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Reliability and Maintenance strategies for the Gas Systems of the LHC experiments

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Abstract

The aim of this thesis was to analyse and to improve, by a systematic approach, the maintenance strategies used for the gas systems of the CERN LHC experiment detectors. These systems are very complex, consisting of numerous racks and components that need to be continuously in run phase to provide the gas mixture to the detectors. Therefore, it was essential to establish a structured and robust approach, such as Reliability Centered Maintenance (RCM), to set a methodology which ultimate goal was to increase the reliability and availability of these systems.

In particular, the analysis focused on the gas systems for the Resistive Plate Chambers (RPC) detectors, chosen as a reference. The strategy involved examining all past maintenance activities, recorded failures and interventions documented in the CERN Gas Team logbook, known as eLOGs. This approach allowed the extraction of valuable information on the technical history of these systems, highlighting critical issues in the past management of maintenance activities. For example, a significant difference between the ATLAS and CMS RPC entries was spotted, despite the systems are quite similar.

This study aimed to gather the necessary information to implement an industrial and widely used tool: Failure Modes, Effects and Criticality Analysis (FMECA). To apply this procedure, all mechanical components were listed, starting from those present in the P&IDs, and subdividing them module by module. For each component, one or more failure modes were identified along with their potential causes and effects on the module and on the system as a whole.

At this point, the criticality risk indexes, frequency and severity, and the risk matrices, defined in the work methodology, were used to rank the failures. This procedure allowed the prioritization of the most critical events with dedicated preventive maintenance tasks or improving the system design through interventions to reduce the severity of failures.

The analysis of the studied systems, for the definition of a working methodology,

led to some design improvements, both for the point of view of the maintenance and of the operations, that were considered for the implementation by the Gas Team. For example, for some critical components preventive maintenance tasks were scheduled, as well as some improvements in the control logic, like the addition of warnings before full stop alarms are triggered. Moreover, this study allowed the development of a general and systematic approach for the maintenance management that can be extended to the other systems.

Acknowledgments

This work marks the conclusion of my university studies, which began with a Bachelor's degree in Energy Engineering, continued with a Master's degree in Nuclear Engineering and completed with the Technical Student experience at CERN. For this reason, I would like to thank all the people who have been part of this journey.

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Chapter 1

Introduction

The present work was written at CERN (European Organization for Nuclear Research), in the EP-DT-FS Gas Team, which is the responsible for the maintenance and operations (M&O) of the gas systems for the particle detectors of the Large Hadron Colliders (LHC) experiments, during a traineeship and technical student period at the organization. In addition, the gas group is in charge for the research and development (R&D) activities, to upgrade the systems and to reduce the greenhouse emissions due to the particular and environmentally harmful gas mixtures provided to the detectors.

The gas systems at CERN are complex and very sensitive systems, which required particular attention in order to work continuously and in the correct way. In particular, these systems are in run 24h / 7d, to fulfil the detectors requirements, both during the particle beam collision period, where most of the data taking is performed, and during the stop of operations period. As explained, these systems are always in run, even if there are not particles in the accelerator, just to keep the gaseous detectors wet, when some upgrades or test are performed.

For the above mention reasons, to have the gas systems always working, it is necessary to continuously monitor the performances and to be ready to react in case of some component failures or deviations from the nominal conditions. However, even though these systems are really complex and made of many components, there is not a proper maintenance program, with few exceptions, and the most used is strategy is to replace the components after failures and restart the operations. This is not an optimal way to correctly perform the maintenance tasks, since it can lead to unexpected events which can cause the stop of one of the gas systems and loss of data taking at the experiments side. Some general maintenance procedure are established, but in the past years they were barely used.

The aim of the present work is to investigate the detailed functioning of these systems, finding all the potential sources of critical failures, in order to prevent unwanted scenarios. In particular, the idea behind this thesis is to implement some industrial based approaches to improve maintenance activity performances, such as the Reliability Centered Maintenance (RCM) method with the application of the Failure Modes, Effects and Criticality Analysis (FMECA) as a supportive tool. In this way, it is possible to find the most critical components for the systems and to set some proper maintenance tasks for them to prevent failures.

Since there are about 30 gas systems among the four main experiments of the LHC, the analysis is performed on just the RPC gas systems for ATLAS and CMS experiments. Even though these systems have their own peculiarities, such as mixtures, flows, pressures, they have similar characteristics and designs and therefore it can be possible to adapt the FMECA analysis also to the other ones and to establish new maintenance strategies for all of them.

In *Chapter 2*, a detailed description of the RPC gas systems was presented, highlighting how they are subdivided into functional modules, and all the operative and monitoring aspects that are used to keep them working.

In *Chapter 3*, the current maintenance strategies and procedure were described. In particular, an example of the established procedure for the pump module and how the spare parts inventories were organised, were shown. In addition, the main adopted maintenance strategies were described with their pros and cons, focusing on the choice of the corrective and reactive ones, which are the most used.

In *Chapter 4*, the work methodology used for enhancing the maintenance tasks performances was explained. In particular, it was analysed the necessity of considering a structured industrial maintenance method, such as the Reliability Centered Maintenance approach, with the support of the FMECA analysis. In particular, the latter was deeply described, since it was applied on the systems, in order to identify and prioritize the maintenance tasks on those components which are more critical.

In *Chapter 5*, the past history of maintenance activities for these gas systems were analysed from the eLOGs entries created during the last 8 years. In this way, it was possible to get the necessary and useful information that were needed for the filling of the FMECA tables. Moreover, it was useful also to understand which components have experienced most of the problems during the operations and which kind of effects they had on the modules and on the systems. In addition, observing the eLOGs for the two RPC gas systems, it was possible to notice the recording discrepancies of such tasks, considering the different responsible technicians reports.

In *Chapter 6*, the FMECA analysis was performed on all the modules of the RPCs gas systems, identifying all the possible failure modes, the local and on the systems effects and assigning the criticality indexes to them, such as the frequency and severity ones. In this way, it was possible to build the risk matrix related to the modules, in order to have a complete overview of the system criticalities. Finally, from the output of the FMECA, it was possible to understand which components required some improvement actions, such as modification of the plant design, and to define some proper preventive maintenance activities to avoid unexpected scenarios.

1.1 LHC experiments at CERN

The European Organization for Nuclear Research, also known as CERN, is the largest physics laboratory concerning the high energy physics domain and its aim is to investigate the universe formation and its nature, studying and analysing particle collisions at energy values nearly to the one that could be observed few instants after the Big Bang. Born 70 years ago, in 1954, CERN became the centre of the world of physics when in 2012, ATLAS and CMS experiments confirmed the existence of a particle, which characteristics were compatible with the Higgs' boson, theorized in 1964 by the physicist Peter Higgs. This discovery allowed Peter Higgs and François Englert to win the Nobel prize for physics in 2013.

The *Large Hadron Collider* (LHC) is the biggest particle accelerators on Earth, with a circumference of 27 km and installed at 100 m underground, it is equipped with more 1000 superconducting magnets, which can generate a magnetic field of 8.3 T, using currents of 11.8 kA. This structured allows the particles to gain an energy of about 14 TeV in the proton-proton collisions. Before being injected in the main accelerator (LHC), these protons are at first accelerated in a linear one, called Linac, then sent to a circular, called Proton Synchrotron (PS), and then to a second one called Super Proton Synchrotron (SPS). On the LHC ring, the particles collide into 4 main points, where the main LHC experiments are installed to take data after the beam collisions. These experiments are ATLAS (A Toroidal LHC ApparatuS), CMS (Compact Muon Solenoid), ALICE (A Large Ion Collider Experiment) and LHCb (Large Hadron Collider beauty). In figure 1.1, it is possible to see the layout of the CERN accelerators complex, where all stages before LHC are shown.

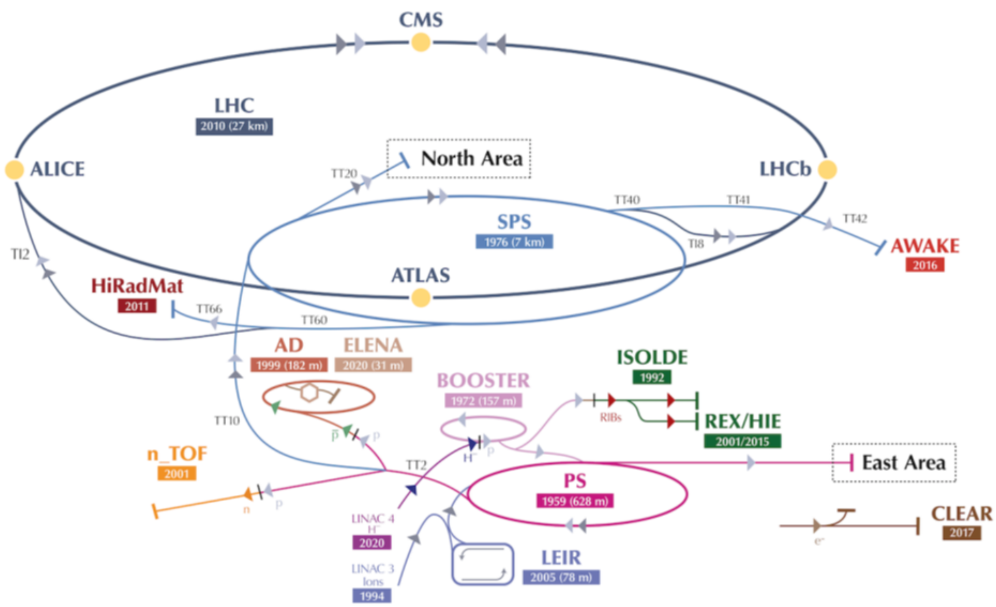


Figure 1.1: CERN's accelerator complex [11]

In principle, these experiments are equipped with different types of detectors, depending on the kind of measurements they need to perform. In particular, they can be divided into the following types [17]:

- *Inner detectors*: they are installed closed to the collision points, in order to perform precise measurements of the momentum of charge particles and the vertices reconstruction.

- *Hadronic and electromagnetic calorimeters*: they are responsible for measuring the hadrons, electrons and photons energy, based on the energy loss of the emerging particles.

- *Muon systems*: these detectors are used to track and detect muons that easily escape the inner detectors and the calorimeters. For this reason, they are set at the peripheral part of the experiments, at the external layer.

In particular, the gas systems are used to deliver the right gas mixtures to the muon systems since they are in principle gaseous detectors.

In figure 1.2, the CMS experiment structure is represented, with the different detectors layout and position with respect the particles collisions points.

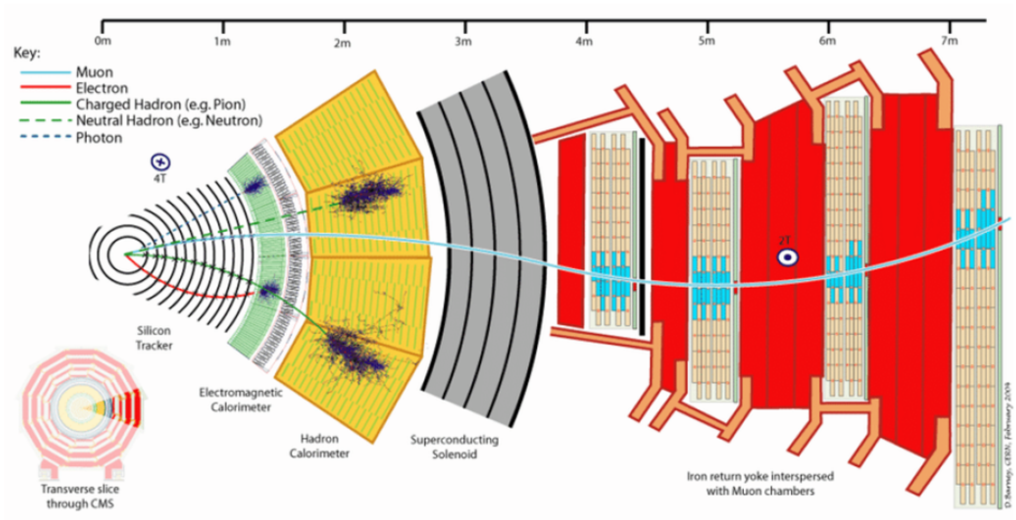


Figure 1.2: Transverse section of CMS detectors [2]

1.2 Muon detectors

Since the main focus of this thesis are the gas systems for the LHC experiments, it is useful to give a brief introduction and description of the muon detectors design and functioning.

As explained before, the muon systems are particular gaseous detectors which aim is to detect and track the muons that are generated after the collisions and that escape the inner detectors layers of the experiments.

1.2.1 ATLAS gaseous detectors

The ATLAS experiment, the largest experiment conducted at CERN, relies on a high-performance physics program that spans a wide range of transverse momentum. Its muon system features three large superconducting air-core toroids and precision tracking chambers to ensure accurate momentum resolution, supported by an efficient trigger system. This system employs different detector technologies: RPCs are utilized in the barrel section, with two layers of chambers in the middle station and a third layer in the outer chamber station. The endcap trigger system, on the other hand, employs Thin Gap Chambers (TGC), multi-wire chambers operating in saturated mode. Three multi-layers are situated in the middle tracking station, while others form part of the inner station. Precise measurements are facilitated by Monitored Drift Tubes (MDT), which can sustain high rates without aging and exhibit minimal sensitivity to space charge. These MDTs require extremely accurate mechanical construction to fully leverage their tracking precision. Additionally, the use of CSCs in the inner station of the end-cap ensures optimal performance despite the high background rates in this region.

1.2.2 CMS gaseous detectors

The CMS experiment, one of the biggest experiments at CERN, consists of powerful superconducting solenoid with a magnetic field strength of 3.8 T. This setup houses crucial components like the tracker, electromagnetic, and hadronic calorimeters within its field. Additionally, the iron yoke integrates a muon spectrometer for identification, triggering, and momentum measurement. The system is structured into five separate wheels in the barrel, featuring four concentric layers of detectors, while the positive and negative endcaps boast four independent disks each. Various gaseous detector technologies are utilized: Drift Tubes (DT) in the barrel, with Gas Electron Multipliers (GEM) to be introduced in Run 3, and Cathode Strip Chambers (CSC) in the end-cap region, designed to handle higher rates and non-uniform magnetic fields. Lastly, Resistive Plate Chambers (RPC) are installed in both the barrel and endcap regions.

1.2.3 ALICE gaseous detectors

Since the ALICE experiment is entirely focused on heavy ion physics, its muon spectrometer is designed to measure extremely low transverse momentum values across a wide rapidity range. The tracking system, known as MCH (Muon Chambers), comprises five stations, each equipped with two detector planes consisting of cathode pad chambers. These chambers utilize multi-wire proportional technology with a segmented cathode plane. Varying pad densities are employed based on the station's position relative to pseudo-rapidity. Furthermore, the system boasts highly efficient triggering capabilities (MTR, Muon Trigger), featuring four planes of 18 RPCs operating in streamer mode. Positioned approximately 20 meters from the Interaction Point, these RPCs provide real-time data to the central trigger processor.

1.2.4 LHCb gaseous detectors

The primary focus of LHCb experiments is the investigating of the interactions involving the beauty quark (noted as "b" for this quark). LHCb is made of a single-arm spectrometer, covering an angular range from 10 mrad to 300 mrad in the bending plane. This configuration optimally leverages the statistics of b and $\bar{b}$ production, which predominantly occur in the forward or backward regions. The muon detection system plays a crucial role in LHCb, as muons are present in the final states of many CP-sensitive B decays. They serve as a marker for the initial state flavor of accompanying neutral B mesons in semi-leptonic decays. This system provides rapid information for high-transverse-momentum muon triggering at the earliest stage of online event selection, as well as muon identification for high-level triggering and offline analysis. The muon system primarily consists of Multi Wire Proportional Chambers (MWPC), except for the high-rate region where Gas Electron Multipliers (GEM) are utilized. It is divided into five rectangular stations along the beam axis, encompassing a total of 1380 chambers covering 435 m^2. GEMs are situated in the inner region where MWPCs would exceed aging safety limits due to the anticipated particle rate. Finally, the external layer hosts the Outer Tracker, a gaseous detector covering approximately 30 m^2 with twelve double layers of straw tubes.

1.3 RPC detectors

As mentioned before, in this work the gas systems for the RPC detectors are chosen as reference case study. These detectors are present both in CMS and ATLAS experiments, due to their fast space-time tracking for muons and the possibility to trigger parallel signal to the one of DTs and CSCs.

A Restitive Plate Chamber (RPC) detector consists of two parallel plates, made out of phenolic resin (bakelite) with a bulk resistivity of 10^{10} - 10^{11} Ωcm, separated by a gas gap of a few millimeters. The whole structure is made gas tight. The outer surfaces of the resistive material are coated with conductive graphite paint to form the HV and ground electrodes. The read-out is performed by means of aluminum strips separated from the graphite coating by an insulating PET film [16].

When a muon passes through the chamber, electrons are knocked out of the atoms of the gas. These electrons in turn hit other atoms causing an avalanche of electrons. The electrodes are transparent to the signal (the electrons), which are instead picked up by external metallic strips after a small but precise time delay. The pattern of hit strips gives a quick measure of the muon's momentum, which is then used by the trigger to make immediate decisions about whether the data are worth keeping [5].

In principle, the gas mixture that is used in this kind of detectors must follow particular requirements, such as:

- high density of primary ion-electron clusters, to assure high detection efficiency;
- low photon emission/transmission to reduce photon feedback phenomena;
- being electronegative to reduce transversal side of the discharges and improve the localization;
- not dangerous for human health;
- it should be characterised by negligible ozone depletion power (ODP) and low global warming potential (GWP).

It figure 1.3, the general layout of the RPC detector is shown. It is possible to see the two resistive plates (red), anode and cathode, separated by a thin gas film sealed by polyvinyl chloride (light brown). The read-out is performed by means of aluminum strips (yellow), and the high voltage is applied on aluminum foil (grey).

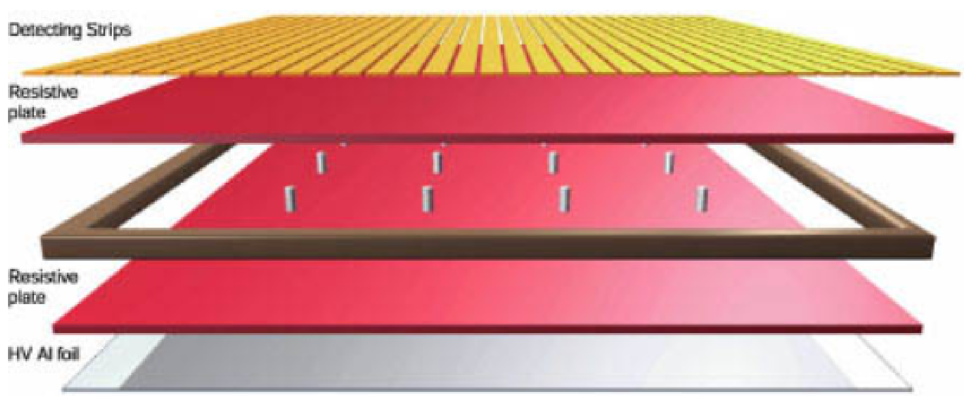


Figure 1.3: Resistive Plate Chamber detector layout [16]

Chapter 2

RPC gas systems

As written before, the muon detectors of the LHC experiments (ATLAS, CMS, ALICE and LHCb) are very important to track and collect information on the muons generated during the collisions and, since they can very easily escape the inner detectors, the dedicated ones are set in external and peripheral part of the experiments. The muon detectors are gaseous detectors and they require particular gas mixtures for the correct signal generation and amplification and, for this reason, they need dedicated gas systems.

In the present work, the RPC gas systems of ATLAS and CMS experiments are considered as case study for the development of new maintenance industrial based strategies, including the application of the FMECA analysis to identify the critical components.

As for the other gas systems, the RPCs follow the same modular design and they are made of mixer module, distribution module, pump module, purifier module, analysis module, exhaust module and humidifier module. In the CMS RPC gas systems some gas recuperation systems are also included: they will be introduced in this chapter but they will not be considered for the study, because they are under development and testing.

The general layout of these gas systems is divided into different level: the surface building (SGX) includes the gas supply, the mixer, purifier and humidifier modules; the underground service cavern (USC) is made of the pump module, analysis module and just for the CMS case the pre-distribution module; while the final level is the underground experiment cavern (UXC) in which the distribution module provide the gas mixture to the detector chambers. This layout is visible in figure 2.1.

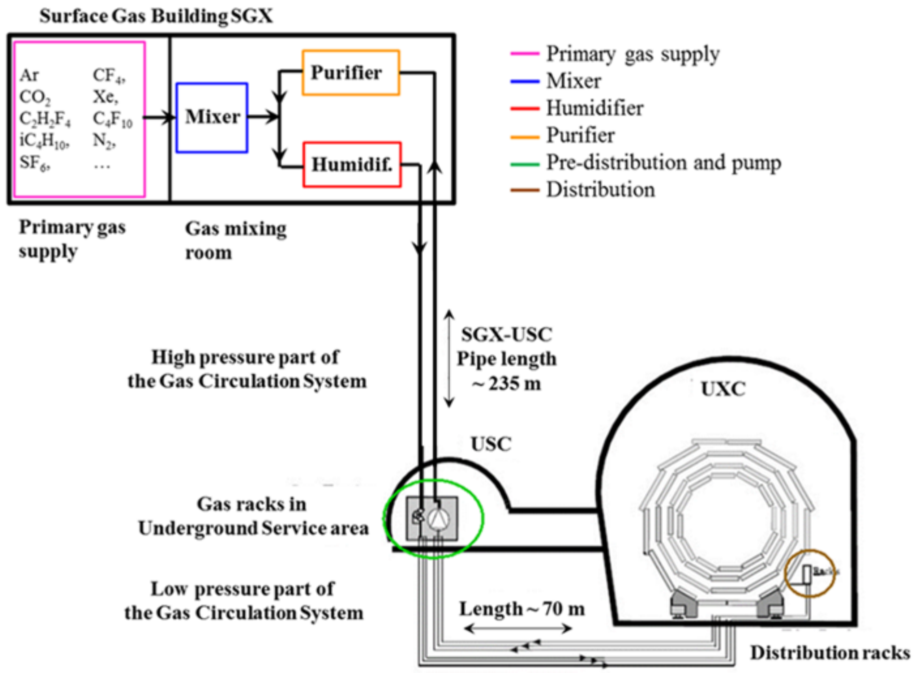


Figure 2.1: General layout of a gas system [1]

The gas systems for the LHC experiments are designed following two main strategies: open-loop or closed-loop. The first type, like ATLAS MMG gas system (built for the ATLAS MicroMegas detectors), foresees that the gas mixture injected by the mixer into the distribution rack, and consequently in the detector chambers, is then exhausted to the atmosphere without any kind of recuperation or recirculation.

The second category, the closed-loop gas systems, is the one most used and the RPCs are part of this group. In practice, once the gas mixture is sent to the distribution, the pump module has the role to recirculate it through the purifiers and to mix with the fresh one coming from the gas supply and mixer. In figure 2.2, the general overview of the RPC gas system is represented and it is possible to observe how the different modules are linked in the close loop design inside the project layout. In particular, the different gases from the supply are provided to the mixer where they are mixed together. A part of the mixture is sent to the analysis 1 module to check the composition and then it joins the other part in the exhaust before going in the humidifier. From there, it is delivered to the distribution which provides the gas mixture to the detectors and after that the recirculation loop, previously described, starts.

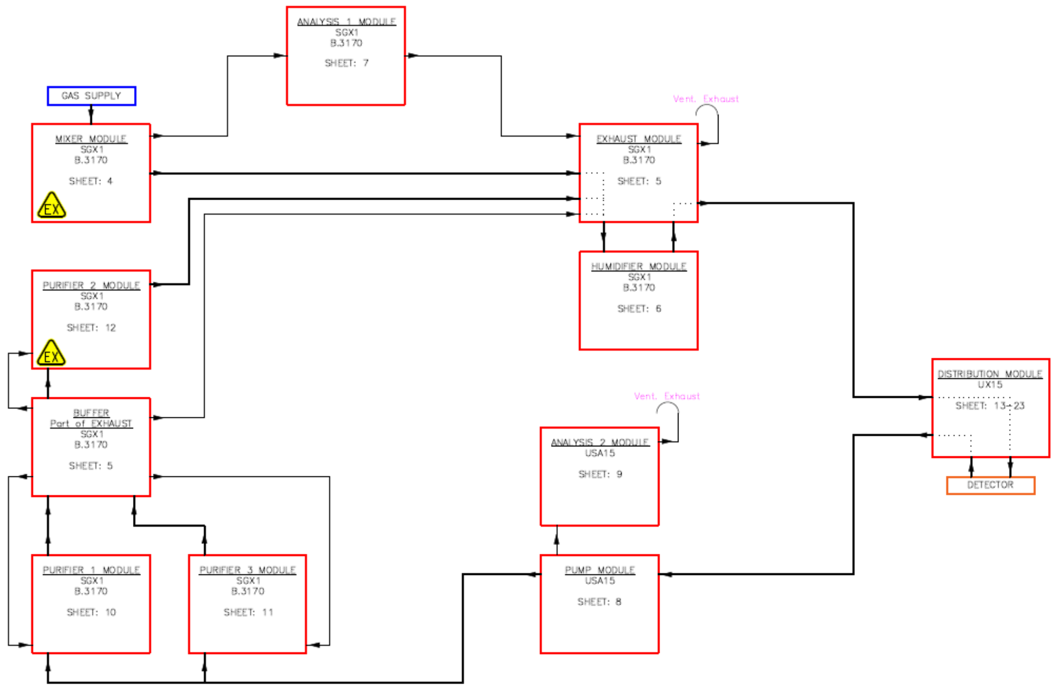


Figure 2.2: General overview of the RPC system [7]

Moreover, since their complexity and the continuous operations 24/7, all the gas systems are monitored and remotely controlled by a Supervisory Control And Data Acquisition (SCADA) software called SIMATIC WinCC Open Architectures (WINCC-OA) by Siemens. In the figure 2.3, an example of this software interface of the ATLAS gas systems is shown (where all systems are present), while in figure 2.4 the ATLAS RPC system overview is represented. From there it is possible to select the gas system and the module in which some operations or monitoring are needed. Inside the module, some process parameter trends can be monitored and compared thanks to the real time data acquisition. Moreover, it is also possible to tune the PID parameters necessary for the correct regulation of the system, as well as introducing some corrections in the position of the valves or change the configuration of the working pumps for example. In addition, in the SCADA software, also the alarms are set: these alarms send messages to the responsible people of the systems (even for the overtime events which are collected by a reference person, the gas Piquet), informing if some monitored variables have reached the high or low level trigger. In some cases, this alarms can also lead to the automatic full stop of the system, if some important parameters have overcome their limits.

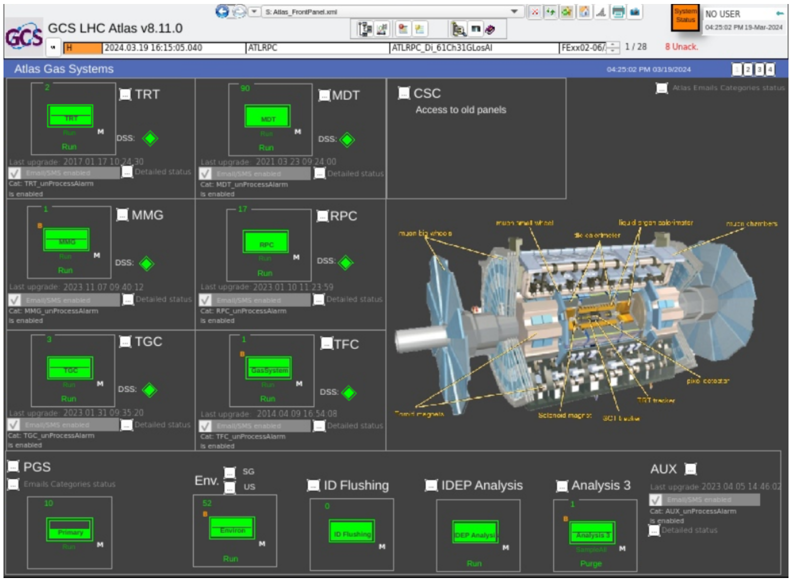


Figure 2.3: ATLAS gas systems interface on the WINCC-OA software

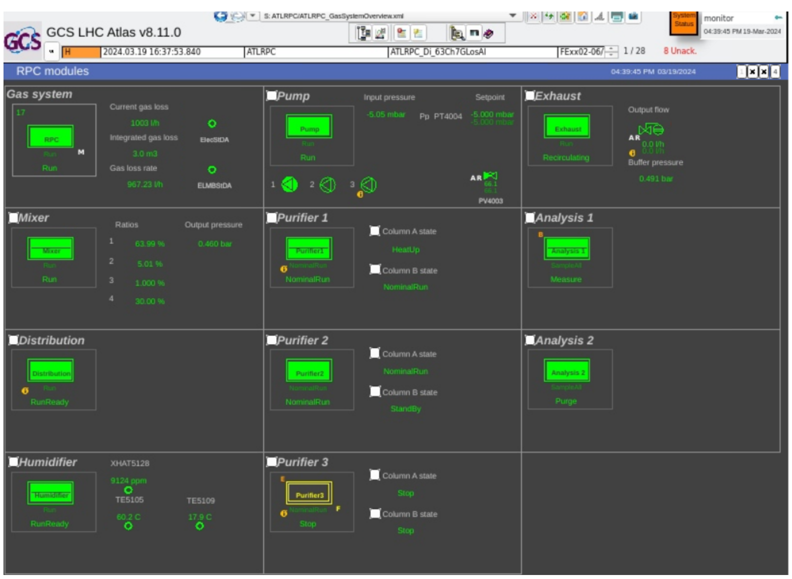


Figure 2.4: ATLAS RPC gas system interface on the WINCC-OA software

2.1 Mixer module description

The mixer module, of the gas systems, is the responsible for providing the correct gas mixture to send to the distribution and the detectors, after receiving the gases from the external supply. In principle, the mixer modules are located in the surface building and far from the electronics for safety reasons. For the RPCs case, the mixer is made of 4 different lines, each one for a specific gas, themselves divided into *High flow line* and L*ow flow line*. Therefore the mixture of the RPC gas system, in the case of ATLAS is made of:

- Tetrafluoroethane ($C_2H_2F_4$), which is also known as Freon $R134a$ - 64%.
- Isobutane (iC_4H_{10}) - 5%.
- Sulphur hexafluoride (SF_6) - 1%.
- Carbon dioxide (CO_2) - 30%.

For what concerns CMS RPC, the CO_2 is not used and the composition is Freon at 95.2%, isobutane at 4.5% and sulphur hexafluoride at 0.3%.

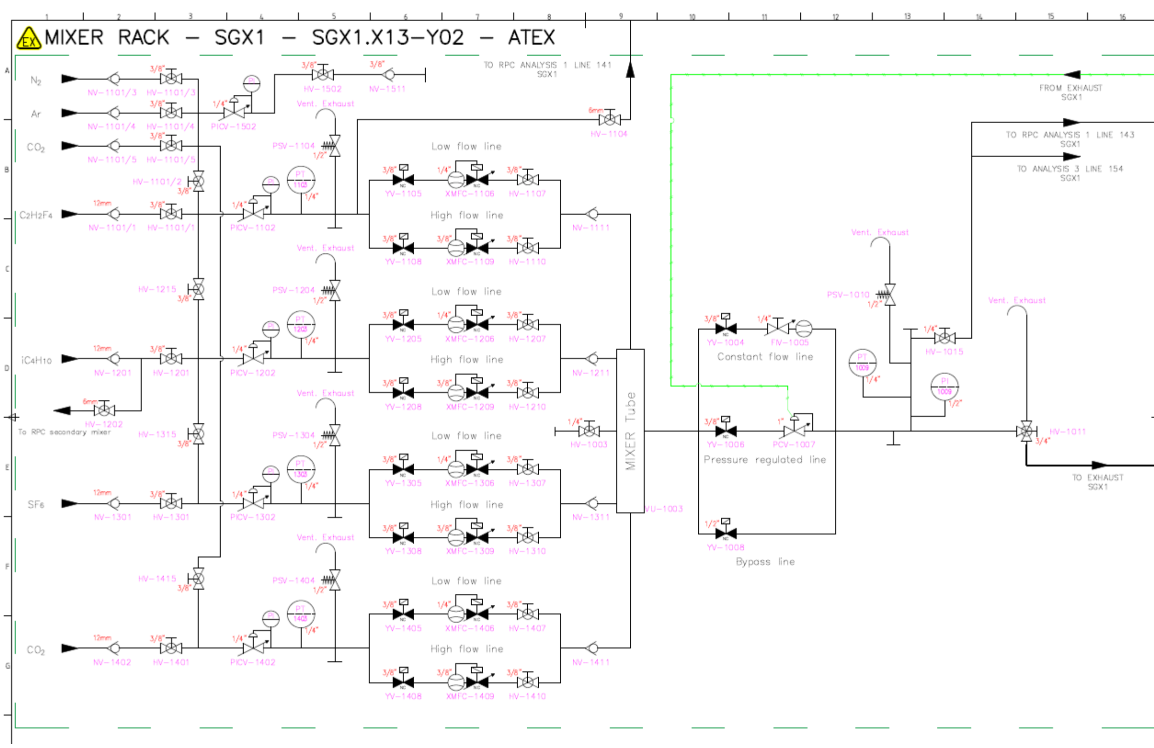


Figure 2.5: ATLAS RPC gas system mixer module P&ID [7]

For each input line from the supply a non-return valve (NV-1x01) is installed to avoid that, in case of accident, the gases can experience a backflow in those lines.

Then, some manual valve (HV-1x01) are mounted just to isolate the lines in case of necessity. The gases form the supply are provided with a certain pressure, higher than the one required for the detector: for this reason also some pressure regulators (PICV-1x02) are present in the input lines to adjust the pressure to the desired value. In addition, also 4 pressure safety valves (PSV-1x04) are installed to guarantee the safety in case of the failure of one of the pressure regulators.

However, the main components of the mixer are the mass flow controllers (XMFC): they are the responsible for providing the right gas flow rate to the mixer tube and coping the necessity of the detector. In the specific case for the Resistive Plate Chamber detectors, they work at constant relative pressure and they are really sensitive to the atmospheric pressure changes: small atmospheric variations can require huge variations of the flow rate to keep the pressure constant. The mass flow controller are installed in two lines for each gases, the high flow and low flow lines: in principle it is possible to switch from high flow line to the low flow line remotely, according to the requirements of detector user. These components required particular attention and they need to be calibrate quite often to guarantee the correct performances during operations. In fact they should also follow and compensate any changes of the flow, due to the detector leaks or decrease in the recirculation performances.

Once the gases flow after the mass flow controller, they are mixed in the mixer tube, which is a static volume with some baffle plate inside that generate the required mixture by a passive and turbulent process.

In the normal operation mode, the gas is supplied to the sub-detector via electrovalve YV-1004 and a manual constant flow adjuster, the rotameter FIV-1005. However, in certain conditions like after a storm when the atmospheric pressure can be rising very fast, this constant flow might not be enough to meet the demands of the detector. For this case, additional gas can be injected via YV-1006 and a pressure regulator PCV-1007. During the refill or the purge mode, when there is the need to change the old gas mixture, the gas will be provided only via YV-1006 and PCV-1007 since these operations require higher flow rates. With the bypass valve YV-1008, it is possible to directly inject in the detector, but in this case the properties of the flow depend only on the mass flow controller set point and not to the gas control system (GCS). Moreover, to have an additional control of the mixture, this can be sent to the analysis module which is equipped with an Infrared analyser (IR) and, for the case of CMS, a Gas Chromatography (GC).

In figure 2.6, the SCADA interface for the ATLAS RPC mixer is shown.

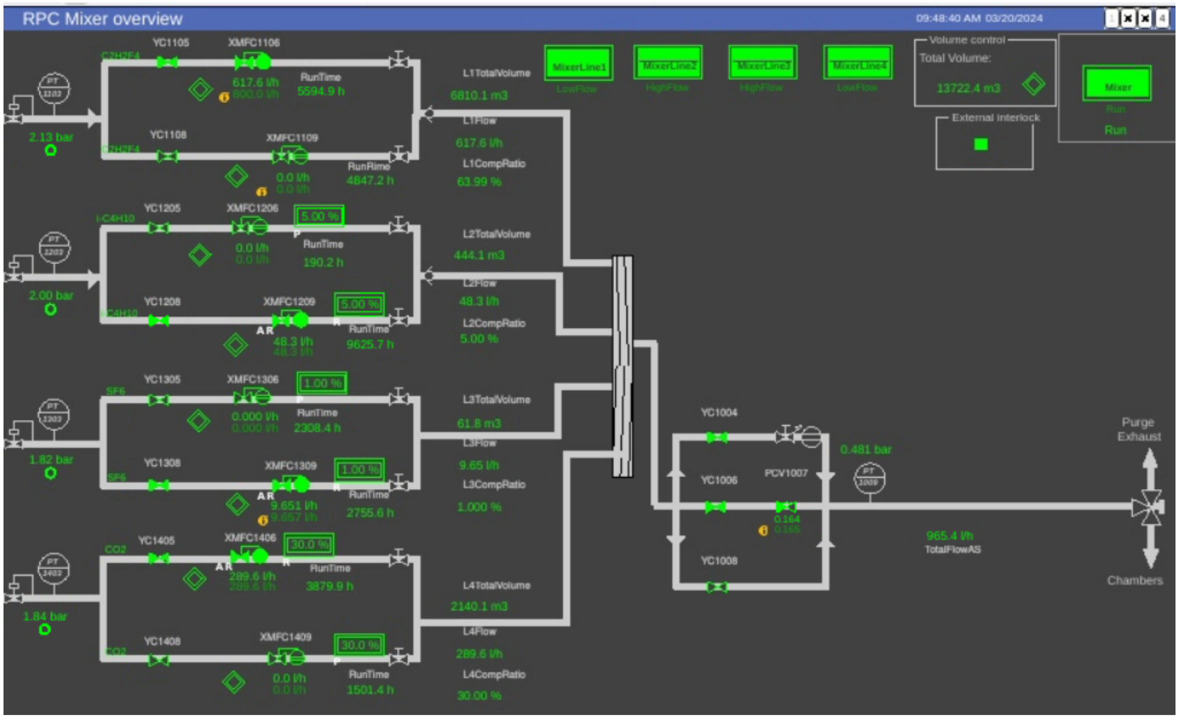


Figure 2.6: ATLAS RPC gas system mixer module SCADA interface

From the GCS software, it is possible to remotely control and monitor the input pressure after the pressure regulator, the volumetric flow rate and the composition after the mass flow controller and the output pressure before going in the exhaust module and consequently to the distribution. Moreover, some alarm are set on these process variables, such as the low pressure alarm on the input side of each line which can trigger the full stop of the module.

In addition, the whole mixer module for the RPC gas systems for ATLAS and CMS experiments is made of full ATEX components, due to the presence of pure isobutane in one line that can be dangerous in case of leak.

2.2 Pump module description

The pump module is one of the essential module for the closed-loop gas systems. The pumps have the role of collecting the used mixture from the experiment cavern and pushing it to the surface building where the purifiers, the mixer and the humidifier are located. In the next figure, the P&ID drawing is shown.

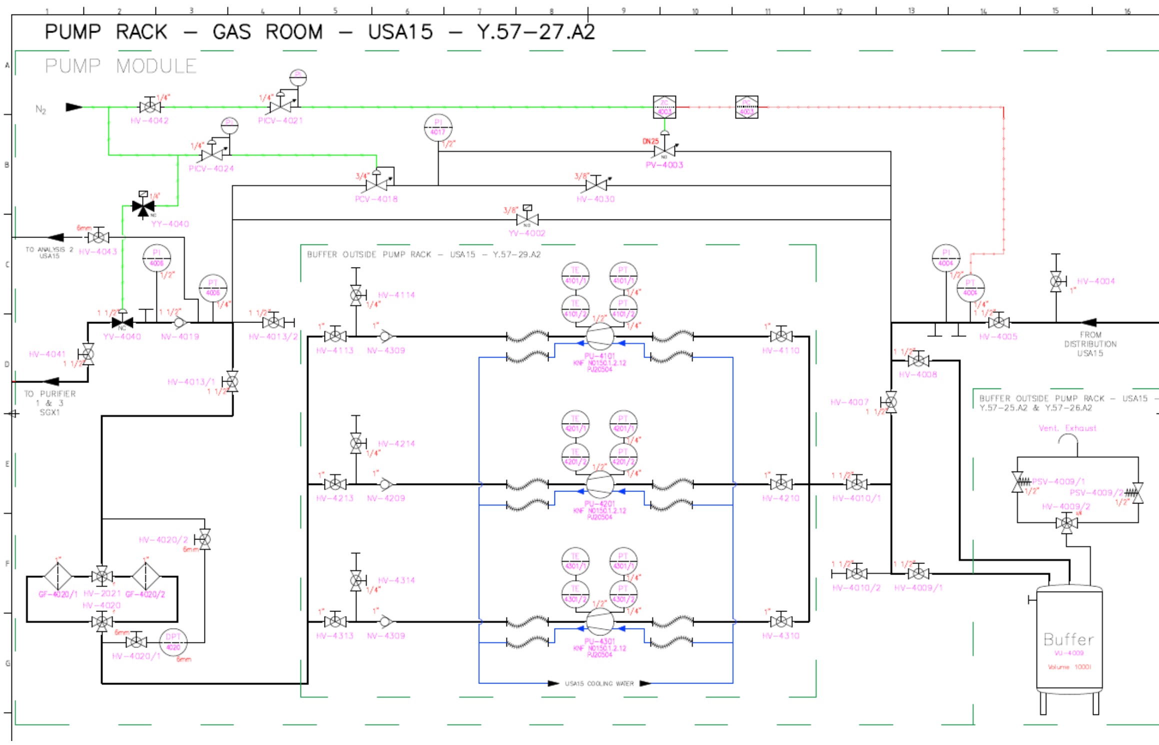


Figure 2.7: ATLAS RPC gas system pump module P&ID [7]

The RPC gas systems are provided of 3 pumps: in the CMS case 2 out of 3 are in run while the third one is in standby and it is used only when one of the working two experiences some issues or needs the membrane replacements, while for the ATLAS system just 1 is in run. This is mainly due to the fact that in CMS the RPC detectors required an higher amount of volumetric flow that needs to be provided to them. In ATLAS it is not necessary having 3 pumps, but to avoid unexpected downtime and the necessity of having the same design among the two RPCs, the choice of adding a third pump was taken. These pumps are particular membrane pumps developed by KNF, which are provided with 2 heads each and they are very important and critical for the correct functioning of the system.

Another important component of the pump module is the regulation valve PV-4003 and its group, made of the actuator and controller. The pump module goal is to keep the detector pressure as stable as possible, since, as explained before, it is very sensitive to the atmospheric pressure changes. In order to perform this action, the module is designed with a recirculation loop, controlled by the regulation valve mentioned before. In practice, the input pressure transmitter PT-4004 sends the pressure reading out of the distribution to the controller which, in addition to the mechanical actuator, regulates the opening position of the valve. If the detector needs a reduced flow, in order to keep the pressure constant, the regulation valve is set to open more, to increase the bypass flow. Vice versa, if the detectors requires more flow, the valve is progressively closing. In addition, before the pumps in the negative relative pressure part, a buffer is installed to help smoothing some possible transient behaviour of the system. Since the pumps involve the motion of mechanical parts, two filters are installed at the output of the module, to trap some impurities or dust that form during the normal run.

For these reasons, the pump module required continuous monitoring and many alarms, that would trigger the full stop of the module and the system as well, are set. In figure 2.8, it is possible to have a look at the SCADA interface for this module.

For example, if the PT-4004 has bad reading or drifts and the input pressure of the pump module is not consistent, the alarm will trigger the stop of module and system, because the information on that parameter is wrong and would significantly affect the correct regulation of the pump bypass and the distribution as well. Moreover, there are also pressure sensors for the membranes and temperature sensor directly mounted on the pump heads which can send signal to stop the system if some parameters exceed the imposed limits.

From the GCS, it is also possible to monitor the regulation valve opening, which is also an indicator of the pumps efficiency and the output pressure of the module or manually switch the pump from standby to run phase.

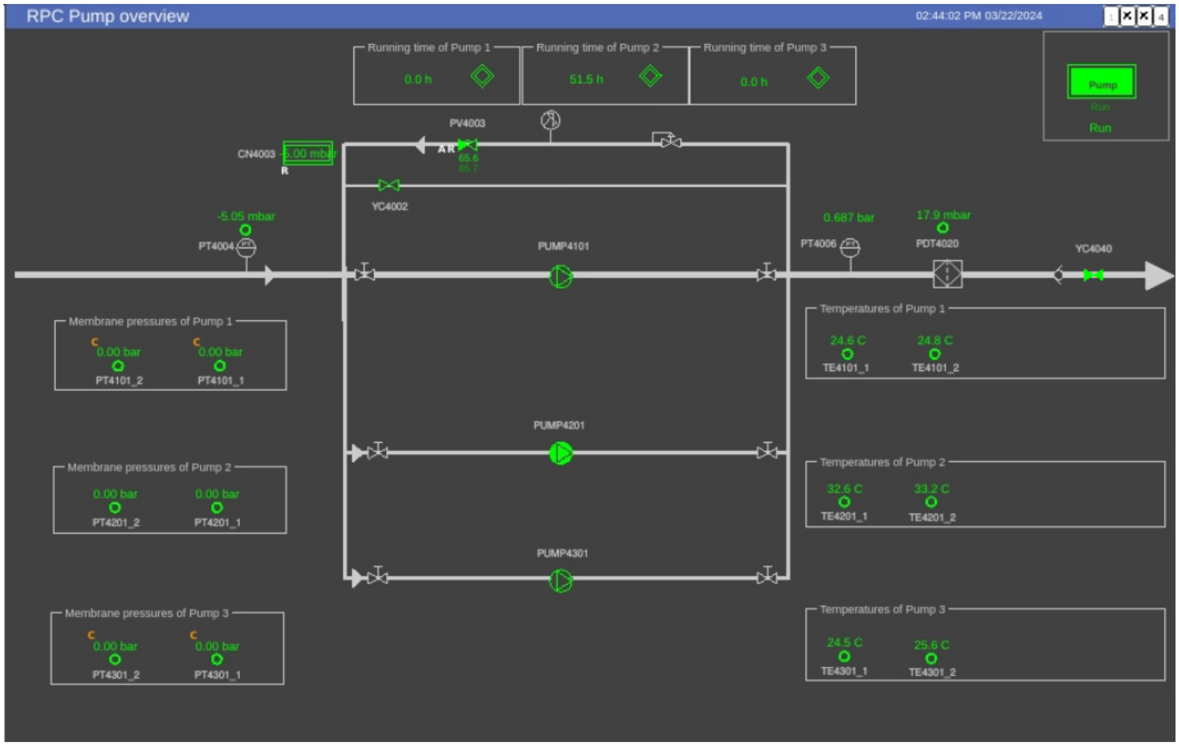


Figure 2.8: ATLAS RPC gas system pump module SCADA interface

2.3 Purifier module description

The purifier modules are present only in the closed-loop system, where the recirculation of the mixture is performed, in order to avoid injected too much greenhouse gases in the atmosphere and to spare some money, since some of them are difficult to get. The gas mixture coming from the the experiments cavern and then through the service cavern, where the pumps are located, has lots of impurities that accumulate in the flow such as oxygen O_2, nitrogen N_2 and water H_2O and, for this reason, it is necessary to have some dedicated racks that are used to clean it before being reinjected in the loop. In the case of the RPC gas systems, there are 3 different purifier module each: 2 of them are used to remove water and work in parallel, while the purifier 2, set after them, is used to remove oxygen. Another difference between the purifiers is that the purifier 2 is made of ATEX components, since the regeneration of the purification columns is driven by argon Ar and hydrogen H_2 mixture: the presence of hydrogen lead to necessity of design it in this way. In figure 2.9 and 2.10, the P&ID of the two type of purifiers are represented.

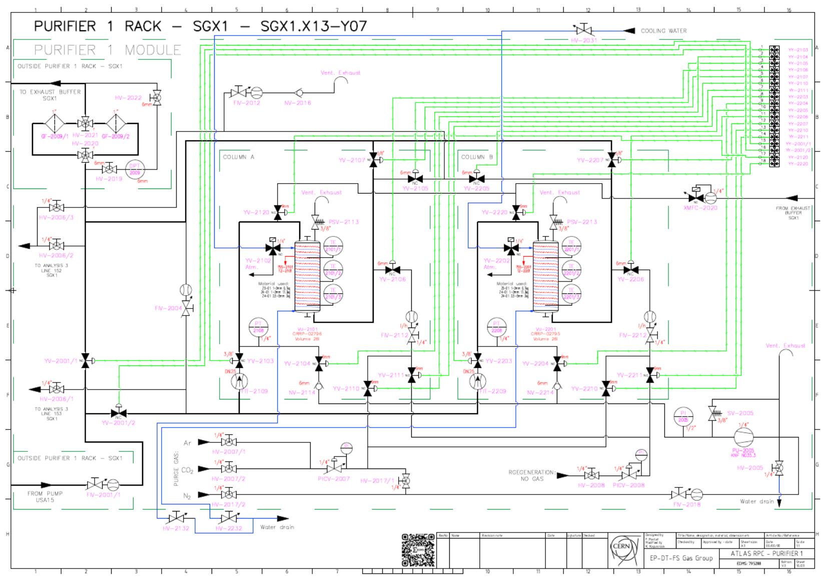


Figure 2.9: ATLAS RPC gas system purifier 1 P&ID [7]

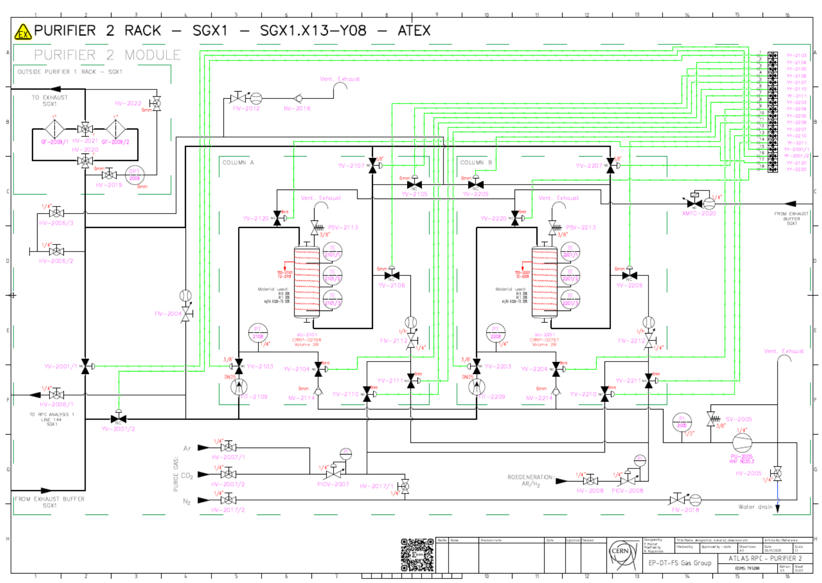


Figure 2.10: ATLAS RPC gas system purifier 2 P&ID [7]

As explained before, the purifiers are used to clean the used mixture from those impurities accumulated during the process or due to the breaking of some gas species when interacting with electric field in the detectors. The purifier 1 and 3 use a molecular sieve for water, while purifier 2 uses a metallic catalyst for the oxygen absorption.

They are equipped with 2 purification columns each, which work in parallel and in an alternately way. During the operation, the working column begin to trap those impurities until its inside material saturates. At that point, the other column is put in run and the first one starts the regeneration phase.

Once a column is saturated, the regeneration phase of the material used inside for the purification is started: the process involves high temperature and a regeneration gas mixture for the purifier 2 (Ar and H_2). In order to accelerate the process, before the regeneration, the column enters the so called 'Preparation phase', in which it is heated up. Finally, the captured impurities need to be exhausted and, to complete this task, a pump is installed to extract and collect them using a purge gas mixture.

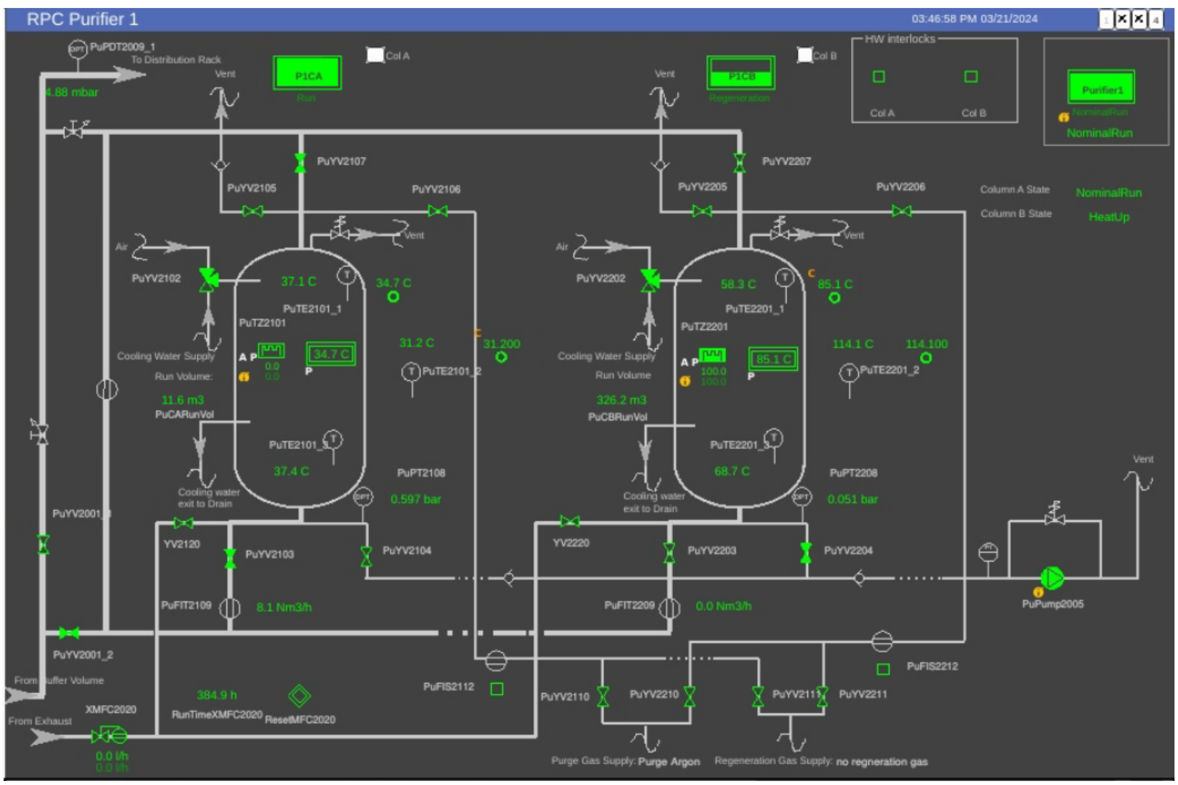


Figure 2.11: ATLAS RPC gas system purifier 1 SCADA interface

In figure 2.11 the SCADA interface for the monitoring of the purifier 1 is shown. In the picture, it is possible to see that column B is regeneration phase, while column A is in nominal run. From the GCS it is possible to control and regulate the right timing for the switch of the two columns, which must be synchronized to the correct operational phase of them. Moreover, it is also important that all the valves, that regulate the flows inside the purification columns, are in the correct position during the different phases.

2.4 Humidifier module description

The gas mixture coming from the mixer and the recirculated one from the purifiers, needs to be enriched with moisture, in order to enhance the detector performances, increasing the avalanche effects. In particular, the humidity for the RPC systems is kept at around 40% and the goal is to not overcome this threshold. In principle, the gas mixture, from the exhaust, is split into two flows, one is kept dry, while the other is humidified passing through a water volume. In the next figure, the P&ID drawing of the humidifier is shown.

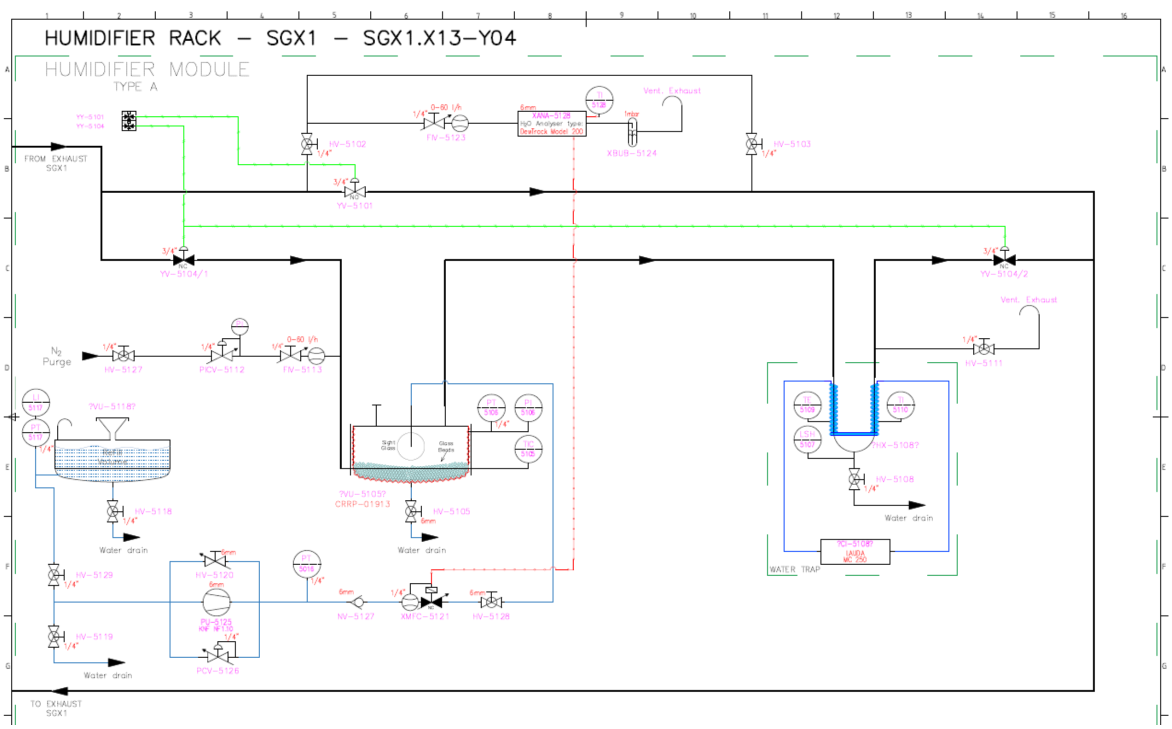


Figure 2.12: ATLAS RPC gas system humidifier module P&ID [7]

The humidifier is provided of a water tank, which sends the water to the evaporator through a pump, in order to produce the required amount of moisture. There the gas mixture flows inside to increase its humidity. During the process the mixture becomes hotter and for this reason, an heat exchanger is installed downstream to cool it down before mixing again with the other half of the flow. The whole process is monitored by an analyser, which measures the content of humidity in the flow and regulates a mass flow controller to tune the correct amount of water into the evaporator.

In figure 2.13, the SCADA monitoring interface is shown. From the Gas Control

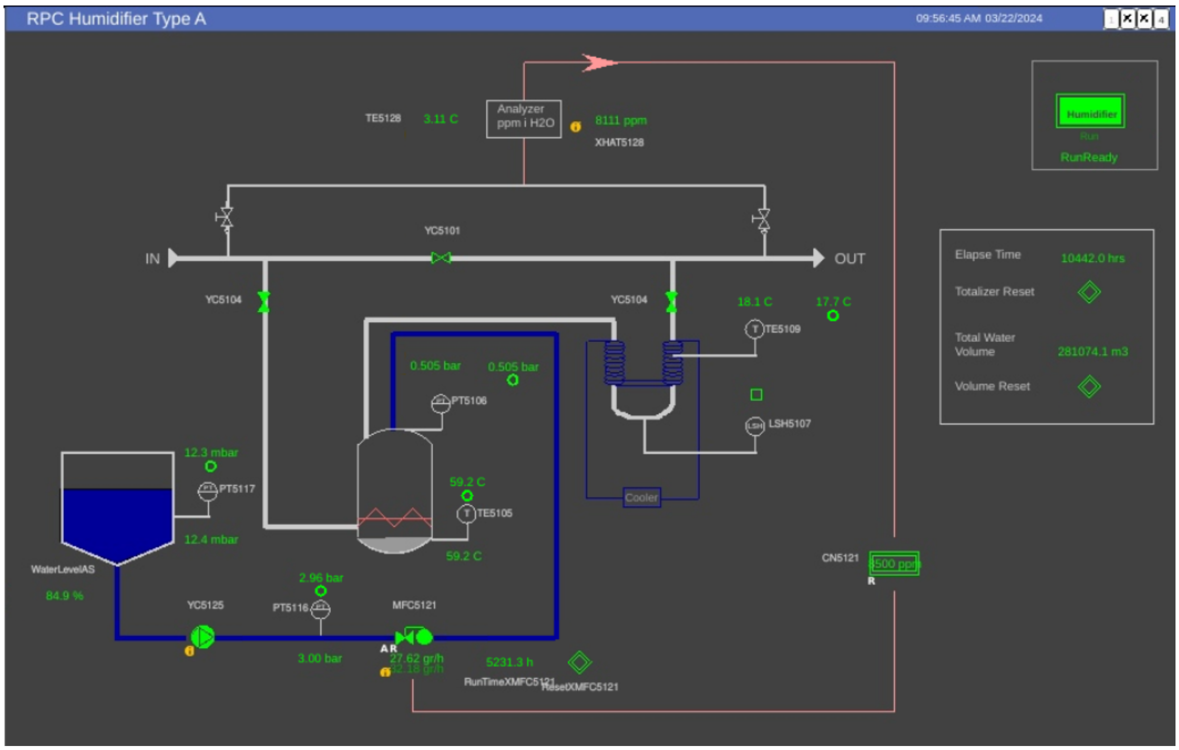


Figure 2.13: ATLAS RPC gas system humidifier module SCADA interface

System, it is possible to monitor the main process parameters related to the temperature of the mixture after the evaporator and after the heat exchanger, as well as the pressure at the first one: this variable can trigger the full stop of the module if they overcome the imposed limit. Other parameters that are remotely controlled are the water level inside the tank, the mixture moisture and the pump water flow and output pressure, which are themselves linked to alarms.

2.5 Exhaust module description

The exhaust module functionality is quite trivial for the open loop gas system, while for the closed-loop like RPC ones it has specific task: it allows the removal of that mixture part that needs to be replaced by fresh gas injected by the mixer module.

The quantity of exhausted gas is controlled by the mass flow controller XMFC-5002. The position of the valve YV-5003 determines the behaviour of the system, if in loop or open mode (all the gas is exhausted). The fresh mixture from mixer module joins the recirculated one from purifier module in the exhaust rack from valve HV-5014. In addition, a filter GF-5030 and a loop flow meter FIT-5010 are also present.

Moreover, another component of the exhaust rack is the buffer, which is located between purifier 1 or 3 and the purifier 2. Its function is to cope the potential atmospheric pressure changes.

In figure 2.14, the P&ID drawing of the module is represented.

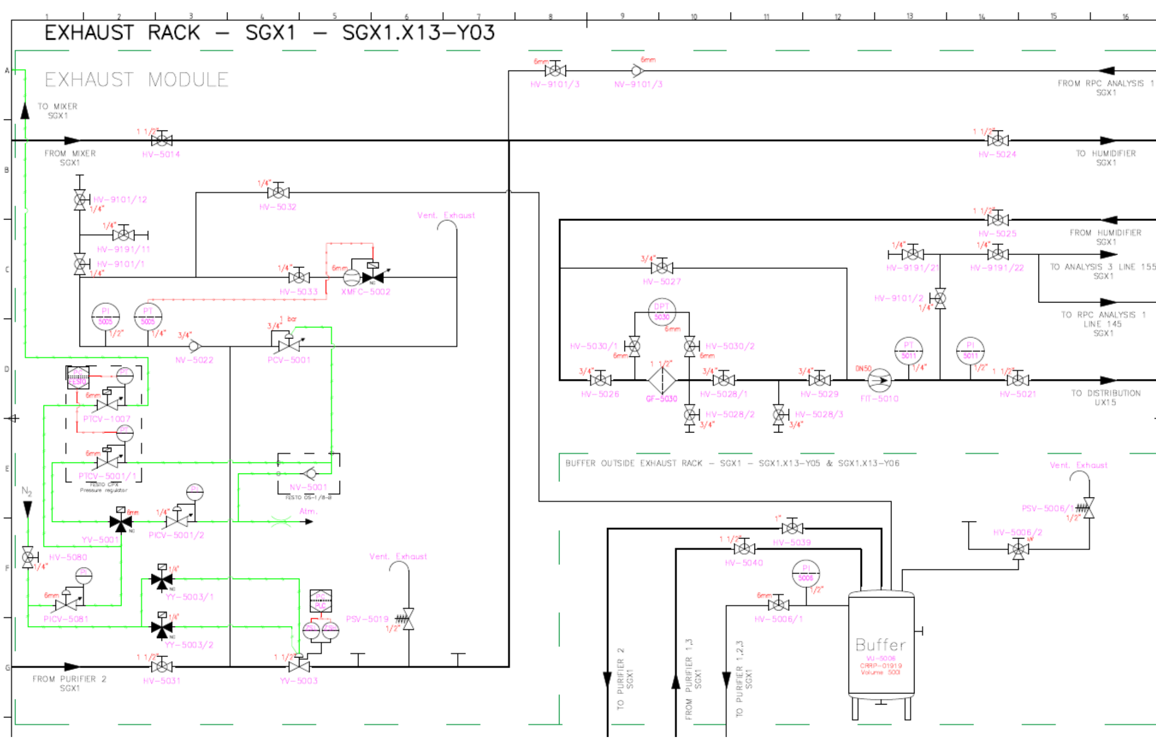


Figure 2.14: ATLAS RPC gas system exhaust rack P&ID [7]

From the SCADA software, it is possible monitor the flow rate through the mass flow controller that is going to be exhausted. In the case of ATLAS, there are many leaks in the detector region and, for this reason, it is set to 0 l/h and the mixer needs to compensate through continuous fresh injection. In the case of CMS, where the recuperation systems are installed, about 10% of flow rate is directed to exhaust line where it is sent to the recuperation. In figure 2.15, the GCS layout is represented.

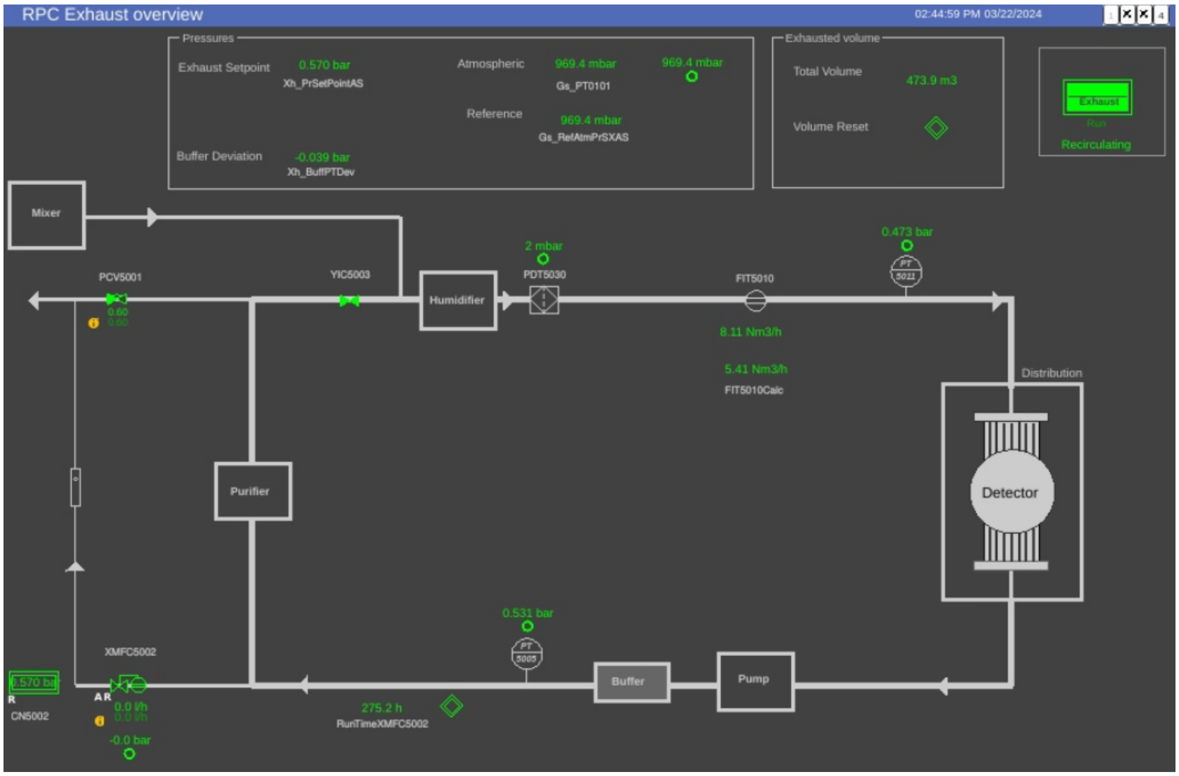


Figure 2.15: ATLAS RPC gas system exhaust rack SCADA interface

2.6 Distribution module description

The distribution module is the responsible for providing the gas mixture into the different detector chambers of the experiments. This module is the only sub-systems that is different for the two RPC gas systems: in fact they are designed in a different way. ATLAS distribution is made of 9 racks located at the different level of the ATLAS (fig. 2.16), 5 of them were built many years ago, while the other 4 are more recent. These new racks have a double regulation valve, one for the input pressure and one for the output flow. CMS distribution is totally different: it is made of 28 racks and they are divided into 6 regulation groups. In this way the pressure regulation is performed before the racks themselves. However, in the last upgrades of the systems, some additional regulation valves have been installed in the distribution racks to have a better regulation of pressure and flow to the chambers.

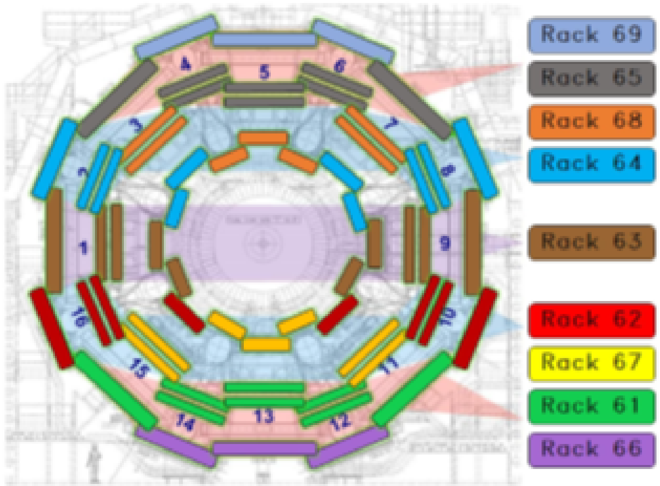


Figure 2.16: ATLAS RPC gas system distribution module location [7]

In the next figures (fig. 2.17 and fig. 2.18), the old and new P&ID racks of ATLAS distribution are compared.

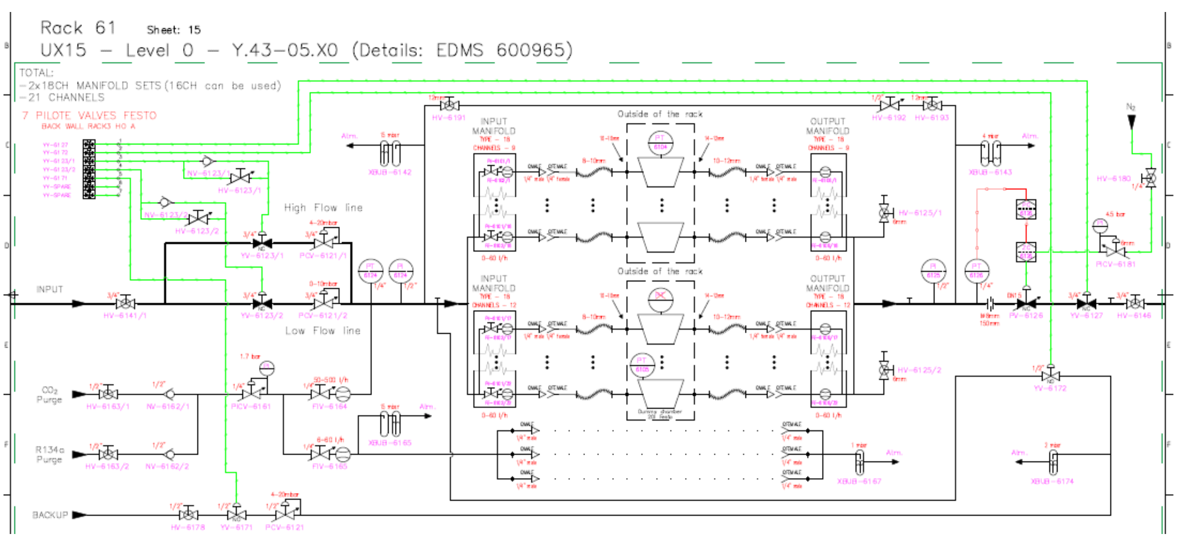


Figure 2.17: ATLAS RPC gas system distribution rack 61 (old version) P&ID [7]

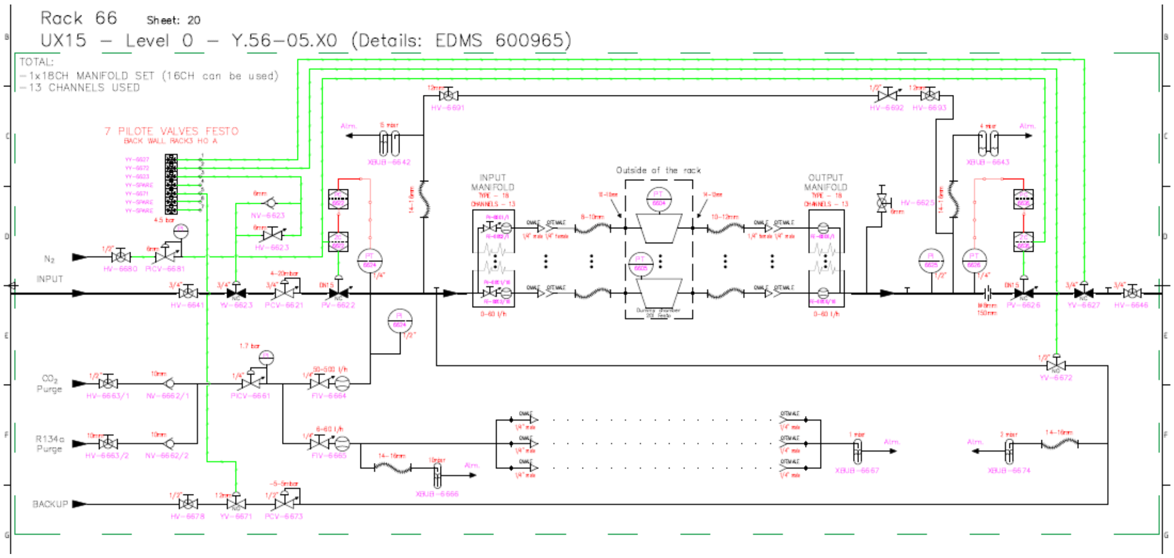


Figure 2.18: ATLAS RPC gas system distribution rack 66 (new version) P&ID [7]

As explained before, the main difference between the two racks is the presence of the regulation valve PV-6622, its actuator and controller, which guarantee an additional automated regulation on the input pressure of the detector chambers, allowing better performances on the detector side. In the old version racks, there were two lines at the input, the high flow line and the low flow line, with pressure regulators installed on each of them. Having a regulation valve installed, with respect to the pressure regulators, allows a faster reaction in case of abrupt variation of operation conditions, such as atmospheric pressure changes.

Each rack, both for CMS and ATLAS, are equipped with the flowcells. These are particular components which measures the flows to and from the detector chambers in order to keep monitoring and spot some possible leaks. For each rack, one input and one output manifolds are installed: each manifold has its own number of flowcells which depends on the type of them. There are manifolds which can contain up to 32 flowcells for supply and 32 for return, while other are suitable for 13, 16 or 26 flowcells for both supply and return. These differences are related to the numbers of chambers of the sub-detector that needs to be filled. The total number of flowcells for ATLAS RPC is 464, while CMS RPC is equipped with 1064, considering both the supply and return.

In the SCADA monitoring, for each rack, it is possible control the input and output pressure of the chambers, as well as the flow measured by the input and output flowcells and the potential gas loss and the total flow of the specific rack. Moreover, each rack has alarms set on the pressure measurement which can trigger the full stop in case of particular condition. Another parameter that is monitored from the GCS of the distribution is the atmospheric pressure, which can cause instabilities in the regulation. In figure , an example of the SCADA monitoring for rack 66 of ATLAS RPC and the flowcells measurement are represented.

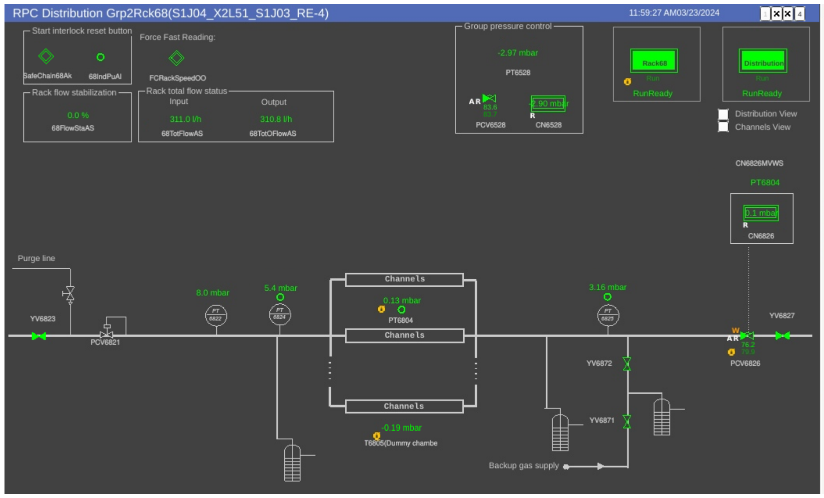


Figure 2.19: CMS RPC gas system distribution rack 68 SCADA interface

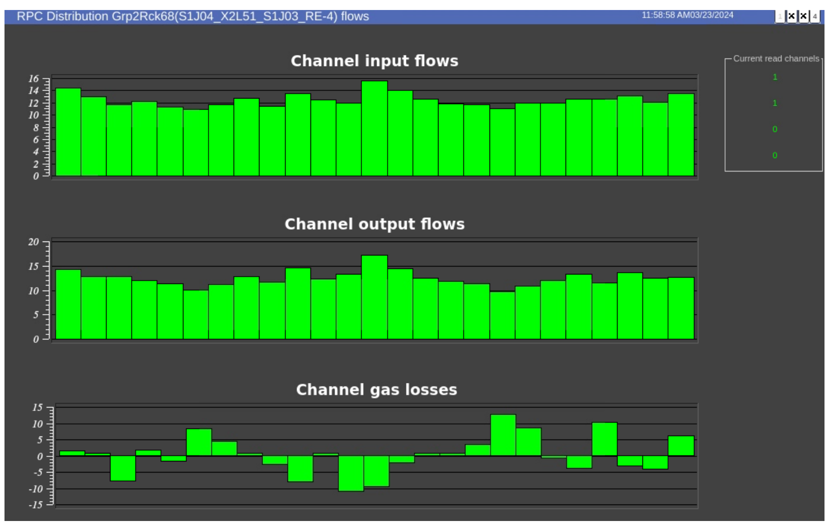


Figure 2.20: CMS RPC gas system distribution rack 68 flowcells measurements

The negative gas losses can be due to the fact that some chambers can leak into other channels and, for this reason, for some of them, the output flow is higher than the input one.

2.7 Analysis module description

In the RPC gas systems, there are also the analysis modules, one is made of the Infrared (IR) analyser and one is for oxygen analysis. The first one is part of the exhaust rack and it is used to perform measurements of the gas composition after the mixer or before the purifier 2, to continuously check the flammability level of the mixture. The oxygen analyser is used to control the oxygen content in the gas mixture after the pump module and the distribution return, before going to the purifier 1 or 3. In the case of ATLAS, the analysis 2 module shared the same rack of the analysis module of Micro-Megas gas systems (MMG). In addition to these analysis modules, the CMS system is also equipped with a Gas Chromatograph (GC) to check the gas mixture composition and eventually the presence of impurities.

Since, the two analysis modules are very similar, just the analysis 1 module P&ID scheme, the infrared one, is represented in figure 2.21. As it is possible to see in the

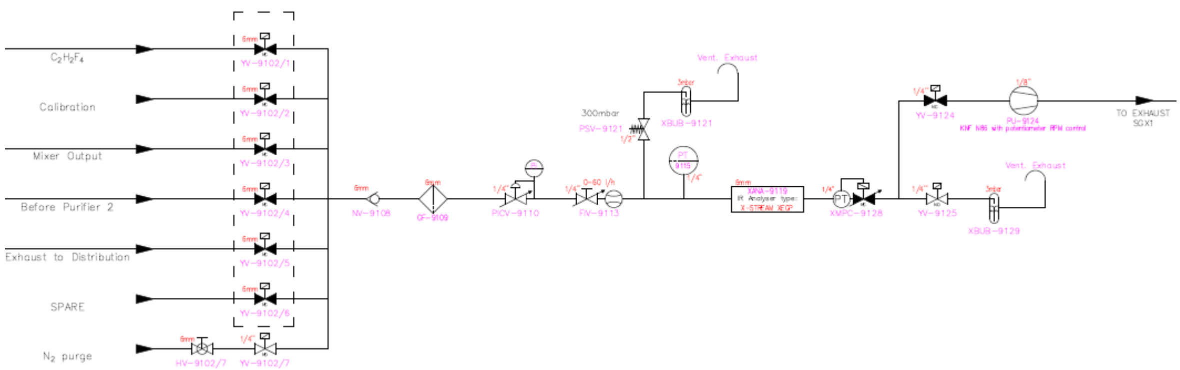


Figure 2.21: ATLAS RPC gas system analysis 1 module (IR) P&ID [7]

figure 2.21, there are different lines: one is for the Freon, one is used for the calibration of the analyser, one is from the exhaust and one is for N_2 purge. There is a filter to trap the impurities that are present in the flow, a mass flow controller after the analyses and a pump to extract the gas and send to the exhaust line.

2.8 Gas recuperation systems

In this section, a quick overview of the CMS *R-134a* recuperation system is described, since it is not the focus of the present work. This system was at first built in ATLAS and then moved to CMS, where it was tested in different configuration. As the name suggests, the recuperation systems, in general, are used to recover those fluorinated greenhouse gases that are too harmful for the environment if released in the atmosphere. Another reason for using this systems, is the increasingly difficulty in finding those gases at an affordable price.

The basic idea is to liquefy the gas mixture coming from purifiers in an heat exchanger. Then the liquid mixture starts to fill a vertical 'cold' buffer, *Buffer 1*. The first buffer is kept at -35°C and due to the boiling point of the SF_6 (-67.6°C), at the corresponding pressure), it is exhausted in the gas phase. Moreover, in this phase the isobutane and Freon forms an azeotropic mixture which is significantly volatile and leaves the system. After that, the mixture flows into the 'warm' horizontal *Buffer 3* (above 0°C) where it vaporizes. Then, it is sent to a second heat exchanger to liquefy again and after that it flows to *Buffer 2* where the other volatile components are removed. In the end, a pumping unit compress the mixture into the refill volume. In the second configuration of the prototype, the second heat exchanger and *Buffer 2* are removed, since the presence of the latter would not influence the quality of the recuperated species.

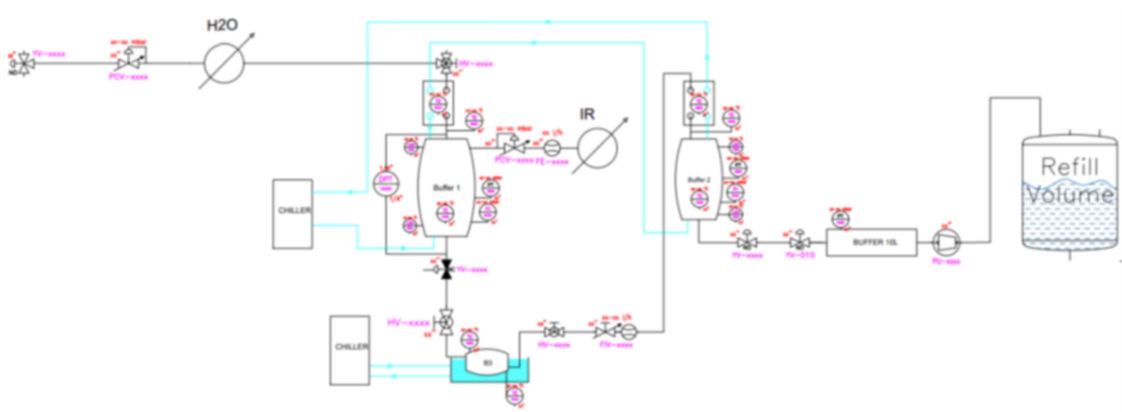


Figure 2.22: *R-134a* recuperation system prototype - first configuration

Chapter 3

Current maintenance procedures and strategies

As previously shown, these gas systems are complex and delicate installations, composed of hundreds of items or components that require some active recurrent maintenance operations to keep them working in the proper conditions. If the systems experience a critical failure, in the worst case scenario there can be the possibility of damaging the detectors chambers which, due to their position, can be difficult to fix or replace, with the consequent loss of data achieving from the experiments.

These systems were built in the years between 2003 and 2007 and progressively upgraded during the period of operations and, for the reasons explained before, they needed some dedicated and standard maintenance procedures, developed and enhanced during the time.

The current maintenance strategies for the gas systems of the LHC experiments foreseen a standard and massive procedure during the Long Shutdown (LS) phase and the End of the Year Technical Stop (EYTS) at CERN. During these periods, it is possible to perform all the dedicated activities, to check the status of the racks and modules equipment, replace faulty components, perform different tests or calibrations and also introducing upgrades for the different systems, in order to have better performances during the following run phase, to guarantee experiment taking data in a reliable and continuous way.

However, during the normal operation, when performing activities on the systems is more difficult, due to the access limitation in some radioactive restricted area (like the UX cavern), the maintenance strategies mostly used are the reactive and corrective maintenance or the run-to-fail strategy for components. Of course, these strategies can minimize the upfront maintenance efforts, but they can also have some drawbacks like:

- Increased downtime: since the intervention is performed just after the occurrence of failures in the racks, this could lead to an increased downtime of the system due to the unplanned activities for repairing or replacement the components that have shown problems or failure.

- Increased maintenance cost: similarly to the previous point, a reactive and corrective strategies could lead to unexpected high cost of maintenance, due to the necessity of requiring components that may not be present in local stores and that need to be delivered, or the overtime payment of technicians, or worst, in some case, the necessity to call and external company to solve the problem. Moreover, unforeseen leaks of some expensive gases necessary in the mixture can cause high costs for the refill.

- Safety risks: if there are not any planned maintenance activities on critical components which are linked to flammable gases, such as the isobutane (iC_4H_{10}), or to some greenhouse gases like Freon R_{134a} and SF_6, in case of some leakage, this could be dangerous for the cavern itself and the environment.

For more critical components, like the pumps of the pump module, the redundancy strategy is used in order to have at least one spare component ready to start in case of necessity. Moreover, during normal operation, pumps have a dedicated scheduled maintenance procedure to increase the reliability of the module. In particular, these pumps are in general special diaphragm pump produced by KNF and they require strictly maintenance activities which involve the membranes: typically, the pump membrane is replaced after 2500 working hours and, after 10000 hours, the pump is removed from the loop, replaced with a spare in the local store or workshop and sent to the manufacturer for inspections, general maintenance and upgrades in order to reestablish its status and efficiency, in a more reliable way.

Also other components, like the filters, are installed in redundancy: in that case, a bypass line equipped with manual valve is built, in order to guarantee an easier switch between the two in case of saturation of the one in use.

For what concerns mass flow controllers, they are important items, especially in the mixer module, since they control the correct flow composition in the system. For this reason, they need particular attention and, periodically, they are removed, tested and recalibrated.

3.1 Standard maintenance procedures

Since there are about 30 gas systems for the LHC experiments, the development of standard maintenance procedures is of fundamental importance. The meaning term *standards* means that every module of the same type has the same maintenance routine, even though the belonging systems are different and with different operational conditions. For example, the maintenance procedure of the Pump module of ATLAS RPC is the same for the Pump module of ALICE TOF gas system.

Moreover, using these standard procedures has also some advantages for the technicians who perform these tasks, for example [20]:

- Minimize errors introduced by operators who, while being really expert, can forget some details due to lack of attention or forgetfulness.

- Minimize arbitrariness introduced by the different way-of-working of operators that can be unpredictable and could lead to different behaviour of the systems in run conditions.

- Reduce the eventuality that every operator acts following his own perceptions without having the proper knowledge and awareness of what he is doing or whatever else his action, even well intended, could affect.

- Provide useful documentation for future technicians who are going to cope with the operation of these complex systems for the first time. The procedure has, therefore, the intention to give them guidelines, thus reducing the risks related to inexperience.

These standard procedures are written for each module and they are structured as an interactive excel worksheet, in order to keep track of the operations that were already performed and the one that need to be taken. In particular, these procedures are divided into 3 main parts:

- Module in RUN, system in RUN.

- Module in STOP, system in RUN or STOP.

- Module in RESTART, system in RUN or STOP.

3.1.1 General description of the procedures

In general, these procedures are written as a general inspection of the modules, checking if all the valves are in the correct position, the analog reading of process variables are the same of the one visualized in the SCADA software or the labels of the components are the same of the one in the P&IDs.

For what concerns the pump module, particular attention is dedicated obviously to the pumps, which have a dedicated procedure for the membrane replacement, and the bypass and recirculation line components, like the regulation valve.

The purifier modules requires additional actions, due to complexity of the operations. For example, a general procedure for the replacement of the regenerant material of the column is used (figure 3.1). Moreover, since they are made of parallel columns, as explained in section 2.3, that work in asynchronous way, they required some additional care of the Festo module, which contains the solenoid valves responsible for the correct position of the pneumatic valves: these are fundamental for the right switch between the operational phases of the columns.

For what concerns the mixer procedure, its main focus is on the calibration of the mass flow controller which covered a crucial role for delivering the right mixture composition to the detectors.

The distribution module procedure is similar to the other ones in terms of activities: the main focus of this procedure is related to flowcells and regulation valves. The flowcells needs to be properly calibrated in order to fulfil their goal of reading the input and output flow of the chambers with high precision and accuracy. The regulation valves must be checked in order to understand if their operations range is still available, in order to proper have control on the pressure and flow to and from the chambers.

Finally, the exhaust and humidifier have not particular focus but just the generic check of all the instrumentation, check of the sensors reading, rotameters status and connections of all the pneumatic lines.

Regenerant material replacement

Before starting, keep in mind that putting the Purif in STOP, you bypass it -> some maintenance can be done even when the system is ON
Material needed for the operation: gloves, mask, aspirator, vacuum cleaner, funnel (maybe take a picture of each one and add here?)

1. Empty the module from gas in the gas room (Surface/Underground)
   a. Depressurize the columns (~5 min) opening YV-2X04
   b. Take out the SV 2X13 (only if you need to re-validate them. Once validated, put them back)
2. Remove old material (~30 mins): ***DANGER***: the regenerant material can be toxic and heats up with air, take proper safety protections, e.g. gloves, mask.
   a. Open metal flanges underneath the column
   b. Recuperate the material with the metal basket (shake if necessary: material may be stuck).
   c. Change the flange joints
   d. Put back the flange
3. Leak test
   a. Open YV-2X10 and YV-2X06
   b. Pressurize with CO2 (or Ar) up to 1-1.5 bar (PT-2X08)
   c. Close YV-2X10 again
   d. Wait to see if pressure decreases, find and fix the leaks (critical spots: SV, flange, valves).
      Tip: valve YV- 2X07 is often cause of the leak: replace the body in case.

4. Material refill (~30mins): ***DANGER***: the regenerant material can be toxic and heats up with air, take proper safety protections, e.g. gloves, mask.
   a. Open the top flange
   b. Refill with new regenerant material (see required quantities in ppt file…)
   c. Put back the flange with new joints
   d. Perform again Leak test (the new material will react with fresh gas -> temperature will increase and pressure will go down. Wait until pressure stabilizes)
5. Regeneration test
   a. Check of bande chauffante: put purifier in regeneration mode
   b. check of the vacuum of the pump if present: does it reach -600/-700mbar to

Figure 3.1: Regenerant material replacement procedure

3.1.2 Example of maintenance procedure for pump module

In this section an example of maintenance procedure worksheet is shown (figures 3.2 and 3.3), using the pump module as an example. In particular is it possible to observe how the sheet is built, considering the case in which all actions had problems (the case module in RESTART is not displayed).

PUMP MAINTENANCE PROCEDURE

Complete the form and print it at the end

SYSTEM:		START DATE:	END DATE:		OPERATOR:
Pump in RUN system ON					
WHAT	**DESCRIPTION**	**STATUS**	**RESULT**	**ACTION LIST**	**Notes**
LEDs check	Press the button in the pump chassis and check if the leds are ok	☑ ~~Done~~	☐ Ok ☑ Problem ☐ Solved	Describe and record the problem. Contact electrical technician	
Inlet Pressure Control	Check PI-4004 reading and compare its value with the corresponding PT-4004 reading on WinCCOA. Is error less than 20%?	☑ ~~Done~~	☐ Ok ☑ Problem ☐ Solved	Take note of the two readings. If possible, check the zero reading of the two devices	
	Check that setpoint is equal to PT-4004 reading on Winccoa Setpoint Value should be as listed in this *Inlet Pressure Table*	☑ ~~Done~~	☐ Ok ☑ Problem ☐ Solved	Try to adjust parameters	
loop regulation check	Valve PV-4003 setting around 50-80%	☑ ~~Done~~	☐ Ok ☑ Problem ☐ Solved	Adjust HV-4030	
Check YV-4002 bypass is closed		☑ ~~Done~~	☐ Ok ☑ Problem ☐ Solved	Close it	
Outlet pressure control	Read PI-4006 pressure and compare its value with the PT-4006 reading on WinCCOA. 2-3 gauge divisions difference acceptable	☑ ~~Done~~	☐ Ok ☑ Problem ☐ Solved	check zero reading	
	pressure value must be in the range 0.5-1 bar	☑ ~~Done~~	☐ Ok ☑ Problem ☐ Solved	Check loop regulation	
check DPT reading	If higher than H treshold (50mbarg) foresee filter replacement at first technical stop	☑ ~~Done~~	☐ Ok ☑ Problem ☐ Solved	GF-4020 must be inspected or DPT doesn't work properly?	
check membrane pressure	it should be zero or few mbar	☑ ~~Done~~	☐ Ok ☑ Problem ☐ Solved	Switch to another pump and replace the membrane	
N2 supply	check N2 supply pressure and PICV-4021 setting (~4bar)	☑ ~~Done~~	☐ Ok ☑ Problem ☐ Solved	Adjust supply pressure/ contact David Jaillet	
	Leak test with Milles Bulles on the pneumatic tubes and connectors	☑ ~~Done~~	☐ Ok ☑ Problem ☐ Solved	Fix the leak as soon as possible	

Figure 3.2: Pump module procedure - pump in RUN, system ON

Pump in STOP system ON or OFF							
Documentation check	P&ID (and electrical) drawings are present in the rack	☑	~~Done~~	☐ Ok ☑ Problem ☐ Solved		Print it from EDMS, after having done next step	
	Documentation is present in EDMS and up to date.	☑	~~Done~~	☐ Ok ☑ Problem ☐ Solved		Ask the responsible of the system to update it	
Drawing VS Reality	Check every component has a label in accordance to the name on the P&ID	☑	~~Done~~	☐ Ok ☑ Problem ☐ Solved		Correct wrong/add missing labels	
PI zero reading check	Take note of the value read: is it less than 50 mbar and more than 0 mbar?	☑	~~Done~~	☐ Ok ☑ Problem ☐ Solved		PI must be replaced	
rubber dampers supporting the pump	Are they in good conditions?	☑	~~Done~~	☐ Ok ☑ Problem ☐ Solved		Replace them if cracked	
N2 supply	Check if all the pneumatic lines connectors are well connected and the conditions of the plastic hoses	☑	~~Done~~	☐ Ok ☑ Problem ☐ Solved		Change connectors/hoses	
Von Rohr check?	ask to Patrick	☑	~~Done~~	☐ Ok ☑ Problem ☐ Solved		Describe the problem	
NV valves	During a LS, consider to change NV valves	☑	~~Done~~	☐ Ok ☑ Problem ☐ Solved		Describe the problem	
Leak tests							
Leak test	Follow the procedure for: **Detectable Gas Leak Test**	☑	~~Done~~	☐ Ok ☑ Problem ☐ Solved		Try to fix the problem. Describe and record the issue	

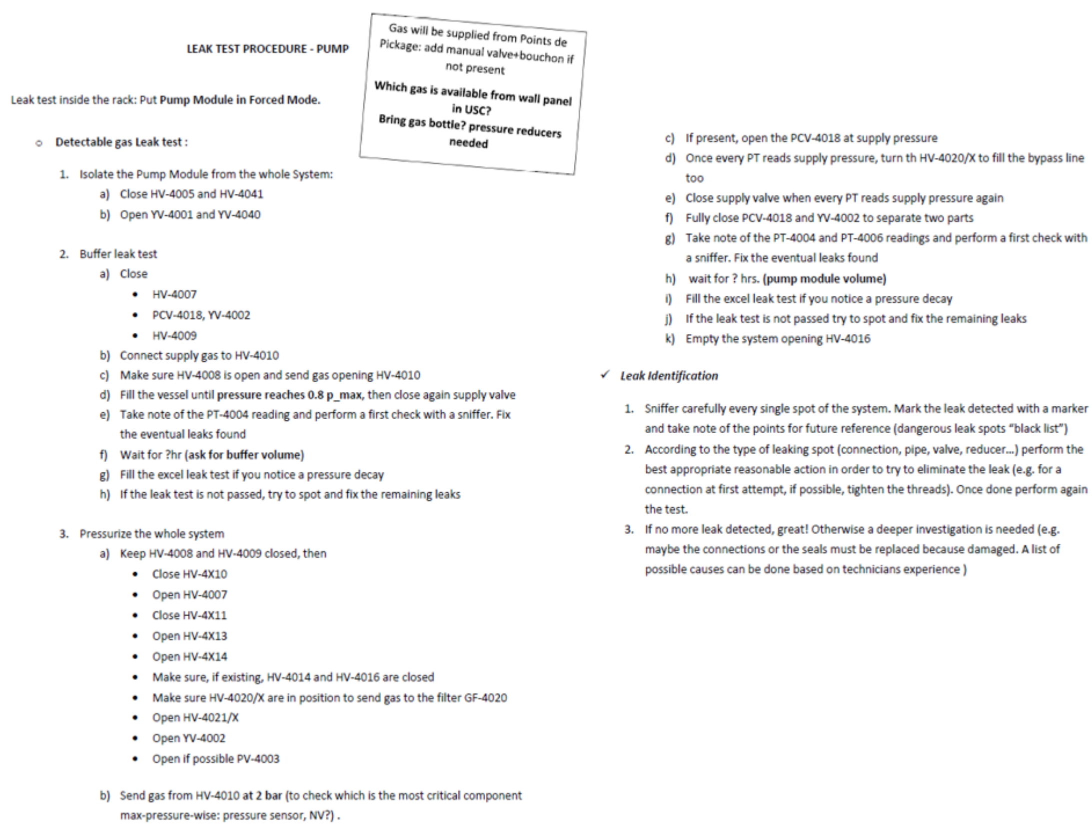
Figure 3.3: Pump module procedure - pump in STOP, system ON or OFF

The tables of the maintenance procedure contain all the required information in the form of checklist, including also the start and end date, since some activities may last more than one day. As written before, these worksheets are interactive and this can be seen in the *results* column. Here, according to the marked box, a different 'messages' would appear, helping the operator that is using them.

3.1.3 Leak test procedure

The standard maintenance procedure for every module, contain the *Leak tests* in the section of *Module in STOP*. These leak tests are particularly important due to the fact that the gas systems are complex installations, with many type of component and connections. These connections can be considered the weak point of the systems because they can be a source of leak. Upgrading the systems with the installation of new components, as pressure sensors or valves, increases the possibility of leaks, since they are an additional potential point of failure.

The used method to perform the leak test is the *pressure decay* method [20]. It consists into isolate the module from the rest of system by closing the manual valve on the line between modules and connections. Then, the module is filled with a gas until a defined pressure is reached. Once all the lines are at this pressure, the gas supply is closed. At this point, the module pressure and temperature are monitored, using the recording of the sensors, for a given amount of time that can be calculated. After this time, the final pressure is compared to the initial one: in this way, knowing the total volume of the filled module, it is possible to compute an approximate leak rate. The main issue with this procedure is that, it is not revealing the position or spot of the leak, but just that some leaks were developed in the module. In order to find the real position of the leak, this procedure can be repeated dividing the module into sub-module and to observe if the leak is in that portion. If it is not spotted there, the sub-module under investigation is increased. Another possibility is to use a leak detector through the whole module to identify the leak spot.



LEAK TEST PROCEDURE - PUMP

Gas will be supplied from Points de Pickage: add manual valve+bouchon if not present

Which gas is available from wall panel in USC?

Bring gas bottle? pressure reducers needed

Leak test inside the rack: Put **Pump Module in Forced Mode.**

- **Detectable gas Leak test :**
  1. Isolate the Pump Module from the whole System:
     a) Close HV-4005 and HV-4041
     b) Open YV-4001 and YV-4040
  2. Buffer leak test
     a) Close
        - HV-4007
        - PCV-4018, YV-4002
        - HV-4009
     b) Connect supply gas to HV-4010
     c) Make sure HV-4008 is open and send gas opening HV-4010
     d) Fill the vessel until **pressure reaches 0.8 p_max,** then close again supply valve
     e) Take note of the PT-4004 reading and perform a first check with a sniffer. Fix the eventual leaks found
     f) Wait for ?hr **(ask for buffer volume)**
     g) Fill the excel leak test if you notice a pressure decay
     h) If the leak test is not passed, try to spot and fix the remaining leaks
  3. Pressurize the whole system
     a) Keep HV-4008 and HV-4009 closed, then
        - Close HV-4X10
        - Open HV-4007
        - Close HV-4X11
        - Open HV-4X13
        - Open HV-4X14
        - Make sure, if existing, HV-4014 and HV-4016 are closed
        - Make sure HV-4020/X are in position to send gas to the filter GF-4020
        - Open HV-4021/X
        - Open YV-4002
        - Open if possible PV-4003
     b) Send gas from HV-4010 **at 2 bar** (to check which is the most critical component max-pressure-wise: pressure sensor, NV?) .
     c) If present, open the PCV-4018 at supply pressure
     d) Once every PT reads supply pressure, turn th HV-4020/X to fill the bypass line too
     e) Close supply valve when every PT reads supply pressure again
     f) Fully close PCV-4018 and YV-4002 to separate two parts
     g) Take note of the PT-4004 and PT-4006 readings and perform a first check with a sniffer. Fix the eventual leaks found
     h) wait for ? hrs. **(pump module volume)**
     i) Fill the excel leak test if you notice a pressure decay
     j) If the leak test is not passed try to spot and fix the remaining leaks
     k) Empty the system opening HV-4016

✓ ***Leak Identification***

1. Sniffer carefully every single spot of the system. Mark the leak detected with a marker and take note of the points for future reference (dangerous leak spots "black list")
2. According to the type of leaking spot (connection, pipe, valve, reducer…) perform the best appropriate reasonable action in order to try to eliminate the leak (e.g. for a connection at first attempt, if possible, tighten the threads). Once done perform again the test.
3. If no more leak detected, great! Otherwise a deeper investigation is needed (e.g. maybe the connections or the seals must be replaced because damaged. A list of possible causes can be done based on technicians experience)

Figure 3.4: Pump module leak test procedure

General Information

Experiment		Target Leak flow at reference conditions	1.00E-03	STD cc/s
Sub-detector				
Module	PUMP			
Rack	Pump			
Test Method:	Pressure decay method			
Persons performing test:				
Location of Test				

Leak test parameter

	Start		**End**		**Difference**	
Time	10/2/19 2:16 PM		10/3/19 3:35 PM		91181	sec
Pressure Inside	3	bara	2.8	bara	0.2	bara
Pressure outside	0.976	bara	0.976	bara	0	bara
Delta P	2.024	bara	1.824	bara	0.2	bara
Temperature	293.3	K	293.3	K	0	K
Volume	900	cm^3				

Results

Leak at test conditions	1.84E-03	Std cc/s	Leak rate conform to specification	YES
Leak flow at reference conditions	7.01E-04	Std cc/s		

Figure 3.5: Pump module leak test results

3.2 Spare part management

Another important aspect related to the maintenance activities is the spare part management. When it is necessary to perform some tasks, it is fundamental to exactly know where they are located and where it is possible to find them. In fact a good management of the spares is crucial for the quick and urgent reactions for some unexpected events. The gas groups, which is the responsible of the gas systems, have a general store in which many components can be found. However, the most used locations are the surface gas room of the experiments, in which the responsible technician keeps track of their own materials. Another location, in which it is possible to find some spare, is the common workshop, where technicians can perform some test and reparation on equipment. Anyway, the spare part management for the group must be revised and structured in a more efficient way. At CERN, there is Computerized Maintenance Management System (CMMS) called Enterprise Asset Management (HxGN EAM), once called Infor EAM. One of the extension of this CMMS is the web interface EAM Store Kiosk, which is dedicated to the registration of the spare parts used in the activities of the different CERN group. Therefore, in order to enhance the performances of the maintenance activities one possibility is to use this software to help in keeping track of the material location, where it is used or where it is stored.

Chapter 4

Work strategy

In this chapter, the idea behind the present work is described, highlighting the work methodology and strategy. The main focus is to enhance the maintenance activities in order to increase the reliability and availability of the systems, applying the Reliability Centered Maintenance (RCM) approach and the FMECA analysis to support the strategy, identifying the potential failure modes effects and ranking their criticalities. In this way, it is possible to prioritize the maintenance and work order tasks for the most critical components.

Before entering the details, it is useful to give some definition of the main concepts behind the work strategy, such as the reliability, availability, and the concepts of failure modes.

4.0.1 Reliability

By definition the reliability is the probability that a system or component is able to perform its function, in a continuous and correct way, without interruption, under given conditions, for a determined period of time called *Mission Time* [13].

For the correct definition of reliability, it is necessary to put emphasis on the above mentioned parameters (mission time, functionality failure and operative condition) and define them as well as possible. As consequence, the concept of *Unreliability* is its exact complement to 1.

4.0.2 Availability

The availability is defined as the probability that a system or component is able to perform its function at a given instant of time t, in well defined operation conditions, independently from its failure history [13]. This definition is used especially for those components which function is protection and safety. For component used for production, availability is defined as the ratio between the total operability time and the total time of observation in case of no failures. In other words, it can be expressed as:

$$A(t) = \frac{MTTF}{MTBF} = \frac{MTTF}{MTTF + MTTR} \tag{4.1}$$

Where the parameters are defined as follows:

- $MTTF$: Mean Time to Failure, which is the average observed time between tow successive failures.
- $MTTR$: Mean Time to Repair, which is a measure on the average time for restoration process for a specific component or failure mode.
- $MTBF$: Mean Time Between Failure, which is sum of the $MTTF$ and $MTTR$.

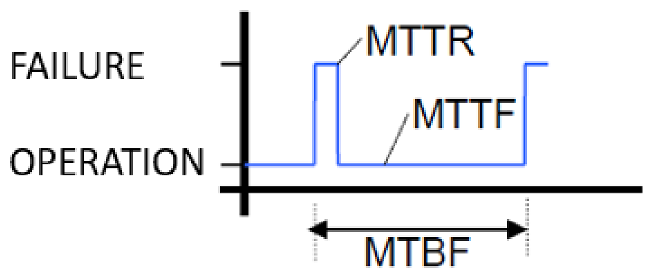


Figure 4.1: Availability parameters [13]

4.0.3 Maintainability

The maintainability is the probability that a failed system or component is restored and put back in its original status within a given a period of time t [13].

In principle maintainability is not an intrinsic characteristic of an asset but it strongly depends on the type of failure mode that has occurred and the maintenance procedure that was carried out on that specific item. Moreover, it is necessary to take into account also the time spent for the fault detection, the technical delays and the accessibility to spare parts required for the work.

4.0.4 Failure mode

A fundamental and key concept is the definition of *failure mode* [13]. Since the RCM is focused on detecting failure modes and assess their consequences on the system, in order to schedule dedicated maintenance plans on the most critical one, is important to give a precise definition of failure mode. Failure mode can be defined as the observed state through which it is possible to declare that a specific component is failed or as the negation of a specific function that is expected when the component is installed. In other words, it is how the faulty item shows itself its failed condition to the operator or technician who is in charge to deal with. Failure mode should not be confused with failure cause (the technical reason that lead to the negation of the function) or neither with the failure effect. Moreover, to define the failure mode for components, it is important to properly declare the operational phase of the systems: different operational phases can lead to different failure mode for a specific component.

In the present work, the failure mode identification, used as part of the FMECA, is crucial: for this reason, the idea is to decompose the system into the basic items which made up the systems (valves, pumps, sensors,...), defined as *Lowest Replaceable Units* (LRU). For them, one or more functions are considered and their denials lead to the definition of the failure modes.

4.1 Work strategy

The idea behind this work is to try to improve the current maintenance strategies for the gas systems. In particular, the main objective is to use an industrial based approach to increase the reliability and availability of these systems and to optimize the maintenance efforts, using targeted interventions on just that equipment that is crucial for correct functioning. Moreover, the focus of this study is to give a comprehensive view of the maintenance management, in order to avoid improvised actions. Therefore, one possible solution is implementing a structured approach, which is considered very robust in its applications, like the Reliability Centered Maintenance (RCM) strategy. Moreover, since the RCM is based on identifying failure modes, the FMECA analysis can be a good supportive tool.

Since it is unfeasible to perform this analysis on all the systems at once, the RPCs gas systems of ATLAS and CMS experiment are selected. This choice is done considering that these 2 systems are designed with similar characteristics and for this reason, there is a higher amount of past information on them. In fact, in order to carry out the study, at the beginning it is fundamental to look back at the whole recorded history of the RPCs. At CERN, in particular in the gas group, the eLOG platform is used to keep track of every intervention, adjustment, calibration, inspection, replacement and in general problems affecting the systems: therefore, to get all the necessary documentation, these eLOG are filtered and analyzed to obtain some useful information to be used in the next steps.

Once all the statistics is collected, the FMECA procedure is performed on the RPC gas systems, to identify all the possible critical failure modes of their components and to take actions in response.

Then, looking at the result of the FMECA, new possible maintenance actions will be defined. Moreover, an additional tool, that can be used in support of the maintenance activities, can be the initialization of a Computerized Maintenance Management System (CMMS). In the case of CERN, HxGN EAM is the one used, so for the gas system is a good opportunity to exploit its advantages.

Later in this chapter, some brief introduction to RCM ideas will be introduced, in addition to a description of all the step required for the FMECA implementation.

4.2 Reliability Centered Maintenance

The Reliability Centered Maintenance (RCM) is a structured and systematic approach, that has its final goal into enhancing the reliability and availability of a complex system and minimizing the downtime period. Since gas systems must ensure a continuous operability throughout the year, without interruption, to allow data taking for experiments, this method could be a powerful tool to reach this objective.

RCM has its basis into answering the following 7 questions, when performing the analysis onto an industrial system [12]:

1. What are the functions and the associated performance standards of the under-investigation system in that operational context?

2. In which way does it fail to fulfill its functions?

3. What are the causes which cause that failure?

4. What happens when each failure occurs?

5. In what ways does each failure matter?

6. What can be done to predict or prevent each failure?

7. What should be done if a suitable proactive task cannot be found?

At its core, the Reliability Centered Maintenance is focused on optimizing the maintenance efforts, in order to achieve the maximum level of assets reliability. In particular, its target is to prioritize the maintenance activities on the most critical components, identifying the potential failure modes and their effects on the system, to reduce the probability of unexpected failure, that could cause a stop in operability and a consequent production or, in other cases, economic damages.

However, implementing the RCM methodology in a complex system is not an easy task. In fact, it requires a very deep knowledge of the installation under investigation and a high level documented history of failures and maintenance activities, or work order released to restore the equipment.

Moreover, the Reliability Centered Maintenance is an important method that should be used to define the proper maintenance strategies: the RCM method prioritize the critical failures and events, but it is also important to set up maintenance activities for less critical components.

4.2.1 Definition of the maintenance strategies

As described before, the RCM is a great tool in helping the maintenance operation of complex systems but it needs to be properly implemented. In fact it is necessary to select the correct maintenance strategy for the equipment, considering their pros and cons, in order to have a complete view on all the possibilities and to not waste maintenance management efforts.

Some of them, that can be interesting to consider are:

- Preventive maintenance (PM): this strategy is made of tasks that are scheduled to prevent the failures of component before they occur. It is based on recurring actions such as routine inspections to keep track of the condition of the assets and to restore the one that show failure symptoms.

- Predictive maintenance (PdM): it is a proactive strategy which aim is to prevent failures by using data analysis, formulas and sensor monitoring to predict when a component is going to break and to intervene before if happens.

- Condition based maintenance (CBM): it is another proactive maintenance strategy which is based on the continuous monitoring of component process parameters, such as temperature, pressure, etc, by using dedicated real-time sensor. Once one parameter exceeds an unacceptable level, a work order to start maintenance is dispatched. In this case, maintenance is performed only when needed.

- Corrective maintenance (CM): as mentioned earlier, this kind of method is a reactive strategy and the maintenance tasks are started only when the asset is failed or broken. This is the easiest strategy in the maintenance field and the one with low organization efforts. Sometime called also run-to-failure, this approach has several drawbacks because it can lead to long period of downtime, and as consequence to a high production or operability loss, and even to unexpected critical failure.

Since the Reliability Centered Maintenance is based on prioritize maintenance task on potential critical failure, according to a deep analysis of failure modes and their effects, an important additional and supportive tool can be the Failure Modes, Effects and Criticality Analysis (FMECA).

4.3 FMECA approach

The *Failure Mode*, *Effects* and *Criticality Analysis* (FMECA) is an important work methodology that was widely used for several years, in large industrial facilities and complex systems. The application of this analysis can be performed both during the design phase of industrial installation and during the operational phase.

The FMECA, which is an extension of the FMEA with the only difference that the Criticality Analysis is not considered, was born during the late 1940s as an application for aerospace and automotive procedure to prevent or limit failures and to find reactive countermeasures to process problems [15]. As the name suggests, FMECA final goal is to identify the most critical components belonging to a particular complex systems, starting from their already occurred or potential failure modes. This is helpful to define some dedicated maintenance programs and tasks, in order to enhance the whole system reliability and maximize the operation or production time. This procedure is a very robust and systematic approach that can be a powerful tool to assist the definition of extended maintenance strategies, considering both scheduled preventive work orders for critical equipment or reactive and corrective action for the one that are less essential for the plant.

The terms contained in FMECA are defined as follows [4]:

- *Failure Modes*: as described in the section 4.0.4, a *Failure Mode* is defined as how the failed component shows up its failed status.

- *Effects*: the *Effects* are the consequences that a specific failure mode has locally (in the close proximity of the faulty equipment), on the sub-system (in the case of gas system, on the reference module) and globally on the whole full system. In particular, for the evaluation it is necessary to consider the operational phase (normal run, stand-by, start, shut-down). For the specific application the normal run is considered, at the exception of the regeneration phase of column B in purifier.

- *Criticality Analysis*: this analysis consists in assigning to each failure mode, that was identified, a risk index for the frequency of the failure and the severity of the consequences of the effects. The procedure for the definition of these indexes will be explained later in this chapter. Moreover, for each failure modes, all the preventive or mitigative measures are considered, together with the failure detectability and improvement actions after the analysis.

The Failure Modes, Effects and Criticality Analysis is made of many different phases which outcomes is a qualitative estimation of the reliability and risk associated to the industrial installation under consideration.

4.3.1 Data documentation

Before starting the FMECA implementation, it is necessary to collect all the available data on past failures and maintenance activity history. This is fundamental for the beginning of the analysis, in order to gather all the relevant information for the achievement of the study. In Chapter 5, will be explained how this step was performed on the RPC gas systems, with all the issues that have risen in the process.

Moreover, in this phase, a very deep knowledge of the systems and experience over the years in their management is required, to better describe and understand what is written in the documentation. Some supportive items are the Pipe and Instrumentation Diagram (P&iD) and the item lists. In addition, it is necessary to examine all the past maintenance activities, their management, the time spent for repairing the failures and how many spare parts were used to restore failed equipment. These information are useful to estimate the detection time for identifying the failure, the technical and logistic delays to be ready for the interventions and the active time spent for the tasks.

4.3.2 First step: system decomposition

In order to properly conduct the analysis, the first step is to define the analysis depth level. In particular, it is fundamental to decide at which layer the system decomposition into elementary components should stop.

In particular, as will be explained in chapter 6, in the case of the gas systems the decomposition will be the following:

- First level: RPC gas system
- Second level: gas system module
- Third level: module rack
- Fourth level: rack component or *Lowest Replaceable Unit*

This is done, to better having a complete and clear picture of a failure and the first necessary factor to successfully implement effective and targeted countermeasures. Moreover, it is essential for the right estimation and evaluation of the failure effects. In this case, the rack components, shown in the P&IDs, are considered as the LRU, because in case of sub-part failures, the item that will be replaced is the equipment itself.

4.3.3 Second step: operation phase definition

The second step of the FMECA is to characterize the system *operational phase*. In this way, components failure modes are easily defined, since they depend on the operative configurations: for example a backup pump, which is standby during normal operations, will have as failure mode "fail to start on demand", while a working one can stop due to a failure. In particular, for the systems under investigation, the operational phase is the normal running operation, since they work 24/7 without stop. The only exception are the purifier modules, because one between purifier 1 and 3 is in standby.

4.3.4 Third step: failure modes and causes identification

Once each components is listed in the FMECA worksheet and the operative condition are defined, the next step is to identify the failure modes, which is the focus of the RCM and FMECA procedure to determine the criticality and establish the proper maintenance decisions.

Since the failure modes are defined as the manner in which an item show up its failed state, one possible way to determine them, is simply to negate the functionality described in the operation phase. For example, if in the operation phase a valve should open, a possible failure mode can be "stuck closed". Another possibility is to look back through the history of that component under investigation, to find if some failure modes were observed on it or to similar equipment which has similar role in the industrial plant.

Then, for each failure mode the failure causes should be determined: in this way, once the FMECA was completed, it is possible to intervene directly on the critical component, knowing the root causes that have generated the failure.

4.3.5 Fourth step: failure effects classification

After having identified all the possible failure modes and failure causes, the successive step is to list their possible effects. In particular, as explained before, these effects can be subdivided into different categories, depending on the type of consequences the are considered. In fact, according to the performed analysis, they can be distinguished between system productivity, environment, people safety or CERN reputation. In the current analysis, just the productivity ones are considered. Moreover, they can also be divided into:

- Local effects: these effects are the one that are observed at the component level or its surrounding equipment.
- Module effects: in the case of these gas systems, the second level of analysis are the modules, since the complex systems are divided into them. In this case, a particular failure of one important component can cause the stop of one of them.
- System effects: finally, at the general level this effects can have consequences on the whole system, causing for example the full stop and consequently stopping of taking data for the experiments.

4.3.6 Fifth step: criticality analysis study

The criticality analysis is the final important step, which classify the failure modes of the equipment according to the assignment of 2 indexes and evaluating the qualitative risk associated to them. These indexes are defined before the evaluation into dedicated tables, properly declared for the purpose of the analysis on that specific system. The indexes are the following:

- Frequency index: this index should provide an indication on how frequent can a failure mode be. This can be evaluated considering the MTTF of the component or the past recorded history.

- Severity index: this index should evaluate the possible consequence damage for the failure effects. In this case, the severity can have different definition according the distinction between effects on productivity, asset integrity, people safety and environment.

- Risk index: this index is the combination of the previous two and it is important for the risk matrix application.

Here below, some example of index definition will be shown (the following pictures are general description and the one use for the case study will be described in chapter 6):

FREQUENCY	
INDEX	DESCRIPTION
1	The event is not expected in system life
2	The event could happen no more than one time in system life
3	The event is expected few times (no more than 1/5y)
4	The event is expected several times (more than 1/5y)

Figure 4.2: Example of frequency indexes [13]

SEVERITY (Production)	
INDEX	DESCRIPTION
1	No effects on prodcuction
2	Slightly impact in productivity - 30% daily loss
3	Significant impact - between 30% and 70% daily loss
4	Above 70% daily loss or full stop

Figure 4.3: Example of production severity indexes [13]

SEVERITY (Safety and health)	
INDEX	DESCRITPION
1	No people affected
2	Minor injury that will be cure in less than 1 week
3	Serious injury that will be cure in 2 months
4	Permanent injury or death

Figure 4.4: Example of safety and health severity indexes [13]

SEVERITY (Environment)	
INDEX	DESCRIPTION
1	No impact on environment
2	Negligible emission or contamination
3	Emission or contamination that required restoration
4	Emission or contamination that generate second pollutants

Figure 4.5: Example of environment severity indexes [13]

In the criticality analysis, it is also important to consider the detectability of the failure. In fact, this parameter indicates the capability of find the failed component before the negative effects have an impact on the systems. Moreover, the detectability is useful to assess the prioritization of specific failure modes: the lower is this parameters, the higher is the criticality of the asset. In addition, in the analysis it is also necessary to consider the countermeasures taken to reduce frequency and severity of the failure modes (prevention and mitigation).

4.3.7 Sixth step: risk matrix completion

Once each failure mode and its associated frequency and severity rankings were assigned, the next step is to construct the so-called risk matrix. This matrix combines the previously determined indexes to provide an indication of the associated risk. Different risk matrices are built based on the type of severity index category used (such as production, environment, safety, and health). Therefore, the procedure involves assigning for each risk matrix cell the number of observed failure modes with the same indexes, to obtain a comprehensive overview of the analyzed system. This aids in identifying critical components and prioritizing them for maintenance planning.

In figure 4.6 is shown an example of 5x5 risk matrix: the number inside represent the risk index associated to the frequency and severity ones. At the end, the final goal is reached by counting how many failure modes fall in each cell. Then, the colouring of the matrix can help in easily visualizing what measures can be taken and the priority of the interventions. The red cells are the one are not acceptable at all for the correct operation of the gas systems. In fact, if some events fall in these zones, it means that there can be serious problems especially for the detectors and, in that case, it would be very difficult for the performance of the experiments, since it would be necessary to stop the detectors and repair the damages. The orange part of the risk matrix indicates those events that are critical for the systems and that would strongly affect the performances. These events need some dedicated interventions, such as setting up preventive maintenance actions or improve the design, in order to respectively reduce the frequency of occurrence and mitigate the damages. The yellow one are those events that are not as critical as the other ones and can be dealt with less urgency. The green one are the acceptable events and they do not need particular actions but it is important to keep them correctly monitored.

RISK MATRIX		FREQUENCY				
		1	2	3	4	5
SEVERITY	1	1	2	3	4	5
	2	2	4	6	8	10
	3	3	6	9	12	15
	4	4	8	12	16	20
	5	5	10	15	20	25

Figure 4.6: Example of risk matrix [13]

In figure 4.7 the legend of the colours is shown with a summary of the definition given in the previous paragraph.

(red)	High critical events, measures for prevention and/or mitigation are requested (NON ACCEPTABLE)
(orange)	Critical events, dedicated interventions are required (ALARP)
(yellow)	Less critical events, few actions are needed (ALARP)
(green)	Non critical events (ACCEPTABLE)

Figure 4.7: Example of risk matrix legend [13]

Moreover, to conclude the FMECA workflow, it is possible also to include additional section to the worksheet, such as some recommendations and comments. In figure 4.8, a possible FMECA table is shown.

SYSTEM													
OPERATION PHASE													
COMPONENT	FAIL. MODE	FAIL. CAUSE	CONSEQUENCE			SAFEGUARDS (in place)	RISK INDEXES					RECOMM (to be implemented)	NOTES
			LOCAL EFFECT	UNIT / SYSTEM EFFECT	PLANT EFFECT	DETECTION PREVENTION MITIGATION	F	D		RISK			
								S	EN	S	EN		
…….	……		……..	……..	………	……….	…	………	…..			…….	…….

Figure 4.8: Example of FMECA table [13]

Chapter 5

Data extraction and analysis

In this chapter, it will be illustrated how the historical data, useful for the FMECA evaluation, are extracted and analyzed. For this purpose, the only source of documentation, that can be used for retrieve some information on past maintenance activities and component failures, are the eLOGs. These eLOGs are provided by the technicians or the operators who performed some interventions on the systems. The main problem, in studying these eLOGs, is that the entries are made in the form of free text, without any template to follow. In fact, every inserted eLOG has its own 'writing style', depending on the person who did and, it can happen sometimes, that some relevant information are missing, such as maintenance or intervention duration, or the actual systems downtime due to repairs. In the pictures below, an example of eLOGs interface and entries is shown:

ID	Date	Author	Experiment	Detector	Gas System Module	Start time of Intervention	Actual System Down Time (Hours)	Type Of Intervention	Type of Operation	Status	Assigned to	Title	Text
5684	07/03/2024, 17:28	[redacted]	CMS	RPC	Mixer	07/03/2024, 00:00	0	Operation	Mechanical | Software	Done		Injection 134a recuperated	Problem found on the new injection line, software open the wrong electrovalves. Problem solved
5683	07/03/2024, 08:40	[redacted]	CMS	CSC	Mixer | Auxiliary	-	0	OTHER(specify)		Problem	[redacted]	SWPC after mixer gain drop after 50/50 injection	In attachment there is the behavior of the gain for the after mixer SWPC. It is possible to see a decrease
5682	06/03/2024, 17:35	[redacted]	CMS	Weekly Summary	Other(Specify in comments)	21/02/2024, 10:28	0	OTHER(specify)	Other (specify)	Done		Weekly summary W10-11	Done: GEM: DT:
5681	06/03/2024, 17:32	[redacted]	CMS	DT	Analysis	06/03/2024, 00:00	0	Operation	Mechanical | Software	Done		Calibration	All chain calibrated at 100ppm calibration done in manual mode: chain one doesn't switch in
5680	06/03/2024, 17:31	[redacted]	CMS	Analysis	Analysis	06/03/2024, 00:00	0	Operation	Mechanical | Software	In Progress		GC calibration	Start calibration GC AR 100ppm
5679	06/03/2024, 17:23	[redacted]	LHCb	MWP	Purifier	06/03/2024, 15:20	1	Preventive Maintenance	Mechanical	Done		MWPC Purifier bascule colonne B -> A	MWPC Purifier bascule colonne B -> A Suite au probleme du 27.02.24 ou la colonne A est passée en alarme
5678	06/03/2024, 10:19	[redacted]	CMS	CSC	Mixer	06/03/2024, 15:23	0	Operation		Done		100% CF4 recuperated (5% in gas mixture)	Injection of CF4 recuperated restarted. 100% recuperated with 5% of CF4 in the gas mixture.

Figure 5.1: eLOG interface

Message ID: **5684**	Entry time: **07/03/2024, 17:28**
Author:	[redacted]
Experiment:	CMS
Detector:	RPC
Gas System Module:	Mixer
Start time of Intervention:	07/03/2024, 00:00
Actual System Down Time (Hours):	0
Type Of Intervention:	Operation
Type of Operation:	Mechanical | Software
Status:	Done
Assigned to:	
Title:	Injection 134a recuperated

Problem found on the new injection line, software open the wrong electrovalves.

Problem solved

Mixer is in RUN with the fourth line: set at 12% of total flow (300l/h)

36 l/h of 134a recuperated.

Analysis GC on going.

Figure 5.2: eLOG entry

Another aspect, which increased the difficulties in the data extraction process, was that the eLOGs were simply grouped by experiment, detector and module, and there were not a priori indications on the content of a specific entry, just few written information in the title. For these circumstances, the data extrapolation activity was quite time-consuming due to the really high number of entries that needs to be filtered to avoid useless documentation that will not add anything to the data analysis and statistics on the systems.

These eLOG recording started in 2016: one of the main issues is that gas systems were in operation since 2007/2008 and therefore there is a big hole of missing documentation from 2007 to 2016. Since eLOG are continuously added, due to the 24/7 working of the gas systems, the data analysis is stopped at January 2024: in this way the analysed eLOGs covered a time span of about 8 years and more than 700 entries.

For the above mentioned reasons, the first necessary action was to perform a entries cleaning and data filtering. In the table below, (table 5.1) the main chosen categories, in which the eLOGs are subdivided, are listed.

Table 5.1: eLOG categories

CATEGORIES
FLOWCELL
SENSOR
MASS FLOW CONTROLLER
LEAK
REGULATION VALVE
FILTER
ROTAMETER
PLC/ELMB
PID
PUMP
PNEUMATIC VALVE
LEAK TEST
PRESSURE OSCILLATION
REGULATION
MANIFOLD/CLEANING
FLOW OSCILLATION
FLOW TEST
NON RETURN VALVE
BUBBLER
CONCENTRATION FLUCTUATION
PRESSURE REGULATOR
COLUMN
HVAC
PRESSURE TEST
ANALYSER
ELECTROVALVE
PROFIBUS
HUMIDITY
WINCCOA
FESTO MODULE
CONDENSER
HEAT EXCHANGER
TANK

Of course, the categories shown in the table are all the one considered. However, since another classification is done, distinguishing the different modules of RPCs, not all of the categories will be listed for every subsystem, but just the one of interest.

These categories are chosen considering both components that constitute the modules and type of operations or generic problems that could affects the latter.

In the next picture (fig. 5.3), an example of the worksheet used for classifying the eLOGs for the exhaust module is represented.

EXHAUST MODULE					
TYPE	**EXPERIMENT**	**DETECTOR**	**DATE**	**COMMENT**	**LINK**
FILTER	CMS	RPC	08/01/24	Filter changed	5478
	CMS	RPC	07/12/22	Filter changed	4650
	CMS	RPC	16/03/22	Filter checked	3997
FESTO MODULE	CMS	RPC	08/01/24	Festo module on Zimmerli does not work - replaced	5478
OPERATION/MAINTENANCE	CMS	RPC	09/10/23	Exhaust flow from XMFC5002 redirected to R134a recuperation	5279
	CMS	RPC	03/02/22	Pressure regulation adjustments (eLOG 3120 3105)	3121
	CMS	RPC	16/04/20	Pressure regulation recipes (eLOG 2388 2368)	2402
FLOWMETER	CMS	RPC	17/03/23	FIT5010 signal okay	4950
	CMS	RPC	01/03/23	Khrone reading 0 since power cut	4884
	CMS	RPC	10/05/22	Khrone reading fixed	4103
	CMS	RPC	16/07/20	Khrone FIT5010 formula to correct flow implemented	2656
	ATLAS	RPC	09/01/19	Problem with FIT5010 readout - reset and problem was solved	1645
SENSOR	CMS	RPC	21/12/22	PT5011 leak - oring replaced to repair (found leak on PT5005 eLOG 4683)	4694
	CMS	RPC	16/12/22	PT5005 small leak	4683
	CMS	RPC	15/12/22	PT5011 replaced because out of service	4678
	CMS	RPC	09/12/22	PT5005 electric problem	4660
	CMS	RPC	08/12/22	Filter DPT installed	4652
PROBLEMS	ATLAS	RPC	14/01/22	Buffer pressure drop - XMFC5002 start to open	3808
	CMS	RPC	13/01/22	Buffer pressure drop (almost completely empty)	3799
	CMS	RPC	17/02/22	PT5011 and PT5005 difference reading increased (PT5005 low) - problem disappear if pur 2 bypassed	3153
	CMS	RPC	17/07/20	Pressure drop on PT5005 increase if both purifier switch column	2664
	ATLAS	RPC	06/02/20	Profibus problem - 8 connector changed (mixer exhaust purifier humidifier)	2238
	ATLAS	RPC	24/09/18	Sudden increase in exhaust flow - only correlation increase in cavern pressure	1497
MASS FLOW CONTROLLER	CMS	RPC	01/11/21	MFC removed for calibration	3650
SAFETY VALVE	ATLAS	RPC	06/02/18	Safety valve on HP buffer checked - added 3 way valve with new safety valve	1072

Figure 5.3: Exhaust module eLOG worksheet

As it is possible to see in figure 5.3, the worksheet is organized in this way:

- Type: which refers to the categories explained before.
- Experiment: in this case can be ATLAS or CMS.
- Detector: for this study, the only gas system considered is that one that provide the mixture to the RPC detector.
- Date: this column is useful to estimate the frequency of intervention or the failures and replacements of some components (frequency that will used as indicator for the FMECA).
- Comments: this is used as short summary of the eLOG content

- Link: direct link to the eLOG entry.

Therefore, this selection of eLOGs is performed on every module, to get an overview of the main recurring problems of the system and to characterize their consequences on the working performances. For each category, which is found in that specific module, the total number of events extracted from eLOGs are counted and distinguished between ATLAS and CMS, to also understand more information if these interventions were properly recorded by technicians. Moreover, it is also possible that the number of events are greater than the entries studied, because, in some of them, it is possible to find more actions. This analysis can help in visualizing how many problems a particular type of component can have and their frequency of occurrence. Of course, this also depends on the number of items for a specific module: for example, since distribution is made of many racks, it is likely that the majority of faulty equipment will be there.

5.1 Mixer module

The first module that is analyzed is the mixer module. In particular, about 150 eLOGs are considered for the statistics, but not all of them were useful or contained relevant documentation on maintenance interventions or faulty components. In the table 5.2, the most important events are listed.

CATEGORY	**Number of events**		
	CMS	**ATLAS**	**TOTAL**
MFC CALIBRATION	21	4	25
MFC PROBLEM	1	0	1
PROFIBUS	1	1	2
ELECTROVALVE	3	0	3
LEAK TEST	2	0	2
PRESSURE OSCILLATION	2	1	3
WINCCOA	2	0	2
PID	1	0	1
CONCENTRATION FLUCTUATION	4	1	5
SENSOR	3	0	3
PRESSURE REGULATOR	1	2	3
FLOW OSCILLATION	3	2	5
ROTAMETER	1	0	1
SUMMARY	**45**	**11**	**56**

Table 5.2: Mixer module events

As expected, the mass flow controller (MFC) is the most recurring component. In the mixer there are 8 mass flow controllers which are split into 4 lines, one for each gas that fill the mixture: for each gas line 2 MFC are used, one for the high flow and one for the low flow. As it is possible to see in the table 5.2, there is a noticeable difference between the CMS and ATLAS mass flow calibrations. This is due to the fact that in CMS RPC gas systems there is the Gas Chromatograph (GC) for the mixture composition analysis, while it is not present in the ATLAS one. This means, that if something is wrong in the mixture, the GC can notice it and a proper work order for mass flow controller calibration is delivered. In addition, another consideration can be done: since both systems are designed in a similar way and the working conditions are pretty much the same, it is unlikely that ATLAS mixer always provide the correct mixture to the detector. In other words, since there is not present the same gas analysis, it is possible that the ATLAS mass flow controllers need calibrations more often than what is done until now. Moreover, this difference can be notice even in the other categories, both related to components and to normal or deviant operations. A possible explanation for this could be that eLOGs for ATLAS and CMS are produced by different technicians, and perhaps not all operations in ATLAS were recorded. In fact, since electrovalve or sensor category is related to replacement due to damages or failures, it is unlikely that in 8 years ATLAS RPC gas system had not any problems for those equipment. The PID category is related to the tuning operation for having a better control on the module. This one is a very important group because it is an indicator if something in the module needed some attention due to lack of proper regulation or some drifts from particular configurations.

In the next pictures (fig. 5.4 and fig. 5.5), a summary for the mixer module is shown.

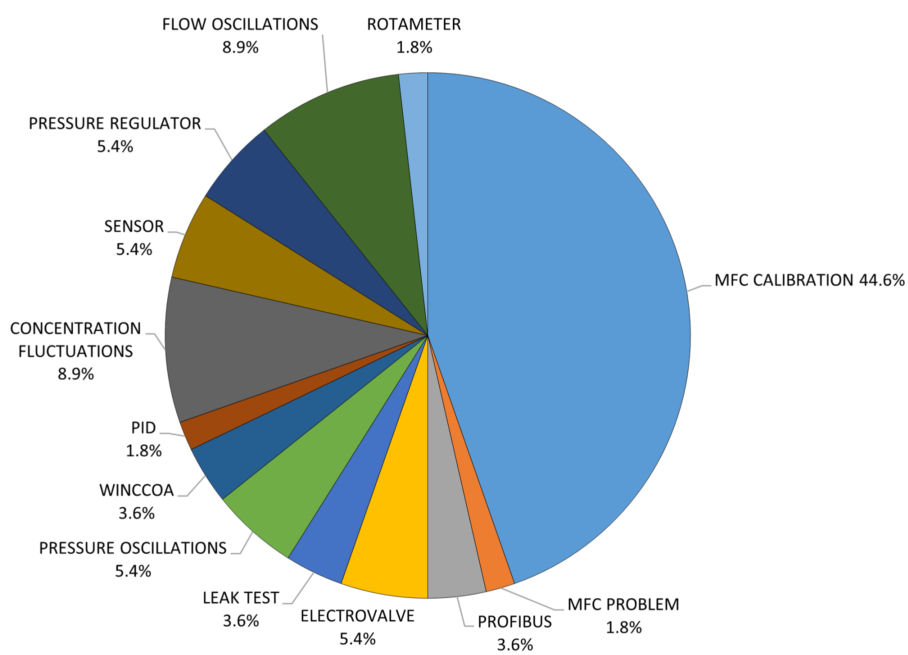


Figure 5.4: Mixer module events pie chart

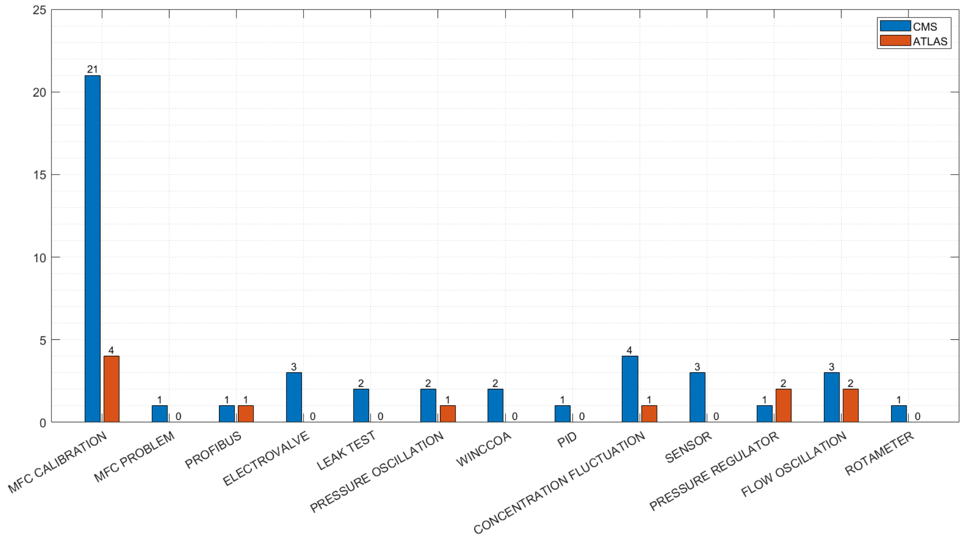


Figure 5.5: Mixer module events histogram plot

5.2 Pump module

The pump module is one of the most important module inside the gas systems, because if for any reasons it stops working, the whole systems will go in full stop condition. For the above mentioned situation, it should be kept under rigorous control, especially the pumps. As explained before, this module applies the concept of redundancy of pumps: in fact 2 are always in run, while the third one is standby for CMS (in ATLAS RPC just one is working and the other 2 are in standby) and it is used once one of the two is under maintenance. In particular, these pumps are specifically designed diaphragm pumps which relies on the performances and status of the membrane. Moreover, another component that is important for the correct functioning of the module is the regulation valve: this item helps the pump into keeping a constant pressure in the system, by recirculating part of the flow rate. In table the main eLOGs categories are shown.

CATEGORY	Number of events		
	CMS	**ATLAS**	**TOTAL**
PUMP PROBLEM	7	0	7
PUMP MEMBRANE REPLACEMENT	24	10	34
FILTER	3	2	5
NON RETURN VALVE	0	1	1
PID	1	0	1
REGULATION VALVE	2	1	3
SENSOR	1	0	1
SUMMARY	**38**	**14**	**52**

Table 5.3: Pump module events

Even in this case there is a great mismatch between CMS ans ATLAS entries. The most relevant one is the number of pump membrane replacements. For sure, the responsible technician of ATLAS gas systems performed the maintenance on the pumps, but he did not update the eLOG information. That is a big problem, because since these important information are omitted in the reports, probably there is other relevant documentation on failures and general problems missing in the database. Moreover, it is very unlikely that the problems affecting pumps, such as membranes rupture causing pump stop, or failure during the switch of standby pump (which stopped after few hours), happened only in the CMS RPC. However, this data can be very useful in improving the maintenance management, asking the technicians for more clearness and completeness during the eLOGs upload. For what concerns the filters, the events recorded are related to the periodical replacement of the cartridges, which trap impurities or dust that can form during the operations until they saturate, from the damaged pump membranes. As mentioned before, the regulation valve is a key item in the module, since it helps the pumps in keeping the correct working pressure: the events that were related to it regarded some leakages but the most interesting one, which can be dangerous is the wrong regulation due to a failure in the actuator.

In the figure 5.6 and figure 5.7, a summary of the entries for pump module is shown.

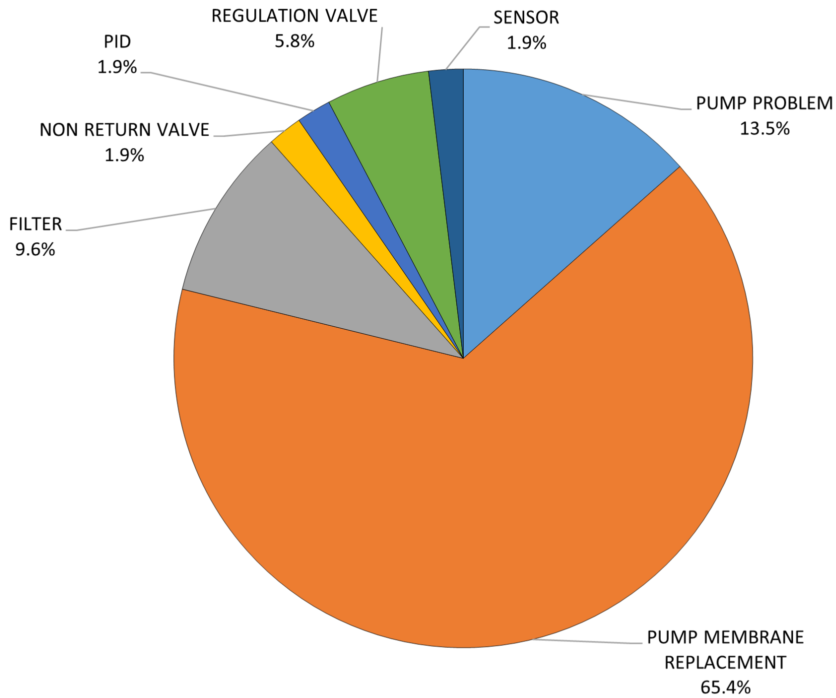


Figure 5.6: Pump module events pie chart

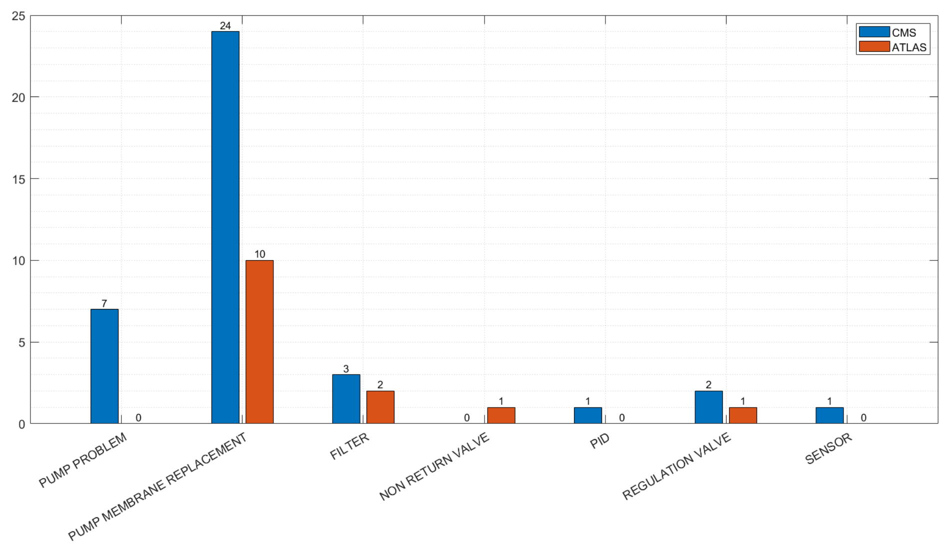


Figure 5.7: Pump module events histogram plot

5.3 Humidifier module

Analyzing the humidifier module eLOGs, it is possible to notice that they are quite balanced in number between ATLAS and CMS and there is not a particular component that has the majority of the problems. This module is not as crucial as the pump one for instance and the whole systems can run without humidifier for a while. In the table the main categories of the entries are listed.

CATEGORY	**Number of events**		
	CMS	**ATLAS**	**TOTAL**
MASS FLOW CONTROLLER	2	2	4
PID	1	2	3
PUMP	1	3	4
SENSOR	1	1	2
CONDENSER	1	0	1
ANALYSER	3	0	3
PRESSURE REGULATOR	1	0	1
TANK	1	0	1
HEAT EXCHANGER	1	0	1
HUMIDITY	1	1	2
SUMMARY	**13**	**9**	**22**

Table 5.4: Humidifier module events

For this module, the most relevant eLOGs are related to the mass flow controller: in particular, these 4 entries of MFC concerns failures such as the stuck status which prevent the required opening for the flow. For what concerns the pump, this one is not a gas pump but it is related to the water necessary for the humidification of the mixture. In this case, the main issues regarded the stopping of operation due to electrical problems or too many working hours. The eLOGs for sensors are linked to small leaks in the humidifier that required the replacement of the faulty items. The others, instead, are related to normal operations of tuning and control the module. Here below, the figures show a summary.

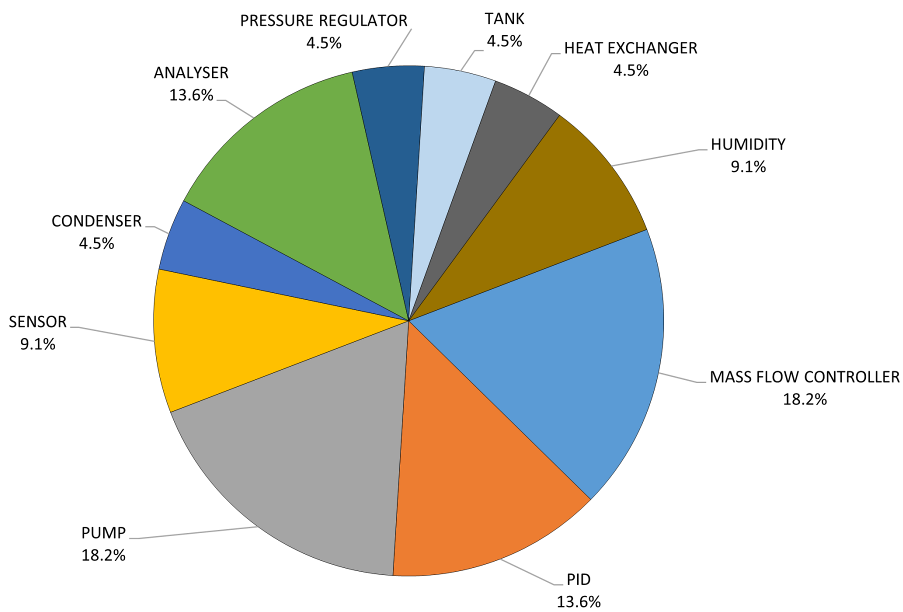


Figure 5.8: Humidifier module events pie chart

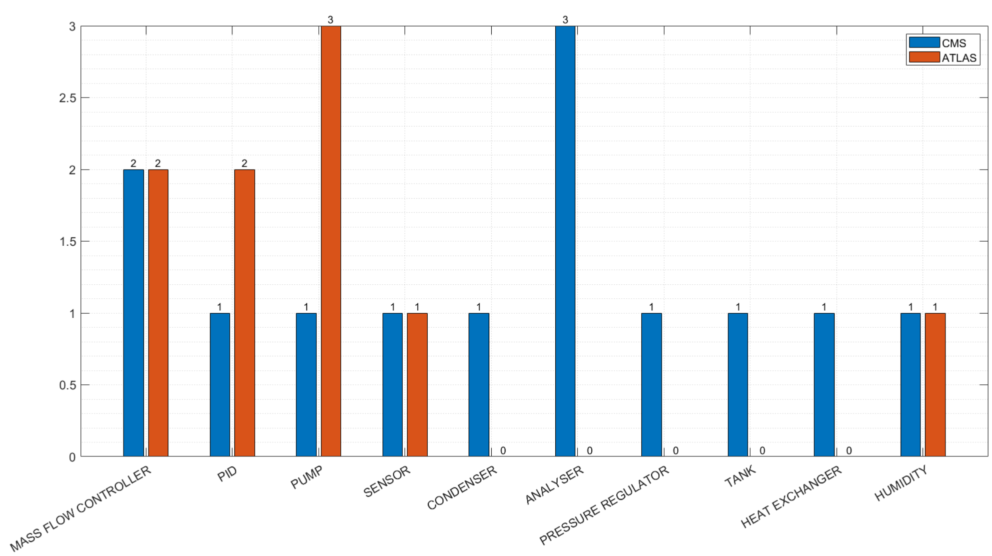


Figure 5.9: Humidifier module events histogram plot

5.4 Purifier module

The purifier module is not a single module, but it is made of 3 different sub-systems: purifier 1, purifier 2 and purifier 3. Purifier 1 and purifier 2 are in series, while the purifier 3 is a redundant module for purifier 1. Purifier 1 and 3 are used for oxygen, while the number 2 for water. Each of them has 2 purification columns that works in an asynchronous way: if one column is in run phase, the other is in regeneration (this phase starts when the column is saturated). For these reasons, due to the high number of components, an high numbers of failures or operation adjustments are expected. In the table below, the recorded events are listed.

CATEGORY	**Number of events**		
	CMS	**ATLAS**	**TOTAL**
PID	0	2	2
NON RETURN VALVE	5	0	5
LEAK TEST	7	0	7
PNEUMATIC VALVE	11	3	14
PUMP	5	2	7
FILTER	9	4	13
ROTAMETER	4	2	6
SENSOR	4	3	7
COLUMN	3	1	4
FESTO MODULE	0	1	1
FLOW OSCILLATION	1	0	1
PRESSURE OSCILLATION	4	0	4
SUMMARY	**53**	**18**	**71**

Table 5.5: Purifier module events

In this case, it is possible to notice a huge difference between the CMS and ATLAS events. Since both purifiers have the same characteristics, it is very unlikely that only CMS had all this problems. It is more probable that the responsible technicians for ATLAS did not put enough efforts in the writing of the eLOGs: certainly, if some issue rose in the past, they managed to solve, but they did not update the performed tasks. Having these missing information is negative for the correct future maintenance management and definition of new strategies, due to lack of clearness of the past history maintenance activities and interventions needed. However, since CMS RPC purifier history was update more, it can be used as the only valuable source to understand the frequency and severity of the failures.

The problems with pneumatic valves are the most frequent issues: in particular, the recorded events are related to replacements due to external leakage and damages after many operation hours. The sensors had problems with wrong pressure readings and needed some calibrations. Rotameters and non return valves were replaced due to observed mechanical damages. Filter cartridges, as in the pump module, were replaced after they become full of impurities. Interesting equipment are the pumps: in this case, they did not have preventive maintenance tasks and it happened that technicians found some external leakage from the pumps caused by the broken membranes. The other entries are related to normal operation and to tune or better control the purifiers. However, also the leak test number is interesting: since this is a standard maintenance procedure, it is very unlikely that there were not any performed leak tests in the ATLAS RPC system.

In the next pictures, a more graphical summary of the purifier module events is shown.

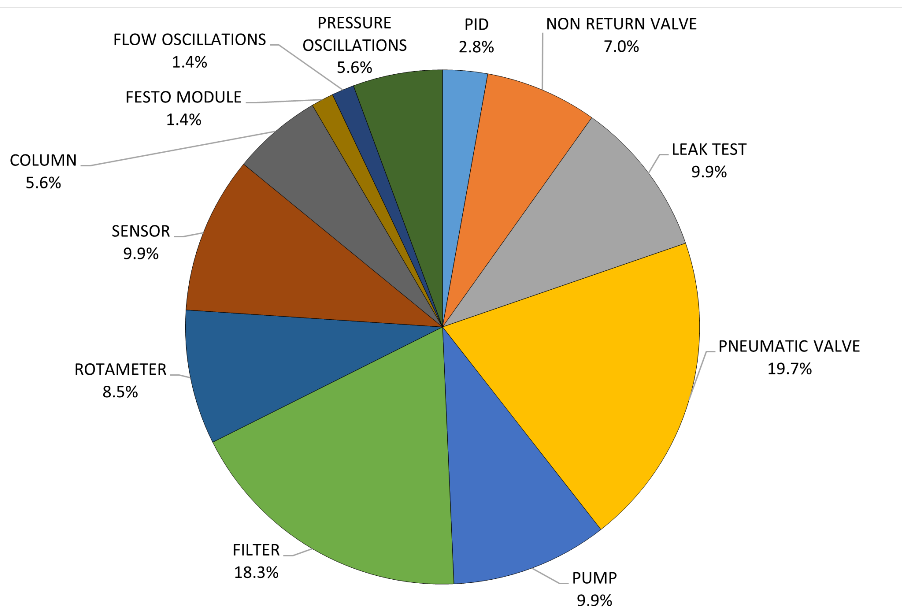


Figure 5.10: Purifier module events pie chart

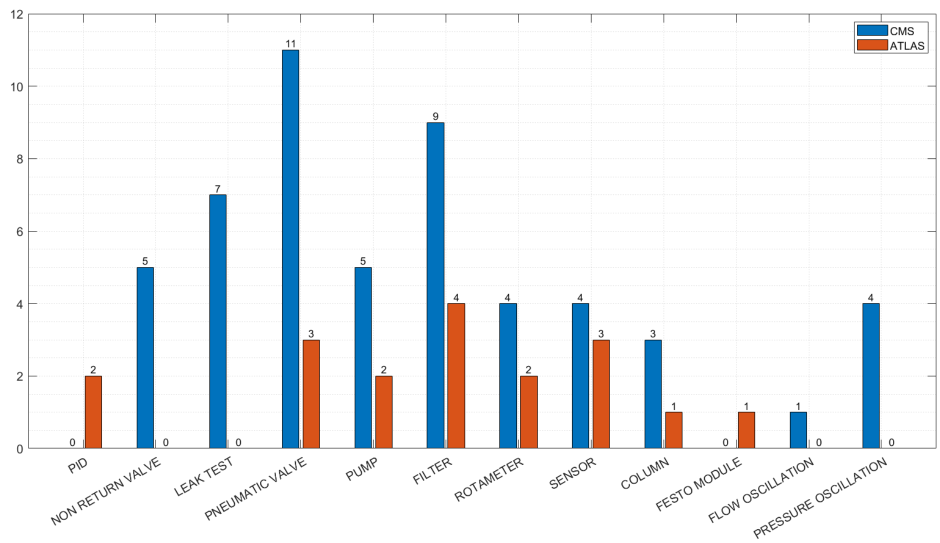


Figure 5.11: Purifier module events histogram plot

5.5 Distribution module

The distribution module is the biggest module in a gas systems: usually it is composed of many different racks because they are the responsible for providing the gas mixture to all the requesting detector chambers. In this case, there is significant difference between ATLAS and CMS designs. ATLAS RPC distribution is organized in 9 different racks, while for CMS the distribution module organized in 28 racks, divided into 4 regulation group and with a pre-distribution module. For these reasons, it is expected that there will be a huge difference between the eLOGs entries for this module, even for the presence of the flowcells which numbers ranges between 32 to 64 per rack.

CATEGORY	**Number of events**		
	CMS	**ATLAS**	**TOTAL**
FLOWCELLS	170	21	191
SENSOR	25	5	30
PRESSURE TEST	0	4	4
FLOW TEST	7	0	7
LEAK TEST	3	0	3
LEAK	18	12	30
FILTER	2	0	2
ROTAMETER	11	0	11
REGULATION VALVE	19	1	20
BUBBLER	5	0	5
PNEUMATIC VALVE	1	0	1
MANIFOLD/CLEANING	8	0	8
HVAC	2	2	4
REGULATION	1	6	7
PRESSURE OSCILLATIONS	1	0	1
PID	7	5	12
PLC/ELMB	20	0	20
PRESSURE REGULATOR	0	1	1
SUMMARY	**300**	**57**	**357**

Table 5.6: Distribution module events

As expected, the category of eLOGs involving the flowcells is the one with the highest number of events. This is due to the very huge amount of them in the distribution module and, since they measure the flows in the different detector chambers, they requested particular monitoring and maintenance operations. However, in this case too there is a significant difference between ATLAS and CMS, even if the events are weighted on the total number of racks. For what concerns the sensors, the failures or operations, such calibration, are quite comparable, considering the numbers of racks. The leak category refers to the observed leak in proximity of the detector chambers: in particular, the RPCs detectors experienced many leaks during normal operations and that is the reason for the high number of leaks. For what concerns other equipment like rotameters, regulation valves and especially PLCs, the difference between ATLAS and CMS is very surprising, considering that are important components for the distribution module. In particular the PLCs are important for distribution, because they are responsible for receiving the input signal from flowcells and usually they are replaced periodically: for this reason, it is unlikely that in ATLAS there were not any interventions for the PLCs.

In the pictures below, a summary for the distribution module is shown.

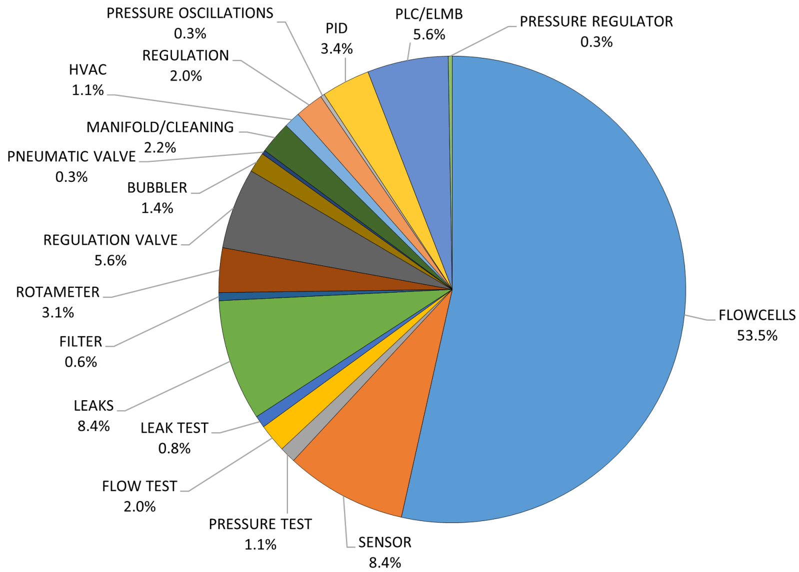


Figure 5.12: Distribution module events pie chart

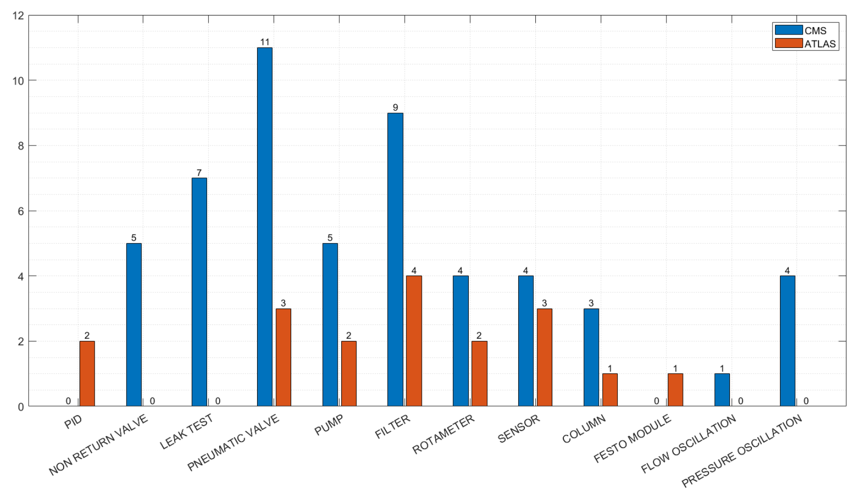


Figure 5.13: Distribution module events histogram plot

5.6 Exhaust module

The exhaust module is the responsible for the correct gas recirculation in the system and it links all the other modules. Since this module is not as complex as other ones, the number of eLOGs is small. In the next table, the main categories are listed.

CATEGORY	**Number of events**		
	CMS	**ATLAS**	**TOTAL**
FILTER	2	0	2
FESTO MODULE	1	0	1
ROTAMETER	3	1	4
SENSOR	4	0	4
PRESSURE OSCILLATIONS	2	1	3
REGULATION	2	0	2
FLOW OSCILLATIONS	0	1	1
MASS FLOW CONTROLLER	1	0	1
PROFIBUS	0	1	1
SUMMARY	**15**	**4**	**19**

Table 5.7: Exhaust module events

Even in this in case, there is a significant difference between the two experiments. The main entries are the related to the sensors and rotameters problems and replacements, which can be helpful for the estimation of the frequency of failure. The other categories are simple regulation, monitoring and inspections during normal operation.

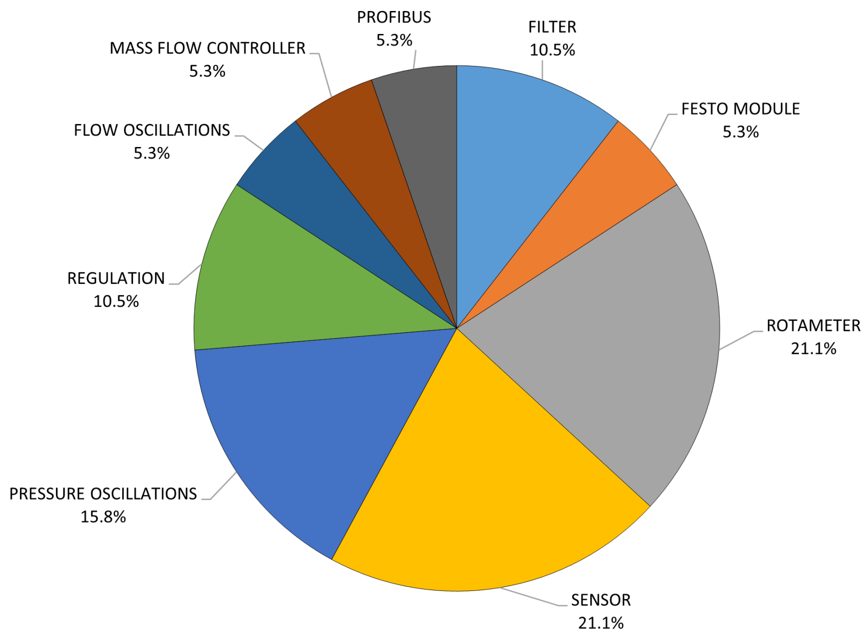


Figure 5.14: Exhaust module events pie chart

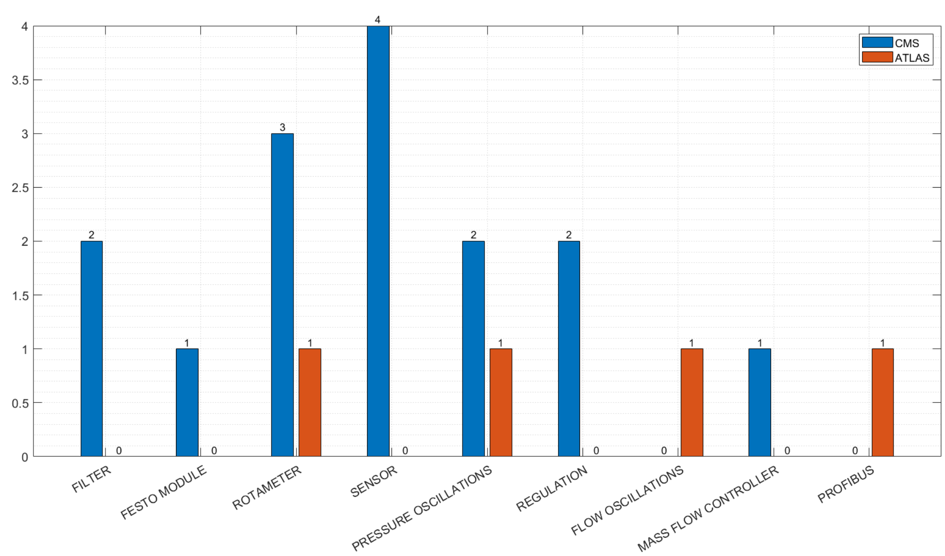


Figure 5.15: Exhaust module events histogram plot

5.7 Summary

As explained before, this analysis was helpful for identifying possible failure modes of components, the frequency of ruptures and all kind of interventions for the correct functioning of the system. Moreover, this information can be a great indicator for the FMECA analysis, assessing all the critical points of failures and their consequences. However, as it is possible to notice, from that eLOGs is difficult to perform a quantitative reliability analysis due to missing information on repair time, mean time to failure and so on. Some qualitative evaluation can be done considering how often a particular component or group has experience some interventions.

Nevertheless it was also interesting to notice that in the past there was a significant difference among the responsible technicians in the upload of these reports between ATLAS and CMS RPCs, even though the systems share important features, apart from the distribution module and racks.

In the next figure and in table 5.8, a summary of all the type of entries and the difference between the experiments are shown.

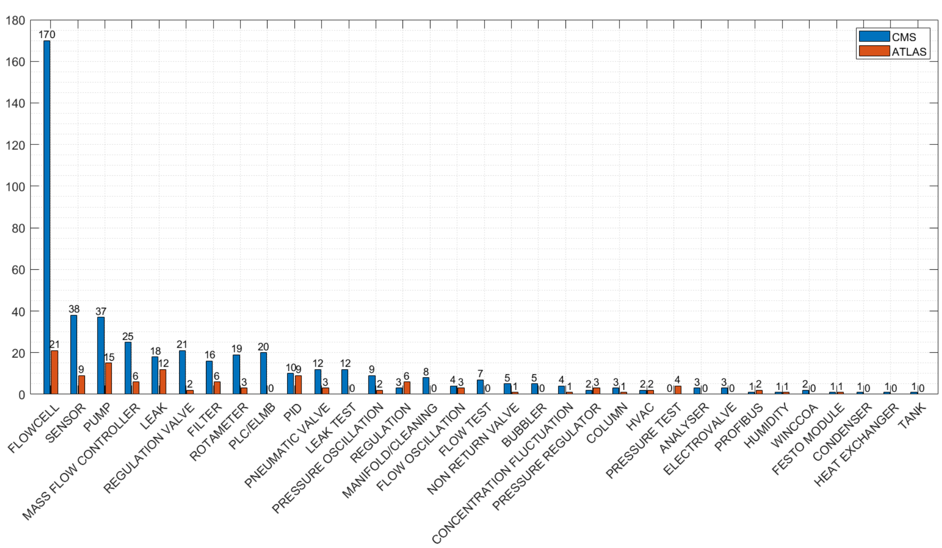


Figure 5.16: Summary of events histogram plot

CATEGORY	Number of events		
	CMS	ATLAS	TOTAL
FLOWCELL	170	21	191
SENSOR	38	9	47
MASS FLOW CONTROLLER	25	6	31
LEAKS	18	12	30
REGULATION VALVE	21	2	23
FILTER	16	6	22
ROTAMETER	19	3	22
PLC/ELMB	20	0	20
PID	10	9	19
PUMP	37	15	52
PNEUMATIC VALVE	12	3	15
LEAK TEST	12	0	12
PRESSURE OSCILLATIONS	9	2	11
REGULATION	3	6	9
MANIFOLD/CLEANING	8	0	8
FLOW OSCILLATIONS	4	3	7
FLOW TEST	7	0	7
NON RETURN VALVE	5	1	6
BUBBLER	5	0	5
CONCENTRATION FLUCTUATIONS	4	1	5
PRESSURE REGULATOR	2	3	5
COLUMN	3	1	4
HVAC	2	2	4
PRESSURE TEST	0	4	4
ANALYSER	3	0	3
ELECTROVALVE	3	0	3
PROFIBUS	1	2	3
HUMIDITY	1	1	2
WINCCOA	2	0	2
FESTO MODULE	1	1	2
CONDENSER	1	0	1
HEAT EXCHANGER	1	0	1
TANK	1	0	1
SUMMARY	**464**	**113**	**577**

Table 5.8: Summary of the events

Chapter 6

Application of the FMECA on the RPC gas systems

As explained before, in chapter 5 the analysis of the past recorded history of the RPC gas systems interventions was very useful to get an overview of the components that have experienced some problems and to obtain a rough estimation of the frequency of occurrence. In addition, to have a deeper understanding of the system and assessing the criticality in an efficient way, failure modes, that were not recorded in the eLOGs but that could be observed in some components, were considered. Moreover, since the LHC gas systems share a general layout, the RPC FMECA analysis can be adapted to the others, by properly identifying the major differences among them.

In chapter 4, the general procedure of the FMECA was described, highlighting the main procedure for the correct implementation the method. To briefly summarize the methodology, the main steps applied to systems are the following:

1. *System decomposition*: the first necessary step is to set the detail level of the analysis. For this purpose the system was divided into the modules and each of them was split at component level using the LRU approach. In particular, the elementary components were selected using the P&IDs of the system. The only exception are the hand regulated valves (HV) because they are only used during the maintenance activities to isolate the line of the components that required some tasks. However, there are few cases, in which they are considered due to their 'more active' role in the process.

2. *Operational phase definition*: as explained in section 4.3.3, in order to identify the failure mode of components it was necessary to define to operational phase of the module. In this case, since the systems and the modules should be always in run,

the only considered phase is the 'Normal operation' configuration. The system purge or short transients during stop and restart are not considered, since they happen few time during the year.

3. *Failure mode and cause identification*: this is the key part of the FMECA. The failure modes identification (and their causes) was used to understand which event can negate the correct function of the system. The input information for this step was the eLOGs analysis and the experience of the technicians who have worked on them for many time.

4. *Failure effects classification*: the aim of this part of the FMECA was to identify the effects and consequences of the potential failures locally, on the process of the modules and in the system. This was important for the evaluation of the severity index.

5. *Criticality analysis study*: this is another important part of the FMECA, because its aim was to rank the failure modes according to the severity of the consequences and frequency of failures, using some properly defined indexes. For this particular application, the severity of the effects are considered just at the *production* level, because the risks associated to safety and environment are limited to specific case, such as release of flammable gases like isobutane. In particular, the safety assessment at CERN is carried out by a different group and not by the gas group which is responsible for the maintenance and operations (M&O) of these systems. In table 6.1 and 6.2 the definition of these indexes are set.

6. *Risk matrix completion*: the final step was using the risk matrices, that are helpful to better visualize the criticality of components and determine the priority in the maintenance tasks and activities (fig. 4.6).

Frequency indexes definition	
Index	**Description**
1	The event is not expected in system lifetime
2	The event could happen one time in system lifetime
3	The event is expected few time in system lifetime (less than 1/5y)
4	The event is expected more than 1/5y but less than 1/y
5	The event is expected to occur more than 1/y

Table 6.1: Frequency indexes definition

Severity (production) indexes definition	
Index	**Description**
1	Negligible effect
2	Module is slightly affected, no stop required
3	Module is stopped for less than 1 hour or performances reduced or system is slightly affected
4	Module is stopped for more than 1 hour or system is affected
5	Gas system is stopped or detector is damaged

Table 6.2: Severity indexes definition

6.1 Pump module FMECA

Before entering into the details of the *Failure Modes*, *Effects* and *Criticality Analysis* of the pump module, it is useful to remind the general layout of this module for the RPC gas system (section 2.3). It is made of 3 pumps in parallel (in the ATLAS one just one is running, while in CMS two are in run mode), which has the role to extract the gas mixture from the detector chambers and to send back to the surface where it can join the flow from the mixer. Since the main goal is to keep almost constant the pressure at the chambers, the regulation valve control the bypass flow by opening or closing depending on the necessity. As explained before, the detail level for the analysis are the LRU that can be found on the P&ID of the pump module (see figure A.1 in appendix A).

6.1.1 FMECA description

In this section, the description of the FMECA table for the pump module was described, highlighting the main components, their failure modes and effects and the criticality indexes that were defined for them (tables 6.1 and 6.2 as references). Moreover, the complete FMECA tables can be seen in the appendix A (figure A.2 and figure A.3).

- **Pump PU-4101 / PU-4201 / PU-4301**
  - *Membrane pressure too high*: the cause of this failure mode is a failure or damage of the pump membrane and the effect is that the pump is immediately stopped after receiving the alarm that the pressure has risen too much. When the pump stops, the module itself is stopped due to missing prevalence of the

pump. As consequence, also the whole system is stopped, since there is not the component that is able to circulate the mixture flow. For this reason, this event is ranked with severity index 5 and the frequency of occurrence is 3.

- *Fail to start on demand*: this failure can be caused by a mechanical or electrical problem which impedes the correct starting of the stand by pump. This can happen when the running pump has overcome the working hours limit for the membrane and to begin the maintenance operation, it is necessary to switch to the other pumps. The consequence is that no pumps are in running, or in case of CMS one pump is not sufficient to guarantee the correct flow and so the module and system need to be stopped. For this reason this event is ranked 5 in severity and 1 for frequency, since it is not expected.
- *Low efficiency*: during normal operations, the membrane status of the pump is decreasing its performances, leading to a reduction of the pump efficiency. For this reason the membrane are periodically replaced. The effects of this efficiency reduction is the decrease of the output flow of the pump which lead to a reaction of the regulation valve which needs to close the bypass loop. Moreover, if the flow is reduced too much, this have effect especially at the distribution side. In this case the severity of this event can be considered 4 while the frequency index is 4.
- *Internal leak*: the membrane rupture can cause also an internal leak of the room air. The air intake is more dangerous for the system, because the mixture composition is altered and does not fulfill the chamber requirements, leading to a performance reduction of the detectors. In this case the severity is 4 and the frequency 2.
- *Stop working*: in the past happened that one pump, after the switch, worked for few hours and then it switched off. The cause of this failure can be both mechanical or electrical, or in one case in other system, the pump water cooling leaked and the pump stopped. As before, in case of pump stop, the module and system is stopped. This is due to the fact, that when the pump switch is performed, some hand valve on the line of the new pump should be manually opened. The severity of this event is 5 while the frequency 2.

- **Non return valve NV-4109 / NV-4209 / NV-4309**
  - *Loss of functionality*: the non return valves used are spring loaded check valves. The loss of functionality can be caused by a mechanical rupture of the

closure disk or by the spring failure inside the valve. If this happens, there can be a backflow to the pump, or if a mechanical rupture happens, there can be a filter clog which collects the damaged parts of the valve. In this case, the module just loose some efficiency into sending the flow and the distribution can be slightly affected: however, this kind of event severity is ranked 2. This loss of functionality was experienced few times and so the frequency index is 3.

- *Stuck closed*: this failure mode can be caused by a mechanical failure and as consequence the flow is blocked and the module and system must stop. This event is unlikely (frequency 1) but with the highest severity 5.

- **Non return valve NV-4019**

  - *Loss of functionality*: differently from the other non return valve, this one is set after the filters, at the pump module output. For this reason, the only effect of this failure is a potential backflow to the module, which can have consequences on the distribution. This failure mode can be more critical if, during restart of operations, the pneumatic valve YV-4040 is failed too and stays closed. Since this case involves two simultaneously failed items and it is very unlikely, the criticality indexes associated to this event are the same as NV-4109.

- **Regulation valve PV-4003**

  - *Blocked*: the regulation valve plays an important role in the pump module, opening the bypass loop to help the pump in keeping the pressure constant. In case of the blockage of this valve, due to a mechanical failure for instance, there is the regulation loss on the recirculation loop which can affect also the pump performances. Moreover, in this state there is also the loss of the failsafe condition. In general, if this event occur, the system would stop and for that its severity rank is 5. However, in the past history of the RPC gas systems, this problem is never found and it is not expected to occur and, therefore, its frequency can be evaluated with index 1.

- **Actuator ZC-4003**

  - *Unstable regulation*: the actuator is the responsible of the correct positioning of the regulation valve (PV-4003). If the internal spring fails, the regulation on the valve becomes unstable, with the latter that can have a wrong opening. Moreover, the pump will have a bad regulation that can affect the distribution module. The severity index is 4 while the frequency of occurrence 2.

- *Stuck*: if the actuator is stuck, due to a mechanical failure, the regulation on the valve, and consequently on the pump, is completely lost and the module and system stop. This event has severity index 5 and frequency 2.

• **Controller PC-4003**

- *Regulation loss*: the controller is component which sends the electrical information to the valve actuator. The regulation loss can be caused by an electrical failure of the controller or feedback problem. This event cause the system stop, due to missing regulation on the valve PV-4003. Therefore the severity is 5, while the frequency of occurrence is considered low, 2.

• **Pressure regulator PCV-4018**

- *Spurious opening*: this pressure regulator is mounted on the bypass loop and helps the regulation valve into the regulation of the module. Therefore, this failure, due to a mechanical problem for instance, can have important effect on the pump regulation and so the distribution itself can be affected. The severity can be considered 4, while the frequency 2.

- *Internal leak*: since this pressure regulator receive the pneumatic signal, in case of rupture of the membrane there can be an internal leak. This would compromise the mixture to the detector. This event is not expected (frequency 1) even if the severity would be 5.

- *External leak*: as explained, due to its position in the recirculation loop, a gas loss, due to seal problem, can affect the regulation and the distribution module. The frequency is considered 2, while the severity 4.

• **Pneumatic valve YV-4040**

- *Stuck closed*: if this valve is stuck closed after a mechanical problem, the module output line will be sealed and system will automatically stop. This is way its severity is ranked 5, while the probability of happening is 2.

• **Solenoid valve YV-4002**

- *Stuck closed*: this valve is on the bypass line. In case of electrical failure and closure of this valve, the pump will not work properly due to the sealing of the recirculation loop. Therefore, the severity is 5 while the event is not expected (frequency 1).

- **Pressure sensor PT-4004**

  - *Drift*: this sensor is very important for the pump regulation. It is at the input of the module and measure the distribution output pressure. This measurement is used by the pump module for the regulation of the flow to keep the pressure as constant as possible. Therefore, a drift of this sensor, would lead to a wrong pump regulation which can affect the distribution. The severity is 4 and frequency is 2.

  - *Broken electronics*: in case of complete signal loss of the sensor, the pump module and system will automatically stop, due to missing information on the regulation pressure. Severity is 5, but the event is not expected (severity 1).

- **Buffer VU-4009**

  - *Internal leak*: the buffer is used to smooth the oscillations at the input of the module and it is at the 'relative negative pressure side'. That's why, in case of seal failure, an internal leak can happen, affecting the gas mixture. The severity is 5 while the frequency 1.

- **Pressure safety valve PSV-4009/1 and PSV-4009/2**

  - *Internal leak*: this safety valve (together with PSV-4009/2) is on the buffer and this can have similar effect like the latter. However, the severity of an intake from the safety valve, is less critical that the one for buffer (severity 4) and the frequency is 2, since it can happen.

- **Pressure sensor PT-4101/1**

  - *Drift*: this sensor is mounted on one pump head (PT-4101/2 on the other one) and measure the membrane pressure. In case of drift, the pump is affected and an alarm will be triggered in the system. This event is ranked as 4 for severity and 2 for frequency.

- *Internal and external leak*: this event can occur in case on pump membrane failure. The effect is that, due to the characteristics of the diaphragm pump, there will be both external leak and air intake and the mixture will be modified and compromised. The severity is 5, because the system will a wrong mixture. The event can happen in system lifetime (frequency 2).

  These failure modes are the same as for the other pressure sensors installed in the pumps.

- **Temperature sensor TE-4101/1**

  - *Drift*: like for the latest sensor, the temperature sensor are installed in the pump heads. A drift of this sensor, would trigger the fullstop of the pump and of the system. Severity 5, while frequency 1.
  - *Broken electronics*: same as drift.

  These failure modes are the same as for the other temperature sensors installed in the pumps.

6.1.2 Criticality analysis and risk matrix

In the following table (table 6.3), the identified failure modes and their assigned indexes are listed, without reporting items that share similar functionalities.

ITEM	FAILURE MODE	FREQ.	SEV.
PU-4101	MEMBRANE PRESSURE TOO HIGH	3	5
	FAIL TO START ON DEMAND	1	5
	LOW EFFICIENCY	3	4
	EXTERNAL LEAK	3	2
	INTERNAL LEAK	2	4
	STOP WORKING	2	5
NV-4109	LOSS OF FUNCTIONALITY	3	2
	EXTERNAL LEAK	1	2
	STUCK CLOSED	1	5
NV-4019	LOSS OF FUNCTIONALITY	2	3
	EXTERNAL LEAK	1	2
	STUCK CLOSED	1	5

ITEM	FAILURE MODE	FREQ.	SEV.
PV-4003	EXTERNAL LEAK	2	3
	BLOCKED	1	5
ZC-4003	UNSTABLE REGULATION	2	4
	STUCK	2	5
PC-4003	REGULATION LOSS	2	5
PICV-4021	SPURIOUS OPENING	2	2
	EXTERNAL LEAK	2	2
PCV-4018	SPURIOUS OPENING	2	4
	EXTERNAL LEAK	2	4
	INTERNAL LEAK	1	5
PICV-4024	SPURIOUS OPENING	2	1
	EXTERNAL LEAK	2	2
HV-4030	EXTERNAL LEAK	2	3
YV-4040	STUCK CLOSED	2	5
	EXTERNAL LEAK	2	2
YY-4040	STUCK CLOSED	1	5
YV-4002	STUCK CLOSED	1	5
	EXTERNAL LEAK	2	2
GF-4020/1	CLOGGED	3	2
	EXTERNAL LEAK	3	2
PT-4004	DRIFT	2	4
	BROKEN ELECTRONICS	1	5
	INTERNAL LEAK	1	4
PT-4006	DRIFT	2	1
	BROKEN ELECTRONICS	1	1
	EXTERNAL LEAK	1	2
DPT-4020	DRIFT	2	1
	BROKEN ELECTRONICS	1	1
	EXTERNAL LEAK	2	2
VU-4009	INTERNAL LEAK	1	5
PSV-4009/1	INTERNAL LEAK	2	4
	STUCK	1	5
PT-4101/1	DRIFT	2	4
	BROKEN ELECTRONICS	1	5
	INTERNAL AND EXTERNAL LEAK	2	5

ITEM	FAILURE MODE	FREQ.	SEV.
TE-4101/1	DRIFT	1	5
	BROKEN ELECTRONICS	1	5

Table 6.3: Pump module FMECA summary

The next step is to use the 2 defined indexes for building the risk matrix related to this module, in order to better visualize the events that can be very critical for the system (fig. 6.1).

RISK MATRIX		FREQUENCY				
		1	2	3	4	5
SEVERITY	1	2	3	0	0	0
	2	5	6	10	0	0
	3	0	3	0	0	0
	4	1	15	3	0	0
	5	33	12	3	0	0

Figure 6.1: Pump module risk matrix

Summarizing, a total of 96 failure modes are analysed, with the following distribution:

- 17 non critical failure modes;
- 61 less critical failure modes;
- 18 critical failure modes;
- 0 high critical failure modes.

The majority of the criticalities are related to the pump failure modes, in particular to the severity of these events which lead, in general, to stop of the system. Another important contribution is given by the regulation group, made of the regulation valve, actuator and controller, and all the the other equipments that are installed on the bypass loop, such as the pressure regulator and the solenoid valve. In addition, the input pressure sensor is very important, since the whole regulation of the module is performed following its readout. Finally, other items that can be impactful for the pumps are their sensors which failures can cause the pump stop. The events with frequency 1 and severity 5 need to be kept under particular attention, due to the highest severity index even if their occurrence is unlikely: such events can stop the system and therefore some actions can be taken.

6.1.3 Improvement actions and comments

As explained in the previous section, the components that are fundamental and the most critical are the pumps. For them, a scheduled maintenance procedure were developed to replace the end of life membranes. However, during the maintenance replacement, it is also a good moment to check if the seals are tight to avoid the possibility of external leak and air intake. Usually this activities are performed every 2500 working hours and after 30000 they are send to company for additional maintenance. A good practice for the preventive tasks of these pumps is too add some checks and inspections after 10000 hours for the electrical part and cooling system of the asset. Moreover, in case of the failure mode *Membrane pressure too high*, a reasonable precaution, to avoid the system stop, is to add some warnings, in the alarms logic, since there is still time to act on the pump and correct the increase of pressure.

The regulation valve, together with its actuator and controller, is another critical group for the systems. In this case there are not any scheduled maintenance tasks. A suggestion can be a mechanical inspection of the valve and the actuator every EYTS, while during the Long Shutdown period, the replacement of the actuator spring can be a good choice.

The same can be set for the pressure regulator on the pneumatic line, which is the responsible for the correct regulation of the bypass loop. In addition, since the bypass loop flow is monitored only with the opening of the valve, a suggestion can be the installation of a flowmeter to read the flow in the loop and compared with the valve, just to have a redundant information.

A critical component that required particular attention is the pressure transmitter PT-4004. As explained, the whole regulation of the module, and implicitly of the system is based on its reading and a failure would lead to the system stop. An idea can be the installation of a parallel pressure transmitter in the same location, in order to have a second reading. Otherwise, with the regular inspections, it can be a good practice to re-calibrate and test or replace after two years of functioning.

The other component failure modes to which the severity 5 and frequency 1 are assigned, are mostly related to the air intake or the failures of the pumps temperature and pressure sensors. For the first case, one suggestion is to increase the periodical inspection of the seals of these equipments. For the sensors installed on the pumps, the idea, as before can be the addition of warnings, in order to avoid the full-stop. For example, if the pressure sensor of one head completely fails due to an electrical problem, there can be an alarm to inform that something is not working well and not shut the pump off. That is because there is still time to investigate if the pump has problem or if it is related to the sensor and then some corrective actions can be performed.

6.2 Mixer module FMECA

The mixer module is the responsible for the provision of the fresh mixture that needs to be injected in the system to recover the gas losses occurred through the circulation loop. It is made of 4 main lines, one for each gas request by the RPC detectors. ATLAS RPC runs with 64% of R-134a, 30% of CO_2, 5% of isobutane and 1% of SF_6, while in CMS 95.2% of R-134a, 4.5% of isobutane and 0.3% of SF_6. This concentration are managed by the mass flow controllers, which are very important component for the correct mixture generation. Moreover, the mixer is equipped with a detection head which detects huge Freon losses or small release of the flammable isobutane and, in that case, the module is stopped. In figure B.1 (appendix B), the mixer drawing is reported to better identify the components under investigations.

6.2.1 FMECA description

For each component, the failure modes which are related to the higher criticality are listed, with a brief discussion of the consequences and effects on the module and on the system. (For a better understanding of the FMECA, see figure B.2, figure B.3 and B.4).

- **Pressure safety valve PSV-1204**
  - *External leak*: safety valves are installed for each line in order to release the pressure in case of problem. This particular safety valve is on the line of the isobutane (flammable gas) and even a small leak would trigger the system full stop. Severity is 5 and frequency 1. The other gas lines do not have this potential problem at the exception of the Freon one (PSV-1104). Even in that case a big loss of R-134a would trigger full stop.

- **Mass flow controller XMFC-1106 / XMFC-1109**

  - *Wrong readout*: mass flow controllers are key items that regulate the right concentration of the gas. Since their precision fundamental into providing the correct gas flow, it can happen that after some time of operations, they went out of calibration. This has effect on the mixture composition which can be wrong with respect the detector necessity. This event can happen many times during the lifetime of the system and for this reason its frequency is set to 3, while the severity is 4. This failure mode is common also to the other mass flow controllers.

  - *External leak before*: in the case of external leak before the mass flow controller, since XMFC-1106 (as well as XFMC-1109) is installed in the Freon line, there is the possibility of module and system stop, if the leak trigger the detection head. For this reason it is ranked with severity 4 and frequency 2.

  - *External leak after*: if the external leak is after the mass flow controller, the system can be stopped due to the Freon leak or it can have effect on the mixture composition since some gas is loss after the regulated flow. In both case the severity is 4 and the frequency is 2. The latter case can be applied also to the other lines.

  - *No communication*: this event can be observed in the case of electrical failure of the mass flow controller. The effect is that the flow from that line is stop, causing also the module to stop if the other MFC is not adequate to compensate for flow injection. The frequency is 2, while the severity is 4. This is valid also for the other lines.

- **Mass flow controller XMFC-1206 / XMFC-1209**

  - *External leak*: since this line is the isobutane one, in case of gas loss, the detection head will trigger the system full stop. Severity 5, frequency 2.

- **Solenoid valve YV-1205 / YV-1208**

  - *Suck closed*: these solenoid valves are installed before each mass flow controller, to close the line of the one not used. However, if the valve stays closed due to an electrical failure, the line is sealed and the mixture can be affected.

In this case the severity is 3 and frequency 2. This failure mode is shared with the other valves.

- *External leak*: as before, an external leak in the isobutane line will shut down the system. The severity is 5 and frequency is 2. In case of the Freon line, the severity is 4.

- **Pressure regulator PICV-1102**

  - *Sudden opening*: the pressure regulator at the input reduces the supply flow pressure, allowing the mixture formation at the desired set point, since each supply line is at its own value. In case of the Freon line, if the regulator opens, the R-134a can stay in liquid phase and impede the SF_6 to join the mixture. For this reason the severity is 4, while the frequency is set at 2.
  - *External leak*: as for the other components installed in the Freon line, a gas loss can stop the system.

    These two failure modes are the same for each regulator but severity is higher just for this line and the isobutane one. Moreover, the external leak of the PICV-1202, will lead to the system stop (severity 5), due to flammable gas loss.

- **Pressure regulator PCV-1007**

  - *Internal leak*: this pressure regulator at the mixer output is regulated by a nitrogen pneumatic line. In case of internal leak, due to the broken membrane, the N_2 can leak in the main line and contaminate the mixture. The chosen severity is 4, while the frequency is 2.

- **Pressure transmitter PT-1103 / PT-1203 / PT-1303 / PT-1403**

  – *Drift*: these sensors are installed at the supply lines of the mixer. A drift of one of these sensors can have some effects on the mixture composition and for this reason the severity is set as 3 while frequency 2.

  – *Broken electronics*: in case of broken electronics and loss of pressure reading in those line, the mixer is immediately stopped. The system performances are affected since there is not the fresh mixture injection and, if the detectors leaks, as in the ATLAS case, are too big, the recirculation flow is not sufficient to cope the detector requirements and the system will gradually empty and stop. The severity is 4 in general, but for specific cases can be 5.

In general, in the mixer module, the critical failure modes are related to the external leaks from components installed in the lines of the Freon R-134_a and isobutane, since they will trigger the detection head and system full stop. However, some failures of the mass flow controller can be detrimental for the correct working of the RPC gas system, since the desired mixture will can be affected or, in worst cases, contaminated.

6.2.2 Criticality analysis and risk matrix

The table 6.4 collects a summary of the most relevant failure modes associated to the components of the mixer, with their respective criticality indexes, without considering those items which have similar characteristics.

ITEM	FAILURE MODE	FREQ.	SEV.
PSV-1104	SUDDEN OPENING	1	2
	EXTERNAL LEAK	1	4
PSV-1204	SUDDEN OPENING	1	2
	EXTERNAL LEAK	1	5
PSV-1304	SUDDEN OPENING	1	2
	EXTERNAL LEAK	1	2
PSV-1010	SUDDEN OPENING	1	2
	EXTERNAL LEAK	1	4
XMFC-1106	WRONG READOUT	3	4
	STUCK	1	3
	EXTERNAL LEAK (after)	2	4
	EXTERNAL LEAK (before)	2	4
	INTERNAL LEAK	2	3
	UNSTABLE	2	3
	NO COMMUNICATION	2	4
XMFC-1206	WRONG READOUT	3	4
	STUCK	1	3
	EXTERNAL LEAK (after)	2	5
	EXTERNAL LEAK (before)	2	5
	INTERNAL LEAK	2	3
	UNSTABLE	2	3
	NO COMMUNICATION	2	4

ITEM	FAILURE MODE	FREQ.	SEV.
XMFC-1306	WRONG READOUT	3	4
	STUCK	1	3
	EXTERNAL LEAK (after)	2	4
	EXTERNAL LEAK (before)	2	2
	INTERNAL LEAK	2	3
	UNSTABLE	2	3
	NO COMMUNICATION	2	4
XMFC-1406	WRONG READOUT	3	4
	STUCK	1	3
	EXTERNAL LEAK (after)	2	4
	EXTERNAL LEAK (before)	2	2
	INTERNAL LEAK	2	3
	UNSTABLE	2	3
	NO COMMUNICATION	2	4
YV-1105	STUCK CLOSED	2	3
	EXTERNAL LEAK	2	4
	INTERNAL LEAK	1	4
YV-1205	STUCK CLOSED	2	3
	EXTERNAL LEAK	2	5
	INTERNAL LEAK	1	4
YV-1305	STUCK CLOSED	2	3
	EXTERNAL LEAK	2	2
	INTERNAL LEAK	1	4
YV-1004	STUCK CLOSED	2	2
	EXTERNAL LEAK	2	2
PICV-1102	SUDDEN OPENING	2	4
	EXTERNAL LEAK	2	4
PICV-1202	SUDDEN OPENING	2	4
	EXTERNAL LEAK	2	5
PICV-1302	SUDDEN OPENING	2	2
	EXTERNAL LEAK	2	2
PICV-1007	SUDDEN OPENING	2	3
	EXTERNAL LEAK	2	2
	INTERNAL LEAK	2	4

ITEM	FAILURE MODE	FREQ.	SEV.
NV-1101/1	LOSS OF FUNCTIONALITY	2	3
	EXTERNAL LEAK	1	4
	STUCK CLOSED	1	4
NV-1102	LOSS OF FUNCTIONALITY	2	3
	EXTERNAL LEAK	1	5
	STUCK CLOSED	1	4
VU-1009	EXTERNAL LEAK (flammable input)	1	5
	EXTERNAL LEAK	1	4
PT-1103	DRIFT	2	3
	BROKEN ELECTRONICS	1	4
	EXTERNAL LEAK	2	4
PT-1203	DRIFT	2	3
	BROKEN ELECTRONICS	1	4
	EXTERNAL LEAK	2	5

Table 6.4: Mixer module FMECA summary

Finally, considering all the identified failure modes of the mixer module, the risk matrix related to this sub-system can be observed in figure 6.2.

RISK MATRIX		FREQUENCY				
		1	2	3	4	5
SEVERITY	1	1	7	0	0	0
	2	12	25	0	0	0
	3	8	37	0	0	0
	4	30	23	8	0	0
	5	5	8	0	0	0

Figure 6.2: Mixer module risk matrix

Summarizing, a total of 164 failure modes were found, with the following distribution:

- 83 non critical failure modes;
- 65 less critical failure modes;
- 16 critical failure modes;

- 0 high critical failure modes.

6.2.3 Improvement actions and comments

As it is possible to see in figure 6.2, the majority of the events are classified with frequency 2, since it is unlikely that they would happen. However, some of them will have consequences on the system that need to be taken under consideration. For this reason, even though they are rare, some recurrent maintenance inspections are necessary, to avoid unexpected scenarios. For example, one possible event, which can lead to the system stop, is the external leak from components installed on the isobutane line. For such components, it can be useful that all the piping connections are checked and tightened if necessary, especially when some of them, like the mass flow controllers, are removed for calibration. Another, suggestion can be modifying the alarm logic of the detection head. This is necessary to detect leak of flammable gases which can start a fire: since the pure isobutane is present only in the supply line and after the mixer tube the mixture is not considered as flammable, one possibility is to add some warnings at a certain concentration level, in order to have time to intervene before the detection head will trigger the full stop.

In general, the most critical components are the mass flow controllers, due to their importance for the module and system. These assets are calibrated mainly in CMS RPC gas system due to the presence of the GC for the analysis, which can spot if some composition are wrong. In ATLAS, the GC is not used and they are not calibrated for many times leading to the doubt that the composition are really exact. For this reason, one good practice can be the establishment of a routine calibration task every year or when the GC analysis reveal the necessity for a calibration for the CMS ones, since the operative conditions are similar. The main problem of having a scheduled maintenance task is the high number of mass flow controllers that need to be checked, considering also the other 30 gas systems and for this reason, this action is not taken regularly. However, due to their importance, at least the ones installed in this module required these actions. Another possibility can be the introduction of the GC also in the ATLAS gas system.

Other components that needs some checks are the pressure regulators installed in the Freon and isobutane line. Even though the probability of sudden opening is very low, its effect can be very dangerous for the system. In fact, since this lines are at quite higher pressure and at higher concentration with respect the CO_2 and SF_6 ones, in case of opening and the regulator fails to keep the pressure set point, the Freon and isobutane can push away the other gases. In addition, the isobutane is in liquid phase and, if the pressure is not reduced, it will not change phase, damaging all the equipment which is suitable only for gases.

Finally, also the pressure sensors installed in the supply lines require some dedicated activities, for instance calibrations or checks of the electrical parts, since a failure can cause the mixer stop, with the already discussed consequences on the whole system.

6.3 Exhaust module FMECA

The exhaust module is an important module since it is the responsible for the connections between the modules. It receives the gas mixture from the mixer, it sends it to the humidifier, then to the distribution, pump and purifier and back to the line from the mixer. Moreover, from the exhaust the gas is also sent to the analysis modules. However, its main goal is to exhaust the part of the mixture which needs to be replaced by the mixer, while the system is in closed loop. In normal operations, the detector requires that part of the mixture is made of fresh gas and, for this reason, part of the flow collected after the distribution is vented and recovered by the mixer. To fulfil this task, a mass flow controller is installed to regulate the exhausted mixture, while a pneumatic valve is used to set if the loop needs to be used in closed or opened loop, which are two of the most important component of this module. In figure C.1 (appendix C), the exhaust drawing is shown, in order to have a better visualization of the components analyzed in FMECA.

6.3.1 FMECA description

In this section, the identified most critical failure modes of the exhaust components are listed and described, highlighting the motivations behind the choice of the criticality indexes. (For a more detailed view of the FMECA table, see figure C.2).

- **Mass flow controller XMFC-5002**

  - *Wrong readout*: this mass flow controller is essential for the proper gas venting in order to replace this quantity by the mixer. In case of wrong readout, due to a possible lack of calibration, the reading is wrong with fake leak detection and this will induce the mixer to wrongly set the fresh flow. For this reason, both the severity and frequency of occurrence are chosen as 3.

- *Stuck*: in this case, the mass flow controller is blocked at its actual position and it is not able to cope with the necessity of the module. There can be a pressure increase in the system with the necessity of intervention of the regulator PCV-5001.

- **Pressure regulator PCV-5001**

  - *Sudden opening*: this pressure regulator is very important to set the pressure at the exhaust line and it is also as a sort of safety valve if some instabilities arise. In case of sudden opening due to a mechanical problem, the line will open bypassing the mass flow controller and there is an additional vented flow, which in worst case scenario could lead to the emptying of the system. The severity index chosen is 4, while the frequency 2.
  - *Internal leak*: in case of internal leak in combination with a low pressure in the line, there can be the possibility of backflow of the mixture, causing some trouble in the module. The severity is 3 and frequency 2.

- **Pressure regulator PTCV-5001/1**

  - *Spurious opening*: this regulator is directly controlled by the Festo module to properly set the pressure regulator PCV-5001. In case of unintended opening, the pneumatic line will be filled with nitrogen which can cause effect on the PCV-5001. However, in the exhaust a redundant regulator is installed in the pneumatic line to help the regulation. Therefore, the severity is 3 while the frequency is 2.
  - *Bad communication / wrong reading*: in case of electrical problem and the communication with the controller is lost or the device has a bad reading, there can be some troubles in keeping the position of the PCV-5001, which can be set in wrong configuration. In this case the severity is 4 and frequency is 2.

- **Pressure regulator PTCV-1007**

  - *Spurious opening*: this is similar to PTCV-5001/1, but its effects are on the pressure regulator in the mixer module.
  - *Bad communication / wrong reading*: this has the same effects as the one of PTCV-5001/1, but on the mixer regulator.

- **Controller PC-FESTO**
  - *Regulation loss*: this controller is the responsible for the correct functioning and regulation of the PTCVs. In case of loss of regulation, there can be effect on both the mixer and the exhaust pressure regulator. In the latter case, the PCV-5001 can open and empty the system. The severity is 4 and frequency is 2.
- **Solenoid valve YV-5003/1 and YV-5003/2**
  - *Sudden opening / closure*: this two valve are responsible for the regulation and control of the pneumatic valve YV-5003, which, according to its position, is used to set the system into open or closed mode. The two valves are used to send N_2 to the piston of the pneumatic one, to set the position. If one of the two fails, by opening or closing suddenly, the piston is not regulated anymore and the pneumatic valve is stuck on its actual position. The severity in this case is 5, because the whole system flow is not correctly regulated and the system can stop. However, the probability of occurrence is very low and can be set as 1.
  - *External leak*: in case of external leak of pneumatic gas, due to a mechanical problem of the valves, the YV-5003 is not regulated well and there can be effect on the system. The severity is 4 and the frequency is 2.
- **Pneumatic valve YV-5003**
  - *Sudden closure / opening*: since this valve is the responsible of the operation mode of the system, closed loop or opened loop, if this valve suddenly opens, the system will be in full close loop. The main problem is if this valve completely closes and lead the system to the open mode, exhausting all the gas. The severity is 5 while the frequency is 1.
- **Flowmeter FIT-5010**
  - *Stuck*: this flowmeter measures the flow rate before the distribution module. If this flowmeter gets stuck, a big flow impedance is created with the results of high pressure drop. This can have significant effect on the distribution and on the system itself and therefore its severity is 4, while the frequency 2.

- **Pressure transmitter PT-5005**
  - *Drift*: this sensor is installed in the mass flow controller line to monitor the pressure at the exhaust output. The regulation of the latter is performed on the reading of this sensor and therefore it is very important for the module. In case of drift there can be wrong regulation of the module and of the system and, for this reason the severity is ranked as 4. However, the frequency of occurrence is 2.
  - *Broken electronics*: this event is most dangerous than the drift because it would lead to the module and system stop. The severity is 5, while the frequency is 1.

6.3.2 Criticality analysis and risk matrix

As for the other modules, the table 6.5 collects all the most relevant failure modes found in the exhaust module with their respective criticality indexes.

ITEM	FAILURE MODE	FREQ.	SEV.
XMFC-5002	WRONG READOUT	3	3
	STUCK	2	3
	EXTERNAL LEAK	2	2
	INTERNAL LEAK	1	3
PCV-5001	SUDDEN OPENING	2	4
	EXTERNAL LEAK	2	2
	INTERNAL LEAK	2	3
PTCV-5001/1	SPURIOUS OPENING	2	3
	EXTERNAL LEAK	2	3
	BAD COMMUNICATION	2	4
	STUCK CLOSED	1	4
PTCV-1007	SPURIOUS OPENING	2	3
	EXTERNAL LEAK	2	3
	BAD COMMUNICATION	2	4
	STUCK CLOSED	1	4
PC-FESTO	REGULATION LOSS	2	4
YV-5003/1	STUCK CLOSED / OPENED	1	5
	EXTERNAL LEAK	2	4

ITEM	FAILURE MODE	FREQ.	SEV.
YV-5003	EXTERNAL LEAK	2	2
	INTERNAL LEAK	1	2
	SUDDEN OPENING / CLOSURE	1	5
	STUCK	1	3
FIT-5010	STUCK	2	4
	EXTERNAL LEAK	2	2
	WRONG READOUT	3	1
PT-5005	DRIFT	2	4
	BROKEN ELECTRONICS	1	5
	EXTERNAL LEAK	2	1

Table 6.5: Exhaust module FMECA summary

Considering all the components and their associated failure modes, the resulting risk matrix for the exhaust module is the one shown in figure 6.3.

RISK MATRIX		FREQUENCY				
		1	2	3	4	5
SEVERITY	1	6	2	1	0	0
	2	3	12	0	0	0
	3	3	9	1	0	0
	4	6	9	0	0	0
	5	4	0	0	0	0

Figure 6.3: Exhaust module risk matrix

In particular, 56 failure modes are found, with the following distribution:

- 33 non critical failure modes;
- 23 less critical failure modes;
- 0 critical failure modes;
- 0 high critical failure modes.

As it is possible to see, this module has less critical components with respect to the pump or mixer ones. There are not found potential failures which can lead to the system stop. However, some components required a certain attention during operations, such as the mass flow controller, the pressure regulator and the sensor which manage the correct exhaust flow, or the pneumatic valve and its regulation valve group which can cause some trouble to the system in case of failures.

6.3.3 Improvement actions and comments

Since the mass flow controller is the key component for the correct exhaust flow rate, it requires periodical calibrations to prevent some bad reading that can influence the system performance, venting too much or too low gas. One possibility to improve the design of the module is to add a new mass flow controller in parallel, in order to have a spare one in case of failure of the other one.

For this purpose, also the pressure transmitter (PT-5005) on the line is crucial for the correct functioning of the former and for this reason some replacement or deep inspections can be scheduled once every 2 year of working, in addition to the periodical check during the maintenance procedures.

Other components that needs additional inspections and periodic verification of the conditions are the one that made up the Festo module: the controller and the pressure regulators which set the value for the correct functioning of the ones installed in the line.

Even though it is not so crucial for the system, the flowmeter FIT-5010 can be problematic if it gets stuck, creating a huge pressure drop. For this reason it can be useful to installed a bypass loop that is used in case of this event, or to simple have the possibility of replace it without stopping the line.

Finally, for the pneumatic valve YV-5003, which is used to set the module and system in closed or opened mode, some periodic checks of the mechanical part and piston can be useful to prevent unwanted scenarios. Since the likelihood of failure is low, a good option is to deep investigate its parts and the pneumatic lines connections, once every 2 year, to have a precise understanding of the status of this valve.

6.4 Humidifier module FMECA

As explained in section 2.4, the humidifier module is the responsible of monitoring and set the correct moisture content of the gas mixture to cope with the detectors requirements. It is equipped with an analyser unit, which output is used to regulate the amount of water needed in the evaporator. In figure D.1 of appendix D, the drawing of the humidifier layout is shown and useful for the FMECA description.

6.4.1 FMECA description

This module, is simpler with respect the other ones and it is made of relatively small number of components. However, some of them can be critical for the correct functioning of this module. In the following list, the most critical failure mode are listed. (For a complete overwiew of the FMECA table, see figure D.2).

- **Pneumatic valve YV-5104/1 and YV-5104/2**
  - *Sudden closure*: these two valves are installed at the input and output of the humidifier loop. In case of mechanical failure of one of the two, the gas mixture does not manage to enter the evaporator to increase its humidity level, or for the second one, the humidifier is completely bypassed. The frequency of occurrence is 2, while the severity rank is 3, since it can cause the module stop.
- **Pump PU-5125**
  - *Stop working*: this pump is used to extract the water from the tank and send it to the evaporator, where the moisture is produced. In case of the stopping of this pump, due to a mechanical or electrical failure, the evaporator is not able to receive the necessary water for the moisture generation and the module will be stopped, since the mixture does not have the right amount of humidity. The both the frequency and severity are ranked as 4.
- **Mass flow controller XMFC-5121**
  - *Wrong readout*: this mass flow controller is very important for sending the right amount of water to the evaporator in order to produce the required humidity to add to the mixture. In case of this failure mode, that can happen when it is out of calibration, as explained the effects can be on the moisture

regulation and this would affected the mixture and partially the system. The severity is 3 while the frequency is 2.

- *Stuck*: similarly to the previous one, in case of this component gets stuck, the water flow is not regulated anymore and the module can be stopped. For this reason the severity can be ranked 4, while the frequency is 3, since this event happened few times in the past.

- **Rotameter FIV-5123**
  - *Blocked*: this rotameter is installed in the line that provides the mixture to the analyser. In case of blockage of this rotameter, there is not the possibility for the flow to reach the analyser and this would have effect on the regulation of the module, causing the stop. The severity is 4, while the frequency 2.

- **Sensor PT-5116 / PT-5117 / PT-5106 / TIC-5105 / TE-5109**
  - *Drift*: all these sensors, pressure and temperature, are related to the measurements of these parameters related to the water tank, evaporator and heat exchanger and they are linked to fullstop alarm. In case of drift, due to electrical problem, the module is affected, especially with sensor PT-5116 which is related to the water pressure. For this reason the severity is 3 and frequency 2.
  - *Broken electronics*: in case of complete failure of these sensors, the module will be stopped. Although the severity is high (4), it is unlikely such event which lead to frequency 1.

- **Evaporator VU-5105**
  - *No heating*: the evaporator is the responsible for generating the humidity and it is provided of an electrical part which heats the water up. In case of electrical failure, the heating is off and the humidifier can be stopped, causing troubles for the system. The severity is 4, while the frequency of occurrence is 2.

- **Analyzer XANA-5128**
  - *Wrong reading*: as explained before, the analyser receives part of the humidifier output mixture, in order to check its moisture content and regulate the water mass flow controller. In case of electrical problem, which leads to a

wrong reading, the mass flow controller is not regulated well and the mixture can be affected. Both the severity and the frequency are 3.

– *No communication*: this is similar to the former one, but it is the worst scenario and the module will be stopped. Severity 4 and frequency 2.

6.4.2 Criticality analysis and risk matrix

Once all the possible failure modes and their rankings are collected in the FMECA tables, the following step is to build the risk matrix associated to this module to have a complete overview of the criticality distribution. In the table 6.6, the most critical failure modes of the humidifier are summarized.

ITEM	FAILURE MODE	FREQ.	SEV.
YV-5104/1	SUDDEN CLOSURE	2	3
	EXTERNAL LEAK	2	2
PU-5125	STOP WORKING	4	4
	EXTERNAL LEAK	2	2
XMFC-5121	WRONG READOUT	2	3
	EXTERNAL LEAK	2	2
	STUCK	3	4
VU-5105	NO HEATING	2	4
	EXTERNAL LEAK	2	2
FIV-5123	BLOCKED	2	4
	EXTERNAL LEAK	2	2
XANA-5128	WRONG READING	3	3
	NO COMMUNICATION	2	4
XANA-5128	WRONG READING	3	3
	NO COMMUNICATION	2	4
CI-5108	NO OUTPUT FLOW	2	3
PT-5116	DRIFT	2	3
	BROKEN ELECTRONICS	1	4
	EXTERNAL LEAK	2	2

Table 6.6: Humidifier module FMECA summary

Therefore, considering all identified failure modes, the risk matrix associated will be the one shown in figure 6.4.

In particular, 49 failure modes are found, with the following distribution:

RISK MATRIX		FREQUENCY				
		1	2	3	4	5
SEVERITY	1	0	5	0	0	0
	2	2	17	0	0	0
	3	1	9	1	0	0
	4	9	3	1	1	0
	5	0	0	0	0	0

Figure 6.4: Humidifier module risk matrix

- 34 non critical failure modes;
- 13 less critical failure modes;
- 2 critical failure modes;
- 0 high critical failure modes.

6.4.3 Improvement actions and comments

This module is less critical than the previous modules, as can be observed in the picture. The main issues are related to the water pump, the mass flow controller, the analyser and the sensors.

The pump was prone to some frequent issues and required the replacement of the whole asset in case of failure. For this reason, a proposed solution is to change this pump, once every 6 months or 1 year, in order to have a new one ready for working. Moreover, this pump is a small one and its cost is not so expensive, therefore it is possible to have some spare to be installed periodically and to send the previous one to the manufacturer to restore its initial conditions.

The mass flow controller, few times in the past, was found blocked or stuck in a wrong position and, for this reason, it is useful to adopt some preventive actions to avoid these events. For instance, it can be replaced periodically by a spare one and the old can be checked, verified and calibrated to be ready to be reinstalled lately. The same can be set for the analyser, since it has few problems in past and needed to be replaced or calibrated.

For what concerns the sensors, their high severity effects are due to their link with specific alarms which can trigger the stop of the module. For this reason for them is sufficient periodical inspections or if needed having some spare to put in place once every 2 year at least, in order to increase the availability of the module. In addition, a second humidity sensor can be installed, in order to have another reading on the amount of water used. Moreover, also a warning on the humidity level can be considered.

6.5 Distribution module FMECA

The distribution module in both ATLAS and CMS experiments consists in many racks, which deliver the gas mixture to the associated detectors chambers. In other words, the RPC detectors is divided in many chambers and for each of them a particular distribution channel is dedicated.

For the following FMECA analysis, the distribution rack 67 for ATLAS experiments is chosen, since it is one of the new type of racks installed for the experiment. The main difference with respect to the old ones is the presence of a second regulation valve installed at the input of the rack. In addition, for the analysis, the same risk ranking tables are considered, even though in case of some equipment failures, the whole distribution is not arrested but just the rack itself. In particular, even if the rack is stopped, it is equipped with a backup gas line of Freon which will be opened, in order to continue having the detector chamber wet with the gas which covers the majority of the gas mixture composition.

In figure E.1 (appendix E), the layout of the ATLAS distribution rack 67 is shown.

6.5.1 FMECA description

In this section, the most critical identified failure modes are described, focusing on the effects that they can have on the module and on the system. (For a deeper understanding of the FMECA procedure for the distribution, see figure E.2 and figure E.3).

- **Pneumatic valve YV-6723**
  - *Sudden closure*: this valve is the rack input valve and in principle it should stay open. If it has a mechanical failure and suddenly closes, there is not the flow to the rack and it will stop, causing some troubles for the system and the detector chambers associated. Therefore, the severity is 4, while the frequency is 2.
- **Pneumatic valve YV-6727**

  - *Sudden closure*: as for the YV-6723, this valve is at the output of the rack and it should be opened. If it closes, the rack will be stopped since there is not the output flow.
  - *External or internal leak*: since this valve is after the detectors, it is at a relative small pressure. In some cases, during the normal operations, the pressure can be negative and an external leak can turn into an air intake. If this happens, the mixture gets contaminated and it will have effects on the system. The severity is 4 and frequency is 2.

- **Pneumatic valve YV-6771**
  - *Sudden opening*: this valve is the input for the backup gas, which is pure Freon, used when the rack stops and detectors required to be filled with at least the major gas of the mixture. If this valve opens and the YV-6772 is closed, the Freon can be exhausted through the bubbler XBUB-6774, causing a huge loss of this gas. Therefore the severity is 4 and frequency is 2.
  - *External leak*: as previously discussed, an external leak of this gas can be dangerous since it is Freon, but in this case it is expected to be less then the *sudden opening* case. Severity is 3, frequency is 2.

- **Pneumatic valve YV-6772**
  - *Sudden opening*: this one is installed in the backup line. In case of opening, the gas mixture of the detector can be lost through the the bubbler XBUB-6774. Therefore the severity is 3 and frequency is 2.
  - *External leak*: since it is on the Freon line, the effects are the same as the YV-6771.

- **Pressure regulator PCV-6721**
  - *Spurious opening*: this pressure regulator is at the input of the rack and its role is to reduce the pressure to cope with the detector requirements. In case of opening, the input pressure will not be regulated and the regulation valve need to compensate, having effects on the whole distribution and system. Therefore the severity is 4 and frequency is 2.

- **Regulation valve PV-6722 / PV-6726**

  - *Blocked*: this valve are particularly important to regulate and keep the right pressure in the detectors chambers. One is set at the input and one at the output. If one of them is blocked in its actual position, there is not the regulation anymore and the system will be affected. In particular, if the input one is blocked the rack is stopped, while for the output one there are just effects on the module. For this reason the severity is 4, while the frequency is 2 for the PV-6722, while severity is 3 for PV-6726.
  - *Leak*: in case for PV-6722, a seal failure would lead to a gas loss, but for the PV-6726 this failure would cause an air intake due to atmospheric variations. In fact, in this case it is considered with severity 4.

- **Actuator ZC-6722 / ZC-6726**
  - *Unstable regulation*: in case of unstable regulation, the effect will be the immediate stop of the rack. The severity is 4 and frequency of occurrence is 2.
  - *Stuck*: the same as the unstable regulation.

- **Controller PC-6722 / PC-6726**
  - *Regulation loss*: even in this case, the rack will be stopped, due to missing regulation on the valves. The risk indexes are the same as for the actuators.

- **Input and output flowcells FE-6702 / FE-6706**
  - *Wrong readout*: each rack of the distribution module is made of many different flowcells, which roles is to read the input and output flows of every channels, in order to detect potential leaks at the detector chambers. They are just flow readers and they observed failure mode is the wrong readout, which is not so relevant for the system operations. However, these flowcells need to be calibrated very often since this event happens many times during the operations. Therefore, even if the severity is low, the frequency of occurrence is ranked as 4, this is the reason for their high criticality.

6.5.2 Criticality analysis and risk matrix

To summarize the FMECA of the rack 67, the most critical components are the pneumatic valves (rack input and output and the one in backup line), the input pressure regulator, the flowcells and the two regulation valve groups. In the table 6.7, the main failure modes are listed, considering also other items with low criticality.

ITEM	FAILURE MODE	FREQ.	SEV.
YV-6727	SUDDEN CLOSURE	2	4
	EXTERNAL / INTERNAL LEAK	2	4
YV-6771	SUDDEN CLOSURE	2	4
	EXTERNAL LEAK	2	3
YV-6772	SUDDEN CLOSURE	2	3
	EXTERNAL LEAK	2	3
PCV-6721	SPURIOUS OPENING	2	4
	EXTERNAL LEAK	2	3
PV-6726	EXTERNAL / INTERNAL LEAK	2	4
	BLOCKED	2	3
ZC-6726	UNSTABLE REGULATION	2	4
	STUCK	2	4
PC-6726	REGULATION LOSS	2	4
PT-6704	SMALL DRIFT	3	3
	BIG DRIFT	1	4
	BROKEN ELECTRONICS	1	4
	EXTERNAL LEAK	2	2
FE-6702	WRONG READOUT	4	2

Table 6.7: Distribution rack 67 FMECA summary

For the building of the risk matrix, the flowcells are counted as one group for input and one for output, without considering the single flowcells. The resulting risk matrix for the distribution rack is the one shown in figure 6.5.

RISK MATRIX		FREQUENCY				
		1	2	3	4	5
SEVERITY	1	2	10	0	0	0
	2	4	12	2	2	0
	3	4	10	2	0	0
	4	11	13	0	0	0
	5	0	0	0	0	0

Figure 6.5: Distribution rack risk matrix

The identified 72 failure modes are distributed as follows:

- 43 non critical failure modes;
- 29 less critical failure modes;
- 0 critical failure modes;
- 0 high critical failure modes.

6.5.3 Improvement actions and comments

As it is possible to see from the risk matrix, a single distribution rack has not critical events which can cause serious effects on the systems. The reason is that you can run without a single rack for short period, if the others work correctly.

However, to guarantee high performances, some actions can be considered. For example, the regulation valve groups (valve, actuator and controller) are really important to keep the pressure by regulating the flow and some dedicated inspections and tests can be required during the EYTS, in order to check their status. In addition, the pressure sensors at input and output are really important, due to their role for the regulation, and, for these reasons, a good practice can be the calibration once every year, when the cavern is accessible. Finally, particular importance is covered by the valves controlled by the Festo module and therefore some preventive maintenance tasks on it can be scheduled.

6.6 Purifier module FMECA

As explained before, in the RPC systems there are 3 purifier modules, 2 for water and for oxygen removal. For this analysis, just one purifier module is examined, considering as operational phase that column A is in run, while column B is in regeneration mode. This is important to define and set, since in these modules there are many pneumatic and solenoid valves, which tune the operational phase change and which failure modes can vary according to the run or regeneration period. If some valves must stay open for the normal run of one column, the corresponding ones for the other column must be in closed position. Therefore, the criticalities of this module lie on the correct positioning of the pneumatic valves.

In figure F.1 (appendix F), the purifier P&ID is represented, in order to have a better understanding of the components position.

6.6.1 FMECA description

In this section, the main criticalities for the purifier modules are explained. (For the complete FMECA table, see figure F.2, figure F.3 and figure F.4).

- **Pneumatic valve YV-2103**
  - *Sudden closure*: this valve is at the input of the column in run, in this case column A (valve YV-2203 is for the column B and must stay closed in this phase) and if it suddenly closes the flow in the module stops, causing also a stop for the system itself. For this reason the severity is 5, while the frequency is 3.
- **Pneumatic valve YV-2104**
  - *Sudden opening*: this valve is on the regeneration line and for column A it should stay closed, otherwise it can lead to a huge process gas loss. Both the severity and frequency are ranked as 3.
- **Pneumatic valve YV-2106**
  - *Sudden opening*: as for the the previous one, this valve is in the regeneration line and in particular at the input. If, after a mechanical failure, this valve opens, there will be a mixture contamination with the regeneration gas and for this reason it is classified with severity 4, while the frequency is 2.
- **Pneumatic valve YV-2107**
  - *Sudden closure*: this pneumatic valve is at the output of the column A and in case of closure the gas flow is arrested causing the stop of the module and of the whole system. The severity is 5, while the frequency is 2.
- **Pneumatic valve YV-2203**
  - *Sudden opening*: with respect to the YV-2103, this valve is the input of column B, which is considered in regeneration mode. Therefore, in case of opening, the gas mixture enters the column, causing contamination of the mixture. Moreover, in this case the module is stopped and therefore its severity is ranked as 4, while frequency 2.
- **Pneumatic valve YV-2204**

  - *Sudden closure*: in case of closure of this valve, column B does not regenerate and the module is affected. The severity is 4, while the frequency is 3.

- **Pneumatic valve YV-2206 / YV-2210 / YV-2211**
  - *Sudden closure*: similarly to the YV-2204, these valves are installed in the regeneration line and a closure of one of them will affected the column B regeneration. The severity is the same, but in this case frequency is considered 2.

- **Pneumatic valve YV-2001/1**
  - *Sudden opening*: this valve is at the input of the module and it is normally closed. In case of sudden opening, due to wrong input or mechanical failure, the gas flow can bypass the purifier column in run, causing trouble to the mixture and the module is stopped. In this case the severity is 4, while the frequency is 2.

- **Pneumatic valve YV-2001/2**
  - *Sudden closure*: pneumatic valve YV-2001/2 is at the input of the module, as the previous one, and a sudden closure will stop the module. Therefore, severity is 4 and frequency is 2.

- **Non return valve NV-2214**
  - *Loss of functionality*: this non return valve is installed in the regeneration line, after the pneumatic YV-2204. In case of failure, the regeneration of column B is strongly affected. In fact, the severity is 4 and the frequency is 3.

- **Flowmeter FIT-2109**
  - *Stuck*: the flowmeter is installed at the input of column A. If it gets stuck, there is not the flow regulation and the pressure drop can increase across the module, causing effects on the system. Therefore, the severity is 4, while the frequency is 2.
  - *Wrong readout*: in case of electrical failure or wrong calibration of the input flowmeter, there can be the possibility of bad reading, which can affect the performances of the module, since a wrong flow enters the column in run. In this case the severity is ranked as 3, while frequency 2.

- **Rotameter FIV-2001/1**
  - *Blocked*: this rotameter is installed at the input of the module and if it gets blocked, the whole flow is interrupted, causing the module and system stop. The severity is ranked as 5, while frequency is 2.
- **Pump PU-2005**
  - *Stop working*: the pump is in charge of generating and keeping the vacuum in the regeneration column. In case of failure, this condition is not reached and there are some troubles for the regenerating one. Therefore the severity is 4 and frequency is 3.
  - *External leak*: if the pump has an external leak, the regeneration phase of column is affected, reducing its efficiency. Therefore, the severity is 3 and frequency 2.
- **Mass flow controller XMFC-2023**
  - *Wrong readout*: this mass flow controller is responsible for regulate the flow from the exhaust buffer to the regenerated column for the preparation phase. In case of wrong readout, the amount of gas for the preparation phase can be wrong and this can affect the performances of the module. The frequency is 3 and severity is 3.
  - *Stuck*: for the same reason, if it gets stuck, the preparation is affected. In this case the severity is 4, while the frequency is 2.

6.6.2 Criticality analysis and risk matrix

In the following table (table 6.8), the main failure modes are summarized with their respective criticality indexes.

ITEM	FAILURE MODE	FREQ.	SEV.
YV-2103	SUDDEN CLOSURE	3	5
	EXTERNAL LEAK	2	2
YV-2104	SUDDEN OPENING	3	3
	EXTERNAL LEAK	2	2
YV-2107	SUDDEN CLOSURE	2	5
	EXTERNAL LEAK	2	2

ITEM	FAILURE MODE	FREQ.	SEV.
YV-2204	SUDDEN CLOSURE	3	4
	EXTERNAL LEAK	2	2
YV-2001/2	SUDDEN CLOSURE	2	5
	EXTERNAL LEAK	2	2
NV-2214	LOSS OF FUNCTIONALITY	3	4
	EXTERNAL LEAK	1	2
FIT-2109	STUCK	2	4
	EXTERNAL LEAK	2	2
	WRONG READOUT	2	3
FIV-2001/1	BLOCKED	2	5
	EXTERNAL LEAK	2	2
FIV-2012	BLOCKED	2	4
	EXTERNAL LEAK	2	2
PU-2005	STOP WORKING	3	4
	EXTERNAL LEAK	2	3
XMFC-2023	STUCK	2	4
	EXTERNAL LEAK	2	2
	WRONG READOUT	3	3

Table 6.8: Purifier module FMECA summary

Considering all the identified failure mode, for the purifier module, the risk matrix related to it is the one shown in figure 6.6.

RISK MATRIX		FREQUENCY				
		1	2	3	4	5
SEVERITY	1	7	11	2	0	0
	2	7	57	2	0	0
	3	6	5	4	0	0
	4	18	10	3	0	0
	5	4	4	1	0	0

Figure 6.6: Purifier module risk matrix

In particular, 141 failure modes are found, with the following distribution:

- 108 non critical failure modes;
- 25 less critical failure modes;

- 8 critical failure modes;
- 0 high critical failure modes.

6.6.3 Improvement actions and comments

In the purifier modules, the criticalities are related to the correct working and position of the pneumatic valves, which regulate the correct switch between the phases of columns. For this reason, a possible improvement is the addition of warnings on the N_2 pneumatic lines pressure, in order to keep monitored the working point of the valves. Related to this aspect, since all these valves are controlled by the solenoid valves in the Festo module, it is useful to schedule a preventive maintenance activity of this module every year, to check the status of all these components.

Others components, which are crucial for the correct regeneration phase of the columns, are the non return valves (NV-2114 and NV-2214) installed on the lines used for vacuum. Since a failure can compromise the regeneration, some inspections or periodical replacements are required, to enhance the performances of this delicate phase.

Also the flowmeters at the column input (FIT-2109 and FIT-2209) are important for the correct functioning of the module. For them, it is possible to set up preventive maintenance every year, especially calibration activities, to avoid the wrong readout of the gas flow or some mechanical inspections to prevent them from being stuck.

For what concerns the pump, it is another crucial component for the purifier, especially for the regeneration phase. Therefore, it is necessary to perform preventive replacements of the membrane at least twice a year and to add a working hours counter, as for the pump module, in order to have a better planning.

6.7 Summary

In the following table (6.9), all the failure modes collected in the different modules are listed, in order to make a comparisons between the different sub-system. In particular, also the number of analysed components are shown, so it is possible to weight the number of failure modes. Moreover, in this summary, the purifier components and failure modes are tripled (since there are 3 purifier modules) and, for simplicity, for distribution just the 9 racks of ATLAS RPC are considered (not the 28 of CMS) and also the flowcells are counted as 1 at the input and 1 at the output.

RPC gas system						
Module	**Components**	**Failure modes**	Non critical	Less critical	Critical	High critical
Pump	37	96	17	61	18	0
Mixer	49	164	83	65	16	0
Exhaust	23	56	33	23	0	0
Humidifier	23	49	34	13	2	0
Distribution	306	648	387	261	0	0
Purifier	201	423	324	75	24	0
Total	639	1436	878	498	60	0

Table 6.9: FMECA summary for RPC gas systems

Considering the number of components, the pump module is the one with the highest number of critical failure modes, which can cause the stop of the system. Therefore, it is important to consider this module as the first to prioritize, in order to reduce the severity of consequences in case of unwanted events or failures. The other which required particular attention is the mixer, due to presence of pure isobutane line, which can trigger the full stop in case of leak. As discussed before, one possible improvement is the addition of warnings before the shutdown alarm is reached.

In figure 6.7, it is possible to observe the final outcome of the analysis on the RPC gas systems, with the distribution of the failure modes inside the global risk matrix. The majority of the events are considered acceptable or non critical; for what concerns the critical events, the actions that are needed to be taken are summarized and described and, after that, it is likely that the severity and frequency will decrease, allowing a safer operational run of the systems, from the point of view of the 'process'.

RISK MATRIX		FREQUENCY				
		1	2	3	4	5
SEVERITY	1	48	140	7	0	0
	2	79	339	34	18	0
	3	66	163	32	0	0
	4	199	197	21	1	0
	5	54	32	6	0	0

Figure 6.7: RPC gas systems risk matrix

6.7.1 Interventions and upgrades summary

- **Pump module**
  - *Pump sensors*: introduce warnings before full stop is triggered.
  - *Pump head temperature sensors*: before alarms is triggered, check both reading.
  - *Pump efficiency*: check regulation valve position and add a flowmeter on the bypass loop.
  - *Regulation valve group*: additional inspections.
  - *Sensor PT-4004*: add point for calibrations or add another sensor.
- **Mixer module**
  - *Isobutane / Freon line*: add leak warning before detection head alarm for full-stop is triggered.
  - *Gas Chromatograph (GC)*: install in ATLAS RPC mixer.
  - *Mass flow controllers*: increase calibrations.
- **Purifier module**
  - *O_2 purifier*: add warning on H_2 leak.
  - *Pneumatic lines*: add warning on pressure.
  - *FESTO block*: schedule preventive maintenance.
  - *Non return valves*: schedule preventive replacements.
  - *Vacuum pump*: schedule preventive maintenance for membrane replacements.
  - *Regeneration phase*: add alarm if pressure does not decrease in a fixed time interval.
  - *Flowmeters*: schedule preventive maintenance and calibrations every year.
- **Humidifier module**
  - *Water pump*: schedule preventive replacement every year.
  - *Humidity level*: add warning.
  - *Analyser*: schedule periodical calibrations and install an additional humidity sensor.

  - *Mass flow controller*: schedule periodical calibrations.
  - *Evaporator*: improve temperature regulation.

- **Exhaust module**
  - *Pneumatic lines*: add warning on pressure.
  - *Flowmeter*: schedule preventive maintenance and calibrations every year.
  - *Mass flow controller*: schedule preventive maintenance and calibrations every year.

- **Distribution rack**
  - *FESTO block*: schedule preventive maintenance.
  - *Regulation valve groups*: add periodical inspections (when experimental cavern is accessible).
  - *Pressure sensors*: periodical calibration (when experimental cavern is accessible) and install standby sensor.

Therefore, considering all these improvements, from the point of view of the preventive maintenance and upgrades, it is possible to built a new risk matrix, taking into account all the changes. In figure 6.8, the updated version of the matrix is shown.

RISK MATRIX		FREQUENCY				
		1	2	3	4	5
SEVERITY	1	48	140	7	0	0
	2	85	357	34	18	0
	3	102	185	41	0	0
	4	192	192	0	0	0
	5	23	12	0	0	0

Figure 6.8: RPC gas systems risk matrix after interventions and upgrades

It is possible to observe that the majority of the critical events are downgraded to less critical ones. However, even if some critical failures are properly treated, there are others which still required particular attention. In particular, the one remained in the critical zone are related on the mechanical or electrical failure of the pumps, which can cause the system stop. Other criticalities are in those components which are on the main gas line and, in case of blockage, the system would stop due to the missing flow.

Chapter 7

Conclusions and future perspectives

The aim of the thesis was the study of the gas systems installed for the LHC experiments at CERN, in particular the RPC gas systems, from the point of view of the maintenance activities. Since these systems are really complex, with a very high number of components and they need to operate continuously during the year, it was necessary to establish new maintenance tasks and upgrades in order to enhance their reliability and availability. Even though the gas systems are used for experimental research, they can be considered at the same level of industrial plants. Therefore, the idea of this work was to apply some industrial based approach like the Reliability Centered Maintenance and in particular the FMECA analysis, in order to perform a sort of reliability study.

To do that, it was necessary to examine the past history of these systems, recorded in the eLOGs, to get some information about the failures and intervention types. In this study, related to the RPC gas systems for ATLAS and CMS, it was evident that these eLOGs were recorded in different ways between the two experiments. In the ATLAS gas system, the information were way less than the CMS one and, due to similar running conditions, it was unlikely that the problems were only in the second one. Therefore, even though this study was time consuming, it was useful to highlight that the eLOGs needed to be recorded with more care by technicians, including all the necessary information, such as type of failure, time spent to repair, pieces or components that were replaced, in order to be easily accessible for future analysis.

The following step was to use the useful information from the previous analysis in the FMECA. This tool was really important, since it helped in the identification of those critical components which require particular attention and dedicated actions. Some criticalities were already spotted, but there were not considered some actions to reduce their severity in case of failure or unexpected event. This procedure was one the most used in the maintenance field and it provided qualitative results on the risk associated to complex industrial systems. However, one of the drawbacks of this method was the arbitrariness of the indexes used to classify the failure modes, depending on the experience and on the way of thinking of the analyst. In fact, for some failure modes, asking different operators, their severity was considered in different ways. Hence, the FMECA applied on the systems was not the 'final' result, but it would need to be revised iteratively, in order to update the information and the contents after some changes or upgrades of the systems. Moreover, since it was the very first application of this method, it was also possible that some potential failures were not identified. Nevertheless, using the FMECA helped into finding some criticalities that were not considered for maintenance activities and can help for the prevention of system stop.

During the analysis, some critical failures were spotted. For example, the pumps of the pump module, in the past, had some issues regarding the membranes even though their planned preventive replacements. In particular, since they are really important for the system, it is useful to monitor also the efficiency of the pumps, which can decrease during the time. A suggestion to be implemented was to check the bypass regulation valve opening trend and to add a flowmeter for a redundant reading, in addition to regularly inspections of the regulation group. Other critical failures regarded the wrong reading of the mass flow controller in the mixer, which can alter the mixture. Therefore, for them periodic calibrations are needed, in addition to the installation of Gas Chromatograph. Another example is the humidifier pump, which had different stops in the past and, for this reason, it was decided to replace the whole pump every year, installing a spare one and send the 'old' one for maintenance and restoration.

Other types of upgrades of the systems were related to the control logic and alarms. For example, to avoid the pump module stop and consequently systems one, after failure of one the pressure or temperature sensors of the pump heads, it was decided to add some warnings before the threshold of the alarm and full stop is triggered. Similarly, the same thing will be implemented in the mixer, to avoid triggering the detection head in case of R-134a or pure isobutane leak. In general, using the FMECA tool for the study, which is a methodology based on the failure modes identification, can help into changing the point of view related to the maintenance activities for the gas systems. In particular, one aspect that needed to be revised was the eLOGs writing. One suggestion to the maintainer was to try to identify the type of failure modes that has occurred, the possible causes, the type of interventions needed, the time spent for the technical and logistic delays, the actual active repair time. In this way, it would be possible to collect the information easily, to perform a maintainability analysis and a more accurate statistics related to the failures, in order to enhance the maintenance performances.

In addition, in order to improve the maintenance of the gas infrastructures, it is necessary to start using a Computerized Maintenance Management Systems (CMMS), like the Enterprise Asset Management (HxGN EAM) used at CERN. This software helps in visualizing all the equipment that are installed in the racks and to efficiently generate work order for maintenance tasks, preventive scheduled work orders or reactive ones for those components which are less critical. In this way, it is easier to access the past actions that were performed and to estimate mean life of components by looking at the interventions. Moreover, through the software it is also possible to track the spare parts and to locate where they are stored or used, allowing a more structured management.

As explained, this analysis was carried on the RPC gas systems, highlighting all the necessary interventions. One possible development of this work is to extend this study also to other systems which have some peculiarities (an example is the ATLAS TGC gas system, which uses a flammable mixture). Moreover, since some recovery systems were built recently and tested, it is also important to establish for them some maintenance procedures, identifying the criticalities and to make them work in a reliable way.

Summarizing, this work reached the goal of establishing a new structured and solid work methodology for the maintenance of the the gas systems, especially for the identifications of those failures which can have huge impact on the system operations. In particular, this systematic approach aimed to reduce, or if possible to remove, that subjective component of treating the failures and interventions, in order to have a more common methodology among the different operators and maintainers. Moreover, the work reiterated the importance of having a structured maintenance management, such as the use of a CMMS.

This work is not the 'final solution', but it a starting point for a more effective and solid organization of the maintenance tasks: therefore, it will need a continuous revision and update to cope with the changes and evolution of the gas systems.

Appendix A

Pump module: P&ID and FMECA table

In this section the P&ID of the Pump Module is shown with the FMECA table that was used for the analysis.

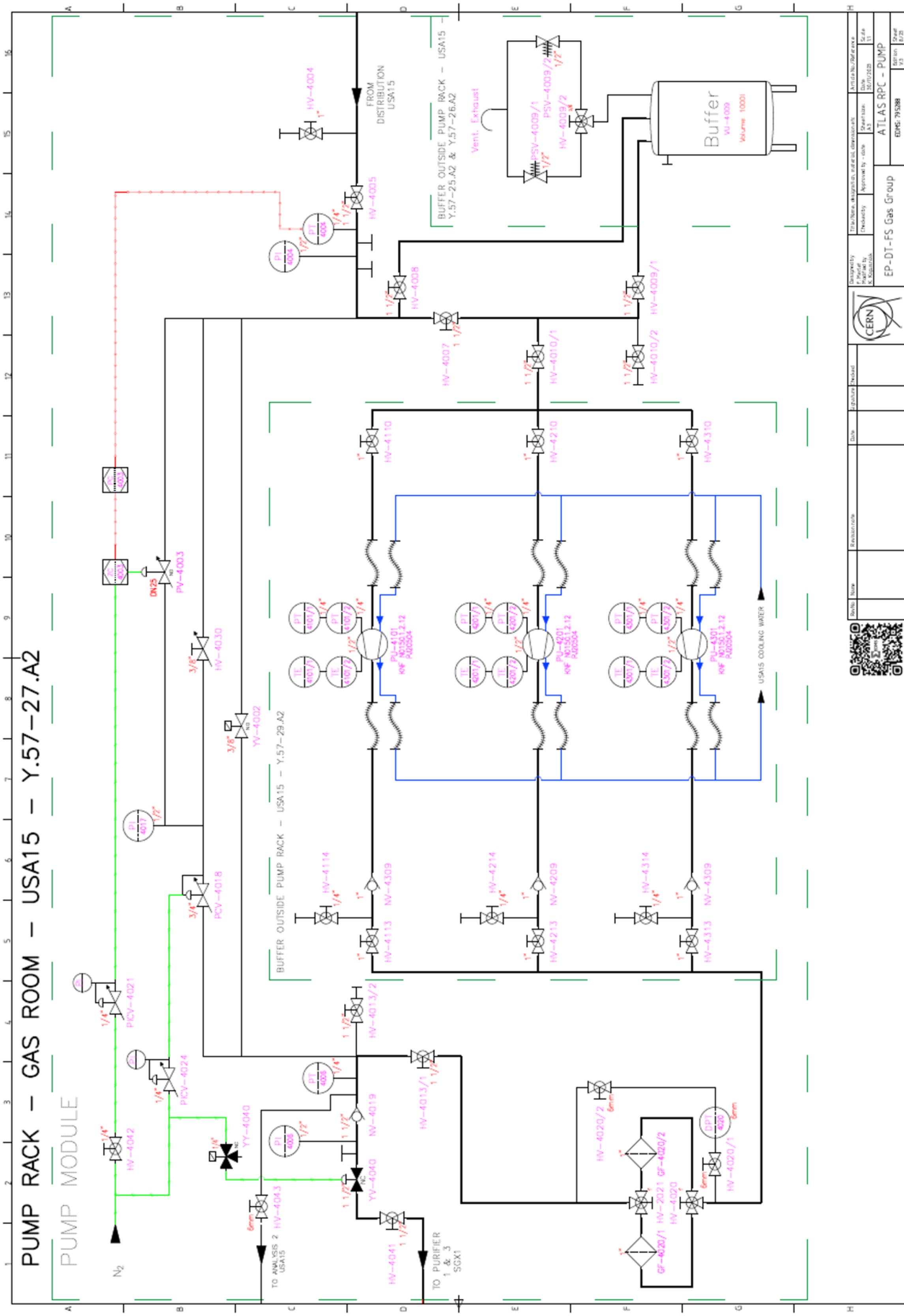


Figure A.1: Pump module P&ID [7]

PUMP MODULE: NORMAL OPERATION											
COMPONENT	P&ID NAME	FAILURE MODE	FAILURE CAUSE	FAILURE EFFECTS			INDEX			IMPROVEMENT ACTION	COMMENT
				LOCALLY	MODULE	SYSTEM	FREQUENCY	SEVERITY	RISK		
PUMP	PU-4101	MEMBRANE PRESSURE TOO HIGH	MEMBRANE DAMAGED	PUMP STOP	MODULE STOP	STOP	3	5	15	add warnings to avoid full stop	severity decrease to 3
		FAIL TO START ON DEMAND	ELECTRICAL or MECHANICAL FAILURE	PUMP NOT WORKING	MODULE STOP	STOP	1	5	5	inspections of the mechanical parts	
		LOW EFFICIENCY	MEMBRANE DAMAGED / MECHANICAL FAILURE	EFFICIENCY DECREASE	LOW OUTPUT FLOW	DISTRIBUTION AFFECTED	3	4	12	check regulation valve position / add flowmeter bypass	worst case scenario: distribution stop
		EXTERNAL LEAK	MEMBRANE DAMAGED	GAS LOSS	GAS LOSS	GAS LOSS	3	2	6		
		INTERNAL LEAK	MEMBRANE DAMAGED	AIR INTAKE	MIXTURE CONTAMINATION	WRONG MIXTURE TO DETECTOR	2	4	8		
		STOP WORKING	WATER LEAK/ELECTRICAL or MECHANICAL FAILURE	PUMP STOP	MODULE STOP	STOP	2	5	10	periodical inspections of the mechanical parts	electrical failure-> trip circuit breaker
PUMP	PU-4201	MEMBRANE PRESSURE TOO HIGH	MEMBRANE DAMAGED	PUMP STOP	MODULE STOP	STOP	3	5	15	add warnings to avoid full stop	severity decrease to 3
		FAIL TO START ON DEMAND	ELECTRICAL or MECHANICAL FAILURE	PUMP NOT WORKING	MODULE STOP	STOP	1	5	5	inspections of the mechanical parts	
		LOW EFFICIENCY	MEMBRANE DAMAGED / MECHANICAL FAILURE	EFFICIENCY DECREASE	LOW OUTPUT FLOW	DISTRIBUTION AFFECTED	3	4	12	check regulation valve position / add flowmeter bypass	worst case scenario: distribution stop
		EXTERNAL LEAK	MEMBRANE DAMAGED	GAS LOSS	GAS LOSS	GAS LOSS	3	2	6		
		INTERNAL LEAK	MEMBRANE DAMAGED	AIR INTAKE	MIXTURE CONTAMINATION	WRONG MIXTURE TO DETECTOR	2	4	8		
		STOP WORKING	WATER LEAK/ELECTRICAL or MECHANICAL FAILURE	PUMP STOP	MODULE STOP	STOP	2	5	10	periodical inspections of the mechanical parts	electrical failure-> trip circuit breaker
PUMP	PU-4301	MEMBRANE PRESSURE TOO HIGH	MEMBRANE DAMAGED	PUMP STOP	MODULE STOP	STOP	3	5	15	add warnings to avoid full stop	severity decrease to 3
		FAIL TO START ON DEMAND	ELECTRICAL or MECHANICAL FAILURE	PUMP NOT WORKING	MODULE STOP	STOP	1	5	5	inspections of the mechanical parts	
		LOW EFFICIENCY	MEMBRANE DAMAGED / MECHANICAL FAILURE	EFFICIENCY DECREASE	LOW OUTPUT FLOW	DISTRIBUTION AFFECTED	3	4	12	check regulation valve position / add flowmeter bypass	worst case scenario: distribution stop
		EXTERNAL LEAK	MEMBRANE DAMAGED	GAS LOSS	GAS LOSS	GAS LOSS	3	2	6		
		INTERNAL LEAK	MEMBRANE DAMAGED	AIR INTAKE	MIXTURE CONTAMINATION	WRONG MIXTURE TO DETECTOR	2	4	8		
		STOP WORKING	WATER LEAK/ELECTRICAL or MECHANICAL FAILURE	PUMP STOP	MODULE STOP	STOP	2	5	10	periodical inspections of the mechanical parts	electrical failure-> trip circuit breaker
NON RETURN VALVE	NV-4109	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	BACKFLOW / FILTER CLOG	MODULE LOOSE EFFCIENCY	DISTRIBUTION AFFECTED	3	2	6	increase periodical inspections on spring / replacement	frequency can be reduced
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	MODULE STOP	SYSTEM STOP	1	5	5		
NON RETURN VALVE	NV-4209	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	BACKFLOW / FILTER CLOG	MODULE LOOSE EFFCIENCY	DISTRIBUTION AFFECTED	3	2	6	increase periodical inspections on spring / replacement	frequency can be reduced
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	MODULE STOP	SYSTEM STOP	1	5	5		
NON RETURN VALVE	NV-4309	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	BACKFLOW / FILTER CLOG	MODULE LOOSE EFFCIENCY	DISTRIBUTION AFFECTED	3	2	6	increase periodical inspections on spring / replacement	frequency can be reduced
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	MODULE STOP	SYSTEM STOP	1	5	5		
NON RETURN VALVE	NV-4019	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	BACKFLOW	MODULE LOOSE EFFCIENCY	DISTRIBUTION AFFECTED	2	3	6	increase periodical inspections on spring / replacement	worst case scenario: distribution stop very critical if failed during system restart with YV-4040 failed
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	MODULE STOP	SYSTEM STOP	1	5	5		
REGULATION VALVE	PV-4003	EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	3	6		
		BLOCKED	MECHANICAL FAILURE	PUMP AFFECTED	NO REGULATION / NO FAILSAFE	SYSTEM STOP	1	5	5	check status once a year	
ACTUATOR	ZC-4003	UNSTABLE REGULATION	SPRING / MEMBRANE FAILURE	PV-4003 WRONG POSITION / NO FAILSAFE	BAD REGULATION ON PUMP	DISTRIBUTION AFFECTED	2	4	8	check status once a year	actuator fail to keep position
		STUCK	MEHCANICAL FAILURE	NO REGULATION ON PV-4003	PUMP REGULATION FAIL	SYSTEM STOP	2	5	10	add and check flowmeter to avoid full stop	severity can be reduced to 4 - time to intervene
CONTROLLER	PC-4003	REGULATION LOSS	ELECTRICAL FAILURE / FEEDBACK PROBLEM	NO REGULATION ON PV-4003	PUMP REGULATION FAIL	SYSTEM STOP	2	5	10	periodical check on electrical part	frequency can be reduced
PRESSURE REGULATOR	PICV-4021	SPURIOUS OPENING	MECHANICAL FAILURE	PV-4003 AFFECTED	REGULATION ON PT-4004 WORSEN (WORST CASE)	DISTRIB. PRESSURE WORSEN (WORST CASE)	2	2	4		it can have effect on actuator and controller
		EXTERAL LEAK	SEAL FAILURE	GAS LOSS (DRY AIR / N2)	REGULATION ON PT-4004 WORSEN (WORST CASE)	DISTRIB. PRESSURE WORSEN (WORST CASE)	2	2	4		
PRESSURE REGULATOR	PCV-4018	SPURIOUS OPENING	MECHANICAL FAILURE	PV-4003 AFFECTED	REGULATION PV-4003 AFFECTED	DISTRIBUTION AFFECTED	2	4	8	it can be removed - additional point of failure	not always used - spurious opening if 4021 got spurious opening
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	REGULATION AFFECTED	DISTRIBUTION AFFECTED	2	4	8		
		INTERNAL LEAK	MEMBRANE FAILURE	DRY AIR / N2 INTAKE	MIXTURE CONTAMINATION	WRONG MIXTURE TO DETECTOR	1	5	5		it can leak in since connected to pneumatic line - N2 contam.
PRESSURE REGULATOR	PICV-4024	SPURIOUS OPENING	MECHANICAL FAILURE	PCV-4018 SLIGHTLY AFFECTED	NEGLIGIBLE EFFECT	NO EFFECT	2	1	2		
		EXTERNAL LEAK	SEAL FAILIURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
MANUAL REGULATION VALVE	HV-4030	EXTERNAL LEAK	SEAL DAMAGE	GAS LOSS	NEGLIGIBLE EFFECT ON PV-4003	NEGLIGIBLE EFFECT ON DISTRIBUTION	2	3	6		
PNEUMATIC VALVE	YV-4040	SUDDEN CLOSED	MECHANICAL FAILURE	NO FLOW FROM PUMP MODULE	MODULE STOP	SYSTEM STOP	2	5	10	check N2 pressure on pneumatic line	very critical if failed during restart with NV-4019
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-4040	STUCK CLOSED	ELECTRICAL PROBLEM	EFFECT ON YV-4040	MODULE STOP	SYSTEM STOP	1	5	5		
			SEAL FAILURE								
ELECTROVALVE	YY-4002	STUCK CLOSED	ELECTRICAL PROBLEM	PUMP NOT WORK	MODULE STOP	SYSTEM STOP	1	5	5		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		

Figure A.2: Pump module FMECA table (part 1)

PUMP MODULE: NORMAL OPERATION											
COMPONENT	P&ID NAME	FAILURE MODE	FAILURE CAUSE	FAILURE EFFECTS			INDEX			IMPROVEMENT ACTION	COMMENT
				LOCALLY	MODULE	SYSTEM	FREQUENCY	SEVERITY	RISK		
FILTER	GF-4020/1	CLOGGED	DUST INSIDE	HIGH Δp	SWITCH ON OTHER FILTER	SYSTEM SLIGHTY AFFECTED	3	2	6		
		EXTERNAL LEAK	MECHANICAL RUPTURE	GAS LOSS	GAS LOSS	GAS LOSS	3	2	6		
FILTER	GF-4020/2	CLOGGED	DUST INSIDE	HIGH Δp	SWITCH ON OTHER FILTER	SYSTEM SLIGHTY AFFECTED	3	2	6		
		EXTERNAL LEAK	MECHANICAL RUPTURE	GAS LOSS	GAS LOSS	GAS LOSS	3	2	6		
PRESSURE SENSOR	PT-4004	DRIFT	ELECTRICAL FAILURE	WRONG READING	WRONG PUMP REGULATION	DISTRIBUTION AFFECTED	2	4	8	additional inspections and calibration	
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	PT-4004 OUT OF SCALE	MODULE STOP	SYSTEM STOP	1	5	5	periodical replacement / add parallel one	additional one reduce severity to 3
		INTERNAL LEAK	MECHANICAL FAILURE	AIR INTAKE	MIXTURE CONTAMINATION	WORNG MIXTURE TO DETECTOR	1	4	4		
PRESSURE SENSOR	PT-4006	DRIFT	ELECTRICAL FAILURE	WRONG OUTPUT READING	NEGLIGIBLE EFFECT	NO EFFECT	2	1	2		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	WRONG OUTPUT READING	NEGLIGIBLE EFFECT	NO EFFECT	1	1	1		
		EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
DIFFERENTIAL PRESSURE SENSOR	DPT-4020	DRIFT	ELECTRICAL PROBLEM	NO PRESSURE LOSS READING	NEGLIGIBLE	NEGLIGIBLE	2	1	2		
		BROKEN ELECTRONICS	ELECTRICAL PROBLEM	NO PRESSURE LOSS READING	NEGLIGIBLE	NEGLIGIBLE	1	1	1		
		EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
BUFFER	VU-4009	INTERNAL LEAK	MECHANICAL FAILURE	AIR INTAKE	MIXTURE CONTAMINATION	WRONG MIXTURE TO DETECTOR	1	5	5		external leak in case of NV-4019 failure and overpressure
PRESSURE SAFETY VALVE	PSV-4009/1	INTERNAL LEAK	MECHANICAL FAILURE	BUFFER PRESSURE AFFECTED	MIXTURE CONTAMINATION	WRONG MIXTURE TO DETECTOR	2	4	8		
		STUCK	MECHANICAL FAILURE	NO PRESSURE RELIEF	BUFFER OVERPRESSURE	SYSTEM OVERPRESSURE	1	5	5		ACCIDENT scenario with NV-4019 failed
PRESSURE SAFETY VALVE	PSV-4009/2	INTERNAL LEAK	MECHANICAL FAILURE	BUFFER PRESSURE AFFECTED	MIXTURE CONTAMINATION	WRONG MIXTURE TO DETECTOR	2	4	8		
		STUCK	MECHANICAL FAILURE	NO PRESSURE RELIEF	BUFFER OVERPRESSURE	SYSTEM OVERPRESSURE	1	5	5		ACCIDENT scenario with NV-4019 failed
PRESSURE SENSOR	PT-4101/1	DRIFT	ELECTRICAL FAILURE	PUMP AFFECTED	MODULE ALARM	SYSTEM ALARM	2	4	8	add warnings	pump can still work - there is time to intervene - severity reduced
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	periodic calibration or replacement	
		INTERNAL AND EXTERNAL LEAK	MEBRANE BROKEN	GAS LOSS AND AIR INTAKE	MIXTURE AFFECTED	WRONG MIXTURE TO DETECTOR	2	5	10		
PRESSURE SENSOR	PT-4101/2	DRIFT	ELECTRICAL FAILURE	PUMP AFFECTED	MODULE ALARM	SYSTEM ALARM	2	4	8	add warnings	pump can still work - there is time to intervene - severity reduced
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	periodic calibration or replacement	
		INTERNAL AND EXTERNAL LEAK	MEBRANE BROKEN	GAS LOSS AND AIR INTAKE	MIXTURE AFFECTED	WRONG MIXTURE TO DETECTOR	2	5	10		
PRESSURE SENSOR	PT-4201/1	DRIFT	ELECTRICAL FAILURE	PUMP AFFECTED	MODULE ALARM	SYSTEM ALARM	2	4	8	add warnings	pump can still work - there is time to intervene - severity reduced
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	periodic calibration or replacement	
		INTERNAL AND EXTERNAL LEAK	MEBRANE BROKEN	GAS LOSS AND AIR INTAKE	MIXTURE AFFECTED	WRONG MIXTURE TO DETECTOR	2	5	10		
PRESSURE SENSOR	PT-4201/2	DRIFT	ELECTRICAL FAILURE	PUMP AFFECTED	MODULE ALARM	SYSTEM ALARM	2	4	8	add warnings	pump can still work - there is time to intervene - severity reduced
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	periodic calibration or replacement	
		INTERNAL AND EXTERNAL LEAK	MEBRANE BROKEN	GAS LOSS AND AIR INTAKE	MIXTURE AFFECTED	WRONG MIXTURE TO DETECTOR	2	5	10		
PRESSURE SENSOR	PT-4301/1	DRIFT	ELECTRICAL FAILURE	PUMP AFFECTED	MODULE ALARM	SYSTEM ALARM	2	4	8	add warnings	pump can still work - there is time to intervene - severity reduced
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	periodic calibration or replacement	
		INTERNAL AND EXTERNAL LEAK	MEBRANE BROKEN	GAS LOSS AND AIR INTAKE	MIXTURE AFFECTED	WRONG MIXTURE TO DETECTOR	2	5	10		
PRESSURE SENSOR	PT-4301/2	DRIFT	ELECTRICAL FAILURE	PUMP AFFECTED	MODULE ALARM	SYSTEM ALARM	2	4	8	add warnings	pump can still work - there is time to intervene - severity reduced
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	periodic calibration or replacement	
		INTERNAL AND EXTERNAL LEAK	MEBRANE BROKEN	GAS LOSS AND AIR INTAKE	MIXTURE AFFECTED	WRONG MIXTURE TO DETECTOR	2	5	10		
TEMPERATURE SENSOR	TE-4101/1	DRIFT	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	add warnings	pump can still work - there is time to intervene - severity reduced
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	check other sensor (control logic)	avoid full stop - severity reduced
TEMPERATURE SENSOR	TE-4101/2	DRIFT	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	alarm should not trigger full stop	pump can still work - there is time to intervene
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	additional inspections	
TEMPERATURE SENSOR	TE-4201/1	DRIFT	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	alarm should not trigger full stop	pump can still work - there is time to intervene
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	additional inspections	
TEMPERATURE SENSOR	TE-4201/2	DRIFT	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	alarm should not trigger full stop	pump can still work - there is time to intervene
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	additional inspections	
TEMPERATURE SENSOR	TE-4301/1	DRIFT	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	alarm should not trigger full stop	pump can still work - there is time to intervene
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	additional inspections	
TEMPERATURE SENSOR	TE-4301/2	DRIFT	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	alarm should not trigger full stop	pump can still work - there is time to intervene
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	PUMP STOP	MODULE STOP	SYSTEM STOP	1	5	5	additional inspections	

Figure A.3: Pump module FMECA table (part 2)

Appendix B

Mixer module: P&ID and FMECA table

In this section the P&ID of the Mixer Module is shown with the FMECA table that was used for the analysis.

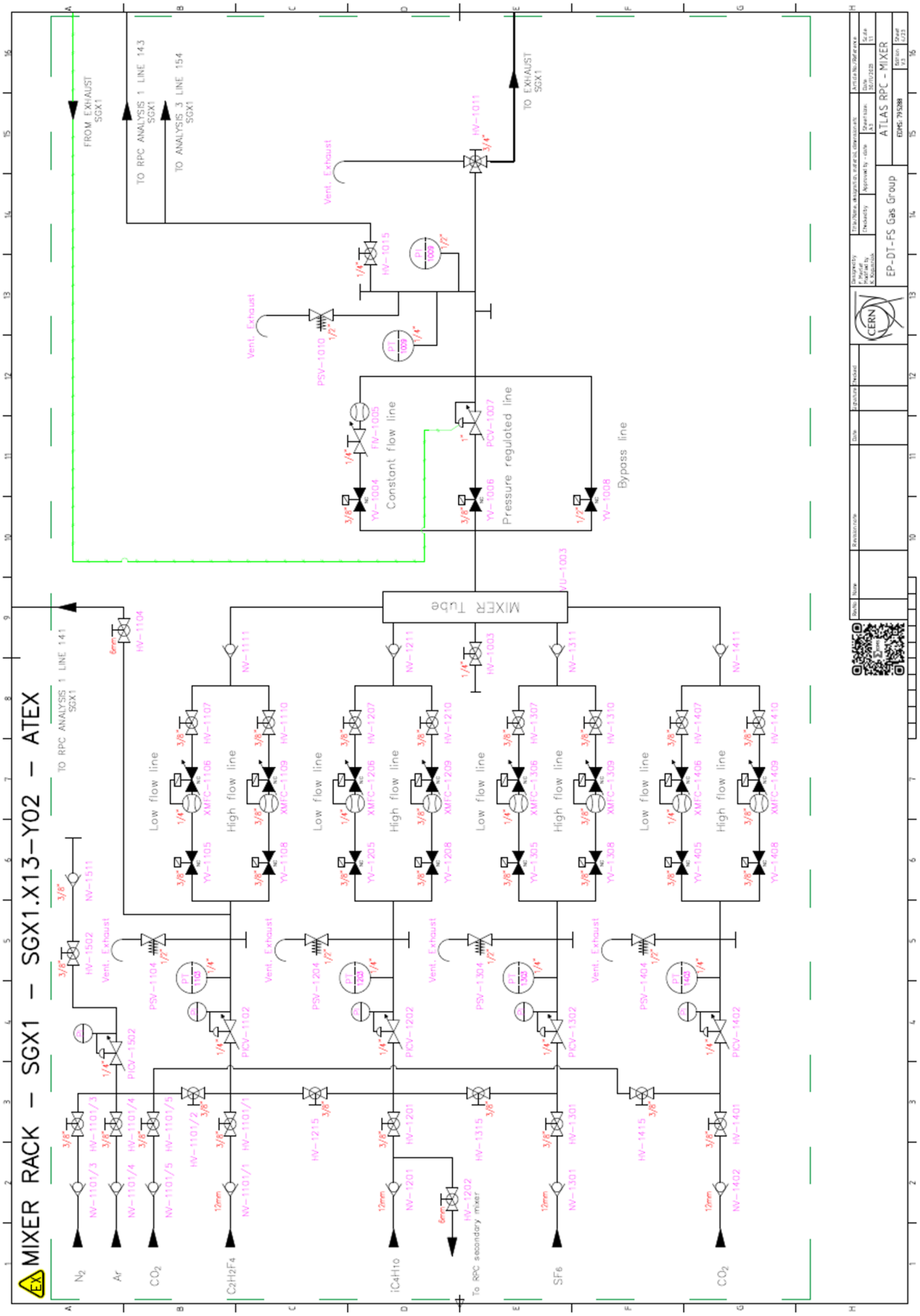


Figure B.1: Mixer module P&ID [7]

MIXER MODULE: NORMAL OPERATION											
COMPONENT	P&ID NAME	FAILURE MODE	FAILURE CAUSE	FAILURE EFFECTS			RISK INDEX			IMPROVEMENT ACTION	COMMENT
				LOCALLY	MODULE	SYSTEM	FREQUENCY	SEVERITY	RISK		
PRESSURE SAFETY VALVE	PSV-1104	SUDDEN OPENING	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	4	4	add warning - threshold before trigger stop	
		EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	GAS LOSS / MODULE STOP	GAS LOSS / SYSTEM STOP	1	4	4	add warning - threshold before trigger stop	FREON: detection head in case huge loss
PRESSURE SAFETY VALVE	PSV-1204	SUDDEN OPENING	MECHANICAL FAILURE	FLAMMABLE GAS LOSS	MODULE STOP	SYSTEM STOP	1	5	5	add warning - threshold before trigger stop	
		EXTERNAL LEAK	MECHANICAL FAILURE	FLAMMABLE GAS LOSS	MODULE STOP	SYSTEM STOP	1	5	5	add warning - threshold before trigger stop	
PRESSURE SAFETY VALVE	PSV-1304	SUDDEN OPENING	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
PRESSURE SAFETY VALVE	PSV-1404	SUDDEN OPENING	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
PRESSURE SAFETY VALVE	PSV-1010	SUDDEN OPENING	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	GAS LOSS / MODULE STOP	GAS LOSS / SYSTEM STOP	1	4	4		high freon concentration
MASS FLOW CONTROLLER	XMFC-1106	WRONG READOUT	OUT OF CALIBRATION	WRONG FLOW	WRONG MIXTURE COMPOSITION	WRONG MIXTURE TO DETECTOR	3	4	12	additional calibration / GC installation	
		STUCK	MECHANICAL FAILURE	NO FLOW	MIXER STOP	PERFORMANCES REDUCED	1	3	3		
		EXTERNAL LEAK after	SEAL FAILURE	GAS LOSS	WRONG MIXTURE COMPOSITION	WRONG MIXTURE TO DETECTOR / STOP	2	4	8	additional inspection for leaks	FREON loss
		EXTERNAL LEAK before	SEAL FAILURE	GAS LOSS	GAS LOSS / MODULE STOP	GAS LOSS / SYSTEM STOP	2	4	8	add warning - threshold before trigger stop	FREON loss
		INTERNAL LEAK	SEAL FAILURE	WRONG MIXTURE	WRONG MIXTURE COMPOSITION	WRONG MIXTURE	2	3	6		more critical for low concentration gas
		UNSTABLE	SOFTWARE PROBLEM	WRONG FLOW	MIXTURE AFFECTED	MIXTURE AFFECTED	2	3	6		
		NO COMUNICATION	ELECTRICAL FAILURE	NO FLOW	MODULE STOP	SYSTEM STOP	2	4	8		
MASS FLOW CONTROLLER	XMFC-1109	WRONG READOUT	OUT OF CALIBRATION	WRONG FLOW	WRONG MIXTURE COMPOSITION	WRONG MIXTURE TO DETECTOR	3	4	12	additional calibration / GC installation	
		STUCK	MECHANICAL FAILURE	NO FLOW	MIXER STOP	PERFORMANCES REDUCED	1	3	3		
		EXTERNAL LEAK after	SEAL FAILURE	GAS LOSS	WRONG MIXTURE COMPOSITION	WRONG MIXTURE TO DETECTOR / STOP	2	4	8	additional inspection for leaks	FREON loss
		EXTERNAL LEAK before	SEAL FAILURE	GAS LOSS	GAS LOSS / MODULE STOP	GAS LOSS / SYSTEM STOP	2	4	8	add warning - threshold before trigger stop	FREON loss
		INTERNAL LEAK	SEAL FAILURE	WRONG MIXTURE	WRONG MIXTURE COMPOSITION	WRONG MIXTURE	2	3	6		more critical for low concentration gas
		UNSTABLE	SOFTWARE PROBLEM	WRONG FLOW	MIXTURE AFFECTED	MIXTURE AFFECTED	2	3	6		
		NO COMUNICATION	ELECTRICAL FAILURE	NO FLOW	MODULE STOP	SYSTEM STOP	2	4	8		
MASS FLOW CONTROLLER	XMFC-1206	WRONG READOUT	OUT OF CALIBRATION	WRONG FLOW	WRONG MIXTURE COMPOSITION	WRONG MIXTURE TO DETECTOR	3	4	12	additional calibration / GC installation	
		STUCK	MECHANICAL FAILURE	NO FLOW	MIXER STOP	PERFORMANCES REDUCED	1	3	3		
		EXTERNAL LEAK after	SEAL FAILURE	FLAMMABLE GAS LOSS	MODULE STOP	SYSTEM STOP	2	5	10	add warning - threshold before trigger stop	
		EXTERNAL LEAK before	SEAL FAILURE	FLAMMABLE GAS LOSS	MODULE STOP	SYSTEM STOP	2	5	10	add warning - threshold before trigger stop	
		INTERNAL LEAK	SEAL FAILURE	WRONG MIXTURE	WRONG MIXTURE COMPOSITION	WRONG MIXTURE	2	3	6		more critical for low concentration gas
		UNSTABLE	SOFTWARE PROBLEM	WRONG FLOW	MIXTURE AFFECTED	MIXTURE AFFECTED	2	3	6		
		NO COMUNICATION	ELECTRICAL FAILURE	NO FLOW	MODULE STOP	SYSTEM STOP	2	4	8		
MASS FLOW CONTROLLER	XMFC-1209	WRONG READOUT	OUT OF CALIBRATION	WRONG FLOW	WRONG MIXTURE COMPOSITION	WRONG MIXTURE TO DETECTOR	3	4	12	additional calibration / GC installation	
		STUCK	MECHANICAL FAILURE	NO FLOW	MIXER STOP	PERFORMANCES REDUCED	1	3	3		
		EXTERNAL LEAK after	SEAL FAILURE	FLAMMABLE GAS LOSS	MODULE STOP	SYSTEM STOP	2	5	10	add warning - threshold before trigger stop	
		EXTERNAL LEAK before	SEAL FAILURE	FLAMMABLE GAS LOSS	MODULE STOP	SYSTEM STOP	2	5	10	add warning - threshold before trigger stop	
		INTERNAL LEAK	SEAL FAILURE	WRONG MIXTURE	WRONG MIXTURE COMPOSITION	WRONG MIXTURE	2	3	6		more critical for low concentration gas
		UNSTABLE	SOFTWARE PROBLEM	WRONG FLOW	MIXTURE AFFECTED	MIXTURE AFFECTED	2	3	6		
		NO COMUNICATION	ELECTRICAL FAILURE	NO FLOW	MODULE STOP	SYSTEM STOP	2	4	8		
MASS FLOW CONTROLLER	XMFC-1306	WRONG READOUT	OUT OF CALIBRATION	WRONG FLOW	WRONG MIXTURE COMPOSITION	WRONG MIXTURE TO DETECTOR	3	4	12	additional calibration / GC installation	
		STUCK	MECHANICAL FAILURE	NO FLOW	MIXER STOP	PERFORMANCES REDUCED	1	3	3		
		EXTERNAL LEAK after	SEAL FAILURE	GAS LOSS	WRONG MIXTURE COMPOSITION	WRONG MIXTURE TO DETECTOR	2	4	8	additional inspection for leaks	
		EXTERNAL LEAK before	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		INTERNAL LEAK	SEAL FAILURE	WRONG MIXTURE	WRONG MIXTURE COMPOSITION	WRONG MIXTURE	2	3	6		more critical for low concentration gas
		UNSTABLE	SOFTWARE PROBLEM	WRONG FLOW	MIXTURE AFFECTED	MIXTURE AFFECTED	2	3	6		
		NO COMUNICATION	ELECTRICAL FAILURE	NO FLOW	MODULE STOP	SYSTEM STOP	2	4	8		
MASS FLOW CONTROLLER	XMFC-1309	WRONG READOUT	OUT OF CALIBRATION	WRONG FLOW	WRONG MIXTURE COMPOSITION	WRONG MIXTURE TO DETECTOR	3	4	12	additional calibration / GC installation	
		STUCK	MECHANICAL FAILURE	NO FLOW	MIXER STOP	PERFORMANCES REDUCED	1	3	3		
		EXTERNAL LEAK after	SEAL FAILURE	GAS LOSS	WRONG MIXTURE COMPOSITION	WRONG MIXTURE TO DETECTOR	2	4	8	additional inspection for leaks	
		EXTERNAL LEAK before	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		INTERNAL LEAK	SEAL FAILURE	WRONG MIXTURE	WRONG MIXTURE COMPOSITION	WRONG MIXTURE	2	3	6		more critical for low concentration gas
		UNSTABLE	SOFTWARE PROBLEM	WRONG FLOW	MIXTURE AFFECTED	MIXTURE AFFECTED	2	3	6		
		NO COMUNICATION	ELECTRICAL FAILURE	NO FLOW	MODULE STOP	SYSTEM STOP	2	4	8		
MASS FLOW CONTROLLER	XMFC-1406	WRONG READOUT	OUT OF CALIBRATION	WRONG FLOW	WRONG MIXTURE COMPOSITION	WRONG MIXTURE TO DETECTOR	3	4	12	additional calibration / GC installation	
		STUCK	MECHANICAL FAILURE	NO FLOW	MIXER STOP	PERFORMANCES REDUCED	1	3	3		
		EXTERNAL LEAK after	SEAL FAILURE	GAS LOSS	WRONG MIXTURE COMPOSITION	WRONG MIXTURE TO DETECTOR	2	4	8	additional inspection for leaks	
		EXTERNAL LEAK before	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		INTERNAL LEAK	SEAL FAILURE	WRONG MIXTURE	WRONG MIXTURE COMPOSITION	WRONG MIXTURE	2	3	6		more critical for low concentration gas
		UNSTABLE	SOFTWARE PROBLEM	WRONG FLOW	MIXTURE AFFECTED	MIXTURE AFFECTED	2	3	6		
		NO COMUNICATION	ELECTRICAL FAILURE	NO FLOW	MODULE STOP	SYSTEM STOP	2	4	8		
MASS FLOW CONTROLLER	XMFC-1409	WRONG READOUT	OUT OF CALIBRATION	WRONG FLOW	WRONG MIXTURE COMPOSITION	WRONG MIXTURE TO DETECTOR	3	4	12	additional calibration / GC installation	
		STUCK	MECHANICAL FAILURE	NO FLOW	MIXER STOP	PERFORMANCES REDUCED	1	3	3		
		EXTERNAL LEAK after	SEAL FAILURE	GAS LOSS	WRONG MIXTURE COMPOSITION	WRONG MIXTURE TO DETECTOR	2	4	8	additional inspection for leaks	
		EXTERNAL LEAK before	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		INTERNAL LEAK	SEAL FAILURE	WRONG MIXTURE	WRONG MIXTURE COMPOSITION	WRONG MIXTURE	2	3	6		more critical for low concentration gas
		UNSTABLE	SOFTWARE PROBLEM	WRONG FLOW	MIXTURE AFFECTED	MIXTURE AFFECTED	2	3	6		
		NO COMUNICATION	ELECTRICAL FAILURE	NO FLOW	MODULE STOP	SYSTEM STOP	2	4	8		

Figure B.2: Mixer module FMECA table (part 1)

MIXER MODULE: NORMAL OPERATION											
COMPONENT	P&ID NAME	FAILURE MODE	FAILURE CAUSE	FAILURE EFFECTS			RISK INDEX			IMPROVEMENT ACTION	COMMENT
				LOCALLY	MODULE	SYSTEM	FREQUENCY	SEVERITY	RISK		
ELECTROVALVE	YV-1105	STUCK CLOSED	ELECTRICAL FAILURE	NO FLOW IN THE LINE	NO FLOW TO MFC	WRONG MIXTURE	2	3	6		switch on other line
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS FREON	GAS LOSS	GAS LOSS	2	4	8	add warning - threshold before trigger stop	
		INTERNAL LEAK	SEAL FAILURE	MIXTURE AFFECTED	MIXTURE AFFECTED	MIXTURE AFFECTED	1	4	4		if also MCF leak through
ELECTROVALVE	YV-1108	STUCK CLOSED	ELECTRICAL FAILURE	NO FLOW IN THE LINE	NO FLOW TO MFC	WRONG MIXTURE	2	3	6		switch on other line
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS FREON	GAS LOSS / MODULE STOP	GAS LOSS / SYSTEM STOP	2	4	8	add warning - threshold before trigger stop	
		INTERNAL LEAK	SEAL FAILURE	MIXTURE AFFECTED	MIXTURE AFFECTED	MIXTURE AFFECTED	1	4	4		if also MCF leak through
ELECTROVALVE	YV-1205	STUCK CLOSED	ELECTRICAL FAILURE	NO FLOW IN THE LINE	NO FLOW TO MFC	WRONG MIXTURE	2	3	6		switch on other line
		EXTERNAL LEAK	SEAL FAILURE	FLAMMABLE GAS LOSS	MODULE STOP	SYSTEM STOP	2	5	10	add warning - threshold before trigger stop	
		INTERNAL LEAK	SEAL FAILURE	MIXTURE AFFECTED	MIXTURE AFFECTED	MIXTURE AFFECTED	1	4	4		if also MCF leak through
ELECTROVALVE	YV-1208	STUCK CLOSED	ELECTRICAL FAILURE	NO FLOW IN THE LINE	NO FLOW TO MFC	WRONG MIXTURE	2	3	6		switch on other line
		EXTERNAL LEAK	SEAL FAILURE	FLAMMABLE GAS LOSS	MODULE STOP	SYSTEM STOP	2	5	10	add warning - threshold before trigger stop	
		INTERNAL LEAK	SEAL FAILURE	MIXTURE AFFECTED	MIXTURE AFFECTED	MIXTURE AFFECTED	1	4	4		if also MCF leak through
ELECTROVALVE	YV-1305	STUCK CLOSED	ELECTRICAL FAILURE	NO FLOW IN THE LINE	NO FLOW TO MFC	WRONG MIXTURE	2	3	6		switch on other line
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		INTERNAL LEAK	SEAL FAILURE	MIXTURE AFFECTED	MIXTURE AFFECTED	MIXTURE AFFECTED	1	4	4		if also MCF leak through
ELECTROVALVE	YV-1308	STUCK CLOSED	ELECTRICAL FAILURE	NO FLOW IN THE LINE	NO FLOW TO MFC	WRONG MIXTURE	2	3	6		switch on other line
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		INTERNAL LEAK	SEAL FAILURE	MIXTURE AFFECTED	MIXTURE AFFECTED	MIXTURE AFFECTED	1	4	4		if also MCF leak through
ELECTROVALVE	YV-1405	STUCK CLOSED	ELECTRICAL FAILURE	NO FLOW IN THE LINE	NO FLOW TO MFC	WRONG MIXTURE	2	3	6		switch on other line
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		INTERNAL LEAK	SEAL FAILURE	MIXTURE AFFECTED	MIXTURE AFFECTED	MIXTURE AFFECTED	1	4	4		if also MCF leak through
ELECTROVALVE	YV-1408	STUCK CLOSED	ELECTRICAL FAILURE	NO FLOW IN THE LINE	NO FLOW TO MFC	WRONG MIXTURE	2	3	6		switch on other line
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		INTERNAL LEAK	SEAL FAILURE	MIXTURE AFFECTED	MIXTURE AFFECTED	MIXTURE AFFECTED	1	4	4		if also MCF leak through
ELECTROVALVE	YV-1004	STUCK CLOSED	ELECTRICAL FAILURE	LINE CLOSED	CONSTANT FLOW LINE CLOSED	CONSTANT FLOW INJECTION LOSS	2	2	4		system find new equilibrium
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YV-1006	STUCK CLOSED	ELECTRICAL FAILURE	LINE CLOSED	CONSTANT PRESSURE LINE CLOSED	CONSTANT PRESSURE INJECTION LOSS	2	2	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YV-1008	STUCK CLOSED	ELECTRICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		purge line
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE REGULATOR	PICV-1102	SUDDEN OPENING	MECHANICAL FAILURE	NO PRESSURE REDUCTION	FREON LIQUID PHASE / SF6 CANNOT ENTER MIXTURE	MIXTURE PROBLEM	2	4	8		more critical if module keep working
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS FREON	GAS LOSS / MODULE STOP	GAS LOSS / SYSTEM STOP	2	4	8		
PRESSURE REGULATOR	PICV-1202	SUDDEN OPENING	MECHANICAL FAILURE	NO PRESSURE REDUCTION	ISOBUTANE LIQUID PHASE/ SF6 CANNOT ENTER MIXTURE	MIXTURE PROBLEM	2	4	8		more critical if module keep working
		EXTERNAL LEAK	SEAL FAILURE	FLAMMABLE GAS LOSS	MODULE STOP	SYSTEM STOP	2	5	10	add warning - threshold before trigger stop	
PRESSURE REGULATOR	PICV-1302	SUDDEN OPENING	MECHANICAL FAILURE	NO PRESSURE REDUCTION	SF6 HIGH PRESSURE	NEGLIGIBLE EFFECT	2	2	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE REGULATOR	PICV-1402	SUDDEN OPENING	MECHANICAL FAILURE	NO PRESSURE REDUCTION	CO2 HIGH PRESSURE	NEGLIGIBLE EFFECT	2	2	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE REGULATOR	PICV-1502	SUDDEN OPENING	MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE REGULATOR	PCV-1007	SUDDEN OPENING	MECHANICAL FAILURE	NO PRESSURE REGULATION	MODULE INSTABILITIES	FLOW OSCILLATIONS	2	3	6		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		INTERNAL LEAK	MEMBRANE FAILURE	N2 CONTAMINATION	MIXTURE CONTAMINATION	WRONG MIXTURE	2	4	8		

Figure B.3: Mixer module FMECA table (part 2)

MIXER MODULE: NORMAL OPERATION											
COMPONENT	P&ID NAME	FAILURE MODE	FAILURE CAUSE	FAILURE EFFECTS			RISK INDEX			IMPROVEMENT ACTION	COMMENT
				LOCALLY	MODULE	SYSTEM	FREQUENCY	SEVERITY	RISK		
NON RETURN VALVE	NV-1101/1	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	POSSIBLE BACKFLOW	POSSIBLE MODULE INSTABILITIES	SYSTEM AFFECTED	2	3	6		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS FREON	GAS LOSS FREON	GAS LOSS FREON	1	4	4	add warning - threshold before trigger stop	
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	WRONG MIXTURE	WRONG MIXTURE	1	4	4		
NON RETURN VALVE	NV-1101/3	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	WRONG MIXTURE	WRONG MIXTURE	1	4	4		
NON RETURN VALVE	NV-1101/4	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	WRONG MIXTURE	WRONG MIXTURE	1	4	4		
NON RETURN VALVE	NV-1101/5	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	WRONG MIXTURE	WRONG MIXTURE	1	4	4		
NON RETURN VALVE	NV-1201	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	POSSIBLE BACKFLOW	POSSIBLE MODULE INSTABILITIES	SYSTEM AFFECTED	2	3	6		
		EXTERNAL LEAK	SEAL FAILURE	FLAMMABLE GAS LOSS	MODULE STOP	SYSTEM STOP	1	5	5	add warning - threshold before trigger stop	
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	WRONG MIXTURE	WRONG MIXTURE	1	4	4		
NON RETURN VALVE	NV-1301	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	POSSIBLE BACKFLOW	POSSIBLE MODULE INSTABILITIES	SYSTEM AFFECTED	2	3	6		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	WRONG MIXTURE	WRONG MIXTURE	1	4	4		
NON RETURN VALVE	NV-1401	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	POSSIBLE BACKFLOW	POSSIBLE MODULE INSTABILITIES	SYSTEM AFFECTED	2	3	6		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	WRONG MIXTURE	WRONG MIXTURE	1	4	4		
NON RETURN VALVE	NV-1111	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	POSSIBLE BACKFLOW	POSSIBLE MODULE INSTABILITIES	SYSTEM AFFECTED	2	3	6		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS FREON	GAS LOSS / MODULE STOP	GAS LOSS / SYSTEM STOP	1	4	4	add warning - threshold before trigger stop	
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	WRONG MIXTURE	WRONG MIXTURE	1	4	4		
NON RETURN VALVE	NV-1211	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	POSSIBLE BACKFLOW	POSSIBLE MODULE INSTABILITIES	SYSTEM AFFECTED	2	3	6		
		EXTERNAL LEAK	SEAL FAILURE	FLAMMABLE GAS LOSS	MODULE STOP	SYSTEM STOP	1	5	5	add warning - threshold before trigger stop	
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	WRONG MIXTURE	WRONG MIXTURE	1	4	4		
NON RETURN VALVE	NV-1311	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	POSSIBLE BACKFLOW	POSSIBLE MODULE INSTABILITIES	SYSTEM AFFECTED	2	3	6		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	WRONG MIXTURE	WRONG MIXTURE	1	4	4		
NON RETURN VALVE	NV-1411	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	POSSIBLE BACKFLOW	POSSIBLE MODULE INSTABILITIES	SYSTEM AFFECTED	2	3	6		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	WRONG MIXTURE	WRONG MIXTURE	1	4	4		
NON RETURN VALVE	NV-1511	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		
		EXTERNAL LEAK	SEAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		
		STUCK CLOSED	MECHANICAL FAILURE	NO FLOW	WRONG MIXTURE	WRONG MIXTURE	1	4	4		
MIXER TUBE	VU-1003	EXTERNAL LEAK (input-flammable)	SEAL FAILURE	FLAMMABLE GAS LOSS	MODULE STOP	SYSTEM STOP	1	5	5		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS (FREON)	GAS LOSS (FREON)	GAS LOSS (FREON)	1	4	4		
ROTAMETER	FIV-1005	EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		STUCK	MECHANICAL FAILURE	BAD FLOW REGULATION	CONSTANT FLOW LINE NOT REGULATED WELL	NEGLIGIBLE EFFECT	2	2	4		
PRESSURE SENSOR	PT-1103	DRIFT	ELECTRICAL FAILURE	BAD READING	MIXTURE COMPOSITION AFFECTED	MIXTURE AFFECTED	2	3	6	inspections and calibrations	
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO READING	MIXER STOP	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL / MECHANICAL FAILURE	GAS LOSS	GAS LOSS FREON	GAS LOSS FREON	2	4	8	add warning - threshold before trigger stop	
PRESSURE SENSOR	PT-1203	DRIFT	ELECTRICAL FAILURE	BAD READING	MIXTURE COMPOSITION AFFECTED	MIXTURE AFFECTED	2	3	6	inspections and calibrations	
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO READING	MIXER STOP	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL / MECHANICAL FAILURE	FLAMMABLE GAS LOSS	MODULE STOP	SYSTEM STOP	2	5	10	add warning - threshold before trigger stop	
PRESSURE SENSOR	PT-1303	DRIFT	ELECTRICAL FAILURE	BAD READING	MIXTURE COMPOSITION AFFECTED	MIXTURE AFFECTED	2	3	6		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO READING	MIXER STOP	SYSTEM AFFECTED	1	4	4		
		LEAK	SEAL / MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE SENSOR	PT-1403	DRIFT	ELECTRICAL FAILURE	BAD READING	MIXTURE COMPOSITION AFFECTED	MIXTURE AFFECTED	2	3	6		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO READING	MIXER STOP	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL / MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE SENSOR	PT-1009	DRIFT	ELECTRICAL FAILURE	BAD READING	WRONG OUTPUT READING	SYSTEM NOT AFFECTED	2	2	4		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO READING	NO PARTICULAR EFFECT	NEGLIGIBILE	1	1	1		regulation on pressure sensor installed in exhaust
		EXTERNAL LEAK	SEAL / MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		

Figure B.4: Mixer module FMECA table (part 3)

Appendix C

Exhaust module: P&ID and FMECA table

In this section the P&ID of the Exhaust Module is shown with the FMECA table that was used for the analysis.

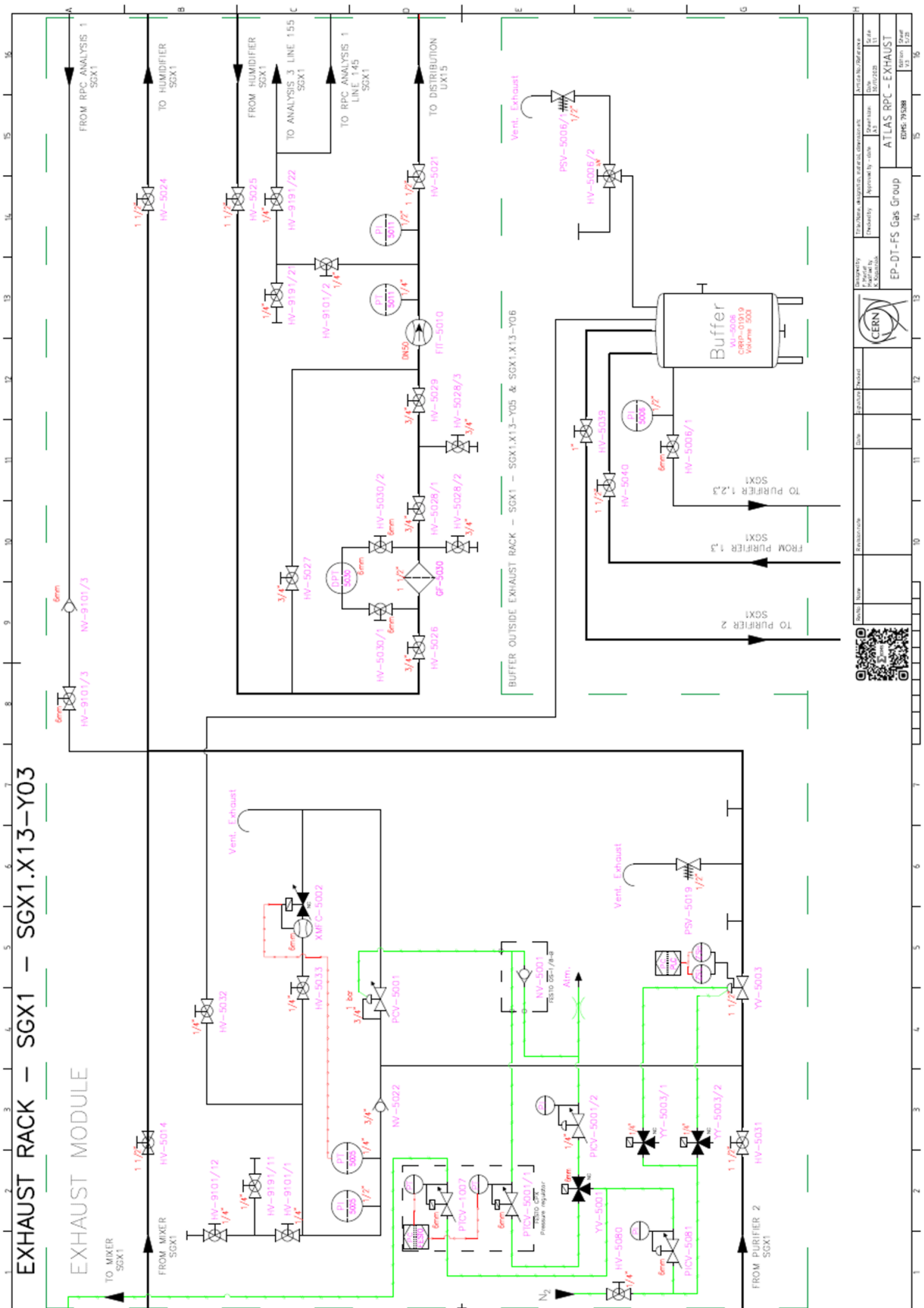


Figure C.1: Exhaust module P&ID [7]

EXHAUST MODULE: NORMAL OPERATION											
COMPONENT	P&ID NAME	FAILURE MODE	FAILURE CAUSE	FAILURE EFFECTS			RISK INDEX			IMPROVEMENT ACTION	COMMENT
				LOCALLY	MODULE	SYSTEM	FREQUENCY	SEVERITY	RISK		
MASS FLOW CONTROLLER	XMFC-5002	WRONG READOUT	OUT OF CALIBRATION	BAD READING	FAKE LEAK DETECTION	MIXER AFFECTED	3	3	9	periodical calibrations	
		STUCK	MECHANICAL FAILURE	PRESSUSRE INCREASE	PCV-5001 INTERVENE (general)	SYSTEM PRESSURE CAN INCREASE	2	3	6	add parallel one	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	2		
		INTERNAL LEAK	SEAL FAILURE	ADDITIONAL GAS TO EXHAUST	ADDITIONAL GAS TO EXHAUST	ADDITIONAL GAS TO EXHAUST	1	3	3		
NON RETURN VALVE	NV-5022	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	1	1	1		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		STUCK	MECHANICAL FAILURE	NO GAS TO XMFC	XMFC MAY NOT WORK	PRESSURE LOOP INCREASE	1	3	3		
NON RETURN VALVE	NV-9101/3	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	1	1	1		it protects from human error
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
		STUCK	MECHANICAL FAILURE	NO FLOW FROM ANALYSIS	WORNG READING	STOP MIXER	1	4	4		
NON RETURN VALVE	NV-5001	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	1	1	1		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS N2	GAS LOSS N2	GAS LOSS N2	1	1	1		
PRESSURE REGULATOR	PCV-5001	SUDDEN OPENING	MECHANICAL FAILURE	NO REGULATION	MORE FLOW TO VENT. EXHAUST	SYSTEM CAN EMPTY	2	4	8	periodical checks	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	2		
		INTERNAL LEAK	MEMBRANE FAILURE	N2 INTAKE / LOSS OF FUNCTIONALITY	POSSIBLE BACKFLOW	SYSTEM AFFECTED	2	3	6		depends on the pressure
PRESSURE REGULATOR	PICV-5001/2	SPURIOUS OPENING	MECHANICAL FAILURE	PRESSURE INCREASE IN THE LINE	WRONG OPENING OF PCV-5001	SYSTEM CAN BE AFFECTED	2	3	6		there is redundant PTCV
		EXTERNAL LEAK	SEAL FAILURE	PRESSURE LOSS ON PCV-5001	GAS LOSS N2	GAS LOSS N2	2	2	4		there is redundant PTCV
PRESSURE REGULATOR	PTCV-5001/1	SPURIOUS OPENING	MECHANICAL FAILURE	PRESSURE INCREASE IN THE LINE	WRONG OPENING OF PCV-5001	SYSTEM CAN BE AFFECTED	2	3	6		
		EXTERNAL LEAK	SEAL FAILURE	PRESSURE LOSS ON PCV-5001	GAS LOSS N2	GAS LOSS N2	2	2	4		
		BAD COMMUNICATION / WRONG READING	ELECTRICAL FAILURE	NO KEEP SETPOINT	EXHAUST STOP	SYSTEM AFFECTED	2	4	8	inspections	loose gas in the loop
		STUCK CLOSED	MECHANICAL FAILURE	NO REGULATION PCV-5001	EXHAUST AFFECTED	SYSTEM AFFECTED	1	4	4		there is redundancy
PRESSURE REGULATOR	PTCV-1007	SPURIOUS OPENING	MECHANICAL FAILURE	PRESSURE INCREASE IN THE LINE	WRONG OPENING OF PCV-1007	MIXER AFFECTED	2	3	6		
		EXTERNAL LEAK	SEAL FAILURE	PRESSURE LOSS ON PCV-1007	GAS LOSS N2	GAS LOSS N2	2	2	4		
		BAD COMMUNICATION / WRONG READING	ELECTRICAL FAILURE	NO KEEP SETPOINT	MIXER AFFECTED	SYSTEM AFFECTED	2	4	8	inspections	
		STUCK CLOSED	MECHANICAL FAILURE	NO REGULATION PCV-1007	MIXER AFFECTED	SYSTEM AFFECTED	1	4	4		
PRESSURE REGULATOR	PICV-5081	SPURIOUS OPENING	MECHANICAL FAILURE	PRESSURE INCREASE IN THE LINE	BAD REGULATION ON PCV-5001	SYSTEM CAN BE AFFECTED	2	3	6		
		EXTERNAL LEAK	SEAL FAILURE	PRESSURE LOSS ON PCV-5001	GAS LOSS N2	GAS LOSS N2	2	2	4		
CONTROLLER	PC-FESTO	REGULATION LOSS	ELECTRICAL FAILURE / FEEDBACK PROBLEM	CONTROL LOSS ON PTCV-5001/1	PCV-5001 CAN OPEN	SYSTEM CAN EMPTY / BIG GAS LOSS	2	4	8	preventive maintenance	
ELECTROVALVE	YV-5001	STUCK CLOSED	ELECTRICAL FAILURE	LOSS OF FUNCTIONALITY	EFFECT ON PCV-5001 / PCV-1007	SYSTEM AFFECTED / MIXER AFFECTED	1	4	4	preventive maintenance	
		EXTERNAL LEAK	SEAL FAILURE	LOSS OF N2 IN PNEUMATIC LINE	REGULATION ON PCV-5001 AFFECTED	SYSTEM CAN EMPTY / BIG GAS LOSS	2	4	8		
ELECTROVALVE	YY-5003/1	STUCK CLOSED / OPEN	ELECTRICAL FAILURE	NO CONTROL ON YV-5003	YV-5003 KEEP POSITION	SYSTEM AFFECTED	1	5	5	preventive maintenance	depends on position of the other
		EXTERNAL LEAK	SEAL FAILURE	LOSS CONTROL YV-5003	EXHAUST FLOW REDUCED	SYSTEM AFFECTED	2	4	8	preventive maintenance	
ELECTROVALVE	YY-5003/2	STUCK CLOSED / OPEN	ELECTRICAL FAILURE	NO CONTROL ON YV-5003	YV-5003 KEEP POSITION	SYSTEM AFFECTED	1	5	5	preventive maintenance	depends on position of the other
		EXTERNAL LEAK	SEAL FAILURE	LOSS CONTROL YV-5003	EXHAUST FLOW REDUCED	SYSTEM AFFECTED	2	4	8	preventive maintenance	
PRESSURE SAFETY VALVE	PSV-5019	SUDDEN OPENING / LEAK	MECHANICAL FAILURE	BIG GAS LOSS	BIG GAS LOSS	SYSTEM AFFECTED	1	4	4		
PRESSURE SAFETY VALVE	PSV-5006/1	SUDDEN OPENING / LEAK	MECHANICAL FAILURE	BIG GAS LOSS	BIG GAS LOSS	SYSTEM AFFECTED	1	4	4		
FLOWMETER	FIT-5010	STUCK	MECHANICAL FAILURE	HIGH PRESSURE DROP	EXHAUST AFFECTED	SYSTEM AFFECTED	2	4	8	preventive maintenance every year	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		WRONG READOUT	ELECTRICAL PROBLEM	BAD FLOW READING	WRONG READING	NEGLIGIBLE	3	1	3	periodical calibration	
CONTROLLER	PC-PLC	POSITION READOUT LOSS	ELECTRICAL FAILURE / FEEDBACK PROBLEM	NO CONTROL ON YV-5003	MODULE CAN BE STOPPED	SYSTEM AFFECTED	2	3	6		
PNEUMATIC VALVE	YV-5003	EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		INTERNAL LEAK	SEAL FAILURE	REGULATION AFFECTED	EXHAUST SLIGHT EFFECT	SLIGHT EFFECT	1	2	2		
		SUDDEN CLOSURE / OPENING	MECHANICAL FAILURE	OPEN LOOP / CLOSE LOOP NO REG.	EXHAUST STOP	SYSTEM STOP	1	5	5	periodical check	
		STUCK	MECHANICAL FAILURE	NO REGULATION	PRESSURE DROP INCREASE	SLIGHT EFFECT	1	3	3		
FILTER	GF-5030	CLOGGED	DUST INSIDE	HIGH PRESSURE DROP	MODULE AFFECTED	SYSTEM AFFECTED	2	3	6		
		EXTERNAL LEAK	MECHANICAL RUPTURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE TRANSMITTER	PT-5005	DRIFT	ELECTRICAL PROBLEM	BAD READING	MODULE REGULATION AFFECTED	SYSTEM AFFECTED	2	4	8	add parallel sensor / reading	regulate using difference with PT-5011
		BROKEN ELECTRONICS	ELECTRICAL PROBLEM	NO PRESSURE REGULATION	MODULE STOP	SYSTEM STOP	1	5	5		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE TRANSMITTER	PT-5011	DRIFT	ELECTRICAL PROBLEM	WRONG READING	NEGLIGIBLE EFFECT	SYSTEM NOT AFFECTED	2	1	2		
		BROKEN ELECTRONICS	ELECTRICAL PROBLEM	NO READING	NEGLIGIBLE EFFECT	SYSTEM NOT AFFECTED	1	2	2		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
DIFFERENTIAL PRESSURE SENSOR	DPT-5030	DRIFT	ELECTRICAL PROBLEM	WRONG READING ON FILTER	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		
		BROKEN ELECTRONICS	ELECTRICAL PROBLEM	NO Δp READING	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	1	1	1		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	2		
BUFFER	VU-5006	EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	MODULE SLIGHT AFFECTED	SYSTEM SLIGHTLY AFFECTED	2	3	6		

Figure C.2: Exhaust module FMECA table

Appendix D

Humidifier module: P&ID and FMECA table

In this section the P&ID of the Humidifier Module is shown with the FMECA table that was used for the analysis.

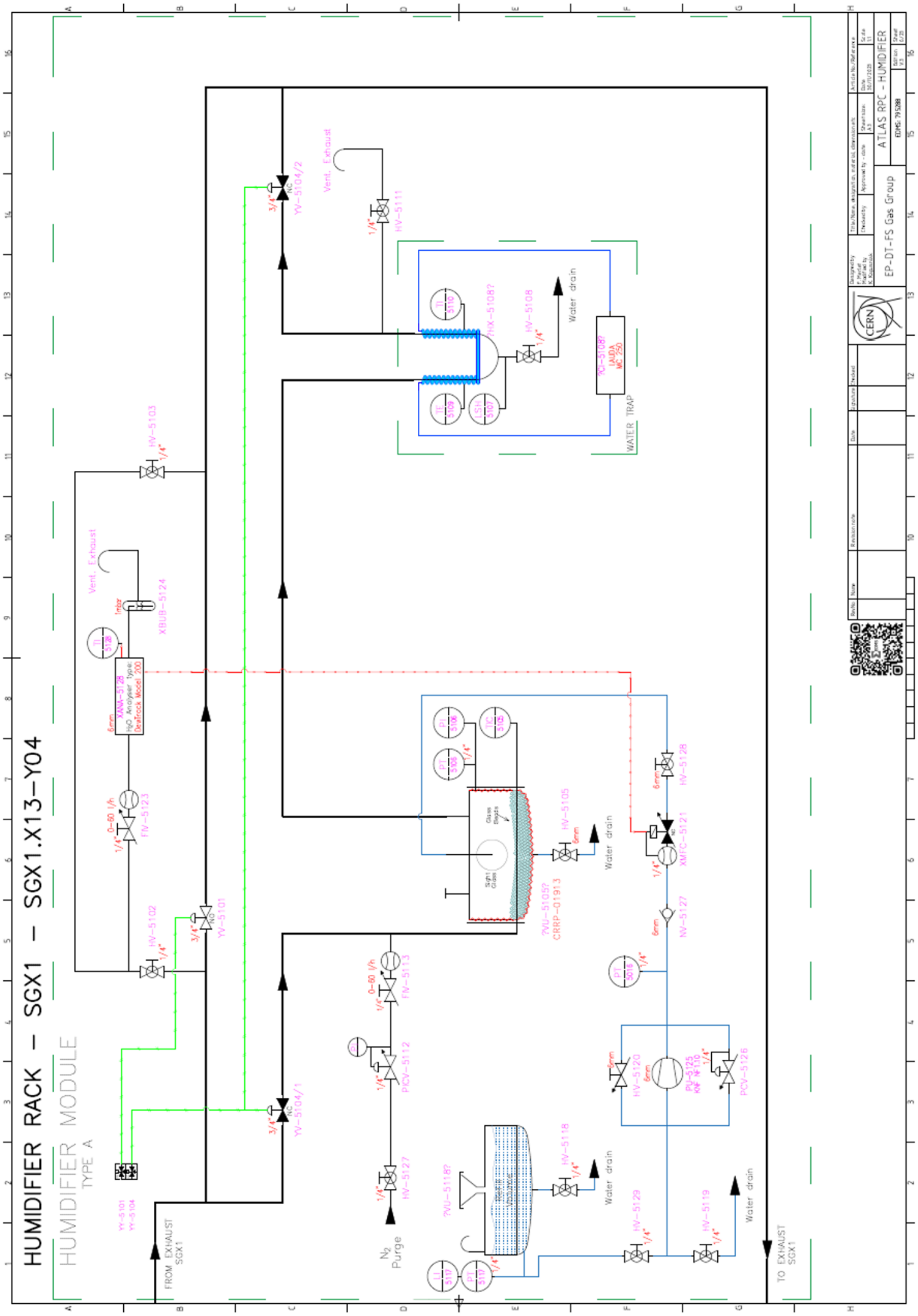


Figure D.1: Humidifier module P&ID [7]

HUMIDIFIER MODULE: NORMAL OPERATION											
COMPONENT	P&ID NAME	FAILURE MODE	FAILURE CAUSE	FAILURE EFFECTS			INDEX			IMPROVEMENT ACTION	COMMENT
				LOCALLY	MODULE	SYSTEM	FREQUENCY	SEVERITY	RISK		
ELECTROVALVE	YY-5101	STUCK CLOSED	ELECTRICAL FAILURE	YV-5101 OPEN	ADDITIONAL BYPASS	SYSTEM AFFECTED	1	3	3		
		EXTERNAL LEAK	SEAL FAILURE	N2 LOSS	EFFECT ON YV-5101	SLIGHTLY AFFECTED	2	2	4		
ELECTROVALVE	YY-5104	STUCK CLOSED	ELECTRICAL FAILURE	YV-5104/1 AND YV-5104/2 CLOSE	NO FLOW TO HUMIDIFIER	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	N2 LOSS	EFFECT ON YV-5104/1 YV-5104/2	SYSTEM SLIGHTLY AFFECTED	2	2	4		
PNEUMATIC VALVE	YV-5101	STUCK OPENED	MECHANICAL FAILURE	LINE OPENED	FLOW BYPASS HUMIDIFIER	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-5104/1	SUDDEN CLOSED	MECHANICAL FAILURE	NO FLOW TO EVAPORATOR	MODULE STOP	SYSTEM AFFECTED	2	3	6	add warning on pneumatic line pressure	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-5104/2	SUDDEN CLOSED	MECHANICAL FAILURE	LINE BLOCKED	MODULE STOP	SYSTEM AFFECTED	2	3	6	add warning on pneumatic line pressure	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
BUBBLER	XBUB-5124	EXTERNAL LEAK	SEAL FAILURE	OIL LOSS	OIL LOSS	OIL LOSS	2	2	4		
PRESSURE REGULATOR	PICV-5112	SPURIOUS OPENING	MECHANICAL FAILURE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	2	1	2		purge line closed
		EXTERNAL LEAK	SEAL FAILURE	N2 LOSS	NEGLIGIBLE	NEGLIGIBLE	2	1	2		
PRESSURE REGULATOR	PICV-5126	SPURIOUS OPENING	MECHANICAL FAILURE	NO PUMP PRESSURE REGULATION	EFFECTS WATER LOOP	SLIGHT EFFECT	2	2	4		
		EXTERNAL LEAK	SEAL FAILURE	WATER LOSS	SLIGHT EFFECT ON EVAPORATOR	NEGLIGIBLE	2	2	4		
PUMP	PU-5125	STOP WORKING	ELECTRICAL FAILURE	NO WATER OUTPUT	MODULE STOP	SYSTEM AFFECTED	4	4	16	pump replacement every year	reduce frequency
		EXTERNAL LEAK	SEAL DAMAGED	WATER LOSS	WATER LOSS	WATER LOSS	2	2	4		
NON RETURN VALVE	NV-5127	FUNCTIONALITY LOSS	SPRING FAILURE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	2	1	2		
		EXTERNAL LEAK	MECHANICAL FAILURE	WATER LOSS	WATER LOSS	WATER LOSS	1	2	2		
		STUCK	MECHANICAL FAILURE	NO WATER THROUGH	EVAPORATOR AFFECTED	SYSTEM AFFECTED	1	4	4		
MASS FLOW CONTROLLER	XMFC-5121	WRONG READOUT	OUT OF CALIBRATION	BAD FLOW REGULATION	EFFECT ON HUMIDITY	SYSTEM AFFECTED	2	3	6	add calibrations	
		EXTERNAL LEAK	SEAL FAILURE	WATER LOSS	SLIGHT EFFECT ON EVAPORATOR	NEGLIGIBLE	2	2	4		
		STUCK	MECHANICAL FAILURE	NO FLOW REGULATION	MODULE STOP	SYSTEM AFFECTED	3	4	12	preventive maintenance	
WATER TANK	VU-5118	EXTERNAL LEAK	SEAL FAILURE	WATER LOSS	WATER LOSS	WATER LOSS	2	2	4		needs to be refilled more often
		EMPTY	HUMAN ERROR / NOT REFILLED	NO WATER	MODULE STOP	SYSTEM AFFECTED	1	4	4		once happened
EVAPORATOR	VU-5105	EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		NO HEATING	ELECTRICAL PROBLEM	NO HUMIDITY	MODULE AFFECTED	SYSTEM AFFECTED	2	4	8	improve temperature regulation	
ROTAMETER	FIV-5113	BLOCKED	MECHANICAL FAILURE	NO N2 FLOW	NEGLIGIBLE	NEGLIGIBLE	2	1	2		purge line closed
		EXTERNAL LEAK	SEAL FAILURE	N2 LOSS	NEGLIGIBLE	NEGLIGIBLE	2	1	2		
ROTAMETER	FIV-5123	BLOCKED	MECHANICAL FAILURE	NO FLOW TO ANALYSIS	MODULE AFFECTED / STOP	SYSTEM AFFECTED	2	4	8	periodical inspection / replacement	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE SENSOR	PT-5116	DRIFT	ELECTRICAL FAILURE	BAD READING WATER OUTPUT	EFFECT ON XMFC-5121	SYSTEM AFFECTED	2	3	6		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO READING	MODULE STOP	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	MECHANICAL FAILURE	WATER LOSS	EFFECT ON EVAPORATOR	NEGLIGIBLE	2	2	4		
PRESSURE SENSOR	PT-5117	DRIFT	ELECTRICAL FAILURE	WRONG READING	MODULE CAN BE STOP	SLIGHT EFFECT	2	3	6		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO READING IN TANK	MODULE STOP	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	MECHANICAL FAILURE	WATER LOSS	NEGLIGIBLE	NEGLIGIBLE	2	1	2		
PRESSURE SENSOR	PT-5106	DRIFT	ELECTRICAL FAILURE	WRONG READING EVAPORATOR	MODULE AFFECTED	SYSTEM AFFECTED	2	3	6		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO READING EVAPORATOR	MODULE STOPPED	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
TEMPERATURE SENSOR	TE-5109	DRIFT	ELECTRICAL FAILURE	WRONG READING EXCHANGER	MODULE AFFECTED	SYSTEM AFFECTED	2	3	6		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO READING EXCHANGER	MODULE STOPPED	SYSTEM AFFECTED	1	4	4		
TEMPERATURE SENSOR	TIC-5105	DRIFT	ELECTRICAL FAILURE	WRONG READING EVAPORATOR	MODULE AFFECTED	SYSTEM AFFECTED	2	3	6		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO READING EVAPORATOR	MODULE STOPPED	SYSTEM AFFECTED	1	4	4		
LEVEL TRANSMITTER	LI-5117	DRIFT	ELECTRICAL FAILURE	WRONG READING TANK	MODULE AFFECTED	SYSTEM SLIGHT AFFECTED	2	2	4		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO READING TANK	MODULE AFFECTED	SYSTEM SLIGHT AFFECTED	1	2	2		
ANALYSER	XANA-5128	WRONG READING	ELECTRICAL PROBLEM	XMFC AFFECTED	MODULE AFFECTED	SYSTEM AFFECTED	3	3	9	perform preventive calibration	
		NO COMMUNICATION	ELECTRICAL FAILURE	XMFC NOT REGULATED	MODULE STOP	SYSTEM AFFECTED	2	4	8	add humidity sensor in parallel	avoid module stop - severity reduced
CHILLER	CI-5108	NO OUTPUT FLOW	ELECTRICAL / MECHANICAL FAILURE	NO COOLING HEAT EXCHANGER	MODULE AFFECTED	SYSTEM AFFECTED	2	3	6		

Figure D.2: Humidifier module FMECA table

Appendix E

Distribution rack: P&ID and FMECA table

In this section the P&ID of a Distribution Rack is shown with the FMECA table that was used for the analysis.

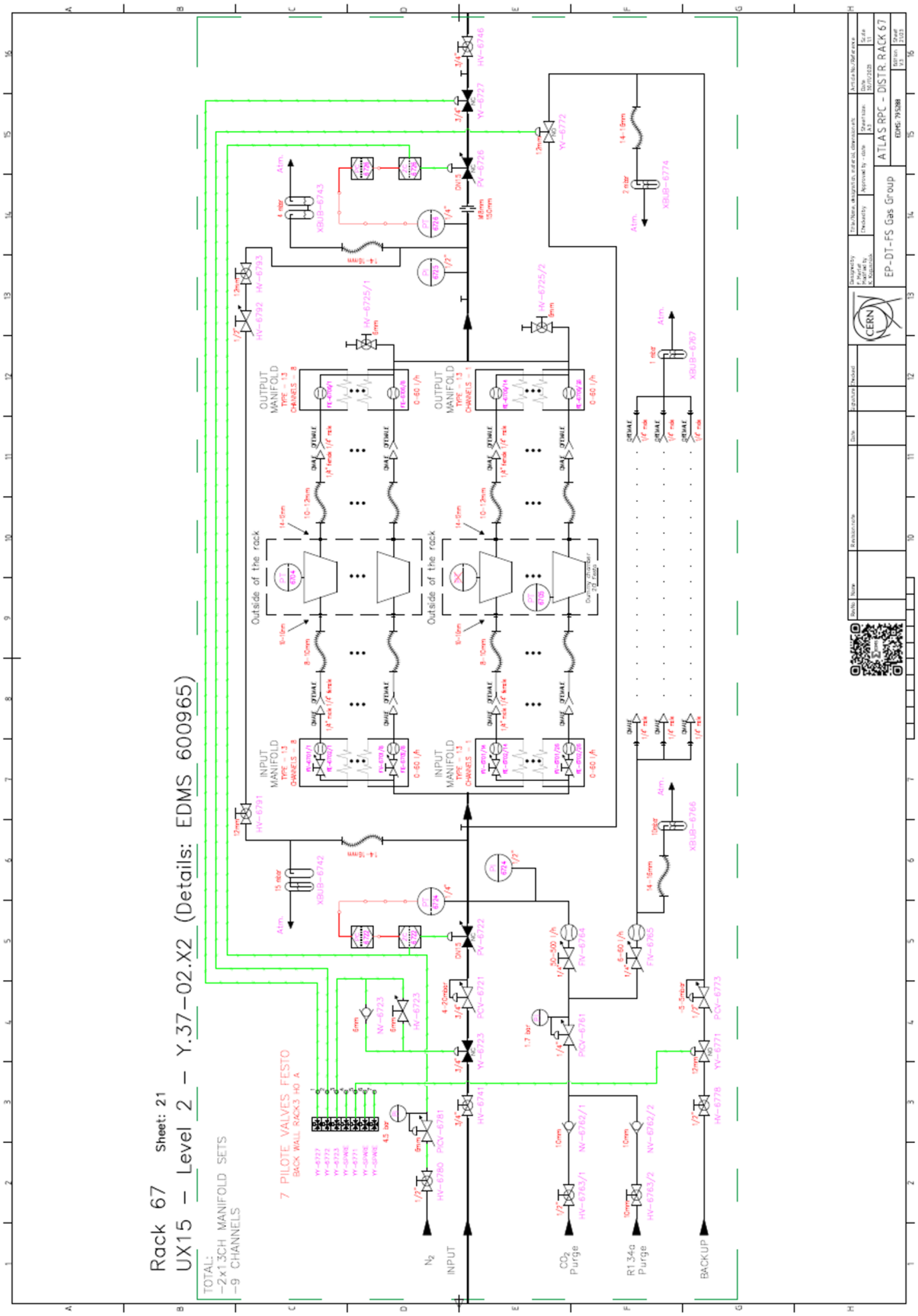


Figure E.1: Distribution rack P&ID [7]

DISTRIBUTION MODULE (ATLAS RACK 67): NORMAL OPERATION											
COMPONENT	P&ID NAME	FAILURE MODE	FAILURE CAUSE	FAILURE EFFECTS			RISK INDEX			IMPROVEMENT ACTION	COMMENT
				LOCALLY	MODULE	SYSTEM	FREQUENCY	SEVERITY	RISK		
SOLENOID VALVE	YY-6727	SUDDEN CLOSURE	ELECTRICAL FAILURE	YV-6727 CLOSES	RACK STOP/MODULE AFFECTED	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	N2 GAS LOSS	N2 GAS LOSS	N2 GAS LOSS	2	2	4		
SOLENOID VALVE	YY-6723	SUDDEN CLOSURE	ELECTRICAL FAILURE	YV-6723 CLOSES	RACK STOP/MODULE AFFECTED	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	N2 GAS LOSS	N2 GAS LOSS	N2 GAS LOSS	2	2	4		
SOLENOID VALVE	YY-6772	SUDDEN CLOSURE	ELECTRICAL FAILURE	YV-6772 OPENS	POTENTIAL FREON INJECTION	SYSTEM AFFECTED	1	3	3		
		EXTERNAL LEAK	SEAL FAILURE	N2 GAS LOSS	N2 GAS LOSS	N2 GAS LOSS	2	2	4		
SOLENOID VALVE	YY-6771	SUDDEN CLOSURE	ELECTRICAL FAILURE	YV-6771 OPENS	HUGE FREON LOSS - BUBBLER	SYSTEM CAN BE STOPPED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	N2 GAS LOSS	N2 GAS LOSS	N2 GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-6723	SUDDEN CLOSURE	MECHANICAL FAILURE	NO INPUT FLOW	RACK STOP / MODULE AFFECTED	SYSTEM AFFECTED	2	4	8	preventive maintenance FESTO	stop case - stuck open
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-6727	SUDDEN CLOSURE	MECHANICAL FAILURE	NO OUTPUT FLOW	RACK STOP / MODULE AFFECTED	SYSTEM AFFECTED	2	4	8	preventive maintenance FESTO	
		EXTERNAL / INTERNAL LEAK	SEAL FAILURE	GAS LOSS / AIR INTAKE	GAS LOSS / MIXTURE CONTAMINATION	GAS LOSS / MIXTURE CONTAMINATION	2	4	8		
PNEUMATIC VALVE	YV-6771	SUDDEN OPENING	MECHANICAL FAILURE	BACKUP GAS LOSS	FREON GAS LOSS - BIG	FREON GAS LOSS - BIG	2	4	8	preventive maintenance FESTO	there is YV-6772
		EXTERNAL LEAK	SEAL FAILURE	BACKUP GAS LOSS	FREON LOSS	FREON LOSS	2	3	6		
PNEUMATIC VALVE	YV-6772	SUDDEN OPENING	MECHANICAL FAILURE	POSSIBLE GAS LOSS	POSSIBLE GAS LOSS	POSSIBLE GAS LOSS	2	3	6	preventive maintenance FESTO	YV-6771 closed
		EXTERNAL LEAK	SEAL FAILURE	BACKUP GAS LOSS	FREON LOSS	FREON LOSS	2	3	6		
PRESSURE REGULATOR	PICV-6781	SPURIOUS OPENING	MECHANICAL FAILURE	REGULATION PNEUMATIC LINE WORSEN	EFFECT ON ACTUATORS	SYSTEM AFFECTED	2	3	6		pneumatic line
		EXTERNAL LEAK	SEAL FAILURE	N2 GAS LOSS	EFFECT ON ACTUATORS	SYSTEM AFFECTED	2	2	4		
PRESSURE REGULATOR	PCV-6773	SPURIOUS OPENING	MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		backup line
		EXTERNAL LEAK	SEAL FAILURE	BACKUP GAS LOSS - FREON	NEGLIGIBLE	NEGLIGIBLE	2	1	2		YV-6771 closed
PRESSURE REGULATOR	PCV-6721	SPURIOUS OPENING	MECHANICAL FAILURE	NO REGULATION INPUT PRESSURE	REGULATION VALVE AFFECTED	SYSTEM AFFECTED	2	4	8	additional inspections	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	3	6		
PRESSURE REGULATOR	PICV-6761	SPURIOUS OPENING	MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		purge line
		EXTERNAL LEAK	SEAL FAILURE	PURGE GAS LOSS	NEGLIGIBLE	NEGLIGIBLE	2	2	4		if FIV-6784 failed - mixture loss
NON RETURN VALVE	NV-6723	LOSS OF FUNCTIONALITY	SPRING / MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	1	3	3		problem when opening
		EXTERNAL LEAK	SEAL FAILURE	N2 LOSS	N2 LOSS	NEGLIGIBLE	1	2	2		
NON RETURN VALVE	NV-6762/1	LOSS OF FUNCTIONALITY	SPRING / MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		
		EXTERNAL LEAK	SEAL FAILURE	PURGE GAS LOSS	PURGE GAS LOSS	PURGE GAS LOSS	1	2	2		
NON RETURN VALVE	NV-6762/2	LOSS OF FUNCTIONALITY	SPRING / MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		
		EXTERNAL LEAK	SEAL FAILURE	PURGE GAS LOSS	PURGE GAS LOSS	PURGE GAS LOSS	1	2	2		
BUBBLER	XBUB-6742	EXTERNAL LEAK	MECHANICAL FAILURE - GLASS	GAS LOSS	GAS LOSS	GAS LOSS	1	3	3		to replace rack stop
		EXTERNAL LEAK	OIL LEVEL WRONG	GAS LOSS	GAS LOSS	GAS LOSS	2	3	6		
BUBBLER	XBUB-6743	EXTERNAL LEAK	MECHANICAL FAILURE - GLASS	GAS LOSS	GAS LOSS	GAS LOSS	1	3	3		to replace rack stop
		EXTERNAL LEAK	OIL LEVEL WRONG	GAS LOSS	GAS LOSS	GAS LOSS	2	3	6		
BUBBLER	XBUB-6766	EXTERNAL LEAK	MECHANICAL FAILURE - GLASS	PURGE GAS LOSS	NEGLIGIBLE	NEGLIGIBLE	1	1	1		
		EXTERNAL LEAK	OIL LEVEL WRONG	PURGE GAS LOSS	NEGLIGIBLE	NEGLIGIBLE	2	1	2		

Figure E.2: Distribution rack FMECA table (part 1)

COMPONENT	P&ID NAME	FAILURE MODE	FAILURE CAUSE	FAILURE EFFECTS: LOCALLY	FAILURE EFFECTS: MODULE	FAILURE EFFECTS: SYSTEM	RISK INDEX: FREQUENCY	RISK INDEX: SEVERITY	RISK INDEX: RISK	IMPROVEMENT ACTION	COMMENT
DISTRIBUTION MODULE (ATLAS RACK 67): NORMAL OPERATION											
BUBBLER	XBUB-6767	EXTERNAL LEAK	MECHANICAL FAILURE - GLASS	PURGE GAS LOSS	NEGLIGIBLE	NEGLIGIBLE	1	1	1		
		EXTERNAL LEAK	OIL LEVEL WRONG	PURGE GAS LOSS	NEGLIGIBLE	NEGLIGIBLE	2	1	2		
BUBBLER	XBUB-6774	EXTERNAL LEAK	MECHANICAL FAILURE - GLASS	BACKUP GAS LOSS	NEGLIGIBLE IN NORMAL RUN	NEGLIGIBLE NORMAL RUN	1	2	2		problem during rack stop
		EXTERNAL LEAK	OIL LEVEL WRONG	BACKUP GAS LOSS	NEGLIGIBLE IN NORMAL RUN	NEGLIGIBLE NORMAL RUN	2	2	4		problem during rack stop
ROTAMETER	FIV-6764	BLOCKED	MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		purge line
		EXTERNAL LEAK	SEAL FAILURE	MIXTURE GAS LOSS	GAS LOSS	GAS LOSS	2	3	6		
ROTAMETER	FIV-6765	BLOCKED	MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		
		EXTERNAL LEAK	SEAL FAILURE	PURGE GAS LOSS	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		purge line
REGULATION VALVE	PV-6722	EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	DISTRIBUTION AFFECTED	SYSTEM AFFECTED	2	3	6	mechanical check	
		BLOCKED	MECHANICAL FAILURE	NO REGULATION	RACK STOP / MODULE AFFECTED	SYSTEM AFFECTED	2	4	8	mechanical check	
ACTUATOR	ZC-6722	UNSTABLE REGULATION	SPRING / MEMBRANE FAILURE	WRONG POSITION PV-6722	RACK REGULATION AFFECTED	SYSTEM AFFECTED	2	4	8	mechanical check	
		STUCK	MEHCANICAL FAILURE	NO REGULATION ON PV-6722	RACK STOP	SYSTEM AFFECTED	2	4	8	mechanical check	
CONTROLLER	PC-6722	REGULATION LOSS	ELECTRICAL FAILURE / FEEDBACK PROBLEM	NO REGULATION ON PV-6722	RACK STOP	SYSTEM AFFECTED	2	4	8	calibrations	
REGULATION VALVE	PV-6726	EXTERNAL / INTERNAL LEAK	SEAL FAILURE	GAS LOSS / AIR INTAKE	DISTRIBUTION AFFECTED /MIXTURE CONTAMINATION	SYSTEM AFFECTED / MIXTURE AFFECTED	2	4	8	mechanical check	
		BLOCKED	MECHANICAL FAILURE	NO REGULATION	MODULE AFFECTED	SYSTEM AFFECTED	2	3	6	mechanical check	
ACTUATOR	ZC-6726	UNSTABLE REGULATION	SPRING / MEMBRANE FAILURE	PV-6726 OSCILLATIONS	RACK REGULATION AFFECTED	SYSTEM AFFECTED	2	4	8	mechanical check	
		STUCK	MEHCANICAL FAILURE	NO REGULATION ON PV-6726	RACK STOP	SYSTEM AFFECTED	2	4	8	mechanical check	
CONTROLLER	PC-6726	REGULATION LOSS	ELECTRICAL FAILURE / FEEDBACK PROBLEM	NO REGULATION ON PV-6726	RACK STOP	SYSTEM AFFECTED	2	4	8	calibrations	
PRESSURE SENSOR	PT-6724	SMALL DRIFT	ELECTRICAL FAILURE	WRONG INPUT PRESSURE READING	MODULE AFFECTED	SYSTEM AFFECTED	3	2	6	add calibration point	add stand by one if possible
		BIG DRIFT	ELECTRICAL FAILURE	WRONG INPUT PRESSURE READING	RACK STOP / MODULE AFFECTED	SYSTEM AFFECTED	1	4	4		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO INPUT PRESSURE READING	RACK STOP / MODULE AFFECTED	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE SENSOR	PT-6726	SMALL DRIFT	ELECTRICAL FAILURE	WRONG INPUT PRESSURE READING	MODULE AFFECTED	SYSTEM AFFECTED	3	2	6	add calibration point	add stand by one if possible
		BIG DRIFT	ELECTRICAL FAILURE	WRONG INPUT PRESSURE READING	RACK STOP / MODULE AFFECTED	SYSTEM AFFECTED	1	4	4		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO INPUT PRESSURE READING	RACK STOP / MODULE AFFECTED	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE SENSOR	PT-6704	SMALL DRIFT	ELECTRICAL FAILURE	WRONG INPUT PRESSURE READING	MODULE AFFECTED	SYSTEM AFFECTED	3	3	9	add calibration point	add stand by one if possible
		BIG DRIFT	ELECTRICAL FAILURE	WRONG INPUT PRESSURE READING	RACK STOP / MODULE AFFECTED	SYSTEM AFFECTED	1	4	4		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO INPUT PRESSURE READING	RACK STOP / MODULE AFFECTED	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE SENSOR	PT-6705	SMALL DRIFT	ELECTRICAL FAILURE	WRONG INPUT PRESSURE READING	MODULE AFFECTED	SYSTEM AFFECTED	3	3	9	add calibration point	add stand by one if possible
		BIG DRIFT	ELECTRICAL FAILURE	WRONG INPUT PRESSURE READING	RACK STOP / MODULE AFFECTED	SYSTEM AFFECTED	1	4	4		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO INPUT PRESSURE READING	RACK STOP / MODULE AFFECTED	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
FLOWCELL	input	WRONG READOUT	OUT OF CALIBRATION	BAD FLOW READING	MODULE SLIGHT AFFECTED	SYSTEM SLIGHT AFFECTED	4	2	8	calibration improvement	no regulation on flowcell - just reading
											flowcells more than one
FLOWCELL	output	WRONG READOUT	OUT OF CALIBRATION	BAD FLOW READING	MODULE SLIGHT AFFECTED	SYSTEM SLIGHT AFFECTED	4	2	8	calibration improvement	in case of ATEX system stop

Figure E.3: Distribution rack FMECA table (part 2)

Appendix F

Purifier module: P&ID and FMECA table

In this section the P&ID of the Purifier Module is shown with the FMECA table that was used for the analysis.

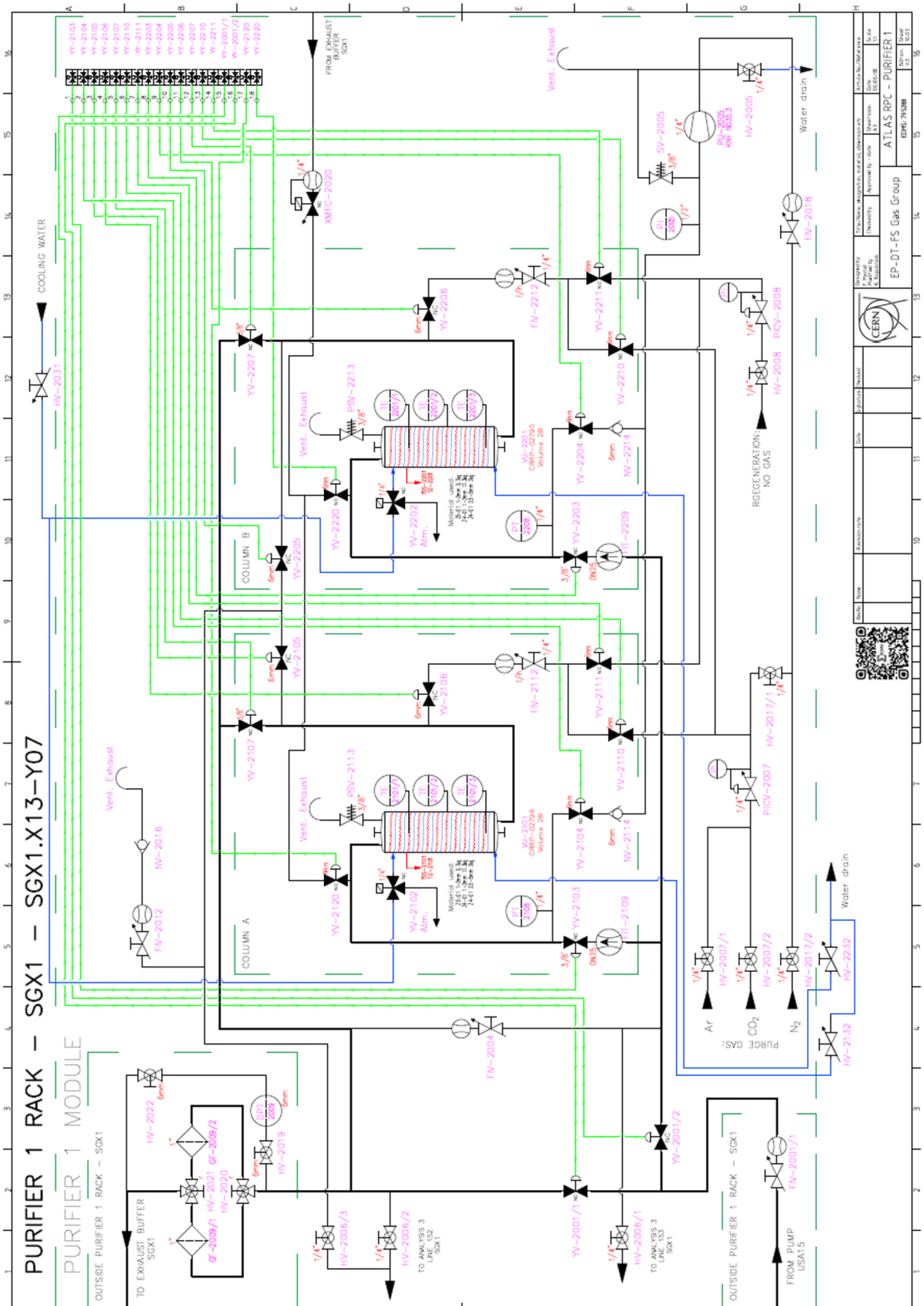


Figure F.1: Purifier module P&ID [7]

PURIFIER MODULE 1: COLUMN A RUN PHASE - COLUMN B REGENERATION PHASE											
COMPONENT	P&ID NAME	FAILURE MODE	FAILURE CAUSE	FAILURE EFFECTS			INDEX			IMPROVEMENT ACTION	COMMENT
				LOCALLY	MODULE	SYSTEM	FREQUENCY	SEVERITY	RISK		
PNEUMATIC VALVE	YV-2103	SUDDEN CLOSURE	MECHANICAL FAILURE	NO FLOW TO COLUMN A	MODULE STOP	SYSTEM STOP	3	5	15	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2104	SUDDEN OPENING	MECHANICAL FAILURE	BIG GAS LOSS	BIG GAS LOSS	BIG GAS LOSS	3	3	9	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2105	SUDDEN OPENING	MECHANICAL FAILURE	BIG GAS LOSS	BIG GAS LOSS	BIG GAS LOSS	2	3	6	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2106	SUDDEN OPENING	MECHANICAL FAILURE	REGENERATION GAS INTAKE	MIXTURE CONTAMINATION	SYSTEM AFFECTED	2	4	8	preventive maintenance FESTO	effect only if 2110 and 2111 fail
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2107	SUDDEN CLOSURE	MECHANICAL FAILURE	NO GAS OUTPUT	MODULE STOP	SYSTEM STOP	2	5	10	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2110	SUDDEN OPENING	MECHANICAL FAILURE	MIXTURE CONTAMINATION PURGE	MIXTURE CONTAMINATION PURGE	SYSTEM AFFECTED	2	2	4		low sev. -> also 2106 need to be failed
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2111	SUDDEN OPENING	MECHANICAL FAILURE	MIXTURE CONTAMINATION REGEN. GAS	MIXTURE CONTAMINATION REGEN. GAS	SYSTEM AFFECTED	2	2	4		low sev. -> also 2106 need to be failed
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2203	SUDDEN OPENING	MECHANICAL FAILURE	CARTRIDGE GAS CONTACT	MODULE STOP	MIXTURE CONTAMINATION	2	4	8	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2204	SUDDEN CLOSURE	MECHANICAL FAILURE	COLUMN B DOES NOT REGENERATE	MODULE PERFORMANCE REDUCED	SYSTEM AFFECTED	3	4	12	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2205	SUDDEN OPENING	MECHANICAL FAILURE	NO REGENERATION PHASE 2	MODULE STOP	SYSTEM AFFECTED	2	4	8	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2206	SUDDEN CLOSURE	MECHANICAL FAILURE	NO REGENERATION FLOW	MODULE STOP	SYSTEM AFFECTED	2	4	8	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2207	SUDDEN OPENING	MECHANICAL FAILURE	GAS MIXTURE CONTAMINATION	MODULE STOP	SYSTEM AFFECTED	2	4	8	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2210	SUDDEN CLOSURE	MECHANICAL FAILURE	NO REGENERATION GAS	MODULE STOP	SYSTEM AFFECTED	2	4	8	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2211	SUDDEN CLOSURE	MECHANICAL FAILURE	NO REGENERATION GAS	MODULE STOP	SYSTEM AFFECTED	2	4	8	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2001/1	SUDDEN OPENING	MECHANICAL FAILURE	PURIFIER BYPASS	MODULE STOP	SYSTEM STOP	2	5	10	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2001/2	SUDDEN CLOSURE	MECHANICAL FAILURE	NO INPUT GAS	MODULE STOP	SYSTEM STOP	2	5	10	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2120	SUDDEN OPENING	MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PNEUMATIC VALVE	YV-2220	SUDDEN CLOSURE	MECHANICAL FAILURE	COLUMN NOT IN PRESSURE	MODULE STOP	SYSTEM AFFECTED	2	4	8	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2103	SUDDEN CLOSURE	ELECTRICAL FAILURE	NO FLOW TO COLUMN A	MODULE STOP	SYSTEM STOP	1	5	5	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2104	SUDDEN OPENING	ELECTRICAL FAILURE	BIG GAS LOSS	BIG GAS LOSS	BIG GAS LOSS	1	3	3		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2105	SUDDEN OPENING	ELECTRICAL FAILURE	BIG GAS LOSS	BIG GAS LOSS	BIG GAS LOSS	1	3	3		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2106	SUDDEN OPENING	ELECTRICAL FAILURE	REGENEATION GAS INTAKE	MIXTURE CONTAMINATION	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		

Figure F.2: Purifier module FMECA table (part 1)

PURIFIER MODULE 1: COLUMN A RUN PHASE - COLUMN B REGENERATION PHASE											
COMPONENT	P&ID NAME	FAILURE MODE	FAILURE CAUSE	FAILURE EFFECTS			INDEX			IMPROVEMENT ACTION	COMMENT
				LOCALLY	MODULE	SYSTEM	FREQUENCY	SEVERITY	RISK		
ELECTROVALVE	YY-2107	SUDDEN CLOSURE	ELECTRICAL FAILURE	NO GAS OUTPUT	MODULE STOP	SYSTEM STOP	1	5	5	preventive maintenance FESTO	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2110	SUDDEN OPENING	ELECTRICAL FAILURE	MIXTURE CONTAMINATION PURGE	MIXTURE CONTAMINATION PURGE	SYSTEM AFFECTED	1	2	2		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2111	SUDDEN OPENING	ELECTRICAL FAILURE	MIXTURE CONTAMINATION REGEN. GAS	MIXTURE CONTAMINATION REGEN. GAS	SYSTEM AFFECTED	1	2	2		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2203	SUDDEN OPENING	ELECTRICAL FAILURE	CARTRIDGE GAS CONTACT	MODULE STOP	MIXTURE CONTAMINATION	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2204	SUDDEN CLOSURE	ELECTRICAL FAILURE	COLUMN B DOES NOT REGENERATE	MODULE PERFORMANCE REDUCED	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2205	SUDDEN OPENING	ELECTRICAL FAILURE	NO REGENERATION PHASE 2	MODULE STOP	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2206	SUDDEN CLOSURE	ELECTRICAL FAILURE	NO REGENERATION FLOW	MODULE STOP	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2207	SUDDEN OPENING	ELECTRICAL FAILURE	GAS MIXTURE CONTAMINATION	MODULE STOP	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2210	SUDDEN CLOSURE	ELECTRICAL FAILURE	NO REGENRATION GAS	MODULE STOP	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2211	SUDDEN CLOSURE	ELECTRICAL FAILURE	NO REGENRATION GAS	MODULE STOP	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2001/1	SUDDEN OPENING	ELECTRICAL FAILURE	PURIFIER BYPASS	MODULE STOP	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2001/2	SUDDEN CLOSURE	ELECTRICAL FAILURE	NO INPUT GAS	MODULE STOP	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2120	SUDDEN OPENING	ELECTRICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	1	1	1		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ELECTROVALVE	YY-2220	SUDDEN CLOSURE	ELECTRICAL FAILURE	COLUMN NOT IN PRESSURE	MODULE STOP	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
NON RETURN VALVE	NV-2016	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	POSSIBLE AIR INTAKE	MIXTURE CONTAMINATION	MIXTURE CONTAMINATION	1	2	2		low severity - valves behind
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
NON RETURN VALVE	NV-2114	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	1	1	1		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
NON RETURN VALVE	NV-2214	LOSS OF FUNCTIONALITY	SPRING DAMAGED / MECHANICAL FAILURE	REGENERATION AFFECTED	MODULE AFFECTED	SYSTEM AFFECTED	3	4	12	preventive replacement every year	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	1	2	2		
FLOWMETER	FIT-2109	STUCK	MECHANICAL FAILURE	HIGH PRESSURE DROP	MODULE AFFECTED	SYSTEM AFFECTED	2	4	8	preventive maintenance every year	
		EXTERNAL LEAK	SEAL DAMAGE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		WRONG READOUT	ELECTRICAL PROBLEM / BAD CALIBRATION	BAD READING COLUMN INPUT	MODULE AFFECTED	SYSTEM AFFECTED	2	3	6	calibration every year	
FLOWMETER	FIT-2209	STUCK	MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		not used in regeneration column
		EXTERNAL LEAK	SEAL DAMAGE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		WRONG READOUT	ELECTRICAL PROBLEM / BAD CALIBRATION	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		
ROTAMETER	FIV-2001/1	BLOCKED	MECHANICAL FAILURE	NO INPUT FLOW TO MODULE	MODULE STOP	SYSTEM STOP	2	5	10	mechanical inspection	
		EXTERNAL LEAK	SEAL DAMAGE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ROTAMETER	FIV-2004	BLOCKED	MECHANICAL FAILURE	BYPASS BLOCKED	CHANGE O2 CONCENTRATION	NEGLIGIBLE	2	2	4		
		EXTERNAL LEAK	SEAL DAMAGE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ROTAMETER	FIV-2018	BLOCKED	MECHANICAL FAILURE	POSSIBLE WATER ACCUMULATION	MODULE SLIGHT AFFECTED	SYSTEM SLIGHT AFFECTED	1	3	3		
		EXTERNAL LEAK	SEAL DAMAGE	PURGE GAS LOSS	PURGE GAS LOSS	PURGE GAS LOSS	2	1	2		

Figure F.3: Purifier module FMECA table (part 2)

PURIFIER MODULE 1: COLUMN A RUN PHASE - COLUMN B REGENERATION PHASE											
COMPONENT	P&ID NAME	FAILURE MODE	FAILURE CAUSE	FAILURE EFFECTS			INDEX			IMPROVEMENT ACTION	COMMENT
				LOCALLY	MODULE	SYSTEM	FREQUENCY	SEVERITY	RISK		
ROTAMETER	FIV-2112	BLOCKED	MECHANICAL FAILURE	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		not used column in run
		EXTERNAL LEAK	SEAL DAMAGE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
ROTAMETER	FIV-2212	BLOCKED	MECHANICAL FAILURE	NO REGENERATION GAS SENT	MODULE AFFECTED	SYSTEM AFFECTED	2	3	6		low severity - sensor for no flow
		EXTERNAL LEAK	SEAL DAMAGE	REGENERATION GAS LOSS	REGENERATION GAS LOSS	REGENERATION GAS LOSS	2	2	4		
ROTAMETER	FIV-2012	BLOCKED	MECHANICAL FAILURE	PHASE 2 AFFECTED	MIXTURE CAN BE WRONG	SYSTEM AFFECTED	2	4	8		
		EXTERNAL LEAK	SEAL DAMAGE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE REGULATOR	PICV-2007	SPURIOUS OPENING	MECHANICAL FAILURE	PRESSURE CAN INCREASE	SLIGHT AFFECTED	SYSTEM SLIGHT AFFECTED	3	2	6		
		EXTERNAL LEAK	SEAL FAILIURE	PURGE GAS LOSS	PURGE GAS LOSS	PURGE GAS LOSS	2	1	2		
PRESSURE REGULATOR	PICV-2008	SPURIOUS OPENING	MECHANICAL FAILURE	PRESSURE CAN INCREASE	SLIGHT AFFECTED	SYSTEM SLIGHT AFFECTED	3	2	6		
		EXTERNAL LEAK	SEAL FAILIURE	REGENERATION GAS LOSS	PURGE GAS LOSS	PURGE GAS LOSS	2	2	4		
PUMP	PU-2005	STOP WORKING	ELECTRICAL / MECHANICAL FAILURE	NO VACUUM	MODULE AFFECTED	SYSTEM AFFECTED	3	4	12	preventive maintenance every year	
		EXTERNAL LEAK	MEMBRANE DAMAGED	LOOSE REGENERATION EFFECIENCY	MODULE AFFECTED	SYSTEM AFFECTED	2	3	6	preventive membrane replacement	if after pump - before negligible
COLUMN A	VU-2101	EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4	warning H2 leak	
		HEATING TAPE FAILURE	ELECTRICAL PROBLEM	CIRCUIT BREAKER OFF	MODULE STOP	SYSTEM STOP	1	5	5		
		CLOGGED	DUST FROM MATERIAL	FLOW IMPEDANCE INCREASE	PERFROMANCE REDUCED	SYSTEM AFFECTED	3	3	9		you can use other purifier in parallel
COLUMN B	VU-2201	EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4	warning H2 leak	
		HEATING TAPE FAILURE	ELECTRICAL PROBLEM	CIRCUIT BREAKER OFF	MODULE STOP	SYSTEM STOP	1	5	5		
		CLOGGED	DUST FROM MATERIAL	FLOW IMPEDANCE INCREASE	PERFROMANCE REDUCED	SYSTEM AFFECTED	3	3	9		you can use other purifier in parallel
CHECK VALVE	SV-2005	STUCK	MECHANICAL PROBLEM	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	2	1	2		
MASS FLOW CONTROLLER	XMFC-2023	WRONG READOUT	OUT OF CALIBRATION	NO PREPARATION COLUMN B	MODULE AFFECTED	SYSTEM AFFECTED	3	3	9	calibration every year	
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		STUCK	MECHANICAL FAILURE	NO PREPARATION COLUMN B	MODULE STOP	SYSTEM AFFECTED	2	4	8	preventive maintenance	
FILTER	GF-2009/1	CLOGGED	DUST INSIDE	FLOW IMPEDANCE INCREASED	MODULE NOT AFFECTED	NEGLIGIBLE	3	1	3		switch on the other filter
		EXTERNAL LEAK	SEAL PROBLEM	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
FILTER	GF-2009/2	CLOGGED	DUST INSIDE	FLOW IMPEDANCE INCREASED	MODULE NOT AFFECTED	NEGLIGIBLE	3	1	3		switch on the other filter
		EXTERNAL LEAK	SEAL PROBLEM	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE SAFETY VALVE	PSV-2113	EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		SUDDEN OPENING	MECHANICAL FAILURE	BIG GAS LOSS	BIG GAS LOSS	BIG GAS LOSS	1	4	4		
PRESSURE SAFETY VALVE	PSV-2213	EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
		SUDDEN OPENING	MECHANICAL FAILURE	BIG GAS LOSS	BIG GAS LOSS	BIG GAS LOSS	1	4	4		
PRESSURE TRANSMITTER	PT-2108	DRIFT	ELECTRICAL FAILURE	WRONG PRESSURE READING	NEGLIGIBLE	NEGLIGIBLE	2	1	2		not used when column A in run
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO READING	NEGLIGIBLE	NEGLIGIBLE	1	2	2		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
PRESSURE TRANSMITTER	PT-2208	DRIFT	ELECTRICAL FAILURE	NO COLUMN B PRESSURE READING	MODULE AFFECTED	SYSTEM AFFECTED	2	3	6	additional calibration	
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	WRONG COLUMN B PRESSURE READING	MODULE AFFECTED	SYSTEM AFFECTED	1	4	4		
		EXTERNAL LEAK	SEAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	4		
TEMPERATURE SENSOR	TE-2101/1	DRIFT	ELECTRICAL FAILURE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	2	1	2		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	1	1	1		
TEMPERATURE SENSOR	TE-2101/2	DRIFT	ELECTRICAL FAILURE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	1	1	1		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	1	1	1		
TEMPERATURE SENSOR	TE-2101/3	DRIFT	ELECTRICAL FAILURE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	1	1	1		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NEGLIGIBLE	NEGLIGIBLE	NEGLIGIBLE	1	1	1		
TEMPERATURE SENSOR	TE-2201/1	DRIFT	ELECTRICAL FAILURE	NO RIGHT TEMPEARATURE REACHED	REGENERATION AFFECTED	SYSTEM AFFECTED	1	3	3		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO REGENERATION TEMPERATURE INFO	COLUMN STOP	SYSTEM AFFECTED	1	4	4		
TEMPERATURE SENSOR	TE-2201/2	DRIFT	ELECTRICAL FAILURE	NO RIGHT TEMPEARATURE REACHED	REGENERATION AFFECTED	SYSTEM AFFECTED	1	3	3		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO REGENERATION TEMPERATURE INFO	COLUMN STOP	SYSTEM AFFECTED	1	4	4		
TEMPERATURE SENSOR	TE-2201/3	DRIFT	ELECTRICAL FAILURE	NO RIGHT TEMPEARATURE REACHED	REGENERATION AFFECTED	SYSTEM AFFECTED	1	3	3		
		BROKEN ELECTRONICS	ELECTRICAL FAILURE	NO REGENERATION TEMPERATURE INFO	COLUMN STOP	SYSTEM AFFECTED	1	4	4		
DIFFERENTIAL PRESSURE SENSOR	DPT-2009	DRIFT	ELECTRICAL PROBLEM	WRONG READING ON FILTER	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	2	1	2		
		BROKEN ELECTRONICS	ELECTRICAL PROBLEM	NO Δp READING	NEGLIGIBLE EFFECT	NEGLIGIBLE EFFECT	1	1	1		
		EXTERNAL LEAK	MECHANICAL FAILURE	GAS LOSS	GAS LOSS	GAS LOSS	2	2	2		

Figure F.4: Purifier module FMECA table (part 3)

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