfaces. The liquid helium purifier works to remove stray water vapour, so any problems reducing its efficiency, or where the cryogenic material is accidentally exposed to the atmosphere (e.g. a leak into a cryostat tank), can result in this type of fault.

These faults are discussed further in Chapter 6, where they are simulated.

3.4. Summary

The importance of the NIB cryopumping system, its relative complexity, and the historic reliance on human diagnostics for fault detection make it a good platform for demonstrating the use of condition monitoring for a fusion application.
In this chapter the operation of the cryopump has been described, together with a description of its constituent subsystems, components and supporting hardware. This, together with design & manufacture drawings obtained from CCFE, provide a basis for the development of a novel model which is presented in the next chapter.

A simplified FMECA procedure for the cryopump was conducted. Forty nine failure modes were identified. A FMECA worksheet for each plant component was complied, and has been presented in Appendix C. A subset of these faults were selected to be simulated to test the condition monitoring scheme.
4. Modelling the Cryopumping System

4.1. Model Overview

An accurate mathematical model of the cryogenic plant allows two useful functions in particular: the ability to simulate the normal operation of the plant in order to generate data useful for the design process on demand, and to simulate plant faults which avoids the trouble and disruption of arranging physical experiments on the working plant. Accordingly, the development of a mathematical model and simulation of the plant was an essential step in this research. The simulation model was used as a substitute for the physical plant during the development process, during both design and testing, and this allowed the design concept to be proven with minimal (zero) impact on the operation of the plant.

Figure 4.1.: An illustration of the helium loop model
4.1. Model Overview

4.1.1. Modelling Objectives

For a mathematical simulation model of the plant to be useful in designing and proving the efficacy of a condition monitoring scheme, it has to fulfil the following objectives:

1. A model based on the known physical parameters of the plant that can be used to simulate the operation of the plant.

2. A model that can be validated against historical data, by producing outputs that are comparable to measurements taken from the physical plant.

3. A model in which the plant parameters or operating condition can be modified (e.g. to simulate faults), and that can provide useful data for fault detection.

4. A model which includes components which have previously failed.

4.1.2. Area of Interest

It is essential to know what parts of a system should and should not be modelled, in terms of both range and resolution; that is, the boundaries of the model and what level of detail is required. In Chapter 3 a description of the entire cryopumping system was provided. The importance of the helium loop was identified and, as such, it was selected as the target for this application. The helium loop does, however, include a number of sub-systems, not all of which necessarily need to be included in the model. Figure 4.1 is an illustration of the helium loop section that was modelled. The boundaries of the model are the helium supply tank and the return valve prior to the expended helium distribution network. By going through the objectives listed above one by one, the selection of boundaries and level of detail can be justified:

1. A model based on the known physical parameters of the plant that can be used to simulate the operation of the plant.

   All of the design parameters of the cryogenic plant are well known, aside from a few detailed parameters of proprietary components. This section of the helium loop however, is particularly accessible to physical analysis because of its relative simplicity and invariance across operating modes, compared to other sections, for example those including the helium liquefier. All the components of the selected section of the loop lend themselves well to first principles physical analysis.
2. A model that can be validated against historical data, by producing outputs which comparable to measurements taken from the physical plant.

   This section of the helium loop is well instrumented. Sufficient process data is available for both the validation process and for direct use in the condition monitoring scheme itself.

3. A model in which the plant parameters or operating condition can be modified (e.g. to simulate faults), and that can provide useful data for fault detection.

   Regardless of operating mode, this section of the helium loop is in use at all times during plant operation. As a result, all of the process data collected from this part of the plant can be used to provide diagnostic information about the plant, at all times. Other parts of the plant are unused or inactive at certain times, which would result in gaps in the usefulness of process data collected on them. In addition to this, changes in heat load strongly affect this part of the system. The rate of vapour evolution in the capillaries in the cryopumping panels is a strong function of heat load, whereas the current drawn by the liquefier system (for example) is not. Unanticipated additional heat load on the plant can be indicative of degraded performance, as will be discussed in the following chapters. Finally, as this section of the helium loop includes the primary active component of the cryogenic pumping system (the heat exchanger), it is particularly sensitive to faults that affect the primary function of the plant - vacuum pumping.

4. A model which includes components which have previously failed.

   Several faults have in the past occurred in this part of the plant. These include a recent valve bypass failure.

4.1.3. Selection of Model Structure

The mathematical model of the helium loop in the cryopumping system is split into nine component models, roughly corresponding with the components depicted in Fig. 4.1. In order to provide structure to the model, the sections have been categorised as either storage or resistive components, allowing a common interface between them and simplifying their analysis. Specifically, the storage components have a pressure associated with them; the resistive components, a flow rate. Figure 4.2 is an illustration of this structure. A description of each of these blocks is presented below, starting with the supporting blocks and moving on to the main block, the heat exchanger.
4.1. MODEL OVERVIEW

Figure 4.2.: Top level model structure

Figure 4.3 is an illustration showing the correspondence between the physical plant (shown in Fig. 4.1) and the sub-models detailed in Section 4.2. The subsections where each component is described are noted in red. Each of the red boxes correspond to one part of the top level model structure shown in Fig. 4.2.

Figure 4.3.: Correspondence between the cryopump and the model sections

Table 4.1 lists all of the inputs and outputs for each model component.

An illustration of the data collected on the helium loop is presented in Appendix B in the form of a “mimic” which is available to the plant operator during operation. The data discussed further in Section 4.3.2, and a summary of the data is presented in Table 4.2.
### Subsystem Input Output

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen shield</td>
<td>Pulse times</td>
<td>Heat load</td>
</tr>
<tr>
<td>Other heat loads</td>
<td>Liquid consumption</td>
<td>Tank fill level</td>
</tr>
<tr>
<td>Helium supply tank</td>
<td></td>
<td>Tank pressure</td>
</tr>
<tr>
<td>Helium return/collection</td>
<td>Inlet flow rate</td>
<td>Return gas pressure</td>
</tr>
<tr>
<td>Supply line</td>
<td>Termination pressure</td>
<td>Outlet flow rate</td>
</tr>
<tr>
<td></td>
<td>Inlet temperature</td>
<td>Line pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Line temperature</td>
</tr>
<tr>
<td>Return line</td>
<td>Inlet flow rate</td>
<td>Outlet flow rate</td>
</tr>
<tr>
<td></td>
<td>Termination pressure</td>
<td>Line pressure</td>
</tr>
<tr>
<td></td>
<td>Inlet temperature</td>
<td>Line temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gas mass</td>
</tr>
<tr>
<td>Control valves</td>
<td>Valve position</td>
<td>Mass flow rate</td>
</tr>
<tr>
<td></td>
<td>Differential pressure</td>
<td></td>
</tr>
<tr>
<td>Heat exchanger</td>
<td>Heat load</td>
<td>Heat exchanger pressure</td>
</tr>
<tr>
<td></td>
<td>Inlet flow rate</td>
<td>Liquid level</td>
</tr>
<tr>
<td></td>
<td>Outlet flow rate</td>
<td>Heat exchanger temperature</td>
</tr>
<tr>
<td></td>
<td>Inlet temperature</td>
<td>Liquid volume</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Steam quality/void coefficient</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vapour volume below liquid level</td>
</tr>
</tbody>
</table>

Table 4.1.: A list of inputs and outputs for each sub-model

<table>
<thead>
<tr>
<th>Process variable</th>
<th>Unit</th>
<th>Time Varying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase separator level</td>
<td>%</td>
<td>✓</td>
</tr>
<tr>
<td>Supply &amp; return valve position</td>
<td>%</td>
<td>✓</td>
</tr>
<tr>
<td>Supply &amp; return line pressure</td>
<td>BarA and BarG</td>
<td>✓</td>
</tr>
<tr>
<td>Capillary delta pressure</td>
<td>mBar</td>
<td>✓</td>
</tr>
<tr>
<td>Helium supply temperature</td>
<td>K</td>
<td>✓</td>
</tr>
<tr>
<td>Helium return temperature</td>
<td>K</td>
<td>✓</td>
</tr>
<tr>
<td>Helium tank fill level</td>
<td>%</td>
<td>✓</td>
</tr>
<tr>
<td>Helium tank fill volume</td>
<td>l</td>
<td>✓</td>
</tr>
<tr>
<td>Vacuum jacket valve state</td>
<td>On/Off</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 4.2.: Summary of measured process variables
4.2. Model Detail

4.2.1. Nitrogen Shield

The amount of useful process data collected from the nitrogen shield is limited. The model presented here reflects that. The main function of the nitrogen shield model is to help calculate the heat load on the helium panels.

Assumptions

1. The nitrogen shield contains a vapour-liquid mixture at atmospheric pressure and saturation temperature

   Historical temperature and pressure measurements confirm that this is the case during normal operation.

2. The temperature of the nitrogen panels is uniform and the same as the temperature of the cryogenic fluid

   Normally, there will be small differences in temperature at various locations on the panels, for example, the temperature gradient between the centre and surface of the panel. However, the magnitude of the temperature differences are too small to be of consequence to the model and are, for the most part, too small to be measured with the transducers available in any case.

3. The nitrogen panels are always full

   In the operating mode of interest (full cool down), which was described in the systems analysis chapter, the level of nitrogen liquid in the panels is controlled such that the panels remain full. The liquid level does fluctuate slightly as the liquid is evaporated and replaced, however, so long as the panel is full or near full then in the context of this model, it is functioning correctly.

4. The nitrogen and helium panels are separated by a vacuum

   During normal operation in full cool down mode, the vessel will maintain an ultra-high vacuum. Obviously, an absolute vacuum is impossible to achieve practically - vacuum is a scalar (as opposed to discrete) phenomenon. For the purpose of this aspect of the model, however, it is close enough as to be indistinguishable. As noted at the head of this section, the purpose of this part of the model is to describe
the heat load placed on the helium panels from the nitrogen panels. The radiative component of this heat load far exceeds any convective heat load, therefore that component is not analysed.

5. The helium panels, as seen from the nitrogen panels, are uniformly isothermal. Temperature variation, either by time or by location is small enough as to be negligible for the purpose of the model in the absence of a fault.

6. Both the helium and nitrogen panels are grey and diffuse. This assumption is true for many engineering surfaces, including machined aluminum, which is the case here.

7. The configuration of the helium and nitrogen panels is such that they can be treated as infinite parallel plates. The total surface area of the panels is large enough that a large majority of the plates are parallel and the effect of the end regions where they are not is small enough to be neglected.

**Fundamental Equations**

The well known equation describing black body radiation is

\[
Q = F_e F_{12} \sigma A_1 (T_2^4 - T_1^4)
\]

(4.1)

Where \(Q\) is the heat load, \(F_e\) is the emissivity factor, \(F_{12}\) is the view factor, \(T_n\) are the temperatures of the objects, \(A_n\) is the surface areas of the objects, and \(\sigma\) is the Stefan-Boltzmann constant.

The emissivity factor, \(F_e\), is described by the following for infinite parallel plate configurations, where \(e_n\) are the emissivity factors of each plate

\[
\frac{1}{F_e} = \frac{1}{e_1} + \frac{1}{e_2} - 1
\]

(4.2)
4.2. MODEL DETAIL

Chapter 4. Modelling

Inputs and Outputs

Under nominal, fault free conditions, there are no inputs to this section of the model and one output: The heat load on the helium panels due to radiation from the nitrogen panels. Additional sources of heat load are identified in the following subsection.

The total emissivity for machine polished aluminum is 0.058 at 4.2K and 0.1 at 77K, as given on page 222 in R. Barron's *Cryogenic Heat Transfer* [87]. Hence,

\[
\frac{1}{F_e} = \frac{1}{0.058} + \frac{1}{0.1} - 1
\]

\[= 26.24\]

\[\therefore F_e = 0.0381\]

(4.3)

From examination of the diagram Fig. 4.4 (below) and illustration of the cryopumping element in Fig. 3.3 (Chapter 3), the area of the pumping surface is:

\[A_1 = 117.304\text{m}^3\]

(4.4)

The helium panels are totally enclosed by the nitrogen panels, therefore the configuration factor, \(F_{12}\), is unity. Therefore the total heat load due to radiation on the helium panels is given by:

\[Q = F_e F_{12} \sigma A_1 (T_2^4 - T_1^4)\]

\[Q = 0.0381 \times 1 \times 56.69 \times 10^{-9} \times 117.304 \times (77^4 - 4.2^4)\]

\[= 8.91W\]

(4.5)

This result is the time invariant output of the nitrogen shield part of the model.

4.2.2. Other Heat Loads

In addition to the radiative heat load detailed in the previous section, there are two other main heat sources: Conduction through supports and heat load due to pumping
Figure 4.4.: A preliminary drawing of the JET cryopump panels (courtesy of CCFE drawings office)
effort. The sum of all three of these sources is the total heat load applied to the helium panels.

**Heat Load due to Pumping**

To calculate the heat load due to pumping effort, times when pumping effort is applied need to be identified. From historical pressure measurements it can be seen that most pumping effort occurs during the “Cool Down” phase (which is not under consideration here) and immediately following the occurrence of a pulse. A typical profile of pressure measured in the NIB during a pulse is displayed below in Fig. 4.5. This data was retrieved from a JET Pulse File (JPF), stored by the JET Control and Data Acquisition System (CODAS). During a pulse, the transient heat load and pressure increase are the only additional inputs to the model.

It can be seen that pressure varies with location. For example, during the depicted pulse, the pressure measured by the NIB8 top penning gage is about half that measured by the bottom penning gage. However, despite that, the profile is similar in shape. For a cryopump of this sort, the instantaneous mass pumping rate is a function of pressure. Therefore the pumping effort and heat load on the pumping surface is also a function of pressure.

**Assumptions**

In order to calculate the instantaneous heat load, the following assumptions are made:

1. The pressure rise during a pulse is mainly caused by injection of neutraliser gas.
   
   The main source of material entering (and remaining in) the NIBs during normal operation is the neutraliser. The total mass flow of neutraliser gas entering the NIBs significantly exceeds the mass flow from other sources (for example, stray beam particles), hence is the main source of a pressure rise.

2. The neutraliser gas is primarily helium.
   
   During normal operation, helium is used as a neutraliser gas.

3. The helium behaves as an ideal gas.
   
   Given the low pressure in the NIB, the relatively low intermolecular forces in helium and the required level of detail, ideal gas assumptions are valid.
Figure 4.5.: Pulse pressure profile measured at four locations during a single pulse
4. The total pump aperture area is $36m^2$

This has been calculated from design drawings obtained from CCFE. There are no significant obstructions to the pumping surface.

5. There is a 20% transmission rate through the pump apertures and a 100% capture rate

The transmission and particle-helium wall incidence rate was taken from an internal CCFE document produced by Robin Stafford Allen[88]. It was calculated at the time the cryopumps were designed. The accommodation coefficient of gaseous helium on machined aluminum is close to 100%[87], and any particle not retained on its first collision with a helium panel typically comes into contact with one or more helium panels, resulting in a near complete capture rate.

6. The nitrogen baffles are kept at 77K

The baffles are cooled by boiling liquid nitrogen at (near) atmospheric pressure, with low deviations in temperature across them (as per their design).

7. The neutraliser gas enters the vacuum vessel at 300K

The neutraliser gas is not refrigerated, and so its temperature tends towards the environment temperature which itself is close to 300K with small deviations.

**Fundamental Equations**

From DJ Hucknall’s Vacuum Technology[89], the mean (RMS) gas velocity entering the chamber is given by:

$$\overline{c} = \sqrt{\frac{8RT}{\pi M}}$$  \hspace{1cm} (4.6)

Where $\overline{c}$ is the RMS gas velocity, $T$ is the gas temperature, $R$ is the molar gas constant, and $M$ is the molar mass of the gas.

With a Maxwellian distribution, the mean $x$-component of the gas velocity is given by

$$x\text{-component velocity} = \frac{\overline{c}}{4}$$  \hspace{1cm} (4.7)

Volumetric pumping speed is given by
4.2. MODEL DETAIL

\[
S_{\text{vol}} = \frac{3}{4} A_p T_x \chi 
\]  

(4.8)

Where \( A_p \) is the pump aperture area, the transmission coefficient is \( T_x \), and the capture rate coefficient is \( \chi \).

Once the volumetric pumping rate has been determined, the following is used to calculate the mass pumping rate, \( S_m \)

\[
P V = nRT \\
\therefore S_m = \frac{P S_{\text{vol}}}{RT} / M 
\]  

(4.9)

From the mass pumping rate, the instantaneous heat load can be calculated as follows

\[
Q = (h_{\text{cond}} + \Delta t C_p) S_m 
\]  

(4.10)

Which is the condensation enthalpy plus the temperature change multiplied by the specific heat capacity, all multiplied by the mass pumping rate. Taking Eq. (4.8), Eq. (4.9) and Eq. (4.10) together gives an aggregate expression for heat load due to pumping.

\[
Q = (h_{\text{cond}} + \Delta t C_p) * \left( \frac{P \frac{3}{4} A_p T_x \chi}{RT} / M \right) 
\]  

(4.11)

**Inputs and Outputs**

The input to this section of the model is the pressure inside the NIB and its output is the heat load placed on the pumping surface due to pumping effort. However, given that instantaneous pressure measurements are not available and, if they were, it is beneficial to decouple pressure rises due to a pulse and pressures rises due to other causes, a better input is simply a binary signal indicating the occurrence of a pulse.

The amount of neutraliser gas injected into the NIB slightly varies with each pulse. Despite this, the profile and amplitude of the change in pressure remains similar.
From Eq. (4.11), a pressure of 15×10^{-6} mbar results in a heat load of around 2.2W on the pumping system. However, historical data suggests the total increase of heat load on the helium panels peaks at about 22W, more than would be expected given the pressure measurements presented in Fig. 4.5. This difference is due to variation of pressure with location; the pressure distribution through the NIB is uneven and the vacuum gauges measure it only at individual locations. The heat profile presented in Fig. 4.6 causes a response in the simulated pump which reflects the data well. This would indicate that, typically, the average gas pressure experienced across the pump during a pulse is a factor of ten greater than that measured by the top vacuum gauges in Fig. 4.5. Given that a larger variation in pressure (a factor in the order of 10^2) can be seen between pressure gauges, the difference in measured and experienced pressure can be reasonably attributed to the uneven pressure distribution with location.

![Figure 4.6.: Heat profile of a typical pulse](image)

**Heat Due to Conduction**

The final heat source on the helium panels is conduction through the panel supports and assembly. When designing cryopumping systems such as this, and indeed any cryogenic system where low temperatures are to be maintained, minimising the conduction of heat through to a low temperature surface or material is an important design consideration. However in most scenarios, it is impractical to entirely eliminate conductive heat loads.
without recourse to elaborate engineering. Typically a trade-off has to be made between low heat loads and other engineering requirements. For the cryopumping system in question, the most significant steady state heat load is due to conduction. Variations in conductive heat load are small and slow, owing to careful design of the cryopumping assembly. As such, for the purpose of this model, it is assumed to be constant at close to 53W. This figure was arrived at by examining the boil-off rate of cryogenic fluid under quiescent steady state conditions, then adjusting for the boil-off rate due to the radiation load described previously.

4.2.3. Helium Supply Tank and Return

The helium supply tank and return constitute part of the model boundary. Both are storage components. All of the helium entering the NIBs come from the 5000l capacity, depicted in top half of Fig. B.1, in the appendix. During the operating mode of interest, under usual conditions, helium from the upper (5K) tank is distributed to four different locations: NIB4, NIB8, a subcooler in the valvebox and the TCF200 liquefier. For gaseous helium evolved from the cryopump, it is typically returned to a liquefier, or failing that, collected in balloons for disposal.

Assumptions

1. The 5K helium tank is periodically refilled
2. When the 5K helium tank is being refilled, it is refilled at a constant, uninterrupted rate
3. The 5K/10K tank cross feed is not active during normal operation
4. The pressure on the return side of the return valve is controlled and constant
5. The helium supply tank pressure and temperature are constant
6. The helium consumption in both NIBs is similar and converges with time
7. Helium tank losses (and hence the amount of material sent to the liquefier) are negligible
Input, Outputs and Control

The helium return is treated as a constant pressure infinite sink. The flow of gaseous helium to the return is therefore simply a function of the return line pressure and the valve position. Treating this helium return this way and setting the return pressure to 13.88PSI matches the data well.

The helium supply tank has a single input and two outputs. The input is the NIB4 liquid consumption, in kg/s. The two outputs are pressure (as seen by the NIB4 supply valve), fixed at 1.088 BarA, and tank fill level, in both % and litres. The tank is fed from an assumed inexhaustible helium supply via a control valve. The valve is automatically controlled. Tank refilling starts when the level drops to 70% and stops when the tank is 85% full. The tank is refilled at a rate of $28 \times 10^{-3}$kg/s.

Fundamental Equations

The following equation describes the rate of change of volume of fluid inside the helium tank:

$$\frac{dV_{ht}}{dt} = K_{kl}q_{tf} - K_{kl} (q_{sc} + q_{ts} + 2q_{tl})$$ (4.12)

Where $V_{ht}$ is the fluid volume in the helium tank, $K_{kl}$ is the specific volume of the helium, $q_{tf}$ is the helium tank fill rate, $q_{sc}$ is the flow rate to the valve box subcooler, $q_{ts}$ is the flow rate of tank losses, and $q_{tl}$ is the flow rate to the (single) NIB transmission line.

Model Parameters

The parameters of the supply tank model and helium return network are summarised in Table 4.3.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Units</th>
<th>Time Varying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium supply tank volume</td>
<td>5000</td>
<td>l</td>
<td></td>
</tr>
<tr>
<td>Helium specific volume</td>
<td>8.04</td>
<td>L/kg</td>
<td></td>
</tr>
<tr>
<td>Tank refill start level</td>
<td>70</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Tank refill stop level</td>
<td>85</td>
<td>%</td>
<td></td>
</tr>
</tbody>
</table>
4.2. MODEL DETAIL

4.2.4. Transmission Lines

The transmission line, despite being a single physical entity, is treated as two separate components in this model. This reflects its construction, which as described in Chapter 3 has a concentric ring structure with bidirectional flow for supplied liquid and returning gas. One component acting as a supply (transmission) line delivering liquid helium from the helium tank to the heat exchanger, and the other, a return line removing gaseous helium from the phase separator and taking it to the return distribution network (and the to the liquefier or helium balloons). Both are considered to be storage elements.

Assumptions

1. Both the helium transmission and return lines are rigid and of fixed volume, regardless of fluid pressure
2. In the absence of a fault, the transmissions line are a perfectly insulated adiabatic system
3. The fluid in the return and supply lines are assumed to be in a saturated state
4. The temperature and pressure in the transmission lines are assumed to be uniform throughout

Inputs and Outputs

The inputs for both models are the mass flow rates into the line, the temperature of material entering the line, and the termination pressure. The outputs of both models are mass flow rate, the pressure inside the line, the mass of material in the line, and the temperature of the material in the line. This is summarised in Table 4.4 and Table 4.5.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Units</th>
<th>Time Varying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank refill rate</td>
<td>0.028</td>
<td>kg/s</td>
<td></td>
</tr>
<tr>
<td>Supply network end pressure</td>
<td>1.088</td>
<td>BarA</td>
<td></td>
</tr>
<tr>
<td>Return network start pressure</td>
<td>13.88</td>
<td>PSI</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3.: Model parameters for the supply tank and helium return network
### 4.2. MODEL DETAIL

#### CHAPTER 4. MODELLING

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Time Varying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow rate into the line</td>
<td>kg/s</td>
<td>✓</td>
</tr>
<tr>
<td>Temperature of inlet material</td>
<td>K</td>
<td></td>
</tr>
<tr>
<td>Termination pressure</td>
<td>Pa</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Time Varying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow rate from the line</td>
<td>kg/s</td>
<td>✓</td>
</tr>
<tr>
<td>Temperature in the transmission line</td>
<td>K</td>
<td>✓</td>
</tr>
<tr>
<td>Pressure in the transmission line</td>
<td>Pa</td>
<td>✓</td>
</tr>
<tr>
<td>Mass of material in the transmission line</td>
<td>kg</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 4.4.: Inputs to the transmission lines

Table 4.5.: Outputs of the transmission lines

### Fundamental Equations

Both the supply and return line models have two states: the average temperature of the contained material, and the mass of the material.

**Supply Line**

The rate of change of liquid mass in the supply line is given by:

\[
\frac{dM}{dt} = q_i - q_o
\]  

(4.13)

Where \( M \) is the mass of liquid in the line, \( q_i \) is the inlet flow rate and \( q_o \) is the outlet flow rate.

The rate of change of temperature inside the supply line is given by:

\[
\frac{dT}{dt} = \frac{dT}{dh} \frac{dh}{dt}
\]  

(4.14)

The rate of change of temperature with specific enthalpy is looked up from a table of thermodynamic properties for saturated helium. In this case the one provided by
National Institute of Standards and Technology (NIST)[90] was used. The rate of change of specific enthalpy, $h$, is given by:

$$\frac{dh}{dt} = \frac{(q_i h_i) - (q_o h)}{M}$$  \hspace{1cm} (4.15)

Where $h_i$ is the specific enthalpy of the liquid entering the transmission line.

As noted in Table 4.5 this model has four outputs. The first of these is the mass flow rate leaving the line, $q_o$. First the density of liquid inside the line, $\rho$, is calculated:

$$\rho = \frac{M}{V_l}$$ \hspace{1cm} (4.16)

Where $V_l$ is the volume of the line. Then:

$$q_o = C_v \sqrt{\frac{P - P_{term}}{\frac{1}{\rho}}}$$ \hspace{1cm} (4.17)

Where $P_{term}$ is the termination pressure at the end of the line, and $C_v$ is the conductance of the end aperture. The pressure inside the supply line, $P$, is another output. This is found by using $T$ (line temperature) to look up the corresponding pressure in the saturated property table.

It should be noted that whilst liquid helium is more compressible than many other liquids (with a bulk modulus of $268$ Bar[91]), a high pressure change is still required to significantly reduce its volume. Under normal conditions, helium is typically compressed no more than $1\%$.

**Return Line**

For the return line, the rate of change of the two states $M$ and $T$ are given by:

$$\frac{dM}{dt} = q_i - q_o$$ \hspace{1cm} (4.18)

And:

$$\frac{dT}{dt} = \frac{1}{C_{shv}} \frac{(q_i h_i) - (q_o h)}{M}$$ \hspace{1cm} (4.19)
Where $C_{shv}$ is the constant volume specific heat capacity of helium gas at cryogenic
temperature (the PV change is negligible under standard operating conditions).

The mass flow rate of gas leaving the return line is calculated using the flow gas equation,
Eq. (4.21). The pressure in the transmission line is looked up using a saturated material
property table, as before.

**Model Parameters**

The parameters of the model are taken from the physical properties of the transmission
line. They are summarised in Table 4.6.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Units</th>
<th>Time Varying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply line termination conductance</td>
<td>0.008</td>
<td>m$^2$</td>
<td></td>
</tr>
<tr>
<td>Return line entry conductance</td>
<td>0.008</td>
<td>m$^2$</td>
<td></td>
</tr>
<tr>
<td>Supply line volume</td>
<td>2.042</td>
<td>m$^3$</td>
<td></td>
</tr>
<tr>
<td>Return line volume</td>
<td>2.711</td>
<td>m$^3$</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.6.: Model parameters for the supply line

**4.2.5. Valves**

The control valves on the transmission line regulate the flow of liquid helium from the
tank into the heat exchanger and the flow rate of gaseous helium out of the return line.
The transmission and return control valves are treated independently, because the former
controls the flow of a (relatively, compared to helium gas) incompressible fluid and the
latter, compressible helium gas. They are both resistive components. In Fig. 4.2, two
resistive blocks are set either side of the storage component of the heat exchanger. These
blocks are treated the same as the valve blocks described in equations (4.20) and (4.21),
with $Y$ set to unity and a conductance representative of the constriction between the
transmission line and heat exchanger.

**Assumptions**

1. Liquid helium entering the transmission line is incompressible
2. Gaseous helium leaving the return line is compressible

3. Both valves have a linear relationship between valve position and conductance (i.e. a linear flow characteristic)

**Inputs and Outputs**

The valve position and pressures on both sides of the valve are the inputs to both blocks. The output of both blocks is a mass flow rate.

**Fundamental Equations**

The flow rate through the transmission valve is described by:

\[ q_{fl} = Y_{tx} C_v \sqrt{\frac{\Delta p}{v_i}} \]  

(4.20)

Where \( C_v \) is the valve conductance, \( \Delta p \) is the differential pressure across the valve, \( Y_{tx} \) is the proportion the valve is open, normalised between zero and unity, and \( v_i \) is the specific volume of the fluid at the valve inlet.

The return valve is described using an equation for valves transmitting compressible gasses referred to by Baumann[92]:

\[ q_{rl} = Y_{rx} C_v 3.22 \sqrt{\Delta p (p_1 + p_2) G_g} \]  

(4.21)

Where, with care to use US units for all the terms and converting afterwards, owing to the empirical scaling factor, \( q_{rl} \) is the return valve flow rate and \( G_g \) is the specific gravity of the gas.

**4.2.6. Phase Separator and Capillaries**

So far, each of the components that make up the model have been relatively simple. The important characteristics of the systems they represent have been described well without the need for longer mathematical derivations. The phase separator and capillaries, however, require a more in depth analysis for its behaviour to be described in sufficient
detail. As noted earlier, the level of detail required here is a reflection of the crucial contribution of these components to the useful operation of the system as a whole.

There are several different ways to model a two phase system such as the one under consideration here. Conceptually, the most straightforward are those that take a mass and energy balance across the system boundaries. There are numerous examples of this technique being used successfully, for example PJ Thomas devotes a chapter of his book on process modelling[93] to it. A commonly cited paper by Astrom and Bell[94] describes how this technique has been used to model drum boilers of the type traditionally used in commercial power generation. There are numerous other examples of this technique being used to analyse a variety of systems, which is a testament to it’s utility in engineering analysis. This technique, as applied to the phase separator and capillaries section of the model, is presented below.

**Inputs, Outputs and Assumptions**

![Figure 4.7: Phase Separator and Capillary Layout](image)

Figure 4.7 is a graphical representation of the capillaries and phase separator as modelled. The circular, top section of the diagram represents the phase separator (with the horizontal return manifold attached), the bottom section represents the capillaries. The boundaries of this part of the model (both in the graphical and coming mathematical representation) is the termination point of the feed and return lines at the bottom of the capillaries and the end of the horizontal manifold respectively. Immediately, it is clear that, in the illustration, the capillaries are drawn as one singular vertical tube.
The same simplification is made in the mathematical analysis of the system. Overall, the mass and energy balance of cryogenic material in the system is not affected by the shape of the capillaries (or, in this case, the singular, lumped capillary) and information about the distribution of the cryogenic fluid between the capillaries is not relevant. Treating the capillaries as a lumped construction simplifies the analysis without any loss of useful information. The coloured portion of the illustration represents the cryogenic fluid, the uncoloured portion represents the gas space above it. The mottled portion of the illustration, at the top of the capillaries and in the phase separator, represents the vapour below the liquid level, rising to the surface. $Q$, $q_f$ and $q_s$ are the main inputs and outputs to the system. As noted in the table below, they are respectively, heat load, liquid flow rate into the capillaries, vapour flow rate out of the manifold. The liquid level in the phase separator is represented by $l$ and the pressure and temperature are represented by $t$ and $p$.

From this point onwards in the analysis, the capillaries will be sometimes referred to as the “riser” and the phase separator as the “drum”. The reason for this is that the system described here has similarities to the drum boiler system described by Astrom and Bell[94] (as do many two-phase systems). Using similar symbols where possible makes the connection between the two more transparent - it becomes easier to identify similarities and differences in the mathematical descriptions and derivations. A comprehensive table of symbols is presented in the appendix for reference.

In order to facilitate the synthesis of this part of the model, the following assumptions have been made. The first of these was referred to above, that is, the capillaries (risers) are treated as a lumped construction. The second assumption is that the system is in thermal equilibrium. Specifically, this means that it is assumed that the temperature of the liquid, the vapour and metalwork are the same temperature at any given moment in time. The third assumption is that the phase separator (drum) contains a saturated vapour-liquid mixture. These assumptions are supported by historical process data and represent that real working of the system very well.

The inputs and outputs to this section of the model are summarised in Table 4.7 and Table 4.8.

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Time Varying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump heat load</td>
<td>W</td>
<td>✓</td>
</tr>
<tr>
<td>Flow rate of liquid into the pump</td>
<td>kg/s</td>
<td>✓</td>
</tr>
</tbody>
</table>

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### Table 4.7.: Inputs to the heat exchanger model

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Time Varying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate of vapour out the pump</td>
<td>kg/s</td>
<td>✓</td>
</tr>
<tr>
<td>Temperature of liquid entering the pump</td>
<td>K</td>
<td>✓</td>
</tr>
</tbody>
</table>

### Table 4.8.: Outputs of the heat exchanger model

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Time Varying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure inside the heat exchanger</td>
<td>Pa</td>
<td>✓</td>
</tr>
<tr>
<td>Heat exchanger liquid level</td>
<td>%</td>
<td>✓</td>
</tr>
<tr>
<td>Temperature of vapour leaving the heat exchanger</td>
<td>K</td>
<td>✓</td>
</tr>
<tr>
<td>Volume of liquid in the heat exchanger</td>
<td>m³</td>
<td>✓</td>
</tr>
<tr>
<td>Steam quality in the heat exchanger (i.e. void coefficient)</td>
<td>Ratio</td>
<td>✓</td>
</tr>
<tr>
<td>Volume of vapour below the liquid level</td>
<td>m³</td>
<td>✓</td>
</tr>
</tbody>
</table>

### Global Mass and Energy Balance

To begin with, the global mass balance of the system is described by:

\[
\frac{d}{dt} \left[ \rho_s V_{st} + \rho_w V_{wt} \right] = q_f - q_s \tag{4.22}
\]

And the energy balance of the system is:

\[
\frac{d}{dt} \left[ \rho_s V_{st} u_s + \rho_w V_{wt} u_w + m_t C_p t_m \right] = Q + q_f h_f - q_s h_s \tag{4.23}
\]

Now, the well known relations between specific enthalpy and specific energy:

\[
h = u + pV \tag{4.24}
\]
are substituted into Eq. (4.23):

\[
\frac{d}{dt} \left[ \rho_s V_{st} h_s + \rho_w V_{wt} h_w + m_t C_p t_m - p V_t \right] = Q + q_f h_f - q_s h_s
\]

(4.26)

The above equations describe the global mass balance of the system, however for the model to be useful, more information is needed - the liquid level in the phase separator and the operating pressure and temperature.

**Local Mass and Energy Balances**

In order to gain access to the information listed above, the distribution and motion of liquid and vapour in the system needs to be modelled. This analysis starts with a statement of the relationship between the volumes of vapour and liquid.

\[
V_t = V_{st} + V_{wt}
\]

(4.27)

And then, the definition of condensation enthalpy:

\[
h_c = h_s - h_w
\]

(4.28)

With these two properties defined, the next step is to examine the mass and energy balance in the capillaries. In the analysis of two-phase boiler systems (for example, power plant boilers), often the term “steam quality” is used to describe the proportion of vapour to liquid at a given location. In the nuclear industry this is also sometimes known as the “void coefficient”. It is a unitless quantity (a ratio), ranging from unity in the case where only vapour is present, to zero when only liquid is present. In this model, recirculation from the phase separator into the capillaries is not explicitly described. Recirculation in the phase separator/capillary is caused by convection. Cooler liquid from the phase separator drops down into the capillaries to replace the rising boiled vapour. This recirculation flow contributes to the replacement of boiled liquid in the capillaries,
4.2. MODEL DETAIL

Together with the flow of liquid into the bottom from the liquid supply line. The equations detailed below that describe the steam quality in the capillaries are a function of the inlet flow - there is no explicit reference to the recirculation flow. The recirculation is, however, implicitly invoked when the equations are solved during simulation and it appears as a negative flow, or as a steam quality ratio greater than unity (for example, when the mass flow rate of vapour leaving the capillaries exceeds the mass flow rate of replacement liquid fed into the bottom of the capillaries).

The mass fraction of vapour in the capillaries (steam quality) is described by:

\[ \alpha_m = \frac{QA}{Qh_c V_z} \]  

(4.29)

If \( \xi \) is the normalised length coordinate along the riser \((0 \leq \xi \leq 1)\), then:

\[ \alpha_m = \alpha_r \xi \]  

(4.30)

Accordingly, the volume fraction of vapour in the capillaries is given by:

\[ \alpha_v = f(\alpha_m) = \frac{\rho_w \alpha_m}{\rho_s + (\rho_w - \rho_s) \alpha_m} \]  

(4.31)

Steam slip (or slip ratio, or velocity ratio) is a measure of the relative average velocities of liquid and gas phases in two phase flow. For the analysis of physically large two-phase systems or systems taking advantage of forced recirculation two-phase flow, the steam slip phenomenon often should be accounted for. A well known derivation of equations governing slip effects was produced by Levy[95]. However, in this model it is assumed that steam slip is negligible, as it’s inclusion significantly increases the complexity of the analysis while not contributing significantly to the output of the model. For similar reasons, it is assumed the the boiling process begins at the bottom of the capillary tubes, rather than the vapour nucleation beginning at some height above that. For additional discussion of boiling, an excellent description of several different boiling regimes and mechanisms can be found in Rohsenow’s 1985 book[96].
Given these assumptions, the average steam volume ratio in the capillaries for a given value of $\alpha_r$ is:\n
\[
\int_0^1 \frac{\rho_w \alpha_r \xi}{\rho_s + (\rho_w - \rho_s) \alpha_r \xi} \, d\xi
\]

(4.32)

Assuming an operating temperature of 4.3K, evaluating Eq. (4.32) for many values of $\alpha_r$ gives the curve marked by crosses in Fig. 4.8.

A fifth order polynomial was fitted to this curve, and has been marked on Fig. 4.8 with a solid red line. This polynomial describes the average steam quality ratio as a function of the final capillary void mass fraction:

\[
\pi_v = 2.6392\alpha_r^5 - 8.3286\alpha_r^4 + 10.4923\alpha_r^3 - 7.0023\alpha_r^2 + 2.9787\alpha_r + 0.0073
\]

(4.33)

Using this average steam volume ratio, the capillary mass balance is given by:

\footnote{In [94] Astrom solves a similar integral symbolically, however the author of this thesis believes that the result presented in that paper is incorrect, because when it is evaluated, it gives values for average steam volume ratio that do not make sense physically.}

Figure 4.8.: Average steam volume ratio against $\alpha_r$
\[
\frac{d}{dt} [\rho_s \alpha_v V_r + \rho_w (1 - \alpha_v) V_r] = q_f - q_r 
\]

(4.34)

Then from this and Eq. (4.25), the capillary energy balance is:

\[
\frac{d}{dt} \left[ \rho_s h_s \alpha_v V_r + \rho_w h_w (1 - \alpha_v) V_r - p V_r + m_r C_p t_s \right] = Q + q_f h_f - (\alpha_r h_c + h_f) q_r 
\]

(4.35)

With the mass and energy balance in the capillaries accounted for, the dynamics of the phase separator and the distribution of vapour within it remain to be analysed.

The volume of vapour in the phase separator, under the liquid level is given by:

\[
\frac{d}{dt} [\rho_s V_{sd}] = \alpha_r q_r - q_{sd} - q_{cd} 
\]

(4.36)

Where the condensation flow rate in the phase separator is given by:

\[
q_{cd} = \frac{1}{h_c} \left[ \rho_s V_{sd} \frac{dh_s}{dt} + \rho_w V_{wd} \frac{dh_w}{dt} - (V_{sd} + V_{wd}) \frac{dp}{dt} + m_d C_p \frac{dt_s}{dt} \right] 
\]

(4.37)

And the flow rate of vapour through the surface is calculated from the velocity and volume of vapour bubbles leaving the risers:

\[
q_{sd} = \frac{\rho_s V_{sd}}{l} \left[ 1.53 \frac{\sigma g (\rho_w - \rho_s)}{\rho_s^2} \right] \frac{1}{4} 
\]

(4.38)

The volume of liquid inside the phase separator is simply calculated by subtracting the amount of liquid in the capillaries from the total amount of liquid in the system:

\[
V_{wd} = V_{wt} - (1 - \alpha_v) V_r 
\]

(4.39)

And this allows the liquid level in the phase separator to be calculated:

\[
\text{level(\%)} = 50 + \left[ \arcsin \left( \frac{2 V_{wd} + V_{sd}}{V_t} \right) - 1 \right] \frac{50}{90} 
\]

(4.40)
Where the trigonometric function is in degrees and the fill level of the phase separator is between 0 and 100%.

**Dynamics of the Capillaries and Phase Separator**

In order to derive a full set of state equations, further manipulation of the mass and energy balance equations are required. To start with, the capillary mass balance described in Eq. (4.34) is multiplied by $- (h_f + \alpha_r h_c)$, in order to eliminate the flow rate out of the capillaries, $q_r$. This gives:

\[
\frac{d}{dt} [\rho_s \alpha_v V_r + \rho_w (1 - \alpha_v) V_r] \left[ - (h_f + \alpha_r h_c) \right] = [q_f - q_r] \left[ - (h_f + \alpha_r h_c) \right]
\]

(4.41)

Then this is added to the capillary energy balance, given in Eq. (4.35):

\[
\frac{d}{dt} \left( \rho_s \alpha_v h_s V_r \right) - (h_f + \alpha_r h_c) \frac{d}{dt} \left( \rho_s \alpha_v V_r \right) \\
+ \frac{d}{dt} \left( \rho_w h_w (1 - \alpha_v) V_r \right) \\
- (h_f + \alpha_r h_c) \frac{d}{dt} \left( \rho_w (1 - \alpha_v) V_r \right) \\
- V_r \frac{dp}{dt} + m_r C_p \frac{dt_s}{dt}
\]

(4.42)

This simplifies to:

\[
Q = q_f h_f - (h_f + \alpha_r h_c) q_r \\
- (q_f - q_r) (h_f + \alpha_r h_c)
\]

\[
= Q - q_f \alpha_r h_c
\]

This simplifies to:
To derive an equation for the capillary flow rate, \( q_r \), again start with the capillary mass balance, Eq. (4.34). This is rearranged into terms of \( p \) and \( \alpha_r \), which as will be shown later, are state variables:

\[
\begin{align*}
q_r &= q_f - V_r \left[ \frac{d\rho_s}{dp} \bar{\alpha}_v \frac{d\alpha_r}{dt} + \frac{d\rho_w}{dp} (1 - \bar{\alpha}_v) V_r \right] \\
&= q_f - V_r \left[ \frac{d\rho_s}{dp} \bar{\alpha}_v \frac{d\alpha_r}{dt} + \frac{d\rho_w}{dp} (1 - \bar{\alpha}_v) \frac{dp}{dt} \right] \\
&= q_f - V_r \left[ \frac{d\rho_s}{dp} \bar{\alpha}_v \frac{d\alpha_r}{dt} + \frac{d\rho_w}{dp} (1 - \bar{\alpha}_v) \frac{dp}{dt} \right] - V_r (\rho_s - \rho_w) \frac{d\alpha_v}{d\alpha_r} \frac{d\alpha_r}{dt} \\
&= q_f - \frac{d\rho_s}{dp} \bar{\alpha}_v \frac{d\alpha_r}{dt} \frac{dp}{dt} - V_r (\rho_s - \rho_w) \frac{d\alpha_v}{d\alpha_r} \frac{d\alpha_r}{dt}
\end{align*}
\]

(4.44)

Which can also be written as:

\[
q_r = q_f - \frac{d\rho_s}{dp} \bar{\alpha}_v \frac{d\alpha_r}{dt} \frac{dp}{dt} - V_r (\rho_s - \rho_w) \frac{d\alpha_v}{d\alpha_r} \frac{d\alpha_r}{dt}
\]

(4.45)

The final step is to derive an expression for the dynamics of the vapour in the phase separator. Substituting the equations for \( q_{cd} \), \( q_{sd} \) and \( q_r \) (Eq. (4.37), Eq. (4.38) and Eq. (4.44)) into the vapour balance equation (Eq. (4.36)) gives:
\[
\begin{align*}
\rho_s \frac{dV_{st}}{dt} + V_{st} \frac{d\rho_s}{dt} &= \alpha_r \left( q_f - V_r \frac{d}{dp} \left[ (1 - \bar{\rho}_s) \rho_w + \bar{\rho}_s \rho_s \right] \frac{dp}{dt} + V_r \left( \rho_w - \rho_s \right) \frac{d\rho_w}{d\rho_s} \frac{d\rho_r}{d\rho_r} \right) \\
&- \frac{\rho_s V_{st}}{l} \left[ \frac{1.53 \sigma g (\rho_w - \rho_s)}{\rho_w} \right]^{1/4} \\
&- \frac{1}{h_c} \left( \rho_s V_{st} \frac{dh_s}{dt} + \rho_w V_{wd} \frac{dh_w}{dt} - [V_{st} + V_{wd}] \frac{dp}{dt} + m_d C_p \frac{dt_s}{dt} \right) \\
\end{align*}
\] (4.46)

This rearranges to:

\[
\begin{align*}
\rho_s \frac{dV_{st}}{dt} + V_{st} \frac{d\rho_s}{dt} &= \alpha_r \left( -V_r \frac{d}{dp} \left[ (1 - \bar{\rho}_s) \rho_w + \bar{\rho}_s \rho_s \right] \frac{dp}{dt} + V_r \left( \rho_w - \rho_s \right) \frac{d\rho_w}{d\rho_s} \frac{d\rho_r}{d\rho_r} \right) \\
&+ \frac{1}{h_c} \left( \rho_s V_{st} \frac{dh_s}{dt} + \rho_w V_{wd} \frac{dh_w}{dt} - [V_{st} + V_{wd}] \frac{dp}{dt} + m_d C_p \frac{dt_s}{dt} \right) \\
&= \alpha_r q_f + \left( \frac{\rho_s V_{st}}{l} \left[ \frac{1.53 \sigma g (\rho_w - \rho_s)}{\rho_w} \right]^{1/4} \right) \\
\end{align*}
\] (4.47)

**State Variables and Equations**

Using four state variables, a full set of state equations that describe this section of the model can be found. The four state variables are pressure, steam quality at the capillary-phase separator junction, total volume of liquid and volume of vapour under the liquid level \((p, \alpha_r, V_{st} \text{ and } V_{sd})\).

Using Eq. (4.27) to eliminate \(V_{st}\) from the global mass and energy balance equations (Eq. (4.22) and Eq. (4.26)), then collecting terms, gives the first two state equations:

\[
\begin{align*}
pe_{11} \frac{dV_{st}}{dt} + pe_{12} \frac{dp}{dt} &= q_f - q_s \\
pe_{21} \frac{dV_{st}}{dt} + pe_{22} \frac{dp}{dt} &= Q + q_f h_f - q_s h_s \\
\end{align*}
\] (4.48)

(4.49)
From Eq. (4.43), the capillary dynamics equation, and Eq. (4.47), the phase separator dynamic equation, the final two state equations are, after collecting terms:

\[ e_{32} \frac{dp}{dt} + e_{33} \frac{d\alpha_r}{dt} = Q - q_f \alpha_r h_c \]  

(4.50)

\[ e_{42} \frac{dp}{dt} + e_{43} \frac{d\alpha_r}{dt} + e_{44} \frac{dV_{sd}}{dt} = \alpha_r q_f - \frac{p_s V_{sd} \left[ \frac{1.53 \sigma \bar{g}_{pw} - \rho_s}{\rho_w} \right]^\frac{1}{2}}{l} \]  

(4.51)

To complete the above state equations:

\[ e_{11} = \rho_w - \rho_s \]  

(4.52)

\[ e_{12} = V_{wt} \frac{d\rho_w}{dp} + V_{st} \frac{d\rho_s}{dp} \]  

(4.53)

\[ e_{21} = \rho_w h_w - \rho_s h_s \]  

(4.54)

\[ e_{22} = V_{st} \left( h_s \frac{d\rho_s}{dp} + \rho_s \frac{dh_s}{dp} \right) + V_{wt} \left( h_w \frac{d\rho_w}{dp} + \rho_w \frac{dh_w}{dp} \right) \]  

\[ - V_r + m_C \frac{dt_s}{dp} \]  

(4.55)

\[ e_{32} = \left( \rho_w \frac{dh_w}{dp} - \alpha_r h_c \frac{d\rho_w}{dp} \right) \left( 1 - \bar{\alpha}_v \right) V_r \]  

\[ + \left[ \frac{1 - \alpha_r}{\rho_s} \right] h_c \frac{d\rho_s}{dp} + \rho_s \frac{dh_s}{dp} \bar{\alpha}_s V_r \]  

\[ + \left( \rho_s + \left[ \rho_w - \rho_s \right] \alpha_r \right) h_c \frac{d\bar{\alpha}_v}{dp} \]  

\[ - V_r + m_C \frac{dt_s}{dp} \]  

(4.56)
\[ e_{33} = (\alpha_r \rho_s + \alpha_r \rho_w) h_v \frac{d\alpha_v}{d\alpha_r} \]  

(4.57)

\[ e_{42} = V_{sd} \frac{d\rho_s}{dp} \]

\[ + \frac{1}{h_c} \left( \rho_s V_{sd} \frac{dh_s}{dp} + \rho_w V_{wd} \frac{dh_w}{dp} - [V_{sd} + V_{wd}] + m_d C_p \frac{dt_d}{dp} \right) \]

(4.58)

\[ - \alpha_r \left( \left[ \left( \frac{\rho_s}{\alpha_v} + (1 - \alpha_v) \frac{\rho_w}{dp} \right) + (\rho_s - \rho_w) \frac{d\alpha_v}{dp} \right] \right) \]

\[ e_{43} = -\alpha_r \left[ -V_r \left( \rho_s - \rho_w \right) \frac{d\alpha_v}{dp} \right] \]  

(4.59)

\[ e_{44} = \rho_s \]  

(4.60)

Saturated steam tables are used to evaluate \( h_s, \ h_w, \ \rho_s, \ \rho_w, \ \frac{d\rho_s}{dp}, \ \frac{d\rho_w}{dp}, \ \frac{h_s}{dp}, \ \frac{h_w}{dp}, \ t_s \) and \( \frac{dt_s}{dp} \) at any given pressure, \( p \).

Finally:

\[ \frac{d\alpha_v}{d\alpha_r} = 13.196\alpha_r^4 - 33.3144\alpha_r^3 + 31.4769\alpha_r^2 - 14.0046\alpha_r + 2.9787 \]  

(4.61)

For simplicity, here \( \frac{d\alpha_v}{dp} \) is set to zero, because it doesn’t change appreciably under the conditions anticipated in the physical plant.

**Model Parameters**

As before, the parameters of the model are taken from the physical properties of the plant, as described in Chapter 3. They are summarised in Table 4.9.
Table 4.9.: Model parameters for the heat exchanger

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Units</th>
<th>Time Varying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drum section volume</td>
<td>0.022</td>
<td>m³</td>
<td></td>
</tr>
<tr>
<td>Total capillary section volume</td>
<td>0.01131</td>
<td>m³</td>
<td></td>
</tr>
<tr>
<td>Total metalwork mass</td>
<td>303.5</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>SHC of aluminium at 4.23K</td>
<td>0.4</td>
<td>J/kg.K</td>
<td></td>
</tr>
<tr>
<td>Capillary metalwork mass</td>
<td>294.6</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>Drum metalwork mass</td>
<td>8.9</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>Liquid helium surface tension</td>
<td>8.954 * 10^{-5}</td>
<td>N/m</td>
<td></td>
</tr>
<tr>
<td>Acceleration due to gravity</td>
<td>9.807</td>
<td>m/s²</td>
<td></td>
</tr>
<tr>
<td>Linearised bubble travel distance</td>
<td>0.025</td>
<td>m</td>
<td></td>
</tr>
</tbody>
</table>

4.3. **Validation**

In order to validate the non-linear simulation model a two stage process was followed: a heuristic analysis of the model’s response, and then a comparison with historical process data. In both stages Matlab and Simulink were used to build and run the simulation models.

Figure 4.9. The top level of the Matlab simulation

Figure 4.9 is an illustration of the top level of the Matlab simulation. Each of the blocks corresponds to one section of the model described in the Section 4.2. The Simulink setup for each of the boxes is illustrated in the rest of this section.

4.3.1. **Heuristic Analysis**

Heuristic analysis is an experience driven technique. In the context of validating this simulation model, the response of the model is compared to its expected behaviour
using engineering judgement. This verifies the general trends of the model’s response, and allows the early identification of unrealistic model behaviour. In addition, if a reasonable degree of confidence can be afforded to predictions made by the model which cannot be compared to historical process data, then the validity of the model is further supported.

Figure 4.9 shows the structure of the Matlab simulation model. Each of the model components (or blocks) are examined individually. Gaussian white noise has been added to the input of each model component. The purpose of this is to make the simulation of each component more closely representative of the physical plant, where the inputs do in reality have small variations over time. This also is used to demonstrate the sensitivity of the model to these small amplitude, high frequency variations which are common during the physical operation of the plant.

**Helium Transmission Line (Supply)**

Figure 4.10 is a schematic of the helium supply line validation experiment, taken from Simulink. The centre block labelled “Transmission Line” is an s-function realisation of the helium supply line. On the left are the inputs to the s-function block. The top input is the mass flow rate of liquid into the line. The middle input is the termination pressure at the end of the supply line. The bottom input is the temperature of the liquid entering the line. On the right are the outputs of the experiment. The topmost output is liquid mass flow rate. The second from top output is the liquid pressure inside the supply line. The third from top output is the mass of liquid inside the supply line. The bottom output is the temperature of liquid inside the supply line.

The liquid mass flow rate was set to $5 \times 10^{-3}$ kg/s, with a step increase of $2 \times 10^{-3}$ kg/s during the simulation. The amplitude of the base mass flow rate was selected because it matches closely the flow rate observed in the physical plant during normal fault-free operation. The amplitude of the step was selected because it is similar to the step in flow rate observed on the physical plant when an experimental pulse is run.

The termination pressure was set to $1.0053 \times 10^5$ Pa, which matches the heat exchanger pressure seen on the physical plant during normal fault-free operation.

The incoming liquid temperature was set to $4.25$ K, with a step of $0.2$ K, because the temperature of the incoming liquid in the physical plant is normally controlled, and kept at $4.25$ K, but will occasionally see a small change of one or two tenths of a Kelvin
for a short period when the operating mode/conditions of the upstream helium supply change.

Gaussian white noise has been added to two of the inputs, with a standard deviation of $\approx 0.01$ kg/s and $\approx 0.02$ K, which consistent with the variance of the inputs to the physical plant.

The pulse generator, constant, and summing block arrangements for the top and bottom inputs are used to simulate a step change in the inlet liquid flow rate and inlet liquid temperature. The step changes are simulated at $t = 4$ and $t = 10$, respectively. This is shown in Fig. 4.11.

The response of the supply line model to these inputs is shown in Fig. 4.12.

Remarks

1. Liquid helium, while more compressible than many other liquids (e.g. water), still requires a large change in pressure for its specific volume to change appreciably[90].
Figure 4.11.: Inputs to the supply line validation experiment
Figure 4.12.: Outputs from the supply line validation experiment
Figure 4.12.: Outputs from the supply line validation experiment
As such, the outlet flow rate tracks the inlet flow rate (while the inlet temperature is unchanged).

2. The outlet flow rate and liquid pressure in the transmission line share the same profile. This is because the outlet flow rate is proportional to the pressure differential across the end of the transmission line, and in this experiment, the outlet pressure is fixed. The pressure change is small. This is because only a small change in pressure will result in a relatively large change in flow. The approximate magnitude of the change has been marked on the chart directly, as it is small compared to the scale.

3. While the inlet temperature is increased, the outlet flow rate is also increased. This corresponds with an increase in the average temperature of the liquid. When the average temperature of the liquid increases, it expands therefore increasing the outlet flow rate and reducing the overall mass of liquid inside the transmission line. The change in average temperature is very small, as would be expected given the comparatively low liquid flow rate compared to the total mass of fluid. For this reason, the magnitude has been marked on the chart directly.

4. The change in temperature and pressure shown in Fig. 4.12 is very small, and difficult to delineate. This is because the change in inlet flow rate and temperature are also relatively small when compared to the total mass of liquid in the transmission line.
Helium Transmission Line (Return)

Figure 4.13 is a schematic of the helium return line experiment, taken from Simulink. In a similar way to the supply line experiment (Fig. 4.10) the centre block is an s-function realisation of the helium gas return line. It takes three inputs and produces four outputs. The top input is a gas inlet flow rate. The middle input is the termination pressure of the line. The bottom input is the temperature of the gas entering the line. The outputs are, from top to bottom, the outlet gas flow rate, the pressure inside the line, the mass of gas inside the line, and the temperature of gas inside the line.

The outlet gas flow rate was set to $5 \times 10^{-3}$ kg/s because, as with the supply line, this is the typical gas flow rate into the return line during normal fault-free operation of the physical plant. For the same reason as the supply line, a step of an additional $2 \times 10^{-3}$
4.3. VALIDATION

kg/s of flow rate was simulated, as this is similar to the step in flow rate observed on the physical plant during pulsed operation.

The termination pressure of the return line was set to $1.032 \times 10^5$ Pa, to match the return pressure of the physical plant.

The temperature of the incoming helium gas was set to 4.25 K, because this is the temperature of the saturated liquid/vapour mix of the physical heat exchanger during normal operation. Again a step of 0.2 K was added to this for a short period, to represent either the occasional changes in the helium supply temperature, or an increase in the liquid/vapour mix temperature in the heat exchanger due to additional thermal loading of the pump.

Gaussian white noise has been added to two of the inputs, with an standard deviation of $\approx 0.01$ kg/s and $\approx 0.02$ K, which consistent the variance experienced by the physical plant.

Again with this experiment, as in the supply line experiment, a pulse generator is used to simulate the period of increased inlet flow rate and increased inlet gas temperature. The inputs to this experiment are shown in Fig. 4.14, and the outputs in Fig. 4.15.

Remarks

1. Gaseous helium has a much higher compressibility than liquid helium, and as a gas, requires a greater delta pressure across a constriction to achieve the same mass flow rate as a liquid. Owing to these reasons, in Fig. 4.15b it can be seen that the flow rate of gas leaving tracks the inlet flow rate relatively slowly compared to the liquid transmission line (Fig. 4.12b).

2. The gas outlet flow rate is proportional to the delta pressure across the outlet constriction. It follows that the return line pressure and flow rate share the same profile.

3. The temperature of gas entering the return line has a relatively small effect upon the four outputs, compared to the inlet flow rate. It can be seen however that increasing the temperature of gas entering the line (counter-intuitively) reduces the average line temperature. This is because the entrant gas comes directly from the heat exchanger, which contains a saturated vapour/liquid mixture, and the enthalpy of saturated helium gas actually decreases as its temperature rises (while $\geq 4.25$K). This results in the energy balance across the transmission line being reduced, and the associated reduction in temperature and pressure. If the entrant gas
Figure 4.14.: Inputs to the return line validation experiment
Figure 4.15.: Outputs from the return line validation experiment
Figure 4.15.: Outputs from the return line validation experiment
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CHAPTER 4. MODELLING

were not saturated, rather it were superheated, then an increased energy balance may be expected, however given the immediate physical proximity of the return line to the saturated vapour/liquid mix in the heat exchanger, it is appropriate to assume the entrant gas remains in a saturated state.

Heat Exchanger

Figure 4.16 is a schematic of the heat exchanger heuristic validation experiment. Figure 4.16a shows the structure of the simulation. The left most block represents the inputs to the simulation, the centre block represents the simulation of the heat exchanger (realised as an s-function in Simulink), and the right most block represents the output of the simulation. The detail of these blocks is shown in Fig. 4.16b, Fig. 4.16c, and Fig. 4.16d.

The central heat exchanger block takes four inputs and six outputs. The inputs are, from top to bottom, the heat load applied to the pump (W), the flow rate of liquid into the pump (kg/s), the flow rate of vapour leaving the pump (kg/s), and the temperature of the liquid entering the pump (K). The outputs are, from top to bottom, the pressure of the vapour/liquid mixture inside the pump (Pa), the fill level of liquid inside the pump (%), the temperature of vapour leaving the pump (K), the volume of liquid within the pump (m$^3$), the steam quality ratio within the pump capillaries (ratio), and the volume of vapour below the pump liquid level (m$^3$). This is also shown in Fig. 4.16b.

To carry out this validation experiment the four inputs to the simulation were predefined, and selected to be consistent with what would be expected on the physical plant during normal operation. The inlet liquid temperature was set to 4.23K (as per the temperature measured in the physical plant) and remained constant during the whole simulation time. The inlet flow rate and pump heat load inputs are shown in Fig. 4.17. Note that the inlet flow rate is approximately half that of the flow rate of the supply line. This is because the simulation is of one of the two cryopump walls in the NIB, and the supply line feeds both. The period of increased inlet flow rate (starting at $t = 50$) corresponds to what might be expected if the inlet valve were to open by an additional 50% from its starting position. This is an approximation however, because the exact inlet flow rate depends on the differential pressure across the valve and the liquid density, neither of which is simulated in this experiment. The period of increased pump heat load (starting at $t = 90$) has a profile and magnitude similar to the heat load on the physical plant during a NBHS pulse (see Section 4.2.2). The gas flow rate out of the pump is dependant on the differential pressure across the outlet constriction and the density of the gas evolved.
Figure 4.16.: The heat exchanger experiment
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from the pump. The gas density is assumed to be constant because the change in pump pressure is not large enough to cause a significant change, and the instantaneous pump pressure is calculated during the simulation. The outputs of the simulation are shown in Fig. 4.18.

Gaussian white noise has been added to all of the simulated inputs to represent the (typically small) variations observed on the physical plant. Their standard deviation is consistent with those of the transmission line simulations (0.01 kg/s, 0.02 K) where appropriate, and the noise added to the heat load is consistent with what would be expected from the varying turbulent flow of gas into the NIB vacuum from the neutraliser device and neutral beam ($\approx 0.03$ W).

Remarks

1. In the near steady state regions (e.g. while $t < 50$), the steam quality is close to unity, the volume of liquid in the heat exchanger is increasing slowly, and the liquid level is changing slowly. The inlet flow rate and thermal load on the heat exchanger are matched, so that almost all of the liquid entering the heat exchanger is boiled before leaving the capillaries.

2. At $t = 50$ the inlet liquid flow rate increases. The increase in flow rate corresponds to a decrease in steam quality in the heat exchanger capillaries. A relatively smaller proportion of the liquid travelling through the capillaries is boiled, because the thermal load on the heat exchanger remains the same.

3. During the period of increased inlet liquid flow rate, the liquid level drops. When the flow rate returns to its steady state level, the liquid level increases until it reaches a point beyond its starting level. This is due to the changing steam quality in the heat exchanger capillaries and the change in liquid volume. While the flow rate is increased, the steam quality drops from unity to around 0.2. As the average ratio of vapour to liquid in the capillaries decreases, the total helium mass in the capillaries occupies less volume, which results in the liquid level dropping. Once the steam quality returns to unity the liquid level increases, and due to the additional liquid now present in the heat exchanger, the final liquid level is higher than the initial liquid level.

4. At $t = 90$ the simulated pump heat load increases. The increased heat load corresponds to a decrease in heat exchanger steam quality, and as above, temporary decrease in liquid level. However, in this case the reduction in steam quality is
Figure 4.17.: Inputs to the heat exchanger validation experiment
Figure 4.18.: Outputs from the heat exchanger validation experiment
Figure 4.18.: Outputs from the heat exchanger validation experiment

(c) Heat Exchanger Temperature

(d) Heat Exchanger Liquid Volume
Figure 4.18.: Outputs from the heat exchanger validation experiment

(e) Heat Exchanger Steam Quality

(f) Heat Exchanger Vapour Volume (below liquid level)
caused by liquid from the “drum” portion of the heat exchanger flowing back into the capillaries. That is, \( q_r \) (see Section 4.2) is negative during this period. When the heat load and steam quality return to their near steady state values, the liquid level is lower than it would have been otherwise due to the extra helium boil off. In this instance, the change in level is small and difficult to delineate using the chart alone, because only a very small amount of helium is additionally boiled.

5. During both the period of increased inlet flow rate (starting at \( t = 50 \)) and during the period of increased heat load (starting at \( t = 90 \)), the heat exchanger pressure and temperature are increased. This is because during these periods the energy balance across the heat exchanger is positive, and the total enthalpy of the system is increasing. As the liquid vapour mix within the heat exchanger is assumed to be saturated, an increase in enthalpy is associated with both an increase in temperature and pressure for this operating point.

6. Figure 4.18f shows the volume of vapour under the liquid level. The volume of vapour corresponds physically to the vapour bubbles travelling upwards through the heat exchanger. Assuming the vapour bubbles travel at the same average velocity, four factors affect their instantaneous total volume: the density of the vapour, the rate at which they are generated, the distance they travel (i.e. the liquid level), and the rate at which they are condensed. It can be seen that during periods where the liquid level is lowered, the vapour volume is lowered accordingly (owing to the shorter travel distance). At \( t = 50 \) there is a transient increase in the volume of vapour below the liquid level. This is due to the increased rate of bubble generation. The bubble generation is assumed to be proportional to the inlet flow rate and average steam quality, and so is relatively higher initially at \( t = 50 \), as the inlet flow rate increases more rapidly than the decrease in steam quality.

### 4.3.2. Comparison with Historical Data

Comparing the predictions made by the simulation model to historical process data is the second important step in validating the model. Process data collected on the 21st February 2012 was used to both drive and validate the model. As noted in Chapter 3, process data collected from the cryogenic plant Supervisory Control and Data Acquisition (SCADA) network is recorded by the General Electric Proficy iFix software[97]. This software was used to export the process data to a Microsoft Excel spreadsheet,
which was then imported into the Matlab environment. Table 4.10 shows the times at which pulses were run on February 21\textsuperscript{st}, together with the (predicted) heating power and JET Pulse Number (JPN). Data from this day was chosen to validate the model, as the operation of the experiment on this day could be considered routine (as much as an experimental application of this sort can be), and no NBHS faults were observed.

<table>
<thead>
<tr>
<th>Pulse Time</th>
<th>JET Pulse Number</th>
<th>NB Power (MW)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>07:08:20</td>
<td>82362</td>
<td>N/A</td>
<td>Test run</td>
</tr>
<tr>
<td>08:35:50</td>
<td>82363</td>
<td>9.2</td>
<td>Aborted run, no pulse</td>
</tr>
<tr>
<td>09:08:29</td>
<td>82364</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>09:42:28</td>
<td>82365</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>10:19:38</td>
<td>82366</td>
<td>10.2</td>
<td></td>
</tr>
<tr>
<td>10:59:52</td>
<td>82367</td>
<td>10.3</td>
<td></td>
</tr>
<tr>
<td>11:35:10</td>
<td>82368</td>
<td>10.2</td>
<td></td>
</tr>
<tr>
<td>12:20:25</td>
<td>82369</td>
<td>N/A</td>
<td>Test run</td>
</tr>
<tr>
<td>13:18:08</td>
<td>82370</td>
<td>10.3</td>
<td></td>
</tr>
<tr>
<td>14:02:11</td>
<td>82371</td>
<td>10.2</td>
<td></td>
</tr>
<tr>
<td>14:49:23</td>
<td>82372</td>
<td>9.1</td>
<td></td>
</tr>
<tr>
<td>15:34:30</td>
<td>82373</td>
<td>5.9</td>
<td>No RF heating</td>
</tr>
<tr>
<td>16:18:13</td>
<td>82374</td>
<td>5.7</td>
<td>No RF heating</td>
</tr>
<tr>
<td>16:53:17</td>
<td>82375</td>
<td>5.8</td>
<td>No RF heating</td>
</tr>
<tr>
<td>17:13:33</td>
<td>82376</td>
<td>3.6</td>
<td>No RF heating</td>
</tr>
<tr>
<td>18:04:15</td>
<td>82377</td>
<td>2.4</td>
<td>No RF heating</td>
</tr>
<tr>
<td>18:45:13</td>
<td>82378</td>
<td>4.8</td>
<td>No RF heating</td>
</tr>
<tr>
<td>19:15:13</td>
<td>82379</td>
<td>N/A</td>
<td>Test run</td>
</tr>
</tbody>
</table>

Table 4.10.: JET pulse times on February 21, 2012

**Data Preparation**

Table 4.11 contains a list of the process data that was imported into Matlab. The physical location of the transducers that collected this data can be found by referring to the mimics in Appendix B.

When the Proficy iFix software is used to display process data during operation in real-time, the GUI is updated every second. However, in order to make best use of computing resources (storage space in particular) the software is configured such that only changes
in process data are recorded, rather than every sample. The threshold of change which causes a data point to be recorded is a small percentage of the total range of the data. In some cases where a transducer has a large measurement range compared to what is it supposed to be measuring, this feature of the software configuration can result in measurements not being recorded when there are small changes in a process variable.

Given that the data imported into Matlab was in a timestamp-value format, it was necessary to interpolate between data points. A piecewise cubic Hermite interpolation technique was used ("PCHIP" in Matlab)\[98\]. This technique produces a smooth piecewise defined series of third order polynomials that fit the known data set. The advantages of this technique over other interpolation techniques are that the resulting spline doesn’t overshoot the known data and the spline doesn’t oscillate in the case of non-smooth known data.

<table>
<thead>
<tr>
<th>Sensor Reference</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV523</td>
<td>%</td>
<td>LHe 5k tank fill valve position</td>
</tr>
<tr>
<td>CV524</td>
<td>%</td>
<td>LHe supply valve position</td>
</tr>
<tr>
<td>CV527</td>
<td>%</td>
<td>GHe return valve position</td>
</tr>
<tr>
<td>CV533</td>
<td>%</td>
<td>Valvebox LHe subcooler fill valve position</td>
</tr>
<tr>
<td>FT733</td>
<td>m$^3$/h</td>
<td>GN2 return flow rate</td>
</tr>
<tr>
<td>LT523</td>
<td>%</td>
<td>LHe 5K tank fill level</td>
</tr>
<tr>
<td>LT523_LTR</td>
<td>l</td>
<td>LHe 5K tank fill volume</td>
</tr>
<tr>
<td>LT533</td>
<td>%</td>
<td>Valvebox LHe subcooler fill level</td>
</tr>
<tr>
<td>MSLA401</td>
<td>%</td>
<td>Wall 1 LHe level gauge</td>
</tr>
<tr>
<td>MTPA401</td>
<td>mBarG</td>
<td>GN2 return pressure, gauge</td>
</tr>
<tr>
<td>MTPA402</td>
<td>mBar</td>
<td>Wall 1 LN2 delta pressure</td>
</tr>
<tr>
<td>MTPA403</td>
<td>mBar</td>
<td>Wall 1 LHe delta pressure</td>
</tr>
<tr>
<td>MTPA404</td>
<td>mBarG</td>
<td>GHe Return pressure, gauge</td>
</tr>
<tr>
<td>MTPA405</td>
<td>mBar</td>
<td>Wall 2 LN2 delta pressure</td>
</tr>
<tr>
<td>MTPA406</td>
<td>mBar</td>
<td>Wall 2 LHe delta pressure</td>
</tr>
<tr>
<td>MTTB401</td>
<td>K</td>
<td>Wall 1 He temperature, top</td>
</tr>
<tr>
<td>MTTB402</td>
<td>K</td>
<td>Wall 2 He temperature, top</td>
</tr>
<tr>
<td>MTTB403</td>
<td>K</td>
<td>Wall 1 He temperature, bottom</td>
</tr>
<tr>
<td>MTTB404</td>
<td>K</td>
<td>Wall 2 He temperature, bottom</td>
</tr>
<tr>
<td>MTTB405</td>
<td>K</td>
<td>Wall 1 N2 temperature, top</td>
</tr>
<tr>
<td>MTTB406</td>
<td>K</td>
<td>Wall 2 N2 temperature, top</td>
</tr>
<tr>
<td>MTTB407</td>
<td>K</td>
<td>Wall 1 N2 temperature, bottom</td>
</tr>
</tbody>
</table>
## Simulation Setup

Figure 4.19 is a schematic of the cryopump process data validation experiment. Figure 4.19a is the top level structure of the simulation, and each of the main blocks is expanded in Fig. 4.19b, Fig. 4.19c, and Fig. 4.19d. As can be seen in the schematic, in this validation experiment the supply line, return line, and heat exchanger models were simulated concurrently. A “stiff” trapezoidal solver was used in the Simulink environment, because otherwise a very small solver step time would have been necessary, which would result in excessively long simulation times.

For the first test, two and a half hours of pump operation (9000 seconds) was simulated, starting at 8.00am, ending at 10.30am, on February 21st 2012. This period was chosen because it includes three standard pulses, preceded by an aborted pulse. The first aborted pulse is included in the simulation window because it shows that the transient effects of a pulse (e.g. the dip in pump liquid level) are caused by the successful completion of a pulse, rather than some other event associated with it. The simulation was driven by setting the simulated LHe supply valve to track the historical position of the physical valve (CV524), and by setting boundary conditions which were determined from the data. The boundary conditions are summarised in Table 4.12. The boundary conditions were selected because they are time-invariant and valid for the operating mode of interest (see Section 4.1.2). The simulated heat load applied to the pump followed the heat load profile derived in Section 4.2, which is a static base heatload (103.75W), with an additional transient load associated with each pulse (a peak of 30W). The other main parameters of the model are as detailed previously in Section 4.2.

---

Table 4.11.: A list of process data imported into Matlab

<table>
<thead>
<tr>
<th>Sensor Reference</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTTB408</td>
<td>K</td>
<td>Wall 2 N2 temperature, bottom</td>
</tr>
<tr>
<td>PT501</td>
<td>BarA</td>
<td>LHe supply line pressure, absolute</td>
</tr>
<tr>
<td>PT504</td>
<td>BarA</td>
<td>GHe return line pressure, absolute</td>
</tr>
<tr>
<td>TT501</td>
<td>K</td>
<td>LHe supply line temperature</td>
</tr>
<tr>
<td>TT504</td>
<td>K</td>
<td>GHe return line temperature</td>
</tr>
<tr>
<td>TT730</td>
<td>K</td>
<td>NIB8 LN2 return</td>
</tr>
</tbody>
</table>

---

In this context, a boundary condition is a time-invariant variable which defines a static operating point or external constraint for a model.
4.3. VALIDATION

CHAPTER 4. MODELLING

(a) Validation experiment top level

(b) Supply line and valve

(c) Heat exchanger

(d) Return line and valve

Figure 4.19.: A schematic of the cryopump validation experiment
For the second test, another window of two and a half hours was simulated, starting at 1.00pm on the same day, and ending at 3.30pm. This period also includes three standard pulses. As before, the simulation was driven by setting the simulated LHe supply valve position equal to its historical position, and simulating the transient heat load associated with each pulse (a peak of 30W) at the appropriate times. The boundary conditions were the same as those in the first experiment (see Table 4.12).

### Simulation Results

Five of the historical process variables were compared to the prediction made by the simulation: PT501 (supply line pressure), PT504/MTPA404 (return line pressure), CV527 (return valve position), and MSLA401 (phase separator fill level), and LT523LTR (helium tank fill level). These process variables were chosen for the following reasons:

1. The phase separator fill level (MSLA401) was chosen because the liquid fill level is sensitive to changes in both pump heat load in the short term, and to the mass flow rate of cryogenic liquid in the long term. For condition monitoring, the liquid fill level is an important indicator of the pump’s performance and state, and as such, it is important that this part of the simulation model is truly representative. MTPA403 and MTPA406, the liquid wall delta pressures were not included in the validation experiment because the the historical process data is of insufficient granularity, making it unsuitable. In addition to this, the delta pressure is a function of the liquid level. Assuming the simulation model predicts the liquid level well, it can by extension be used to predict the delta pressures, if that information is later desired.

2. The return line pressure (PT504 and MTPA404) is another important indicator of the pump’s performance and state. The pressure is sensitive to both the pump heat load and the return valve position. Together with the return valve position, the

<table>
<thead>
<tr>
<th>Boundary Condition</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium Return Pressure</td>
<td>13.88</td>
<td>PSI</td>
</tr>
<tr>
<td>Helium Supply Pressure</td>
<td>1.088084</td>
<td>BarA</td>
</tr>
<tr>
<td>Helium Supply Temperature</td>
<td>4.23</td>
<td>K</td>
</tr>
<tr>
<td>Steady State Pump Heat Load</td>
<td>103.75</td>
<td>W</td>
</tr>
</tbody>
</table>

Table 4.12.: Boundary conditions for the validation experiments
pressure gives an indication of the outlet mass flow rate, which is very difficult to practically measure in this pump configuration. The return valve position (CV527) is included in the experiment because of this relationship to the pump outlet flow rate, and because the measurement noise is of relatively small magnitude.

3. For similar reasons, the supply line pressure (PT501) is also important. The inlet flow rate to the heat exchanger is a function of the supply line pressure. Unfortunately, there is significant measurement noise present in the historical data which makes it difficult delineate small changes in the supply line pressure. As such, the data can only be used to confirm the general pressure trend. Despite this, the measurement has been used in the validation experiment because no better alternative is available, and this process variable is an important indicator of the pump’s performance.

4. The helium tank fill level has been chosen because it can be used to confirm the helium usage predicted by the model, supporting the validity of the simulated operating condition (i.e. The steady state pump heat load and boundary pressures).

5. All of the temperature gauges listed in Table 4.11 are poorly suited to measuring small changes in temperature, because they have a relatively measurement large range. As such, they can only provide a general indication of temperature to within a few degrees, and this makes them unsuitable for use in this validation experiment.

The results from the first validation experiment are shown in Fig. 4.20. The historical measurements are displayed in blue and the outputs from the simulation are displayed in red. From Fig. 4.20a and Fig. 4.20c it can be seen that both the predicted pump liquid level and return valve position match the historical data well. In both cases, the simulation outputs track the main trend, and the three peaks are close to those seen in the historical data in both duration and magnitude. The error between the predicted and historical data can be reasonably attributed to measurement noise and unmodelled high frequency dynamics that are not important, as they have very little impact on the performance of the pump.

The simulated helium tank fill level is shown in Fig. 4.20e. It can be seen that simulation output matches the historical data well, with the exception of when the refill process starts at $t \approx 2000$. The error during this period is caused by the refill valve controller, which requires some time to settle before reaching a steady refill rate. Only the helium usage of the cryopumps was accounted for in the model, therefore the small errors during
the initial refill period most likely correspond to the helium used elsewhere (e.g. the valvebox subcooler) and to the operation of the valvebox. These errors have a negligible impact on the long term helium usage trend, however, and are therefore acceptable.

One of the main factors that influences the pump liquid level is the LHe pressure at the supply line valve inlet port. For the purpose of this simulation, this is treated as a static boundary condition, because it is not directly measured and no historical data is available. However, if that boundary condition is adjusted periodically during the simulation, then the liquid level will track the historical data more closely. In Fig. 4.20a, the liquid level following this adjustment is shown by the dashed magenta line. It is reasonable to assume that this boundary condition does indeed vary over time, especially as the simulation window covers two and half hours. As such, it would arguably be useful to include a pressure sensor at this location on the physical plant.

The predicted return line pressure is a reasonable fit to the data, with the peaks of increased pressure occurring at the correct times. The magnitude of these salient points is not, however, a perfect fit. As noted, the data for the supply line pressure is masked by significant measurement noise, however the predicted and measured average pressure is matches well.
Figure 4.20.: The results of the first historical data validation experiment
4.3. VALIDATION

Figure 4.20.: The results of the first historical data validation experiment
4.3. VALIDATION CHAPTER 4. MODELLING

Figure 4.20.: The results of the first historical data validation experiment

(e) Helium tank fill volume
In Fig. 4.21 the results from the second validation experiment are shown. As before, the historical measurements are displayed in blue and the outputs from the simulation are displayed in red (and in magenta for the liquid level under the adjusted boundary condition).

Figure 4.21a shows the liquid level gauge measurement over the simulation window. The output from the simulation model matches the historical data well, with features and trends the same in both. Assuming a variable pressure boundary condition, the simulated liquid level (in magenta) better tracks the historical data, further supporting the suggestion that it would be useful to measure this process variable. Similarly, Fig. 4.21c shows that the simulated return valve position follows the historical trend and the peaks occur at the correct times, demonstrating that this aspect of the model represents the physical plant effectively. The high frequency noise seen on the historical return valve position corresponds to small valve movements (around one percent of the total range), which can be reasonably attributed to either measurement noise, or to vibrations in the valve itself coming from the environment.

The simulated helium tank fill volume tracks the historical data similarly to the first experiment, with minor errors aside from the initial refill period starting at \( t \approx 2250 \), for the same reasons as stated above.

The return and supply line pressures for the experiment are shown in Fig. 4.21b and Fig. 4.21d, respectively. As in the first experiment, the output from the simulation model is a reasonable fit to the historical data, as the value of each is close, but a significant level of high frequency noise in both historical measurements masks the low frequency trends.

Both of these experiments support the validity of the model and its use as a surrogate plant. It can be seen in both sets of results above that the outputs of the simulation model track the historical data. This therefore shows that the model is sufficiently representative of the plant to be useful as a platform for demonstrating the usefulness of condition monitoring for this application.
Figure 4.21.: The results of the second historical data validation experiment
4.3. VALIDATION  

CHAPTER 4. MODELLING

Figure 4.21.: The results of the second historical data validation experiment
Figure 4.21.: The results of the second historical data validation experiment
4.4. Summary

In this chapter the development of a novel mathematical model and simulation of a section of the cryogenic pumping system have been described. The model has been validated against historical data, and as such is an accurate mathematical representation of the cryopumping system. This model was created in order that it can be used as a surrogate plant for the design procedure described in the following chapter. It is the first mathematical model of the cryopumping system to have been published.

In the first section of this chapter an overview and justification of the model are provided. The helium loop running from the helium tank to the return distribution network was chosen, and it was analysed by splitting it into storage and resistive components.

In the second section the detail and derivation of the model are presented. A first principles analysis was used to develop a model based on the physical properties of the plant described in Chapter 3. The heat exchanger component was the most complicated, but provides several useful estimates of the plant’s physical state.

In the third section the model is validated using both a heuristic analysis and a comparison to historical data. From the heuristic analysis it was found that the output of the models fit what would be expected in the real plant well. From the historical process data analysis, it was shown that several important estimates of process variables produced by the simulation match the historical data well.

In the next chapter this model is used as a substitute for the physical plant during the design process.
5. Design of the Condition Monitoring Scheme

5.1. Design Overview

This chapter concerns the design of the condition monitoring scheme. In the first section the structure of the scheme and the operation of the scheme are explained, followed by a summary of the design methodology used to create it. The subsequent sections then go through each step of the design procedure in detail.

In the literature review (Chapter 2), three main categories of condition monitoring and fault detection schemes were discussed: quantitative model based schemes, qualitative model based schemes, and process history based schemes. The advantages of quantitative model based schemes were listed. Namely, the clear link between physical faults and the outputs of a scheme, fault isolability, quick detection and diagnosis, and the ability to design for robustness to model/measurement uncertainty\[56\][59]. Given these advantages and the availability of detailed design information for the plant, this type of scheme is well suited for this application. However, the large amount of available historical process data would indicate that a process history based scheme might also be suitable. As such, the development of the scheme followed a hybrid approach which is explained below. The aim was to produce a scheme that fits the generic schematic shown in Fig. 5.1.

![Figure 5.1.](image.png)

Figure 5.1.: The generic schematic for a residual generation FDI scheme
Quantitative model based condition monitoring schemes use a numerical model to predict a plant’s behaviour. This prediction is compared to measurements taken from the plant. Discrepancies between the predicted and observed behaviour are indicative of an abnormal condition or fault. This difference is called a residual. The residual, or combination of residuals, are then evaluated using predetermined decision logic and, typically, a signal processing tool (e.g. a low-pass filter, windowed Fourier transform, RMS calculator, etc.). The objective of evaluating the residual signal(s) is to transform it into useful diagnostic information about the plant, in a way which is accessible to the plant operator.

There are, however, two sources of error in the residual which have to be managed: measurement noise, where the measurement taken from a plant is in some way inaccurate, and process noise, where the model of the plant is not genuinely representative of the plant in a fault-free state. Many condition monitoring schemes employ techniques developed specifically to minimise the impact of these sources of error. For this design, a bank a Kalman filters was used to generate residuals in order to mitigate these sources of error.

The Condition Monitoring Scheme Components

![Figure 5.2.: The main components of the condition monitoring scheme](image-url)
5.1. DESIGN OVERVIEW

Figure 5.2 is an illustration of the main components of the condition monitoring scheme designed in this chapter. It shows the flow of information and main processing stages, going from left to right. On the left the cryopumping system is represented (for this design a non-linear simulation model is used as a surrogate plant - see Chapter 4). Data collected from the plant is passed to a bank of Kalman filters. This bank acts as a residual generator. The Kalman filter bank estimates the plant measurements in a fault free state. The difference between the measurements and estimates (the residual) are passed to the middle block: the residual processing block.

The residual processing block represents the detection logic used to determine if the residuals generated by the Kalman filter bank are indicative of a fault. As noted in the previous subsection, process noise and modelling errors will typically cause some degree of inaccuracy in a Kalman filter estimate, therefore a non-zero residual is to be expected, even in the absence of a fault. As such, the detection logic implemented for this design uses thresholds to determine if the residuals are sufficiently large as to be reasonably attributed to a fault. When a residual signal is large enough to cross a threshold, that threshold is flagged, and remains flagged until it is reset by an end user.

The third block (on the right of Fig. 5.2) represents the fault isolation logic. The purpose of the isolation block is to help identify what fault (or set of faults) has occurred, once it has been detected by the residual processing block. When a fault occurs, the residual processing block passes the status of all the threshold flags to this block. The combination of threshold flags can be used to isolate a set of faults (or, ideally, an individual fault), because different faults affect the plant in their own particular way. The faults therefore have a unique manifestation in the residual signals and the detection thresholds are flagged accordingly. This is known as a fault signature. For example, in a cold storage tank system, a leak might cause a drop in fluid level which would flag a threshold associated with a level gauge, but a thermal fault might flag a threshold associated with a temperature gauge. In this case, examination of the residual flags would allow the one fault to be differentiated from the other. For the design presented in this chapter, a fault matrix which lists the combination of flags for each identified fault was created, and the isolation block compares each fault signature with this matrix to isolate faults.

The computer terminal on the right of the illustration represents the final part of the design: the user interface. A simple Graphical User Interface (GUI) was designed and implemented in Matlab, which presents the output of the fault isolation stage in an easy to interpret manner. When the isolation block matches the fault signature to a set of
faults, the candidate faults are presented to the end user in order of their likelihood, together with a written description.

The charts below (Fig. 5.3 through Fig. 5.7) demonstrate each stage of the data processing performed by the scheme, via a simplified example version of the scheme created to illustrate the procedure. It uses a single residual to detect and isolate a fault.\(^1\)

![Figure 5.3: An example output measurement](image)

The first chart, Fig. 5.3, is a demonstration of the first step of the data processing procedure. It is an output measurement taken from the example plant; in this case a temperature measurement. This, together with all corresponding input measurements (not depicted here), are passed to the Kalman filter bank. In this example, a fault occurs one hundred seconds into the simulation, causing the temperature to drop.

Figure 5.4 illustrates how a residual is formed in the Kalman filter bank. The red line is the estimate of the temperature measurement produced by the Kalman filter. In blue is the actual measurement. The difference between the measurement and the estimate is the residual. After the fault is simulated (at \(t = 100\)), the difference between the measurement and estimate grows.

The processed residual itself is presented in Fig. 5.5, in blue. The residual has been passed from the Kalman filter to the residual processing block, where it was low-pass

\(^1\)Multiple residuals are common in fault detection schemes, including the one presented later in this chapter, but a single residual scheme provides a simpler, more concise demonstration of the concept.
Figure 5.4.: An example estimate (red) and measurement (blue)

Figure 5.5.: An example residual (blue) and detection thresholds (red)
filtered (to attenuate the high frequency noise seen in the previous charts), and compared to an upper and lower detection threshold, displayed in red. It can be seen that the processed residual crosses the lower threshold at around $t = 110$.

Figure 5.6.: An example flag status

(a) Upper threshold flag status

(b) Lower threshold flag status
5.1. DESIGN OVERVIEW

The two charts, Fig. 5.6a and Fig. 5.6b, represent the flag status for the upper and lower detection thresholds. The upper flag is zero, as the threshold has not been crossed, and the lower flag at unity, following the crossing at \( t = 40 \). The flag remains at unity, even if the residual crosses back over the threshold, until it is reset by the end user.

![Upper Lower Result Table](image)

Figure 5.7.: An example isolation matrix

Figure 5.7 is an illustration of a fault isolation matrix, and as such represents the penultimate processing stage. As the lower threshold alone has been flagged, the fault indexed by the second row is isolated. Although in this example the fault has a unique signature, the uniqueness is not a requirement, although it is desirable. If more than one faults share a signature, then the isolation matrix will isolate them as a set.

![End User Interface](image)

Figure 5.8.: The end user interface

The end user interface is presented in Fig. 5.8. The interface displays which fault, or set of faults, has been isolated, together with some descriptive information prepared in advance when the isolation matrix was compiled. The exact form of the end user interface will ultimately depend on the software with which it is implemented, but this example GUI (prepared in Matlab) contains the important information that should be displayed: a description of the fault and its relative likelihood (based an a-priori analysis)
if it is one of a set.

The Design Procedure

Figure 5.9 shows the four main steps in the design process for this scheme. This is a model based design process. The non-linear simulation model presented in Chapter 4 was used as a substitute for the physical plant for all stages of the design. This had two important advantages: Firstly, the ability to rapidly simulate the operation of the plant and condition monitoring scheme, which reduced the development time significantly. Secondly, it allowed experiments to be carried out without disrupting the operation of the plant, which was not permitted owing to the busy operational schedule.

![Design Procedure Diagram]

The first step was to generate a set of linear working models of the plant. The purpose of these working models was to provide the basis of the Kalman filter bank, as they were representative of the plant in a fault-free state. These linear working models were generated using a set of system identification techniques, which estimated the working models using data produced by the non-linear simulation model. The second step was to generate the Kalman filter bank using the working models and knowledge of the anticipated measurement and process noise. The third step was to design the residual evaluation scheme. A bank of low-pass filters was designed, with one filter per residual signal. Thresholds for the processed residuals were selected, and an isolation matrix
was designed. The final step was to carry out a model based experiment to test the effectiveness of the scheme. This is a larger topic however, and as such is dealt with separately in Chapter 6. The following sections describe each of the first three steps in detail.

5.2. System Identification

System identification is the name given to the set of statistical techniques used to generate a mathematical model of a system or plant, given a set of historical data. In the context of this design process, the “plant” is the non-linear simulation model derived in the previous chapter, and the “historical data” is a data set produced using a Matlab/Simulink simulation of the non-linear model. The objective of this step was to obtain a set of single-input single-output (SISO) working models which relate each input process variable to each output process variable. These working models are used to design the Kalman filter bank in the next step. SISO models were selected over multiple-input multiple-output (MIMO) models because they allow the design process to be iterated if an additional process variable is to be included in the design at a later date, without having to go back and re-identify or modify models which have already been found. This makes the condition monitoring scheme easier to extend and more generally applicable should the NBHS instrumentation be extended in the future.

Figure 5.10 is an illustration of the relationship between a MIMO system and the proposed SISO (working) models. In this example a 3-input, 3-output system is split into nine SISO models. Assuming an approximate linear relationship between the SISO models, their outputs can be summed to recreate the outputs of the original MIMO system.

Table 5.1 lists the input and output variables for each of the SISO model sets. Both transmission lines are 3-input 3-output systems, therefore nine SISO models were generated. The heat exchanger is a 3-input 4-output system, therefore twelve SISO models were generated. For the entire system thirty SISO models were generated.

The inputs and outputs listed in Table 5.1 were chosen because they fully describe all of the important process variables of the cryopump and they are all physically measurable.
Figure 5.10.: An illustration of the relationship between the MIMO and SISO models
5.2. SYSTEM IDENTIFICATION

5. DESIGN

Input Variable | Units | Output Variable | Units
--- | --- | --- | ---
Inlet flow rate | kg/s | Outlet flow rate | kg/s
Termination pressure | Pa | Line pressure | Pa
Inlet temperature | K | Line temperature | K

(a) Supply line variables

Input Variable | Units | Output Variable | Units
--- | --- | --- | ---
Inlet flow rate | kg/s | Outlet flow rate | kg/s
Valve position | % | Line pressure | Pa
Inlet temperature | K | Line temperature | K

(b) Return line variables

Input Variable | Units | Output Variable | Units
--- | --- | --- | ---
Pump Heat Load | W | Pump fill level | %
Inlet temperature | K | Pump pressure | Pa
| | | Fluid/vapour mix temperature | K

(c) Heat exchanger variables

Table 5.1.: The input and output variables for each model set

The system identification process

There are five steps in a system identification process[99]:

1. Collect a set of suitable process data from the plant, which correspond to the operating mode/point of interest.
2. Prepare the data. This should include removing trends and possibly filtering to minimise noise. Consider splitting the data set in half, and saving one half of it for the final testing step, or alternatively collect a second set of data for the same purpose.
3. Select a model type (e.g. ARX, ARMAX, Box-Jenkins etc.) and model order.
4. Use an identification algorithm/technique to find the model which best fits the data, for this structure.
5. Test the newly identified model by comparing its response to a new set of input-output data. If the model is not suitable for its intended purpose, repeat the process.

How each of the steps was carried out in this research is described below, but first it is instructive to discuss the specific system identification techniques that were used.
5.2. System Identification Techniques

In this research two different system identification techniques were used in parallel: the least squares method, and the instrumental variable method. Both of these techniques were used to identify linear models which fit the following structure:

\[ y(k) = G(k)u(k) + H(k)e(k) \]  

(5.1)

Here, \( q^{-1} \) is the discrete time backwards shift operator. \( G(k) \) and \( H(k) \) are discrete time transfer functions which describe the response of the model to sampled input and noise signals.

A simple way of representing the parameters of Eq. (5.1) is to use an autoregressive with exogenous input (ARX) model structure. An ARX model is a straightforward discrete time linear difference equation, as shown in Eq. (5.2).

\[ y(k) = b_0 u(k) + b_1 u(k - 1) + \ldots + b_m u(k - m) \right. \\
\left. - a_1 y(k - 1) - a_2 y(k - 2) - \ldots - a_n y(k - n) + e(k) \right. \\
= \sum_{i=0}^{m} b_i u(k - i) - \sum_{j=1}^{n} a_j y(k - j) + e(k) \]  

(5.2)

There are several variations of the standard ARX model: output-error (OE) models, autoregressive moving average exogenous inputs (ARMAX) models, finite impulse response (FIR) models, and Box-Jenkins (BJ) models. The main feature that sets these apart from ARX models is that they characterise noise and disturbance within the model independently of the model dynamics. These model types are discussed in detail in [100].
and [99], but are not considered further here. The models identified during this research were used to design Kalman filters, and all the necessary information for that purpose is contained within an ARX model structure. While a model structure which allows the noise term to be characterised independently (e.g. ARMAX) is useful in many applications, and here may potentially represent the system more faithfully, the additional model terms would not be used further in the design process. For this application it is preferable to account for process/measurement noise during the design of the Kalman filters (using the Q and R matrices). It is indeed possible to determine the optimal Kalman gain from a noise characterisation matrix (or matrices) of the sort produced by an ARMAX or Box-Jenkins (etc.) model, because as shown in [101], there is an equivalence between Kalman filters and ARMAX (etc.) models. But to do so would be to lose the ability to tune the Kalman filter for an arbitrary level of noise, which has been judged to be an important part of the design process.

![Figure 5.12.: The ARX model structure](image)

Figure 5.12.: The ARX model structure

The unknown parameters in the ARX model are denoted by $\theta$.

$$\theta = [b_1 \; b_2 \ldots \; b_m \; a_1 \; a_2 \ldots \; a_n]^T$$  \hspace{1cm} (5.3)

And together, the $a$ and $b$ coefficients can be grouped as:

$$A(k) = 1 + a_1(k-1) + \ldots + a_n(k-n)$$

$$B(k) = b_1(k-1) + \ldots + b_m(k-m)$$  \hspace{1cm} (5.4)

Figure 5.12 is a graphical illustration of the ARX model structure. From this, it can be seen that, in an ARX model:
5.2. SYSTEM IDENTIFICATION

\[ G(k, \theta) = \frac{B(k)}{A(k)} \quad H(k, \theta) = \frac{1}{A(k)} \]  (5.5)

Assuming an ARX model structure, the one-sample-ahead prediction for Eq. (5.1) is given by:

\[ \hat{y}(k|\theta) = B(k)u(k) + [1 - A(k)]y(k) \]  (5.6)

This can be rewritten as:

\[ \hat{y}(k|\theta) = \theta^T \varphi(k) = \varphi^T(k)\theta \]  (5.7)

Where:

\[ \varphi(k) = [-y(k-1) \ldots - y(k-n) \ u(k-1) \ldots u(k-m)]^T \]  (5.8)

Equation (5.8) is known as the regression vector and Eq. (5.7) is known as the linear regression model.

Least Squares

Least squares, specifically ordinary/linear least squares, is a widely used technique for fitting the parameters of a linear regression model to a given data set. The general approach of this technique is to minimise the squared error of the regression model[102].

From Eq. (5.7), the prediction error is given by:

\[ \epsilon(k, \theta) = y(k) - \varphi^T(k)\theta \]  (5.9)

Given a set of sampled data \( Z \), with \( N \) samples, the least squares criterion for the ARX model predictor is:

\[ V_N(\theta, Z^N) = \frac{1}{N} \sum_{k=1}^{N} \frac{1}{2} [y(k) - \varphi^T(k)\theta]^2 \]  (5.10)
Assuming the requisite inverse can be found, Eq. (5.10) can be minimised analytically:

\[
\hat{\theta}_{LS}^N = \arg \min_{\theta} V_N(\theta, Z^N) = \left[ \frac{1}{N} \sum_{k=1}^{N} \varphi(k)\varphi(k)^T \right]^{-1} \left[ \frac{1}{N} \sum_{k=1}^{N} \varphi(k)y(k) \right]
\] (5.11)

**Instrumental Variables**

System identification is a data driven technique, and as such, it requires good quality data to be effective. A chief weakness associated with system identification is that, in practice, the identification process relies on a finite set of data, which is in many cases affected by noise. An ARX model identified using a poor (e.g., noisy) data set may not be representative of the underlying process of interest. Rather, it may be a false model, peculiar to that specific set of data; a model bearing the signature of a transitory period of noise, which is ultimately not useful. The instrumental variable method is an extension of the least squares method which is designed to improve the estimate, taking into consideration the effect of noisy data.

The linear regression model (Eq. (5.7)) can be extended to include a noise term, \(v_o(k)\):

\[
\hat{y}(k|\theta) = \varphi^T(k)\theta + v_o(k)
\] (5.12)

With this extension, the prediction error \(\epsilon(t, \theta)\) given by Eq. (5.9) can in part be attributed to the noise term. As such, the prediction error for a given ARX model would now ideally be independent of the regression vector. If the prediction errors generated by several different data sets were correlated, then that would imply that there is information about the process which is not captured by the \(\theta\) parameters.

In the case of a standard least squares estimate which uses a single data set, any correlation between the regression vector \(\varphi^T(k)\) and the noise term \(v_o(k)\) would result in the estimate of the \(\theta\) parameters not tending toward their true value.

In the instrumental variables method, a new vector \(\zeta\) is defined. \(\zeta\) is known as the correlation vector. The elements of \(\zeta\) are known as the instruments. If the correlation vector \(\zeta\) is equal to the regression vector \(\varphi(k)\), then it is uncorrelated with the prediction error, such that:
\[ E\zeta(k)v_0(k) = 0 \]  
(5.13)

And given this a better estimate can be found:

\[
\hat{\theta}_N^{IV} = \text{sol} \left[ \frac{1}{N} \sum_{k=1}^{N} \zeta(k) \left[ y(k) - \varphi^T(k)\hat{\theta} \right] = 0 \right] 
\]
(5.14)

\[
= \left[ \frac{1}{N} \sum_{k=1}^{N} \zeta(k)\varphi^T \right]^{-1} \frac{1}{N} \sum_{k=1}^{N} \zeta(k)y(k)
\]

The challenge therefore lies in selecting the elements of the correlation vector (the instruments). A straightforward choice for the instruments is to match them to the discrete ARX difference equation, as in Eq. (5.2). They can be found using the standard least squares estimation method, among others, or selected manually based on some understanding of the system itself.

**State Space Representation**

Every discrete time linear ARX model can also be expressed in a standard discrete time state space format. The model order is the number of delayed states in the model.

\[
x(k + 1) = A(k)x(k) + B(k)u(k) \\
y(k) = C(k)x(k) + D(k)u(k) + e(k)
\]  
(5.15)

Here, \( x(k) \) is the system state vector. \( u(k) \) and \( y(k) \) are the input and output vectors, respectively. The \( A(k) \) and \( B(k) \) matrices are the state and input matrices, which are determine the rate of change of the state vector. \( C(k) \) and \( D(k) \) are the output and feed-forward matrices, which describe the output of the system in relation to the state vector and input vector (where the \( D(k) \) matrix is non-zero).
5.2. System Identification Procedure

At the start of Section 5.2 a five step system identification process was summarised. This section describes how each of these steps were followed. A graphical summary of the entire identification procedure is presented in Fig. 5.13.

Data Collection

The very first thing to do when collecting a data set for system identification is to choose what process variables are going to be measured, and which of those variables are to be treated as inputs and outputs. In this research, it was straightforward to discriminate between the inputs and outputs, because the physical relationship was clear. Table 5.1 lists the input-output variables that were recorded.

The second activity was to design a suitable set of data collection experiments. As noted previously, the non-linear simulation model was used as a surrogate plant in this research, and as such, this allowed a great deal of flexibility in the design of these experiments. For the collected data to be suitable for system identification, two key criteria must be fulfilled: The data must be sampled at sufficiently high (monotonic) rate to capture any high frequency dynamics of interest, and the experiment must be designed such that the plant is sufficiently excited. In the literature, there has been a significant amount of analysis as to what constitutes a sufficiently exciting input signal (much of which is discussed in [99] and [103]), however the key point is that the frequency spectrum of the input signal must cover all the frequencies of interest to the experiment designed, with sufficient input power. For example, if a model is supposed to represent the response of a plant to a sinusoidal input signal varying between 10Hz and 1kHz, then a “chirp” signal with the same upper and lower frequency spectrum bounds may be appropriate.

A chirp signal is periodic sinusoidal signal with a frequency that sweeps across a given band. It is defined mathematically by:

\[ u(k) = A \sin((ak + b)k) \quad 0 \leq k < K_0 \]  

(5.16)

Where \( K_0 \) is the period of the sweep, \( a = \pi(k_2 - k_1)f_0^2 \), \( b = 2\pi k_1 f_0 \), \( f_0 = 1/K_0 \), and where \( k_1 f_0 \) and \( k_2 f_0 \) are the lower and upper frequency bounds.
5.2. SYSTEM IDENTIFICATION

CHAPTER 5. DESIGN

Select a suitable input signal

Design and build an appropriate Simulink experiment

Run the simulation to collect a new data set

Remove linear trends from the data

Divide the data into identification and validation subsets

Select a model order to try

Identify two ARX model using the “ARX” and “IV4” methods

Use the “compare” method to validate the models

Is either model a good fit?

No

Yes

Pick the model with the best fit

Figure 5.13.: A flow chart of the system identification procedure
The crest factor of a signal is a measure of its peak to average power ratio. For a signal $u(t)$, it is defined by:

$$C(u) = \max \lim_{N \to \infty} \frac{1}{N} \sum_{k=1}^{N} u^2(k)$$

(5.17)

An ideal input signal for (linear) system identification has a crest factor of one, although this is not always achievable. Signals with a higher crest factor inject less power into the plant than those with an equal peak power and lower crest factor.

A pseudo random binary signal (PRBS) is a signal that switches in a random stepwise fashion between two levels, -1 and +1. Practically, binary signals of this type are predetermined and repeated periodically, hence why it is referred to as “pseudo random”. A PRBS signal has two important properties: It has a crest factor of one, and it has frequency components that decrease in inverse proportion to its frequency. As such, this type of signal is useful for system identification. A rule of thumb for choosing a clock frequency for a PRBS generator is to select $f_c = 2.5 f_{max}$, where $f_{max}$ is the maximum frequency of interest (see [103] pp. 157).

In this research, the non-linear simulation models were driven by amplitude modulated pseudo random binary signals, also known as a random walk. Figure 5.14 is an example of such a signal, and Fig. 5.15 shows how the signals were generated in Simulink.

The PRBS was amplitude modulated because of the non-linear properties of the simulation model. Driving the simulation models with an input signal of constant amplitude would not have revealed any non-linearity with respect to the input amplitude. Although the non-linearities could not be entirely captured in a linear model, including the non-linear effects in the data set used for identification does result in a better (i.e. more representative) model. The increased the crest factor is justified for this reason.

The output and input signals were sampled at 50Hz; a rate consistent with what could be achieved in hardware on a physical plant. The frequency response of the three main plant components are shown in Fig. 5.16, Fig. 5.17, and Fig. 5.18. These responses were obtained using the Simulink frequency response estimation tool (using the sinestream method)[104]. From these charts it can be seen that the response of each input/output pair above 10rad/s (1.6 Hz) is significantly attenuated, therefore a 50Hz sample rate is high enough rate to capture the important dynamics of the plant.
Figure 5.14.: An example AMPRBS, or binary walk

(a) An AMPRBS generator in Simulink

(b) Scaling an AMPRS in Simulink

Figure 5.15.: An AMPRBS generated in Simulink
Figure 5.16.: Open loop frequency response of the supply line
Figure 5.17.: Open loop frequency response of the return line
Figure 5.18.: Open loop frequency response of the heat exchanger
5.2. SYSTEM IDENTIFICATION

Figure 5.19 is an example of one set of input-output data. It can be seen that for this experiment, one of the three inputs to the non-linear simulation was varied, while the others were held constant. The outputs therefore corresponds to the change in that particular input alone. The subsequent experiments varied each of the other inputs one by one (holding the others constant), such that the affect of each input on the plant can be identified individually. This procedure was repeated for each of the three non-linear simulation models. One data set for each input-output pair in Table 5.1 was collected.

Depending on the process variable in question, there is a certain degree of measurement noise picked up by the instrumentation on the physical plant. One of the objectives of any condition monitoring scheme should be to minimise (or ideally eliminate) false alarms raised as a consequence of this noise. As such, measurement noise was added to each output signal, with a variance consistent with what could be achieved the physical plant (subject to the reworking of certain sensor hardware - see Section 7.2). Figure 5.20 is an example illustration showing how and where measurement noise was added to each simulation. The variance of the noise superimposed on the output variables is listed in

<table>
<thead>
<tr>
<th>Variable</th>
<th>Standard Deviation</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return line flow rate</td>
<td>$1 \times 10^{-4}$</td>
<td>kgs$^{-1}$</td>
</tr>
<tr>
<td>Return line temperature</td>
<td>$1 \times 10^{-2}$</td>
<td>K</td>
</tr>
<tr>
<td>Return line pressure</td>
<td>100</td>
<td>Pa</td>
</tr>
<tr>
<td>Supply line flow rate</td>
<td>$1 \times 10^{-4}$</td>
<td>kgs$^{-1}$</td>
</tr>
<tr>
<td>Supply line temperature</td>
<td>$1 \times 10^{-2}$</td>
<td>K</td>
</tr>
<tr>
<td>Supply line pressure</td>
<td>100</td>
<td>Pa</td>
</tr>
<tr>
<td>Heat exchanger flow rate</td>
<td>$1 \times 10^{-4}$</td>
<td>kgs$^{-1}$</td>
</tr>
<tr>
<td>Heat exchanger line temperature</td>
<td>$1 \times 10^{-2}$</td>
<td>K</td>
</tr>
<tr>
<td>Heat exchanger line pressure</td>
<td>100</td>
<td>Pa</td>
</tr>
<tr>
<td>Heat exchanger fluid level</td>
<td>0.1</td>
<td>%</td>
</tr>
</tbody>
</table>

Table 5.2.: A list of measurement noise standard deviation

Data Preparation

Two subsets of data for each input-output relation were required for the following steps of the identification process. One subset was used to identify the models, and the other
Figure 5.19.: Example input-output data, heat exchanger with variable inlet flow rate
Figure 5.20.: The addition of measurement noise to the system identification simulations subset was used to test the models. The simplest way to arrive at these two subsets was to split the data collected in the previous step in two.

It was also necessary to remove any trends from the data (sub)sets. For the majority of the data collected during this research, this only involved removing the average value for each signal.

\[
\hat{y}(t) = y(t) - \frac{1}{N} \int_{t=0}^{N} y(t) dt
\]  

(5.18)

There were, however, two exceptions where this was not suitable. The “pump heat load” input signal to the non-linear heat exchanger model (see Table 5.1) was prepared by removing the DC pump heat load (103.75W, as described in Section 4.2.1 and Section 4.2.2) which, because a series of pulses of increased heat load was simulated, was not the same as the average value. In addition to this, the output signals corresponding to this particular experiment were prepared by removing their initial value rather than the mean, for the same reason.

---

\textsuperscript{2}This was achieved using the Matlab “detrend” function, which actually removes the best straight line fit to the data, which is found using least squares. For the data used in this research, the result is functionally the same as the result of Eq. (5.18)
In other scenarios, it may be advantageous to carry out other data preparation steps. Common steps include removing outlier or non-informative data points, low-pass filtering to remove high frequency measurement noise or disturbances, and offsetting drifts. For the data collected in this research, these steps were not necessary.

**Model Structure and Order Selection**

In Section 5.2.1 the merits of using an ARX model structure for this application were discussed. The models that were identified in this structure proved to be suitably representative (as can be seen in the next section), so there was no compelling reason to select a different structure.

The order of the $A(k)$ and $B(k)$ polynomials was found by trial and error, using the Matlab ARX function, as described below. An input-output delay ($k$) of one sample was assumed. In most cases it was found that two $A(k)$ and $B(k)$ parameters were suitable, and good representative models of this order could be identified. Table 5.3 is a list of the polynomial orders for each model.

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
<th>Order of $A(k)$</th>
<th>Order of $B(k)$</th>
<th>Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heat Exchanger:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>Outlet flow rate</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Gas pressure</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Outlet temperature</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Fluid level</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Inlet flow rate</td>
<td>Outlet flow rate</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Gas pressure</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Outlet temperature</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Fluid level</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Heat load</td>
<td>Outlet flow rate</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Gas pressure</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Outlet temperature</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Fluid level</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td><strong>Supply Line:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>Outlet flow rate</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Fluid pressure</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Outlet temperature</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
5.2. **SYSTEM IDENTIFICATION**

### CHAPTER 5. **DESIGN**

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
<th>Order of $A(k)$</th>
<th>Order of $B(k)$</th>
<th>Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet flow rate</td>
<td>Outlet flow rate</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Fluid pressure</td>
<td>Outlet flow rate</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Outlet temperature</td>
<td>Outlet flow rate</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Termination pressure</td>
<td>Outlet flow rate</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Fluid pressure</td>
<td>Outlet flow rate</td>
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<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Outlet temperature</td>
<td>Outlet flow rate</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

**Return Line:**

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
<th>Order of $A(k)$</th>
<th>Order of $B(k)$</th>
<th>Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet temperature</td>
<td>Outlet flow rate</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Gas pressure</td>
<td>Outlet flow rate</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Outlet temperature</td>
<td>Outlet flow rate</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Inlet flow rate</td>
<td>Outlet flow rate</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Gas pressure</td>
<td>Outlet flow rate</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Outlet temperature</td>
<td>Outlet flow rate</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Valve position</td>
<td>Outlet flow rate</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Gas pressure</td>
<td>Outlet flow rate</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Outlet temperature</td>
<td>Outlet flow rate</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 5.3.:** Table of model orders

### Identifying and Testing the Models

For each input-output data set, both the least squares and instrumental variables techniques were used, and two models were identified. In Matlab the **ARX** and **IV4** functions are associated with these techniques. These functions were used to identify the models for each set of input-output data.

The **ARX** function solves the least squares minimisation problem in Eq. (5.11) using QR decomposition (see [105], section 2.1). The output of this function is a discrete time **idpoly** object. An **idpoly** object contains the $A(k)$ and $B(k)$ polynomial coefficients, the variance of the noise source $e(t)$, the model sample rate, and other descriptive information\(^3\). One useful feature of this object type is that it has an associated method which translates the identified model into discrete time state space format.

\(^3\)Matlab uses **idpoly** objects to represent identified models with a range of different structures (e.g. ARMAX, Box-Jenkins etc.), so there are data elements which are unused in the case of an ARX model (e.g. a $C(k)$ polynomial that is normally associated with an ARMAX model).
The \texttt{IV4} function solves the instrumental variables problem described in 5.2.1 in four stages. Initially, the \texttt{ARX} function is called to generate a vector of instruments ($\zeta$). The residuals generated by this model are treated as an AR model, and this is used to filter the input-output data, which is again passed to the IV function. A similar function, IVX, works in a similar fashion, but with a user-defined initial vector of instruments. In both cases, the output is an \texttt{idpoly} object, as with the \texttt{ARX} function[104].

As noted above, the data collected for each input-output relation was split in two, in order to provide a subset of data which can be used to validate the models. The \texttt{compare} function in Matlab was used to validate the models with this data. The \texttt{compare} function uses the input portion of the validation data to drive a model. It plots the response of the model and the output portion of the data in a figure, on the same axis. It also provides a normalised measure of the quality of fit, as a percentage, calculated by:

$$\text{Fit} = 100 \ast \frac{1 - \|y_h y\|}{\|y - \tilde{y}\|}$$

(5.19)

Where $y$ is the measured output, $y_h$ is the output of the model when driven by the measured input, and $\|y\|$ is the matrix/vector norm of $y$.

The tables in Appendix D list the best fitting $A(k)$ and $B(k)$ coefficients that were found for each model, together with the normalised RMS measure of the fit. Figure 5.21 was produced by the \texttt{compare} function, and is graphical demonstration of the quality of the fit for one particular model$^4$.

A final check was carried out by comparing the response of all the linear models, simulated together in one experiment, with the response of the surrogate plant. Both the plant and the linear model sets were driven by realistic inputs (i.e. with all the inputs varying with time, in a way that would be expected on the physical plant) and their outputs tested for consistency. At the end of the procedure the linear model set was confirmed as being suitable for the design of the Kalman filter bank, described below.

\footnote{A model with a relatively poor fit was chosen here, to make it easier to discriminate between the three responses. The fits for the actual design are better. See Appendix D.}
Figure 5.21.: Comparison of a measured output and the models’ time response
5.3. Kalman Filtering

The next stage of the design process is to design a bank of Kalman filters, based on the linear working models found in the previous section. Figure 5.22 is a graphical representation of the structure of a Kalman filter bank, using the example of the liquid supply line.

![Figure 5.22: A three element Kalman filter bank - Supply Line](image)

Before proceeding, it is informative to review the operation of a Kalman filter.

5.3.1. The Kalman Filter

A Kalman filter is an optimal state estimator. It is typically used to estimate the state of a system or process from time series measurements, which have been affected by noise. The Kalman filter is well described in [106], and is summarised below.

Many processes can be approximated by the following discrete time linear difference equation, which is similar to the well known state space structure.

\[
x(k) = A(k)x(k - 1) + B(k)u(k - 1) + w(k - 1) \\
z(k) = H(k)x(k) + v(k)
\]  \hspace{1cm} (5.20)
5.3. KALMAN FILTERING  

Here $A(k)$, $B(k)$, and $H(k)$ are the state, input, and output matrices, respectively. The $w$ and $v$ terms correspond to process and measurement noise, which are assumed to be Gaussian and non-coloured. The state vector is $x(k)$, and the measurement vector is $z(k)$. The index $k$ refers to the sample number.

The matrices $Q$ and $R$ describe the process and measurement noise covariance, respectively. Adjusting these two covariance matrices are the main way a designer can tune the response of the Kalman filter, for a process defined in Eq. (5.20).

\[
p(w) \equiv N(0, Q) \\
p(v) \equiv N(0, R)
\]  

The discrete time Kalman filter uses a two stage process to estimate the state of a system. In the first stage a prediction is made about the state of the system in advance. This is the “a priori” state estimate. In the second stage this estimate is corrected using a current measurement. This is the “a posteriori” state estimate.

The “a priori” and “a posteriori” estimate errors are, respectively, $e^{-k}$ and $e_k$, as defined below.

\[
e^{-k} \equiv x_k - \hat{x}_k \\
e_k \equiv x_k - \hat{x}_k 
\]

The corresponding error covariances are:

\[
P^{-k} = E[e^{-k}e^{-k\,T}] \\
P_k = E[e_ke_k^T]
\]

As noted, the “a posteriori” state estimate is a function of the predicted state and measurements from the plant. This is shown below. $K$ is the Kalman gain matrix.

\[
\hat{x}_k = \hat{x}_k^- + K(z_k - H\hat{x}_k^-)
\]
The Kalman gain matrix is calculated using the equation below. The derivation of this is described in depth in [106].

\[ K_k = P_k^{-1} H^T (H P_k^{-1} H^T + R)^{-1} \]
\[ = \frac{P_k^{-1} H^T}{H P_k^{-1} H^T + R} \]  

(5.25)

The error covariance matrices are calculated by:

\[ P_k^- = A P_{k-1} A^T + Q \]
\[ P_k = (I - K_k H) P_k^- \]  

(5.26)

Assuming the \( Q \) and \( R \) matrices remain invariant over time, the Kalman gain matrix can be calculated in advance, as it will converge deterministically on a certain value. For this application however, the Kalman gain matrix is recalculated as the residual generator bank runs.

### 5.3.2. Kalman Filter Bank Design

The Kalman filter bank is made up of a series of multiple-input single-output (MISO) filters, generated from the SISO models identified in Section 5.2. To build the MISO filters, the \( A \) and \( B \) matrices of the SISO models are arranged in a diagonal structure. The \( C \) matrices are concatenated. For each SISO model \( Q \) matrices are found (see below) and these are also arranged diagonally. The \( R \) matrix remains singular.

Figure 5.23 is an example showing how a 3-input 1-output MISO filter can be generated from three SISO models. Here, the indexes 1, 2, and 3 refer to the three inputs, and the index ‘a’ refers to the output. In this example, each SISO model is assumed to be second order. It can be seen that the output of the MISO model is the same as the sum of the outputs of the three SISO models. It is important to note, however, that this approach is only valid if there is an approximate linear relationship between the SISO models.

For the models generated for this application, this assumption about linearity is correct, and it was confirmed by comparing the output of the MIMO simulation model to the output of the MISO filters.
Figure 5.23.: An illustration of assembling a MISO filter using SISO models
An important factor in the design of these filters is the selection of the \( Q \) and \( R \) matrices, as these affect the magnitude of the residual produced by each filter. A \( Q \) matrix was found for each individual SISO model, and one \( R \) matrix was found for each output.

Each of the non-linear simulation models (described in the previous chapter) had measurement noise superimposed on their outputs, of a magnitude and power consistent with that observed on historical process data taken from the physical plant. The values of the \( R \) matrices were selected based on the magnitude of this noise. Specifically, the noise variance was estimated by running the non-linear simulation model with all the inputs held constant, and finding the variance of the output signals using Eq. (5.27). Holding the inputs constant allowed the measurement noise to be isolated once the (noise-free) plant outputs reached a steady state.

\[
\text{Var}(x) = \frac{1}{n} \sum_{i=1}^{n} (x - \overline{x})^2
\]  

(5.27)

For the \( Q \) matrices, the values were selected according to how well the linear working models represented the plant (the plant in this case being the non-linear simulation model), which was seen during the system identification stage. Specifically, the Matlab function used in the system identification procedure back calculates the variance of the noise source for each ARX model (see Fig. 5.12), using the error between the historical process data and the model prediction. The system identification procedure was carried out with no simulated process noise, therefore the noise source was directly associated with modelling error, or “process noise” in this context. The following equations show the relationship between this noise source and the \( Q \) matrix.

\[
x(k + 1) = A(k)x(k) + B(k)u(k) + K(k)e(k)
\]

\[
Q = \text{diag}[K(k)e(k)]
\]  

(5.28)

Where \( K(k) \) is taken from the \( A(k) \) parameters of the ARX model.

The values of the \( Q \) and \( R \) matrices found during this design step are presented in Appendix E, along with a full list of the SISO models in Appendix D.
5.4. Residual Evaluation

The purpose of residual evaluation is to take the residual signals produced by the Kalman filter bank, use them to detect faults and provide useful diagnostic information. This requires three stages: filtering, thresholding and evaluation. This is illustrated graphically in Fig. 5.1 and Fig. 5.2.

5.4.1. Filters

The residual signals produced by the filter bank discussed in the previous section are noisy, owing to the high frequency measurement noise. Given that this noise provides no useful information for this application, it was sensible to attenuate it. This was achieved using a FIR low-pass filter for each signal.

The filters were designed to have following specification:

1. Passband frequency - 0.5Hz
2. Stopband frequency - 1Hz
3. Passband ripple - 0.1dB
4. Stopband ripple - 100dB

The cut-off frequency and pass band ripples were selected such that faults affecting the main low frequency dynamics of the plant are still detectable in the residual signal, while high frequency noise is attenuated. The stop band ripple was given a wider tolerance, as the particular degree of attenuation for a given frequency is not especially important, so long as it is attenuated enough to work with the thresholding arrangement described in the next subsection.

The Matlab function `fdesign` was used to design the filters, with the above specifications. This function can use several different methods for designing a filter. In this case the equiripple (Parks-McClellan) method was used to find the optimal Chebyshev filter coefficients for the given specification[107]. This type of filter was used because it allows for steep roll-off after the break frequency, at the expense of a stop-band ripple, which is acceptable for this application. It is also inherently stable (with no feedback), and straightforward to design and implement. This type of filter also preserves the sign of
the residual (i.e. positive or negative), which as will be seen in the following chapter is important for this particular application.

One consideration to make when using such a filter is the phase/group delay imposed on any signal passing through it. Given that the scheme presented here is designed to provide diagnostic information to a human operator, a short delay (in the order of seconds) is acceptable. However, were the diagnostic information to be used in a more time sensitive application, the delay would have to be managed appropriately.

![Bode Diagram](image)

Figure 5.24.: The magnitude (upper) and phase (lower) response of the filters

### 5.4.2. Thresholds and Isolation

A residual signal on its own shows the difference between the measured and estimated condition of a plant. A decision has to be made to determine if the deviation is significant. There are several different approaches that can be taken, of which some examples can be found in the literature review, in Chapter 2. In this design, the instantaneous value of each filtered residual is compared against two thresholds: one positive, one negative. If
a threshold is exceeded, the residual is considered “high” for the purpose of diagnosing faults, and is flagged. Once a residual is flagged, it remains flagged until reset by the end user. A combination of flags constitutes a fault signature.

**Threshold Selection**

To select the thresholds, the non-linear simulation model (the surrogate plant) was run with an input similar to the sort that might be expected on the real plant during normal operation. By inspection, the maximum positive and negative values for each residual were found, and the minimum level for each threshold was defined accordingly.

The charts below (Fig. 5.25 through Fig. 5.34) show each of the 10 residuals generated by the scheme when the (fault free) plant is driven as described above. The two detection thresholds for each residual are also marked in red.

![Figure 5.25: Residual One (Supply Line Flow Rate)](image_url)

Figure 5.25: Residual One (Supply Line Flow Rate)
5.4. RESIDUAL EVALUATION

Figure 5.26.: Residual Two (Supply Line Temperature)

Figure 5.27.: Residual Three (Supply Line Pressure)
Figure 5.28.: Residual Four (Return Line Flow Rate)

Figure 5.29.: Residual Five (Return Line Temperature)
Figure 5.30.: Residual Six (Return Line Pressure)

Figure 5.31.: Residual Seven (Heat Exchanger Flow Rate)
Figure 5.32.: Residual Eight (Heat Exchanger Fluid Level)

Figure 5.33.: Residual Nine (Heat Exchanger Pressure)
Figure 5.34.: Residual Ten (Heat Exchanger Temperature)
5.4. RESIDUAL EVALUATION  

CHAPTER 5. DESIGN

Isolation Logic

Each fault affects the residual signals in a specific way, according to its type and magnitude. The difference between these effects are the basis on which specific faults (or groups of faults) are isolated. Using two thresholds per residual allows two features to be easily captured: the direction in which the residual deviates and crossing time. These two features are sufficient to identify and isolate many faults\(^5\).

To map these features onto faults a set of evaluation matrices was created. To do so, the non-linear simulation models were adapted so that they could be used to simulate various faults\(^6\). Each fault was simulated and the effect on the residual observed. The thresholds which were crossed (and hence flagged) were encoded in a matrix. This is presented below in Table 5.4 for the upper thresholds and Table 5.5 for the lower thresholds.

<table>
<thead>
<tr>
<th>Fault name</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>R7</th>
<th>R8</th>
<th>R9</th>
<th>R10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Line Leak</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Line Ice</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Line Thermal</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Line Valve</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Return Line Valve</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Return Line Leak</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Return Line Thermal</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Heat Hxr. Thermal</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Heat Hxr. Leak</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Heat Hxr. Blockage</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 5.4.: The fault isolation matrix (upper thresholds)

<table>
<thead>
<tr>
<th>Fault name</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>R7</th>
<th>R8</th>
<th>R9</th>
<th>R10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Line Leak</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Line Ice</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Line Thermal</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^5\)There are other features that can be extracted from the residual signals. The literature review in Chapter 2 contains some examples of this being done.

\(^6\)See Chapter 6 or Chapter 1 for a full description of each of these faults.
5.4. RESIDUAL EVALUATION

CHAPTER 5. DESIGN

<table>
<thead>
<tr>
<th>Fault name</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>R7</th>
<th>R8</th>
<th>R9</th>
<th>R10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Line Valve</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Return Line Valve</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Return Line Leak</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Return Line Thermal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Hxr. Thermal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Heat Hxr. Leak</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Heat Hxr. Blockage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 5.5.: The fault isolation matrix (lower thresholds)

Data Presentation

The cryogenic plant is more prone to certain failures than others (as is generally the case with all machinery). It is also the case that some faults are difficult to distinguish from others. For example, a valve being blocked by frozen material, or failing in a closed position due to a broken stem has a similar result, and may share a fault signature. As such it is sensible to present the diagnostic information to the end user in a way that takes this into account. Specifically, where the condition monitoring scheme can only isolate a set of faults rather than an individual fault, the end user should be presented with the entire set. Ideally, the possible faults should be ranked by their likelihood. This scheme achieves that by ranking the possible faults in order of mean time to failure, where they share the same fault signature. The information on mean time to failure was gathered during the FMECA exercise, presented in the introduction.

A simple GUI application was programmed in Matlab, which matches fault signatures to a written description of the isolated fault (or fault set). Figure 5.35 illustrates the operation of this application.

The GUI application begins by checking the status of all the detection flags. It checks them periodically until one or more flags are raised. At this point the flag combination is checked against the pre-defined isolation matrix. If the flag pattern matches a fault described by the table, then the user is informed. If the pattern is not matched, then the user is informed of an unknown fault. In either case, the application continues to check the flag status and will update the isolation result accordingly. For example, if a fault that normally raises two flags is detected, but the second flag is raised a ten
Check the status of all detection flags

Any flags raised?

Yes

Compare the flag status to the isolation matrix

Match found?

No

Inform the user of an unidentified fault

Yes

Multiple matches?

No

Present the known fault to the user

Yes

Rank the faults in order of mean time to failure

Present the known fault set to the user

Wait

Figure 5.35.: An illustration of the GUI operation
seconds after the first, the user will for the first ten seconds be informed of an unknown fault, before the fault is correctly isolated ten seconds later. This is a compromise that affords the end user speedy notification of a fault, which was judged to be preferable to the alternative, which would be to wait a set period of time before notification to allow the fault to be isolated.

5.5. Summary

In this chapter a description of the fault detection scheme was provided, together with the design methodology. In the first section the design methodology was summarised. The second, third and fourth sections described the details of how that design methodology was followed. The result of the design steps (i.e. The linear models, the Kalman filter parameters, and residual evaluation matrices) were presented.

In the next chapter, the non-linear model is used to simulate the effect of several faults, and the response of the condition monitoring scheme is shown in full.
6. Simulation and Verification of the Condition Monitoring Scheme

6.1. Simulation Overview

In order to examine the response of the condition monitoring scheme designed in the previous chapter to faults, the non-linear simulation models were adapted to allow various faults to be injected into the simulation. The outputs of the fault simulations were passed to the condition monitoring scheme to test its effectiveness at identifying and isolating the simulated faults. The results obtained from this process are presented in this chapter. The flow chart presented below (Fig. 6.1) summarises the test methodology that was used.

![Flow chart illustration of the test methodology](image)

Figure 6.1.: A flow chart illustration of the test methodology
6.1. Methodology

Selection of Faults

The first step of the test procedure was to select a suitable set of faults to simulate. The selection (presented in Section 3.3) was carried out with the objective of identifying the most severe faults which affect the helium loop of the cryopumping system, together with their relative likelihood. The following faults were selected:

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Fault</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Line</td>
<td>Leak Fault</td>
<td>Cryogenic fluid leaking from the transmission line to atmosphere</td>
</tr>
<tr>
<td></td>
<td>Ice Fault</td>
<td>Cryogenic fluid contamination or impurity resulting in ice formation in the transmission line</td>
</tr>
<tr>
<td></td>
<td>Insulation Fault</td>
<td>Compromised vacuum jacket resulting in deteriorated thermal insulation between the cryogenic fluid and atmosphere</td>
</tr>
<tr>
<td>Broken Valve Stem</td>
<td></td>
<td>Mechanical damage of the inlet valve stem resulting in loss of valve control and debris passing into the transmission line</td>
</tr>
<tr>
<td>Return Line</td>
<td>Worn Valve</td>
<td>Mechanical wear of return line valve resulting in loss of fine valve control</td>
</tr>
<tr>
<td></td>
<td>Leak Fault</td>
<td>Loss of helium gas to atmosphere or vacuum jacket from the return line</td>
</tr>
<tr>
<td></td>
<td>Insulation Fault</td>
<td>Compromised vacuum jacket resulting in deteriorated thermal insulation between the helium gas and atmosphere</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>Heat Fault</td>
<td>Unplanned heat load on pumping surface owing to reduced thermal insulation or gas leak into NIB vacuum space</td>
</tr>
</tbody>
</table>
Leak Fault  
Cryogenic fluid leaking from the heat exchanger to atmosphere or NIB vacuum space

Manifold Blockage  
Ice formation on the return manifold owing to cryogenic vapour impurity

Table 6.1.: Table of Selected Faults

**Determination of the Fault Effects**

Each of the selected faults was analysed on a first principles basis. The aim of the analysis was to determine the change in plant state, parameter or structure caused by each fault. Describing the faults in these three terms allowed for straightforward adjustment of the non-linear simulation models, while at the same time allowing for a more authentic recreation of their effects than would be afforded by a direct prescriptive approach (e.g. by superimposing effects determined \emph{a priori} on the output of the simulations alone).

**Modifications of the Simulation Models**

The non-linear simulation models (see Chapter 4) were implemented in Matlab/Simulink as custom “s-function” scripts. These scripts were modified to include one or more conditional statements per fault which altered the states, parameters or structure of the simulation when triggered.

The non-linear simulation models were altered as follows.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Fault</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Line</td>
<td>Leak Fault</td>
<td>A value corresponding to the size of the leak is subtracted from the mass of fluid state at each simulation step</td>
</tr>
<tr>
<td>Ice Fault</td>
<td></td>
<td>The termination capacitance of the transmission line is reduced</td>
</tr>
</tbody>
</table>

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6.1. SIMULATION OVERVIEW

CHAPTER 6. SIMULATION

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Fault</th>
<th>Alteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation Fault</td>
<td>A value corresponding</td>
<td>to the magnitude of the fault is added to the enthalpy state at each simulation step</td>
</tr>
<tr>
<td>Broken Valve Stem</td>
<td>A random walk is added</td>
<td>to the inlet flow rate followed by a reduction in termination capacitance a short time later, to represent the lodging of debris in the transmission line</td>
</tr>
<tr>
<td>Return Line Line</td>
<td>Worn Valve</td>
<td>A small (+/- 10%) random walk is added to the valve position</td>
</tr>
<tr>
<td>Leak Fault</td>
<td>A value corresponding</td>
<td>to the size of the leak is subtracted from the mass of gas state at each simulation step</td>
</tr>
<tr>
<td>Insulation Fault</td>
<td>A value corresponding</td>
<td>to the magnitude of the fault is added to the enthalpy state at each simulation step</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>Heat Fault</td>
<td>An additional unmeasured heat load is added to the simulation</td>
</tr>
<tr>
<td>Leak Fault</td>
<td>A value corresponding</td>
<td>to the size of the leak is subtracted from the mass of fluid state at each simulation step</td>
</tr>
<tr>
<td>Manifold Blockage</td>
<td>The termination capacitance of the heat exchanger is reduced, according to the magnitude of the fault</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.2.: Table of Simulation Alterations

Simulation Procedure

Each of the modified simulation models was run once for each fault scenario. Each fault was triggered a short period of time into the simulation, so that the deviation from nominal behaviour could be observed. The input and output to the simulations were
recorded and saved in Matlab. Each measured signal had white noise superimposed on it, with a power consistent with that observed in the historical process data. The signals were then passed to a Simulink implementation of the condition monitoring scheme (c.f. Chapter 5) to demonstrate its effectiveness at detecting the faults.

**Comparative assessment**

To demonstrate the utility of using two thresholds for the isolation logic, a comparative assessment was conducted. A second set of simulations were run using a modified version of the isolation logic which utilised a single threshold, which is a more common approach to using thresholds. Aside from the modified isolation logic, the second set of simulations followed the same procedure as the first. The modified detection logic took the same residuals generated by the Kalman filter bank as an input as the unmodified scheme. These residuals were passed through a low-pass pre-filter (with the same response as the original FIR filter), then their RMS values over a window of 50 samples were calculated. The RMS values were then to a single threshold to generate the flags required for a modified isolation matrix. This sample window of 50 samples was selected because it corresponds to a one second period - a period small enough to provide timely response to faults, but large enough to provide additional noise filtering. Figure 6.2 is a graphical comparison between the original and modified isolation logic.

![Diagram](image)

**Figure 6.2.: A graphical comparison of the original and modified isolation logic**

In the next section the response of the condition monitoring scheme to each of the fault simulations is presented, together with the response of the modified RMS version of the scheme. Further commentary is given in the final section.
6.2. Simulation Results

In this section the results of the simulation procedures are presented. Each of the charts below show the output of the condition monitoring scheme: the processed residuals. The upper and lower thresholds of detection for the residuals (i.e. the levels at which they are flagged as abnormal) are marked in red. For each simulated fault, a chart showing the isolation matrix summarises the detection thresholds that were crossed. For each fault simulation, only the residuals corresponding to the subsystem affected by the fault are shown, as all the other residuals do not cross any thresholds.

6.2.1. Supply Line Faults

Four supply line faults were simulated, as per Table 3.2.

Leak Fault

The first supply line fault is a simulated fluid leak fault, injected at \( t = 20 \). The fault has a magnitude of \( 2 \times 10^{-3} \) kg/s (this is a relatively large leak). The effect of this leak fault is that the output flow rate of the transmission line to drop below its fault-free level. The three processed residuals corresponding to the supply lin (residuals one, two, and three) are shown in Fig. 6.3, below.
6.2. SIMULATION RESULTS

(a) Residual one (supply line flow rate)

(b) Residual two (supply line temperature)
Figure 6.3.: Residuals associated with a supply line leak fault
6.2. SIMULATION RESULTS

It can be seen in Fig. 6.3a that residual one (R1) has crossed both the upper and lower thresholds by $t \approx 24$, which are flagged accordingly. Residuals two (R2) and three (R3) remain within their thresholds and are not flagged. As a result the correct fault can be isolated approximately four seconds after its onset, although there is a short period prior to this where only one threshold (the lower R1 threshold) has been crossed, causing a delay between the fault being detected and correctly diagnosed. The final status of the detection flags at the end of the simulation is shown in Table 6.3.

<table>
<thead>
<tr>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>R7</th>
<th>R8</th>
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</table>

Table 6.3.: Isolation matrix - Supply line leak fault

In Fig. 6.4 the equivalent RMS residuals for the modified isolation logic and the associated thresholds are shown. The RMS residual one (R1x) crosses the detection threshold at $t \approx 22$ and is flagged. As before, the RMS residuals two (R2x) and three (R3x) do not cross a detection threshold, and remain unflagging by the end of the simulation.
Figure 6.4.: RMS residuals associated with a supply line leak fault
Table 6.4 shows the final RMS detection flag status at the end of the leak fault simulation.

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<thead>
<tr>
<th>Upper</th>
<th>R1x</th>
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<th>R3x</th>
<th>R4x</th>
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Table 6.4: RMS isolation matrix - Supply line leak fault

**Ice Fault**

The second supply line fault is a simulated ice formation fault, injected at $t = 20$. This fault causes the termination capacitance of the line to drop to 60% of its normal level. The three processed residuals corresponding to the supply line (residuals one, two, and three) are shown in Fig. 6.5. The residuals corresponding to the other subsystems remain unaffected by the fault, and are not depicted.

The ice formation fault causes R1 to first cross the lower threshold at $t \approx 23$, and then the upper threshold immediately after. At $t \approx 32$ the R1 residual returns to close to its pre-fault average level, but both detection flags remain raised, as per the scheme design. The other two residuals, R1 and R2, remain within their thresholds. The main effect of the fault on the output of the non-linear simulation model is that, for a short period
6.2. SIMULATION RESULTS

Figure 6.5.: Residuals associated with a supply line ice fault

(b) Residual two (supply line temperature)

(c) Residual three (supply line pressure)
after its occurrence, the transmission line outlet flow rate drops. The inlet flow rate now exceeds the outlet flow rate causing the pressure within the line to increase until the outlet flow rate once again matches the inlet flow rate. It is for the reason that the R1 residual only temporarily crosses the detection threshold. Given the change of pressure in the transmission line, it is likely that the R3 residual (associated with pressure) is affected, but only to a small degree, such that it is masked by the measurement noise.

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Table 6.5.: Isolation matrix - Supply line ice fault

Figure 6.6 shows the RMS residuals for the modified detection logic, for the same ice formation fault. As with the non-RMS residuals, the supply line flow rate residual detection threshold is crossed at $t \approx 23$. The other two residuals, R2x and R3x, remain below their detection thresholds.
Figure 6.6.: Residuals associated with a supply line ice fault

(b) RMS residual two (supply line temperature)

(c) RMS residual three (supply line pressure)
Table 6.6 shows the RMS detection flag status at the end of the simulation. Only the R1x threshold is flagged.

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Table 6.6.: RMS isolation matrix - Supply line ice fault

**Insulation Fault**

The third supply line fault is an insulation fault, injected at \( t = 20 \). A transmission line insulation fault represents the loss of insulation between the cryogenic fluid and its surroundings, for example when the vacuum jacket is compromised. In this case, the magnitude of the fault is an additional 0.1kW heat load on the fluid in the transmission line. The effect of the fault on the three supply line residuals is shown in Fig. 6.7.

At \( t \approx 25 \) R1 crosses its upper threshold briefly, before returning and crossing the lower threshold at \( t \approx 30 \). It remains below the lower threshold (on average) until the end of the simulation. Accordingly, both the upper and lower thresholds are flagged. The R2 and R3 thresholds are not significantly affected, remaining within their detection thresholds for the whole duration of the simulation. Consequently, they are not flagged.
Figure 6.7.: Residuals associated with a supply line insulation fault

(b) Residual two (supply line temperature)

(c) Residual three (supply line pressure)
The final flag status is shown in Table 6.7. The fault was initially detected at $t \approx 25$ and correctly isolated at $t \approx 30$. The fact that residual $R_1$ remains only just crosses the detection threshold indicates that the magnitude of this fault is close to the minimum needed for it to be successfully detected.

| Upper | ✓ |
| Lower | ✓ |

Table 6.7.: Isolation matrix - Supply line insulation fault

The RMS residuals associated with this supply line insulation fault are shown in Fig. 6.8. The $R_{1x}$ residual is again the only one to cross its threshold (at $t \approx 25$), with $R_{2x}$ and $R_{3x}$ remaining below their respective detection levels.

(a) RMS residual one (supply line flow rate)
Figure 6.8.: RMS residuals associated with a supply line insulation fault
The final RMS flag status is shown in Table 6.8.

<table>
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Table 6.8.: RMS isolation matrix - Supply line insulation fault

**Broken Valve Stem**

The fourth and final supply line fault is a broken valve stem fault. This is a complex fault with two stages. The first stage represents the main effect of a broken supply valve stem, that is, both loss of control over the valve position and an incorrect position being reported to the position controller and FDI scheme. For the purpose of the non-linear simulation mode, a random walk was added to the valve position, starting at $t = 30$. The second stage represents the effect of debris (parts of the broken valve stem) becoming lodged part way down the transmission line. For the simulation, this is represented by a drop in the supply line termination capacitance at $t = 200$. The residuals produced during this simulation are shown in Fig. 6.9.

From Fig. 6.9a it can be seen that the first residual R1 initially crosses the upper detection threshold at $t \approx 40$, then approximately four seconds later crosses the lower
6.2. SIMULATION RESULTS

Figure 6.9.: Residuals associated with a broken supply valve stem fault

(b) Residual two (supply line temperature)

(c) Residual three (supply line pressure)
6.2. SIMULATION RESULTS

It can also be seen that the deviation of R1 is at least one order of magnitude greater than the deviations caused by the previous supply line faults, but this additional information is not captured by the scheme. At $t \approx 210$ a small peak in the R1 residual can be seen (this is associated with the line blockage), but from the perspective of the detection logic, it is masked by the larger deviations and does not cause any change in the detection flag status. The R2 and R3 residuals remain within their detection thresholds throughout the simulation. The final detection flag status can be seen in Table 6.9.

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Table 6.9.: Isolation matrix - Supply line broken valve stem fault

The RMS residuals for this fault are shown in Fig. 6.10. As with the non-RMS residuals, R2x and R3x remain under the threshold of detection. Residual R1x crosses its detection threshold at $t \approx 40$. The small transient peak at $t \approx 210$ is more difficult to discriminate here.
Figure 6.10.: Residuals associated with a broken supply valve stem fault

(b) RMS residual two (supply line temperature)

c) RMS residual three (supply line pressure)

Figure 6.10.: RMS residuals associated with a broken supply valve stem fault
6.2. SIMULATION RESULTS

The final RMS flag status is shown in Table 6.10.

<table>
<thead>
<tr>
<th>Upper</th>
<th>R1x</th>
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Table 6.10.: RMS isolation matrix - Supply line broken valve stem fault

6.2.2. Return Line Faults

Three faults affecting the return line subsystem were simulated. These faults were: a worn return valve, a gas leak fault, and an insulation fault. All of these faults affected only those residuals associated with the return line subsystem, residuals four (R4), five (R5), and six (R6), so it is the response of these three residuals that are shown in this section.

Worn valve

The first of the return line faults was a worn valve fault. Here, the effect of a worn return valve actuator was simulated by deviating its true position $+/- 10\%$ from its reported position, by means of adding a random walk to its position value. The fault begins at $t = 30$. The response of the three residuals associated with this subsystem are shown in Fig. 6.11.

Residual R4 is shown in Fig. 6.11a. It crosses the lower threshold at $t \approx 40$ and the upper threshold at $t \approx 48$. The upper and lower thresholds of R4 are flagged accordingly. Residual R5 can, by inspection, be seen to deviate from its steady state value at $t \approx 50$, but it does not cross the upper threshold until $t \approx 65$. R5 does not cross the lower threshold during the simulation, thus only the upper R5 threshold is flagged. Similarly, residual R6 is flagged crossing the upper threshold at $t \approx 65$, with the lower threshold remaining unflagged at the end of the simulation. The outcome of the simulation is that a fault is detected at $t \approx 40$, and it is correctly isolated at $t \approx 65$. The final state of the isolation matrix for this fault is shown in Table 6.11.

<table>
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<th>R1</th>
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Table 6.11.: Isolation matrix - Return line worn valve fault
6.2. SIMULATION RESULTS

(a) Residual four (return line flow rate)

(b) Residual five (return line temperature)
The RMS residuals for the return line worn valve fault are shown in Fig. 6.12.
6.2. SIMULATION RESULTS

Figure 6.12.: Residuals associated with a worn return valve fault

(b) RMS residual five (return line temperature)

(c) RMS residual six (return line pressure)
RMS residual R4x first crosses the detection threshold at \( t \approx 40 \), and the two other return line RMS residuals, R5x and R6x, cross their respective thresholds shortly later, at \( t \approx 65 \). As such, with this version of the detection logic, the fault is detected at \( t \approx 40 \) and correctly isolated at \( t \approx 65 \). The final state of the RMS isolation matrix is shown in Table 6.12.

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Table 6.12.: RMS isolation matrix - Return line worn valve fault

**Leak Fault**

A gas leak fault was the second return line fault to be simulated. This fault represents the unplanned loss of helium gas from the return line, perhaps due to an improperly fitted valve seal or mechanical damage. The fault was injected at \( t = 20 \), and the magnitude of the fault was \( 2 \times 10^{-3} \) kg/s loss of gas. The response of the three return line residuals to this fault is shown in Fig. 6.13.

All three residuals cross their lower thresholds and are flagged. Residuals R4 and R6 cross at \( t \approx 30 \), whereas R5 crosses at \( t \approx 40 \). The leak fault is therefore detected at
6.2. SIMULATION RESULTS

Figure 6.13.: Residuals associated with a return line leak fault
$t \approx 30$ and correctly isolated at $t \approx 40$. The final detection flag status is shown in Table 6.13. It can be seen from these charts that all of the three residuals cross the threshold by some margin, indicating that it may be possible to detect gas leaks of a smaller magnitude.

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Table 6.13.: Isolation matrix - Return line leak fault

The RMS residuals for this gas leak fault are shown in Fig. 6.14. Again here, R4x and R6x cross the detection threshold at $t \approx 30$, followed by R5x at $t \approx 40$. Consequently, both the detection and isolation times are the same as with the non-RMS isolation logic.

(a) RMS residual four (return line flow rate)
Figure 6.14.: RMS residuals associated with a return line leak fault

(b) RMS residual five (return line temperature)

(c) RMS residual six (return line pressure)
The final state of the RMS isolation matrix is shown below, in Table 6.14.

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Table 6.14.: RMS isolation matrix - Return line leak fault

**Insulation Fault**

The third and final return line fault simulation was for an insulation fault. As with the transmission line, this type of fault could be caused by a vacuum jacket failure, excessive thermal load from a valve, or similar. The simulated fault is of 1kW in magnitude, and is injected at $t = 100$. The residuals resulting from this fault are shown in Fig. 6.15, below.

Residual R6 is shown in Fig. 6.15c. Following the injected fault at $t = 100$, it eventually cross the upper detection threshold at $t \approx 205$, where it is flagged. Residual R7 also takes time to cross the threshold, doing so at $t \approx 280$ by a small margin. By inspection, it can be seen that the average value of R5 increases, but not by enough to cause a
(b) Residual five (return line temperature)

(c) Residual six (return line pressure)

Figure 6.15.: Residuals associated with a return line insulation fault
detection threshold to be flagged. Given this result, it seems likely that a fault of a smaller magnitude may be difficult to detect and correctly isolate. The final isolation flag status for this simulation is shown in Table 6.15.

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Table 6.15.: Isolation matrix - Return line insulation fault

The RMS residuals used for the modified isolation logic are shown below, in Fig. 6.16. The trend is similar in that both R6x and R5x can, by inspection, be seen to increase. However, R5x does not cross the detection threshold, suggesting the fault is of insufficient magnitude to be correctly isolated. The fact that R6x crosses a detection threshold does mean that an unidentified fault is detected, however, at $t \approx 200$.

![RMS residual four (return line flow rate)](image)

(a) RMS residual four (return line flow rate)

Figure 6.16.: Residuals associated with a return line insulation fault
Figure 6.16.: RMS residuals associated with a return line insulation fault
The final RMS isolation matrix is presented in Table 6.16, below.

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Table 6.16.: RMS isolation matrix - Return line insulation fault

### 6.2.3. Heat Exchanger Faults

The final subsystem to be examined was the heat exchanger. Three heat exchanger faults were simulated: a thermal fault, a liquid leak fault, and a return manifold blockage. The response of the four residuals associated with the heat exchanger subsystem, residuals seven (R7), eight (R8), nine (R9), and ten (R10), are shown in the following subsections. The response of the first six residuals was unaffected, and as such, they are not shown.

**Thermal fault**

The first of the heat exchanger faults was a thermal fault, injected at $t = 20$, with a magnitude of 20W. This fault represents an event causing an additional heat load on the pump panels. This could be caused by a compromised vacuum in the neutral injection box, the degradation of an insulating component, or unplanned contact between the pumping panels and a warm body. The four heat exchanger residuals are shown below, in Fig. 6.17.

Residual R7 is shown in Fig. 6.17a. It crosses the upper detection threshold at $t \approx 26$, at which point it is flagged. Residual R9 similarly crosses its upper threshold, and is flagged at approximately the same time. At $t \approx 24$, residual R8 crosses the lower detection threshold and residual R10 crosses the upper threshold. Both R8 and R10 are flagged accordingly. As such, the thermal fault is detected at $t \approx 24$ and correctly isolated at $t \approx 26$. The final isolation flag status for this simulation is presented in Table 6.17.

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Table 6.17.: Isolation matrix - Heat exchanger thermal fault

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6.2. SIMULATION RESULTS

(a) Residual seven (heat exchanger flow rate)

(b) Residual eight (heat exchanger fluid level)
Figure 6.17.: Residuals associated with a heat exchanger thermal fault

(c) Residual nine (heat exchanger pressure)

(d) Residual ten (heat exchanger temperature)
The RMS residuals for this fault are presented in Fig. 6.18. Here, R8x and R10x cross their detection thresholds at $t \approx 24$, followed by R7x crossing at $t \approx 24$, and by R9x crossing at $t \approx 32$. As opposed to the non-RMS isolation logic, the fault is detected at $t \approx 24$ and but it is not correctly isolated until $t \approx 32$. 

(a) RMS residual seven (heat exchanger flow rate)
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(b) RMS residual eight (heat exchanger fluid level)

(c) RMS residual nine (heat exchanger pressure)
(d) RMS residual ten (heat exchanger temperature)

Figure 6.18.: Residuals associated with a heat exchanger thermal fault
The final RMS isolation flag status is shown in Table 6.18.

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<td>Upper</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 6.18.: RMS isolation matrix - Heat exchanger thermal fault

**Leak Fault**

The second heat exchanger fault to be simulated was a fluid leak fault. This fault is associated with the loss of fluid from the bottom of the cryogenic panels. The fault was inject at $t = 20$, and had a magnitude of $6 \times 10^{-3}$ kg/s. The response of the four heat exchanger residuals to this fault is presented in Fig. 6.19.

(a) Residual seven (heat exchanger flow rate)
6.2. SIMULATION RESULTS

(b) Residual eight (heat exchanger liquid level)

(c) Residual nine (heat exchanger pressure)
(d) Residual ten (heat exchanger temperature)

Figure 6.19.: Residuals associated with a heat exchanger leak fault
It can be seen from Fig. 6.19 that the only residual to cross a threshold is residual R8 (Fig. 6.19b). It crosses the lower threshold at $t \approx 25$ and is flagged accordingly. The other three residuals do not cross any thresholds and remain unflagged by the end of the simulation. The final isolation flag status is shown in Table 6.19.

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>R7</th>
<th>R8</th>
<th>R9</th>
<th>R10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.19.: Isolation matrix - Heat exchanger leak fault

The RMS residuals used for the modified isolation logic are shown below, in Fig. 6.20. As with the non-RMS residuals, the only residual to cross a threshold is R8x. It crosses the threshold at $t \approx 25$ at which point it is flagged. In terms of detection and isolation speed, the performance of the RMS and non-RMS detection logic is the same for this fault.

![RMS residual seven (heat exchanger flow rate)](image)
6.2. SIMULATION RESULTS

(b) RMS residual eight (heat exchanger liquid level)

(c) RMS residual nine (heat exchanger pressure)
(d) RMS residual ten (heat exchanger temperature)

Figure 6.20.: Residuals associated with a heat exchanger leak fault
The final RMS fault flag status is shown in Table 6.20.

<table>
<thead>
<tr>
<th>Upper</th>
<th>R1x</th>
<th>R2x</th>
<th>R3x</th>
<th>R4x</th>
<th>R5x</th>
<th>R6x</th>
<th>R7x</th>
<th>R8x</th>
<th>R9x</th>
<th>R10x</th>
</tr>
</thead>
</table>

Table 6.20.: RMS isolation matrix - Heat exchanger leak fault

**Manifold blockage**

A partial return gas manifold blockage fault was the last fault to be simulated. This fault occurs when ice forms around the return manifold, which can be a result of atmospheric gas entering the helium loop, or water vapour impurities in the liquid helium. The fault is injected at $t = 20$. For the purpose of the simulation, the capacitance of the gas manifold is reduced by 5%.

It can be seen in Fig. 6.21 that even a small reduction in the return manifold capacitance results in a strong response from the four heat exchanger residuals. Residual R7 crossed the lower detection threshold at $t \approx 28$, and was flagged. Residual R8 crossed its lower detection threshold at $t \approx 26$, yet it took a long period of time to cross the upper detection threshold, not doing so until $t \approx 90$. R8 is the residual associated with the liquid level, and the unusual profile is a reflection of the liquid level state. The liquid level
6.2. SIMULATION RESULTS

(b) Residual eight (heat exchanger liquid level)

(c) Residual nine (heat exchanger pressure)
drops significantly, below the lowest point he level gauge can measure, until \( t \approx 90 \), when it begins to return to its normal level. The zero level gauge measurement accounts for the unusual profile. Residual R9 crossed its upper threshold at \( t \approx 28 \), followed shortly thereafter by R10 at \( t \approx 31 \). Both residuals were flagged accordingly. The outcome of this simulation was that the fault was first detected at \( t \approx 26 \) and successfully isolated at \( t \approx 90 \). The final state of the isolation flags is presented in Table 6.21.

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>R7</th>
<th>R8</th>
<th>R9</th>
<th>R10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Lower</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.21.: Isolation matrix - Heat exchanger manifold blockage fault

The equivalent RMS residuals for this fault are shown in Fig. 6.22. All four of the heat exchanger residuals cross their thresholds: R7x at \( t \approx 27 \), R8x at \( t \approx 25 \), R9x at \( t \approx 29 \), and R10x at \( t \approx 30 \). As such, the fault is first detected at \( t \approx 27 \), then is successfully isolated at \( t \approx 30 \). This is a better performance in terms of isolation speed than with the non-RMS isolation logic.
6.2. SIMULATION RESULTS

(a) RMS residual seven (heat exchanger flow rate)

(b) RMS residual eight (heat exchanger liquid level)
6.2. SIMULATION RESULTS

(c) RMS residual nine (heat exchanger pressure)

(d) RMS residual ten (heat exchanger temperature)

Figure 6.22.: Residuals associated with a heat exchanger manifold blockage fault
The final state is the RMS isolation flags is shown in Table 6.22.

<table>
<thead>
<tr>
<th>Upper</th>
<th>R1x</th>
<th>R2x</th>
<th>R3x</th>
<th>R4x</th>
<th>R5x</th>
<th>R6x</th>
<th>R7x</th>
<th>R8x</th>
<th>R9x</th>
<th>R10x</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 6.22.: RMS isolation matrix - Heat exchanger manifold blockage fault

6.3. Discussion of Results

Ten faults were simulated in total. Four faults relating to the supply line subsystem were simulated, and three faults each were simulated for the return line and heat exchanger subsystems. The response of the scheme to each of these faults was shown, both using the original isolation logic as described in Chapter 5, and using a modified RMS version of the isolation logic, in order to demonstrate the utility of using two thresholds per residual.

Using the original, dual threshold logic, all ten faults caused at least one residual to deviate across a detection threshold and were thus detected by the condition monitoring scheme. Six of the ten faults produced a unique combination of threshold crossings (a signature), allowing them to be isolated. Four of the ten faults shared a signature.

Using the modified isolation logic, again all ten faults resulted in at least one threshold being flagged, however there were only five unique fault signatures. The table below, Table 6.23, shows the complete set of RMS isolation flags generated by the modified isolation logic. This can be compared to the original isolation flag matrix in Table 5.4 and Table 5.5.

<table>
<thead>
<tr>
<th>Fault name</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>R7</th>
<th>R8</th>
<th>R9</th>
<th>R10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Line Leak</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Line Ice</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Line Insulation</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Line Valve</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Return Line Valve</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Return Line Leak</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Return Line Insulation</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Hxr. Thermal</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Hxr. Leak</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

232
For the original isolation logic, the maximum detection time (i.e. the longest time taken for at least one threshold to be crossed following the onset of a simulated fault) was approximately 105 seconds, although most faults were detected faster. In all cases, an equal or slightly longer period of time was required for the fault to be correctly isolated, but in one case, the time from detection to isolation was approximately 75 seconds.

For the modified RMS isolation logic the performance was similar. In most cases the similar detection and isolation times were close. The RMS scheme, however, came at the expense of having fewer unique fault signatures, as noted above.

Given that the condition monitoring scheme was designed to provide diagnostic/supervisory information to a plant operator the detection and isolation speed of the scheme using the both the original and modified logic is sufficient, and compared to the traditional manual detection and diagnostic method currently employed, it is a significant improvement in terms of speed. The speed of a manual diagnosis and detection procedure primarily depends on the nature of the fault and the experience of the engineer. An obvious fault, like a gross cryogenic fluid leak, might be detected within a few minutes and isolated in less than an hour. A more obscure fault, such as one of the line blockage faults tested here, would take longer to identify and isolate, or perhaps even go unnoticed until it caused a secondary fault later on. In both of these cases, the condition monitoring scheme is an improvement.

The comparison table below (Table 6.24) lists the approximate detection and isolation times for each variation of the scheme.

<table>
<thead>
<tr>
<th>Fault name</th>
<th>Detection</th>
<th>Isolation</th>
<th>Detection (RMS)</th>
<th>Isolation (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Line Leak</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Supply Line Ice</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Supply Line Insulation</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Supply Line Valve</td>
<td>10</td>
<td>13</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Return Line Valve</td>
<td>10</td>
<td>35</td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>Return Line Leak</td>
<td>10</td>
<td>20</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>
6.3. DISCUSSION OF RESULTS

<table>
<thead>
<tr>
<th>Fault name</th>
<th>Detection</th>
<th>Isolation</th>
<th>Detection (RMS)</th>
<th>Isolation (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return Line Insulation</td>
<td>105</td>
<td>180</td>
<td>200</td>
<td>N/A</td>
</tr>
<tr>
<td>Heat Hxr. Thermal</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Heat Hxr. Leak</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Heat Hxr. Blockage</td>
<td>6</td>
<td>70</td>
<td>7</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 6.24.: Approximate detection & isolation times for each scheme variation, in seconds

The supply line “broken valve stem” simulation included a secondary fault part way into the simulation. The effect of the secondary fault was masked by the first because both faults affected the same residual. The choice of isolation logic had no effect on this.

Both variations of the isolation logic could not discriminate between the four supply line faults: the leak fault, the insulation fault, and the broken valve stem fault. While these three faults share the same signature, further inspection reveals that the residuals associated with them have unique characteristics. For the leak fault, residual one crosses the upper threshold before dropping below the lower threshold, where it remains. For the insulation fault, residual one only briefly crosses both detection thresholds before returning to near it’s normal value. The valve stem fault causes relatively large deviations in residual one, which are sustained and do not reach a steady state. These characteristics are plain to see on inspection. Increasing the number of thresholds used in the isolation logic, or perhaps using the times at which the isolation flags are raised for the diagnosis, could allow the scheme to discriminate between them. This would, however, come at the cost of additional complexity, and it raises the question as to what point the end user would be best served by presenting the residuals themselves.

The objective of this research was to demonstrate the usefulness of the condition monitoring scheme as a tool for diagnosing faults in fusion engineering setting. As a result the target plant may be subject to change, because it is an experimental device. Given this, both the fault signatures and the residuals themselves should be made available to the end user. While the results indicate that the scheme presented here would be successful at detecting and isolating a range of faults, it is difficult to guarantee that every possible fault can be anticipated and their fault signatures determined for isolation. Where there is scope for ambiguity in an automatic diagnosis it is preferable to provide as much information as possible. More sophisticated isolation logic could perhaps increase the proportion of known/anticipated faults that could be isolated, but an expert human
operator would benefit most from the addition information provided by the residuals themselves once a fault is detected, provided they have the experience to interpret the information. This is particularly the case in an experimental environment where the technology and equipment is subject to change.

6.4. Summary

In this chapter the condition monitoring scheme was tested in simulation. Ten fault scenarios were simulated and the response of the scheme examined. Two different isolation logic schemes were tested. With both logic variations, all ten faults were detected. With the first isolation logic variation six faults could be uniquely isolated, whereas with the second isolation logic variation only five faults could be uniquely isolated. The detection and isolation times were similar in both cases. Both were an improvement over the manual detection and isolation time. On that basis it was concluded that the scheme could be usefully employed in detecting faults, with a preference for the using first isolation logic variation (with two thresholds) because of its improved isolation capability. The end user would also be best served by being provided with both the fault signatures and the processed residuals together with the fault diagnosis.
7. Conclusions and Future Research

7.1. Discussion and Conclusions

The primary aim of the research presented in this thesis was to prove the usefulness of model based condition monitoring techniques for fusion applications by means of a demonstration simulation. At the Joint European Torus (JET), current condition monitoring practice is restricted to a traditional approach: straightforward alarm thresholds for important conditions and safety interlocks. Diagnosis of faults has been largely a manual process, driven by the expertise of the engineers and scientists responsible for the continued operation of the experiment. Similarly, the literature shows that model based condition monitoring has not been adopted by other fusion experiments, at least not to a level where it is reported, with the exception of the Tore Supra experiment in France. As fusion energy research continues its progress from a purely scientific research endeavour to a viable means of energy production, improving the availability of fusion hardware and the supporting plant becomes increasingly important. The success of condition monitoring in other industries[108] (including the nuclear fission industry[14]) suggests that it could also be usefully employed in fusion applications. This consideration provided the motivation for this research.

At the beginning of the research, an initial study was conducted to identify what would constitute a good demonstration. The outcome of this initial study was that a condition monitoring scheme to detect faults in the cryogenic pumping system would be most appropriate because it provides an essential function (the creation and maintenance of a vacuum) on which the availability of the entire experiment relies. An novel application of a condition monitoring scheme to this subsystem in particular was deemed to be a good demonstration.

Given this target subsystem, the next step was to determine what condition monitoring techniques were best suited to this application. In Chapter 2, a review of the three main classes of condition monitoring technique is presented and their relative merits are
described. Ultimately, a quantitative model based scheme was selected, owing to the availability of detailed plant information, its deterministic nature, and adaptability.

The neutral beam heating systems at JET are essential for the running of the experiment and the scope for modification (including the addition of extra sensor hardware) and time for experimentation is minimal, unless directly necessitated by the main development programme. As such, a simulation based design approach and demonstration was very attractive. A novel, accurate non-linear simulation model of the cryopumping system was developed, implemented in Simulink, then validated using historical process data. This model is presented in Chapter 4. It constitutes one of the main areas of novelty in this thesis and is currently unique in the literature. Using this model as a surrogate plant was essential, allowing the design of experiments both to develop and test the scheme. These would otherwise not have been possible, given the practical limitations imposed by the duties of the physical plant.

The design of the condition monitoring scheme is covered in Chapter 5. The design methodology had three main stages: the generation of linear working models, Kalman filter design, and the design of the residual processing and evaluation stage. In the first stage, the non-linear model (the surrogate plant) was used to generate several sets of input-output data. These were used to identify a set of single-input single-output (SISO) autoregressive with exogenous input (ARX) models, relating each input to each output. A bank of Kalman filters were generated, using the SISO models generated in the previous step. The process and measurement noise parameters (R and Q) were selected according to the observed measurement noise in the historical data, and the anticipated process noise, which was estimated from the overall difference between the non-linear simulation model and working models. The residuals produced by the Kalman filters were correlated with the difference between the surrogate plant and the linear models, and hence would be larger than normal with the presence of a fault, providing the basis for fault detection. The final step was to design a method of processing these residuals. To do so, a bank of finite impulse response (FIR) low-pass filters was designed, with the objective of attenuating any high frequency measurement noise manifest in the residuals, such that the main trend was not masked. A set of two detection thresholds (upper and lower) for each residual was determined by inspection of the maximum deviation of the residuals while the surrogate plant was in a fault-free state. The purpose of the thresholds was to enable any residual to be flagged should it become sufficiently large. An evaluation matrix was designed, so that when any combination of residuals crossed their thresholds, the combination can be mapped onto a specific fault, or set of faults.
7.1. DISCUSSION AND CONCLUSIONS

This design is summarised graphically in Fig. 7.1.

To test the scheme, the non-linear simulation model was adapted to simulate the occurrence of several faults. A Simulink implementation of the condition monitoring scheme was then used to detect these faults. The effectiveness of using a dual threshold approach was compared to using a single threshold approach. This investigation and its conclusions are the second novel contribution of this thesis. The results of all the test simulations are presented in Chapter 6. The faults were selected according to their relative likelihood (or historical occurrence) and their impact on the overall experiment. In total, ten faults were simulated and all were detected in a timely manner by the scheme. Six of the ten faults could be isolated owing to their unique signature.

The design and testing of this type of condition monitoring scheme for a cryogenic pump application are unique in both the literature and to CCFE, and as such constitute the third main novel contribution of this thesis.

It has been demonstrated, via simulation, that a quantitative model based condition monitoring scheme could be successfully applied to a cryogenic pumping system. It has also been shown the such a scheme could be used to detect a range of faults, including some which have occurred historically, and those which might incur considerable lost
7.2. FUTURE WORK

During the course of this research, some issues requiring further investigation presented themselves. These are summarised here.

**Appropriate selection of sensor hardware**

One of the main challenges for this research was the restriction of working exclusively with pre-existing sensor hardware. This was somewhat mitigated by the high level of instrumentation already present on the physical plant, but in several cases the sensors in place were not appropriate for fault detection; notably, all the helium temperature sensors and the supply line pressure gauge. The helium temperature sensors which collected the process data used for this research had a relatively large measurement scale, ranging from room temperature, down to ultra low cryogenic temperature (i.e. the single digit Kelvin region). Given that these sensors would ideally be used to measure very small temperature deviations in a condition monitoring application, even a fraction of a percentage error or a small non-linearity in their output has a significant effect on their usefulness when the scale is this large. Currently the helium temperature sensors are only accurate to within two or three degrees Kelvin when at cryogenic temperature, which is not sufficient for this application. A similar scaling issue also applies to the supply line pressure gauge. Were the scheme presented in this thesis to be commissioned, one essential area of future work would be to rectify this issue. This may involve inclusion of an additional sensor (or sensors) with a smaller measurement range, or modification to the existing active or passive sensor components.
Design of experiments to collect identification data

Using a non-linear simulation model as a surrogate plant for this research had a number of advantages. In particular, the ability to drive the plant with a pseudo random binary signal (PRBS) to generate a set of data for system identification was very helpful. Unfortunately, this procedure would be difficult to repeat using the physical plant, owing to various practical limitations. As such, a series of identification experiments will have to be designed, or a suitable set of historical process data found (i.e. a “natural experiment”).

Study of hardware specific issues

For the future commissioning of this scheme to be successful, it will be necessary to investigate and account for any issues associated with the hardware on which it is to be run. This issues could be related to sensitivity to variable word length, communications delay, sample rate limitations, or other such practical issues. In addition, the integration between the PLC hardware on which the scheme would be run and the HMI/CODAS system would also need to be considered.

Long term stability

The stability of the scheme has been examined over the short term (in Chapter 5) and was shown not produce spurious diagnoses. However, as part of a commissioning process, a scheme of this type would need to be tested over a longer term (i.e. days and weeks), to guarantee its long term stability and robustness.

Offline or batch processing

At CCFE, many of the routine physics calculations and diagnostics are carried out overnight, by a batch processing procedure. Perhaps an initial option for commissioning a condition monitoring scheme of the type presented in this research could adopt a similar approach: batch processing of process variables overnight to check for faults. The downside to this is the loss of the real-time detection capability, but it does lower the challenge of implementation. This might be considered an acceptable trade-off, however, for a follow up experiment.
Glossary

abstraction hierarchy A model that can defines the functional or structural relationship between process variables. 42

additive fault A class of fault that affects a state or measurement directly. 40

analytical redundancy Using one or more sensor to predict the measurement of another, and identifying discrepancies between the prediction and measurement. 39

ARMAX autoregressive moving average exogenous inputs. 144

ARX autoregressive with exogenous input. 144, 236

BJ Box-Jenkins. 144

boundary condition A time-invariant variable which defines a static operating point or external constraint for a model. 120

CCFE Culham Centre for Fusion Energy. 12

chirp signal The name given to a periodic sinusoidal signal where the frequency is swept up and down between two arbitrarily defined frequencies. 149

CODAS Control and Data Acquisition System. 31, 74

digest factor A measure of the peak to average power ratio of a waveform. 151

digraph A representation of a cause-effect model using a node-arc structure. 41

disturbance An unknown (and uncontrolled) input acting on a system. 35

EPICS Experimental Physics and Industrial Control System. 32

equiripple The name of a FIR filter design method, also known as the Parks-McClellan method. 168
error  A deviation between a measured or computed value (of an output variable) and
the true, specified or theoretically correct value. 35

ETA  Event Tree Analysis. 59

expert system A fault diagnosis and identification scheme that uses symbolic or rule-
based reasoning, based on a qualitative model. 45

failure  A permanent interruption of a system’s ability to perform a required function
under specified operating conditions. 35

fault  A permitted deviation of at least one characteristic property or parameter of the
system from the acceptable / usual / standard condition. 35

fault detection  Determination of the faults present in a system and the time of detection. 35

fault diagnosis  Determination of the kind, size, location and time of detection of a fault. 35

fault identification  Determination of the size and time-variant behaviour of a fault. 35

fault isolation  Determination of the kind, location and time of detection of a fault. 35

fault signature  The name given to a pattern which identifies a particular fault. 170

FDI  Fault Detection and Isolation. 34

FEID  Fractional Energy Ion Dump. 27

FFA  Functional Failure Analysis. 59

FIR  finite impulse response. 144, 168, 236

FMECA  Failure Mode Effect and Criticality Analysis (FMECA) is a common formal
method for identifying failures in a plant, and their consequence. 45, 59, 62

FTA  Fault Tree Analysis. 59

GUI  Graphical User Interface. 135, 177

JET  Joint European Torus. 10, 235

JPF  JET Pulse File. 74
**least squares** A technique for estimating the parameters of a model to fit a given data set. 146

**MIMO** multiple-input multiple-output. 141

**model based design** A method for addressing the challenges of control systems design using mathematical modelling. Typically, a model of a plant is used as a substitute for a physical plant during a design process, which allows the easier synthesis of a control scheme. 140

**model order** The number of differential or delayed states in a model. 148

**monitoring** A continuous real-time task of determining the conditions of a physical system, by recording information, recognising and indicating anomalies in the behaviour. 36

**multiplicative fault** A class of fault that affects the parameters of a process. 40

**NBHS** Neutral Beam Heating System. 14

**NBI** Neutral Beam Injector. 27

**neural network** A computational method inspired by biology and neuroscience, commonly used in pattern recognition and control. 45, 46, 48

**NIF** National Ignition Facility. 10

**NIST** National Institute of Standards and Technology. 83

**OE** output-error. 144

**parity relations** A technique for detecting faults using analytical redundancy. 38

**PCA** Principle Component Analysis. 45

**PINI** Positive Ion Neutral Injector. 16, 26

**PLC** Programmable Logic Controller. 31

**PRBS** pseudo random binary signal. 151, 239
Proficy iFix is a software application produced by General Electric which provides ergonomic access to data collected on a supervisory control and data acquisition system. 117

QTA Qualitative Trend Analysis (QTA) is a technique for analysing a time series set of data to explain relationships and trends in a qualitative manner. 44

qualitative physics A field concerned with representing physical phenomena qualitatively, typically for software or artificial intelligence applications. 42

RBD Reliability Block Diagram. 59

reliability Ability of a system to perform a required function under stated conditions, within a given scope, during a given period of time. 35, 36

residual A fault indicator, based on a deviation between measurements and model-equation-based computations. 35, 39

RHVV Rotary High Vacuum Valve. 27

SCADA Supervisory Control and Data Acquisition. 117

SISO single-input single-output. 141, 236

supervision Monitoring a physical system and taking appropriate actions to maintain the operation in the case of faults. 36

symptom A change of an observable quantity from normal behaviour. 35

system identification The name given to the set of statistical techniques used to generate a mathematical model of a system or plant, given a set of historical data. 141


A. List of Symbols

Subscript Description

- $r$ Relating to capillaries (riser)
- $d$ Relating to phase separator (drum)
- $f$ Relating to supply (feed)
- $w$ Relating to fluid
- $s$ Relating to vapour
- $m$ Relating to metalwork or assembly
- $t$ Relating to whole system
- $tl$ Relating to the transmission line
- $rl$ Relating to the return line

Table A.1.: Table of Subscripts

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$</td>
<td>W</td>
<td>Heat load</td>
</tr>
<tr>
<td>$F_e$</td>
<td>Unitless</td>
<td>Emissivity Factor</td>
</tr>
<tr>
<td>$F_{nm}$</td>
<td>Unitless</td>
<td>View Factor</td>
</tr>
<tr>
<td>$T$</td>
<td>K</td>
<td>Temperature</td>
</tr>
<tr>
<td>$A_n$</td>
<td>$m^2$</td>
<td>Surface area</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>$Js^{-1}m^{-2}K^{-4}$</td>
<td>Stefan-Boltzmann constant</td>
</tr>
<tr>
<td>$c$</td>
<td>ms$^{-1}$</td>
<td>Velocity</td>
</tr>
<tr>
<td>$M$</td>
<td>kgmol$^{-1}$</td>
<td>Molar mass</td>
</tr>
<tr>
<td>$R$</td>
<td>JK$^{-1}$mol$^{-1}$</td>
<td>Molar gas constant</td>
</tr>
<tr>
<td>$q_f$</td>
<td>kg/s</td>
<td>Feed mass flow rate</td>
</tr>
<tr>
<td>$q_s$</td>
<td>kg/s</td>
<td>Gas return mass flow rate</td>
</tr>
<tr>
<td>$p$</td>
<td>Pa</td>
<td>Phase separator pressure</td>
</tr>
<tr>
<td>$l$</td>
<td>m</td>
<td>Phase separator fluid level</td>
</tr>
</tbody>
</table>
### APPENDIX A. LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v$</td>
<td>m$^3$</td>
<td>Volume</td>
</tr>
<tr>
<td>$\rho$</td>
<td>kg/m$^3$</td>
<td>Density</td>
</tr>
<tr>
<td>$u$</td>
<td>J/kg</td>
<td>Specific internal energy</td>
</tr>
<tr>
<td>$h$</td>
<td>J/kg</td>
<td>Specific enthalpy</td>
</tr>
<tr>
<td>$t$</td>
<td>K</td>
<td>Temperature</td>
</tr>
<tr>
<td>$m_t$</td>
<td>kg</td>
<td>Metalwork mass</td>
</tr>
<tr>
<td>$m_r$</td>
<td>kg</td>
<td>Mass of capillaries and panels</td>
</tr>
<tr>
<td>$C_p$</td>
<td>J/K</td>
<td>Specific heat capacity</td>
</tr>
<tr>
<td>$\alpha_m$</td>
<td>Unitless</td>
<td>Steam quality in capillaries</td>
</tr>
<tr>
<td>$\alpha_r$</td>
<td>Unitless</td>
<td>Steam quality at top of capillaries</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Unitless</td>
<td>Normalised length</td>
</tr>
<tr>
<td>$z$</td>
<td>m</td>
<td>Length coordinate</td>
</tr>
<tr>
<td>$\bar{\lambda}$</td>
<td>Unitless</td>
<td>Average steam volume ratio</td>
</tr>
<tr>
<td>$A_d$</td>
<td>m$^2$</td>
<td>Phase separator wet surface</td>
</tr>
<tr>
<td>$l_w$</td>
<td>m</td>
<td>Phase separator level deviation due to fluid change</td>
</tr>
<tr>
<td>$l_s$</td>
<td>m</td>
<td>Phase separator level deviation due to vapour change</td>
</tr>
<tr>
<td>$V_{sd}$</td>
<td>m$^3$</td>
<td>Volume of vapour below fluid level</td>
</tr>
<tr>
<td>$V_{wd}$</td>
<td>m$^3$</td>
<td>Volume of fluid below fluid level</td>
</tr>
<tr>
<td>$V_{st}$</td>
<td>m$^3$</td>
<td>Volume of vapour above fluid level</td>
</tr>
<tr>
<td>$q_{sd}$</td>
<td>kg/s</td>
<td>Flow rate of vapour through fluid</td>
</tr>
<tr>
<td>$q_{cd}$</td>
<td>kg/s</td>
<td>Flow rate of condensation</td>
</tr>
<tr>
<td>$T_{sd}$</td>
<td>s</td>
<td>Vapour flow time coefficient</td>
</tr>
<tr>
<td>$t_s$</td>
<td>K</td>
<td>Vapour Temperature</td>
</tr>
<tr>
<td>$t_m$</td>
<td>K</td>
<td>Metalwork Temperature</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>kg/m$^3$</td>
<td>Fluid density from steam table</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>kg/m$^3$</td>
<td>Vapour density from steam table</td>
</tr>
<tr>
<td>$V_{ht}$</td>
<td>l</td>
<td>Fluid volume in the helium tank</td>
</tr>
<tr>
<td>$K_{KI}$</td>
<td>l/m$^3$</td>
<td>Factor for converting m$^3$ to litres</td>
</tr>
<tr>
<td>$q_{tf}$</td>
<td>kg/s</td>
<td>Helium tank refill rate</td>
</tr>
<tr>
<td>$q_{sc}$</td>
<td>kg/s</td>
<td>Flow rate from helium tank to subcooler</td>
</tr>
<tr>
<td>$q_{tl}$</td>
<td>kg/s</td>
<td>Flow rate to a transmission line</td>
</tr>
<tr>
<td>$q_{ts}$</td>
<td>kg/s</td>
<td>Flow rate of helium tank losses</td>
</tr>
</tbody>
</table>

Table A.2.: Table of Symbols
B. Cryogenic Plant Mimics

Figure B.1.: Helium tanks mimic
Figure B.2.: Valve box one mimic
Figure B.3.: Valve box two mimic
Figure B.4.: Nitrogen tanks mimic
Figure B.5.: NIB4 mimic
Figure B.6.: NIB8 mimic
Figure B.7.: TCF200 liquefier mimic
Figure B.8.: TCF200 purifier mimic
C. Cryogenic Plant FMECA Worksheet

Figure C.1.: A graphical representation of the system components, their functions, and interactions
<table>
<thead>
<tr>
<th>Unit Description Function</th>
<th>Description of Failure</th>
<th>Failure Mode</th>
<th>Failure Cause</th>
<th>Effect of Failure</th>
<th>Other Systems</th>
<th>This System</th>
<th>Assessment</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contain fluid</td>
<td>Fluid is not con-</td>
<td>Accidental</td>
<td></td>
<td>Loss of LHe supply pressure</td>
<td>Vessel is leaking helium</td>
<td>Catastrophic</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>tained</td>
<td>punct-</td>
<td></td>
<td>Unwanted material in He supply</td>
<td>Vessel pressure drops</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ture</td>
<td></td>
<td>Unwanted material sent to the liquefier</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintain liquid</td>
<td>Incorrect fluid pres-</td>
<td>Transmission</td>
<td></td>
<td>Loss of LHe supply pressure</td>
<td>Vessel pressure drops</td>
<td>Catastrophic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pressure and tem-</td>
<td>sure</td>
<td>line</td>
<td></td>
<td>Unwanted material in He supply</td>
<td>Loss of helium gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>seal failure</td>
<td></td>
<td>Unwanted material sent to the liquefier</td>
<td>Increased tank losses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Incorrect fluid temperature</td>
<td>Increase in LHe supply pressure</td>
<td>Fluid temperature rises</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Increase in LHe supply temperature</td>
<td>Fluid pressure rises</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Higher liquefier load</td>
<td>Increased tank losses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit Description Function</td>
<td>Description of Failure</td>
<td>Failure Mode</td>
<td>Failure Cause</td>
<td>Effect of Failure</td>
<td>Other Systems</td>
<td>This System</td>
<td>Assessment</td>
<td>Severity</td>
</tr>
<tr>
<td>---------------------------</td>
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</tr>
<tr>
<td>Permit liquid to enter and leave the tank</td>
<td>Helium exit line blocked</td>
<td>Ice build up owing to helium contamination</td>
<td>Reduced LHe flow rate</td>
<td>Reduced LHe consumption</td>
<td>Critical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Line kink or pinch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Helium feed line blocked</td>
<td>Ice build up owing to helium contamination</td>
<td>Loss of He supply</td>
<td>Tank is not refilled</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Line kink or pinch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimise tank losses</td>
<td>Excessive tank losses</td>
<td>Liquefier control valve fails open</td>
<td>Higher liquefier load</td>
<td>Tank pressure drops</td>
<td>Major</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Increased helium boil off</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tank insulation degradation</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Increase in LHe supply pressure</td>
<td>Fluid temperature rises</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Increase in LHe supply temperature</td>
<td>Fluid pressure rise</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Higher liquefier load</td>
<td>Increased tank losses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit Description Function</td>
<td>Description of Failure</td>
<td>Failure Mode</td>
<td>Failure Cause</td>
<td>Effect of Failure</td>
<td>Other Systems</td>
<td>This System</td>
<td>Assessment</td>
<td>Severity</td>
</tr>
<tr>
<td>---------------------------</td>
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<td>-----------------</td>
<td>---------------</td>
<td>-------------</td>
<td>-----------</td>
<td>---------</td>
</tr>
<tr>
<td>Transmission line seal failure</td>
<td>Loss of LHe supply pressure</td>
<td>Loss of LHe supply pressure</td>
<td>Vessel pressure drops</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unwanted material in He supply</td>
<td></td>
<td></td>
<td>Loss of helium gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unwanted material sent to the liquefier</td>
<td></td>
<td></td>
<td>Increased tank losses</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Table C.1.: The helium tank FMECA worksheet
<table>
<thead>
<tr>
<th>Unit Description</th>
<th>Description of Failure</th>
<th>Effect of Failure</th>
<th>Other Systems</th>
<th>This System</th>
<th>Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contain liquid</td>
<td>Fluid is not contained</td>
<td>LHe supply pressure drops</td>
<td>Transmission line is leaking</td>
<td></td>
<td>Catastrophic</td>
</tr>
<tr>
<td></td>
<td>Tx line is punctured</td>
<td>Rx line pressure tends towards atmosphere</td>
<td>Tx line pressure tends towards atmosphere</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transmission line is incorrectly fitted</td>
<td>He supply/return is contaminated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>N2 supply/return is contaminated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vacuum jacket pressure rise</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vacuum jacket contaminated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmit liquid</td>
<td>Fluid transmission rate reduced</td>
<td>N2 supply/return flow rate drops</td>
<td>Tx line flow rate Critical (conductance) drops</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tx line kinked or pinched</td>
<td>Transmission line is incorrectly fitted</td>
<td>He return flow rate drops</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ice build up owing to helium contamination</td>
<td>Possible downstream ice build up</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tx line flow rate drops</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit Description Function</td>
<td>Description of Failure</td>
<td>Failure Mode</td>
<td>Failure Cause</td>
<td>Effect of Failure Other Systems</td>
<td>This System</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>------------------------</td>
<td>--------------</td>
<td>--------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Minimise heat load on the liquid</td>
<td>Excessive fluid heat load</td>
<td>Tx line insulation failure</td>
<td>Higher temperature fluid fed to heat exchanger</td>
<td>LHe temperature rise/vapour formation</td>
<td>Tx line pressure rises</td>
</tr>
<tr>
<td>Contain gas</td>
<td>Gas is not contained</td>
<td>Rx line is punctured</td>
<td>He supply (possibly) is contaminated</td>
<td>Transmission line is leaking</td>
<td>N2 supply/return (possibly) is contaminated</td>
</tr>
<tr>
<td>Transmit gas</td>
<td>Gas transmission rate reduced</td>
<td>Rx line kinked or pinched</td>
<td>N2 supply/return flow rate drops</td>
<td>Rx line pressure tends towards atmospheric</td>
<td>Vacuum jacket pressure rise</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Vacuum jacket contaminated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Phase sep. pressure tends towards atmospheric</td>
</tr>
<tr>
<td>Unit Description Function</td>
<td>Description of Failure</td>
<td>Effect of Failure</td>
<td>Other Systems</td>
<td>This System</td>
<td>Assessment</td>
</tr>
<tr>
<td>---------------------------</td>
<td>------------------------</td>
<td>------------------</td>
<td>---------------</td>
<td>-------------</td>
<td>------------</td>
</tr>
<tr>
<td>Transmission line is He supply flow rate drops</td>
<td>He supply flow rate drops</td>
<td>Ice build up owing to helium contamination Possible downstream ice build up Rx line flow rate drops</td>
<td>Minimise heat load on the gas Excessive gas heat load Rx line insulation failure Higher temperature fluid fed to heat exchanger</td>
<td>Rx line pressure rises</td>
<td>Major</td>
</tr>
</tbody>
</table>

Table C.2.: The transmission lines FMECA worksheet
<table>
<thead>
<tr>
<th>Unit Description Function</th>
<th>Description of Failure</th>
<th>Failure Mode</th>
<th>Failure Cause</th>
<th>Effect of Failure</th>
<th>Other Systems</th>
<th>This System</th>
<th>Assessment Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condense trace gasses</td>
<td>Trace gasses not being condensed</td>
<td>Excessive panel heat load</td>
<td>Vacuum vessel pressure increases</td>
<td>Previously condensed gasses evaporating Inappropriate panel regeneration Increased LHe boil-off</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allow passage of helium through capillaries</td>
<td>Capillary flow rate is impaired</td>
<td>Capillaries blocked/obstructed</td>
<td>Vacuum vessel pump rate possibly impaired</td>
<td>Capillary refill rate Critical reduced</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contain helium gas and liquid</td>
<td>Helium is not contained</td>
<td>Mechanical damage to panels</td>
<td>Helium leak into vacuum vessel</td>
<td>Heat exchanger is leaking fluid and gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit Description</td>
<td>Description of Failure</td>
<td>Effect of Failure</td>
<td>Other Systems</td>
<td>This System</td>
<td>Assessment</td>
<td>Severity</td>
<td></td>
</tr>
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<td>-----------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>Function</td>
<td>Failure Mode</td>
<td>Failure Cause</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Panels not correctly</td>
<td>Tx line pressure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>fitted</td>
<td>tends towards</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>atmospheric</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transmission line</td>
<td>Heat hxr. pressure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>not correctly fitted</td>
<td>tends towards</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>atmospheric</td>
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<td>Heat hxr. level</td>
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<td></td>
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<td>drops</td>
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<tr>
<td></td>
<td></td>
<td>Helium supply and</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>return is</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>contaminated</td>
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</tbody>
</table>

Table C.3.: The heat exchanger FMECA worksheet
<table>
<thead>
<tr>
<th>Unit Description Function</th>
<th>Description of Failure</th>
<th>Effect of Failure</th>
<th>Other Systems</th>
<th>This System</th>
<th>Assessment</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contain N2 fluid and gas</td>
<td>Nitrogen is not contained</td>
<td>Mechanical damage to the panels</td>
<td>Vacuum vessel pressure rise</td>
<td>Panels/Phase Separators are leaking</td>
<td>Catastrophic</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seal failure</td>
<td>Increased heat load on helium panels</td>
<td>Loss of cooling efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Increased N2 usage</td>
<td>Phase separator level drop</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allow passage of N2 fluid and gas</td>
<td>Capillaries or exit manifold blocked</td>
<td>Ice build up in the capillaries or phase separator</td>
<td>Increased pressure in the N2 feed line</td>
<td>Panels are not being filled correctly</td>
<td>Critical</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Drop in N2 return flow rate</td>
<td>Pressure rise inside panels and/or phase sep.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Increased heat load on helium panels</td>
<td>Loss of cooling efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Possible drop in pumping efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enclose LHe panels</td>
<td>LHe panels not enclosed correctly</td>
<td>Panels are not fitted correctly</td>
<td>Increased heat load on helium panels</td>
<td>Possible future mechanical damage</td>
<td>Critical</td>
<td></td>
</tr>
<tr>
<td>Provide sacrificial radiation shielding</td>
<td>Excessive N2 panel temperature</td>
<td>Reduced N2 supply</td>
<td>Increased heat load on helium panels</td>
<td>Increased N2 boil rate</td>
<td>Critical</td>
<td></td>
</tr>
<tr>
<td>Unit Description Function</td>
<td>Description of Failure</td>
<td>Effect of Failure</td>
<td>Other Systems</td>
<td>This System</td>
<td>Assessment</td>
<td>Severity</td>
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<td>----------</td>
</tr>
<tr>
<td>Excessive thermal load</td>
<td></td>
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Table C.4.: The radiation shield FMECA worksheet
<table>
<thead>
<tr>
<th>Unit Description Function</th>
<th>Description of Failure</th>
<th>Effect of Failure</th>
<th>Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHe tank valves move to the correct position</td>
<td>Incorrect fill valve position</td>
<td>Incorrect tank refill rate</td>
<td>Critical</td>
</tr>
<tr>
<td></td>
<td>Stuck valve</td>
<td>Incorrect tank refill rate</td>
<td>Critical</td>
</tr>
<tr>
<td></td>
<td>Broken valve stem</td>
<td>Incorrect tank pressure</td>
<td>Valve unavailable for mode change</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Incorrect cross feed valve position</td>
<td>Incorrect flow to or from 10/5K tank</td>
<td>Critical</td>
</tr>
<tr>
<td></td>
<td>Stuck valve</td>
<td>Incorrect tank pressure</td>
<td>Valve unavailable for mode change</td>
</tr>
<tr>
<td></td>
<td>Broken valve stem</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Incorrect exit valve position</td>
<td>Incorrect fluid delivery state</td>
<td>Unable to stop LHe exit flow</td>
</tr>
<tr>
<td></td>
<td>Stuck valve</td>
<td></td>
<td>Critical</td>
</tr>
<tr>
<td></td>
<td>Broken valve stem</td>
<td>Unwanted LHe supply</td>
<td>Valve unavailable for mode change</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unwanted pressure boundary</td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHe tank valves move at the required speed</td>
<td>Fill valve movement</td>
<td>Tank refill is delayed</td>
<td>Minor</td>
</tr>
<tr>
<td></td>
<td>Sticky valve</td>
<td>Delayed change in flow rate</td>
<td></td>
</tr>
<tr>
<td>Unit Description</td>
<td>Description of Failure</td>
<td>Effect of Failure</td>
<td>Assessment</td>
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<td>------------</td>
</tr>
<tr>
<td>Function</td>
<td>Failure Mode</td>
<td>Failure Cause</td>
<td>Other Systems</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cross feed valve</td>
<td>Sticky valve</td>
<td>Delayed flow to or from 10/5K tank</td>
</tr>
<tr>
<td></td>
<td>movement speed impaired</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exit valve movement speed impaired</td>
<td>Sticky valve</td>
<td>Delayed change in fluid delivery state</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LHe tank valves</td>
<td>Ice build up on valve</td>
<td>Incorrect tank refill rate</td>
</tr>
<tr>
<td></td>
<td>conduct correct volume of fluid</td>
<td>Mechanical damage to valve</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fill valve conductance changed</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fill valve is bypassed</td>
<td>Valve incorrectly seated</td>
<td>Incorrect tank refill rate</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit Description</td>
<td>Description of Failure</td>
<td>Effect of Failure</td>
<td>Assessment</td>
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</tr>
<tr>
<td>Function</td>
<td>Failure Mode</td>
<td>Other Systems</td>
<td>Severity</td>
</tr>
<tr>
<td>Valve seal is degraded or damaged</td>
<td>Tank fluid is contaminated</td>
<td>Major</td>
<td></td>
</tr>
<tr>
<td>Cross feed valve conductance changed</td>
<td>Ice build up on valve</td>
<td>Incorrect flow to or from 10/5K tank</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mechanical damage to valve</td>
<td>Incorrect tank pressure</td>
<td></td>
</tr>
<tr>
<td>Cross feed valve is bypassed</td>
<td>Valve incorrectly seated</td>
<td>Incorrect flow to or from 10/5K tank</td>
<td>Major</td>
</tr>
<tr>
<td></td>
<td>Valve seal is degraded or damaged</td>
<td>10/5K tank fluid is contaminated</td>
<td></td>
</tr>
<tr>
<td>Exit valve conductance changed</td>
<td>Ice build up on valve</td>
<td>LHe supply flow changed</td>
<td>Critical</td>
</tr>
<tr>
<td></td>
<td>Mechanical damage to valve</td>
<td>Incorrect exit valve flow rate</td>
<td></td>
</tr>
<tr>
<td>Unit Description Function</td>
<td>Description of Failure</td>
<td>Failure Mode</td>
<td>Failure Cause</td>
</tr>
<tr>
<td>---------------------------</td>
<td>------------------------</td>
<td>--------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Exit valve is bypassed</td>
<td>Valve incorrectly seated</td>
<td>Valve seal is degraded or damaged</td>
<td>Incorrect LHe supply flow</td>
</tr>
<tr>
<td>Tx valves move to the correct position</td>
<td>Incorrect valve position</td>
<td>Stuck valve</td>
<td>Incorrect LHe flow rate</td>
</tr>
<tr>
<td>Tx valves move at required speed</td>
<td>Valve movement speed impaired</td>
<td>Sticky valve</td>
<td>Delayed change in LHe flow rate</td>
</tr>
<tr>
<td>Tx valves conduct correct volume of fluid</td>
<td>Valve conductance changed</td>
<td>Ice build up on valve</td>
<td>Incorrect LHe flow rate</td>
</tr>
<tr>
<td>Unit Description Function</td>
<td>Description of Failure</td>
<td>Effect of Failure</td>
<td>Assessment Severity</td>
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</tr>
<tr>
<td></td>
<td>Mechanical damage to valve</td>
<td>Valve is bypassed</td>
<td>Incorrect LHe flow rate</td>
</tr>
<tr>
<td></td>
<td>Valve is bypassed</td>
<td>Valve is incorrectly seated</td>
<td>Helium in Tx line is (potentially) contaminated</td>
</tr>
<tr>
<td></td>
<td>Valve seal is damaged or degraded</td>
<td>Incorrect LHe flow rate</td>
<td>Valve no longer controls flow rate</td>
</tr>
<tr>
<td>Rx valves move to the correct position</td>
<td>Stuck valve</td>
<td>Incorrect He flow rate</td>
<td>Critical flow rate</td>
</tr>
<tr>
<td></td>
<td>Broken valve stem</td>
<td></td>
<td>Valve unavailable for mode change</td>
</tr>
<tr>
<td>Rx valves move at required speed</td>
<td>Sticky valve</td>
<td>Delays change in He flow rate</td>
<td>Major flow rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Delayed response to mode change</td>
</tr>
<tr>
<td>Rx valves conduct correct volume of fluid</td>
<td>Valve conductance changed</td>
<td>Incorrect He flow rate</td>
<td>Incorrect Rx valve</td>
</tr>
<tr>
<td>Unit Description</td>
<td>Description of Failure</td>
<td>Effect of Failure</td>
<td>Assessment</td>
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<tr>
<td>------------------</td>
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</tr>
<tr>
<td>Valve</td>
<td>Valve is bypassed</td>
<td>Valve no longer</td>
<td>Critical</td>
</tr>
<tr>
<td></td>
<td>Valves incorrectly</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>seated</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Valve seal is damaged</td>
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</tr>
<tr>
<td></td>
<td>or degraded</td>
<td></td>
<td></td>
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<tr>
<td>Vacuum jacket</td>
<td>Broken valve stem</td>
<td>Incorrect vacuum</td>
<td>Critical</td>
</tr>
<tr>
<td>valve in correct</td>
<td></td>
<td>generation</td>
<td></td>
</tr>
<tr>
<td>position</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical damage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>to valve</td>
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<td></td>
</tr>
</tbody>
</table>

Table C.5.: The valve box FMECA worksheet
<table>
<thead>
<tr>
<th>Unit Description</th>
<th>Description of Failure</th>
<th>Failure Mode</th>
<th>Failure Cause</th>
<th>Other Systems</th>
<th>This System</th>
<th>Assessment</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Select appropriate tank valve positions</td>
<td>Inappropriate fill valve position selected</td>
<td>Tank level gauge failure</td>
<td>Inappropriate tank fill rate</td>
<td>None</td>
<td>Critical</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deliver tank control signal</td>
<td>Control signal not delivered to fill valve</td>
<td>Mechanical damage to signal cable</td>
<td>Inappropriate tank fill rate</td>
<td>Unavailable for mode change</td>
<td>Catastrophic</td>
<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Parametric change in valve or LHe tank/source

Control software failure

Loss of power

Loss of power

Control software failure
<table>
<thead>
<tr>
<th>Unit Description Function</th>
<th>Description of Failure</th>
<th>Failure Mode</th>
<th>Failure Cause</th>
<th>Effect of Failure Other Systems</th>
<th>This System</th>
<th>Assessment Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control signal not delivered to cross feed valve</td>
<td>Mechanical damage to signal cable</td>
<td>Unable to start/stop cross feed</td>
<td>Loss of power</td>
<td>Control software failure</td>
<td>Unavailable for mode change</td>
<td></td>
</tr>
<tr>
<td>Control signal not delivered to exit valve</td>
<td>Mechanical damage to signal cable</td>
<td>Unable to start/stop fluid delivery</td>
<td>Loss of power</td>
<td>Control software failure</td>
<td>Unavailable for mode change</td>
<td></td>
</tr>
<tr>
<td>Respond to supervisory system tank command</td>
<td>Not responding to supervisory system</td>
<td>Mechanical damage to signal cable</td>
<td>Potential inappropriate tank fill rate</td>
<td>Unavailable for Major mode change</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Loss of power</td>
<td>Potential inappropriate cross feed state</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Control software failure</td>
<td>Potential inappropriate fluid delivery state</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit Description Function</td>
<td>Description of Failure</td>
<td>Failure Mode</td>
<td>Failure Cause</td>
<td>Effect of Failure</td>
<td>Other Systems</td>
<td>This System</td>
</tr>
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<td>---------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Select appropriate Tx valve position</td>
<td>Inappropriate valve position selected</td>
<td>Phase separator delta pressure gauge failure</td>
<td>Inappropriate Tx valve position</td>
<td>None</td>
<td></td>
<td>Catastrophic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Parametric change in valve, Tx line, or Heat Xchr</td>
<td>Inappropriate LHe flow rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control software failure</td>
<td>Inappropriate Tx valve position</td>
<td>Possibly unavailable for mode change</td>
<td>Inappropriate LHe flow rate</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Loss of power</td>
<td>Inappropriate Tx valve position</td>
<td>Unavailable for mode change</td>
<td>Inappropriate LHe flow rate</td>
<td></td>
</tr>
<tr>
<td>Deliver Tx control signal</td>
<td>Control signal not delivered to Tx valve</td>
<td>Mechanical damage to signal cable</td>
<td>Inappropriate Tx valve position</td>
<td>Unavailable for mode change</td>
<td></td>
<td>Catastrophic</td>
</tr>
<tr>
<td>Unit Description Function</td>
<td>Description of Failure</td>
<td>Effect of Failure</td>
<td>Other Systems</td>
<td>This System</td>
<td>Assessment</td>
<td>Severity</td>
</tr>
<tr>
<td>---------------------------</td>
<td>------------------------</td>
<td>------------------</td>
<td>---------------</td>
<td>-------------</td>
<td>------------</td>
<td>----------</td>
</tr>
<tr>
<td>Respond to supervisory system Tx command</td>
<td>Not responding to supervisory system</td>
<td>Mechanical damage to signal cable</td>
<td>Potential inappropriate Tx valve position</td>
<td>Unavailable for mode change</td>
<td>Major</td>
<td></td>
</tr>
<tr>
<td>Select appropriate Rx valve position</td>
<td>Inappropriate valve position selected</td>
<td>Phase separator delta pressure gauge failure</td>
<td>Inappropriate Rx valve position</td>
<td>None</td>
<td>Critical</td>
<td></td>
</tr>
</tbody>
</table>

- Loss of power
- Inappropriate LHe flow rate
- Control software failure
- Mechanical damage to signal cable
- Potential inappropriate Tx valve position
- Loss of power
- Potential inappropriate LHe flow rate
- Control software failure
- Parametric change in valve, Rx line, or Heat Xchr
- Inappropriate He flow rate
- Control software failure
- Inappropriate Rx valve position
- Possibly unavailable for mode change
<table>
<thead>
<tr>
<th>Unit Description</th>
<th>Description of Failure</th>
<th>Effect of Failure</th>
<th>Other Systems</th>
<th>This System</th>
<th>Assessment Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inappropriate He flow rate</strong></td>
<td><strong>Loss of power</strong></td>
<td>Inappropriate Rx valve position</td>
<td><strong>Unavailable</strong> for mode change</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Inappropriate Rx valve position</strong></td>
<td><strong>Unavailable for mode change</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Critical</strong></td>
<td><strong>Loss of power</strong></td>
<td>Inappropriate He flow rate</td>
<td><strong>Unavailable</strong> for Critical mode change</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Loss of power</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Control software failure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Respond to supervisory system Rx command</strong></td>
<td>Not responding to supervisory system</td>
<td>Mechanical damage to signal cable</td>
<td>Potential inappropriate Rx valve position</td>
<td><strong>Unavailable</strong> for Major mode change</td>
<td></td>
</tr>
<tr>
<td><strong>Loss of power</strong></td>
<td>Potential inappropriate He flow rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Control software failure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table C.6.: The control and data acquisition FMECA worksheet

| Unit Description Function | Description of Failure Failure Mode | Failure Cause | Effect of Failure Other Systems | This System Assessment Severity |
|---------------------------|-------------------------------------|--------------|----------------------------------|-------------------------------|----------------|


## D. List of Linear Models

### Heat exchanger

**Input:** Inlet fluid flow rate  
**Output:** Outlet gas flow rate  

\[
\begin{align*}
A(k) & : \quad 1 - 1.07(k - 1) + 0.07168(k - 2) \\
B(k) & : \quad 0.0001792(k - 1) + 6.01 \times 10^{-5}(k - 2) \\
\text{Fit} & : \quad 98.92 \% \\
\text{Best ID technique} & : \quad \text{Least squares}
\end{align*}
\]

### Input: Inlet fluid flow rate  
**Output:** Gas pressure  

\[
\begin{align*}
A(k) & : \quad 1 - 1.054(k - 1) + 0.05568(k - 2) \\
B(k) & : \quad 680.1(k - 1) + 244.3(k - 2) \\
\text{Fit} & : \quad 98.94 \% \\
\text{Best ID technique} & : \quad \text{Least squares}
\end{align*}
\]

### Input: Inlet fluid flow rate  
**Output:** Gas temperature  

\[
\begin{align*}
A(k) & : \quad 1 - 0.9981(k - 1) + 7.419 \times 10^{-5}(k - 2) \\
B(k) & : \quad 0.006954(k - 1) + 0.003055(k - 2) \\
\text{Fit} & : \quad 98.92 \% \\
\text{Best ID technique} & : \quad \text{Instrumental variables}
\end{align*}
\]

### Input: Inlet fluid flow rate  
**Output:** Fluid level  

\[
\begin{align*}
A(k) & : \quad 1 - 1.969(k - 1) + 0.9694(k - 2) \\
B(k) & : \quad 25.37(k - 1) + 26.36(k - 2)
\end{align*}
\]
# APPENDIX D. LIST OF LINEAR MODELS

## Heat exchanger

**Fit:** 58.65 %  
**Best ID technique:** Least squares

**Input:** Inlet fluid temperature  
**Output:** Outlet gas flow rate  
**$A(k):****  
$$1 - 1.042(k - 1) + 0.04376(k - 2)$$  
**$B(k):****  
$$1.431 \times 10^{-6}(k - 1) + 6.717 \times 10^{-7}(k - 2)$$  
**Fit:** 99.9 %  
**Best ID technique:** Least squares

## Input: Inlet fluid temperature  
**Output:** Gas pressure  
**$A(k):****  
$$1 - 1.041(k - 1) + 0.04331(k - 2)$$  
**$B(k):****  
$$5.437(k - 1) + 2.555(k - 2)$$  
**Fit:** 99.9 %  
**Best ID technique:** Least squares

## Input: Inlet fluid temperature  
**Output:** Gas temperature  
**$A(k):****  
$$1 - 1.041(k - 1) + 0.04331(k - 2)$$  
**$B(k):****  
$$5.559 \times 10^{-5}(k - 1) + 2.613 \times 10^{-5}(k - 2)$$  
**Fit:** 99.9 %  
**Best ID technique:** Least squares

## Input: Inlet fluid temperature  
**Output:** Fluid level  
**$A(k):****  
$$1 - 2.011(k - 1) + 1.025(k - 2) - 0.01351(k - 3)$$  
**$B(k):****  
$$-0.1746(k - 1) + 0.08175(k - 2) + 0.09282(k - 3)$$  
**Fit:** 90.96 %  
**Best ID technique:** Instrumental variables
Heat exchanger

Input: Heat load
Output: Outlet gas flow rate
\[ A(k) = 1 - 0.04981(k - 1) - 0.499(k - 2) \]
\[ B(k) = 8.141 \times 10^{-8}(k - 1) + 4.176 \times 10^{-8}(k - 2) \]
Fit: 96.81 %
Best ID technique: Instrumental variables

Input: Heat load
Output: Gas pressure
\[ A(k) = 1 - 0.6278(k - 1) + 0.3695(k - 2) \]
\[ B(k) = 0.311(k - 1) - 0.1151(k - 2) \]
Fit: 99.96 %
Best ID technique: Instrumental variables

Input: Heat load
Output: Gas temperature
\[ A(k) = 1 - 0.4981(k - 1) - 0.499(k - 2) \]
\[ B(k) = 3.18 \times 10^{-6}(k - 1) + 1.584 \times 10^{-6}(k - 2) \]
Fit: 99.48 %
Best ID technique: Least squares

Input: Heat load
Output: Fluid level
\[ A(k) = 1 - 3.103(k - 1) + 3.211(k - 2) - 1.107(k - 3) \]
\[ B(k) = -0.007996(k - 1) + 0.01696(k - 2) - 0.009035(k - 3) \]
Fit: 78.42 %
Best ID technique: Instrumental variables

Table D.1.: A list of linear heat exchanger models
APPENDIX D. LIST OF LINEAR MODELS

Supply line

Input: Inlet Flow Rate
Output: Outlet Flow Rate

\[ A(k): 1 - 1.0194(k - 1) + 0.01077(k - 2) \]

\[ B(k): 0.9993(k - 1) - 1.007(k - 2) \]

Fit: 99.92 %

Best ID technique: Instrumental variables

Input: Inlet Flow Rate
Output: Line Temperature

\[ A(k): 1 - 0.9528(k - 1) - 0.0002761(k - 2) \]

\[ B(k): 0.6341(k - 1) - 0.6044(k - 2) \]

Fit: 99.91 %

Best ID technique: Instrumental variables

Input: Inlet Flow Rate
Output: Line Pressure

\[ A(k): 1 - 1.148 \times 10^{-7}(k - 1) - 0.0002041(k - 2) \]

\[ B(k): 1.183 \times 10^{-7}(k - 1) - 9.261 \times 10^{-11}(k - 2) \]

Fit: 63.5 %

Best ID technique: Instrumental variables

Input: Inlet Temperature
Output: Outlet Flow Rate

\[ A(k): 1 - 0.9457(k - 1) + 0.0001617(k - 2) \]

\[ B(k): 0.005396(k - 1) - 0.005101(k - 2) \]

Fit: 99.87 %

Best ID technique: Instrumental variables

Input: Inlet Temperature
Output: Line Pressure
APPENDIX D. LIST OF LINEAR MODELS

Supply line

\[ A(k) = 1 - 0.9603(k - 1) + 8.62 \times 10^{-5}(k - 2) \]
\[ B(k) = 0.006835(k - 1) - 0.006562(k - 2) \]
\[ \text{Fit: } 99.85\% \]
\[ \text{Best ID technique: Instrumental variables} \]

Input: Inlet Temperature
Output: Line Temperature

\[ A(k) = 1 - 1.016(k - 1) + 0.01594 \]
\[ B(k) = 3.75 \times 10^{-7}(k - 1) - 3.75 \times 10^{-7}(k - 2) \]
\[ \text{Fit: } 99.47\% \]
\[ \text{Best ID technique: Least Squares} \]

Input: Termination Pressure
Output: Outlet Flow Rate

\[ A(k) = 1 - 1.988(k - 1) + 0.9883(k - 2) \]
\[ B(k) = -0.1226(k - 1) + 0.3667(k - 2) - 0.3656(k - 3) + 0.1215(k - 4) \]
\[ \text{Fit: } 90.22\% \]
\[ \text{Best ID technique: Least Squares} \]

Input: Termination Pressure
Output: Line Temperature

\[ A(k) = 1 - 1.968(k - 1) + 0.9677(k - 2) \]
\[ B(k) = 1.917 \times 10^{-7}(k - 1) - 3.775 \times 10^{-7}(k - 2) + 1.858 \times 10^{-7}(k - 3) \]
\[ \text{Fit: } 98.45\% \]
\[ \text{Best ID technique: Least Squares} \]

Input: Termination Pressure
Output: Line Pressure

\[ A(k) = 1 - 1.557(k - 1) - 0.9452(k - 2) \]
\[ B(k) = 0.3672(k - 1) \]
## Supply line

*Fit*: 98.66 %  
*Best ID technique*: Least Squares

Table D.2.: A list of linear supply line models

### Return line

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Flow Rate</td>
<td>Outlet Flow Rate</td>
</tr>
<tr>
<td>$A(k)$:</td>
<td>$1 - 0.9932(k - 1) + 0.005778(k - 2)$</td>
</tr>
<tr>
<td>$B(k)$:</td>
<td>$0.001053(k - 1) + 1.224 \times 10^{-6}(k - 2)$</td>
</tr>
<tr>
<td><em>Fit</em>:</td>
<td>98.89 %</td>
</tr>
<tr>
<td><em>Best ID technique</em>: Instrumental variables</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Flow Rate</td>
<td>Line Temperature</td>
</tr>
<tr>
<td>$A(k)$:</td>
<td>$1 - 1.999^{-1} + 0.9989(k - 2)$</td>
</tr>
<tr>
<td>$B(k)$:</td>
<td>$0.00371(k - 1) - 0.00371(k - 2)$</td>
</tr>
<tr>
<td><em>Fit</em>:</td>
<td>98.99 %</td>
</tr>
<tr>
<td><em>Best ID technique</em>: Least Squares</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Flow Rate</td>
<td>Line Pressure</td>
</tr>
<tr>
<td>$A(k)$:</td>
<td>$1 - 1.999^{-1} + 0.9989(k - 2)$</td>
</tr>
<tr>
<td>$B(k)$:</td>
<td>$362.8(k - 1) - 362.8(k - 2)$</td>
</tr>
<tr>
<td><em>Fit</em>:</td>
<td>98.99 %</td>
</tr>
<tr>
<td><em>Best ID technique</em>: Least Squares</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Temperature</td>
<td>Outlet Flow Rate</td>
</tr>
<tr>
<td>$A(k)$:</td>
<td>$1 - 1.996(k - 1) + 0.9963(k - 2)$</td>
</tr>
</tbody>
</table>
APPENDIX D. LIST OF LINEAR MODELS

Return line

\[ B(k): -2.993 \times 10^{-8}(k - 1) - 2.974 \times 10^{-8}(k - 2) \]
Fit: 78.88 %
Best ID technique: Least Squares

---

Input: Inlet Temperature
Output: Line Pressure
\[ A(k): 1 - 1.996(k - 1) + 0.9963(k - 2) \]
\[ B(k): -0.01035(k - 1) + 0.01028(k - 2) \]
Fit: 78.89 %
Best ID technique: Least Squares

---

Input: Inlet Temperature
Output: Line Temperature
\[ A(k): 1 - 0.9991(k - 1) \]
\[ B(k): -1.066 \times 10^{-7}(k - 1) - 7.753 \times 10^{-8}(k - 2) \]
Fit: 99.47 %
Best ID technique: Least Squares

---

Input: Valve Position
Output: Outlet Flow Rate
\[ A(k): 1 - 0.3407(k - 1) - 0.341(k - 2) - 0.317(k - 3) \]
\[ B(k): 4.108 \times 10^{-5}(k - 1) - 4.109 \times 10^{-5}(k - 2) \]
Fit: 30.13 %
Best ID technique: Instrumental Variables

---

Input: Valve Position
Output: Line Temperature
\[ A(k): 1 - 0.9993(k - 1) - 7.54 \times 10^{-5}(k - 2) + 3.44 \times 10^{-5}(k - 3) \]
\[ B(k): -1.18 \times 10^{-7}(k - 1) - 1.152 \times 10^{-7}(k - 2) \]
Fit: 92.53 %
Return line

*Best ID technique:* Instrumental Variables

---

**Input:** Valve Position  
**Output:** Line Pressure  

\[ A(k) : 1 - 0.9989(k - 1) - 0.0005593(k - 2) + 0.0001615(k - 3) \]  

\[ B(k) : -0.01154(k - 1) - 0.01127(k - 2) \]  

**Fit:** 92.53 %  

*Best ID technique:* Instrumental Variables

Table D.3.: A list of linear return line models
## E. List of Kalman Filter Parameters

### Heat exchanger subsystem

**Input:** Inlet fluid flow rate  
**Output:** Outlet gas flow rate  

\[
R = \begin{bmatrix}
4.9516 \times 10^{-8} \\
3.4120 \times 10^{-20} & 0 \\
0 & 2.2859 \times 10^{-21}
\end{bmatrix}
\]

\[
Q = \begin{bmatrix}
4.6118 \times 10^{3} \\
4.1194 \times 10^{-7} & 0 \\
0 & 2.1766 \times 10^{-8}
\end{bmatrix}
\]

**Input:** Inlet fluid flow rate  
**Output:** Gas pressure  

\[
R = \begin{bmatrix}
2.7463 \times 10^{-4} \\
4.2112 \times 10^{-17} & 0 \\
0 & 3.130 \times 10^{-21}
\end{bmatrix}
\]

**Input:** Inlet fluid flow rate  
**Output:** Gas temperature  

\[
R = \begin{bmatrix}
0.3095 \\
7.7534 \times 10^{-5} & 0 \\
0 & 3.8167 \times 10^{-5}
\end{bmatrix}
\]

**Input:** Inlet fluid flow rate  
**Output:** Fluid level  

\[
R = \begin{bmatrix}
0.3095 \\
7.7534 \times 10^{-5} & 0 \\
0 & 3.8167 \times 10^{-5}
\end{bmatrix}
\]
APPENDIX E. LIST OF KALMAN FILTER PARAMETERS

Heat exchanger subsystem

\[ \begin{align*}
\text{Input:} & \quad \text{Inlet fluid temperature} \\
\text{Output:} & \quad \text{Outlet gas flow rate} \\
R: & \quad \begin{bmatrix} 4.9516 \times 10^{-8} \\ 3.4120 \times 10^{-21} \\ 0 \end{bmatrix} \\
Q: & \quad \begin{bmatrix} 0 & 1.8233 \times 10^{-22} \\ 0 & 1.8233 \times 10^{-22} \\ 0 & 1.8233 \times 10^{-22} \end{bmatrix}
\end{align*} \]

\[ \begin{align*}
\text{Input:} & \quad \text{Inlet fluid temperature} \\
\text{Output:} & \quad \text{Gas pressure} \\
R: & \quad \begin{bmatrix} 4.6118 \times 10^3 \\ 6.1962^{-8} \\ 0 \end{bmatrix} \\
Q: & \quad \begin{bmatrix} 0 & 2.5767 \times 10^{-9} \\ 0 & 2.5767 \times 10^{-9} \\ 0 & 2.5767 \times 10^{-9} \end{bmatrix}
\end{align*} \]

\[ \begin{align*}
\text{Input:} & \quad \text{Inlet fluid temperature} \\
\text{Output:} & \quad \text{Gas temperature} \\
R: & \quad \begin{bmatrix} 2.7463 \times 10^{-4} \\ 6.4781 \times 10^{-18} \\ 0 \end{bmatrix} \\
Q: & \quad \begin{bmatrix} 0 & 2.6939 \times 10^{-19} \\ 0 & 2.6939 \times 10^{-19} \\ 0 & 2.6939 \times 10^{-19} \end{bmatrix}
\end{align*} \]

\[ \begin{align*}
\text{Input:} & \quad \text{Inlet fluid temperature} \\
\text{Output:} & \quad \text{Fluid level} \\
R: & \quad \begin{bmatrix} 0.3095 \\ 1.1154 \times 10^{-10} \\ 0 \end{bmatrix} \\
Q: & \quad \begin{bmatrix} 0 & 5.6832 \times 10^{-11} & 0 \\ 0 & 5.6832 \times 10^{-11} & 0 \\ 0 & 5.6832 \times 10^{-11} & 7.4926 \times 10^{-13} \end{bmatrix}
\end{align*} \]

\[ \begin{align*}
\text{Input:} & \quad \text{Heat load} \\
\text{Output:} & \quad \text{Outlet gas flow rate}
\end{align*} \]
### Heat exchanger subsystem

<table>
<thead>
<tr>
<th>Input:</th>
<th>Heat load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output:</td>
<td>Gas pressure</td>
</tr>
</tbody>
</table>
| \( R: \)   | \[
4.9516 \times 10^{-8} \\
1.9304 \times 10^{-18} \]
| \( Q: \)   | \[
\begin{bmatrix}
6.7123 \times 10^{-6} & 0 \\
0 & 3.951 \times 10^{-6}
\end{bmatrix}
\]

### Supply line subsystem

<table>
<thead>
<tr>
<th>Input:</th>
<th>Inlet Flow Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output:</td>
<td>Outlet Flow Rate</td>
</tr>
</tbody>
</table>
| \( R: \)   | \[
4.9516 \times 10^{-8}
\]
APPENDIX E. LIST OF KALMAN FILTER PARAMETERS

Supply line subsystem

\[
Q: \begin{bmatrix}
1.4622 \times 10^{-12} & 0 \\
0 & 1.5451 \times 10^{-14}
\end{bmatrix}
\]

\[R: \begin{bmatrix}
2.7463 \times 10^{-4} \\
1.4672 \times 10^{-27} & 0
\end{bmatrix}\]

**Input:** Inlet Flow Rate  
**Output:** Line Temperature  

\[Q: \begin{bmatrix}
1.4672 \times 10^{-27} & 0 \\
0 & 2.6071 \times 10^{-24}
\end{bmatrix}\]

\[R: \begin{bmatrix}
4.6118 \times 10^{3} \\
1.0673 \times 10^{-13} & 0 \\
0 & 1.3958 \times 10^{-16}
\end{bmatrix}\]

**Input:** Inlet Flow Rate  
**Output:** Line Pressure  

\[Q: \begin{bmatrix}
2.2033 \times 10^{-12} & 0 \\
0 & 4.7811 \times 10^{-15}
\end{bmatrix}\]

\[R: \begin{bmatrix}
4.9516 \times 10^{-8} \\
2.2033 \times 10^{-12} & 0 \\
0 & 4.7811 \times 10^{-15}
\end{bmatrix}\]

**Input:** Inlet Temperature  
**Output:** Outlet Flow Rate  

\[Q: \begin{bmatrix}
2.4745 \times 10^{-11} & 0 \\
0 & 5.9675 \times 10^{-14}
\end{bmatrix}\]

\[R: \begin{bmatrix}
4.6118 \times 10^{3} \\
2.4745 \times 10^{-11} & 0 \\
0 & 5.9675 \times 10^{-14}
\end{bmatrix}\]

**Input:** Inlet Temperature  
**Output:** Line Pressure  

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Supply line subsystem

Output: Line Temperature

\[
R: \begin{bmatrix} 2.7463 \times 10^{-4} \\ 7.0264 \times 10^{-19} & 0 \\ 0 & 1.1025 \times 10^{-20} \end{bmatrix}
\]

\[
Q: \begin{bmatrix} 2.7463 \times 10^{-4} \\ 7.0264 \times 10^{-19} & 0 \\ 0 & 1.1025 \times 10^{-20} \end{bmatrix}
\]

Input: Termination Pressure

Output: Outlet Flow Rate

\[
R: \begin{bmatrix} 4.9516 \times 10^{-8} \\ 2.7605 \times 10^{-13} & 0 & 0 \\ 0 & 1.3715 \times 10^{-13} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\]

\[
Q: \begin{bmatrix} 4.9516 \times 10^{-8} \\ 2.7605 \times 10^{-13} & 0 & 0 \\ 0 & 1.3715 \times 10^{-13} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\]

Input: Termination Pressure

Output: Line Temperature

\[
R: \begin{bmatrix} 2.7463 \times 10^{-4} \\ 2.7202 \times 10^{-23} & 0 & 0 \\ 0 & 1.1919 \times 10^{-22} & 0 & 0 \end{bmatrix}
\]

\[
Q: \begin{bmatrix} 2.7463 \times 10^{-4} \\ 2.7202 \times 10^{-23} & 0 & 0 \\ 0 & 1.1919 \times 10^{-22} & 0 & 0 \end{bmatrix}
\]

Input: Termination Pressure

Output: Line Pressure

\[
R: \begin{bmatrix} 4.6118 \times 10^3 \\ 0.0240 & 0 \\ 0 & 4.1002 \times 10^{-5} \end{bmatrix}
\]

\[
Q: \begin{bmatrix} 4.6118 \times 10^3 \\ 0.0240 & 0 \\ 0 & 4.1002 \times 10^{-5} \end{bmatrix}
\]

Table E.2.: A list of supply line kalman filter parameters

Return line subsystem

Input: Inlet Flow Rate
APPENDIX E. LIST OF KALMAN FILTER PARAMETERS

Return line subsystem

Output: Outlet Flow Rate

\[ R: \begin{bmatrix} 4.9516 \times 10^{-8} \\ 1.3107 \times 10^{-17} & 0 \\ 0 & 7.6259 \times 10^{-20} \end{bmatrix} \]

\[ Q: \begin{bmatrix} 2.2213 \times 10^{-22} & 0 \\ 0 & 1.1086 \times 10^{-22} \end{bmatrix} \]

Input: Inlet Flow Rate

Output: Line Temperature

\[ R: \begin{bmatrix} 2.7463 \times 10^{-4} \\ 1.8009 \times 10^{-22} & 0 \\ 0 & 8.9997 \times 10^{-23} \end{bmatrix} \]

Input: Inlet Flow Rate

Output: Line Pressure

\[ R: \begin{bmatrix} 4.6118 \times 10^{3} \\ 1.7225 \times 10^{-12} & 0 \\ 0 & 8.6081 \times 10^{-13} \end{bmatrix} \]

Input: Inlet Temperature

Output: Outlet Flow Rate

\[ R: \begin{bmatrix} 4.9516 \times 10^{-8} \\ 2.2213 \times 10^{-22} & 0 \\ 0 & 1.1086 \times 10^{-22} \end{bmatrix} \]

Input: Inlet Temperature

Output: Line Pressure

\[ R: \begin{bmatrix} 4.6118 \times 10^{3} \\ 2.6564 \times 10^{-11} & 0 \\ 0 & 1.3257 \times 10^{-11} \end{bmatrix} \]
APPENDIX E. LIST OF KALMAN FILTER PARAMETERS

Return line subsystem

\[ \text{Input:} \quad \text{Inlet Temperature} \]

\[ \text{Output:} \quad \text{Line Temperature} \]

\[ R: \begin{bmatrix} 2.7463 \times 10^{-4} \\ 3.8525 \times 10^{-19} & 0 \end{bmatrix} \]

\[ Q: \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \]

\[ \text{Input:} \quad \text{Valve Position} \]

\[ \text{Output:} \quad \text{Outlet Flow Rate} \]

\[ R: \begin{bmatrix} 4.9516 \times 10^{-8} \\ 6.6292 \times 10^{-12} & 0 & 0 \end{bmatrix} \]

\[ Q: \begin{bmatrix} 0 & 6.6335 \times 10^{-12} & 0 \\ 0 & 6.1682 \times 10^{-12} \\ 0 & 0 & 0 \end{bmatrix} \]

\[ \text{Input:} \quad \text{Valve Position} \]

\[ \text{Output:} \quad \text{Line Temperature} \]

\[ R: \begin{bmatrix} 2.7463 \times 10^{-4} \\ 1.2993 \times 10^{-14} & 0 & 0 \end{bmatrix} \]

\[ Q: \begin{bmatrix} 0 & 9.8139 \times 10^{-19} & 0 \\ 0 & 0 & 4.4780 \times 10^{-19} \end{bmatrix} \]

\[ \text{Input:} \quad \text{Valve Position} \]

\[ \text{Output:} \quad \text{Line Pressure} \]

\[ R: \begin{bmatrix} 4.6118 \times 10^3 \\ 1.2445 \times 10^{-4} & 0 & 0 \end{bmatrix} \]

\[ Q: \begin{bmatrix} 0 & 6.9685 \times 10^{-8} & 0 \\ 0 & 0 & 2.0116 \times 10^{-8} \end{bmatrix} \]

Table E.3.: A list of return line kalman filter parameters
F. List of Thresholds and Evaluation Matrices

<table>
<thead>
<tr>
<th>Residual Description</th>
<th>Upper Threshold</th>
<th>Lower Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx Line Thresholds:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1 Flow Rate</td>
<td>+1e-5</td>
<td>-8e-5</td>
</tr>
<tr>
<td>R2 Temperature</td>
<td>+3e-3</td>
<td>-3e-3</td>
</tr>
<tr>
<td>R3 Pressure</td>
<td>+0.1</td>
<td>-0.1</td>
</tr>
<tr>
<td>Rx Line Thresholds:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R4 Flow Rate</td>
<td>+6e-5</td>
<td>-6e-5</td>
</tr>
<tr>
<td>R5 Temperature</td>
<td>+5e-3</td>
<td>-5e-3</td>
</tr>
<tr>
<td>R6 Pressure</td>
<td>+250</td>
<td>-250</td>
</tr>
<tr>
<td>Heat Exchanger Thresholds:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R7 Flow Rate</td>
<td>+5e-5</td>
<td>-5e-5</td>
</tr>
<tr>
<td>R8 Liquid Level</td>
<td>+0.1</td>
<td>-0.1</td>
</tr>
<tr>
<td>R9 Pressure</td>
<td>+40</td>
<td>-40</td>
</tr>
<tr>
<td>R10 Temperature</td>
<td>+3.5e-3</td>
<td>-3.5e-3</td>
</tr>
</tbody>
</table>

Table F.1.: The fault detection thresholds (dual threshold)

<table>
<thead>
<tr>
<th>Residual Description</th>
<th>RMS Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx Line RMS Thresholds:</td>
<td></td>
</tr>
<tr>
<td>R1x Flow Rate</td>
<td>+8e-5</td>
</tr>
<tr>
<td>R2x Temperature</td>
<td>+3e-3</td>
</tr>
<tr>
<td>R3x Pressure</td>
<td>+0.1</td>
</tr>
<tr>
<td>Rx Line RMS Thresholds:</td>
<td></td>
</tr>
<tr>
<td>R4x Flow Rate</td>
<td>+6e-5</td>
</tr>
<tr>
<td>R5x Temperature</td>
<td>+5e-3</td>
</tr>
<tr>
<td>R6x Pressure</td>
<td>+250</td>
</tr>
<tr>
<td>Heat Exchanger RMS Thresholds:</td>
<td></td>
</tr>
<tr>
<td>R7x Flow Rate</td>
<td>+5e-5</td>
</tr>
</tbody>
</table>
APPENDIX F. LIST OF_THRESHOLDS AND EVALUATION MATRICES

<table>
<thead>
<tr>
<th>Residual Description</th>
<th>RMS Threshold</th>
</tr>
</thead>
<tbody>
<tr>
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<td>R10x Temperature</td>
<td>+3.5e-3</td>
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Table F.2.: The fault detection thresholds (Single threshold)

<table>
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<tr>
<th>Fault name</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>R7</th>
<th>R8</th>
<th>R9</th>
<th>R10</th>
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Table F.3.: The fault isolation matrix (upper thresholds)

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<th>R7</th>
<th>R8</th>
<th>R9</th>
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Table F.4.: The fault isolation matrix (lower thresholds)
### Table F.5.: The RMS fault isolation matrix

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G. Cryogenic Plant Control Logic Diagrams
APPENDIX G. CRYOGENIC PLANT CONTROL LOGIC DIAGRAMS