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| **European Spallation Source**  **Cryogenic Distribution System for the Lund Test Stand2**  **Estimation of the Probability and Consequences of Failures in the Equipment** | |
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# Aim and scope of the document

The aim of the document is to identify failure modes of the Cryogenic Distribution System for Lund Test Stand 2. Presented analysis includes identification of possible causes and consequences of all recognized failures. Based on the available data concerning defects of the cryogenic equipment, the probability of the system failure occurrence has been assessed.

# Cryogenic Distribution System Architecture

The CDS for Lund Test Stand 2 is dedicated to transferring cooling power from the TICP to the ESS elliptical cryomodules under their site acceptance tests in the test stand bunker. The system includes a cryogenic transfer line (CTL), one valve box and four auxiliary process lines.

The CTL runs from the TICP cold box in the cold box building to the test stand bunker placed in the klystron gallery. The line is a vacuum insulated multichannel line and its vacuum jacket houses four cold process lines (so-called headers), thermal shield, supports and thermal compensation system. The cryoline ends in the test stand valve box, in which four branch process lines connect the headers with the cryomodule cold circuits. Thus the whole system consists of four main and four branch cold process lines. Their names and acronyms are as follows:

* helium supply lines: helium supply main line (MC) and helium supply branch line (BC),
* vapour low-pressure lines: VLP main line (MB) and VLP branch line (BB),
* thermal shield supply lines: TS supply main line (ME) and TS supply branch line (BE),
* thermal shield return lines: TS return main line (MF) and TS return branch line (BF).

The CDS includes also 4 auxiliary process lines that connect the tested cryomodule and valve box with the warm compressor station (WCS) of the TICP. There are four main (headers) and four branch auxiliary process lines. Their names and acronyms are as follows:

* high pressure line: HP main line (MH) and HP branch line (BH),
* purge return line: Purge return main line (MP) and Purge return branch line (BP),
* safety valve relief line: SV relief main line (MS) and SV relief branch line (BS),
* helium recovery line: helium recovery main line (MR) and helium recovery branch line (BR).

The main auxiliary process lines run from the compressor building along the CTL duct and gallery and further to the cold box building and klystron gallery alongside the cryogenic transfer line.

The process and instrumentation diagram of the CDS is shown in Figure 2.1. The system is spread among the following three interfaces:

* interface to the cold box of the Test and Instruments Cryogenic Plant,
* interface to the warm compressor station of the Test and Instruments Cryogenic Plant,
* interface to the elliptical cryomodule.

All the CTL cold main process lines at the interface to the cold box are equipped with temperature sensors TT11, TT12, TT13 and TT14. These sensors are mainly dedicated for the measurements of the thermal performance of the whole CDS. Other instrumentation required for the commissioning tests, such as flow and pressure transmitters, will be located in the cold box and is contracted out separately.

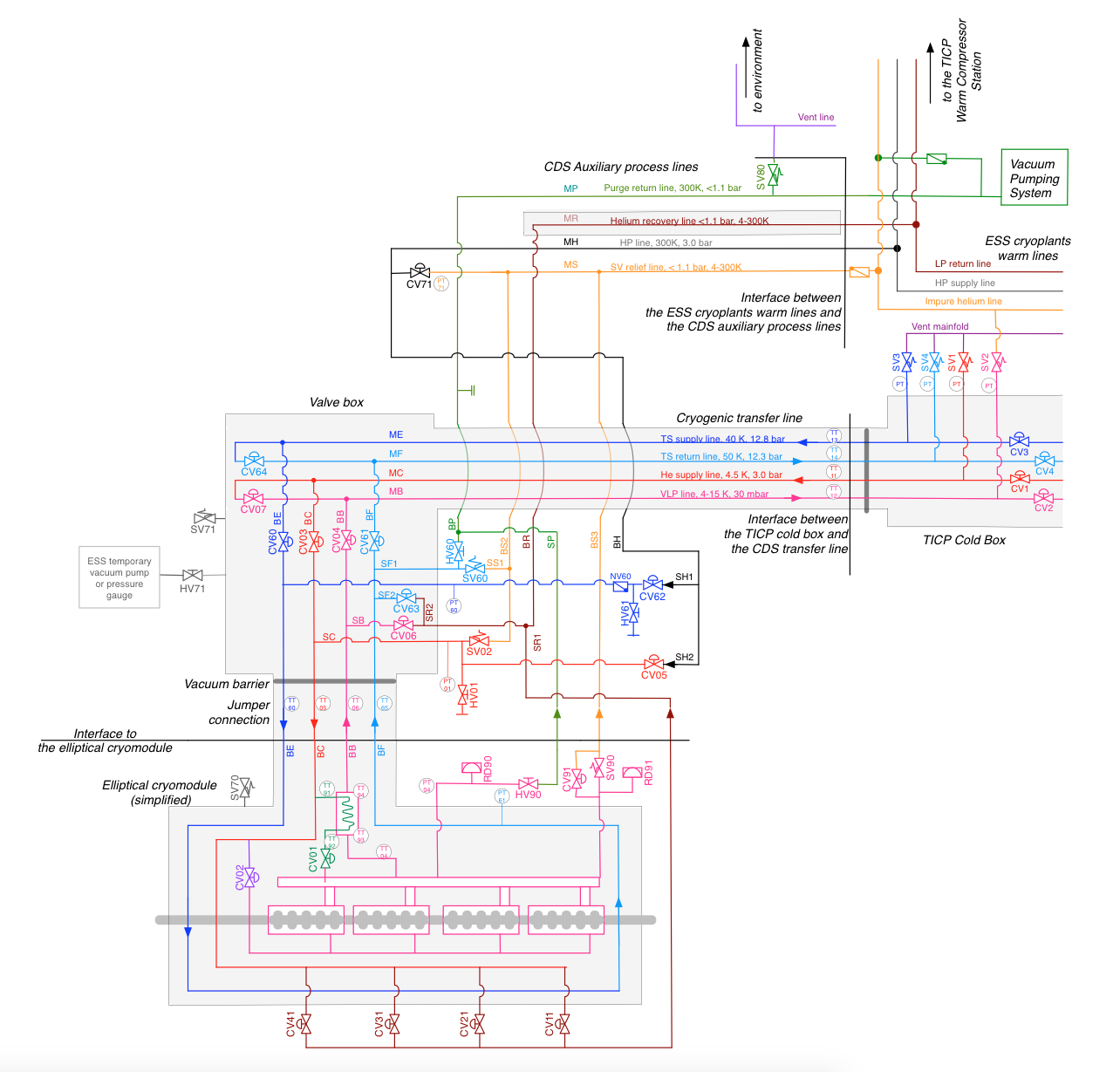


Figure 2.1. Process and instrumentation diagram of the CDS for Lund Test Stand 2

The valve box is dedicated for the direct connecting of the tested cryomodules and controlling the helium flows in different operation modes. For these purposes it is equipped with a branch cryoline (so-called jumper connection) and a set of control valves. As shown in Figure 2.1 the valve box includes the following devices:

* + 8 cryogenic control valves (CV03, CV04, CV06, CV07, CV60, CV61, CV63, CV64),
  + 2 warm control valves (CV05 and CV62),
  + check valve (NV60),
  + 2 safety valves (SV02, SV60),
  + 3 hand valve (HV01, HV60 and HV61),
  + 2 pressure transmitters (PT01 and PT60),
  + 4 temperature transmitters (TT05, TT06, TT60 and TT65).

Control valves CV03, CV04, CV60 and CV61 are for opening and closing the cold helium circuit and thermal shield circuit in the cryomodule. Two other cryogenic control valves, CV06 and CV63, as well as warm control valves CV05 and CV62 connect the cryomodule circuits to the helium recovery line and HP line, respectively. This set of valves is primarily used for warming up the tested cryomodule while keeping the TICP and CTL at 4.5 K stand by mode. During this phase the ambient temperature helium flows from the HP line into the cryomodule circuits and on to the helium recovery line, whilst cold helium flows from the helium supply and TS supply lines are reversed to the VLP and TS return lines via control valves CV07 and CV64.

Control valves CV05 and CV62 are used for flushing and purging the cryomodule circuits. During this operation, the valves allow filling the circuits with clean helium, while hand valves HV60 and HV90 direct the contaminated helium to the purge return line.

All closed sections of the helium circuits in the valve box and cryomodule are protected against excessive pressure by a set of pressure relief devices. The valve box is equipped with two spring-loaded safety valves, while the other devices are placed on the cryomodule. Safety valve SV02 protects the helium supply branch line (BC line section downstream CV03) and SV60 guards the whole branch thermal shield circuit, i.e. TS supply branch line (BE) and TS return branch lines (BF) from CV60 to CV61.

The auxiliary process lines in the klystron gallery and cold box room run alongside the CDL, and further in the CTL gallery and duct to the WCS. The valve box is connected to the following main auxiliary process lines: HP main line (MH), purge return main line (MP), helium recovery main line (MH) and SV relief main line (MS), whereas the cryomodule is connected to the purge return main line (MP), helium recovery main line (MR) and SV relief main line (MS). For all these connections a pipework composed of branch and side auxiliary process lines is used, as presented in Figure 2.1. The safety devices of the auxiliary process lines are located in the WCS.

The section of the helium recovery line located in the klystron gallery and cold box room is vacuum insulated. Then, in the CTL gallery and duct, the line does not have any insulation and acts as an ambient heater, which warms up the discharged cold helium while transferring it to the WCS.

## Identification and Codes of the Failure Modes

Cryogenic-related failure mode has been defined as the accidental event involving helium or air transfer between process pipes, vacuum insulation, external envelope and/or environment being a result of any construction element break or malfunctioning (e.g. bellow or pipe break, valve leakage or weld non-tight).

Failure modes of the Cryogenic Distribution System for Lund Test Stand 2 are presented in Table 2.1

Table 2.1. Codes of the failure identification

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Cryogenic failure modes** | | |
|  | Valve box and CTL |  | Auxiliary Lines |
| F1 | Air flow to insulation vacuum | F1A | Air flow to insulation vacuum of He Recovery Line (MR) |
| F2 | Helium flow to insulation vacuum | F2A | Helium flow to insulation vacuum of He Recovery Line (MR) |
| F3 | Air flow to sub-atmospheric helium |  |  |
| F4 | He flow to sub-atmospheric helium | F4A | Helium flow to sub-atmospheric line (PRL) |
| F5 | Helium flow to environment | F5A | Helium flow to environment |

# Identification of the Possible Failures at the Cryogenic Distribution System

The detailed analysis has been performed to identify both causes and physical consequences of the possible failures at the Cryogenic Distribution System for Lund Test Stand 2. The results are presented in 3 tables. First table gathers the cryogenic-related failures with their potential causes and the list of the system elements where specific defect can occur. Second one presents the results of the probability assessment whereas third one gives both event sequences and physical consequences of all failure modes, the failure detection as well as risk mitigation method.

## Valve Box and Cryogenic Transfer Line

Valve box and Cryogenic Transfer Line are enclosed in the common vacuum (Figure 3.1). Therefore, they are identified and analyzed as one node.

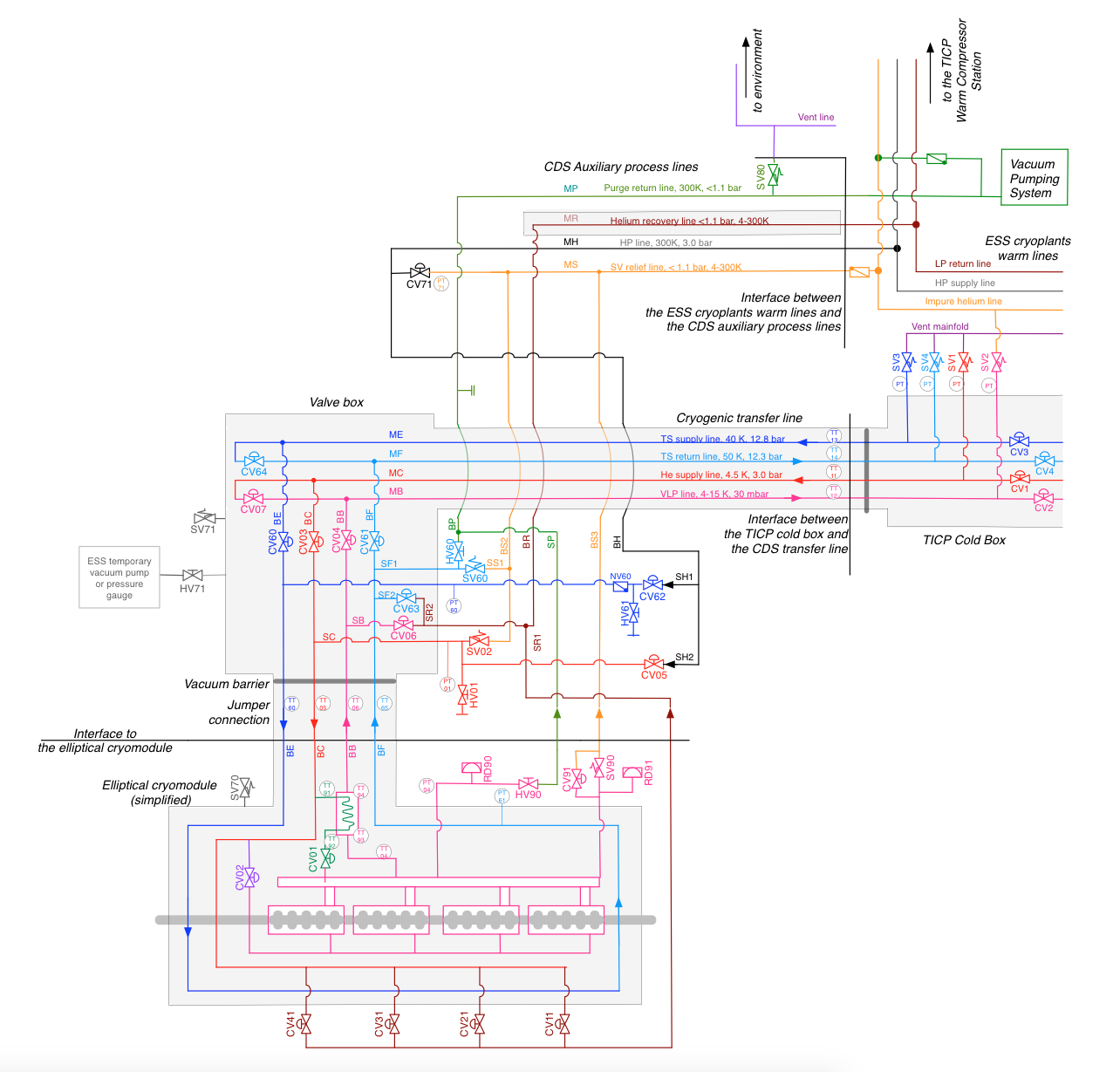


Figure 3.1. Process and instrumentation diagram of the valve box and CTL

The pipework of cold process lines is composed of main, branch and side process lines. The dimensions and operating conditions of the cold process lines are presented in Table 3.1.

The main cold process lines run inside the CTL and the branch and side cold process lines form a pipework inside each valve box. The branch cold lines connect the main lines to the cryomodule process lines, whereas the side cold process lines connect the branch lines with process control equipment, such as control valves, safety valves and manual valves.

Table 3.1. Design parameters of the cold process lines

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Type of  process line** | **Process  line  name** | **Process line acronym** | **Size** | **Design pressure a** | **Nominal operating pressure a** | **Nominal operating temperature** |
| Main cold process lines (headers) | He supply line | MC | DN15 | 16 bar | 3 bar | 4.5 K |
| VLP line | MB | DN65 | 12 bar | 27 mbar | 3 K - 5 K |
| TS supply line | ME | DN15 | 22 bar | 12.8 bar | 40 K |
| TS return line | MF | DN15 | 22 bar | 12.5 bar | 50 K |
| Branch cold process lines | He supply branch line | BC | DN10 | 16 bar | 3 bar | 4.5 K |
| VLP branch line | BB | DN50 | 12 bar | 27 mbar | 3 K - 5 K |
| TS supply branch line | BE | DN10 | 22 bar | 12.8 bar | 40 K |
| TS return branch line | BF | DN10 | 22 bar | 12.5 bar | 50 K |
| Side cold process lines | He supply side line 1 | SC1 | DN10 | 16 bar | 3 bar | 4.5 K |
| He supply side line 2 | SC2 | DN10 | 16 bar | 3 bar | 4.5 K |
| VLP side line | SB | DN50 | 12 bar | 27 mbar | 3 K - 5 K |
| TS supply side line | SE | DN10 | 22 bar | 12.8 bar | 40 K |
| TS return side line 1 | SF1 | DN10 | 22 bar | 12.5 bar | 50 K |
| TS return side line 2 | SF2 | DN10 | 22 bar | 12.5 bar | 50 K |

a - all pressure values are given as absolute pressures

The results of failure identification for Valve Box and Cryogenic Transfer Line are presented in Tables 3.2 – 3.4. Table 3.2 presents potential causes and system elements which can fail. Table 3.3 gives the results of the probability assessment whereas Table 3.3 gives general information concerning the failure consequences.

Table 3.2. Identified failures of Valve Box and Cryogenic Transfer Line

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Code** | **Failure** | **Potential Causes** | **System elements** | **Total** |
| F1 | Air flow to insulation vacuum | **VALVE BOX** | | |
| Weld non-tight | Interconnections | 42 m |
| vacuum flanges  (valves, side lines) | 6 m |
| Valve leak | Hand valve HV71 | 1 |
| O-ring leak (1) | Sealing HV71 – KF40 | 1 |
| **CTL** | | |
| Weld non-tight | Interconnections  (9 angles) | 9.5 m |
| Vacuum flanges SV71 (2) | 1.5 m |
| Bellows (2) | 12 m |
| Muffs (12) | 45.5 m |
| Valve leak | SV71 | 2 |
| O-ring leak | SV71 | 2 |
| Bellow leak | External bellows (2) | 2 |
| Feed through non-tight | Temperature sensors | 1 |
| F2 | Helium flow to insulation vacuum | **VALVE BOX** | | |
| Cold weld non-tight | Interconnections (valves, pipes) | 12 m |
| Cold pipe break | BE-SE, BC-SC1-SC2, BB-SB, BF-SF1-SF2 | 28 m |
| Control valve leak | Cryogenic valves: CV03, CV04, CV06, CV07, CV60, CV61, CV63, CV64 (bonnet, body leak) | 8 |
| **CTL** | | |
| Cold weld non-tight | Interconnections (pipes, bellows) | 24 m |
| Cold pipe leak | VLP line, TS Supply line, TS return line, He Supply line (52.48 m each) | 210 m |
| Cold bellow failure | 6 bellows per one process pipe | 24 |
| F3 | Air flow to sub-atmospheric helium | Helium guard break | CV04 | 1 |
| F4 | He flow to sub-atmospheric helium (VLP line) | Control valve leak | CV07 through seat | 1 |
| F5 | Helium flow to environment | Control valve leak | CV03, CV05, CV07, CV60, CV61, CV62, CV63, CV64, | 8 |
| Hand valve leak | HV60, HV61, HV01 | 3 |
| Safety valve leak | SV02, SV60 | 2 |
| Check valve leak | NV01, NV02, NV60 | 3 |
| Seal leak | SV02, SV60 | 4 |
| Capillary break | PT01, PT60 | 2 |
| Pressure transmitter leak | PT01, PT60 | 2 |

The probability of each failure has been assessed basing on the cumulative failure rate (CFR).

The following formula has been adopted for the assessment of the general probability of the failure:

, (3.1)



where:

– general probability of the i-th failure

– cumulative failure rate of n-th defect

The CFR is given by a product of the failure rate FR of the defect (potential cause of the failure, see Appendix 1) and a quantity of elements in the system that can fail, see equation (3.2)

, (3.2)



where:

– failure rate of the n-th defect

– total number of elements in the system that can fail (e.g. total length of the welds, number of valves)

Table 3.3 presents the results of the probability assessment for the failures of the valve box and CTL.

Table 3.3. Probability of failures F1-F5

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **F1. Air flow to vacuum insulation** | | | | |
| n | Defect (potential cause) | Total length of weld/number of elements | FR of the element | Cumulative failure rate CFR of the defect |
| 1 | Weld non-tight | 116.5 m | 5.26·10-6 m-1·year-1 | 6.12·10-4 year-1 |
| 2 | Valve leak | 3 | 8.76·10-5 year-1 | 2.63·10-4 year-1 |
| 3 | O-ring leak | 3 | 2.63·10-2 year-1 | 7.88·10-2 year-1 |
| 4 | External bellow leak | 2 | 8.76·10-5 year-1 | 1.75·10-4 year-1 |
| 5 | Feed through non-tight | 1 | 2.63·10-2 year-1 | 2.63·10-2 year-1 |
|  |  |  | CFR1 | 1.06·10-1 year-1 |
| Defect leading to F1 (Air flow to vacuum insulation) can be expected every **9 years** | | | | |
| **F2. Helium flow to vacuum insulation** | | | | |
| 1 | Weld non-tight | 36 m | 5.26·10-6 m-1·year-1 | 1.89·10-4 year-1 |
| 2 | Cold pipe leak | 238 m | 8.76·10-6 m-1·year-1 | 2.08·10-3 year-1 |
| 3 | Control valve leak | 8 | 8.76·10-5 year-1 | 7.01·10-4 year-1 |
| 4 | Cold bellow | 24 | 8.76·10-5 year-1 | 2.10·10-3 year-1 |
|  |  |  | CFR2 | 5.08·10-3 year-1 |
| Defect leading to F2 (Helium flow to vacuum insulation) can be expected every **196 years** | | | | |
| **F3. Air flow to sub-atmospheric helium** | | | | |
| 1 | Helium guard break (CV04) | 1 | 5.26·10-7 year-1 | 5.26·10-7 year-1 |
|  |  |  | CFR3 | 5.26·10-7 year-1 |
| Defect leading to F3 (Air flow to sub-atmospheric helium) can be expected in more than **10.000 years** | | | | |
| **F4. Pressurized helium flow to sub-atmospheric helium** | | | | |
| 1 | Control valve (CV07)  leak through seat | 1 | 7.20·10-2 day-1 | 7.20·10-2 day-1 |
|  |  |  | CFR4 | 7.20·10-2 day-1 |
| Defect leading to F4 (Pressurized helium flow to sub-atmospheric helium ) can be expected every **2 weeks** | | | | |
| **F5. Helium flow to environment** | | | | |
| 1 | Valve leak (external leak) | 14 | 8.76·10-5 year-1 | 1.23·10-3 year-1 |
| 2 | Safety valve leak | 2 | 8.76·10-2 year-1 | 1.75·10-1 year-1 |
| 3 | Seal leak | 4 | 2.63·10-2 year-1 | 1.05·10-1 year-1 |
| 4 | Capillary break | 2 | 2.00·10-8 year-1 | 4.00·10-8 year-1 |
|  |  |  | CFR5 | 2.82·10-1 year-1 |
| Defect leading to F5 (Helium flow to environment) can be expected **every 3years** | | | | |
| 5 | Pressure transmitter leak | 2 | 6.1 year-1 | 12.1 year-1 |
|  |  |  | CFR5 | 12.5 year-1 |
| Defect of instrumentation leading to helium release can be expected every **29 days** | | | | |

Table 3.4. Recognized failures of the Valve Box, Cryogenic Transfer Line and their consequences

|  |  |  |
| --- | --- | --- |
| **Failure mitigation** | Connect to vacuum pump  If pumping not efficient - intervention required | Connect to vacuum pump  If pumping not efficient - intervention required |
| **Failure**  **detection** | Pressure transmitter: PT71 | Pressure transmitters: PT01, PT60 |
| **Risk to system** | Air contamination of vacuum space of the Valve Boxe and Cryogenic Transfer Line  Chemical burning of MLI | Contamination of vacuum space of Valve Boxe and CTL  MLI mechanical destruction  Cold helium jet from the vacuum envelope – risk of low temperature for equipment in the TS2 bunker |
| **Risk to personnel** | No | ODH  Freezing of tissue |
| **Events** | Pressurization up to 1 bar of vacuum space of the valve box and CRT  Oxygen enriched air condensation of the process pipes  Heat load to process pipes – helium released to SV Relief Line through safety valves SV02 and SV60 | Pressurization above 1 bar of vacuum space of the valve box and CRT  Helium vented to vacuum space of the valve box and CRT – opening of safety valves (SV71) – helium flow to the TS2 bunker  Heat load to process pipes – helium released to SV Relief Line through safety valves SV02 and SV60 |
| **Failure** | Air flow to insulation vacuum | Helium flow to insulation vacuum |
| **Code** | F1 | F2 |

|  |  |  |  |
| --- | --- | --- | --- |
| **Failure mitigation** | Intervention required | In case of He flow of a leak order – no significant consequences expected  He flow above leak order – intervention required | Intervention required |
| **Failure**  **detection** | Temperature sensors: TT06, TT12 | Temperature sensors: TT06, TT12 | Oxygen concentration sensors |
| **Risk to system** | Air contamination of VLP line | Destabilization of the system parameters  Quench of RF Cavities can be provoked - further analysis required | Loss of cryogenic medium |
| **Risk to personel** | No | No | ODH  Freezing of tissue |
| **Events** | Air condensation and freezing – VLP line blockage  Temperature increase in cryomodule | Temperature and pressure increase in VLP line  Change of helium inlet parameters to cold compressors  Increase temperature in cryomodule | Defect of elements can result in cold He release to the TS2 bunker |
| **Failure** | Air flow to sub-atm. helium | He flow to sub-atm. helium | Helium flow to environment |
| **Code** | F3 | F4 | F5 |

## Auxiliary Lines

The pipework of auxiliary process lines is also formed by main, branch and side lines. The design parameters of the auxiliary process lines are presented in Table 3.5. The branch and side auxiliary process lines form a pipework at the valve box and cryomodule.

As helium recovery main line will be cooled down to cryogenic temperatures relatively often. Therefore it is vacuum insulated but only in the klystron gallery and cold box room. The other section of this process line is not insulated, as it act as an ambient heater.

Table 3.5. Design parameters of auxiliary process lines

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Type of process line** | **Process line**  **name** | **Process line**  **code** | **Size** | **Design pressure a** | **Nominal operating pressure a** | **Nominal operating temperature** |
| Main auxiliary process lines (headers) | SV relief line | MS | DN100 b | 6 bar | 1.1 bar | 4K - 300 K |
| HP line | MH | DN25 | 16 bar | 3.0 bar | 300 K |
| Purge return line | MP | DN50 | 6 bar | 0 bar -  - 1.1 bar | 300 K |
| Helium recovery line | MR | DN50 c | 6 bar | 1.1 bar | 4 K - 300 K |
| Branch auxiliary process lines | SV relief branch line 2 | BS2 | DN50 | 6 bar | 1.1 bar | 4K - 300 K |
| SV relief branch line 3 | BS3 | DN40 | 6 bar | 1.1 bar | 4K - 300 K |
| HP branch line | BH | DN25 | 16 bar | 3.0 bar | 300 K |
| Purge return branch line | BP | DN10 | 6 bar | 0 bar -  - 1.1 bar | 300 K |
| Helium recovery  branch line | BR | DN50 | 6 bar | 1.1 bar | 4 K - 300 K |
| Side  auxiliary process lines  Side  auxiliary process lines | SV relief side line 1 | SS1 | DN25 | 6 bar | 1.1 bar | 4K - 300 K |
| SV relief side line 2 | SS2 | DN40 | 6 bar | 1.1 bar | 4K - 300 K |
| HP side line 1 | SH1 | DN10 | 16 bar | 3.0 bar | 300 K |
| HP side line 2 | SH2 | DN10 | 16 bar | 3.0 bar | 300 K |
| Purge return side line | SP | DN10 | 6 bar | 0 bar -  - 1.1 bar | 300 K |
| Helium recovery  side line 1 | SR1 | DN25 | 6 bar | 1.1 bar | 4 K - 300 K |
| Helium recovery  side line 2 | SR2 | DN25 | 6 bar | 1.1 bar | 4 K - 300 K |

a - all pressure values are given as absolute pressures  
b - the SV relief line is equipped with a drip tray in the test stand bunker  
c - the helium recovery line is vacuum insulated in the klystron gallery and cold box room;  
the size of its external envelope is DN100

Results of the auxiliary lines analysis are presented in Tables 3.6 - 3.8.

Table 3.6. Identified failures of the auxiliary lines

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Code** | **Failure** | **Potential Causes** | **System elements** | **Total** |
| F1A | Air flow to insulation vacuum of He Recovery Line (HeRL) | Weld non-tight | interconnections, elbows, external bellows | 26 m |
| Bellow failure | bellows of the external jacket | 2 |
| O-ring (1) leak | safety valve protecting vacuum | 1 |
| F2A | Helium flow to insulation vacuum of He Recovery Line | Cold weld non-tight | Interconnections, bellows | 9 m |
| Cold bellow failure | He Recovery Line | 5 |
| Cold pipe break | He Recovery Line | 53 m |
| F4A | Helium flow to sub-atmospheric line (PRL) | Hand valve leak | HV60 – seat leak, human error | 1 |
| F5A | Helium flow to environment | Weld non-tight | HP Line 5.8 m  Purge Return Line 11.4 m  SV Relief Line 20.5 m | 38 m |
| Pipe break | HP Line  Purge Return Line, SV Relief Line | 159 m |
| Control Valve leak | CV71 | 1 |
| Capillary break | PT71 | 1 |
| Bellow/metal hose failure | BS2 line (1)  SV Relief line (2) | 3 |
| Pressure transmitter leak | PT71 | 1 |

Table 3.7. Probability of failures F1A-F5A

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **F1A. Air flow to insulation vacuum of He Recovery Line (HeRL)** | | | | |
| n | Defect (potential cause) | Total length of weld/number of elements | FR of the element | Cumulative failure rate CFR of the defect |
| 1 | Weld non-tight | 26 m | 5.26·10-6 m-1·year-1 | 1.37·10-4 year-1 |
| 3 | O-ring leak | 1 | 2.63·10-2 year-1 | 2.63·10-2 year-1 |
| 4 | External bellow leak | 2 | 8.76·10-5 year-1 | 1.75·10-4 year-1 |
|  |  |  | CFR1 | 2.66·10-2 year-1 |
| Defect leading to F1A (Air flow to vacuum insulation of HeRL) can be expected every **37 years** | | | | |
| **F2A. Helium flow to insulation vacuum of He Recovery Line** | | | | |
| 1 | Weld non-tight | 9 m | 5.26·10-6 m-1·year-1 | 4.73·10-5 year-1 |
| 2 | Cold pipe leak | 53 m | 8.76·10-6 m-1·year-1 | 4.64·10-4 year-1 |
| 4 | Cold bellow | 5 | 8.76·10-5 year-1 | 4.38·10-4 year-1 |
|  |  |  | CFR2 | 9.50·10-4 year-1 |
| Defect leading to F2A (He flow to insulation vacuum of He RL) can be expected in more than **1.000 years** | | | | |
| **F4A. Pressurized helium flow to sub-atmospheric line (PRL)** | | | | |
| 1 | Hand valve opening – human error | 1 | 10-3 per demand | 10-3 per demand |
|  |  |  | CFR4 | 10-3 per demand |
| Defect leading to F4A (Pressurized helium flow to sub-atmospheric line ) can be expected once per **1000** manual operations (opening, closing, regulation) of the hand valves | | | | |
| **F5A. Helium flow to environment** | | | | |
| 1 | Weld non-tight | 38 | 5.26·10-6 m-1·year-1 | 2.00·10-4 year-1 |
| 2 | Pipe break | 159 | 8.76·10-6 m-1·year-1 | 1.39·10-3 year-1 |
| 3 | Valve leak (external leak) | 1 | 8.76·10-5 year-1 | 8.76·10-5 year-1 |
| 4 | External bellow leak | 3 | 8.76·10-5 year-1 | 2.63·10-4 year-1 |
| 5 | Capillary break | 1 | 2.00·10-8 year-1 | 2.00·10-8 year-1 |
|  |  |  | CFR5 | 1.94·10-3 year-1 |
| Defect of construction leading to F5A (He flow to environment) can be expected in more than **100 years** | | | | |
| 6 | Pressure transmitter leak | 1 | 6.1 year-1 | 6.1 year-1 |
|  |  |  | CFR5 | 6.1 year-1 |
| Defect of instrumentation leading to helium release can be expected every **59 days** | | | | |

Table 3.8. Recognized failures of the auxiliary lines and their consequences

|  |  |  |  |
| --- | --- | --- | --- |
| **Failure mitigation** | Connect to vacuum pump  If pumping not efficient - intervention required | Connect to vacuum pump  If pumping not efficient - intervention required | Connect to vacuum pump  If pumping not efficient - intervention required |
| **Failure detection** | Temperature sensors and pressure transmitters at Warm Compressor Station | Temperature sensors and pressure transmitters at Warm Compressor Station | Instrumentation of the Vacuum Pumping System |
| **Risk to system** | Air contamination of the HeRL vacuum space | Loss of the HeRL vacuum insulation | BP line (purge return branch line ) pressurization above design pressure possible – cause: human error (opening of HV60) – further analysis required |
| **Risk to personnel** | No | ODH  Freezing of tissue | No |
| **Events** | Pressurization up to 1 bar of the HeRL vacuum space  Oxygen enriched air condensation on the HeRL  Heat load to HeRL – helium temperature and pressure increase | Pressurization up to 1.1 bar of the HeRL vacuum space  Helium vented to vacuum space – heat load to HeRL – helium temperature and pressure increase inside the HeRL – intensification of helium release to vacuum space – opening of safety valve – helium flow to the TS2 area (outside the bunker) | Pressurization of Purge Return Line |
| **Failure** | Air flow to vacuum insulation of He Recovery Line | Helium flow to vacuum insulation of He Recovery Line | Helium flow to sub-atm. Line (Purge Return Line) |
| **Code** | F1A | F2A | F4.A |

|  |  |
| --- | --- |
| **Failure mitigation** | Intervention required |
| **Failure**  **detection** | Oxygen concentration sensors |
| **Risk to system** | Loss of cryogenic medium |
| **Risk to personnel** | ODH  Freezing of tissue |
| **Events** | Break of elements will result in helium release to the tunnel |
| **Failure** | Helium flow to environment |
| **Code** | F5A |

# Conclusions

9 failure modes Cryogenic Distribution System have been identified. Tables 4.1 and 4.2 summarize the analysis results for valve box & CTL node and auxiliary lines node, respectively. Colours distinguish low (green) and high (red) probability of the defect occurrence and low (green) or high (red) level of expected consequences.

Table 4.1. Summary of the valve box and CTL analysis

|  |  |  |  |
| --- | --- | --- | --- |
|  | Probability of failure occurrence | Consequences for personnel | Consequences for system |
| F1. Air flow to vacuum insulation of He Recovery Line | Once in 9 years | NO | Leak order - vacuum pumping – system in operation |
| Rupture order – test stop |
| F2. Helium flow to vacuum insulation | Once in 196 years | YES | Leak order - vacuum pumping – system in operation |
| Rupture order – test stop |
| F3. Air flow to sub-atmospheric helium | Once in more than 10.000 years | NO | Air condensation and freezing – VLP line blockage |
| Temperature increase in cryomodule |
| F4. He flow to sub-atm. helium | Once in 2 weeks | NO | Leak order – no significant consequences expected |
| Destabilization of the system parameters |
| Quench of RF Cavities can be provoked |
| F5. He flow to environment | Construction element  Once in 3 years | YES | Loss of helium |
| Instrumentation  Once in 29 days | NO | Leak order - no significant consequences expected |

Table 4.2. Summary of the auxiliary line analysis

|  |  |  |  |
| --- | --- | --- | --- |
|  | Probability of failure occurrence | Severity for personnel | Severity for machine |
| F1A. Air flow to vacuum insulation | Once in 37 years | NO | Leak order - vacuum pumping – system in operation |
| Rupture order – intervention required |
| F2A. Helium flow to insulation vacuum of He Recovery Line | Once in more than 1.000 years | YES | Leak order - vacuum pumping – system in operation |
| Rupture order – intervention |
| F4A. Helium flow to sub-atmospheric line (PRL) | Once per 1000 operations | NO | Leak order – vacuum pumping – system in operation |
| Line pressurization above design pressure |
| F5A. He flow to environment | Construction element  Once in 100 years | YES | Loss of helium |
| Instrumentation  Once in 59 days | NO | Leak order - no significant consequences expected |

Analysis of the potential causes and consequences leads to the following conclusions:

1. Air or helium flow to insulation vacuum of valve box &CTL or auxiliary line: leak order should not lead to significant consequences, efficient vacuum pumping should allow to remain system in operation mode. In case of inefficient pumping intervention and test stop can be required.
2. Air flow to sub-atmospheric helium can be caused by break of CV04 helium guard. The probability of this event is very low (due to the fact that both capillary break and leak of control valve would need to occur at the same time), however the consequences would be serious for the system operation (VLP line blockage and contamination, temperature increase in cryomodule). Special attention should be focused to the quality of cryogenic valve CV04.
3. Helium flow to sub-atmospheric helium can be caused by control valve CV07 leak through the seat. The failure can lead to quench of the RF cavities. Therefore, special attention should be focused to the quality of cryogenic valve CV07.
4. Helium flow to environment can be caused by defect of either construction element (low probability) or instrumentation (high probability). In case of defect of the construction element, the consequences for personnel can be expected (incl. ODH and cold helium release).
5. There is a potential risk of Purge Return branch line (BP) pressurization above design pressure – opening of HV60 (caused by human error) during the system operation mode – special labeling of the valve and further analysis are recommended.

# Reference and related documents

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[2] Cadwallader L.C., *Cryogenic System Operating Experience Review for Fusion Applications*, Idaho National Engineering Laboratory, USA 1992

[3] *Failure Frequency Guidance, Process Equipment Leak Frequency Data for Use in QRA*, <http://www.dnv.com/services/software/products/phast_safeti/safeti/leak_frequency_guidance.asp>

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[5] Chorowski M., Fydrych J., Grabowski M., *Risk analysis of the ITER cryodistribution system*, Technical Report WUT-IO\_TR\_015-1010

[6] Piotrowska A., Chorowski M., *The update of the Preliminary Risk Analysis of the LHC cryogenic system*, Technical Report WUT \_TR\_18-2012

[7] Peterson T., *Helium and nitrogen ODH analysis for ICB Engineering Laboratory*, Fermilab, 1991

[8] ESS-0015216R1.1 - Technical Specification of the Cryogenic Distribution System for Lund Test Stand 2

# Appendix 1

Table 1. Failure rates of the most common defects of cryogenic equipment:

|  |  |  |
| --- | --- | --- |
| Defect | Failure rate | Source |
| Cold weld non-tight | 5.26⋅10-6 m-1⋅year -1 | 1 |
| Control valve (leak through the seat) | 26.28 year -1 | 1 |
| Pressure transmitter leak | 6.13 year -1 | 1 |
| Cold pipe leakage | 8.76⋅10-6 m-1⋅year -1 | 2 |
| Control, hand, check valve (external leak) | 8.76⋅10-5 year -1 | 2 |
| Safety valve (premature open) | 8.76⋅10-2 year -1 | 2 |
| O-ring leak, | 2.63⋅10-2 year -1 | 2 |
| Cold bellows rupture | 8.76⋅10-5 year -1 | 3 |
| Capillary break | 2.0⋅10-8 year -1 | 4 |
| Feed through non-tight | 2.63⋅10-2 year -1 | Estimated |
| Helium guard break | 5.26⋅10-7 year -1 | 2,4\* |

1. Cadwallader L.C., Cryogenic System Operating Review for Fusion Application, Idaho National Engineering Laboratory, USA, 1992
2. Cryogenic and Oxygen Deficiency Hazard Safety: ODH Risk Assessment Procedures, Chapter 36, SLAC Environment, Safety and Health Manual, 2006

http://www-group.slac.stanford.edu/esh/hazardous\_substances/cryogenic/

1. Cadwallader L. Vacuum Bellows, Vacuum Piping, Cryogenic Break and Copper Joint Failure Rate Estimates for ITER Design Use, Idaho National Laboratory, USA, 2010
2. Peterson T., Helium and nitrogen ODH analysis for ICB Engineering Laboratory, Fermilab, 1991

\* Failure rate of helium guard break has been calculated as a product of capillary break and control valve leak through the seat