Industrial Electrical Engineering and Automation

New System for Control and Monitoring of a Helium Liquefaction Plant Implemented in LabVIEW

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Abstract

This master's thesis report describes the development of a new system for control and monitoring of a helium liquefaction plant which has been carried out at Kryolab, Lund University. At the plant, helium gas is purified and then cooled in several steps until it condensates. The plant is very similar to the ones constructed today, but Kryolab wished to replace the outdated control system. The new system has been programmed in LabVIEW and is run on a CompactRIO from National Instruments. It replaces the original analogue boards and a complementary software based system.

In the early stages of the project the behaviour of the process was studied. Programs for plotting and logging were implemented for this purpose and used along with other available resources such as manuals, drawings and collected data from the plant. The code has been developed iteratively and every part of it has been tested before it was used to control the real plant. To verify the program behaviour in different situations a user interface with the possibility to set sensor values manually has been developed. New functions have been tested and added successively.

The new system presents more data and a better overview of the process than previously available. Increased possibility to manually control some valves and to adjust trigger and set points used in the control has also been added. A new alarm system has been implemented and the start and stop sequences have been further automated.

The project has been very successful. The improved overview aids in identifying potential problems and their causes. It has proved possible to run the plant under more difficult circumstances with the extended ability to adjust the control system. The opportunity to supervise and control the plant from a computer or telephone outside Kryolab has reduced the need to go to Kryolab outside regular working hours and made it possible to avoid some emergency stops.

The new system provides the operator with improved insight in how the control works. The aspiration is that this will facilitate further development and improvement of the system.

Sammanfattning

Denna rapport beskriver ett examensarbete utfört på Kryolab på Lunds Universitet. Ett nytt styrsystem för en anläggning för förvätskning av helium har utvecklats. I anläggningen renas heliumgas för att sedan kylas i flera steg till dess att den kondenserar. Den befintliga anläggningen är mycket lik de som byggs idag, men systemet för styrning och övervakning är föråldrat, och Kryolab önskade uppdatera detta. Det nya systemet är programmerat i LabVIEW och körs på en CompactRIO från National Instruments. Det ersätter det ursprungliga systemet bestående av analoga kort och ett kompletterande mjukvarubaserat system.

I arbetets första fas har maskinens beteende studerats genom loggning och plottning. Även befintlig litteratur i form av manualer, ritningar och sparad data från tidigare körningar har utnyttjats. Koden har utvecklats iterativt och varje del av koden har testats innan den använts på den verkliga anläggningen. För att verifiera programmets beteende i olika situationer har ett användargränssnitt med möjlighet att manuellt ange sensorvärden utvecklats. Nya funktioner har testats och lagts till successivt.

Det nya systemet presenterar betydligt mer data än tidigare och ger en helt annan överblick över processen. Det nya systemet erbjuder också ökade möjligheter att manuellt justera vissa ventiler och att förändra gränsvärden och börvärden som används i regleringen. Ett nytt alarmsystem har implementerats och start- och stoppsekvenserna har ytterligare automatiserats.

Projektet har som helhet varit mycket lyckat. Den förbättrade överblicken underlättar såväl identifieringen av potentiella problem som orsaken till dem. De ökade möjligheterna att påverka styrningen har gjort det möjligt att köra anläggningen under svårare omständigheter än tidigare. Möjligheten att övervaka maskinen från en dator eller telefon utanför Kryolab har gjort det möjligt att i högre utsträckning undvika nödstopp och minskat behovet av att ta sig till Kryolab utanför planerad arbetstid.

Det nya systemet ger operatören bättre insyn i hur regleringen fungerar och förhoppningen är att detta ska bidra till en kontinuerlig utveckling och förbättring av styrsystemet.

Acknowledgements

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1 Introduction

1.1 Background

This master thesis in Industrial Electrical Engineering and Automation forms the last part of a degree in Mechanical Engineering with a specialisation towards Mechatronics at LTH, the Faculty of Engineering at Lund University. It has been carried out at Kryolab, the cryogenic facility of Lund University in cooperation with IEA, the division of Industrial Electrical Engineering and Automation at LTH.

Kryolab is located at the Department of Physics and produces liquid nitrogen and helium used mainly in research at the university and elsewhere in the region. When possible, used helium is returned as gas to be liquefied and redistributed. Helium's scarcity on earth makes it a valuable resource to recover. The plant for purification and liquefaction of helium gas is from 1985 and is physically very similar to plants constructed today and uses the same principles, but the control system needs to be updated. The plant is currently experiencing regular stops caused by malfunctions in the control system and unforeseen blockages.

1.2 Task

The task is to replace the control system of a helium liquefier plant. A list of the original requirements can be found in Appendix E and is summarised below.

The new system should be easier to understand and program, have a high reliability and include some additional features. The new control program should have a higher level of automation, provide increased possibilities to adjust control parameters and provide a clearer overview of the state of the machine. This will hopefully increase the capacity and reduce the number of stops.

In addition to the original control system based on analogue circuit boards there is also a PLC from SattControl implementing additional functionality. The new system will be implemented on CompactRIO 9022 using LabVIEW. Most of the old control system based on analogue circuit boards and the entire PLC system are to be replaced. The new system should mimic the behaviour of the old to the extent possible. The replacement must be done such that the normal production is not interrupted.

1.3 Outline of the project

The first step of the project is to gather information about the current system. Available documentation includes primarily the manual of the plant but also short film sequences and notes by the Kryolab staff. The work is to be carried out at Kryolab, so help and guidance regarding the functionality of the plant will be available. To be able to study the behaviour of the current control program and the general process behaviour, programs for basic plotting and logging should be implemented.

The gathered information will be used to build a basic control program with a possibility to provide manually controlled input data, and to force a desired state of the logic. This is needed to test the behaviour of the control program before it is connected to the real process. Control will gradually be moved over to the new system after testing. For this reason it must be possible to turn on and off outputs separately in the control program. To be able to control as many parameters in the control program as possible during the testing and development the cRIO can publish a graphical interface directly connected to the control program on a separate computer during development and testing. cRIO itself does not have any screen.

A real standalone user interface run on a host computer must then be implemented. The control program must be independent of this user interface. The user interface should present information and possibilities to transfer information to the control program to influence the process. Possibilities for remote control of this user interface should be added. Documentation of the work and some kind of user manual will be necessary.

1.4 Report overview

This chapter contains information about the task as well as some background information and the basic outline of the work. More information about Kryolab can be found in Appendix A.

Chapter 2 contains background theory needed to understand the report. It describes the old control system, the new hardware and LabVIEW that is used for the programming. There is also a brief description of the plant and the liquefaction process. Further information about helium can be found in Appendix B and a brief description of the field of Cryogenics and basic refrigeration cycles in Appendix C. The functionality of the machine TCF-20 for which the control system is to be replaced is described in Appendix D, as is the rest of the helium liquefaction plant.

Chapter 3 describes the implementation of the new control system. Section 3.1 gives an overview of the requirements set up for the new system and explains some of them. The full list of requirements can be found in Appendix E. The basic structure for the logic is implemented as state machines, the reasons for this design choice is described in 3.2. Sections 3.3-3.4 describe the process to implement the new control system and 3.5-3.6 provide an overview of programs and the implemented logic. Section 3.7 describes the demands on the control regarding scan cycle times. Section 3.8 describes the new alarm system and automatic shutdown that has been implemented. The transformation of measurements and its limited accuracy is discussed in Section 3.9.

The testing has been done continuously during the project and Chapter 4 provides examples of tests. Chapter 5 contains the results, comparing the system to the specification in Appendix E. The project and its results are discussed in Chapter 6 and suggestions for future work can be found in Chapter 7.

2 Theory and preconditions

2.1 Background

This chapter describes the preconditions for the new control system. In the early stages of the project, time was spent on studying the plant and the liquefaction process as well as the existing control system and the hardware already chosen for the new implementation. The following sections should be sufficient to understand this report. Additional background theory is kept in appendices. Appendix A contains a short description of the purpose of Kryolab and the activity there. Facts about helium can be found in Appendix B and a brief description of the field of Cryogenics and some basic refrigeration cycles and how they compare to the one used in the plant in Appendix C. The functionality of the machine TCF-20 for which the control system is to be replaced is described in Appendix D, as is the rest of the helium liquefaction plant.

2.2 Plant overview

The returned gas that is to be liquefied is compressed and put in storage *(see Figure 2.1)*. The gas contains impurities, essentially air, which needs to be removed. In the Purifier the gas is cooled until all impurities condensate or solidify and the pure helium can be transferred to a buffer tank. As impurities build up in the Purifier it needs to be regularly heated and purged with pure helium gas.

    The Liquefier is supplied with pure helium gas from the buffer. In the Liquefier the helium is cooled, this is described in Section 2.3. The liquid helium is collected in the machine tank from where it is transferred to other vessels for delivery.
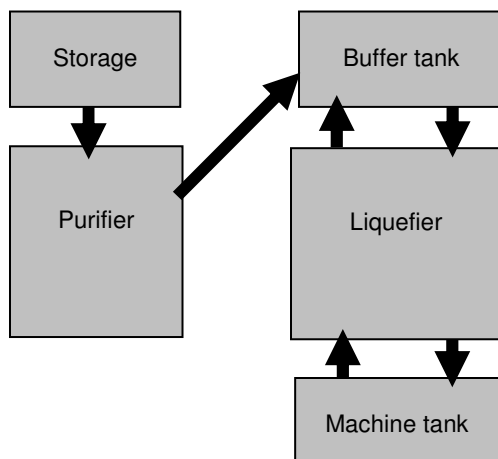
Figure 2.1: Overview of the plant.

2.3 Liquefaction process

The Helium gas is cooled in a cycle where it is alternately compressed by screw compressors and cooled during expansion through turbines. The work needed for the cooling is provided by the compressors. High pressure gas enters the Liquefier from the compressors and gas with low pressure returns *(see Figure 2.2)*.

    On the way to the machine tank, the incoming high pressure gas is cooled in a series of heat exchangers. After the first heat exchangers, part of the incoming gas is led to the turbines and part continues through another series of heat exchangers to the machine tank.

The part of the helium which goes through all the heat exchangers is approximately 7 K when it reaches the throttling valve (Joule-Thomson valve) leading to the machine tank. As the gas is expanded through this valve to 1.3 bars it becomes a mixture of liquid and gas at 4.2 K. The liquid stays in the machine tank and the gas goes back to the low pressure return stream that passes through the heat exchangers.

The refrigeration required to keep the heat exchangers cool is provided by the use of turbines. The part of the gas that is directed here exerts work on the turbines which causes it to cool. This side stream of gas returning from the turbines is cold and added to the low pressure return stream. The low pressure return stream, consisting of a mixture of gas from the turbines and from the machine tank, is used to cool down the incoming gas from the high pressure side.
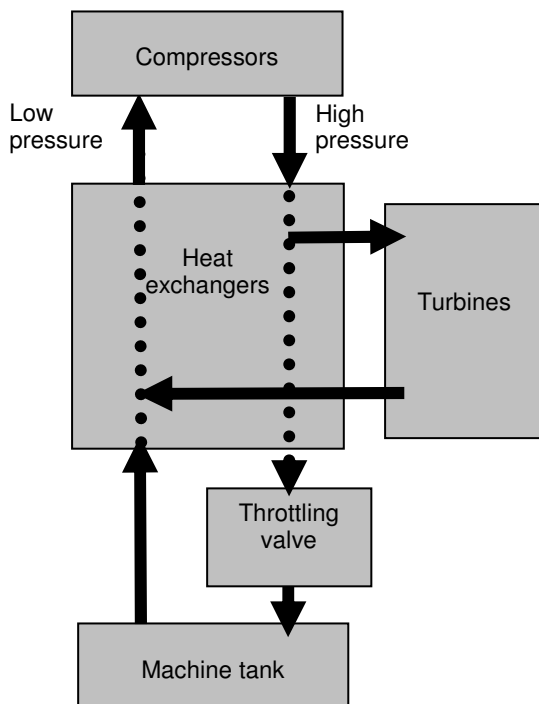
Figure 2.2: Simplified view of the Liquefier.

2.4 Current control systems

The machine used at Kryolab today to liquefy helium return gas is from 1985. The process for cooling helium is the same in newer machines but the control system is outdated and is in some respects not working properly. The system is well documented in the manual and drawings of the analogue control circuitry are available.

During the nineties a second control system was added. It was implemented on a PLC from SattControl making the previously entirely manual start and stop sequences semiautomatic. Data from this system is fed to a computer which presents key data on a web page. The new control system replaces this system and many of the analogue boards.

2.5 CompactRIO

The use of CompactRIO from National Instruments was a precondition and the selection process was not included in this project. Some comments on the experiences with CompactRIO can be found in Chapter 6 and 7.

The CompactRIO 9022 is modular system for control and data acquisition. The controller has a real time processor which makes it possible to run deterministic programs. The IO modules come in many different versions and are connected to the controller via a backplane. The core of this backplane is a reconfigurable hardware, an FPGA, which can be used for signal processing and control. It has direct contact with each IO module and provides contact with them in LabVIEW Real-Time. This can be configured automatically activating scan mode. [1] The use of the FPGA for local control can be valuable when high speed is important. As the controlled process is fairly slow and the computing power more than enough, it has not been necessary to use it.

Communication with the host computer is done via Ethernet. The host is the computer used to deploy the program on cRIO and to show the user interface as cRIO has no display.

2.6 LabVIEW

The programming is done in LabVIEW, which is a programming environment for a graphical programming language. The code makes it easy to follow the dataflow which is represented as wires. All LabVIEW code is inherently parallel and the order of execution is dependent on the dataflow. A LabVIEW program is called a Virtual Instrument, a VI. Each VI has a Front Panel and a Block Diagram. The Front Panel displays a graphical representation of inputs and outputs, e.g. buttons and meters, that can be used by an operator. A VI can also be used as a subVI within another VI that then controls it via the inputs and outputs. In the Block Diagram most of the programming is done by connecting different function nodes and subVIs with wires.

2.7 Real time

It is important to create a reliable control of the plant. The user interface will be implemented and run on a Windows computer as cRIO has no display, but the actual control must be implemented as a standalone application on cRIO. In this case it means that it must work regardless of network connection. The communication with the user interface can not be allowed to delay the control actions and the control should not rely on any information from the operator during normal operation. All control actions are placed in one VI which is given the highest priority. The handling of communication over Ethernet with the host computer is taken care of by other VIs with lower priorities. The cRIO is fast compared to the cycle times needed to control the plant, generally only approximately 13 % of the processor capacity is used. This means that even if the VIs handling the communication has a lower priority, it is unlikely that cRIO will have difficulties to maintain the communication. During the development it is possible to be online and show the Front Panels of cRIOs VIs on the host computer. This is very useful to monitor and influence the control and fine tune the parameters used, but determinism cannot be guaranteed.

3 Method and implementation, program description

3.1 Revised requirements

From the original criteria specifying the new system and with the environment in which it would be done taken into consideration a set of demands and tasks where formulated to guide the work. These are presented in the list of revised requirements in Appendix E. Some of these criteria and the reasons for them are described in the following sections.

3.1.1 Overall limitations

Since the machine is operational and running for the most part, the possibilities to test the code will be limited. It is important that any added code is functional from the beginning. The machine is stopped at fairly regular intervals but normally only for a short amount of time. It is important to use each such opportunity to make updates to the control system, replacing and testing limited parts each time.

The new control system is to replace and extend an already operational control system, the parts that serve as replacement should in all essentials work as the old system. The logic, set-points etc. should initially be the same as in the old system but can be revised to increase performance as the new system is tested.

3.1.2 Hardware and signals

It is decided that the system should be built with LabVIEW 2011 and CompactRIO 9022. Hardware modules for the IO already available are NI9205, 0-10V DC for inputs and NI9477 60V sink and NI9476 24V source for the outputs. The measurement signals that are to be read are direct current voltages, most of them with a maximum value of 5 or 10 V but some ranging to 24 V.

There are also some signals with alternating current and voltages up to 220 V. If at all possible these will not be measured and used. High voltage increases the risk of personal injuries and should not be integrated in a system that is to a high extent open and easily accessible to the operator.

3.1.3 Control program, software on cRIO

The main analogue control program is now controlling the action of the purifier and all the valves of the liquefier when the machine is running. It is well documented in the manual for the original machine, TCF-20. The semiautomatic start and stop programs that should be replaced are governed by a PLC from SATT control and have been more difficult to retrieve code and documentation for.

The values for setpoints and conditions should be chosen as the ones used now, at least initially. It is important to measure these values as they might have been modified and are not necessarily the same as in the existing documentation.

3.1.4 User interface, software on host computer

A user interface similar to the old operator panel should be used to present information about the current state of the process. The current operator panel shows a simplified view of the piping of the system but gives a good overview. Keeping this design as a basis for the new user interface will make it easier for the operator to know where to look for the information needed.

A number of measurements, control signals and the current state of the logic should be presented on this operator panel. Buttons to start and stop the machine and manually regulate the control valves should also be implemented.

3.1.5   Alarms and warnings

The system for alarms and warnings is completely new so there is no previous system indicating reasonable threshold values. This means that these must be chosen based on experience of normal process values. There is an existing system that turns of the power to the compressors when the turbines are speeding, it is important that the turbines are not allowed to speed up so much that they reach that limit. Not only the values but also the actions needed to reduce unwanted behaviour must be identified.

3.1.6   Remote operator control

This interface must be made available over the Internet. There is built-in functionality in LabVIEW for this. Any Front Panel can be published by the host computer; to be able to use the panel it is necessary that the connecting unit has LabVIEW Runtime Engine / Web Browser Plugin installed. The panel can also be presented simply as a picture in which case the plugin is not needed.

3.2 Choice of state machines

Going through the documentation for TCF-20 it became evident that although the regulation of some valves only depended on specific measurement values most of the control actions where influenced by the state of the Purifier. The addition of a control structure to automatically open and close the valves that where previously manually controlled and related to starting and stopping the machine meant that almost all control actions where now placed in a context and related to the state of the machine. Additionally, these states followed each other in a fixed order with few exceptions. It seemed reasonable to place the logic for the control actions in a state machine or other similar structure. In some cases this would not have been necessary as the behaviour of the process itself would ensure that a specific value triggering an action could not be reached during wrong state. The choice to connect almost all actions to the state machine was made partly because sensors sometimes can give an erroneous value but also because it was pointless using computing power for comparisons that, provided everything worked, would always provide the same result.

The choice to make multiple state machines was not an obvious one, but it was decided to use separate state machines for the Liquefier and Purifier. It would have been possible to merge these into one without the problem of a high increase in number of states as the Liquefier basically has one running state and all the rest are connected to the start up and shut down of the system. The Purifier could be limited to be active only when the Liquefier is in its stable running state. However, the separation into two state machines represents the real structure and mimics the original behaviour of the control system better. The Liquefier can be run without the Purifier if it is provided with clean helium; this possibility was kept even if it is not normally used. The modularisation also facilitates a future extension of the system. If other parts are to be connected (as would later be the case with the LIN-cooling) they would also have there own separate state machines, possibly with the states of the Liquefier and Purifier as inputs.

3.3 Study of the system with plotter and logger

Before the construction of the new system could begin the behaviour of the process and the old control programs were studied. This was done with the help of two very simple VIs used

to plot and log measurements from the machine. To be able to follow the variations in temperatures and pressures throughout the process caused by the current state of the Purifier and to get an idea of how exact measurement values that would be possible to obtain would prove very useful.

The data from these first VIs and the available documentation for the original control program where used to choose the set points that the new control program tries to reach and the conditions that would trigger specific actions. These values have since been revised to improve the performance but these first measurements gave good starting points.

3.4 Incremental replacement of control system parts

The first very basic version of a control program had direct contact with the host computer. At this point the structure of the logic, including which states and conditions were to be used, was finished only on paper. In the first version a limited number of these states where used in the program and it processed few measurement values and governed even fewer output signals. To test the responses from this control program a panel was added in which measurement data could be provided manually including a switch that decided if real live data or these manual inputs should be used. Possibilities to force the state machine into a desired state were also added. Using this it was possible to test the program's reaction to different measurement signals and check that the behaviour was correct before the wire with the old control signal was replaced by a signal from cRIO. The new piece of logic implemented could then be monitored from the *plotter* VI, checking that the overall behaviour was stable and similar to the old control or better. In this way the control of the different relays and motors was gradually transferred to the new control unit in an iterative process. Each new control signal was verified first with a set of different inputs manually, then on real data comparing outputs from the two systems and lastly with connection to the real process.

3.5 Program structure

The program consists of several VIs and a couple of libraries providing variables used as a way of transmitting data from one VI to another. The following sections describe each of the VIs and their purpose. The sketch is intended to give an overview of the program structure *(see Figure 3.1)*.
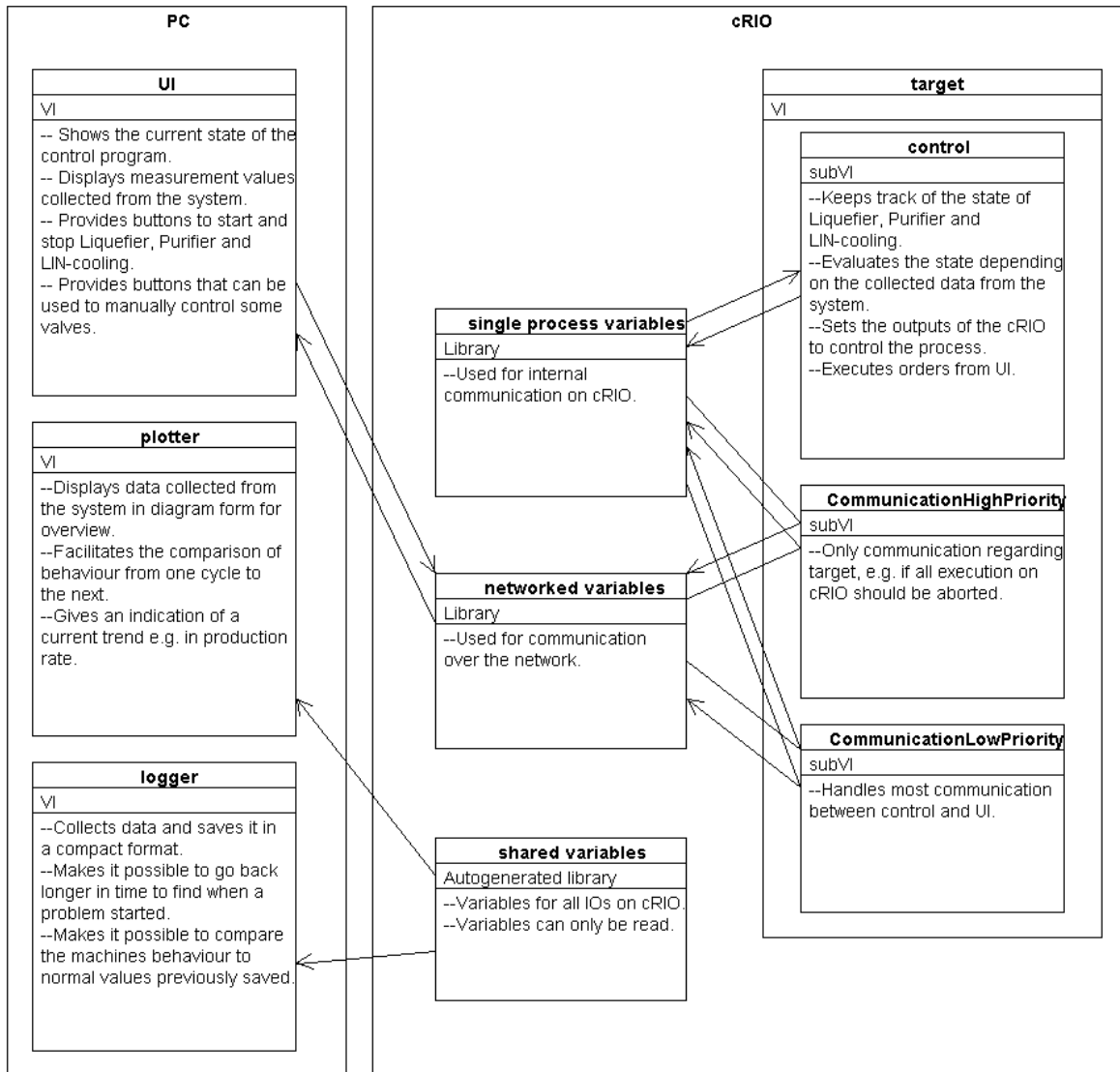
Figure 3.1: Sketch of the program structure.

3.5.1   UI

The Front Panel of *UI* provides an intuitive user interface. The design is based on the physical user panel of the TCF-20 *(see Figure 3.2)* mainly for two reasons. Firstly the similarities make it easier for the operator to understand and know where to look for different information. Secondly the original panel shows how the different parts of the machine are connected and how the gas flow is moving in a good way. The illustration of the machine pipes and valves is obviously very simplified but gives a good overview. The *UI* Front Panel *(see Figure 3.3)* provides much more detailed information than the old control panel as the number of diodes and displays have been increased.
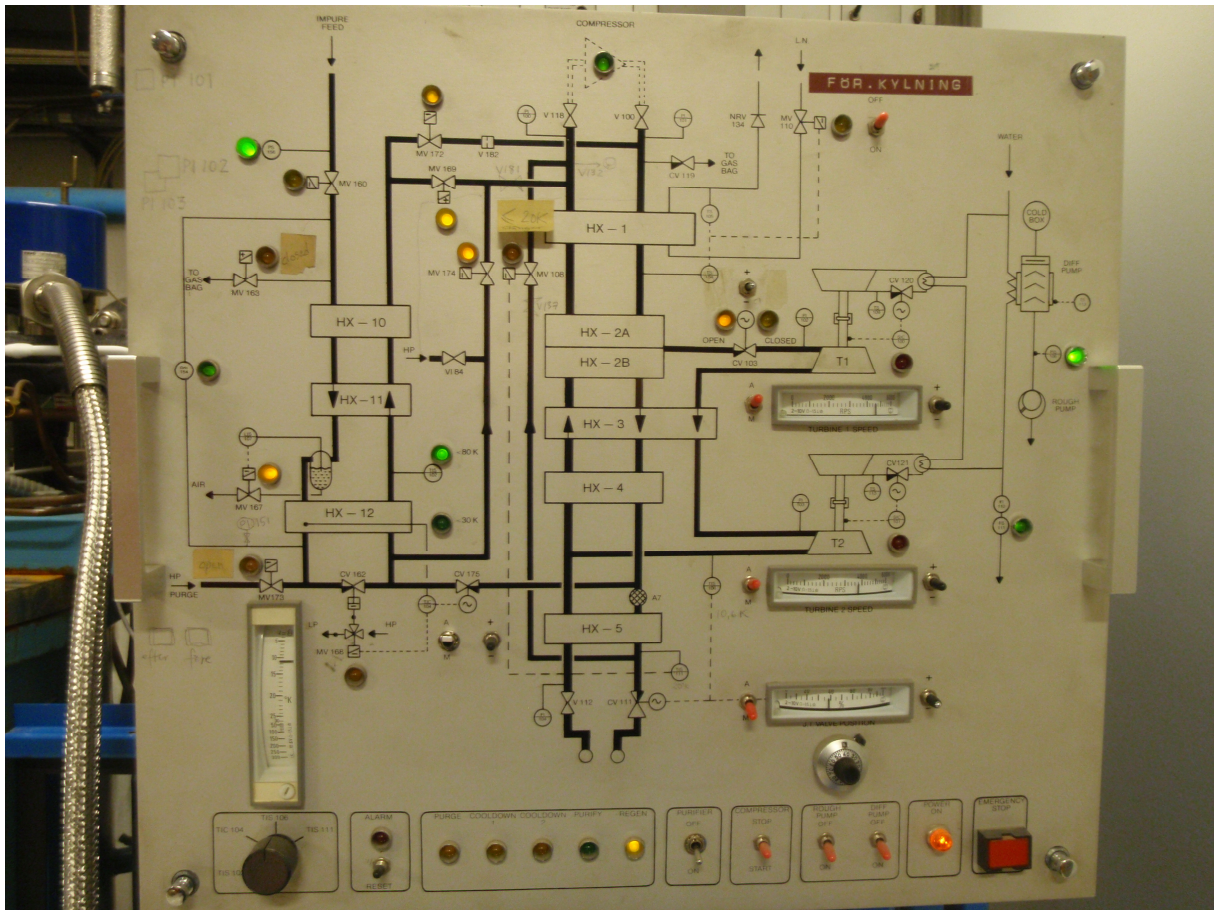
Figure 3.2: Original user panel of TCF-20.

There are also some elements not present on the old control panel that have been added. This includes the boxes to the right *(see Figure 3.3)* providing information about the state of the control system. With some basic knowledge of the process it means that it is easy to see what the control system is trying to achieve, how the gas is flowing and which temperatures should be reached.

Some elements have been added to the original sketch as a way of presenting information about parts of the system located a bit further away like the compressors, storage, buffer tank etc. without loosing the general feel for how they are connected to the system.

The user interface also provides an opportunity for the operator to gain some manual control over the system. The control valves can be regulated manually instead of by the control system, however it is not recommended unless the process for some reason shows unexpected behaviour. The build up of frozen impurities or aging of gaskets causing small leaks are two examples of things that can cause a change in process behaviour. This will cause a reduction in production rate as the control system parameters have been chosen during other circumstances. In such a case a fixed valve position provided by the operator might be a better choice than the one provided by the control system and make it possible for the machine to keep producing (but at a slower rate than normal) until a stop for service is possible.

The possibility to manually control valves during run time also increases the possibility to identify problems while the machine is running and has made it simpler to find out if unexpected behaviour by a specific valve was caused by a relay, the valve itself or maybe an intermittent cable and if it was necessary to shut down the machine to fix the problem or not.

In the upper right corner is a box related to the Liquid Nitrogen pre-cooling. It is possible to select the state of the cooling using a drop down list. There is also a little box

displaying a list of alarms and warnings placed at the bottom left. Under normal conditions this list will be empty.
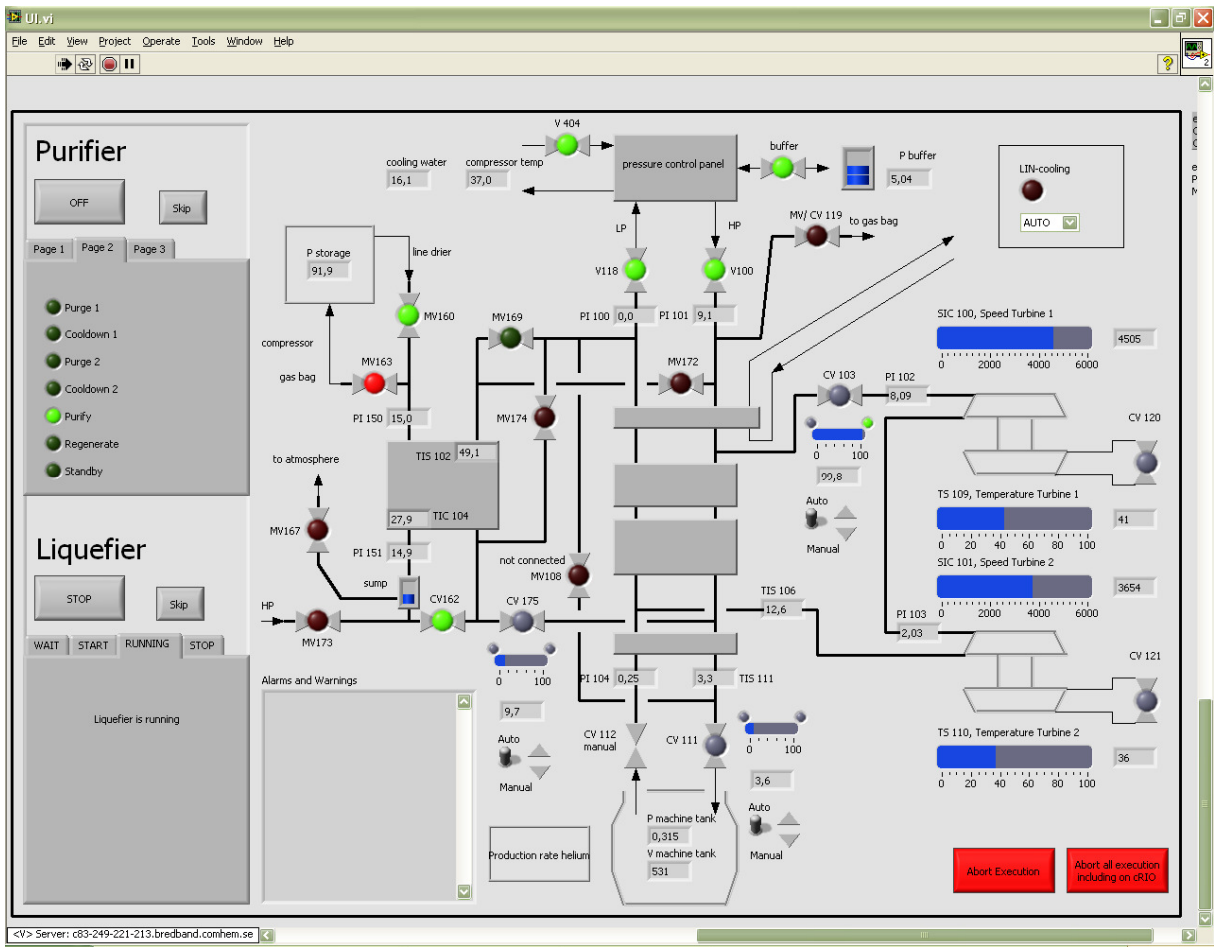
Figure 3.3: Front Panel of UI.vi

Diodes indicating the position of a solenoid valve are red when closed and green when open *(see Figure 3.3 and 3.4)*. A valve that is normally closed is depicted as dark red in its passive closed state and light green in its active open state. A valve that is normally open is depicted as dark green in its passive open state and red in its active closed state. Control valve diodes are normally grey indicating a valve in a static position. A green diode means that the motor is working to further open the valve and a red that the valve is closing.
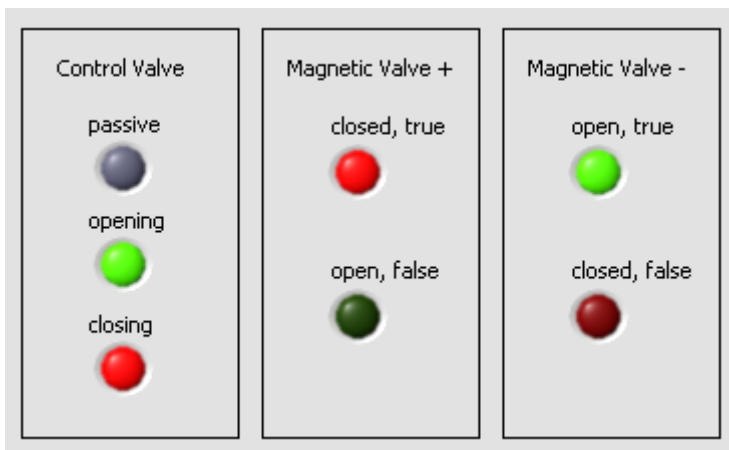
Figure 3.4: The diode types at the *UI* Front Panel.

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3.5.2 Logger

The VI called *logger* is run on the PC and must be started separately. It is entirely passive and stores all data provided on the network by cRIO. The collection of log files is not necessary but can help to trace when a specific problem first occurred or compare data over longer periods of time. The Front Panel of *logger* only provides buttons to turn the logging on or off.

To view or analyse the data a separate program is needed that can import the files. It is possible to choose the file format in *logger*. The default is to store the data in a LabVIEW Measurement File (.lvm file), a plain text file that is arranged in rows and columns. [2] This format was chosen as it can be opened even in a very simple text editor, but to plot or analyse the data the use of Excel or Matlab would be a better option. The data can also be saved in more compact binary formats; these are also LabVIEW specific file formats but can be read in Matlab, Excel etc. sometimes requiring the installation of an add-in.

3.5.3 Plotter

The diagrams provided on the Front Panel of *plotter (see Figure 3.5)* shows some key measurement values over a shorter period of time, enough to be able to see what has happened during a night and to get an overview of a few cycles. This makes it possible to spot trends, like regular problems with blockage in the Purifier which are often caused by high levels of impurities in the return gas. It also makes it easier to estimate the rate at which the storage is emptied and the production rate. Temporary variations caused by filling of dewars and drop in production rate when the Purifier uses part of the cool gas during cool down can easily be seen and taken into account. The plots are also useful to monitor turbine behaviour if the machine is started from an unusual state e.g. very cool which can cause the turbines to spin too fast.
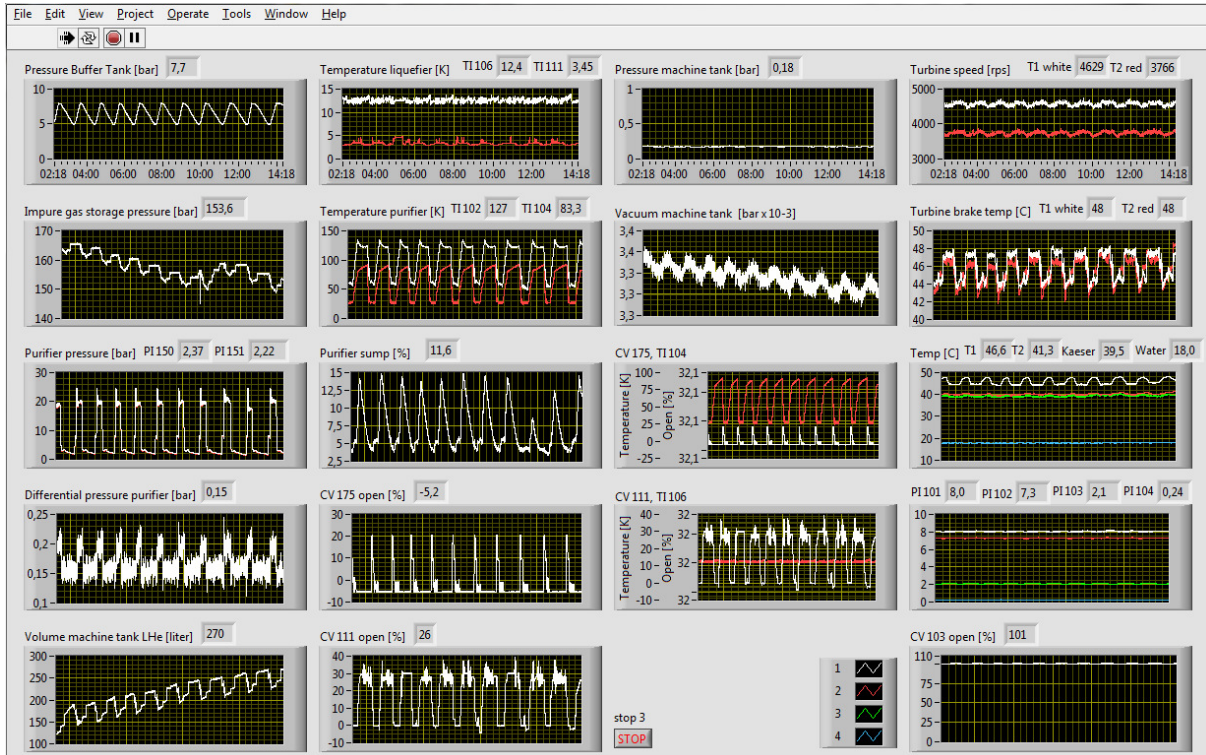

Figure 3.5: Front Panel of *plotter*.

3.5.4   Communication and libraries

The communication between the control program *control* run on cRIO and *UI* is done via shared variables. The library *networked variables* is available to any device on the local network and *UI* reads specific variables and displays the data to the user. *UI* can also write to some variables in the library which are used to provide instructions to the control program. The library *single process variables* contains another set of variables with similar names but is only available to VIs on cRIO. This is where the control program reads instructions from and writes information to *UI*. This is to ensure that *control* is not affected by network communication. This is instead taken care of by the two Communication VIs. They copy information between the libraries. No variables are used for two way communication; they are either written by *UI* and read by *control* or vice versa. The communication VIs use a subVI to determine if the connection is active or not called *ConnectionActive*. This is to ensure that the manual mode is discontinued if cRIO accidently looses contact with the host computer to minimise the risk that settings that have not been tested remain active when the operator can no longer control them.

3.5.5   Target

The VI named *target* starts all VIs run on cRIO, *CommunicationHighPriority*, *CommunicationLowPriority* and *control*. The communication VIs are responsible for the contact with the host computer and are run as lower priority threads. The most important VI is *control* which also has the highest scheduling priority. Out of all the VIs *control* is the most complex one. It keeps track of the state of the process and what is to be achieved with the help of state machines. It is responsible for the evaluation of all the data collected about the process and the outputs. Essentially *control* is the complete control system. A description of the logic and states used in *control* is available in the next section.

3.6 Control program logic

The machine essentially consists of the Liquefier with supporting systems, e.g. the Purifier and the liquid nitrogen cooling. The Liquefier can run separately without the Purifier if it is provided with pure helium from another source. It can also run without the extra cooling, this normally gives a production rate high enough to liquefy all return gas.

The control program controls the Liquefier and Purifier. The state of the control program can be described as a combination of the states of the Liquefier and Purifier. An early thought was to merge these states into one state machine as the Liquefier normally is in a steady running mode when the Purifier operates. The main reason for instead keeping the state logic separate and making one state machine each was the scalability. The later addition of another state machine for the LIN-cooling was facilitated this way. Like the Purifier it runs independently but will shut down if it detects that the Liquefier for any reason performs a stop sequence.

Even though the Purifier operates largely independently all control logic is placed in the same VI. The main reason for this design choice is how the program is compiled before it is loaded to the cRIO. In order to guarantee a deterministic behaviour the code is compiled into one single thread. Two different loops or VIs can not both be guaranteed to meet their deadlines, only one can have the highest priority. Separating the Liquefier and Purifier would mean that the control of either of them would have priority over the other which is undesirable. Slightly increased loop times will still yield a good over all behaviour as long as both are controlled at regular intervals as one is dependent of the other. Any other activity where determinism is required must consequently also be integrated in this VI. This is the case with e.g. the Alarm system. It is desirable that it can affect the logic with regular intervals and must not be starved.

The control logic is as previously stated based on state machines. Any particular state does not necessarily represent fixed control signals, rather it describes where in a process the machine is, to which values measurement signals should be controlled and the direction of gas flow.

3.6.1   Liquefier logic, description of states

The different liquefier states normally follow each other in the order they are described in this section. There is also an illustration showing how they are interconnected *(see Figure 3.6)*.

STANDBY

Standby is a state suited only for short term shutdown. It is assumed that the operator has ensured that certain requirements are met before the system is started. This includes correct valve positions on manual valves and that the system is filled with pure helium.

START 0 prepare

Control valves are regulated to their start positions, CV103 fully closed, CV111 fully closed, CV175 fully closed, CV120 and CV121 80-90% open.

START 1 open buffer

The valves to the buffer tank and the outlet valve from the low pressure side of the Liquefier to the compressors are opened.

START 2 compressor 1

The compressors are started by a current signal during one second. V404 is opened.

START 3 compressor 2

Immediately after compressor start, V100 begins to open and pressure starts building up at the Liquefier inlet, PI101.

START 4 open CV 103 to 0.7 bar

When the pressure at PI101 reaches 8 bar the inlet valve to the turbines, CV103, is slowly opened until the inlet pressure on the first turbine, PI102, reaches 0.7 bar. At this point the program goes no further until the turbines are spinning. (SIC100 and SIC101 are higher than 200 rps or the operator forces the program to continue.)

START 5 open CV 103 to 1 bar

This is the next security level where it is controlled that the turbines are spinning properly, at one bar turbines should be reaching at least 1000 rps. If the turbines do not spin properly the operator can take manual control or activate the stop program.

START 6 open CV 103 to T2 3200 rps

When it is ensured that the turbines are spinning properly the inlet pressure is increased until the second turbine reaches the point where it is automatically controlled, approximately 3000 rps. The braking is reduced and the turbine speed is stabilised to the interval 4300-4500 rps.

START 7 static CV 103 T2 warm up

The reduced braking and cooling by CV121 will cause an increase in turbine temperature which should be allowed to stabilise during five minutes when the inlet pressure is kept steady.

START 8 open CV 103 to T1 3200 rps

The valve to the turbine inlet is further opened until turbine 1 is regulated to its optimum speed or the valve is fully open. If the valve is fully opened the running state is immediately entered.

START 9 static CV 103 T1 warm up

This state allows time for turbine one to warm up.

START 10 open CV 103 fully

Once turbine one has been warmed up CV103 continues to open slowly until it is fully open. When this is done the machine enters state RUNNING.

RUNNING

At this point mainly MV108 and CV111 are controlled to stabilise the temperatures at TI111 and TI106. The set points should be chosen such that the production rate of liquid helium is as high as possible. Set points can be manipulated in *control*.

STOP 1 closing CV 103

The inlet valve to the turbines is closed slowly, as the pressure decreases so does turbine speed until the turbines eventually come to a halt.

STOP 2 close V 100

The inlet valve to the Liquefier is closed.

STOP 3 open CV 111

The valve to the machine tank is opened and cold gas can leave the system to the buffer during a five minute period.

STOP 4 close V 118

The outlet valve from the Liquefier to the turbines is closed.

STOP 5 compressor 2

The compressors are stopped.

STOP 6 compressor 1

Valve 404 is closed.

STOP 7 close buffer

The valves to the buffer are closed

STOP 8 venting

24 hours are allowed for the system to vent any remaining impurities to the balloon via CV119.

STOP 9 prepare standby

Control valves are regulated to resting positions, CV103 open, CV111 closed, CV175 closed.
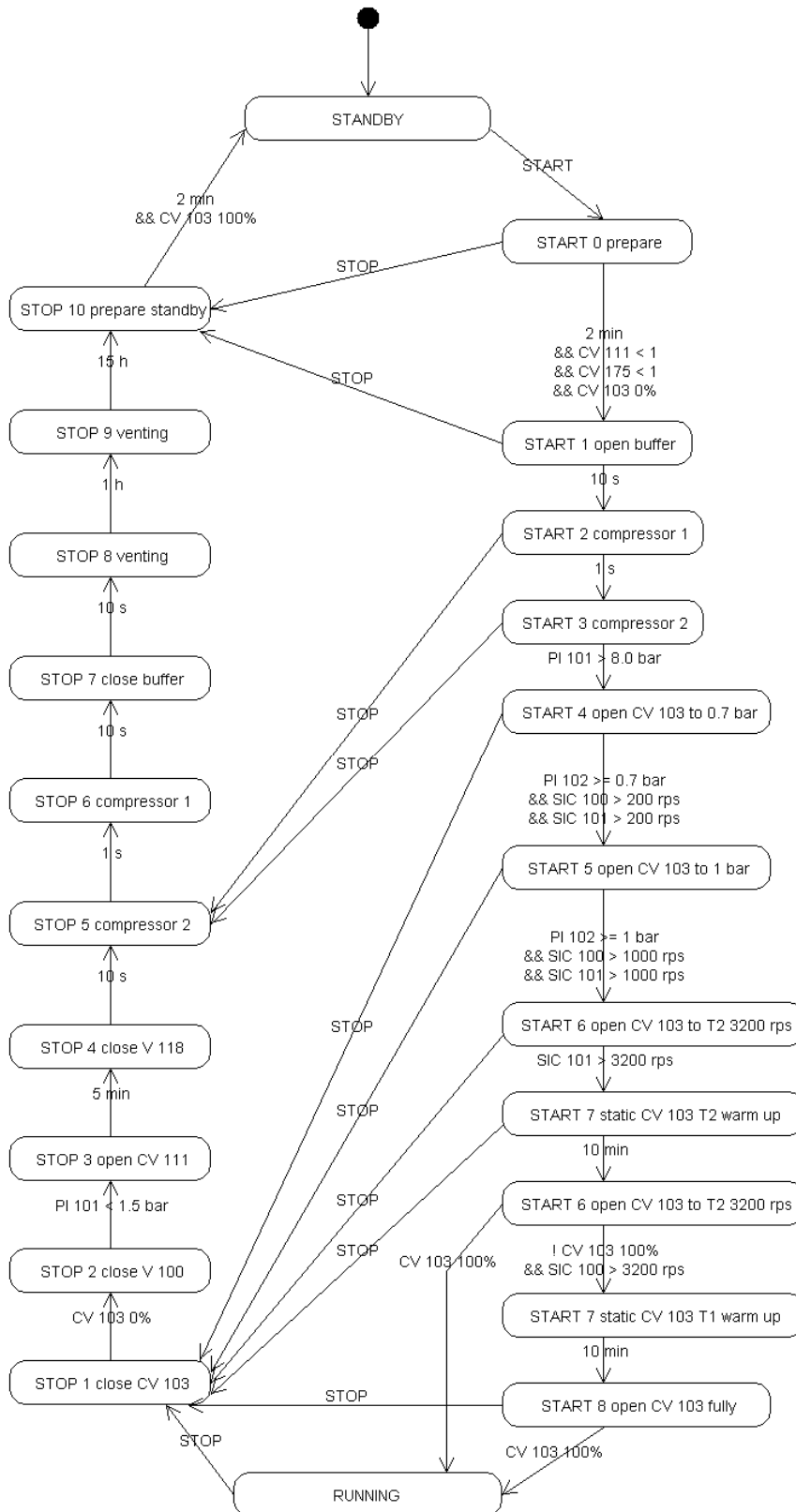
Figure 3.6: Liquefier states.

3.6.2 Purifier logic, description of states

The Purifier provides the Liquefier with pure helium gas. Before the return gas enters the Purifier it has been dried of any water vapour. In the Purifier the gas is cooled down in a heat exchanger causing any impurities e.g. nitrogen to condense or freeze on the wall. The impurities fall into the sump, either immediately or when the Purifier is reheated during regeneration. Regeneration is triggered when the buffer tank is full or when too much impurity has built up on the walls. The state machine for the Purifier is based on the normal cycle of the Purifier which is described in Appendix D about the machine TCF-20.

In the user interface described in Section 3.5.1 the Purifier can be found to the left. The valves controlled by the purifier logic are MV160, MV163, MV167, MV173, CV162/MV168, CV175, MV169, MV172 and MV174 *(see Figure 3.7)*.

Figure 3.7: On the Front Panel of the *UI* vi, the Purifier is depicted on the left.

The rest of this section contains the description of the states in the Purifier logic. An overview of these states and how they are related is found last in this section *(see Figure 3.11)*.

Off

When the Purifier is turned off all inlet valves are closed *(see Figure 3.8)*. The only connection between the Liquefier and the Purifier is from the secondary side of the Purifier to the low pressure side of the Liquefier via valve MV169. This prevents pressure from building up as the gas in the Pu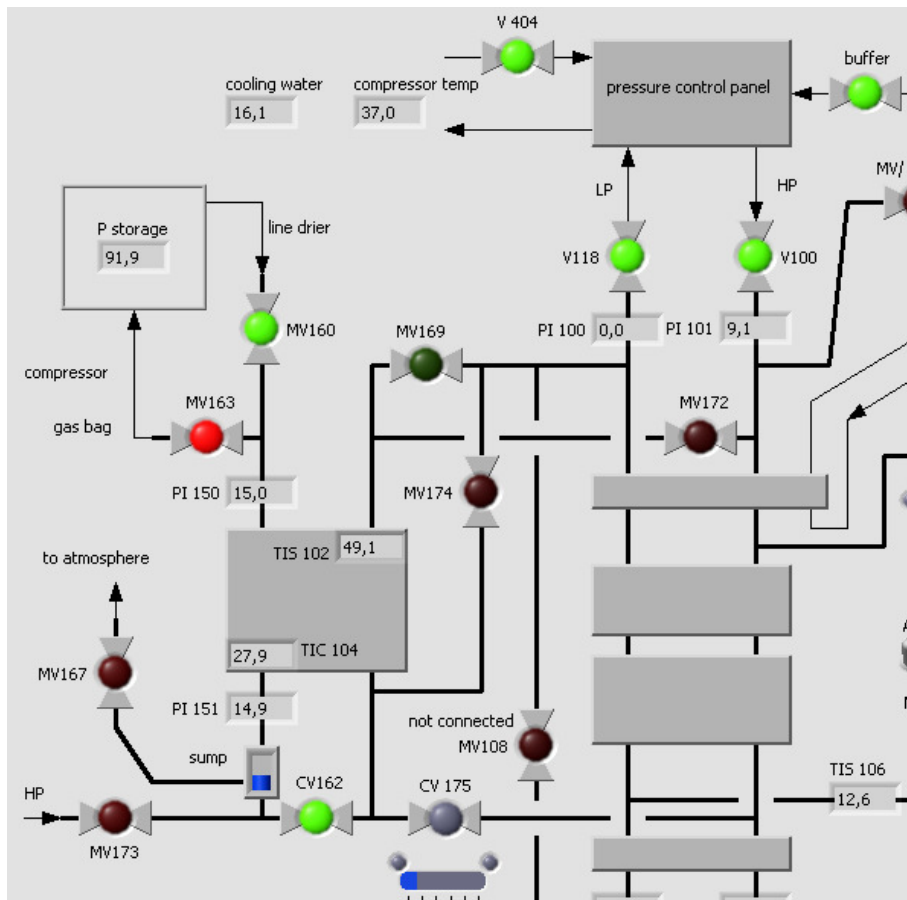rifier expands when it is warmed up to room temperature by the surroundings. On the primary side valve MV163 is open to the gas bag keeping the pressure low.

Standby

The Purifier is turned on by pushing the designated button on the Front Panel of the VI named *UI*. This causes the control program to automatically enter the state called Standby. It remains in Standby until the pressure in the buffer tank reaches a set limit, normally equivalent to about half full, or the state is forced to shift by the operator.

Figure 3.8: Off.

Purge 1

As the Purifier is triggered to start, clean helium gas is blown through the primary side of the Purifier for 5 seconds to blow any remaining impurities from the last cycle to the gas bag where return gas is collected before it is compressed to storage. After this the valve to the gas bag, MV163 is closed.

Cooldown 1

To cool down the Purifier cool helium gas from the Liquefier is let in through valve CV175 *(see Figure 3.9)*. This gas goes through the secondary side and back to the low pressure side. The secondary and primary sides are still kept separate by valve MV168/CV162. To avoid pressure drop on the primary side as the Purifier is cooled down valve MV173 remains open for clean helium gas from the high pressure side of the Liquefier to the primary side of the Purifier, keeping the pressure constant.

Figure 3.9: Cooldown 1.

Purge 2a and 2b

As the temperature reaches below 80 K on the secondary side the primary side is purged with clean helium gas from the high pressure side of the Liquefier again. MV163 is then closed and after another five seconds the inlet of clean helium gas, MV173, too.
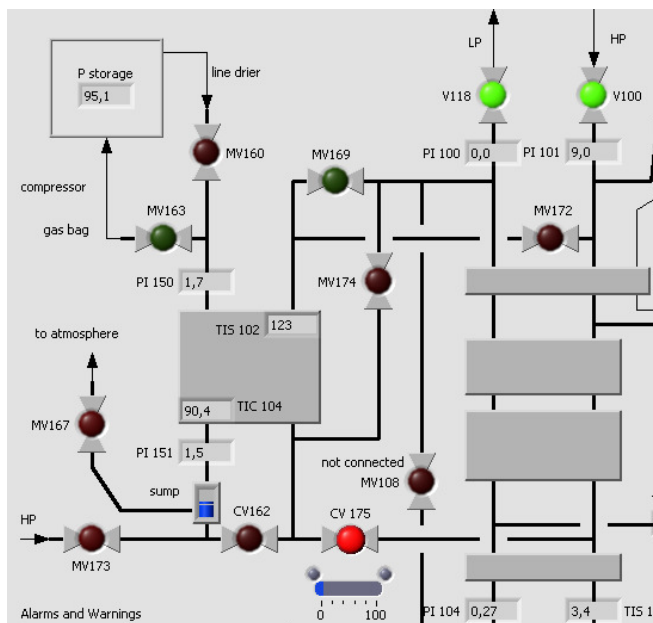
Cooldown 2

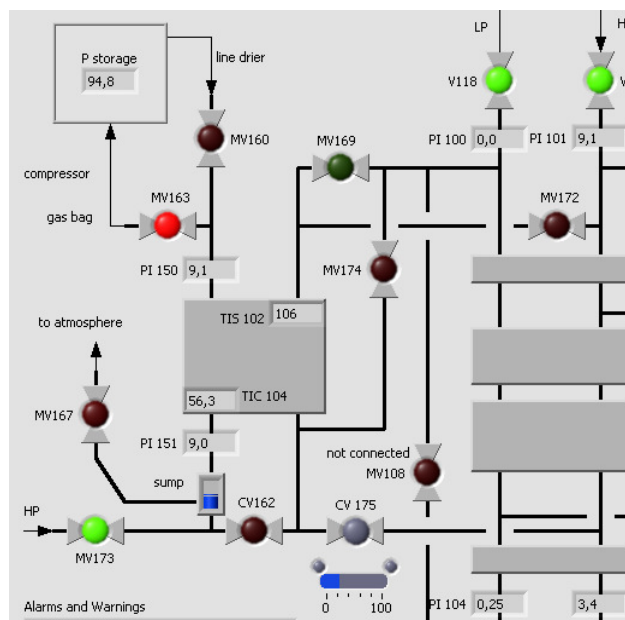The cooling of the Purifier continues and as it grows colder the pressure on the primary side will drop. When it reaches below 30 K it is so cold that any impurities will condensate on its walls and fall into the sump.

Purify, Purify Reset and Pre Purify

At this point valve MV160 from the storage of dirty gas will open. As long as the temperatures are maintained low enough MV168/CV162 is open. This allows dirty gas to enter on the primary side where any impurities will remain either frozen or in liquid form and move on to the secondary side where it is used to cool new incoming gas before it enters the Liquefier on the low pressure side.

As the gas in the storage is room temperature, it will cause the temperature reading to jump when the valve is first opened. MV168/CV162 then closes allowing more time on the primary side so the gas is properly cooled. MV168/CV162 will open and close a few times in the beginning before the walls of the heat exchanger are thoroughly cooled, not only the gas in it, and the valve remains in an open position. When the Purifier has been running for a while, CV175 will gradually close more and more. By the time the walls of the heat exchanger are cooled the cleaned gas itself will be cool enough to cool the incoming dirty gas with little help from the gas cooled in the Liquefier.

The reason for the three states is that it is important that the temperatures have stabilised before regulation of CV175 starts. The flow of cool gas should not be restricted because of temporary low temperatures; it should be kept steady until the Purifier is genuinely cold. In "Pre Purify" CV175 is consequently kept open and the state is time limited to 30 s. Should the temperatures during this time get to high "Purify Reset" is entered, from where it automatically goes back to "Pre Purify". Essentially these two extra states function like a timer, where "Purify Reset" is just passed through "resetting" the time temperatures have been stable.

"Purify" is left when the buffer of helium gas is full, when there is too much build up of impurities in the heat exchanger or when the operator turns of the Liquefier or in some other way performs an action that forces the state machine.

Regenerate and Controlled Stop

When no more gas should be purified the heat exchanger is warmed to make any frozen impurities melt and fall into the sump. At this point MV168/CV162 is closed and warm gas is taken from the high pressure side of the Liquefier and run through the secondary side in the reverse direction via valves MV172 and MV174 *(see Figure 3.10)*. As the Purifier is warmed the gas on the primary side will expand and is led to the gas bag via MV163. This is aborted when the temperature is so high that all impurities have melted. From the sump the impurities (mainly oxygen and nitrogen) are blown to atmosphere.
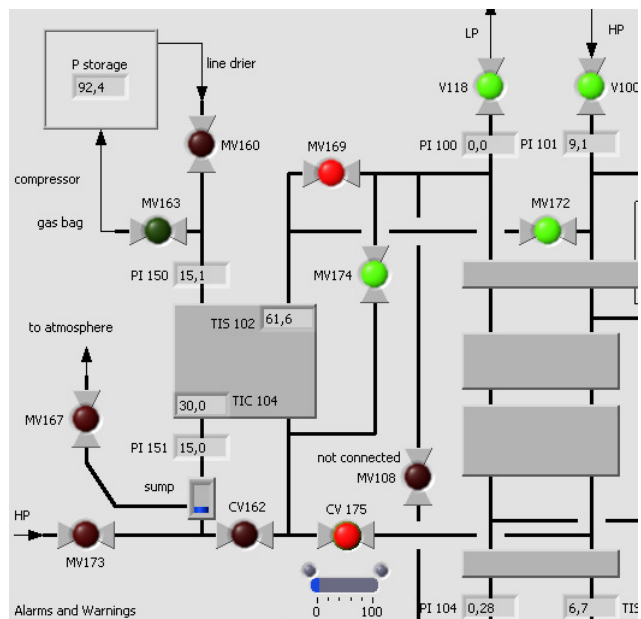
Figure 3.10: Regenerate.
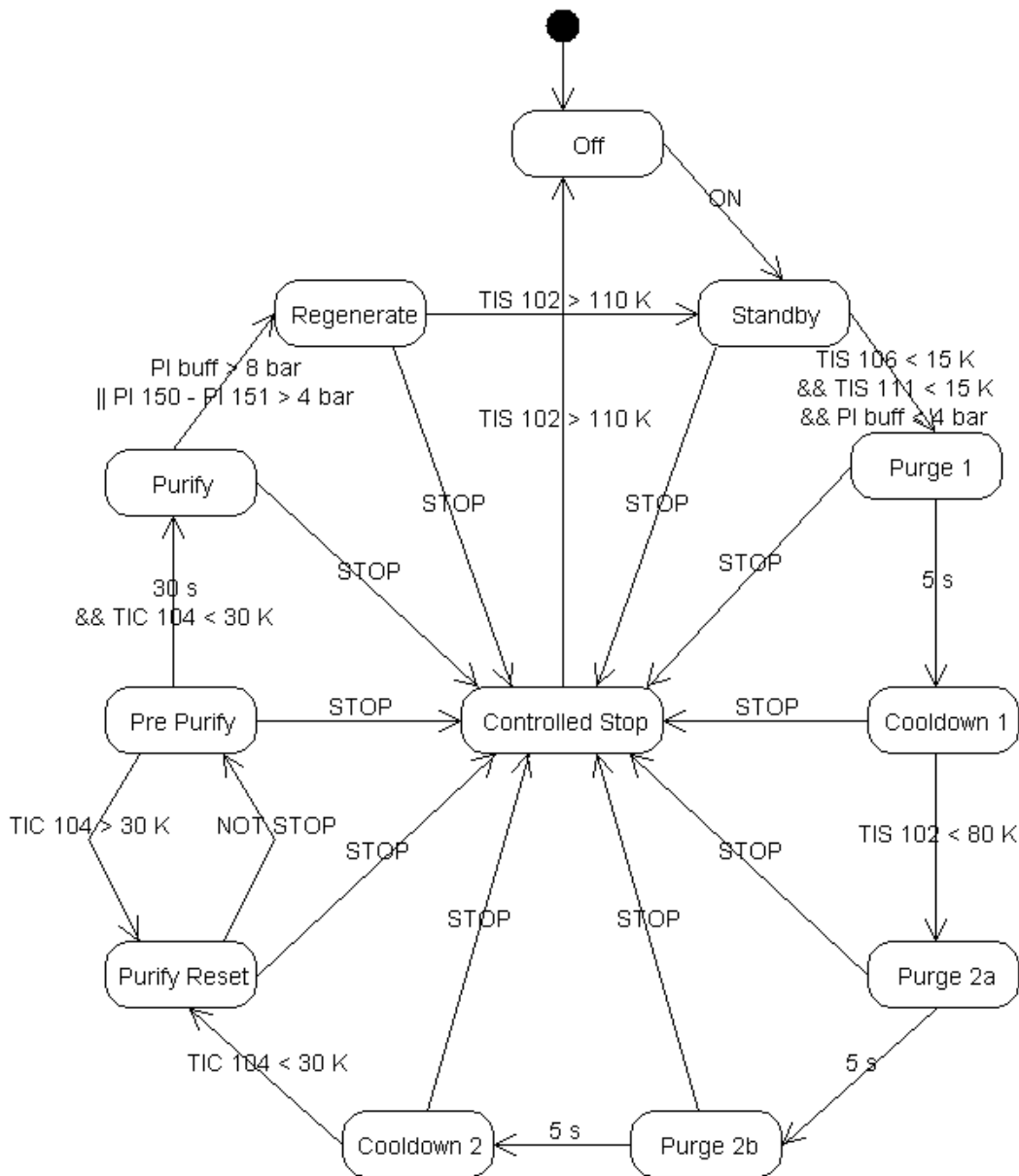
Figure 3.11: Purifier states.

3.7 Timing

The loop time is set to 200 ms which gives a considerably slower control than the old analogue continuous one. The process itself is stable and slow in its responses so this is fast enough. The hardware can easily handle much faster regulation but it is not necessary in this case. The response times can in some cases be a second or more, creating risks for overcompensating and much regulation is done even slower than 5 times per second, when opening a valve for example it is done little by little to ensure the process has time to stabilise not to overcompensate for small disturbances. In the case of control valve CV 175, which is controlling the flow of cooling gas from the Liquefier to the Purifier, this is done with a PID-regulator calculating a desired valve position rather than just seeing that the valve should open more or close more.

The control program is run on the cRIO and is built separate from the network communication and is compiled into a single thread. This is to ensure all deadlines are met. To guarantee this, it is essential that the program is actually run as a standalone application and not presenting an interface on the host computer. If the Front Panel is needed, (to tune parameters or in other ways change things in the program), deterministic behaviour cannot be guaranteed. Under normal circumstances this is not a problem as the capacity of the hardware is much higher than the program actually requires.

The presentation that the operator sees on the screen of the host computer is updated at a slower rate than the control and is not guaranteed to be updated exactly at regular intervals as other processes on the host computer might pre-empt the program. This adds to the initially very small delay caused by the Ethernet communication.

3.8 Alarms and automatic shutdown

The most critical part of the plant is the turbines and the turbine speed must always be monitored. This is done to ensure that they do not spin too fast when the machine is running but also to ensure that they start rotating in a good way when the machine is started. Build up of frozen impurities on the turbines can prevent them from spinning correctly and lose pieces can damage the turbines. The system of warnings presents a warning to the operator when the turbine speed is becoming too high and shuts down the plant when necessary to avoid damage to the turbines. Other cases where warnings are presented include if the cooling is not working properly causing compressors or turbines to overheat and if the pressure across the Purifier is too high which is normally caused by a blockage.

The trigger points have originally been chosen taking documentation and the recorded behaviour of the process into account. During the months that the plant has been running with the new control system, many of the values have been adjusted through simple trial and error to new values to ensure that the warnings and alarms are not issued with unnecessary regularity and that they really are active when necessary.

3.9 Transformation

The transformations of measurement values from voltages to other units are generally simple. In most cases they are done by linear equations and give good measurement values close to the working points of the machine and less good for extreme temperatures or pressures. For some temperature sensors more complex approximations have been used in combination with an offset to compensate for the drifting over time. In some cases the transformation has been chosen such that the values are in accordance with the ones measured by the old system and have not been further validated. To get good and accurate measurement values which are truly correct and not approximate and based on previous systems a recalibration is in some cases necessary and has not been done.

4 Testing and evaluation

The revised list of requirements in Appendix E presents not only features of the system but also guidelines for the work. This chapter is mainly about the features and behaviour of the system and how it was tested.

Typically each new control signal was verified first with a set of different manual inputs, then on real data comparing outputs from the two systems and lastly with connection to the real process. All these steps have taken some time and although the final tuning with connection to the real system was more time consuming, the actual work involved has been as much in the earlier tests. The examples of testing presented in this report are all from the phase when there was a connection to the real process. This is because it is more interesting when it can be shown how the process actually reacts and not only what the control system is attempting to do.

Figure 4.1: Front Panel of *control*.
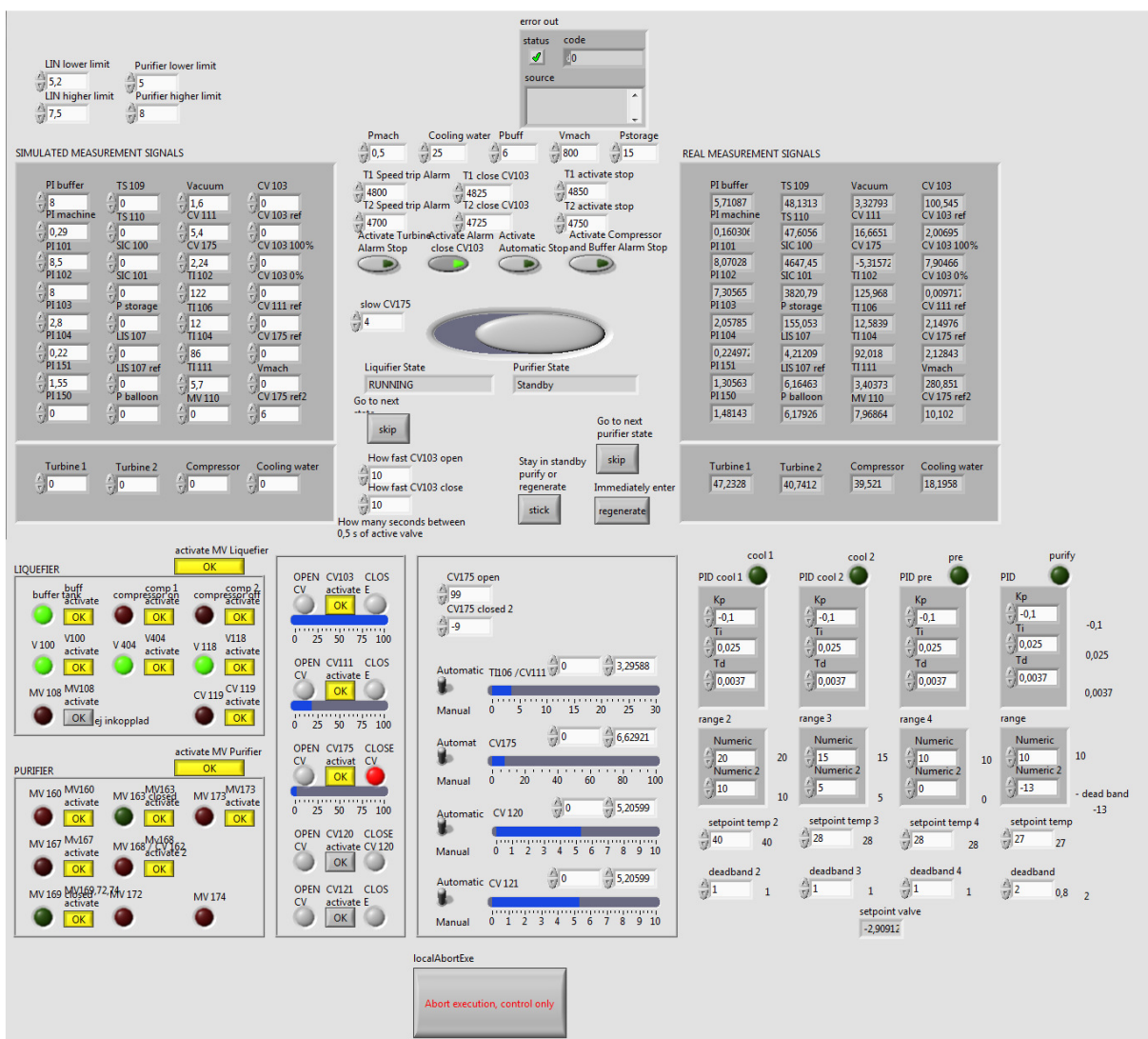
To be able to do all these tests the VI named *control* has a Front Panel with a lot of different options *(see Figure 4.1)*. When *control* is run as a standalone application on cRIO this Front Panel is not drawn anywhere. However, *control* can present the Front Panel on the screen of the host computer via Ethernet. This makes it possible to individually turn on and off all of

the control signals, to try different set points and vary how fast valves open and close, among other things. It is also possible to choose if inputs should be taken from the machine or entered manually or by another VI.

To show that the old and new system behaves similarly it is important to ensure similar test conditions. Small variations like build ups of frozen impurities or leaking gaskets influence the behaviour. Even normal variations during production like the pressure in the storage for return gas impacts the measurement values. The original plan was to run the two systems at the same occasion, thereby under similar conditions, and compare their behaviour. In reality, comparison between the old system and the final solution has not been possible during the same test run. The main reason for this is that parts of the old system where no longer functional at the time of final verification.

In most cases however, testing and comparison have been possible regarding individual features. Even though the original test plan was not followed the testing has been enough to ensure a similar behaviour part by part and a continued development into a fully functioning system. It would have been easier to show that the testing has been systematically done if all the data from the tests during the development had been saved.

In some cases the old system stopped working before the new one was implemented. In the case of the control of CV175, strange or even wrong behaviour in the old control was a reason for making that part of the implementation a priority. In this case a comparison with the old system has not been possible and the behaviour has been compared to old documentation of the system.

Even if only a part of the tests during the development have been saved there is still a lot of documentation of different tests and problems that showed up over time. All of that material is not included in this report but some examples are given in this chapter. All of the plots are from the Front Panel of the *plotter* VI. When comparing these plots it can be seen that the visualisation has undergone small changes in appearance over time. This was to ensure that the most significant plots for the current tests could fit on the screen at the same time. Only the most relevant plots for each example are presented rather than the full Front Panel.

4.1 Examples of testing

4.1.1   Improvement, CV 111 before and after

This is one example of how it could look when a new control signal was connected. In this case it was attempted to reduce the large variations in how open the valve to the machine tank was, hoping that a more stable temperature would help increase production rate. This means that the behaviour of the old and new system in this case is not exactly the same which makes it a little easier to see when the new system is connected.

The temperature at TI106 is dependent on the gas flow which increases when valve CV111 is opened. The plots *(see Figure 4.2)* show the measured values of how open the valve is and the temperature. An optimum working point lays somewhere around 12 K.

The value of interest is the temperature, any difference in the position of CV111 is meant to adjust the temperature to a given set point. The markings on the time axis are set one minute apart. The plots show first the old analogue control and then around 13.44 the new controller and at 13.54 a change in its set point from 12 to 13 K. This was the first attempt to take over the control of this valve and after this the code was improved step by step to try to find a good set point and reduce the oscillations. Motor speed can not be controlled so the final solution opens and closes the valve in steps allowing time for the temperature to stabilise. This is a common solution for most of the control valves, though the duration of and distance between the current pulses differs.
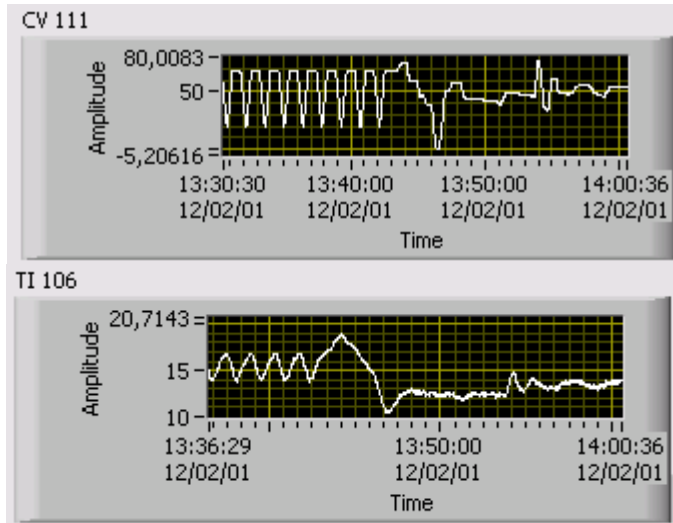
Figure 4.2: Inlet valve to the machine tank, CV111, and temperature at turbine outlet, TI106. The first parts of the plots show the behaviour with the old control and the later parts the first attempt to control the valve with cRIO.

4.1.2   Varying conditions, start up from cold and warm

The process behaviour at start up is strongly influenced by temperature. The most critical parts of the plant are the turbines and when the machine is started from cold the turbines gain speed very quickly even at low inlet pressures. As a low temperature can cause the turbines to spin too fast during start up it was important to test the start sequence starting from different temperatures.

The increase in pressure on the turbines and the time allowed for turbine warm up, have been chosen such that they provide a wide safety margin for most cases. However, if the machine is started from very cold, (as would be the case if it has been stopped and then immediately is started again), it is important to keep an eye on the turbines. The regulation of the turbines is dependent on their speed rather than the cooling capacity. When a turbine reaches a specific speed during start up it is regulated to its optimum working point. This decrease in braking of the turbine means that the cooling decreases. At this point it is essential that the pressure on the inlet is kept stable long enough for the temperature on the cooling side of the turbine to rise so that the possible cooling capacity is high enough to brake the turbine at the new faster speed when necessary. If the pressure is increased the turbine speed will increase and it will not be possible to brake. When the machine is started from room temperature the first turbine will not reach enough speed to be regulated to optimum speed during the start up sequence, instead it will be braking fully still as the inlet valve reaches its fully open position. If the machine is started from a colder state or LIN-cooling is used the first turbine will reach optimum speed during the opening of the inlet valve just like the second turbine. When this happens it is important to allow time for the turbine to warm up, meaning that the opening of the inlet valve should be paused again.

The plots to the left show the behaviour of the inlet valve and the turbines when the machine is started with gas at room temperature, approximately 292 K *(see Figure 4.3)*. To the right is an example of when the machine and the gas inside it are colder, approximately 230 K and LIN-cooling is used. Please note that the time scale is not the same on the two plots, time markings on the x-axis are set 5 minutes apart on the first and 10 minutes apart on the second.
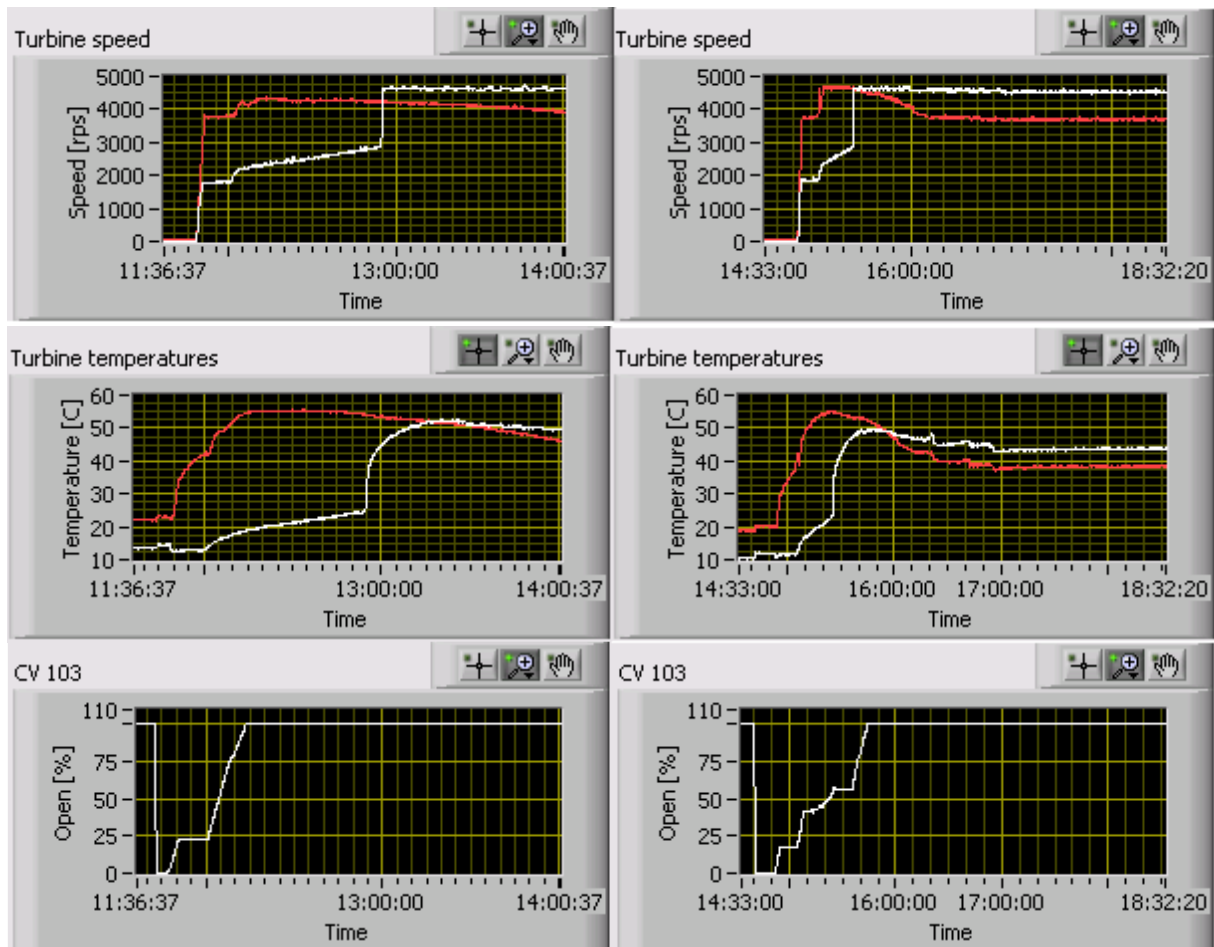
Figure 4.3: Measurements during the start sequence of Turbine speed and temperatures and the opening of the inlet valvet to the turbines, CV103. Plots to the left show the behaviour with warm gas in the system and plots to the right colder gas in the system with additional use of Liquid Nitrogen Cooling.

In the case with warmer gas in the system the first turbine (white) does not reach its full speed while the control valve CV103 is being opened. With colder gas and LIN-cooling both turbines reach their full speed during the opening of CV103. To allow time for the turbines to warm up, the opening is paused when the turbines are allowed to reach optimum speed. There is also a strange shape of the curve for CV103 between 15.10 and 15.25, this is to slow down the increase in pressure and consequently speed and is necessary because of the LIN-cooling.

During the testing of the cool and warm start up a special case appeared that the code can not handle. The tests showed that in the case of a start with very cool gas in the system, (as in the special case where the machine is started immediately after it has been stopped), the first turbine will start spinning before the second one *(see Figure 4.4)*. The code does not support this special condition; the control monitors the speed of only the second turbine in the beginning. This means that there is a risk that the first turbine will not have enough time for warm up as the opening of the inlet valve and thus increase in pressure will continue. This is not a common situation and usually only occurs after some kind of problem or adjustment requiring a stop. For special situations like these the start of the plant should be monitored but even so it could be worthwhile to change the code for this special situation to make it easier for the operator. It is not complicated to change but there has not been enough time for it during this project.

When the machine is started from such a cool state the production starts while the start up sequence is still running. The gas is cold enough to condense when it is expanded through

the control valve to the machine tank. This is the reason why CV111 opens so early even if it the system has not yet reached its full cooling capacity. In the case with the warm plant the production has still not started almost two hours after full pressure has been achieved on the turbines.
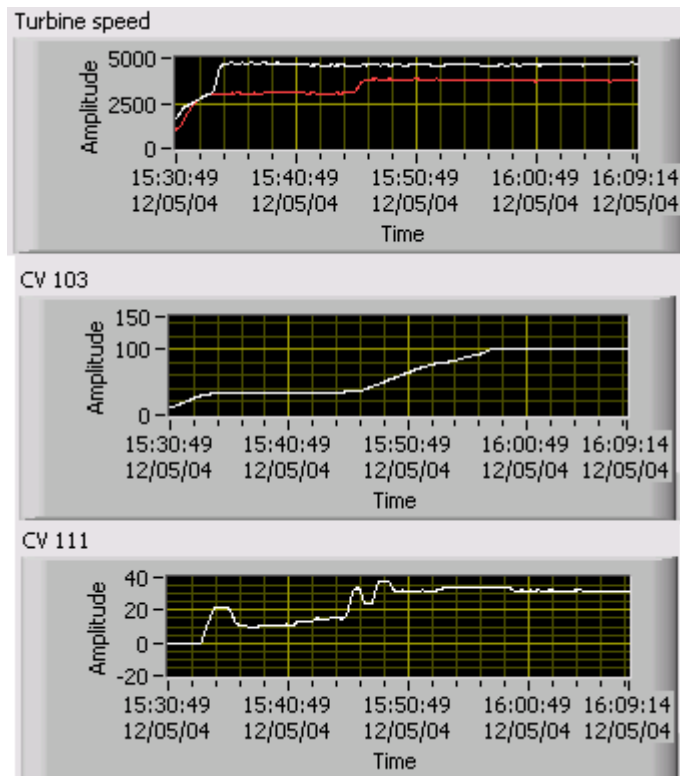

Figure 4.4: Measurements during the start sequence of Turbine speed, the opening of the inlet valvet to the turbines (CV103) and the valve to the machine tank (CV111). Plots show the behaviour with very cold gas in the system.

5 Results

The overall goal of the project was to extend or replace the existing semi-automatic control program, interfacing the already operational helium liquefaction machine, as well as provide improved remote monitoring functions. The system has now been in use for over six months and has been functioning as planned. This is the best indicator of a successful project. Almost all of the old control system is replaced; the main difference is the addition of an extensive user interface. Interesting signals that were previously internal to the control system are now presented both in their context on the *UI* Front Panel and by graphs. The plots make it easier to see patterns and deviances early. The operator has information about all output values, valve positions and the current state of the logic. The user interface also provides increased possibilities for the operator to control the process and affect logic and set points in a way that was previously not possible. The new automatic start and stop sequences and the remote control are working well. No problems have been detected with cRIO and the control of the plant.

List of requirements:
Restructuring and refining the original list of requirements a revised list was created during the analysis phase and it has been used for system evaluation and acceptance. Both the original requirements and the revised list can be found in Appendix E. Almost all of the 42 criteria listed have been fulfilled. These requirements are not only focused on functionality but also in some cases instructions on how things should be done. In some cases things have been done differently than originally intended and in a couple of cases (12, 17) this leaves room for further improvement. In three cases the criteria have not been met because of lower priority and lack of time (16, 20, 41). All requirements that have been met differently than planned or that have not been fulfilled because of time constraints are specifically commented in the following sections with their reference number.

Overall limitations:
The integration of the new control system and the replacement of the old control step by step has been carried out successfully. Testing outside the machine was done with the help of created input data for extreme conditions and by running the new system in parallel with the old one but without connection to the process to ensure similar behaviour. All adjustments of the plant have been carried out during the ordinary planned stops. Sometimes this has imposed limitations on the work and adjustments in the planned work sequence of the project but it has not caused any disturbances of the production.

Hardware and signals:
The choice of hardware was a prerequisite for this project and it has functioned as intended. Almost all of the initial requirements and ideas have been carried out as planned with exception for requirements 11 and 12. The need for an AD converter module for measurements up to 24 V (11) was solved differently than planned with a simple home made analogue board using voltage division.

The ambition to avoid integrating 220V signals (12) into a system that contains only low voltage signals and is so easily accessible to the operator was only a limitation regarding the measurement of valve positions for the valves controlling the speed of the turbines (CV120 and CV121). These two valves may never be fully closed as there should always be some brake applied. At this point the control of these two valves is implemented but not tested or connected. The signal showing when the valves have reached their "closed" position is a 220V signal and needed for the control. At this point the old analogue board is still in use.

Control program software on cRIO:
The manual start and stop sequences have been automated in accordance with the descriptions in the manual for the original plant. This has facilitated the work with the plant. Logic for LIN-cooling has been added based on operator experience. The current control program is completely standalone and not in any way dependent on the user interface presented on a separate computer. If contact is lost with the user interface during manual control of one or more parameters automatic control is resumed.

Frequency sampling of turbine speed (20) has not been implemented. The sampling rates used in the rest of the project are too low but it should be possible to implement this functionality on the backplane FPGA. It was decided to continue the usage of the old analogue board that converts the speed to a voltage. This kind of unit is neither expensive nor hard to find and time was better invested in other parts of the project.

User interface, software on host computer
The new user interface is similar in appearance to the original operator terminal but provides much more detailed information and significantly improved possibilities to both supervise and control the process.

Additional data display
All key measurements are continuously presented in graph form. This is very helpful to view trends and detect similarities in and deviances from the normal cycle pattern. All measurement data can be stored in log files. This can be used to see patterns over longer periods of time or plot a specific measurement value retrospectively.

Alarms and warnings
Threshold values for warnings and emergency stop have been identified. In many cases a possibility to change them at runtime has also been implemented. Suitable stop sequences have been identified, implemented and tested for all possible states as well as a fast shutdown for critical situations. The external emergency shutdown of the power to the compressors is still in use. Normally the routine for handling of speeding turbines or the fast shutdown is sufficient, but this should be kept as an extra safety precaution. The vast possibilities to influence the control means that it is possible to e.g. set a threshold value for controlled shutdown such that it is not triggered in time. This external emergency cut of power is a safety precaution in case of an incorrect behaviour of the control, whether introduced by an operator or hardware malfunction.

Remote operator control
It was planned to used existing features in LabVIEW to expose the user interface over internet (40, 42). This has been used and it worked very well to run the plant from home. At this point remote desktop is used to fulfil the same need, as the current LabVIEW options for password protection do not suit the needs in this specific case.

A very simple test program has been made to see that it is possible to send emails with notifications of warnings (41) but this is not a working feature in the project as it was a lower prio feature.

6 Discussion and conclusions

The most important requirements set up in the beginning of the project have been met and the system has now been in use for more than six months. The plan for the work has been followed and the iterative process and stepwise replacement of the old system worked very well. The staff at Kryolab has been involved in the design and evaluation of the new control system. This has been a key to make the final version not only a competent control software but also extendible and adjustable according to future needs.

The new automatic start and stop sequences are working well, facilitating the work of the operator. All of the parts in the old systems that where no longer functioning properly have been replaced and the current system is much more stable and reliable.

The improved possibilities to visualize collected data have provided a lot of information and an opportunity to understand the process better. Variations in behaviour over the cycle can be followed and it is much easier to see deviations from normal behaviour now. The increased knowledge and understanding of the process that the visualisation has brought to everyone involved is probably the most important side effect of this project.

The increased possibilities to adjust the control also mean that it is possible to run the machine under more difficult circumstances. In some cases this can be very good, and the opportunity to use remote control of the plant can, for example, be used to prevent the need for an emergency stop. However, when the plant is run under abnormal conditions it will have to be monitored continuously. It is important to be aware of this and not use this possibility more than necessary. Even if the remote control ability means that whoever is responsible for the machine can monitor it around the clock, it was meant to reduce work for the operator, not to create a situation where the plant controls the operator. When the automatic control system can not handle operation it should be seen as an indication of maintenance need.

That the control system should be run separately and deterministically was one of the most important requirements. However, in reality it is often not. A list of all the parameters that should be possible to control manually was established early in the project. But during the construction of the VI *control* it was necessary to implement a Front Panel to make it possible to tune and adjust far more parameters in the control during runtime. Since the control parameters have been chosen and tested the Front Panel of *control* should not be needed anymore during normal operation, but the opportunity to adjust as many parameters as possible was so appreciated that it is still normally used. So far the cRIO always had so much extra computing capacity that it could present its Front Panel on the host computer without causing any disturbances of the control. It has been ensured that the control program in cRIO resumes normal control if contact is lost with the host computer. If contact is lost with the host computer the possibility to use the Front Panel of *control* is lost, even as the connection is re-established again. The VI *UI* will still work though, so the behaviour can still be affected yet at a higher level, the level that was originally intended. Even if this works and the extra capacity of cRIO makes it unlikely that the control should not meet its deadlines it is important to note that determinism cannot be guaranteed unless the program is uploaded to cRIO as a standalone application.

It has not been a goal of this project to evaluate LabVIEW, but some of the experiences of the programming environment in this particular project are summarized below. This is from a beginner's point of view. Previous programming experience consisted primarily of projects in Java and other textual languages. The experience of more graphical approaches was small and limited to the graphical languages defined in IEC 61131-3 for programmable logic controllers and the graphical extension of Matlab called Simulink.

LabVIEW was a good environment to work in, although it took some time finding the most suitable language features and determining which program design patterns that where best for this language. It is very easy to get started, and construction of simple implementations is intuitive. The problem is that those implementations do not always scale well. A lot of time was spent in the early stages of the project trying to figure out a good format for the program to make it easily extendable and also testing different kinds of functionality to see what was possible to do and what was not. This exploration of possibilities was necessary to do before the basic structure of the implementation could be chosen. To invest some time in the basic courses early on is probably good for beginners. A wider knowledge of the available functions and to have someone to discuss format with would have been beneficial. There are many things that are already implemented but it is not so easy to find if you do not know exactly which subVI or example you are looking for. Better previous knowledge of LabVIEW would have speeded up the process considerably. The discussion board on the NI website is an excellent source of information; most problems that you might experience have probably already been posted there by somebody else, usually with good replies and solutions.

One of the main drawbacks of being only one student in the project was the lack of someone to discuss problems with. Not necessarily someone who could provide solutions, but a person to discuss questions with and explain problems to. The NI support was excellent when it came to basic LabVIEW questions, and the manuals and the Kryolab staff provided much information regarding the plant and how it worked. But often a combined knowledge of both the plant and the programming environment was needed to understand the challenges. It is a benefit when solving problems to have more than one point of view and multiple sources of ideas. For the implementation time on the other hand it would probably not have made as big a difference since the timing was much related to opportunities for testing.

The response from Kryolab on the project has been very positive. All of the important criteria set up by the Kryolab staff at the beginning have been met and the new control has made it possible to handle increasing amounts of return gas. This leads to the conclusion that it has been a successful project.

7 Future work

It has been the aim to build this control system in such a way that it is easily expanded and some changes are already prepared for. Code already written but not tested includes regulation of control valves CV 120 and CV 121 which control turbine speed and the magnetic valve MV 108 providing a bypass for the gas when the machine is too warm to open the valve to the machine tank. At this point the analogue boards provide an excellent and robust regulation of these valves, but should it be necessary to replace these boards in the future the activation of this code could be useful. It is, however, not tested and built according to the description in the user manual for TCF-20; in particular the set point values for different actions must be chosen in accordance with the behaviour of this specific machine.

The structure was designed to allow an easy addition of logic for LIN-cooling and a basic control for LIN-cooling has been added after the project. Further development of this to optimise the production rate could be of interest. To facilitate the use of Liquid Nitrogen for pre-cooling the installation of a permanent pipe from the Nitrogen Liquefier tank could be highly useful. Worth noting though is that at this point in time the plant has no difficulties liquefying all return gas even without this increase in efficiency. Continued work to increase the fraction of the helium sold which is returned as return gas is advisable.

Many of the control parameters in *control* can be further optimised. The system is running and working well at this point but the behaviour can obviously always be improved. As it has been the goal to provide measurements comparable to the old system the original transformations have in many cases been copied and recalibrations have not been done. This makes it easier for the operator to recognise patterns and deviances based on experience. In a longer perspective it would be better if the measurements where really correct and calibration should be done on a regular basis. The transformations used are approximations and provide the most reliable data within the natural working range of the plant. It would be interesting to redo the calibrations and maybe also develop more complex transformations that give more accurate measurement values. It would make it easier to compare the plant with others or with future data. The current solution for the filtering of signals is very simple using only an average value over a number of samples. This is enough to give the intended behaviour of the control but could be improved to provide more accurate information to the operator.

Continued development of the logging and warning systems could also be useful, including the use of e-mails or SMS to communicate errors and potential problems as well as tools to easier diagnose incorrect system behaviour from the logged data.

There have been occasional disturbances in the communication between the host computer and cRIO as well as a few crashes of LabVIEW on the host computer providing the user interface. It is hard to determine to which extent this is caused by this project, as the same problem has also occurred earlier with some simple programs used to log the behaviour of other systems at Kryolab. It is likely that this is related to LabVIEW or other activities carried out by the PC rather than the code for the user interface of this project. These crashes do not affect the control system in any way as it is built to work separately from the host computer. This independency was one of the most important requirements. To regain access to the plots and options for manual control a restart of LabVIEW on the host computer is necessary after which connection can be re-established with cRIO. Data collection from the crashes on the host computer could help explain these problems. At this point the logging is limited to the collected data from the plant. More information about what is happening on the host computer and on cRIO is needed to determine how to solve this problem.

Most importantly it would be advisable for any operator of the machine to strive for a basic knowledge of LabVIEW and the program structure as the program is prepared with the explicit goal of making code that can be altered and further evolved by the operator. It has

been the intention to make it as open and easily understandable as possible. Still, some basic understanding of how changes in one part of the code will affect the rest is a necessity.

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Appendix A: Kryolab

Kryolab is located at the Department of Physics and provides liquid helium and nitrogen for coolant purposes. Liquid nitrogen is extracted from the air through liquefaction and fractional distillation. The abundance of nitrogen in air makes it comparatively cheap and with a boiling point at 77 K it is a good cooling agent. For some applications this is not enough and helium is used. Helium has the lowest boiling point of all elements at 4.22 K. It also has a very low chemical reactivity as it is a noble gas. These unique properties make it particularly useful in cryogenics. As helium is not so easily accessible it is important to try to reuse it when possible.

The liquid gases are used mainly for experiments where cooling is needed. There are many different options on how to supply the cooling. When the fluid is used to cool a sample it can be evaporated to the atmosphere or recovered. In the case with nitrogen which is comparatively cheap and originally extracted from the atmosphere there is little need for recovery. Helium, however, is a limited resource and often accounts for a significant part of the cost for an experiment, thus it should be the aim to recover the gas when possible, particularly if larger amounts are used. If the helium can be recovered it can be liquefied at the Kryolab plant and reused. Most of the helium is used in closed cryostats from which the boiled off helium gas is collected. The gas used by the helium liquefier plant primarily comes from permanent pipes from research labs throughout the university. Helium gas has very small molecules so it is hard to avoid leaks. There are also customers who do not recover the helium gas. Currently about 60 % of the delivered helium is returned to Kryolab as gas.

Kryolab also purchases liquid gases to account for the helium that boils off and when demand is higher than the production capacity of nitrogen. [3]

Appendix B: Helium

Helium has the lowest boiling point of all elements at 4.22 K and is not found in solid state unless pressurized. It also has a very low chemical reactivity as it is a noble gas. These unique properties make it particularly useful in cryogenics.

Helium is not so easily accessible on earth even though it is the second most abundant element in the universe, outnumbered only by hydrogen. The low weight means that a large fraction of helium atoms evaporated from the cloud of earth and dust that would eventually form Earth. Helium atoms can easily reach high speed and escape from the atmosphere so the volume percent of helium gas in the atmosphere is very low (a few ppm) and helium is not commercially obtained by distillation of liquid air. Most of the helium used today is found in natural gas from which it is extracted using fractional distillation. This helium has been created by radioactive decay of larger atoms and collected under rock formations over long periods of time; alpha particles are in fact the same as helium-4 nuclei.

The use of helium for buoyancy in air ships is no longer a large market but helium is used for many other purposes such as helium-neon lasers, dilution of oxygen for deep sea diving, pressurization of rocket fuel, in balloons, as a protective gas in arc welding and silicon wafer manufacturing. As no other coolant can be used to reach as low temperatures as helium it is also to a great extent used for cooling purposes in high-energy accelerators, MRI-scanners and all sorts of cryogenic applications. [4][5]

As helium is a natural gas by-product, the extraction of natural gas greatly influences the amount of available helium. But the helium content also varies greatly between different geographical regions and not all natural gas fields produce helium. Most of the helium produced today is produced in the United States, where gas fields have been found with helium contents ranging up to 7%. In general, concentrations above 0.3% are of commercial interest. [6] The Federal Helium Program was initiated in 1925 and was supposed to ensure supplies of helium for defence, research and medical purposes. The military particularly valued it for its use in buoyant aircraft. Over the years a large amount of helium was stored in the Federal Helium Reserve. In 1996 it was decided in the Helium Privatisation Act that the helium should be sold off to repay the debts of the program as federal use of helium was low. The past five years approximately 75% of the world production came from the U.S. and a great part of it from the Federal Helium Reserve. Figures from the U.S. Geological Survey indicates that about 30% of the helium used worldwide is extracted from this resource. Other production sites around the world currently running include fields in Algeria, Russia, Poland and Quatar. The demand for helium is increasing and the fact that helium is produced at a very limited number of production and refinement sites and that the production is so dependent on the demand of natural gas means that the availability of helium on the world market has been unstable in recent years. [4][7][8]

Appendix C: Cryogenics and refrigeration cycles

C.1 Cryogenic fluids

Cryogenics is the production and application of low temperature phenomena. It is a utility enabling applications such as liquefaction, separation, storage and transport of gases and the altering of material and fluid properties by reduced temperature. The temperature range in question has been defined as ranging from absolute zero to 123 K. [9]

In a cryogenic system a cryogenic fluid is used as a working and cooling agent. These fluids must have a low triple point. Hydrogen, neon, nitrogen and oxygen all have triple points below 100 K. Oxygen is difficult and dangerous to work with because of the high reactivity, and the use of hydrogen has diminished over the years for the same reason. The inert gas neon is generally considered too expensive. Nitrogen is along with helium most widely used. Helium is exceptional as it has no triple point at all. It may solidify only at pressures above 2.5 MPa. The lambda point of helium, often found in tables instead of the triple point, refers to the point where two kinds of liquid helium (one of which contains a superfluid part) and gas coexist rather than solid, liquid and gas. The fact that helium evaporates at such an extremely low temperature makes helium the most useful and popular option for cryogenic purposes. Nitrogen does not have as useful characteristics but is still widely used when it is possible due to the lower cost. [10]

C.2 Thermodynamical theory of the plant

To understand the theory behind the Liquefier some knowledge in thermodynamics is essential. This chapter briefly describes some basic concepts particularly useful for this purpose. These descriptions are intended as reminders rather than exhaustive explanations. Some useful expressions can be found in the list in Appendix F.

C.2.1   The ideal gas law and the Joule-Thomson effect

Enthalpy is the total amount of energy in a thermodynamic system. If no energy is added and no work is done on a system the enthalpy should remain constant. How much energy a system with gas has depends on how much gas there is (number of molecules), which volume it occupies and which pressure and temperature it is kept at. These entities are dependent on each other and the ideal gas law defines a relationship between them, $pV=nRT$, where R is a constant, p pressure, V volume, T temperature and n number of moles of the molecule. This is valid only for the theoretical ideal gases and is a good approximation for many gases at normal temperatures and pressures. It does not hold for real gases, especially not in cryo temperatures. This means that when a gas undergoes isenthalpic expansion ($pV =$ constant) its temperature will change.

If the temperature increases or decreases depends on the gas, pressure and temperature. In the property region inside the Joule-Thomson inversion curve the expansion will cause the gas to cool *(see Figure C.1)*. This is called the Joule-Thomson effect and is used in a Joule-Thomson or Linde cycle.
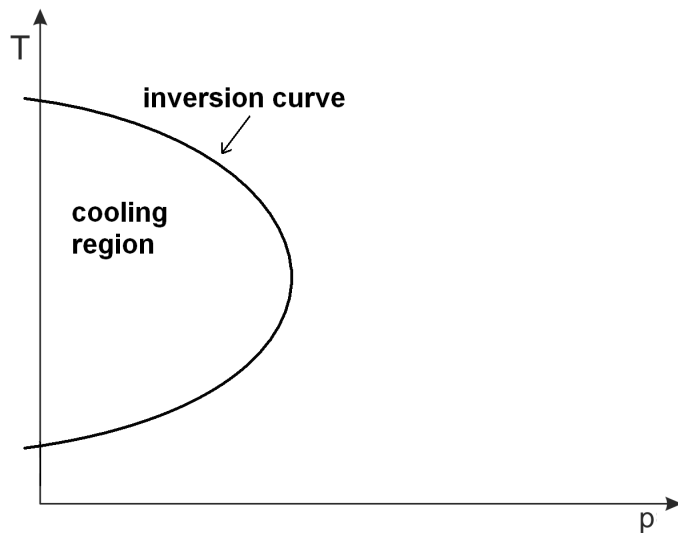
Figure C.1: Joule-Thomson inversion curve.

C.2.2 Basic refrigeration cycles

One of the most well known examples of a reversible cycle in thermodynamics is the Carnot cycle. The theoretical Carnot heat engine operates on this cycle using the temperature difference between two reservoirs to create work. The Carnot factor defines the maximum amount of work that can be extracted from a process given the temperature levels. Similarly the needed minimum work input of the Carnot refrigerator, which is operating on the reverse, can be estimated. In the Ts (temperature, entropy) diagram in Figure C.2 the work is equal to the enclosed area (1,2,3,4).
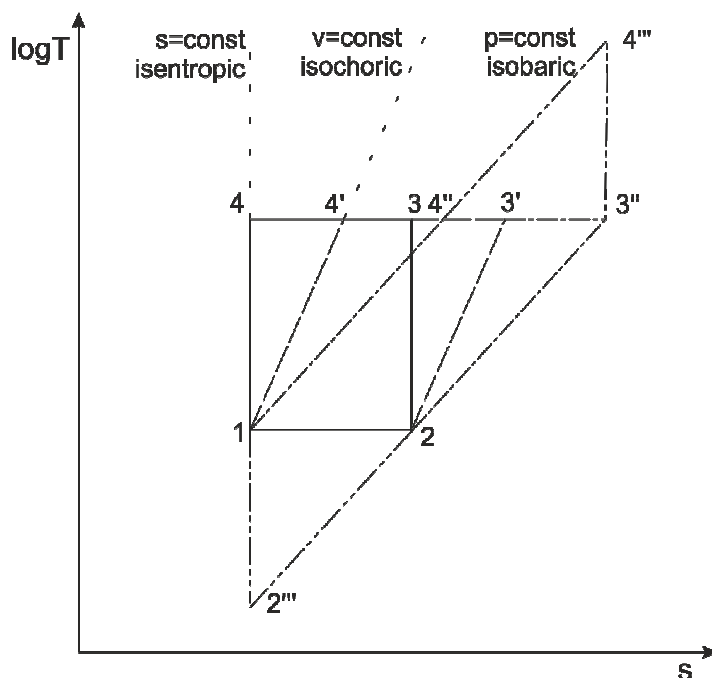

Figure C.2: Ts-diagram for various cycle processes. T is temperature, s is entropy. Carnot cycle (1,2,3,4). Stirling cycle (1,2,3',4').Ericsson cycle (1,2,3'',4''). Brayton cycle (1,2''',3'',4''').

Other theoretical alternatives to the Carnot cycle that are also very efficient could be the Stirling or Ericsson cycles. During the temperature increase the entropy is allowed to increase,

and instead either the volume or the pressure is kept constant. The three basic cryogenic refrigeration cycles with isothermal expansion and compression discussed here, the Carnot (1,2,3,4), Stirling (1,2,3',4') and Ericsson (1,2,3'',4'') cycles, are all "ideal" cycles with good theoretical efficiencies *(see Figure C.2).* They all enclose a small area which should indicate that a small amount of work is needed to cool gas in this way. But the isotherm (constant temperature) transitions are very difficult to approximate. The Brayton cycle (1,2''',3'',4''') makes use of isobaric compression and expansion like the Ericsson cycle and isentropic expansion and compression like the Carnot cycle. This way no isothermal expansion and compression is needed. It has significantly lower efficiency by definition than the other cycles, this is represented by the larger area enclosed in the Ts-diagram. But it is also much easier to approximate than the other cycles. It can be said to form part of the basis for the cycle used in the Liquefier but some alterations are still needed.
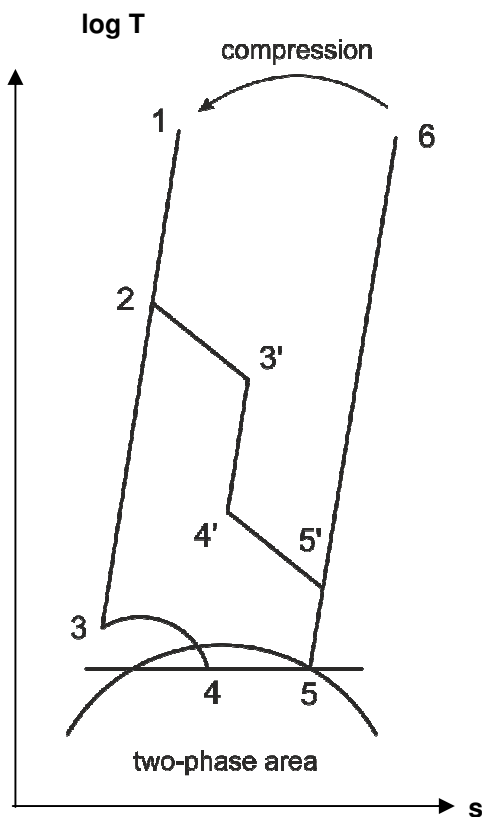
C.2.3 Liquefier refrigeration cycle

Figure C.3: Ts-diagram for the Liquefier TCF-20.

Figure C.3 depicts the Ts-diagram for the Liquefier where a cycle very close to the Brayton cycle can be identified (1,2,5',6). The cooling (1,3) and heating (5,6) is done at constant pressure. The gas compressors are in their nature isentropic (6,1) even though some cooling is applied to limit the temperature. And the expansion through the turbines (2,3') (4',5') is at least ideally isentropic though in reality polytropic. The work exerted on the turbines causes the gas to cool. The purpose of the turbines and consequently the Brayton cycle is to reach low enough temperatures to be able to use the phenomenon previously described, the Joule-Thomson effect.

In the Liquefier helium gas at low enough temperature and pressure is expanded in a valve (3,4) becoming so cooled that it enters the two phase area, the liquid is collected in the

machine tank and the gas is used to cool incoming gas through a series of heat exchangers on the way back to the compressors. This cooling during expansion is due to the fact that the temperature and pressure are so low, the gas would be represented inside the Joule-Thomson curve *(see Figure C.1)*. This is the cooling used in a Joule-Thomson or Linde cycle. It is not possible to liquefy helium (though most other gases) in a pure Joule-Thomson cycle. At ambient temperature we are far outside the cooling region in the Tp-diagram in Figure C.1. The helium must first be pre-cooled. It is the combined use of the turbines and the throttling that cools the gas. This combined cycle is also more efficient than the pure Joule-Thomson cycle. The combined cycle described here is often referred to as a Claude cycle. [8][11]

Appendix D: Helium liquefaction plant

D.1 Overview

This appendix contains a description of the Helium Liquefaction Plant, which parts it consists of and the helium's path through it. A more basic description of the functionality of the plant can be found in Chapter 2. More information about the theory behind the Liquefier and a basic description of the refrigeration cycle is available in Appendix C. The information on which this appendix is based has been gathered from the manual of TCF-20 [12], from Kryolabs web page [2] and from the Kryolab staff.

The Helium Liquefaction plant is used to collect incoming gas, clean it from any impurities, liquefy it and transfer it to vessels for delivery. Figure D.1 shows a simplified view of the helium's path through the system. The return gas handling and the storage is described in Section D.3. How the Purifier works is described in D.4 and the Liquefier and surrounding units in D.2.
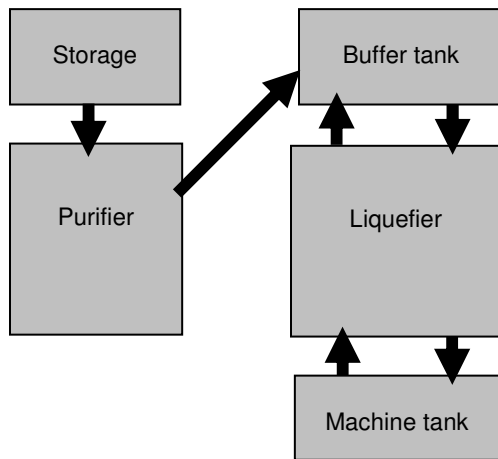

Figure D.1: Overview of the plant.

D.2 Liquefier

Figure D.2 shows a simplified view of the piping of the Purifier and the Liquefier. This part of the plant is located inside or close to the cold box. The purpose of the cold box is to isolate the piping from the surrounding air. The vacuum inside the cold box is maintained by a pump to minimise the heat transfer between the piping and the surroundings.

Inside the cold box a series of heat exchangers cools down the pressurised gas. They are depicted as simple boxes in Figure D.2. If liquid nitrogen pre-cooling is used this is done in one of the first heat exchangers. Apart from the possible LIN-cooling the refrigeration required is provided by the turbines acting on a side stream of gas which is returned to the low pressure stream of the cold box after expansion. A brake is applied to the turbines by two gas compressors mounted on the respective shafts.

The part of the helium which goes through all the heat exchangers is approximately 7 K when it reaches the J-T valve (CV111). As it is expanded in the valve to 1.3 bar it becomes a mixture of liquid and gas at 4.2 K. The liquid stays in the machine tank and the gas goes back to the low pressure stream of the cold box. The low pressure return stream is used to cool down the incoming gas from the high pressure side.
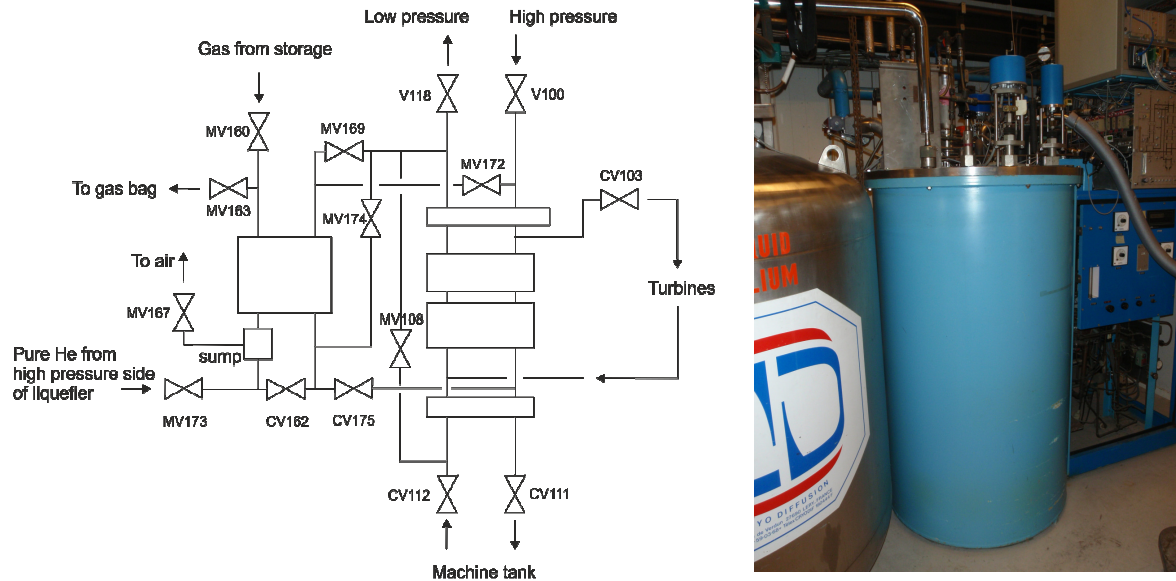
Figure D.2: Left: Simplified view of the piping of Purifier and Liquefier. Right: The cold box.

It is important to keep the pressure at the high pressure inlet at the correct level *(see Figure D.2)*. This is achieved by the pressure control panel *(see Figure D.3)*. Both the gas from the high pressure side and the low pressure side passes through it. The pressure regulation is achieved with the help of a buffer tank, containing helium gas at a pressure of 4-8 bar. The Purifier is providing gas on the low pressure side, and when there is a surplus in the system part of the gas is stored in the buffer tank to keep the pressure steady on the high pressure side. The gas in the buffer tank is then used to maintain the pressure when the amount of gas in the system is insufficient; part of the gas is continuously leaving the system through the liquefaction. The compression and consequently work needed for the cooling is done by screw compressors. Cooling of these main compressors and the braking compressors used for the turbines is provided through the district cooling system that supplies cold water.

Figure D.3: Left: Pressure control panel. Middle: Buffer tank. Right: Screw compressors.

D.3 Return gas handling

Return gas arriving in pipes from research labs throughout the university is measured by flow meters and collected in a big gas bag or "balloon" *(see Figure D.4)*. Before it is compressed into the storage which holds gas to a maximum of 200 bar it is dried of any water vapour. Gas that is collected from the plant itself e.g. the gas going through valve MV163 *(see Figure D.2)* during the purging process of the Purifier is also collected in the gas bag and handled the same way. Remaining return gas comes in gas bottles that can be connected either instead of the regular storage or in parallel with it such that gas from both sources is fed to the Purifier through valve MV160.

Figure D.4: Upper left: The gas flow meters measuring return gas. Upper right: The gas bag.
Lower left: Gas compressor. Lower right: The storage of incoming gas.

D.4 Purifier

The dirty gas enters via a pressure regulator through valve MV160 *(see Figure D.5)*. The box on the left hand side represents a heat exchanger where the incoming gas is cooled in two steps. In the first step it is cooled to 70 K. If the impurity level is above 1.5 % the impurities will condensate and the liquid is collected in the vessel called the sump from which it is blown to atmosphere. In the second step it is cooled to approximately 30 K causing any remaining impurities to freeze on the finned tubes of the heat exchanger.

After expansion through valve CV162 the gas is joined by a stream of cool helium provided by the Liquefier through CV175. It is the stream through CV175 that cools the Purifier. The cold helium is used in the heat exchangers to cool the incoming dirty gas before it enters the low pressure line via valve MV169.
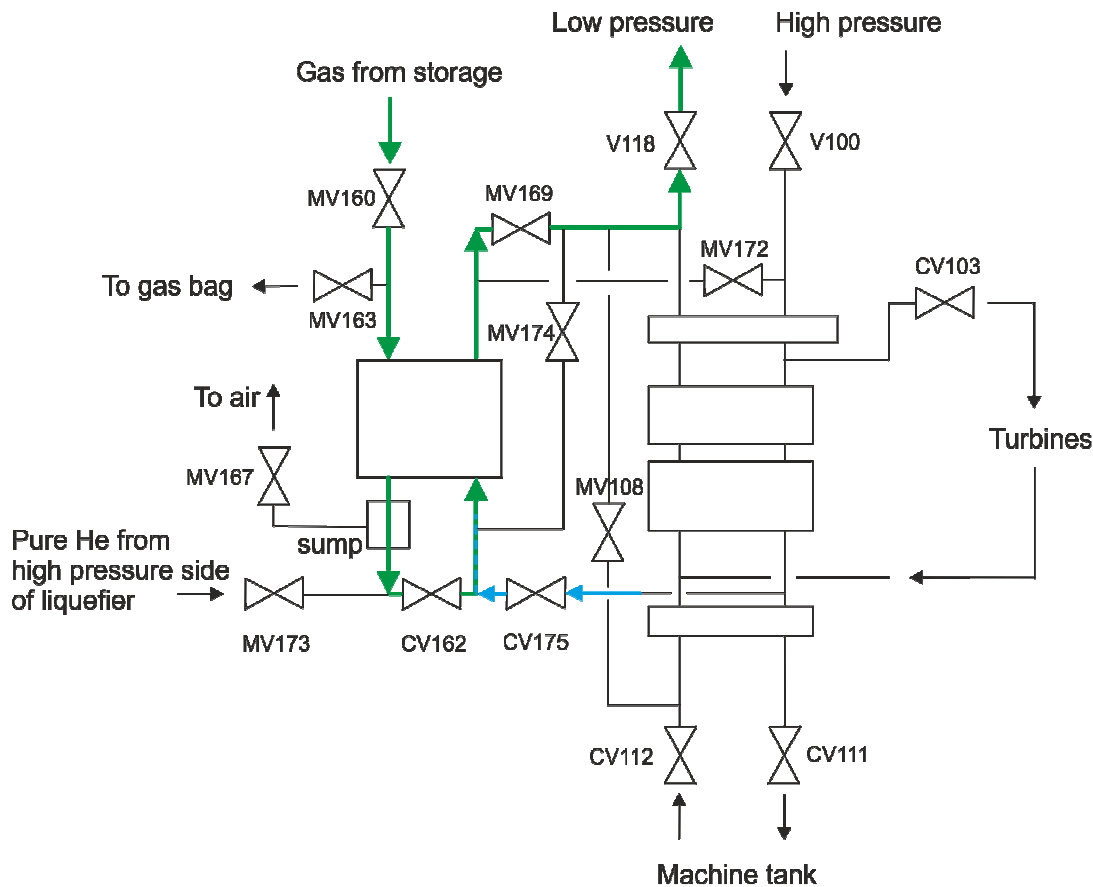
Figure D.5: Gas flow through the Purifier when gas from the storage is being purified.

When the Purifier is running it adds more gas to the system than the Liquefier can liquefy, causing the buffer tank to fill. When the Purifier is blocked with solid impurities it needs to be warmed up, purged and then cooled down again. During this time the pressure in the buffer tank will decrease.

To warm up the Purifier warm helium gas from the high pressure stream of the Liquefier is used *(see Figure D.6)*. It enters through valve MV172 and returns to the low pressure side via valve MV174. This will cause solid impurities to melt and vaporise.

Before the Purifier is cooled again with gas from the Liquefier through CV175 the remaining impurities are blown to the balloon/gas bag with help of gas from the high pressure side *(see Figure D.7)*.

Figure D.6: Gas flow through the Purifier during regeneration when the heat exchanger is warmed to remove any frozen impurities.

Figure D.7: Gas flow through the Purifier during Purge when any remaining impurities are blown to atmosphere after regeneration.

Appendix E: System specification

List of original requirements

The overall goal is to extend or replace the existing semi-automatic control program, interfacing the already operational helium liquefier machine, as well as provide improved remote monitoring functions.

- The system will be implemented in LabVIEW on cRIO.
- Approximately 30-40 different voltage signals (analogue and digital) should be sampled and transformed from a voltage to pressure/temperature/rotational speed etc, and presented on a user interface on the host computer. These values should be used to determine the action in the control program.
- Several of these signals will have one or more threshold limits that should activate warnings or activate the stop program.
- Important parameters should be possible for the operator to adjust during run time.
- Collected data should be gathered in log files and presented in a graphical format.
- Examples of values to measure and present:
    - level in machine tank
    - pressure in machine tank
    - pressure in storage
    - pressure in buffer tank
    - pressures (PI 100), PI 101, PI 102, PI 103, PI 104, PI 150, PI 151
    - speed of turbines
    - temperature of turbines
    - temperatures TI 102, TI 104, TI 106, TI 111
    - temperature in compressors
    - level in sump
    - positions of valves CV 103, CV 111, CV 162, CV 175
    - (vacuum pressure in cold box)
    - (estimated production of LHe per hour)
- A start program, making the start process automatic.
- A stop program, making the stop process automatic.
- A controller for the purifier, controlling all valves associated with it in a predefined sequence and keeping track of the state.
- Control of the valve connecting Liquefier and Purifier (CV 175) making TIS 102 approach 28K.
- Control of the flow to the machine tank via valve CV111 to keep TIS 106 at 12 K.
- Control of MV 108 to enable bypass if TIS 111 is higher than 20 K.
- Control of MV 110 to enable the connection of Liquid Nitrogen Cooling, TIS 108 should aspire a predefined value
- Control of CV120 and CV121 to regulate turbine speed.
- A user interface in LabVIEW from which the Liquefier can be supervised, controlled, started, stopped etc. Control should be possible from both Windows and Mac OS and from a local host with direct contact and over Internet with remote log in. A locally placed panel should contain functions such as manual on/off, start/stop of the Liquefier, start/stop of the Purifier, start/stop of compressors and V 404, manual control of CV 103, CV 111, CV 175.

Revised requirements

The original set of requirements was restructured and refined during the analysis phase and eventually became this list. This list of **final requirements** was the one used for system evaluation and acceptance.

Overall limitations

1. Production should not be halted apart from normal stops.
2. Replace parts of the control system incrementally
3. New parts must have similar characteristics to those replaced.
4. Ensure testing outside the machine before integration.
5. Revise control parameters as an optional improvement.

Hardware and signals

6. CompactRIO 9022 with additional IO modules is selected controller.
7. LabVIEW 2011 is the controller software platform.
8. cRIO can be connected to existing LAN with wired IP connection.
9. If suitable, the IO modules should be wired directly to the machine.
10. AD converter module available for measurements, max 10 V DC.
11. AD converter module for measurements, max 24 V DC is needed.
12. Avoid if possible to use any of the 220 V AC signals.
13. Need to drive 24 V output signal.
14. Need to sink 24 V output signal.
15. There are limited number of IO ports and only the most important signals can be used.

Control program, software on cRIO

16. Each probe will require specific calibration and conversion in SW.
17. SW filter or regulator may be needed to stabilize measurements.
18. SW regulator may be needed for output signal control.
19. Measurements read from AD-converter represent pressure, temperature, etc.
20. SW frequency sampling needed to read turbine speed.
21. Timers required to measure time.
22. Start and stop sequences should be based on the instructions for manual start and stop found in the manual for TCF-20 and (if needed) the behaviour of the current semi-automatic system on the SATT-control.
23. The logic controlling the purifier should be based on the old analogue control system.
24. Logic for LIN-cooling must be decided based on current operator experience.
25. When documentation and behaviour differs, the current behaviour is rule.
26. The control program should be possible to run with direct contact to the host computer, presenting a Front Panel there that can be used to change process parameters in the control program at runtime. Run this way the program is not required to be deterministic.
27. The control program must be possible to run as a standalone application on cRIO in which case it must be deterministic.

User interface, software on host computer

28. The control SW is standalone and functions well without UI.
29. The software user interface should mimic the current analogue operator panel, with additional detail added.
30. UI contains LED representing the control signals to the valves.
31. UI contains numeric values representing key pressure and temperature readings.
32. Start and stop buttons to control Liquefier, Purifier and LIN-cooling implemented.
33. Buttons to control all the control valves manually.

Additional data display

34. A separate display shows measurement readings in graph form.
35. Key readings, output signals and state information are continuously stored to log file.

Alarms and warnings

36. Warning events are triggered at certain levels of key measurements.
37. At critical events an emergency stop must be performed.
38. Threshold values for warnings and emergency stop must be decided.
39. Safe emergency stop sequences must be decided for each state and system.

Remote operator control

40. Existing LabVIEW feature is used to expose user interface over internet.
41. Email notifications on warnings is a lower prio feature.
42. Ordinary HTTP password protection is a sufficient security level.

Appendix F: Glossary

backplane	The backplane is located in the chassis of the CompactRIO. All modules are connected to the backplane bus over which the communication is carried out. Apart from the bus the backplane of cRIO also contains an FPGA for fast calculations and signal processing.
Block Diagram	The logic of a VI in LabVIEW. Inputs and outputs are connected to function blocks and subprograms with wires. The wires represent the data flow in the program. A program is executed starting at the inputs and following the wires to the outputs. The execution is completely dependent on the dataflow, the place in which function blocks are placed in the Block Diagram has no significance, only how they are interconnected. The code is inherently parallel.
cRIO, CompactRIO	An embedded control and acquisition system from NI. It consists of a chassis, a controller and modules.
dewar	Vacuum flask used to store e.g. liquid helium. Size ranges from 20-500 litres at the Kryolab facility. It is like a large thermos with double walls with near vacuum in between for insulation.
enthalpy	A systems internal energy or thermodynamic potential denoted h, where $h = U + pV$, and U is internal energy, p pressure and V volume. The unit used for enthalpy is Joule.
entropy	A systems disorder denoted s. The unit is Joule/Kelvin. For a gas the entropy is related to the amount of kinetic energy the molecules have, i.e. the temperature of the gas.
FPGA	Field-programmable Gate Array. An integrated circuit that can be configured for different tasks. In the CompactRIO the FPGA can be configured to execute part of the program in dedicated hardware to make it more efficient than the normal CPU.
Front Panel	The definition and graphical representation of the inputs and outputs of a VI in LabVIEW. The inputs and outputs are represented by buttons, meters etc. as in a physical operator panel.
IEA	Division of Industrial Electrical Engineering and Automation at LTH.
isenthalpic	Describes a process where the system has constant enthalpy.
isenthropic	Describes a process where the system has constant entropy.
isobar	Describes a process where the system has constant pressure.
isochor	Describes a process where the system has constant volume.
isoterm	Describes a process where the system has constant temperature.
LabVIEW	The programming environment used to make programs for NI controllers.
LIN-cooling	Liquid Nitrogen Cooling. Liquid nitrogen is used to help cool the helium gas. The nitrogen cools some of the first heat exchangers the helium gas passes after compression. This increases the production rate.

liquefaction	The process where a solid or gas is converted to liquid form. In this report exclusively the conversion of gases to liquid by cooling.
LTH	The Faculty of Engineering at Lund University. (Lunds Tekniska Högskola.)
NI	National Instruments. An American corporation founded in 1976. Currently active in many fields, including electronics.
TCF-20	The original machine or plant, in this report referred to as the Liquefier and the Purifier.
triple point	The temperature and pressure for a substance where the three different phases (solid, liquid and gas) coexist.
VI	Virtual Instrument. A LabVIEW program or sub-program consisting of a Front Panel with inputs and outputs and a Block Diagram with logic.