CONTROL PHILOSOPHY

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Distribution :

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MODIFICATIONS RECORDING

ISSUE OF MODIF	DATE	WRITTEN BY	CHECKED BY	EVOLUTION OF THE DOCUMENT (Updated pages)	JUSTIFICATION OF THE MODIFICATION
(0)	07/27/2016	G.FLAVIEN	V. GRABIE	Issue for FDR	-
(1)	10/18/2017	G.FLAVIEN		Update due to FMEA comments and Vacuum skid clarification	• Control loops integration windup • LHe level update • Turbines Efficiency Calculation • Vacuum System Sequence • Emergency stop • Alarm, Interlock and Trip list update
(2)	08/29/2018	G.FLAVIEN		General Update following JLAB comments	• Meeting from Sept 27.28, 2018
(3)	01/21/2019	G.FLAVIEN		Update following JLAB comments	• JLAB Comments On January 10th, 2019
(4)	06/28/2019	G.FLAVIEN		Update following JLAB comments	• JLAB Comments On April 2nd, 2019
(5)	01/08/2020	G.FLAVIEN		Update following Dec 2019 Test Bench week at JLAB	•

TABLE OF CONTENTS

1. INTRODUCTION

This document explains how the cold box will operate.

It identifies and describes manual and automatic operations of LCLS-II 4.5K CB system.

2. REFERENCE DOCUMENTS

REF	Document Reference	Document Title
[R1]	C1303 A 120	PID
[R2]	C1303 DS 240	Turbines Data Sheets
[R3]	C1303 A 116	PFD – Control Loops

3. GLOSSARY AND ABBREVIATIONS

LCB	Lower Cold Box
LPL	Low pressure
LPR	Cold Box Medium Pressure
MP	Compression Station Medium Pressure
HP	High Pressure
MCS	Main Compression Station
PINCH	Local temperature difference within an exchanger that is substantially less than either of two terminal differences and is minimum in the exchanger. By extension used also for terminal differences.
SP	Set Point (value used by a regulation loop)
TRIM	Valve Lift (Different from actual CV opening)
UCB	Upper Cold Box
LCB	Lower Cold Box

4. CONTROL LOOPS

4.1 CONTROL LOOPS - GENERAL

4.1.1 PID action definition

Direct action: If the "Process Value" increases, the PID/actuator value increases.

(Sensor ↗ → PID Output ↗).

Indirect action: If the "Process Value" increases, the PID/actuator value decreases,

(Sensor ↗ → PID Output ↘).

4.1.2 Set points

The set points of the control loops shall be adjustable from the HMI.

Modifications of these parameters are restricted to authorized personal.

Calculated set points (such as Turbines speed) shall be edged and the calculation shall not allow the set point to overpass the defined range.

4.1.3 Integration windup

Integral windup particularly occurs with process saturation, when the output of the process is limited at the top or bottom of its scale, making the error constant.

For example, the position of a valve cannot be any more open than fully open and also cannot be closed any more than fully closed.

Integral windup makes the actuator reaction way too long in case of a process change.

For instance, Turbines inlet valve may be 100% open for a long time, with Turbine speed still below the set point. In such condition, the speed controller must always be ready to decrease valve opening if Turbine speed needs to be limited.

In this case anti-windup can actually involve the integrator being turned off for periods of time until the response falls back into an acceptable range.

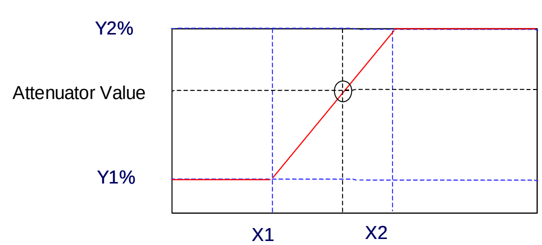
4.1.4 Attenuators definition

Attenuators can be implemented on control loops in order to avoid side effect which can be generated by the control loop.

For instance: discharge temperature of the turbine too low.

The attenuator is calculated and used as follows:

Attenuator	Sensor:	XT xxxxx	
	Sensor Value	X1	X2
	Attenuator Value	Y1	Y2



X1, X2, Y1 and Y2 shall be adjustable from the HMI.
Modifications of these parameters are restricted to authorized personal.

NB: A control loop can have several attenuators. In this case, the product of the attenuators applies to the loop.

NB: The attenuator coefficient will then apply to the Set Point i.e.:

- ✓ Turbines: .... Speed
- ✓ Valves:.. Opening
    - ✓ Heater: .... Power
    - ✓ …

4.1.5 SYSTEM ACTION AT FIRST SCAN

At first scan (Power ON), all Automatic actuators (Control Valves, ON/OFF Valves, Heaters) shall be set in Automatic in their Failure Position.

Control loops shall all be turned OFF.

> JLAB:
> System Action at First Scan: all automatic actuators is set to Automatic mode in their failure position.
> In case previous mode was manual, then code will change the mode from manual to auto mode during first scan. Is it ok with you?
> ALATUS:
> Yes

4.2 CONTROL LOOPS WARM HP FLOW SHARING

4.2.1 Introduction

The duty of the HP flow sharing control is to limit the waste of refrigeration from LPR and LPL lines to limit the consumption of Liquid Nitrogen.

Two control valves (PV-22400 and PV-22402) on the HP line drive the flow towards the HP/LPR/LN2 Heat Exchanger (HX-1A) and the HP/LPL Heat Exchangers (HX-1B).

4.2.2 TIC-22400 – HP Flow sharing controller on PV-22400 and PV-22402

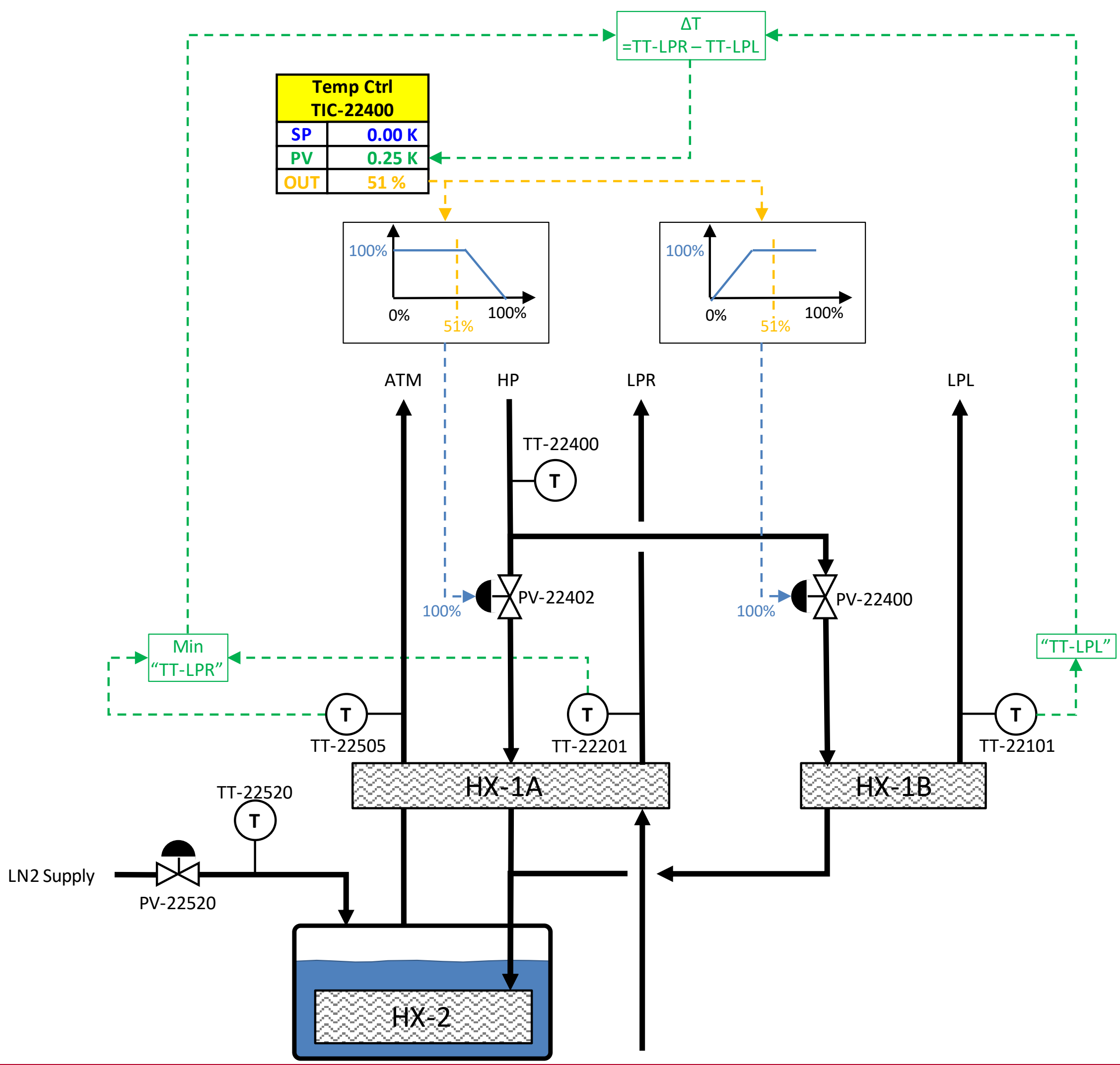
TIC-22400 tries to minimize the difference of temperature of the various flow streams returning from the Cold Box:

- If LPR or N2 flows from HX-1A are colder than the LPL flow from HX-1B:

  → the controller will reduce HP flow to HX-1B to force more exchange with cold flow from HX-1A.

- If LPR or N2 flows from HX-1A are warmer than the LPL flow from HX-1B:

  → the controller will reduce HP flow to HX-1A to force more exchange with cold flow from HX-1B.



■ TIC-22400: Warm HP flow repartition using PV-22400 and PV-22402

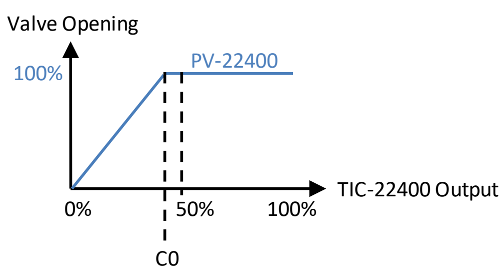
DTIC-22400	Object :	**HP flow control**
	Actuators :	**PV-22400 and PV-22402**
	Process Value:	**Min(TT-22505,TT-22201) – TT-22101**
	Set Point :	**0.0K***
	Action :	Direct

* Indicative Values: Accessible from HMI.

4.2.3 CORRESPONDANCE BETWEEN TIC-22400 OUTPUT AND PV-22400 and PV022402 OPENING

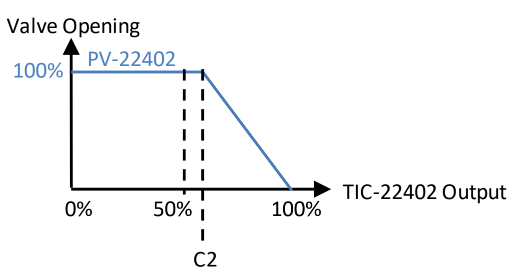
The correspondence between the controller output and the Valves opening shall be coded as follows:

- PV-22400:



C0 shall be set at 45% and shall be adjustable from HMI.

- PV-22402:



C2 shall be set at 55% and shall be adjustable from HMI.

When TIC-22400 is turned OFF:

- TIC-22400 output is forced at 0%
- PV-22400 and PV-22402 remains in their position (the program or the operator takes over on the control of these 2 valves)

When TIC-22400 is turned ON:

- TIC-22400 output is forced at 0%
- PV-22402 opening to 100% shall be on a ramp 1%/s

JLAB:
What is the failure position for TIC-22400 control?
- PV22402 = 100% and PV22400 = 0%?
- Or both valve 0%?
ALATUS:
Both Valves at 0%

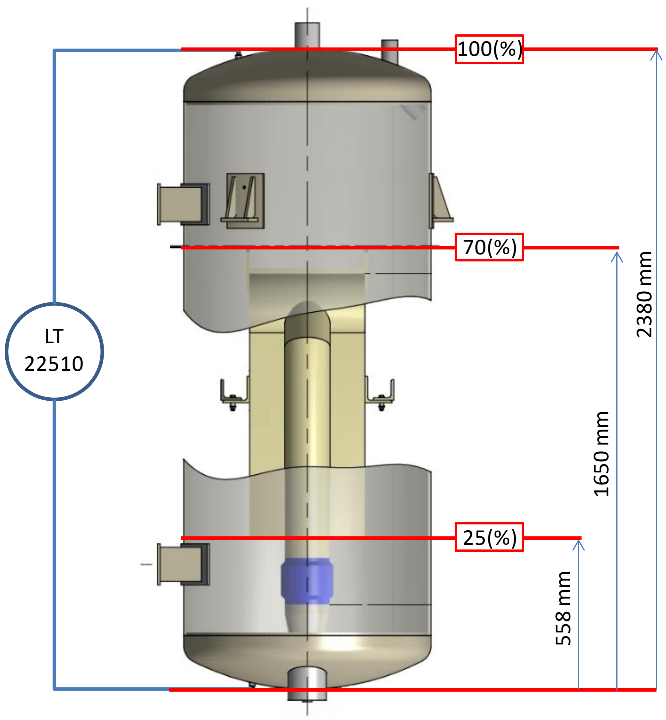
4.3 CONTROL LOOPS – LIC-22520 : LN2 LEVEL

The LN2 level regulator will control the level of LN2 in the phase separator using the LN2 inlet valve PV-22520.

- **LIC-22520: LN2 phase separator level**

LIC-22520	Object :	**LN2 level**
	Actuator :	**PV-22520**
	Process Value:	**LT-22510**
	Set Point :	**70% ~ 130 mbar**
	Action :	Indirect

* Indicative Values: Accessible from HMI.



Conversion Formulae:

$$Level\ \% = \frac{LT - 22510\ [mbar]}{190\ [mbar]}$$

4.4 CONTROL LOOPS – ADSORBERS REGENERATION HEATERS

The regeneration heaters are wrapped around the adsorber vessels.

The control will consist in an ON/OFF heating until heater temperature reaches a maximum value.

4.4.1 TIC-22418 (A & B) – 80K Regeneration Heaters Temperature

- **TIC-22418 (A-B): 80K Adsorbers regeneration Heaters Temperature**

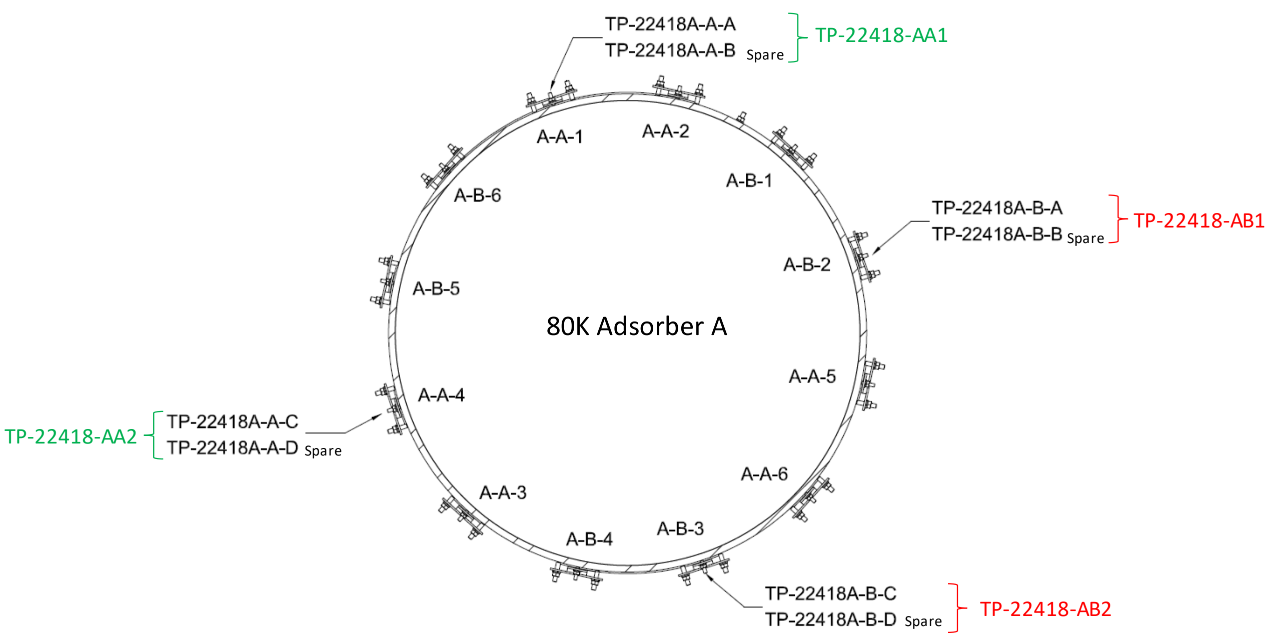
Each 80K Adsorber is equipped with a set of Heaters:

- 80K Adsorber A:
  - 3 sets of 2 Heaters (A-A-1, A-A-2), (A-A-3, A-A-4), (A-A-5, A-A-6) connected by default.
  - 3 Heaters (A-B-1, A-B-2), (A-B-3, A-B-4), (A-B-5, A-B-6) not connected initially (Spares)
- 80K Adsorber B:
  - 3 sets of 2 Heaters (B-A-1, B-A-2), (B-A-3, B-A-4), (B-A-5, B-A-6) connected by default.
  - 3 Heaters (B-B-1, B-B-2), (B-B-3, B-B-4), (B-B-5, B-B-6) not connected initially (Spares)

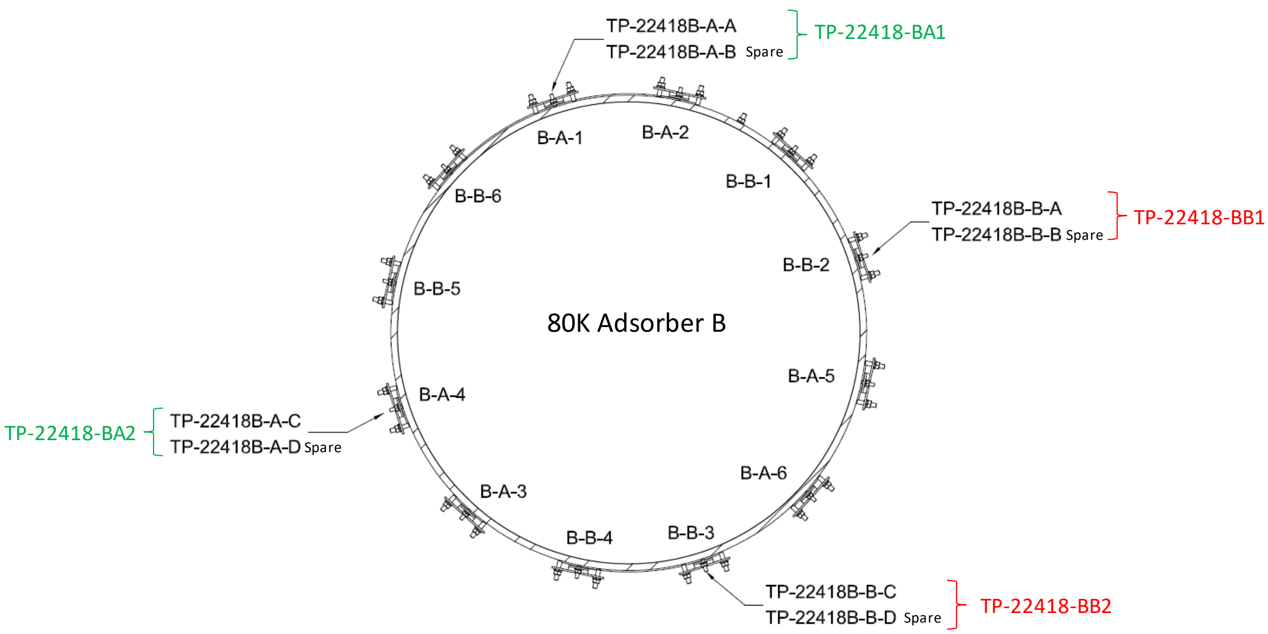
Some Heating element are equipped with doubled Temperature sensors.
The program shall use the 2 temperature sensors corresponding to the 2 equipped heating elements being used.

The following describes the Heating elements with the corresponding Temperature sensors.

- 80K Adsorber A:



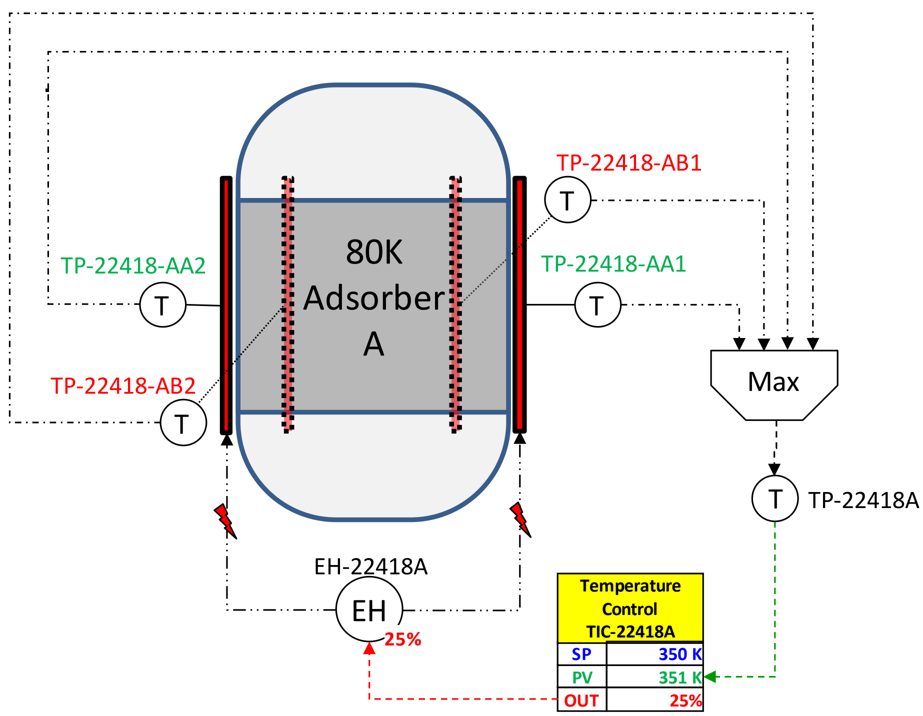
- 80K Adsorber B:



For the Heating control, the temperature to be controlled will be calculated as follows:

TT-22418 A = Max [TT-22418-AA1 / TT-22418-AA2 / TT-22418-AB1 / TT-22418-AB2]

TT-22418 B = Max [TT-22418-BA1 / TT-22418-BA2 / TT-22418-BB1 / TT-22418-BB2]



TIC-22418 (A/B)	Object :	**80K Adsorbers Heaters temperature**
	Actuator :	**80K Ads A → EH-22418A** **80K Ads B → EH-22418B**
	Process Value:	**80K Ads A → TT-22418 A** **80K Ads B → TT-22418 B**
	Set Point :	**350K**
	Action :	**Indirect**

* Indicative Values: Accessible from HMI.

Note: if TT-22418-AA1 / TT-22418-AA2 have more than 30C difference, an alarm shall be triggered.
if TT-22418-AB1 / TT-22418-AB2 have more than 30C difference, an alarm shall be triggered.

Note: if TT-22418-BA1 / TT-22418-BA2 have more than 30C difference, an alarm shall be triggered.
if TT-22418-BB1 / TT-22418-BB2 have more than 30C difference, an alarm shall be triggered.

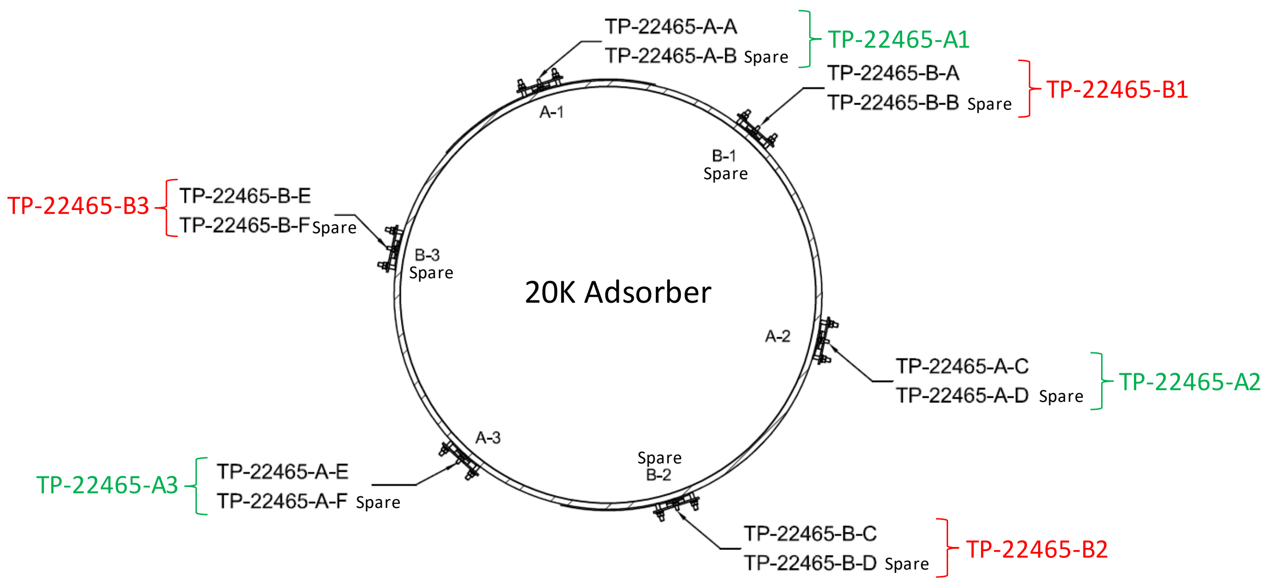
4.4.2 TIC-22465 – 20K Regeneration Heaters Temperature

The 20K Adsorber is equipped with a set of Heaters:

- 3 Heaters A-1, A-2, A-3 connected by default.
- 3 Heaters B-1, B-2, B-3 not connected initially (Spares)

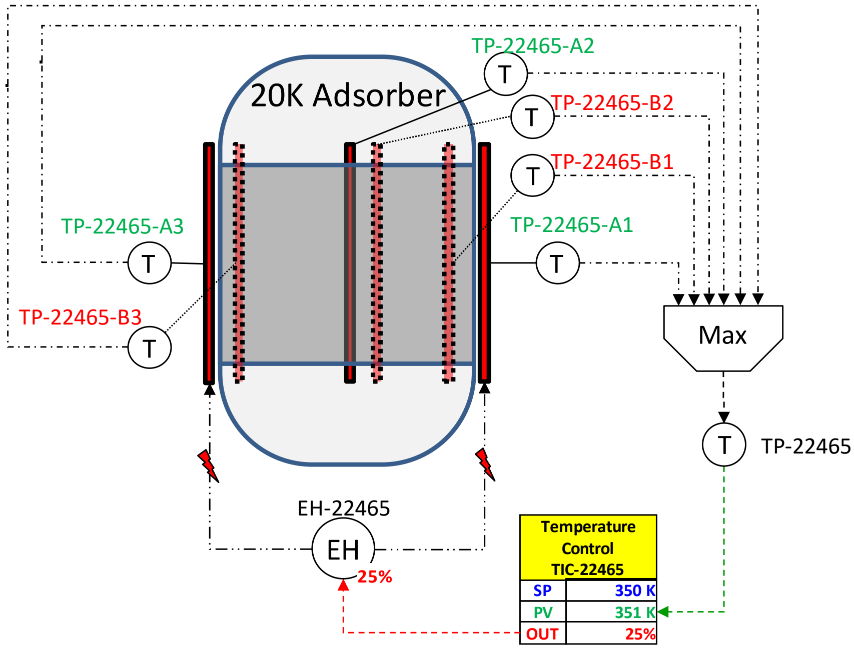
Each Heating element is equipped with doubled Temperature sensors.
The program shall use the 3 temperature sensors corresponding to the 3 heating elements being used.

The following describes the Heating elements with the corresponding Temperature sensors.



For the Heating control, the temperature to be controlled will be calculated as follows:

TT-22465 = Max [TT-22465-A1 / TT-22465-A2 / TT-22465-A3 / TT-22465-B1 / TT-22465-B2 / TT-22465-B3]



TIC-22465	Object :	**20K Adsorbers Heaters temperature**
	Actuator :	**EH-22465**
	Process Value:	**TT-22465**
	Set Point :	**350K**
	Action :	**Indirect**

* Indicative Values: Accessible from HMI.

Note: if TT-22465-A1 / TT-22465-A2 / TT-22465-A3 have more than 30C difference, an alarm shall be triggered.

if TT-22465-B1 / TT-22465-B2 / TT-22465-B3 have more than 30C difference, an alarm shall be triggered.

4.5 CONTROL LOOPS - TURBINES

4.5.1 PFD : Turbines Control

The LN2, turbine 1, turbine 2 and turbine 3 provide cooling power to pre-cool the Helium before final Expansion through Turbine 4. For optimal pre-cooling, the turbines 1, 2 and 3 control the liquefier temperature profile. Turbine 4 controls the production rate.

TURBINES 1, 2, 3: Pre-Cooling & Cold Box Temperature Profile

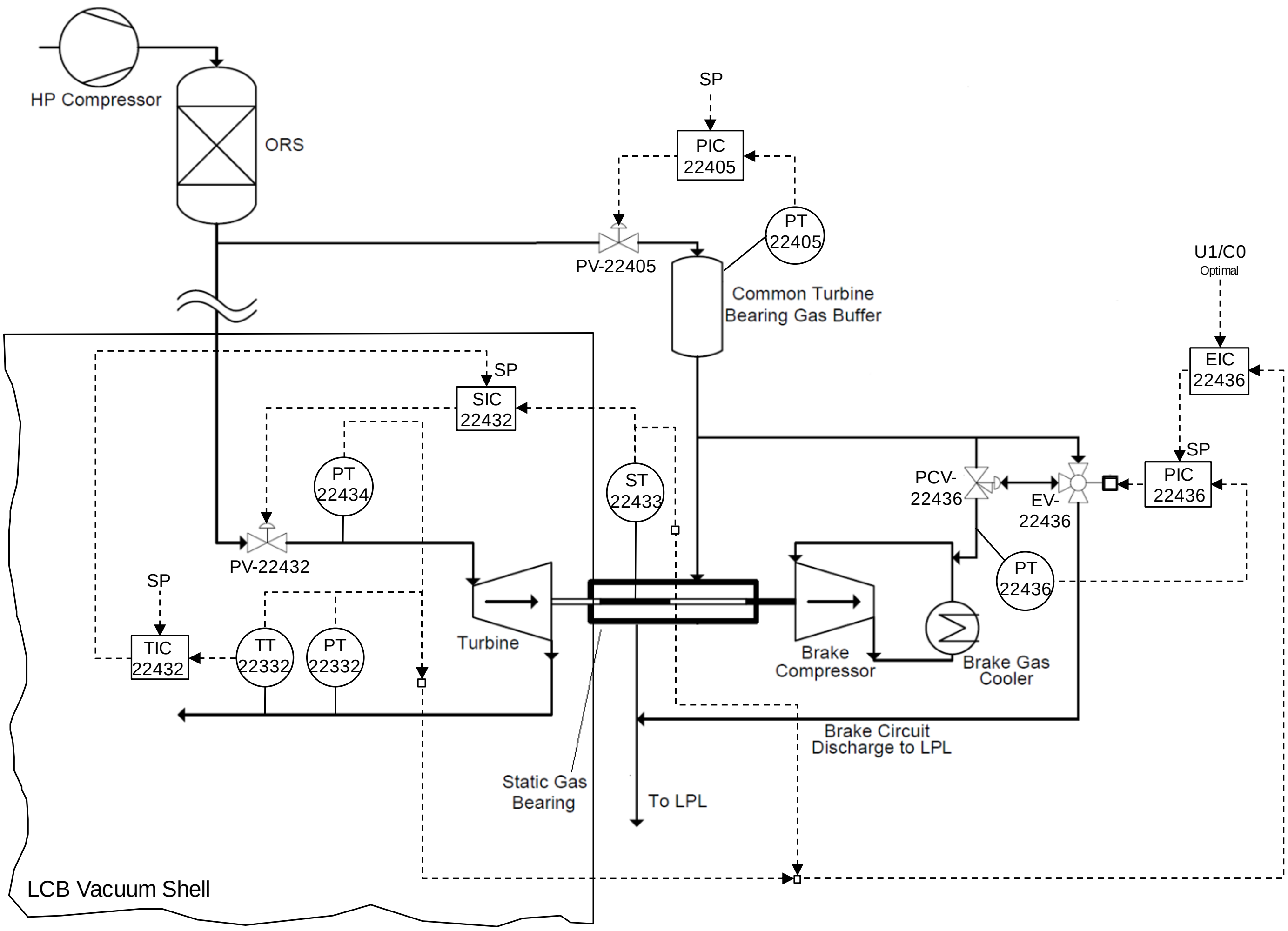
- Their speed is controlled by their inlet valves.
- Their speed is adapted to maintain a constant discharge temperature.
- However, T1, T2 and T3 will be slow down by controllers, if
  - LPR or LPL Pressure is too High
  - Level of LHe is too high
  - Refer to section 4.5.3.3 for complete attenuator list

TURBINE 4: Production Rate

- Speed will be kept to its nominal value to maximize production.
- However, T4 will be slow down by controllers, if the production is such that:
  - Adsorber Temperature 20K cannot be kept.
  - Refer to part 4.5.3.3 for complete attenuator list

5 Control loops related to the Turbines are used:

- Bearing Pressure control loop (1 controller for all 4 Turbines)
- Speed Control loop
  - Turbine discharge temperature Control loop
- Brake Pressure Control loop
  - Efficiency optimization Control loop


HP Compressor
ORS
SP
PIC
22405
PT
22405
PV-22405
Common Turbine
Bearing Gas Buffer
U1/C0
Optimal
EIC
22436
SP
SIC
22432
PT
22434
ST
22433
PV-22432
PCV-
22436
EV-
22436
SP
PIC
22436
PT
22436
SP
TIC
22432
TT
22332
PT
22332
Turbine
Brake
Compressor
Brake Gas
Cooler
Brake Circuit
Discharge to LPL
Static Gas
Bearing
To LPL
LCB Vacuum Shell

4.5.2 PIC-22405 - Bearings Pressure

Note: Bearing pressure controller PIC-22405 start / stop automatically starts / stops all 4 Turbines Brake pressure controllers PIC-224X6.

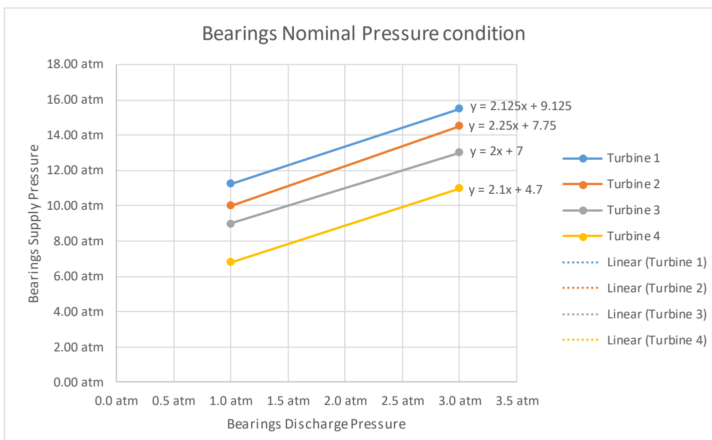
PIC-22405	Object :	**Turbines Bearings Pressure**
	Actuator :	**PV-22405**
	Process Value:	**PT-22405**
	Set Point :	**12 Atm*** Entering lower value prevented
	Action :	Indirect

* Indicative Values: Accessible from HMI.

The minimum pressure required at turbines bearing inlet determines the set point for this regulation.

Turbines bearing inlet pressure is continuously compared to the bearing discharge pressure to ensure a sufficient stiffness of the Bearing.

The following graph gives the nominal pressure conditions for the 4 Turbines:



12 Atm is the lowest acceptable set point for this control loop.

The discharge pressure is not expected to move far from a nominal 1.5 atm value.

→ The Bearing Pressure set point should thus be fix. But if the operation of the Cold Boxes shows that Turbines discharge pressure varies in wider proportions, a logic to adjust the set point can be developed.

4.5.3 SIC-224X2 & TIC-223X2 - Turbines speed

Turbine Speed is controlled using a cascade regulation:

- Turbine discharge temperature: TIC-223x2
  → The output of this regulator is used as a set point for the 2nd controller: Speed Control
- Turbine Speed: SIC-224x3
  → Controls the turbine speed by adjusting the turbine inlet valve.
  → This controller will have **attenuators** to lower the turbine speed set point before it reaches OFF-DESIGN or UNSAFE conditions.

Note: The objective is to operate the Turbines with the inlet valve 100% open. The set points for the Speed and for the discharge Temperature are therefore slightly further the nominal values (Speed slightly Higher, Temperature slightly lower), but still in the range of a safe operation of the turbines.

Note: For Turbine 4 (Joules Thomson), the discharge temperature is not controlled.
→Turbine upstream temperature is controlled (20K adsorber temperature is used for this controller).

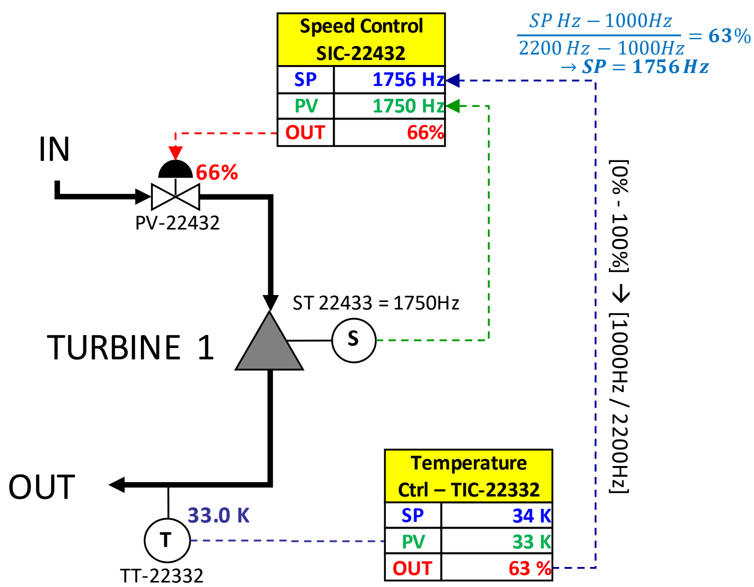
NOTE: WHILE STARTING CONTROL LOOPS IN CASCADE:

Starting the Control Loops shall be performed smoothly, using Tracking, i.e:

1. **When the Speed Control Loops (SIC) is started:**
   a. The Output of the regulator is set equal to the Control Valve (CV) position. (no Step)
   b. The SP (Set point) is equal to the PV (Process Value), i.e. the actual Turbine Speed.

2. **When the Temperature Control Loops (TIC) is started:**
   a. The Output of the regulator is forced at Speed Control Loop SP (Set Point).
   b. The SP is equal to the PV, i.e. the actual Turbine Discharge Temperature.

3. **Once the SIC and TIC have been started:**
   a. TIC SP can be ramped to the defined value (refer to Turbine Sequences for Ramp value).
      → This will increase TIC output, which will increase SIC set point progressively.
      → **No step in Control Valve is expected!**



JLAB:
SIC224X2 set point = Maximum speed if TIC224X2 is OFF.
We have no scenario in control philosophy where SIC is ON and TIC is OFF.
Only situation we can think -> At X514 (turbine nominal state), if operator make TIC loop manual, and then tries to dial in a X % to go to a specific speed point.
Do we foresee this condition of TIC OFF and ramping speed up to maximum speed automatically during commissioning?
ALATUS:
I have no opinion just yet. I believe it can work in any condition with both controllers ON, but I let the window open for a possible disconnection of TIC if found necessary during commissioning

4.5.3.1 SIC-224X2 - SPEED

Note: It shall be possible to set a maximum opening for Each Turbine inlet valve that will be defined during the commissioning. This value will ensure a fast response time of the valve.

- **SIC-22432: Turbine 1 Speed**

SIC-22432	Object :	**Turbine 1 speed**	
	Actuator :	**PV-22432**	
	Process Value:	**ST-22433**	**[%]**
	Set Point :	**2220 Hz if TIC-22332 is OFF** **TIC-22332 output if TIC-22332 is ON** **[0% - 100%] →[1000 Hz –2220 Hz]**	
	Action :	Indirect	

- **SIC-22452: Turbine 2 Speed**

SIC-22452	Object :	**Turbine 2 speed**	
	Actuator :	**PV-22452**	
	Process Value:	**ST-22453**	**[%]**
	Set Point :	**2020 Hz if TIC-22352 is OFF** **TIC-22352 output if TIC-22352 is ON** **[0% - 100%] →[1200 Hz – 2020 Hz]**	
	Action :	Indirect	

- **SIC-22472: Turbine 3 Speed**

SIC-22472	Object :	**Turbine 3 speed**	
	Actuator :	**PV-22472**	
	Process Value:	**ST-22473**	**[%]**
	Set Point :	**1450 Hz if TIC-22372 is OFF** **TIC-22372 output if TIC-22372 is ON** **[0% - 100%] →[850 Hz – 1450 Hz]**	
	Action :	Indirect	

- **SIC-22482: Turbine 4 Speed**

SIC-22482	Object :	**Turbine 4 speed**	
	Actuator :	**PV-22482**	
	Process Value:	**ST-22483**	**[%]**
	Set Point :	**1180 Hz if TIC-22466 is OFF** **TIC-22466 output if TIC-22466 is ON** **[0% - 100%] →[800 Hz – 1180 Hz]**	
	Action :	Indirect	

4.5.3.2 TIC-224X2 / TIC-22466 – OUTLET TEMPERATURE

Note: When TIC-223X2 is OFF, the PID calculation shall stop, and controller output must be aligned with Speed controller primary set point.

- **TIC-22332: Turbine 1 discharge temperature**

TIC-22432	Object :	**Turbine 1 discharge temperature**
	Actuator :	**PID SIC-22432 for T1 speed set point calculation**
	Process Value:	**TT-22332**
	Set Point :	**34 K***
	Action :	Direct

* Indicative Values: Accessible from HMI.

- **TIC-22352: Turbine 2 discharge temperature**

TIC-22452	Object :	**Turbine 2 discharge temperature**
	Actuator :	**PID SIC-22452 for T2 speed set point calculation**
	Process Value:	**TT-22352**
	Set Point :	**13 K***
	Action :	Direct

* Indicative Values: Accessible from HMI.

- **TIC-22372: Turbine 3 discharge temperature**

TIC-22472	Object :	**Turbine 3 discharge temperature**
	Actuator :	**PID SIC-22472 for T3 speed set point calculation**
	Process Value:	**TT-22372**
	Set Point :	**6.5 K***
	Action :	Direct

* Indicative Values: Accessible from HMI.

- **TIC-22466: 20K adsorber outlet temperature**

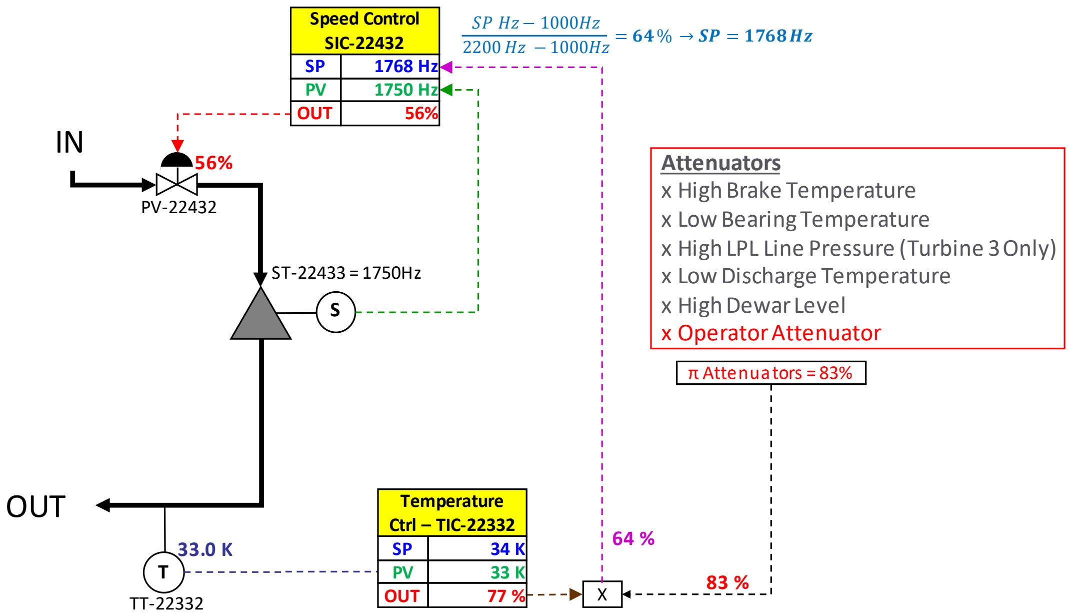
TIC-22466	Object :	**20K Adsorber Outlet Temperature**
	Actuator :	**PID SIC-22482 for T4 speed set point calculation**
	Process Value:	**TT-22466**
	Set Point :	**18.5 K***
	Action :	Indirect

* Indicative Values: Accessible from HMI.

4.5.3.3 ATTENUATORS

A speed controller controls the turbines. The turbine speed set point is computed from different parameters (discharge temperature for T1, T2 and T3, and Adsorbers temperature for T4).

The attenuators can decrease the turbine speed set point: SP = Computed SP x π Attenuators.



ATTENUATORS SHALL BE CONSIDERED AS SAFE GUARDS. (Slow down turbine before Alarms/Trips)

When Turbine parameters approach UNSAFE or OFF-DESIGN conditions, the Turbine Speed Set point is decreased in order to avoid UNSAFE or OFF-DESIGN zones. The following Attenuators are implemented:

ATTENUATORS PARAMETERS ARE AVAILABLE FROM THE HMI FOR PROCESS ADJUSTMENT.

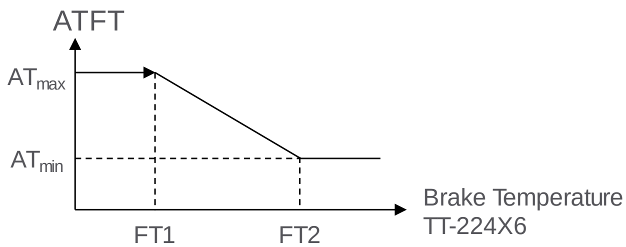
Speed set point is calculated by multiplication of Turbine nominal speed with a series of attenuators (value between 0.5 and 1), depending of process conditions, as follows:

Set Point = NS x [ATFT x ATBT x ATLP x ATDT x ATDL x ATOP]

- NS = Nominal Speed
- ATFT = Attenuator on Brake Temperature:
  → Slows down turbine if the Brake is too hot.
- ATBT = Attenuator on Bearing Temperature:
  → Slows down turbine if the Bearing is too cold.
- ATLP = Attenuator on LPL Line Pressure:
  → Slows down turbine 3 if LP pressure is too high.
- ATDT = Attenuator on Discharge Temperature:
  → Slows down turbine if discharge temperature is too cold.
- ATDL = Attenuator on Dewar Level:
  → Slows down turbine Dewar Level is too high.
- ATOP = Attenuator for the Operator: Allows the operator to manually slow down a turbine. The operator can directly enter a value for ATOP on the HMI.

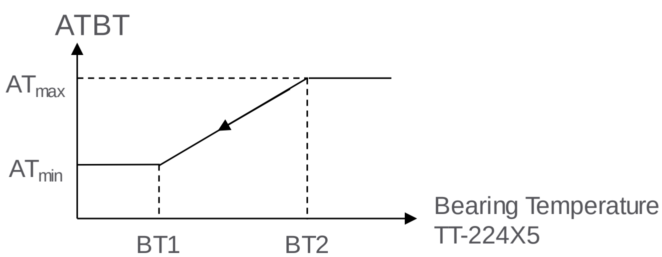
If all attenuators = 1 and TIC-224X2 / TIC-22466 then **Set Point = Nominal Speed**.

- ATFT – Turbine Brake Temperature Attenuator:



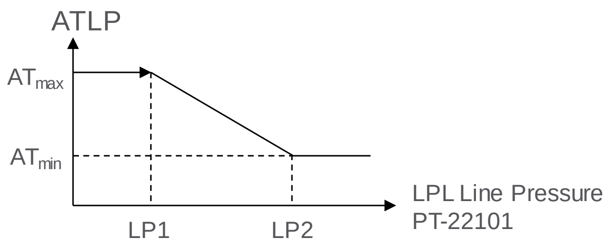
Attenuator	Attenuator Parameters	Turbine 1	Turbine 2	Turbine 3	Turbine 4
ATFT	Sensor	TT-22436	TT-22456	TT-22476	TT-22486
	AT_{min}	50%	50%	50%	50%
	AT_{max}	100%	100%	100%	100%
	FT 1	360 K	360 K	360 K	360 K
	FT 2	370 K	370 K	370 K	370 K

- ATBT – Turbine Bearing Temperature Attenuator:



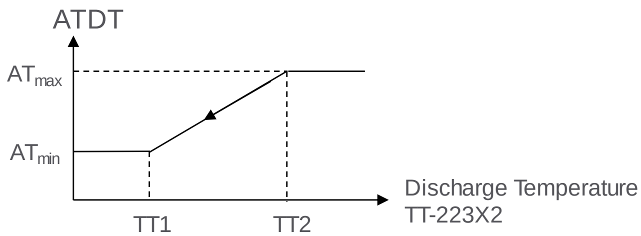
Attenuator	Attenuator Parameters	Turbine 1	Turbine 2	Turbine 3	Turbine 4
ATBT	Sensor	TT-22435	TT-22455	TT-22475	TT-22485
	AT_{min}	80%	80%	80%	80%
	AT_{max}	100%	100%	100%	100%
	BT 1	275 K	275 K	275 K	275 K
	BT 2	280 K	280 K	280 K	280 K

- ATLP – LPL Line pressure attenuator:



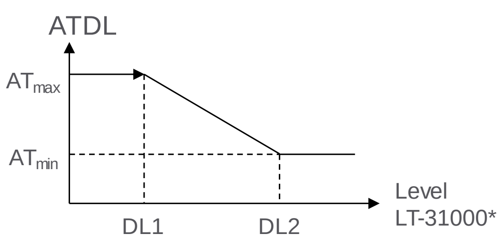
Attenuator	Attenuator Parameters	Turbine 1	Turbine 2	Turbine 3	Turbine 4
ATLP	Sensor	-	-	PT-22101	-
	AT_{min}	-	-	50%	-
	AT_{max}	-	-	100%	-
	LP 1	-	-	1.2 atm	-
	LP 2	-	-	1.3 atm	-

- ATDT – Turbines Discharge Temperature Attenuator:



Attenuator	Attenuator Parameters	Turbine 1	Turbine 2	Turbine 3	Turbine 4
ATDT	Sensor	TT-22332	TT-22352	TT-22372	-
	AT_{min}	50%	50%	50%	-
	AT_{max}	100%	100%	100%	-
	TT 1	25 K	10 K	5 K	-
	TT 2	30 K	11 K	5.5 K	-

- ATDL – Dewar Level Attenuator:



*LT-31000 is the level transmitter on Customer Dewar.

Attenuator	Attenuator Parameters	Turbine 1	Turbine 2	Turbine 3	Turbine 4
ATDL	Sensor	LT-31000*	LT-31000*	LT-31000*	-
	AT_{min}	70%	70%	70%	-
	AT_{max}	100%	100%	100%	-
	DL 1	75 %	75 %	75 %	-
	DL 2	80 %	80 %	80 %	-

- ATOP – Operator Attenuator:

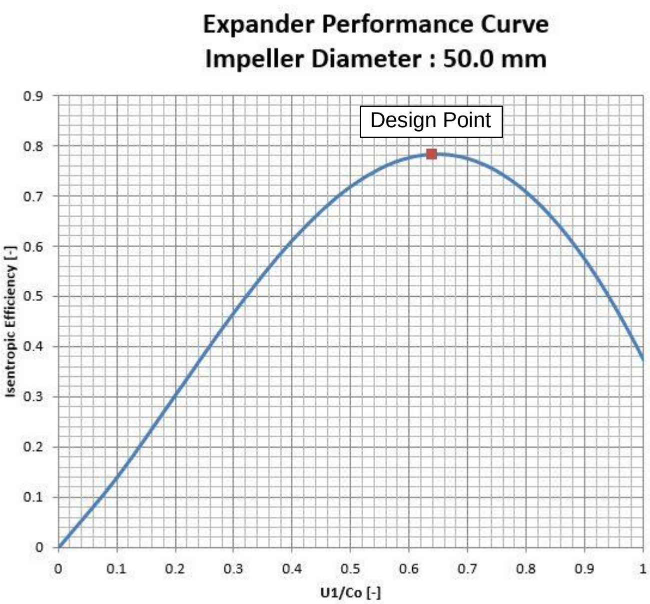
Attenuator	Attenuator Parameters	Turbine 1	Turbine 2	Turbine 3	Turbine 4
ATOP	Sensor	Forced on HMI	Forced on HMI	Forced on HMI	Forced on HMI
	AT_{value}	$20\% \leq X \leq 100\%$	$20\% \leq X \leq 100\%$	$20\% \leq X \leq 100\%$	$20\% \leq X \leq 100\%$

4.5.4 PIC-224X6 & EIC-224X6 – Turbines Brake and Efficiency

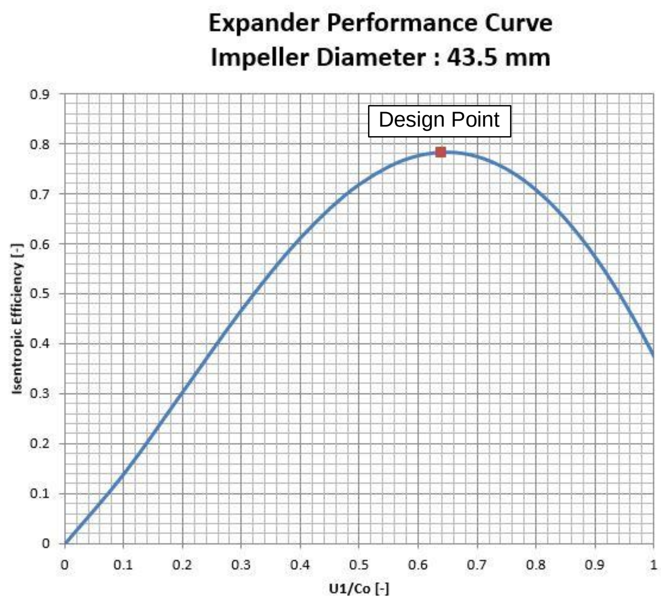
An important parameter to consider for Turbo-expander performance is the U1/C0 factor. This is a non-dimensional parameter where U1 is the tip speed of the wheel and C0 is the spouting velocity. The spouting velocity is the fluid speed that would be achieved if the entire isentropic enthalpy drop were to be converted into speed. In other words, it is the speed that is created from putting work into the system.

The following curves are the Efficiency characteristics for each of the 4 Turbines:

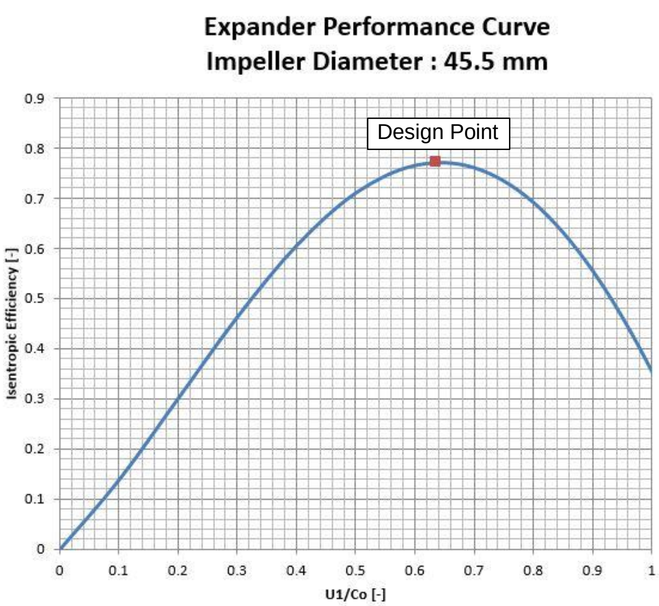
Turbine 1:



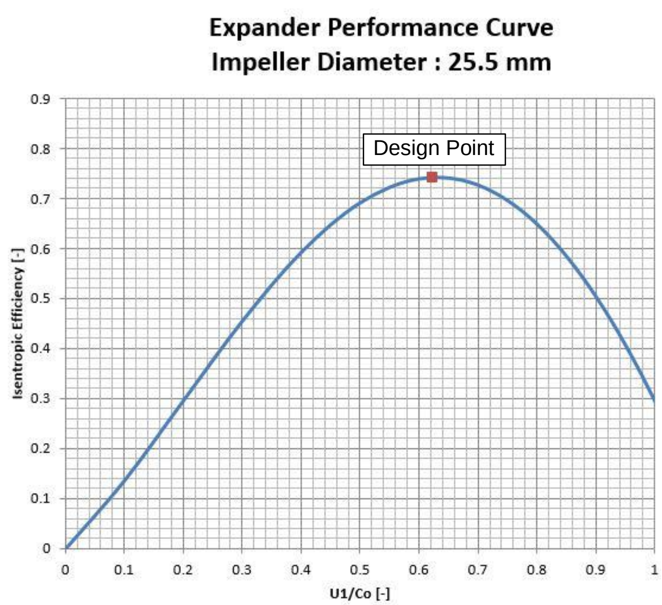
Turbine 2



Turbine 3:



Turbine 4



Air Liquide turbo-expanders are equipped with a brake pressure regulation: EIC-224X6

- Brake Pressure regulator:
  - Use brake pressure measurement and compares it to the set point.
  - The Output acts on Brake Electro-valve.

The set point of this regulation is fixed whenever the Turbine does not work close to its design temperature.

When the turbine works in its design temperature range, the brake pressure set point is determined by the output of a 2nd regulator, called Efficiency Regulator, set in cascade:

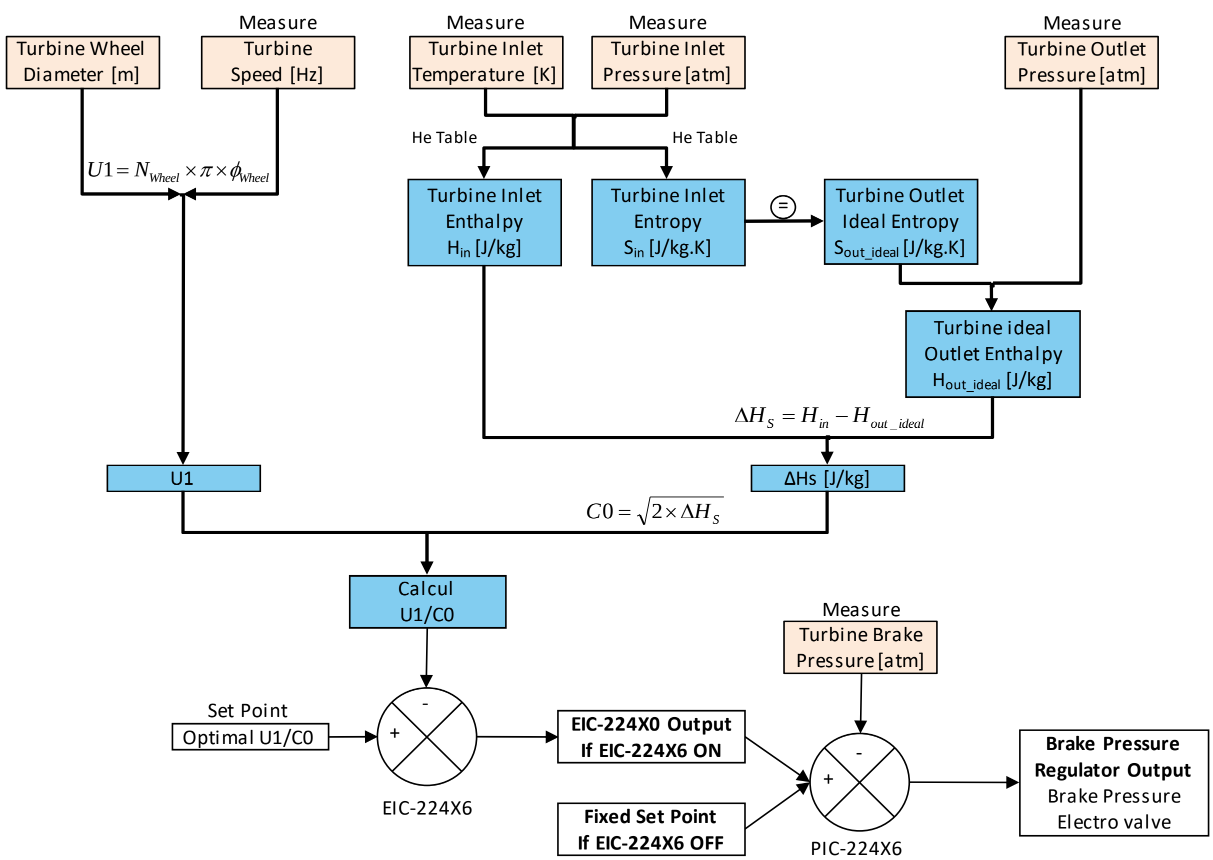
- Efficiency regulator: EIC-224X6
  - Calculate the actual U1/C0 of the Turbo-expanders and compares it to the set point (optimal U1/C0 for the turbine).
  - The Output defines the set point for the brake pressure regulation.

- The process variables for the calculation have the following units:

Wheel Diameter	m
Turbine Speed	Hz
Turbine Inlet / Outlet Temperature	K
Turbine Inlet / Outlet / Brake Pressure	atm

- Turbines wheel diameter:

Turbine 1	50.0 mm	Turbine 3	45.5 mm
Turbine 2	43.5 mm	Turbine 4	25.5 mm



4.5.4.1 PIC-224X6 - BRAKE PRESSURE

Note: Brake pressure controllers PIC-224X6 are started / stopped with bearing pressure controller PIC-22405.
When PIC-224X6 is stopped, EV-224X6 shall be closed.

■ **PIC-22436: Turbine 1 brake pressure**

PIC-22436	Object :	**Turbine 1 brake pressure**
	Actuator :	**EV-22436**
	Process Value:	**PT-22436**
	Set Point :	• **5.0 atm if EIC-22436 is OFF** • **EIC-22436 Output if EIC-22436 is ON:** **[0% - 100%] → [4.0 atm – 6.0 atm]**
	Action :	Indirect

■ **PIC-22456: Turbine 2 brake pressure**

PIC-22456	Object :	**Turbine 2 brake pressure**
	Actuator :	**EV-22456**
	Process Value:	**PT-22456**
	Set Point :	• **5.0 atm if EIC-22456 is OFF** • **EIC-22456 Output if EIC-22456 is ON:** **[0% - 100%] → [2.0 atm – 6.0 atm]**
	Action :	Indirect

■ **PIC-22476: Turbine 3 brake pressure**

PIC-22476	Object :	**Turbine 3 brake pressure**
	Actuator :	**EV-22476**
	Process Value:	**PT-22476**
	Set Point :	• **5.0 atm if EIC-22476 is OFF** • **EIC-22476 Output if EIC-22476 is ON:** **[0% - 100%] →[3atm – 5.5atm]**
	Action :	Indirect

■ **PIC-22486: Turbine 4 brake pressure**

PIC-22486	Object :	**Turbine 4 brake pressure**
	Actuator :	**EV-22486**
	Process Value:	**PT-22486**
	Set Point :	• **5.0 atm if EIC-22486 is OFF** • **EIC-22486 Output if EIC-22486 is ON:** **[0% - 100%] →[3.3atm – 5.5atm]**
	Action :	Indirect

4.5.4.2 EIC-224X6 - "EFFICIENCY" (OPTIMAL U1/C0)

Note: The Efficiency controller has a direct action. When the U1/C0 calculation increases, the set point of the Brake control loop shall increase to slow-down the Turbine.

Note: When EIC-224X6 is OFF, the PID calculation shall stop, and controller output must be aligned with Brake Pressure controller primary set point.

- **EIC-22436: Turbine 1 U1/C0**

EIC-22436	Object :	**Turbine 1 U1/C0**
	Actuator :	**PID PIC-22436 for T1 brake pressure set point calculation**
	Process Value:	**Calculated U1/C0**
	Set Point :	**U1 / C0 = 0.65**
	Action :	Direct

- **EIC-22456: Turbine 2 brake pressure**

EIC-22456	Object :	**Turbine 2 U1/C0**
	Actuator :	**PID PIC-22456 for T2 brake pressure set point calculation**
	Process Value:	**Calculated U1/C0**
	Set Point :	**U1 / C0 = 0.64**
	Action :	Direct

- **EIC-22476: Turbine 3 brake pressure**

EIC-22476	Object :	**Turbine 3 U1/C0**
	Actuator :	**PID PIC-22476 for T3 brake pressure set point calculation**
	Process Value:	**Calculated U1/C0**
	Set Point :	**U1 / C0 = 0.64**
	Action :	Direct

- **EIC-22486: Turbine 4 brake pressure**

EIC-22486	Object :	**Turbine 4 U1/C0**
	Actuator :	**PID PIC-22486 for T4 brake pressure set point calculation**
	Process Value:	**Calculated U1/C0**
	Set Point :	**U1 / C0 = 0.62**
	Action :	Direct

4.5.4.3 HELIUM DATA FOR TURBINE EFFICIENCY CALCULATION

The following Helium Tables are to be entered in the PLC and shall be used by Turbine Efficiency Controller. Helium data points shall be interpolated linearly in the PLC.

Note: If the U1/C0 calculation is "out of Range", the last valid value shall be kept and only replaced when the U1/C0 calculation gives a value in the range.

IMPORTANT NOTE: Enthalpy & Entropy (Hin, Sin and Sout_ideal) tabular values hereunder are given in J/g.K and J/g for reading purpose. They shall be multiplied by 1000 to convert unit to J/kg.K and J/kg during PLC coding.

- **Helium Data for Turbine 1**

P_{in}	7 atm		8 atm		9 atm		10 atm		11 atm		12 atm		13 atm		14 atm		15 atm		16 atm		17 atm		18 atm		19 atm		20 atm	
T_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}
70 K	380	20.0	381	19.7	381	19.5	381	19.2	381	19.0	381	18.9	382	18.7	382	18.5	382	18.4	382	18.3	383	18.1	383	18.0	383	17.9	383	17.8
69 K	375	19.9	375	19.6	376	19.4	376	19.2	376	19.0	376	18.8	376	18.6	377	18.5	377	18.3	377	18.2	377	18.0	378	17.9	378	17.8	378	17.7
68 K	370	19.8	370	19.5	370	19.3	371	19.1	371	18.9	371	18.7	371	18.5	371	18.4	372	18.2	372	18.1	372	18.0	372	17.9	373	17.7	373	17.6
67 K	365	19.7	365	19.5	365	19.2	365	19.0	366	18.8	366	18.6	366	18.5	366	18.3	366	18.2	367	18.0	367	17.9	367	17.8	367	17.7	367	17.6
66 K	359	19.7	360	19.4	360	19.1	360	18.9	360	18.7	361	18.5	361	18.4	361	18.2	361	18.1	361	17.9	362	17.8	362	17.7	362	17.6	362	17.5
65 K	354	19.6	354	19.3	355	19.1	355	18.8	355	18.6	355	18.5	355	18.3	356	18.1	356	18.0	356	17.9	356	17.7	357	17.6	357	17.5	357	17.4
64 K	349	19.5	349	19.2	349	19.0	350	18.8	350	18.6	350	18.4	350	18.2	350	18.1	351	17.9	351	17.8	351	17.7	351	17.5	351	17.4	352	17.3
63 K	344	19.4	344	19.1	344	18.9	344	18.7	345	18.5	345	18.3	345	18.1	345	18.0	345	17.8	346	17.7	346	17.6	346	17.5	346	17.3	346	17.2
62 K	339	19.3	339	19.1	339	18.8	339	18.6	339	18.4	340	18.2	340	18.1	340	17.9	340	17.8	340	17.6	341	17.5	341	17.4	341	17.3	341	17.1
61 K	333	19.3	334	19.0	334	18.7	334	18.5	334	18.3	334	18.1	334	18.0	335	17.8	335	17.7	335	17.5	335	17.4	335	17.3	336	17.2	336	17.1
60 K	328	19.2	328	18.9	329	18.6	329	18.4	329	18.2	329	18.0	329	17.9	329	17.7	330	17.6	330	17.4	330	17.3	330	17.2	330	17.1	331	17.0
59 K	323	19.1	323	18.8	323	18.6	323	18.3	324	18.1	324	18.0	324	17.8	324	17.6	324	17.5	325	17.4	325	17.2	325	17.1	325	17.0	325	16.9
58 K	318	19.0	318	18.7	318	18.5	318	18.2	318	18.1	319	17.9	319	17.7	319	17.5	319	17.4	319	17.3	319	17.1	320	17.0	320	16.9	320	16.8
57 K	312	18.9	313	18.6	313	18.4	313	18.2	313	18.0	313	17.8	313	17.6	314	17.5	314	17.3	314	17.2	314	17.0	314	16.9	314	16.8	315	16.7
56 K	307	18.8	307	18.5	308	18.3	308	18.1	308	17.9	308	17.7	308	17.5	308	17.4	309	17.2	309	17.1	309	17.0	309	16.8	309	16.7	309	16.6
55 K	302	18.7	302	18.4	302	18.2	302	18.0	303	17.8	303	17.6	303	17.4	303	17.3	303	17.1	303	17.0	304	16.9	304	16.7	304	16.6	304	16.5
54 K	297	18.6	297	18.3	297	18.1	297	17.9	297	17.7	297	17.5	298	17.3	298	17.2	298	17.0	298	16.9	298	16.8	298	16.6	299	16.5	299	16.4
53 K	291	18.5	292	18.2	292	18.0	292	17.8	292	17.6	292	17.4	292	17.2	293	17.1	293	16.9	293	16.8	293	16.7	293	16.5	293	16.4	293	16.3
52 K	286	18.4	286	18.1	287	17.9	287	17.7	287	17.5	287	17.3	287	17.1	287	17.0	287	16.8	288	16.7	288	16.6	288	16.4	288	16.3	288	16.2
51 K	281	18.3	281	18.0	281	17.8	281	17.6	282	17.4	282	17.2	282	17.0	282	16.9	282	16.7	282	16.6	282	16.5	282	16.3	283	16.2	283	16.1
50 K	276	18.2	276	17.9	276	17.7	276	17.5	276	17.3	276	17.1	277	16.9	277	16.8	277	16.6	277	16.5	277	16.3	277	16.2	277	16.1	277	16.0
49 K	271	18.1	271	17.8	271	17.6	271	17.4	271	17.2	271	17.0	271	16.8	271	16.7	271	16.5	272	16.4	272	16.2	272	16.1	272	16.0	272	15.9
48 K	265	18.0	265	17.7	265	17.5	266	17.3	266	17.1	266	16.9	266	16.7	266	16.5	266	16.4	266	16.3	266	16.1	267	16.0	267	15.9	267	15.8
47 K	260	17.9	260	17.6	260	17.4	260	17.1	260	16.9	261	16.8	261	16.6	261	16.4	261	16.3	261	16.1	261	16.0	261	15.9	261	15.8	261	15.7
46 K	255	17.8	255	17.5	255	17.3	255	17.0	255	16.8	255	16.6	255	16.5	255	16.3	256	16.2	256	16.0	256	15.9	256	15.8	256	15.7	256	15.6
45 K	249	17.7	250	17.4	250	17.1	250	16.9	250	16.7	250	16.5	250	16.4	250	16.2	250	16.1	250	15.9	250	15.8	250	15.7	251	15.5	251	15.4
44 K	244	17.5	244	17.3	244	17.0	244	16.8	245	16.6	245	16.4	245	16.2	245	16.1	245	15.9	245	15.8	245	15.7	245	15.5	245	15.4	245	15.3
43 K	239	17.4	239	17.1	239	16.9	239	16.7	239	16.5	239	16.3	239	16.1	239	16.0	240	15.8	240	15.7	240	15.5	240	15.4	240	15.3	240	15.2
42 K	234	17.3	234	17.0	234	16.8	234	16.5	234	16.3	234	16.2	234	16.0	234	15.8	234	15.7	234	15.5	234	15.4	234	15.3	234	15.2	235	15.1
41 K	228	17.2	228	16.9	229	16.6	229	16.4	229	16.2	229	16.0	229	15.9	229	15.7	229	15.6	229	15.4	229	15.3	229	15.2	229	15.0	229	14.9

Inlet Enthalpy (J/g) and Entropy (J/g.K) function of Inlet Pressure and Temperature

P_{out}	1 atm	1.25 atm	1.5 atm	1.75 atm	2 atm	2.25 atm	2.5 atm	2.75 atm	3 atm	3.25 atm	3.5 atm	3.75 atm	4 atm	4.25 atm	4.5 atm
$S_{out\_ideal = Sin}$	H_{out_ideal}														
20	183	199	212	225	237	247	257	267	276	284	292	300	308	315	322
19.5	167	182	194	206	216	226	235	244	252	260	267	274	281	288	294
19	153	166	178	188	198	207	215	223	230	237	244	250	257	263	268
18.5	141	153	163	172	181	189	197	204	210	217	223	229	235	240	245
18	129	140	149	158	166	173	180	186	193	198	204	209	214	219	224
17.5	119	128	137	145	152	159	165	171	176	182	187	191	196	201	205
17	109	118	126	133	139	145	151	156	161	166	171	175	179	184	188
16.5	100	108	116	122	128	133	139	143	148	152	156	160	164	168	172
16	93	100	106	112	117	122	127	132	136	140	143	147	151	154	157
15.5	85	92	98	103	108	112	117	121	125	128	132	135	138	141	144
15	79	85	90	95	99	103	107	111	114	118	121	124	127	129	132
14.5	73	78	83	87	91	95	99	102	105	108	111	114	116	119	121
14	67	72	77	81	84	88	91	94	97	99	102	104	107	109	111

Outlet Ideal Enthalpy (J/g) function of Inlet Entropy (J/g.K) and Outlet Pressure

- **Helium Data for Turbine 2**

P_{in}	4 atm		5 atm		6 atm		7 atm		8 atm		9 atm		10 atm		11 atm		12 atm		13 atm		14 atm		15 atm		16 atm		17 atm		18 atm		19 atm		20 atm	
T_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}
45 K	249	18.8	249	18.4	249	18.0	249	17.7	250	17.4	250	17.1	250	16.9	250	16.7	250	16.5	250	16.4	250	16.2	250	16.1	250	15.9	250	15.8	250	15.7	251	15.5	251	15.4
44 K	244	18.7	244	18.3	244	17.9	244	17.5	244	17.3	244	17.0	244	16.8	245	16.6	245	16.4	245	16.2	245	16.1	245	15.9	245	15.8	245	15.7	245	15.5	245	15.4	245	15.3
43 K	239	18.6	239	18.1	239	17.7	239	17.4	239	17.1	239	16.9	239	16.7	239	16.5	239	16.3	239	16.1	239	16.0	240	15.8	240	15.7	240	15.5	240	15.4	240	15.3	240	15.2
42 K	234	18.5	234	18.0	234	17.6	234	17.3	234	17.0	234	16.8	234	16.5	234	16.3	234	16.2	234	16.0	234	15.8	234	15.7	234	15.5	234	15.4	234	15.3	234	15.2	235	15.1
41 K	228	18.4	228	17.9	228	17.5	228	17.2	228	16.9	229	16.6	229	16.4	229	16.2	229	16.0	229	15.9	229	15.7	229	15.6	229	15.4	229	15.3	229	15.2	229	15.0	229	14.9
40 K	223	18.2	223	17.8	223	17.4	223	17.0	223	16.8	223	16.5	223	16.3	223	16.1	223	15.9	223	15.7	223	15.6	223	15.4	223	15.3	224	15.2	224	15.0	224	14.9	224	14.8
39 K	218	18.1	218	17.6	218	17.2	218	16.9	218	16.6	218	16.4	218	16.2	218	16.0	218	15.8	218	15.6	218	15.4	218	15.3	218	15.1	218	15.0	218	14.9	218	14.8	218	14.7
38 K	213	18.0	213	17.5	213	17.1	213	16.8	213	16.5	213	16.2	213	16.0	213	15.8	213	15.6	213	15.5	213	15.3	213	15.1	213	15.0	213	14.9	213	14.8	213	14.6	213	14.5
37 K	207	17.8	207	17.3	207	17.0	207	16.6	207	16.3	207	16.1	207	15.9	207	15.7	207	15.5	207	15.3	207	15.2	207	15.0	207	14.9	207	14.7	207	14.6	207	14.5	207	14.4
36 K	202	17.7	202	17.2	202	16.8	202	16.5	202	16.2	202	16.0	202	15.7	202	15.5	202	15.3	202	15.2	202	15.0	202	14.9	202	14.7	202	14.6	202	14.5	202	14.3	202	14.2
35 K	197	17.5	197	17.0	197	16.7	197	16.3	197	16.1	197	15.8	197	15.6	197	15.4	196	15.2	196	15.0	196	14.9	196	14.7	196	14.6	196	14.4	196	14.3	196	14.2	196	14.1
34 K	192	17.4	191	16.9	191	16.5	191	16.2	191	15.9	191	15.6	191	15.4	191	15.2	191	15.0	191	14.9	191	14.7	191	14.5	191	14.4	191	14.3	191	14.1	191	14.0	191	13.9
33 K	186	17.2	186	16.7	186	16.4	186	16.0	186	15.7	186	15.5	186	15.3	186	15.1	186	14.9	186	14.7	186	14.5	186	14.4	185	14.2	185	14.1	185	14.0	185	13.9	185	13.7
32 K	181	17.0	181	16.6	181	16.2	181	15.9	181	15.6	181	15.3	180	15.1	180	14.9	180	14.7	180	14.5	180	14.4	180	14.2	180	14.1	180	13.9	180	13.8	180	13.7	180	13.6
31 K	176	16.9	176	16.4	175	16.0	175	15.7	175	15.4	175	15.2	175	14.9	175	14.7	175	14.5	175	14.4	175	14.2	175	14.0	174	13.9	174	13.8	174	13.6	174	13.5	174	13.4
30 K	170	16.7	170	16.2	170	15.8	170	15.5	170	15.2	170	15.0	170	14.7	169	14.5	169	14.3	169	14.2	169	14.0	169	13.9	169	13.7	169	13.6	169	13.5	169	13.3	169	13.2
29 K	165	16.5	165	16.1	165	15.7	165	15.3	164	15.0	164	14.8	164	14.6	164	14.4	164	14.2	164	14.0	164	13.8	163	13.7	163	13.5	163	13.4	163	13.3	163	13.1	163	13.0
28 K	160	16.3	160	15.9	159	15.5	159	15.1	159	14.9	159	14.6	159	14.4	159	14.2	158	14.0	158	13.8	158	13.6	158	13.5	158	13.3	158	13.2	158	13.1	157	12.9	157	12.8
27 K	155	16.1	154	15.7	154	15.3	154	14.9	154	14.7	153	14.4	153	14.2	153	14.0	153	13.8	153	13.6	153	13.4	152	13.3	152	13.1	152	13.0	152	12.9	152	12.7	152	12.6
26 K	149	15.9	149	15.5	149	15.1	148	14.7	148	14.5	148	14.2	148	14.0	148	13.8	147	13.6	147	13.4	147	13.2	147	13.1	147	12.9	146	12.8	146	12.6	146	12.5	146	12.4
25 K	144	15.7	144	15.3	143	14.9	143	14.5	143	14.2	142	14.0	142	13.7	142	13.5	142	13.3	142	13.2	141	13.0	141	12.8	141	12.7	141	12.6	140	12.4	140	12.3	140	12.2
24 K	139	15.5	138	15.0	138	14.6	138	14.3	137	14.0	137	13.8	137	13.5	136	13.3	136	13.1	136	12.9	136	12.8	135	12.6	135	12.5	135	12.3	135	12.2	134	12.1	134	11.9
23 K	133	15.3	133	14.8	132	14.4	132	14.1	132	13.8	131	13.5	131	13.3	131	13.1	130	12.9	130	12.7	130	12.5	130	12.4	129	12.2	129	12.1	129	11.9	129	11.8	128	11.7
22 K	128	15.1	127	14.6	127	14.2	127	13.8	126	13.5	126	13.3	125	13.0	125	12.8	125	12.6	124	12.4	124	12.3	124	12.1	124	12.0	123	11.8	123	11.7	123	11.5	123	11.4
21 K	122	14.8	122	14.3	122	13.9	121	13.6	121	13.3	120	13.0	120	12.8	119	12.6	119	12.4	119	12.2	118	12.0	118	11.8	118	11.7	117	11.5	117	11.4	117	11.3	117	11.1
20 K	117	14.5	116	14.1	116	13.6	116	13.3	115	13.0	115	12.7	114	12.5	114	12.3	113	12.1	113	11.9	112	11.7	112	11.5	112	11.4	111	11.2	111	11.1	111	11.0	110	10.9

Inlet Enthalpy (J/g) and Entropy (J/g.K) function of Inlet Pressure and Temperature

P_{out}	1 atm	1.25 atm	1.5 atm	1.75 atm	2 atm	2.25 atm	2.5 atm	2.75 atm	3 atm	3.25 atm	3.5 atm
S_{out_ideal}	H_{out_ideal}										
19.0	153	166	178	188	198	207	215	223	230	237	244
18.5	141	153	163	172	181	189	197	204	210	217	223
18.0	129	140	149	158	166	173	180	186	193	198	204
17.5	119	128	137	145	152	159	165	171	176	182	187
17.0	109	118	126	133	139	145	151	156	161	166	171
16.5	100	108	116	122	128	133	139	143	148	152	156
16.0	93	100	106	112	117	122	127	132	136	140	143
15.5	85	92	98	103	108	112	117	121	125	128	132
15.0	79	85	90	95	99	103	107	111	114	118	121
14.5	73	78	83	87	91	95	99	102	105	108	111
14.0	67	72	77	81	84	88	91	94	97	99	102
13.5	62	67	71	74	78	81	84	86	89	91	94
13.0	58	62	66	69	72	75	77	80	82	84	86
12.5	54	57	61	64	66	69	71	73	75	77	79
12.0	50	53	56	59	61	64	66	68	70	71	73
11.5	47	50	52	55	57	59	61	62	64	66	67
11.0	43	46	48	51	52	54	56	58	59	61	62

Outlet Ideal Enthalpy (J/g) function of Inlet Entropy (J/g.K) and Outlet Pressure

- **Helium Data for Turbine 3**

P_{in}	4 atm		5 atm		6 atm		7 atm		8 atm		9 atm		10 atm		11 atm		12 atm		13 atm		14 atm		15 atm		16 atm		17 atm		18 atm		19 atm		20 atm	
T_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}
25 K	144	15.7	144	15.3	143	14.9	143	14.5	143	14.2	142	14.0	142	13.7	142	13.5	142	13.3	142	13.2	141	13.0	141	12.8	141	12.7	141	12.6	140	12.4	140	12.3	140	12.2
24 K	139	15.5	138	15.0	138	14.6	138	14.3	137	14.0	137	13.8	137	13.5	136	13.3	136	13.1	136	12.9	136	12.8	135	12.6	135	12.5	135	12.3	135	12.2	134	12.1	134	11.9
23 K	133	15.3	133	14.8	132	14.4	132	14.1	132	13.8	131	13.5	131	13.3	131	13.1	130	12.9	130	12.7	130	12.5	130	12.4	129	12.2	129	12.1	129	11.9	129	11.8	128	11.7
22 K	128	15.1	127	14.6	127	14.2	127	13.8	126	13.5	126	13.3	125	13.0	125	12.8	125	12.6	124	12.4	124	12.3	124	12.1	124	12.0	123	11.8	123	11.7	123	11.5	123	11.4
21 K	122	14.8	122	14.3	122	13.9	121	13.6	121	13.3	120	13.0	120	12.8	119	12.6	119	12.4	119	12.2	118	12.0	118	11.8	118	11.7	117	11.5	117	11.4	117	11.3	117	11.1
20 K	117	14.5	116	14.1	116	13.6	116	13.3	115	13.0	115	12.7	114	12.5	114	12.3	113	12.1	113	11.9	112	11.7	112	11.5	112	11.4	111	11.2	111	11.1	111	11.0	110	10.9
19 K	112	14.3	111	13.8	110	13.4	110	13.0	109	12.7	109	12.4	108	12.2	108	12.0	107	11.8	107	11.6	107	11.4	106	11.2	106	11.1	105	10.9	105	10.8	105	10.7	104	10.5
18 K	106	14.0	105	13.5	105	13.1	104	12.7	104	12.4	103	12.1	103	11.9	102	11.7	101	11.4	101	11.3	100	11.1	100	10.9	100	10.7	99	10.6	99	10.5	98	10.3	98	10.2
17 K	101	13.7	100	13.2	99	12.7	99	12.4	98	12.1	97	11.8	97	11.5	96	11.3	95	11.1	95	10.9	94	10.7	94	10.6	93	10.4	93	10.2	92	10.1	92	10.0	92	9.8
16 K	95	13.3	94	12.8	94	12.4	93	12.0	92	11.7	91	11.4	91	11.2	90	10.9	89	10.7	89	10.5	88	10.3	88	10.2	87	10.0	87	9.9	86	9.7	86	9.6	85	9.4
15 K	90	13.0	89	12.4	88	12.0	87	11.7	86	11.3	85	11.0	84	10.8	84	10.5	83	10.3	82	10.1	82	9.9	81	9.8	80	9.6	80	9.4	79	9.3	79	9.2	79	9.0
14 K	84	12.6	83	12.0	82	11.6	81	11.2	80	10.9	79	10.6	78	10.3	77	10.1	77	9.9	76	9.7	75	9.5	74	9.3	74	9.1	73	9.0	73	8.8	72	8.7	72	8.6
13 K	78	12.1	77	11.6	76	11.2	75	10.8	74	10.4	73	10.1	72	9.9	71	9.6	70	9.4	69	9.2	68	9.0	68	8.8	67	8.6	66	8.5	66	8.3	66	8.2	65	8.1
12 K	72	11.7	71	11.1	70	10.7	68	10.3	67	9.9	66	9.6	65	9.3	64	9.1	63	8.8	62	8.6	61	8.4	61	8.2	60	8.1	59	7.9	59	7.8	59	7.6	58	7.5
11 K	66	11.2	65	10.6	63	10.1	62	9.7	60	9.3	59	9.0	58	8.7	57	8.4	56	8.2	55	8.0	54	7.8	53	7.6	53	7.4	52	7.3	52	7.1	52	7.0	51	6.9
10 K	60	10.6	58	10.0	57	9.5	55	9.0	53	8.6	52	8.3	50	8.0	49	7.7	48	7.5	47	7.3	47	7.1	46	6.9	46	6.7	45	6.6	45	6.5	45	6.4	45	6.3
9 K	54	9.9	51	9.2	49	8.7	47	8.2	45	7.8	44	7.4	42	7.1	41	6.9	40	6.6	40	6.5	39	6.3	39	6.1	39	6.0	39	5.9	39	5.8	39	5.7	39	5.6
8 K	47	9.0	44	8.3	41	7.7	38	7.2	36	6.8	35	6.4	34	6.2	33	5.9	33	5.8	33	5.6	32	5.5	32	5.4	33	5.3	33	5.2	33	5.1	33	5.1	33	5.0

Inlet Enthalpy (J/g) and Entropy (J/g.K) function of Inlet Pressure and Temperature

P_{out}	0.5 atm	0.75 atm	1 atm	1.25 atm	1.5 atm	1.75 atm
S_{out_ideal}	H_{out_ideal}					
16.0	74	84	93	100	106	112
15.5	68	78	85	92	98	103
15.0	63	72	79	85	90	95
14.5	59	67	73	78	83	87
14.0	55	62	67	72	77	81
13.5	51	57	62	67	71	74
13.0	48	53	58	62	66	69
12.5	45	50	54	57	61	64
12.0	42	46	50	53	56	59
11.5	39	43	47	50	52	55
11.0	37	40	43	46	48	51
10.5	34	38	41	43	45	47
10.0	32	35	38	40	42	43
9.5	31	33	35	37	39	40
9.0	29	31	33	35	36	37
8.5	27	29	31	32	34	35
8.0	25	27	29	30	31	32
7.5	23	25	27	28	29	30
7.0	22	23	25	26	26	27
6.5	20	21	22	23	24	25
6.0	18	19	20	21	22	22
5.5	16	17	18	19	19	20
5.0	14	15	16	17	17	17

Outlet Ideal Enthalpy (J/g) function of Inlet Entropy (J/g.K) and Outlet Pressure

- ## Helium Data for Turbine 4

P_{in}	4 atm		5 atm		6 atm		7 atm		8 atm		9 atm		10 atm		11 atm		12 atm		13 atm		14 atm		15 atm		16 atm		17 atm		18 atm		19 atm		20 atm	
T_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}	H_{in}	S_{in}
7.0 K	38	7.9	34	7.0	30	6.3	28	5.9	27	5.5	27	5.3	26	5.2	26	5.0	26	4.9	27	4.8	27	4.7	27	4.7	27	4.6	28	4.5	28	4.5	28	4.4	29	4.4
6.9 K	37	7.7	32	6.8	29	6.2	27	5.7	26	5.4	26	5.2	26	5.1	26	4.9	26	4.8	26	4.7	26	4.7	27	4.6	27	4.5	27	4.5	28	4.4	28	4.4	28	4.3
6.8 K	36	7.6	31	6.6	28	6.0	26	5.6	26	5.3	25	5.1	25	5.0	25	4.9	25	4.8	26	4.7	26	4.6	26	4.5	26	4.5	27	4.4	27	4.4	27	4.3	28	4.3
6.7 K	35	7.4	30	6.5	27	5.8	26	5.4	25	5.2	25	5.0	25	4.9	25	4.8	25	4.7	25	4.6	25	4.5	26	4.5	26	4.4	26	4.3	27	4.3	27	4.2	27	4.2
6.6 K	33	7.2	29	6.3	26	5.7	25	5.3	24	5.1	24	4.9	24	4.8	24	4.7	24	4.6	25	4.5	25	4.5	25	4.4	25	4.3	26	4.3	26	4.2	27	4.2	27	4.1
6.5 K	32	7.0	27	6.1	25	5.5	24	5.2	23	5.0	23	4.8	23	4.7	24	4.6	24	4.5	24	4.5	24	4.4	25	4.3	25	4.3	25	4.2	26	4.2	26	4.1	27	4.1
6.4 K	31	6.8	26	5.8	24	5.3	23	5.1	23	4.9	23	4.7	23	4.6	23	4.5	23	4.5	24	4.4	24	4.3	24	4.3	25	4.2	25	4.1	25	4.1	26	4.1	26	4.0
6.3 K	29	6.6	25	5.6	23	5.2	22	5.0	22	4.8	22	4.7	22	4.5	23	4.5	23	4.4	23	4.3	23	4.2	24	4.2	24	4.1	25	4.1	25	4.0	25	4.0	26	4.0
6.2 K	28	6.3	23	5.4	22	5.1	22	4.8	22	4.7	22	4.6	22	4.5	22	4.4	22	4.3	23	4.2	23	4.2	23	4.1	24	4.1	24	4.0	25	4.0	25	3.9	25	3.9
6.1 K	26	6.0	22	5.3	21	4.9	21	4.7	21	4.6	21	4.5	21	4.4	22	4.3	22	4.2	22	4.2	23	4.1	23	4.0	23	4.0	24	4.0	24	3.9	25	3.9	25	3.8
6.0 K	24	5.7	21	5.1	21	4.8	20	4.6	20	4.5	21	4.4	21	4.3	21	4.2	21	4.2	22	4.1	22	4.0	23	4.0	23	3.9	23	3.9	24	3.8	24	3.8	25	3.8
5.9 K	22	5.5	20	4.9	20	4.7	20	4.5	20	4.4	20	4.3	20	4.2	21	4.1	21	4.1	21	4.0	22	4.0	22	3.9	23	3.9	23	3.8	23	3.8	24	3.7	24	3.7
5.8 K	21	5.2	20	4.8	19	4.6	19	4.4	19	4.3	20	4.2	20	4.1	20	4.1	21	4.0	21	3.9	21	3.9	22	3.8	22	3.8	23	3.8	23	3.7	24	3.7	24	3.7
5.7 K	20	5.0	19	4.7	19	4.5	19	4.3	19	4.2	19	4.1	19	4.1	20	4.0	20	3.9	21	3.9	21	3.8	21	3.8	22	3.7	22	3.7	23	3.7	23	3.6	24	3.6
5.6 K	19	4.8	18	4.5	18	4.4	18	4.2	18	4.1	19	4.1	19	4.0	19	3.9	20	3.9	20	3.8	21	3.8	21	3.7	21	3.7	22	3.6	22	3.6	23	3.6	23	3.5
5.5 K	18	4.6	17	4.4	17	4.3	18	4.2	18	4.1	18	4.0	19	3.9	19	3.8	19	3.8	20	3.7	20	3.7	21	3.7	21	3.6	22	3.6	22	3.5	23	3.5	23	3.5
5.4 K	17	4.5	17	4.3	17	4.2	17	4.1	17	4.0	18	3.9	18	3.8	19	3.8	19	3.7	19	3.7	20	3.6	20	3.6	21	3.5	21	3.5	22	3.5	22	3.4	23	3.4
5.3 K	16	4.4	16	4.2	16	4.1	17	4.0	17	3.9	17	3.8	18	3.8	18	3.7	19	3.6	19	3.6	19	3.6	20	3.5	20	3.5	21	3.4	21	3.4	22	3.4	22	3.3
5.2 K	16	4.2	16	4.1	16	4.0	16	3.9	17	3.8	17	3.7	17	3.7	18	3.6	18	3.6	19	3.5	19	3.5	20	3.5	20	3.4	21	3.4	21	3.3	22	3.3	22	3.3
5.1 K	15	4.1	15	4.0	15	3.9	16	3.8	16	3.7	17	3.7	17	3.6	17	3.6	18	3.5	18	3.5	19	3.4	19	3.4	20	3.4	20	3.3	21	3.3	21	3.3	22	3.2
5.0 K	14	4.0	15	3.9	15	3.8	15	3.7	16	3.6	16	3.6	17	3.5	17	3.5	17	3.4	18	3.4	18	3.4	19	3.3	19	3.3	20	3.3	20	3.2	21	3.2	21	3.2

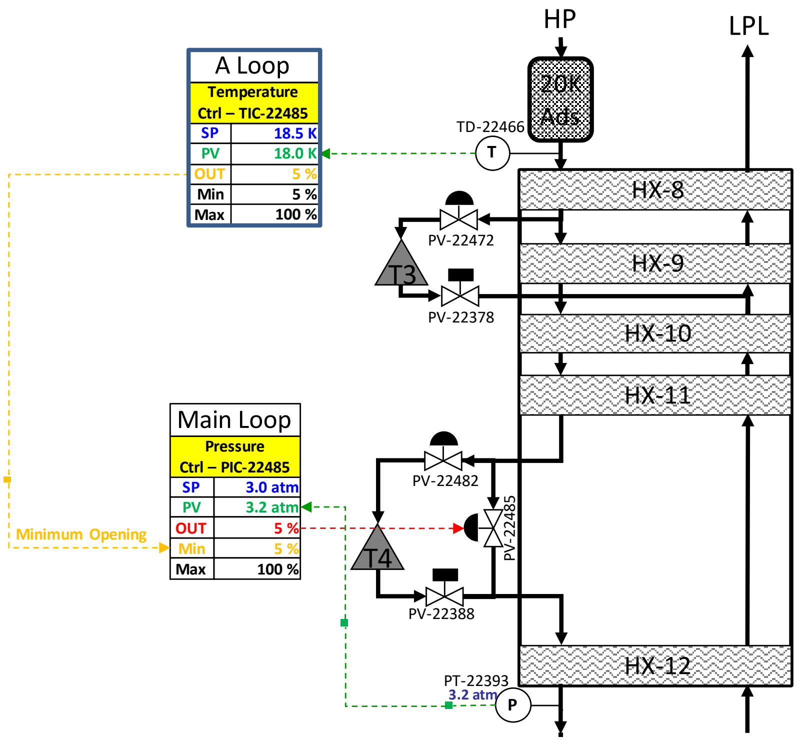
Inlet Enthalpy and Entropy (J/g.K) function of Inlet Pressure and Temperature

P_{out}	2.6 atm	2.7 atm	2.8 atm	2.9 atm	3 atm	3.1 atm	3.2 atm	3.3 atm	3.4 atm	3.5 atm
S_{out_ideal}	H_{out_ideal}									
8.0	35	35	36	36	36	36	37	37	37	37
7.8	34	34	34	35	35	35	35	36	36	36
7.6	33	33	33	33	34	34	34	34	35	35
7.4	31	32	32	32	32	33	33	33	33	34
7.2	30	31	31	31	31	31	32	32	32	32
7.0	29	29	30	30	30	30	30	31	31	31
6.8	28	28	28	29	29	29	29	29	30	30
6.6	27	27	27	28	28	28	28	28	28	29
6.4	26	26	26	26	27	27	27	27	27	27
6.2	25	25	25	25	25	26	26	26	26	26
6.0	24	24	24	24	24	24	25	25	25	25
5.8	23	23	23	23	23	23	23	24	24	24
5.6	22	22	22	22	22	22	22	22	23	23
5.4	20	21	21	21	21	21	21	21	21	22
5.2	19	20	20	20	20	20	20	20	20	20
5.0	18	18	19	19	19	19	19	19	19	19
4.8	17	17	17	18	18	18	18	18	18	18
4.6	16	16	16	17	17	17	17	17	17	17
4.4	15	15	15	15	16	16	16	16	16	16
4.2	14	14	14	14	15	15	15	15	15	15
4.0	13	13	13	14	14	14	14	14	14	14
3.8	12	12	12	13	13	13	13	13	13	13
3.6	11	11	12	12	12	12	12	12	12	12
3.4	11	11	11	11	11	11	11	11	11	11
3.2	10	10	10	10	10	10	10	10	10	10
3.0	9	9	9	9	9	9	9	9	10	10

Outlet Ideal Enthalpy (J/g) function of Inlet Entropy (J/g.K) and Outlet Pressure

4.6 CONTROL LOOPS - TURBINE 4 BY-PASS

4.6.1 PFD:



4.6.2 TIC-22485 - Turbine 4 by-pass

TIC-22485	Object :	**20K Adsorber Temperature by allowing more or less flow in HP Line**
	Actuator :	**PIC-22485 minimum output (ie PV-22485 minimum opening)**
	Process Value:	**TT-22466**
	Set Point :	**18K***
	Action :	Indirect

* Indicative Values: Accessible from HMI.

Note: By acting on PIC-22485 minimum output, this regulator imposes PV-22485 minimum opening. Since PIC-22485 as a Set Point lower than the nominal value for PT-22393 (see section 4.8.4), PIC-22485 will always tend to have a minimum output, and therefore TIC-22485 will act on PV-22485 opening.

PV-22485 shall always remain slightly open even during T4 operation to maintain it cold and ready to operate without disturbing the process.

Therefore, this control loop will always have a minimum output (5% for instance, to be tested and adjusted onsite).

4.6.3 Turbine 4 by-pass valve – Opening action when Turbine 4 stops

When the Turbine 4 is Stopped or Tripped, the by-pass valve PV-22485 already controls the Temperature TT-22466, but may be closed on its minimum opening value (5%).

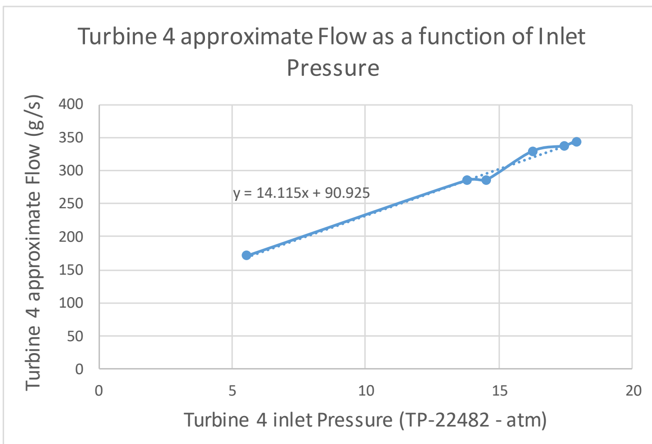
PV-22485 opening shall be forced by the system at a higher value. This allows a faster reaction of the valve and avoids too important flow variations in HP Line.

The opening value for PV-22485 shall be calculated to match with the flow in Turbine 4 when the stop occurs. This logic is used in Turbine 4 Stop and Trip sequences.

The calculation below approximates the required valve opening depending on Turbine 4 Flow.

1/ Turbine 4 Flow as a function of Turbine 4 inlet pressure PT-22482:

We can use Turbine 4 inlet pressure PT-22482 as a representation of the flow in turbine 4:



→ We will use this function: $Qm_{Turbine\ 4} = 14.115 \times PT22482 + 90.925$

2/ Cv of PV-22485 as a function of the calculated Mass Flowrate

PV-22485 shall open to a value that will allow a flow similar to the one in Turbine 4.

In operation, the temperature at PV-22485 will remain between 5.5K and 7K and the pressure between 9 atm and 18 atm.

In this Pressure/Temperature range, the helium density varies from 108 kg/m^3 to 152 kg/m^3, which represents a total variation of maximum 40%.

P (atm)	Density @5.5K (kg/m^3)	Density @6K (kg/m^3)	Density @6.5K (kg/m^3)	Density @7K (kg/m^3)
9	134.9	127.5	118.8	108.4
10	137.6	130.9	123.1	114.1
11	140.0	133.8	126.8	118.7
12	142.2	136.4	129.9	122.7
13	144.2	138.8	132.8	126.0
14	146.1	141.0	135.3	129.0
15	147.8	143.0	137.6	131.7
16	149.5	144.8	139.7	134.2
17	151.0	146.6	141.7	136.4
18	152.5	148.2	143.6	138.5

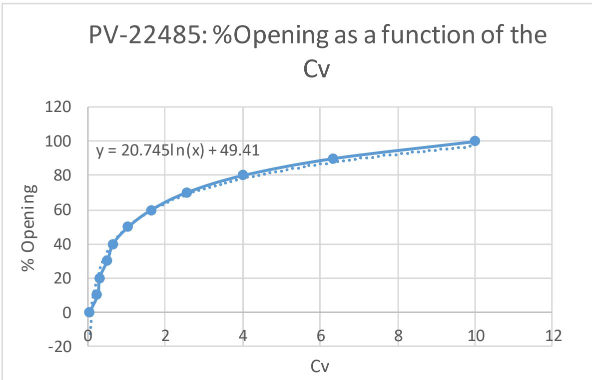
We consider the following for PV-22485 Cv calculation:

- Inlet Pressure = Constant → 14 atm.
- Inlet Temperature = Constant → 6.5K.
- Density of gas = Constant → 136 kg/m³
- Cv relation: $Cv = k \times Qm$ → $k = \sqrt{\rho \times Tin}/(245 \times Pin) = 0.00866$

→ We use this function: $Cv = 0.00866 \times Qm$

3/ % Opening of PV-22485 as a function of the calculated Cv

The relation between PV-22485 Cv and its opening is given below:



→ We use this function: $\%Opening_{PV-22485} = 20.745 \times Ln(Cv) + 49.41$

Finally, the approximate required opening for PV-22485 based on PT-22482 before a stop of Turbine 4 would be:

$$\%Opening_{PV-22485} = 20.745 \times Ln[0.00866 \times (14.115 \times PT22482 + 90.925)] + 49.41$$

The table below gives examples of the calculated opening of PV-22485:

PT-22482 (atm)	Qm (g/s)	Cv (USGPM)	PV-22485 %Open
2	119	1.03	50
3	133	1.15	52
4	147	1.28	54
5	162	1.40	56
6	176	1.52	58
7	190	1.64	60
8	204	1.77	61
9	218	1.89	63
10	232	2.01	64
11	246	2.13	65
12	260	2.25	66
13	274	2.38	67
14	289	2.50	68
15	303	2.62	69
16	317	2.74	70
17	331	2.87	71

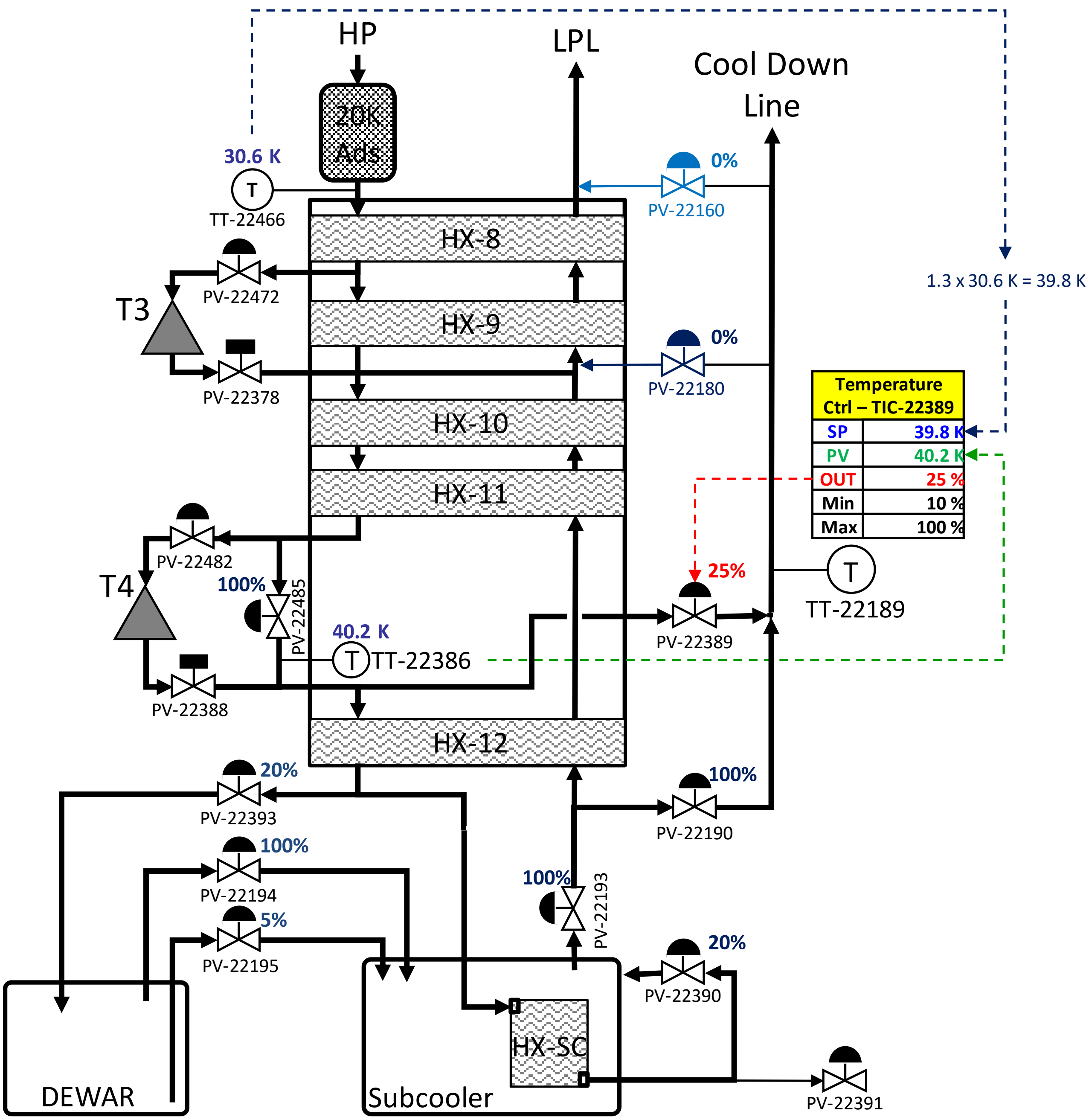
Conclusion: Calculation in this Section provides an overall idea about opening range for PV-22485 when T4 is stops: 50% to 71%. In order to simplify the logic, as soon as a turbine 4 trip/stop is detected, the system shall jump/ramp open PV-22485 to 50% and then let PID loops (PIC-22485 and TIC-22485) to handle the additional opening regulation.

4.7 CONTROL LOOPS - COLD END BY PASS

4.7.1 PFD:

The Cold End by-pass is used to force flow in the Cold Box during the cool down.

TIC-22389 diagram:



4.7.2 TIC-22389: Cold End by-pass

During the cool down of the cold box, PV-22389 has two main roles:

- Drive as much warm gas as possible towards the cold end of the cold box when Cold Box is warm.
- Adjust the gas flow towards the cold end when cold box is cold, and helium gas is more dense.

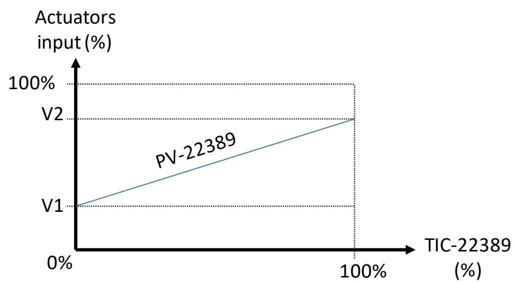
At the beginning of the cold box, PV-22389 will be fully open.

When the cold box cools down, a controller adjusts the position of PV-22389 to adapt the flow in the HP line to the cool down capacity of the Cold Box.

The comparison between the temperature at 20K adsorber level (TT-22466) and the temperature at PV-22389 level (TT-22386) determines the flow in the HP line.

TIC-22389	Object :	**Cold end by pass flow**
	Actuator :	**PV-22389**
	Process Value:	**TT-22386**
	Set Point :	**SP: 1.3* x TT-22466 if TT-22466 > 30K** **SP: 1.15* x TT-22466 if 25K < TT-22466 ≤ 30K** **SP: TT-22466 if TT-22466 ≤ 25K**
	Action :	Direct

* Indicative Values: Accessible from HMI.



- V1 and V2 shall allow minimum and maximum opening on PV-22389.
- These parameters shall be accessible from the HMI.
- By default, the following values can be set:
  - V1= 10%
  - V2=100%
- These values will be adjusted during commissioning

4.8 CONTROL LOOPS - TURBINE 4 DISCHARGE PRESSURE

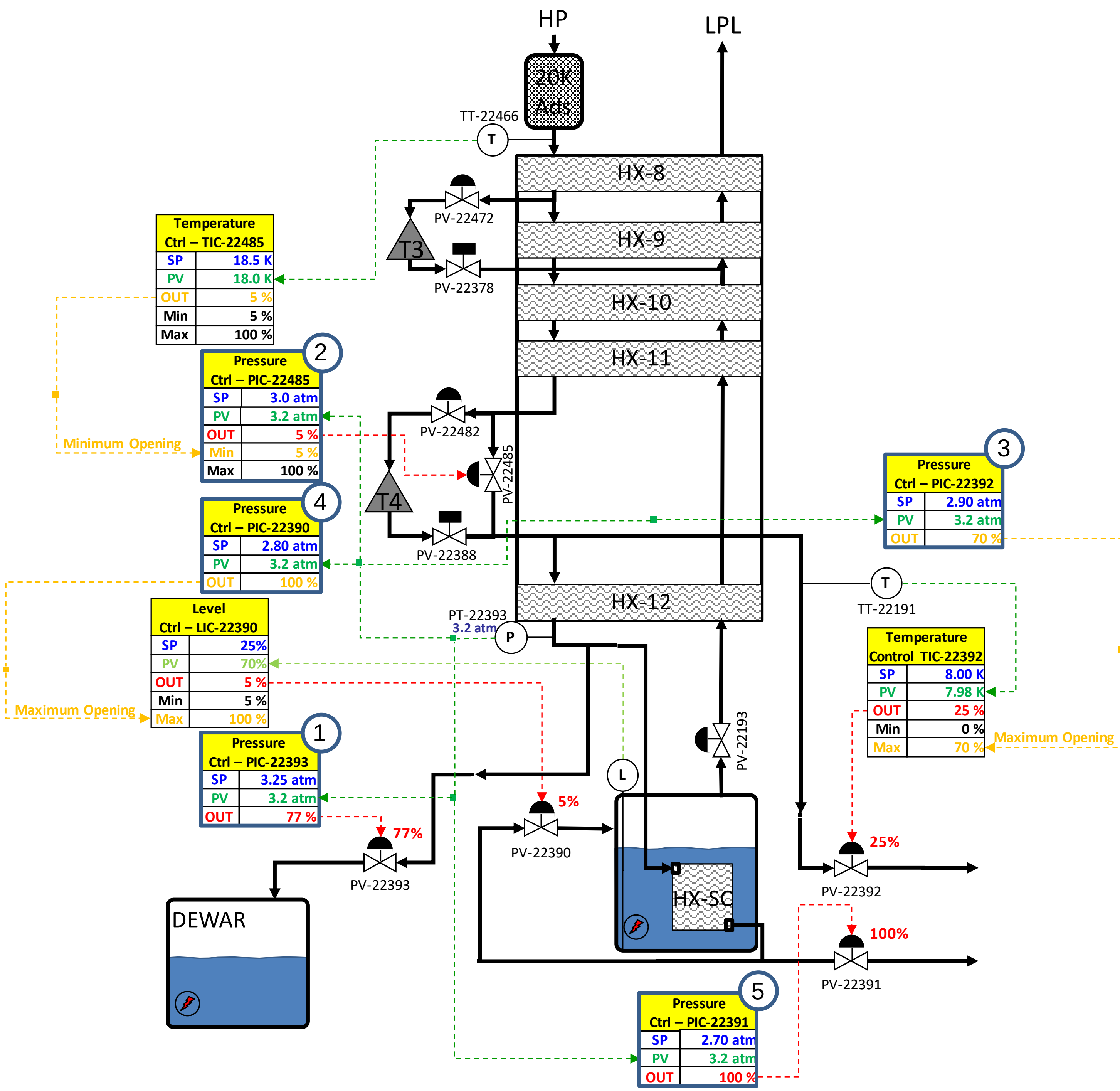
Turbine 4 discharge pressure is a critical parameter to control.

Indeed, the other turbines are discharging in LPL line or LPR. The discharge volume is important and acts as a buffer, which limits pressure variations.

Turbine 4 discharges in the HP line, a restricted volume limited by five control valves, and located at a temperature level where Helium density varies a lot.

The control philosophy described in this section is inspired from JLAB experience based on the 18kW Cold Box currently in operation on CHL2.

4.8.1 PFD

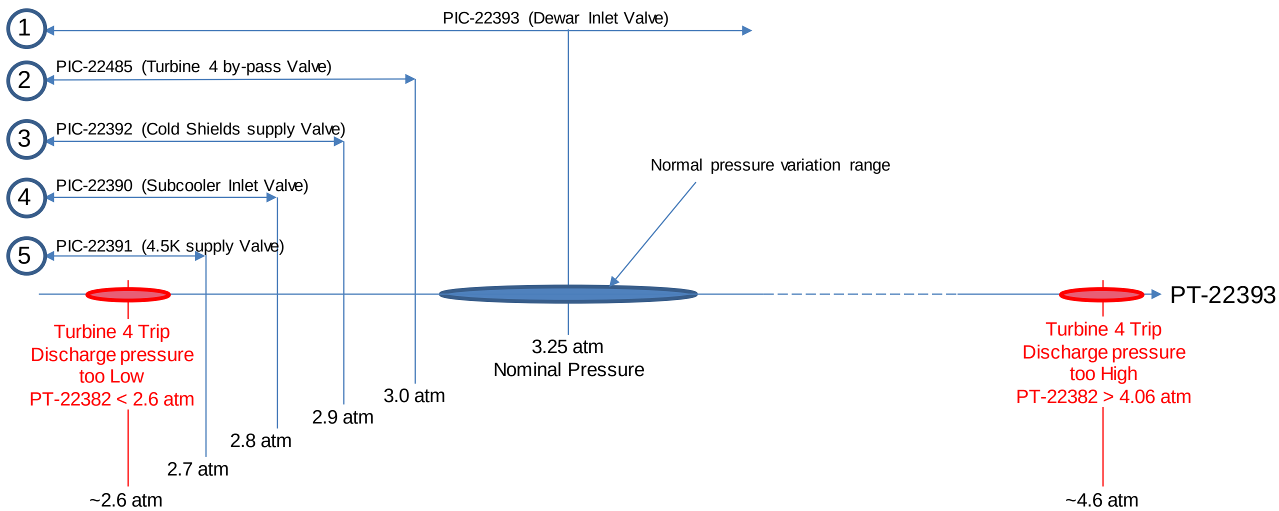

HP
LPL
20K Ads
TT-22466
T
HX-8
HX-9
HX-10
HX-11
HX-12
HX-SC
PV-22472
T3
PV-22378
PV-22482
PV-22485
T4
PV-22388
PT-22393
3.2 atm
P
TT-22191
T
PV-22193
L
PV-22390
5%
PV-22393
77%
PV-22392
25%
PV-22391
100%
DEWAR
Temperature Ctrl – TIC-22485
SP 18.5 K
PV 18.0 K
OUT 5 %
Min 5 %
Max 100 %
Minimum Opening
2
Pressure Ctrl – PIC-22485
SP 3.0 atm
PV 3.2 atm
OUT 5 %
Min 5 %
Max 100 %
4
Pressure Ctrl – PIC-22390
SP 2.80 atm
PV 3.2 atm
OUT 100 %
Level Ctrl – LIC-22390
SP 25%
PV 70%
OUT 5 %
Min 5 %
Max 100 %
Maximum Opening
1
Pressure Ctrl – PIC-22393
SP 3.25 atm
PV 3.2 atm
OUT 77 %
3
Pressure Ctrl – PIC-22392
SP 2.90 atm
PV 3.2 atm
OUT 70 %
Temperature Control TIC-22392
SP 8.00 K
PV 7.98 K
OUT 25 %
Min 0 %
Max 70 %
Maximum Opening
5
Pressure Ctrl – PIC-22391
SP 2.70 atm
PV 3.2 atm
OUT 100 %

4.8.2 Control Loops Overview

Five control valves edge turbine 4 discharge circuit. A pressure controller controls each of them directly or indirectly.

PIC-22393 acts on PV-22393 (Dewar inlet valve) and is the main Turbine 4 discharge pressure controller.

The four other pressure controllers will act consecutively to maintain Turbine 4 discharge pressure above its low trip level:



- PV-22393: Dewar inlet valve
  - Controlled by PIC-22393, which is the main controller for Turbine 4 discharge pressure.
- PV-22485: Turbine 4 by-pass valve
  - Primarily controlled by a Temperature controller TIC-22485 on TT-22466
  - A Pressure controller PIC-22485 acts on the minimum output of TIC-22485 to force the valve to open if Turbine 4 discharge pressure drops below 3.0 atm.
- PV-22392: Cold Shields supply valve
  - Primarily controlled by a Temperature controller TIC-22392 on TT-22392
  - A Pressure controller PIC-22392 acts on the minimum output of TIC-22392 to force the valve to open if Turbine 4 discharge pressure drops below 2.9 atm.
- PV-22390: Subcooler inlet valve
  - Primarily controlled by a Level controller LIC-22390 on LT-22195A (see section 4.10.4)
  - A Pressure controller PIC-22390 acts on the maximum output of LIC-22390 to force the valve to open if Turbine 4 discharge pressure drops below 2.8 atm.
- PV-22391: 4.5K supply valve
  - This valve is more an interface valve than a regulation valve
  - However, controller PIC-22391 will close it if Turbine 4 discharge pressure becomes too low.

4.8.3 PIC-22393: Dewar supply

The Dewar supply valve's main objective is to produce LHe in the Dewar. The pressure at Turbine 4 discharge is a good indicator for this valve:

- If the pressure tends to be high, it means that a lot of flow comes from Turbine 4 level.
  - The temperature in the Cold Box tends to be cold (Higher liquefaction capacity),
  - One of the cold consumers demand decreased (the excess of gas can be liquefied and stored in the Dewar).
- On the contrary, if the pressure tends to be low, it means that a less flow comes from Turbine 4 level:
  - The temperature in the Cold Box tends to be high (Lower liquefaction capacity),
  - One of the cold consumers demand increased (the deficit of gas shall be compensated by a decrease of the amount of gas that is liquefied and stored in the Dewar).

PIC-22393	Object :	**Turbine 4 discharge pressure**
	Actuator :	**PV-22393**
	Process Value:	**PT-22393**
	Set Point :	**3.25 atm***
	Action :	Direct

* Indicative Values: Accessible from HMI.

4.8.4 PIC-22485: Turbine 4 by-pass

The Turbine 4 by-pass valve has two main objectives:

- Adjusting the flow in the HP line to cold consumers by controlling the temperature at 20K Adsorbers level (see section 4.6 on TIC-22485), especially when Turbine 4 is Off.
- Helping Controlling the **<u>pressure at Turbine 4 discharge</u>**

PIC-22485	Object :	**Turbine 4 discharge pressure**
	Actuator :	**PV-22485**
	Process Value:	**PT-22393**
	Set Point :	**3.0 atm***
	Action :	Indirect

* Indicative Values: Accessible from HMI.

4.8.5 PIC-22392: Cold Shields supply

The Cold Intercepts supply valve has two main objectives:

- Adjusting the flow to the Cold Intercepts by controlling the return temperature (see section 4.12.3 on TIC-22392)
- Helping Controlling the **<u>pressure at Turbine 4 discharge</u>**

PIC-22392	Object :	**Turbine 4 discharge pressure**
	Actuator :	**Maximum Output of TIC-22392, acting on PV-22392**
	Process Value:	**PT-22393**
	Set Point :	**2.9 atm***
	Action :	Direct

* Indicative Values: Accessible from HMI.

4.8.6 PIC-22390 - Subcooler supply

The Subcooler supply valve has two main objectives:

- Supplying cold or liquid Helium to the Subcooler (see section 4.10.4 on LIC-22390)
- Helping Controlling the **pressure at Turbine 4 discharge**

PIC-22390	Object :	**Turbine 4 discharge pressure**
	Actuator :	**Maximum Output of LIC-22390, acting on PV-22390**
	Process Value:	**PT-22393**
	Set Point :	**2.8 atm***
	Action :	Direct

* Indicative Values: Accessible from HMI.

4.8.7 PIC-22391: 4.5K supply

PIC-22391	Object :	**Turbine 4 discharge pressure**
	Actuator :	**PV-22391**
	Process Value:	**PT-22393**
	Set Point :	**2.7 atm***
	Action :	Direct

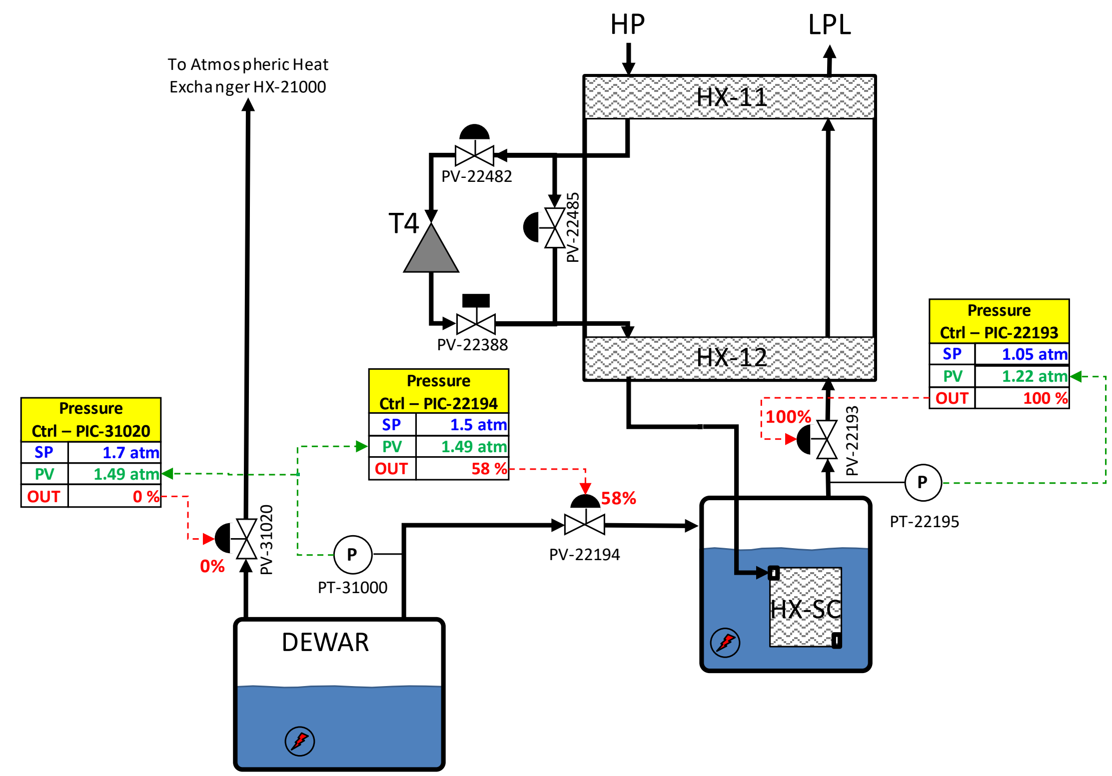
* Indicative Values: Accessible from HMI.

4.9 CONTROL LOOPS - SUB-COOLER AND DEWAR PRESSURE

4.9.1 PFD:

The Subcooler return valve can control the pressure in the subcooler. The set point of the controller PIC-22193 will be set at a very low value (1.05 atm for instance) to be sure that PV-22193 is 100% open.

It could be interesting to control the pressure in the subcooler during LINAC pump down to avoid backflow in return line (tbd during commissioning).



4.9.2 PIC-22193: Subcooler pressure

PIC-22193	Object :	**Subcooler pressure control**
	Actuator :	**PV-22193**
	Process Value:	**PT-22195**
	Set Point :	**1.05 atm***
	Action :	Direct

* Indicative Values: Accessible from HMI.

4.9.3 PIC-22194: Dewar Pressure

The dewar vapor return valve is dedicated to the control of the pressure in the dewar. Controlling a higher pressure in the dewar compared to the subcooler allows transferring LHe to the subcooler.

PIC-22194	Object :	**Dewar pressure control**
	Actuator :	**PV-22194**
	Process Value:	**PT-31005**
	Set Point :	**1.5 atm***
	Action :	Direct

* Indicative Values: Accessible from HMI.

4.9.4 PIC-31020: Dewar Overpressure

An additional line supplied by JLAB allows depressurizing the Dewar to the Compression Station via the Atmospheric Heat Exchanger. This depressurization line will be used as a back-up if the pressure increase too much in the Dewar.

PIC-31020	Object :	**Dewar pressure control**
	Actuator :	**PV-31020**
	Process Value:	**PT-31005**
	Set Point :	**1.7 atm***
	Action :	Direct

* Indicative Values: Accessible from HMI.

4.10 CONTROL LOOPS - SUB-COOLER & DEWAR LEVEL

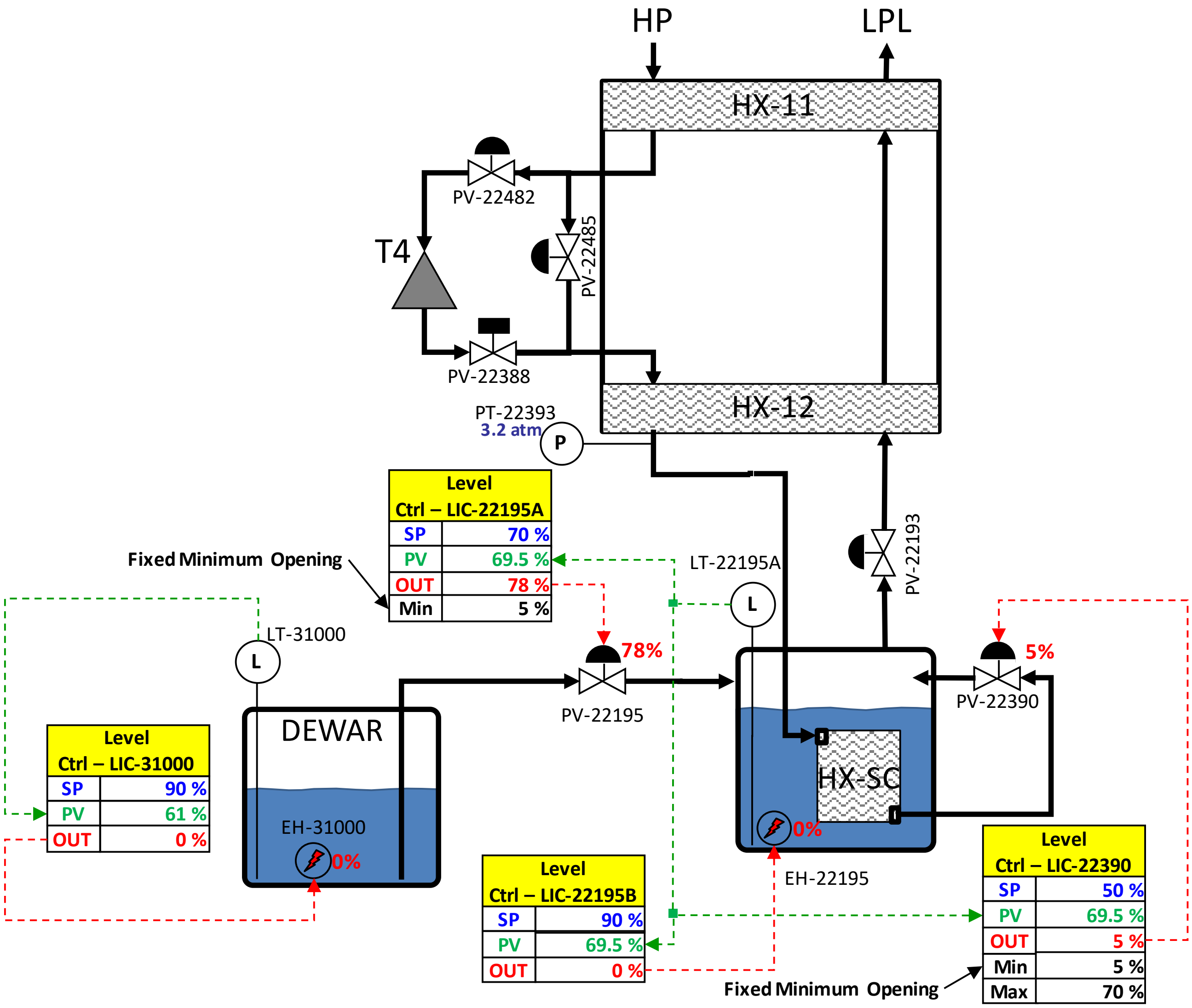
4.10.1 PFD:

As described in section 4.8.3, the Dewar supply valve will control the pressure downstream Turbine 4.

Therefore, LHe produced by the cold box will primarily be delivered to the Dewar.

The LHe in the subcooler will thus come from the Dewar.

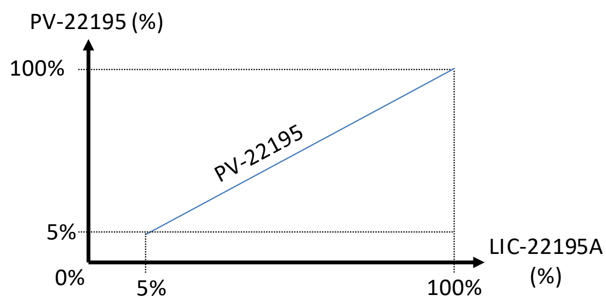
If the cold box capacity exceeds the refrigeration requirements from the users, the LHe level will increase in the Dewar. The Heaters in the Dewar will be used to control the level in the Dewar.



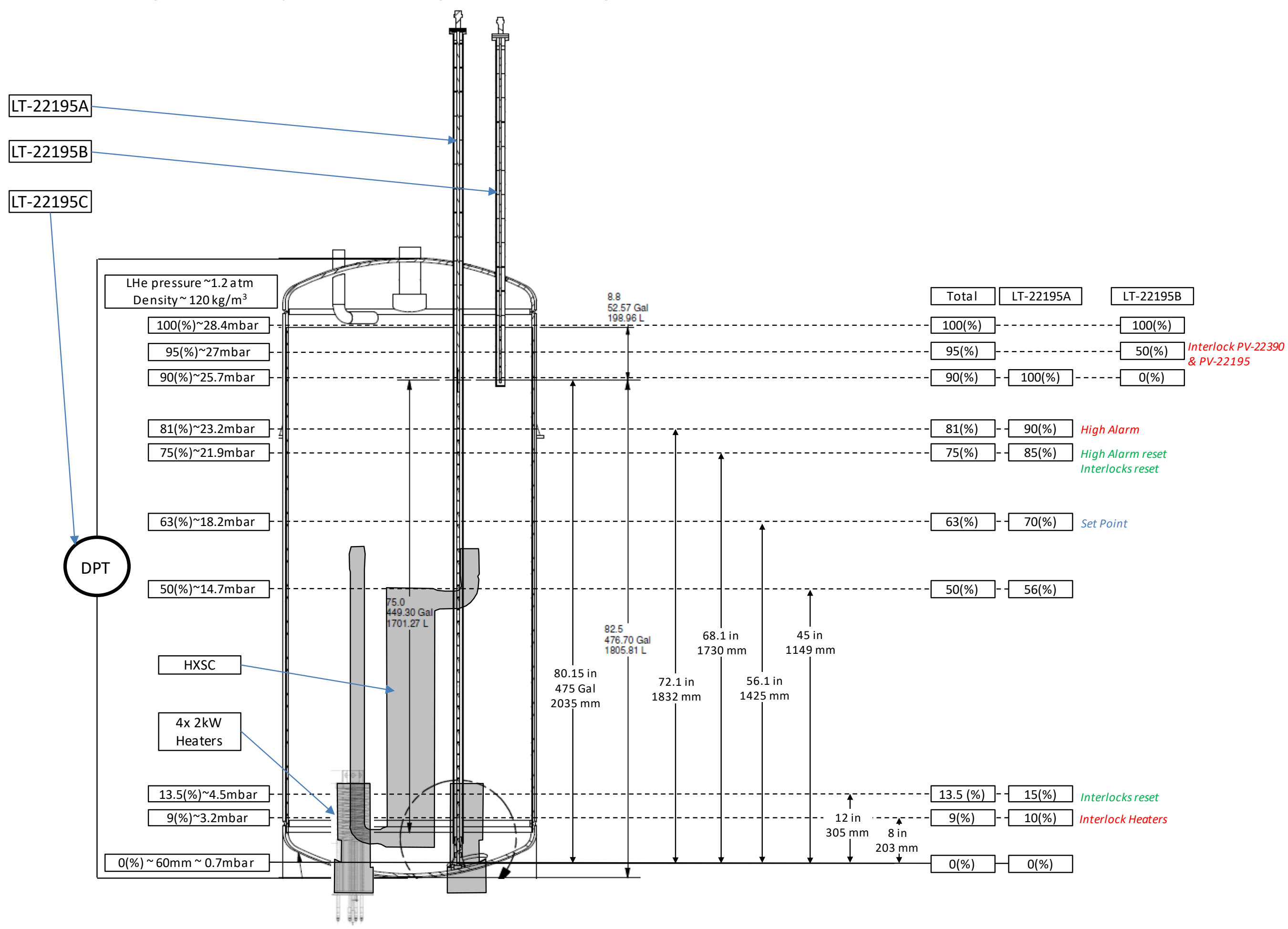
4.10.2 LIC-22195A - Subcooler LHe Level (Primary)

LIC-22195A	Object :	**Subcooler level control**
	Actuator :	**PV-22195**
	Process Value:	**LT-22195A (Superconductive probe)***
	Set Point :	**70%***
	Action :	Indirect

* Indicative Values: Accessible from HMI.



Note: While 3 different instrumentations are dedicated to the measure of the LHe level in the LHe phase separator, only the lower superconductive probe will be used to control the level.



The differential pressure transmitter LT-22195C may be used in place of the superconductive probeLT-22195A if it is found to offer a more reliable measurement.

Based on the profile of the LHe phase separator and the density of Helium of 120 kg/m3 at 1.2 atm pressure, the expected measurements are:

LT-22195C	Height (in)	Height (mm)	Pressure (mbar)	DPT-22195C	Description
-	0	0	0.0	0%	Bottom of the LHe phase separator
0%	2.4	59.7	0.7	2.3%	Zero of LT 22195A
9%	10.4	262.9	3.2	10.7%	Heaters Interlock
14%	14.4	364.5	4.5	15.0%	Heaters Interlock reset
50%	47.4	1202.7	14.7	49.0%	Top of the Subcooler Exchanger
63%	58.5	1484.6	18.2	60.7%	Level Controller Set Point
75%	70.5	1789.4	21.9	73%	High Level Alarm reset
81%	74.5	1891.0	23.2	77.3%	High Level Alarm
90%	82.5	2095.5	25.7	85.7%	100% of LT-22195A / Zero of LT 22195B
95%	86.9	2207.3	27.0	90.0%	Interlock PV-22390 and PV-22195 closed
100%	91.3	2319.0	28.4	94.7%	100% of LT 22195B

4.10.3 LIC-22195B - Subcooler LHe Level (Auxiliary)

In case the level would be too high in the subcooler (when cold box is running not connected to the Dewar for instance), a controller acts on the power supply unit HT-22195 which control three pre-wired heaters (EH-22195A, EH-22195B, EH-22195C) in the subcooler.

The set point is set to a high value so that the heater shall not act in normal operation of the system.

LIC-22195B	Object :	**Subcooler level control**
	Actuator :	**HT-22195**
	Process Value:	**LT-22195A (Superconductive probe)***
	Set Point :	**90%***
	Action :	Direct

* Indicative Values: Accessible from HMI.

4.10.4 LIC-22390 – Subcooler LHe Level (Auxiliary)

The subcooler supply valve PV-22390 will supply LHe to the subcooler when the Dewar is not doing it.

The set point will be defined at a lower value than LIC-22195A to ensure that the Dewar remains the primary LHe source to the subcooler.

LIC-22390	Object :	**Subcooler level control**
	Actuator :	**PV-22390**
	Process Value:	**LT-22195A (Superconductive probe)***
	Set Point :	**50%***
	Action :	Indirect

* Indicative Values: Accessible from HMI.

A minimum output on this controller acts as a minimum opening on PV-22390 to ensure that the valve remains always cold in operation.

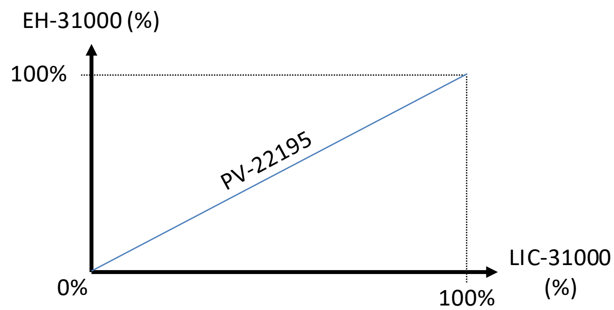
The Turbine 4 pressure controller PIC-22390, which helps increasing the pressure if required to avoid Turbine 4 trip, controls the maximum output (refer to section 4.8.6).

4.10.5 LIC-31000 - Dewar Level

In order to limit the level in the Dewar, the heaters installed in the Dewar are used to decrease the level.

LIC-31000	Object :	**Dewar level control**
	Actuator :	**EH-31000**
	Process Value:	**LT-31000 (Superconductive probe)**
	Set Point :	**90%***
	Action :	Direct

* Indicative Values: Accessible from HMI.



4.11 CONTROL LOOPS - WARM SHIELDS

4.11.1 Connection Switch

The warm shields can be connected or disconnected from the Cold Box.

To allow this selection, a dedicated switch must be available on the supervision.

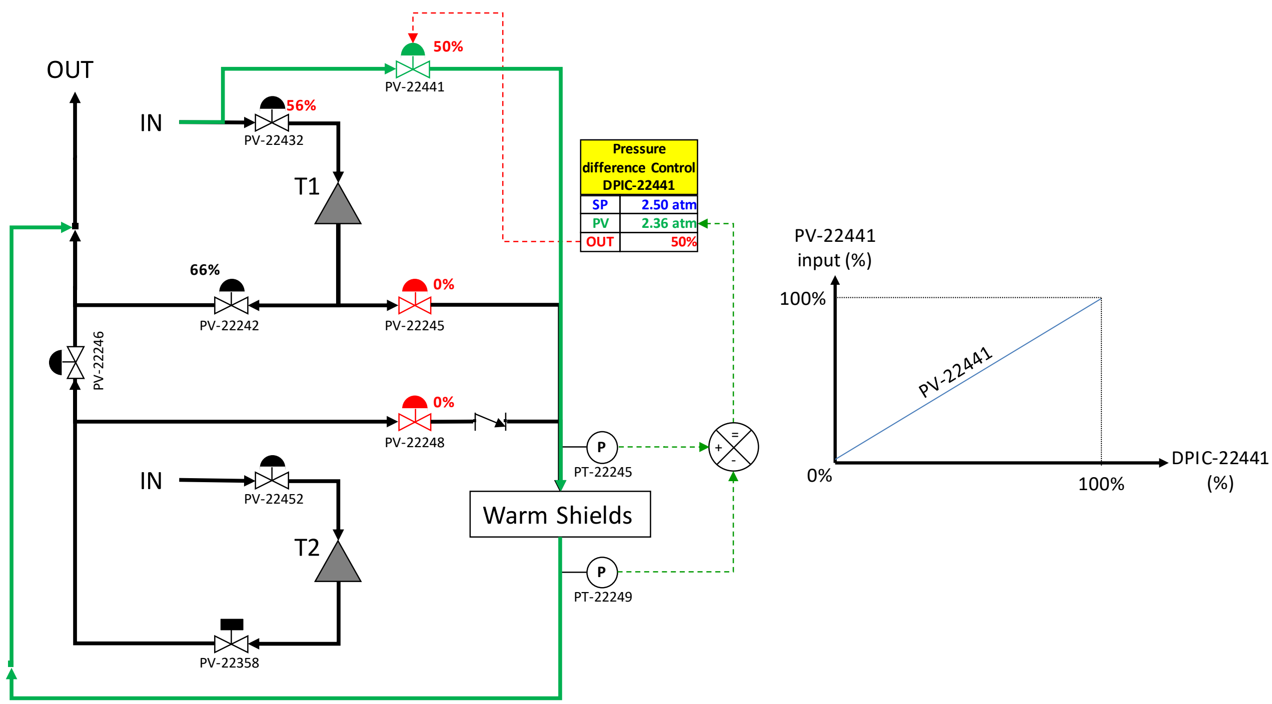
4.11.2 DPIC-22241 - Warm Shields Supply flow during Cool Down

During the cool down phase of the Warm Shields, the cold gas is supplied by PV-22441 which will allow cooling the shields down to 80K.

PV-22441 controls a constant pressure drop across the shields. The pressure difference controller acting on PV-22441 is only used:

- during the warm shields cool down
- or during nominal operation of the Warm Shields, when Turbine 1 is OFF.

PIC-22441 shall have a set point higher than the one controlled in nominal operation to allow a sufficient cooling flow:



■ **DPIC-22441: Warm Shields Pressure drop control (Cool Down)**

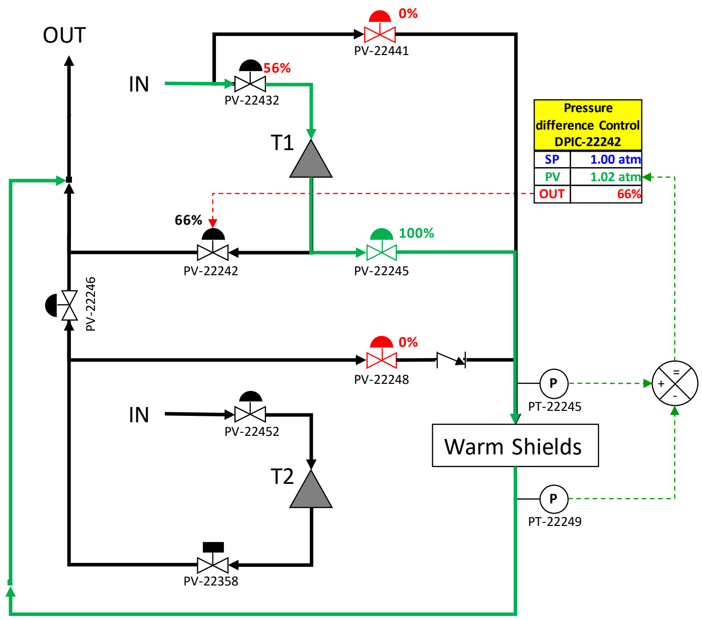
DPIC-22241	Object :	**Warm Shields Pressure drop control – Cool Down**
	Actuator :	**PV-22441**
	Process Value:	**PT-22245-PT-22249**
	Set Point :	**2.5 atm**
	Action :	Indirect

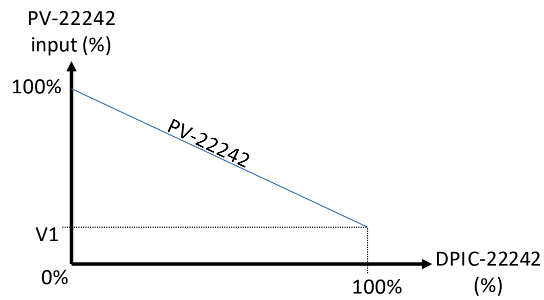
* Indicative Values: Accessible from HMI.

4.11.3 DPIC-22242 - Warm Shields Supply flow during Nominal Operation

In nominal operation, the flow to the warm shields is provided from the outlet line of Turbine 1 via valve PV-22245 which is set 100% open.

In order to allow sufficient flow to the Warm shields, a constant pressure drop across them will be controlled using PV-22242, which duty is to increase the pressure downstream T1:





V1 is the minimum position for PV-22242
- Avoids complete closure of the valve
- This shall be accessible from the HMI.
- Indicative value: 20%

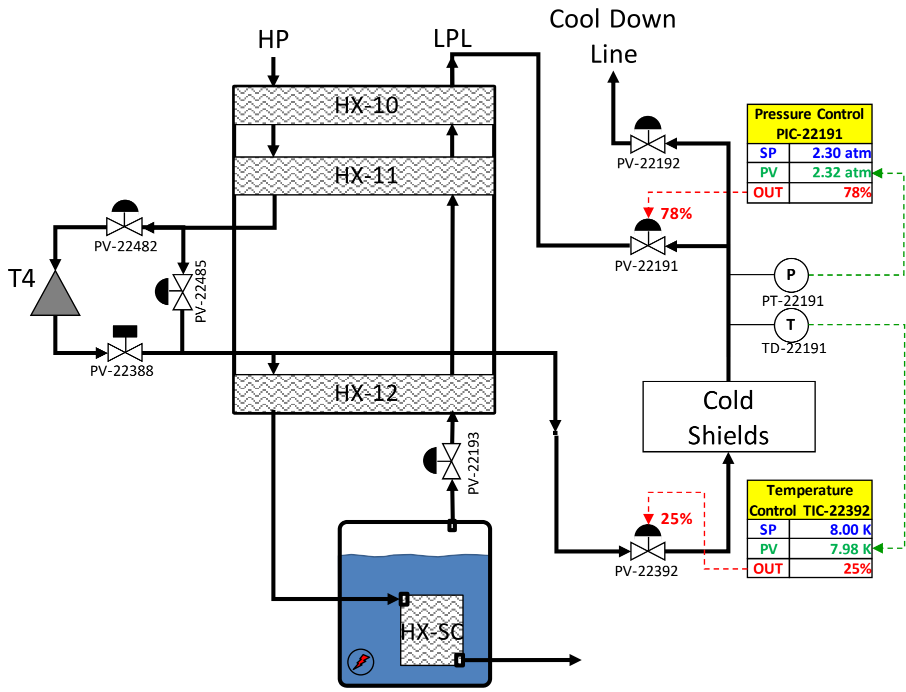
■ DPIC-22242: Warm Shields Pressure drop control (Nominal Operation)

DPIC-22242	Object :	**Warm Shields Pressure drop control**
	Actuator :	**PV-22242**
	Process Value:	**PT-22245-PT-22249**
	Set Point :	**1 atm**
	Action :	Direct

* Indicative Values: Accessible from HMI.

4.12 CONTROL LOOPS - COLD INTERCEPT

4.12.1 PFD:



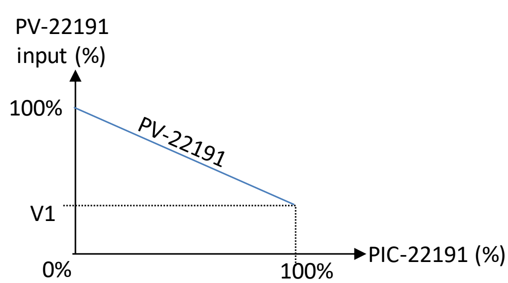
4.12.2 PIC-22191 - Cold Intercept Pressure

The control of the pressure in the Cold Intercepts guaranties that the flow is never diphasic.
The pressure in the Cold Intercepts is controlled using the return valve PV-22191.

■ PIC-22191: Cold Intercepts return Pressure control

PIC-22191	Object :	**Cold Intercepts Pressure control**
	Actuator :	**PV-22191**
	Process Value:	**PT-22191**
	Set Point :	**2.3 atm***
	Action :	Direct

* Indicative Values: Accessible from HMI.



- V1 serves as a minimum opening for PV-22191.
- It is only active when PIC-22191 is active.
- Indicative value is 10%.

Note: During the cool down of the cold intercepts, the valve used is PV-22192 and the gas is returned in the cool down line. This control loop is used only when the gas returning from the cold intercepts is below 10K. Refer to section 13.1.

4.12.3 TIC-22392 - Cold Intercept Temperature

The flow sent to the Cold Intercepts is controlled by monitoring the return temperature.

- **TIC-22392: Cold Intercepts return Temperature control**

TIC-22392	Object :	**Cold Intercepts return Temperature control**
	Actuator :	**PV-22392**
	Process Value:	**TT-22191**
	Set Point :	**8K***
	Action :	Direct

* Indicative Values: Accessible from HMI.

Note: This control loop shall be very slow so as not to disturb to much the pressure regulation downstream Turbine 4.

Test Heaters:

1. Warm Shield Heater: EHTR22240

Contactor Command to be on: EHTR22240CMD
User Heat Request %: EHRT22240RQST [of 30,000 Watts]
Heat Readback: EHTR22240WM
Heater Contactor Status: EHTR22240R

.

The Conditions for turning off will be if return temp TD22249 >100 K, Flow FT22245 < 25 g/s, or the valves PV22245/PV22441 being closed or in state X600 or signal failure (TD22249, PDT22245)

.

2. Cold Shield Heater: EHTR22191

Contactor Command to be on: EHTR22191CMD
User Heat Request %: EHRT22191RQST [of 4,000 watts]
Heat Readback: EHTR22191WM
Heater Contactor Status: EHTR22191R

.

The Conditions for turning off will be if return temp TD22191 >25K, Flow FT22392 < 10 g/s, or the valves PV22191O/PV22192O being closed or in state X600 or signal failure (TD22191, PDT22392).

.

3. 4.5K Supply Heater: EHTR22190

Contactor Command to be on: EHTR22190CMD
User Heat Request %: EHRT22190RQST [of 40,000 watts]
Heat Readback: EHTR22190WM
Heater Contactor Status: EHTR22190R

.

The Conditions for turning off will be if return temp TD22190 >100K, Flow FT22190 < 20 g/s, or the valve PV22393 being closed or in state X600 or signal failure (TD22190, PDT22190).

5. COOL DOWN LINE LOGIC

5.1 PRESENTATION

The cool-down line allows recovering cold helium from:

- The 2K Cold Box (From Sub Atmospheric Line)
- The Cold Intercepts, during their cool down
- The Cold Box cold end by-pass, during cold box cool down.

Note: The Cool Down line also recovers Helium from Warm Shields cool down, but the logic is associated to the Warm Shields Cool Down Logic (See section 12.1).

The temperature inside this line can vary continuously. Helium must be distributed to the corresponding temperature level in the cold box.

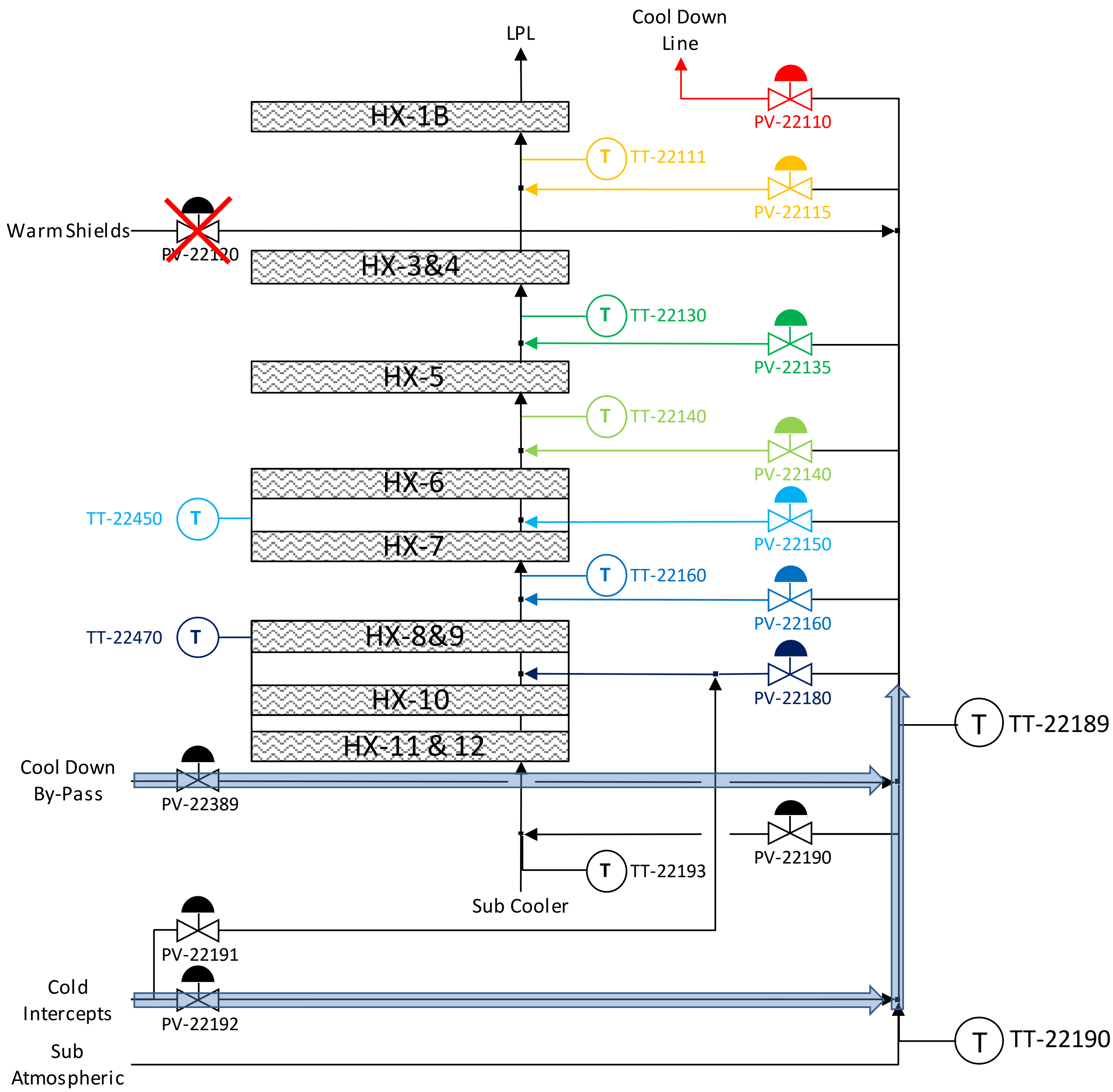
Two Cool down line logics are developed:

- One for Cold Box Cool Down and Cold Intercepts Cool Down.
  - We call this logic "Transient Modes Cool Down Line Logic"
  - This logic is active when:
    - Sequence 600 – Cold Box Cool Down is not in Initial step X600
    - And PV-22220 is closed (Warm Shields not in Initial Cool Down)
    - And Sequence 900 – 4.5K Supply is in initial step X900 .
  - This logic uses TT-22189 as main temperature sensor.
- One for Sub Atmospheric line recovery
  - We call this logic "Sub Atmospheric Recovery Cool Down Line Logic"
  - This logic is active when:
    - Sequence 600 – Cold Box Cool Down is in Nominal step X610
    - And Sequence 900 – 4.5K Supply is not in initial step X900 .
  - This logic uses TT-22190 as main temperature sensor.

-in X608 or X609 or X610 as in page 92
- in X620 in page 79 (This requires cool down logic to remain active as in X620 we still have 4.5k Supply ON)

Note: An interlock forces open PV-22110 when PT-22190 > 3 atm and PT-22190 > PT-21000.

5.2 TRANSIENT MODES COOL DOWN LINE LOGIC

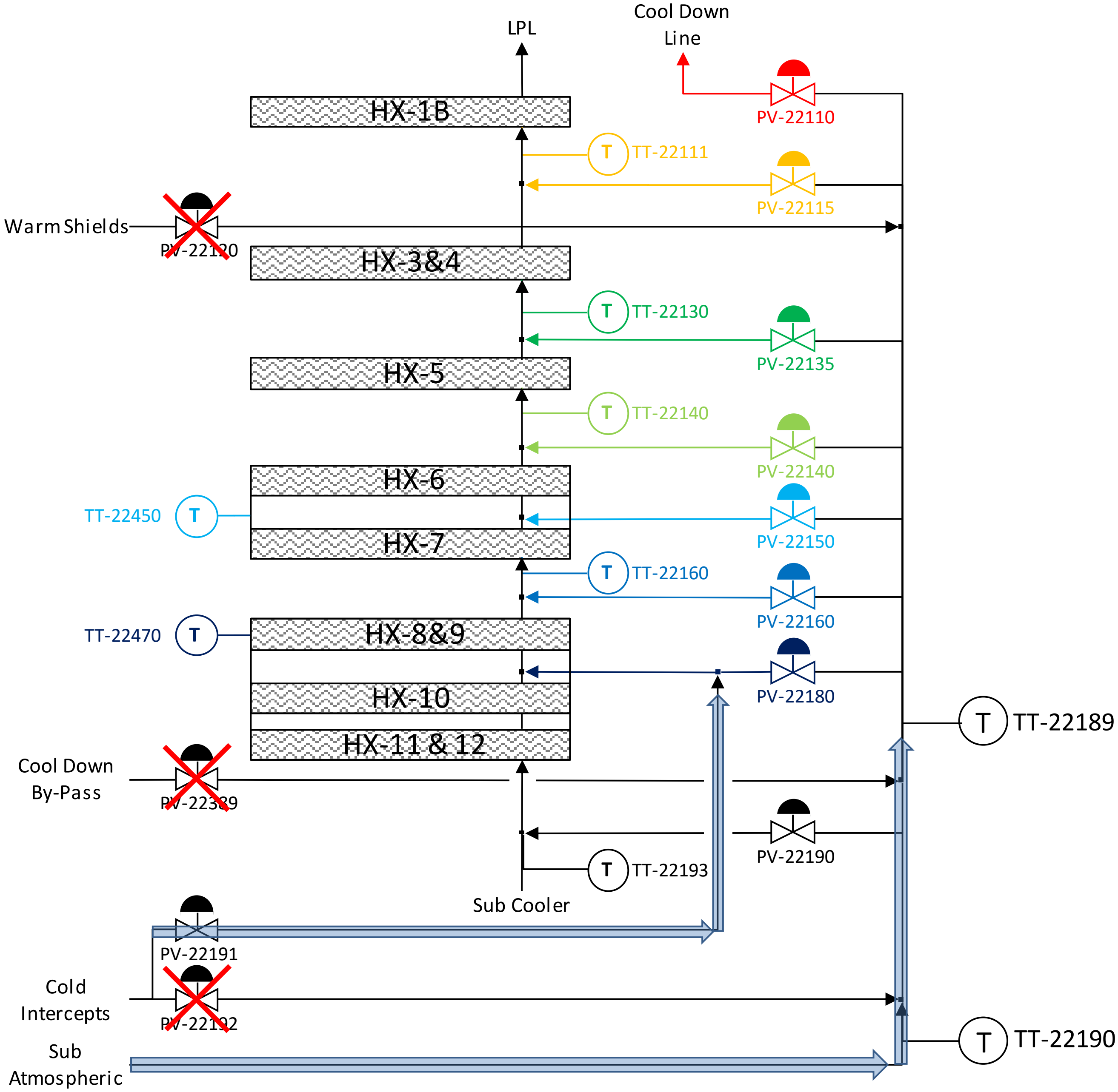


The cool down line valves opening logic is as follows:

Valve	Opening Speed	Closing Speed	Opening Condition
PV-22110	5%/sec	10%/sec	• Not opening condition for PV-22115 & PV-22135 & PV-22140 & PV-22150 & PV-22160 & PV-22180
PV-22115	2%/sec	10%/sec	• |TT-22189 – TT-22411| < 30K • TT-22189 ≥ 70K
PV-22135	2%/sec	10%/sec	• |TT-22189 – TT-22430| < 30K • 70K > TT-22189 ≥ 40K
PV-22140	2%/sec	10%/sec	• |TT-22189 – TT-22440| < 30K • 40K > TT-22189 ≥ 30K
PV-22150	2%/sec	10%/sec	• |TT-22189 – TT-22450| < 30K • 30K > TT-22189 ≥ 20K
PV-22160	2%/sec	10%/sec	• |TT-22189 – TT-22466| < 30K • 20K > TT-22189 ≥ 10K
PV-22180	2%/sec	10%/sec	• |TT-22189 – TT-22470| < 30K • 10K > TT-22189

Note : When the logic is lost for one valve, it starts to close only when the following valve to open is opened at 100%

5.3 SUB ATMOSPHERIC RECOVERY COOL DOWN LINE LOGIC



The cool down line valves opening logic is as follows:

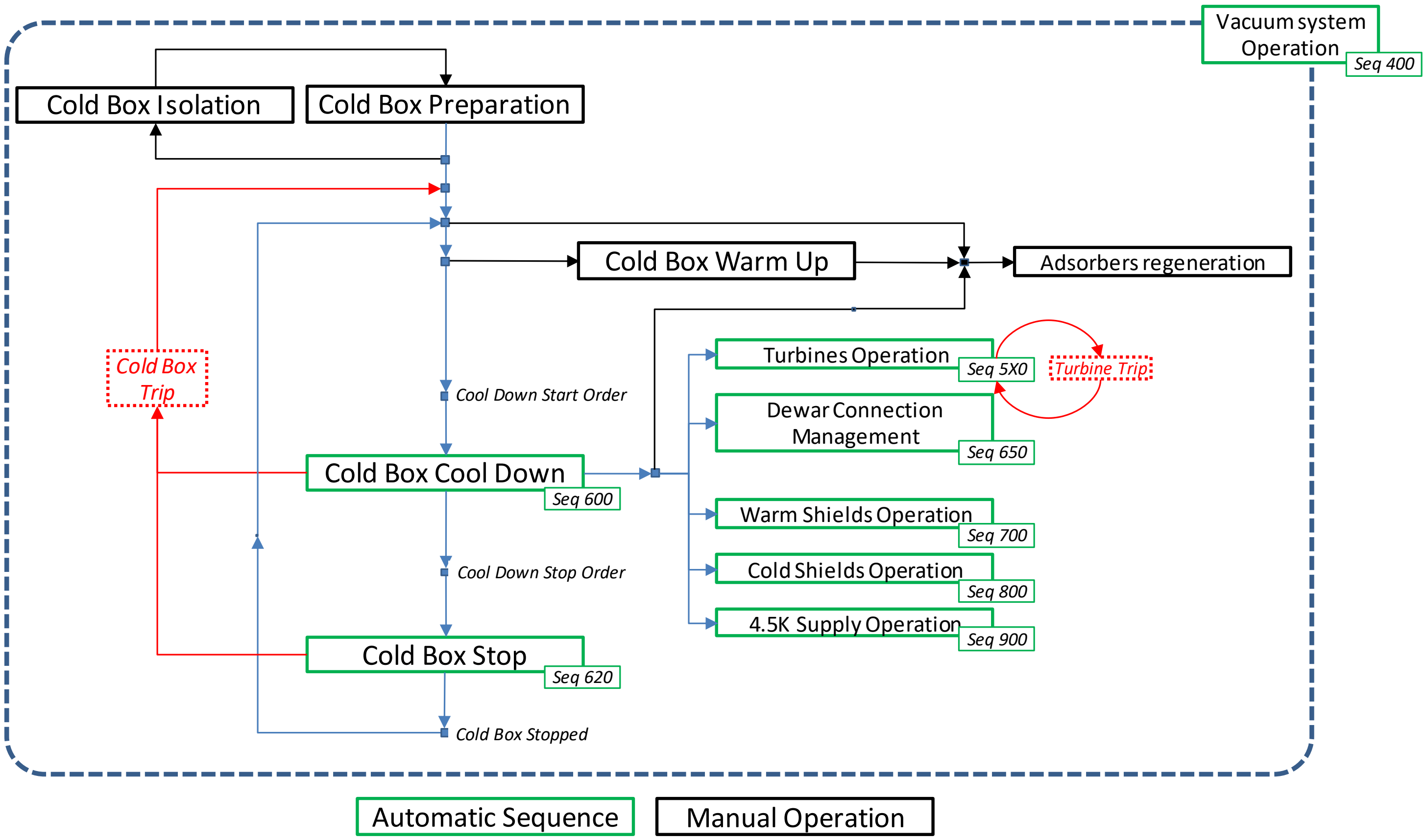
Valve	Opening Speed	Closing Speed	Opening Condition
PV-22110	5%/sec	10%/sec	• Not opening condition for PV-22115 & PV-22135 & PV-22140 & PV-22150 & PV-22160 & PV-22180
PV-22115	2%/sec	10%/sec	• |TT-22190 – TT-22411| < 30K • TT-22190 ≥ 70K
PV-22135	2%/sec	10%/sec	• |TT-22190 – TT-22430| < 30K • 70K > TT-22190 ≥ 40K
PV-22140	2%/sec	10%/sec	• |TT-22190 – TT-22440| < 30K • 40K > TT-22190 ≥ 30K
PV-22150	2%/sec	10%/sec	• |TT-22190 – TT-22450| < 30K • 30K > TT-22190 ≥ 20K
PV-22160	2%/sec	10%/sec	• |TT-22190 – TT-22466| < 30K • 20K > TT-22190 ≥ 10K
PV-22180	2%/sec	10%/sec	• |TT-22190 – TT-22470| < 30K • 10K > TT-22190 > 6K
PV-22190	0.5%/sec	10%/sec	• 6K > TT-22190

Note : When the logic is lost for one valve, it starts to close only when the following valve to open is opened at 100%

PV-22115, PV-22140 and PV-22160 have interlock to prevent large delta T across heat exchangers.
As soon as one of these interlock active, the valve is closed to 0% (no ramp). It then takes 20 seconds to fully open PV-22110 to 100% and provide a return flow path to cool down line.
This may cause momentary increase in back pressure at cool down line and may trip cold compressors. Do you prefer to jump open PV-22110 during these interlock?

6. OVERALL CONTROL PHILOSOPHY

The following graph is a simplified representation of the overall operation logic.
It shows all the automatic sequences and the manual operations allowing operating the Cold Box.



7. SEQUENCE 410 / 430 - VACUUM SYSTEMS

The logic shall be the same for the Upper Cold Box vacuum system (Sequence 410) and the Lower Cold Box Vacuum System (Sequence 430).

This section will be developed based on the tags from Upper Cold Box Vacuum System.

Same logic sequence will be used for LCB Vacuum Sequence replacing the tags in PLC programming.

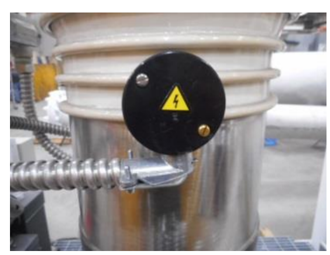
7.1 VACUUM SYSTEM – PRE REQUISITS

- Operator check list (Manual Operation):
    - Roughing Pump Disconnect switched “ON”
    - Diffusion Pump Disconnect switched “ON”
    - Cooling water supply and return valves open (MV-23411, MV-23419)
    - MV-23611 (Vacuum Gauge Vent) “Closed”
    - MV-23610 (Vacuum Gauge Isolation Valve) “Open”
    - MV-23613 (Diffusion Pump Oil Add Port) “Closed”
    - MV-23612 (Vacuum Cart Valve) “Closed”
    - MV-23616 (Vacuum Cart Valve) “Closed”
    - MV-23615 (Roughing Pump Isolation Valve) “Open”
      → In order to avoid roughing pump overheating, MV-23615 shall be partially open only to limit the flow in the roughing pump until the pressure in the Vacuum shell is lower. This procedure is described in the Operator Manual.
- System permissive:
    - E-Stop not engaged
    - Instrument Air “ON”
    - All actuators to be controllable by the control system (No operator mode)
    - No active Alarm or interlock

7.2 VACUUM SYSTEM – DIFFUSION PUMPS THERMAL SNAP SWITCHES

- “Cooling-fail thermal snap-switch” - TSH-23610:

This component protects the Diffstak against damage due to failure of the cooling-water supply. If the temperature of the Diffstak increases above the normal operating level, the switch will operate to disconnect the heater from the electrical supply. The switch is preset during manufacture and automatically resets when the temperature of the pump returns to normal. The switch is mounted on the fixing plate, which is permanently attached to the cooling-coil on the Diffstak body.



- “Pump-ready thermal snap-switch” - TSH-23611:

This switch indicates when the pump is in a fully operational state. The switch will operate at a preset temperature level when the jet system in the pump has reached operating temperature. The switch is positioned at the end of the ejector-stage housing.

7.3 VACUUM SYSTEM - START

UCB Vacuum Sequence - Start

410 ↓	- No Vacuum related Active alarm or interlock - UCB Vacuum start Order	
X411	- Start VP-23610 - Open PV-23614 - Start Timer 5 minutes	*Roughing Pump* *Connect Roughing Pump to Diffusion Pump* *Allow Roughing pump to warm up*
411 ↓	- End of Timer 5 minutes	
X412	- If PT-23618 < PT-23610 Then Open PV-23616	If Vacuum at Roughing pump lower than vacuum in the chamber Then Connect Roughing Pump to the Chamber
412 ↓	- PT-23610 < 200mTorr (~0.26 mbar) And PT-23615 < 200mTorr (~0.26 mbar)	Pressure sufficiently low in Vacuum Chamber (Pressure difference low on Gate Valve) Pressure low sufficiently low in Diffusion Pump
X413	- Start EH-23610	*Diffusion Pump*
413 ↓	- PT-23610 < 200 mTorr (~0.26mbar) and - TSH-23611	*Pump-ready thermal snap-switch*
X414	- Open PV-23611	*Connect Vacuum Chamber to Diffusion Pump*
414 ↓	- ZSH-23611	*Gate Valve Open*
X415	- Close PV-23616	*Close Diffusion Pump by-pass*

At State X413 add:
If PT23618 < PT-23610
Then Open PV-23616

This step is the nominal step

JLAB:
This 'Pump ready thermal snap-switch' TSH23611 is not found at the electrical drawing C1303-ED-103(B). Following temporary edits are made till confirmation
- Replaced with TSH23610.
- 40 min timer added to heat up the oil.
ALATUS:
On-site check is pending.
JLAB:
Issue solved as cable for TSH is now installed and code rely on TSH23611.

7.4 VACUUM SYSTEM – STOP OR TRIP

UCB Vacuum Sequence - Stop or Trip		
411, 412, 413, 414, 415 ↓	- Vacuum System Stop Order Or - Vacuum System Trip	
X416	- Close PV-23611 and PV-23616 - Stop EH-23610 - Start Timer 1 minute	*Isolate Vacuum Chamber* *Stop Diffusion Pump*
416 ↓	- ZSL-23611 - End Timer 1 minute	*Gate Valve closed* *Vacuum Pump Cool down*
X410	- Close PV-23611, PV-23614 and PV-23616 - Stop VP-23610 - Stop EH-23610	*Isolate Vacuum Chamber* *Stop Roughing Pump* *Stop Diffusion Pump*

7.5 VACUUM SYSTEM – EMERGENCY STOP

If an E-stop generates the following:

- Sequence is stopped and reset (Step 410)
- All actuators fail in their safe position

TURBINE SEQUENCES

JLAB: While entering state X514: SIC is OFF -> SIC output is equal to X% of the PV22432 opening in order to reach 200 Hz.
SIC turns ON -> TIC turns ON at the same time. Is it required to ramp the speed up to either (i) minimum speed (1000 Hz for T1) or (ii) maximum speed (2220 Hz for T1) in a 50Hz/s ramp before and then turn TIC ON for further regulation?

ALATUS:(i): No, (ii): No

JLAB:We need to ramp the speed to the new speed set point (in between 1000-2220 Hz) obtained from Attenuators (and TIC as soon as TIC is ON).

ALATUS:Yes. And if we want to have the option not to start TIC, we can ramp set point to Calculated speed (which is maximal speed * Attenuators coefficients)

TURBINE SEQUENCES

JLAB:
Before starting SIC, TIC and EIC control loop, do we need to unlatch the manual mode (only once while entering to step X514) and set it to auto mode. This may eliminate error possibility of code if user left it in manual mode during previous run and forget.

ALATUS: Yes

JLAB: Counter argument is -> if user really wants to keep one of these control loops in manual mode at X514, then what?

ALATUS: He should be able to turn it in manual once it is 1st automatically started in X514.

8. SEQUENCES - TURBINES

Turbo-expanders rotation is generated by a pressure difference on the Turbo wheel. Starting the turbines consists in opening the inlet valve progressively. The four turbines being on different configurations, there operating sequences slightly differ from one to another.

8.1 SEQUENCE 510 - TURBINE 1

8.1.1 Turbine 1 - Start

Turbine 1 Sequence - Start		
510 ↓	- Turbine 1 Authorization	*Switch on the Supervision to be activated by the operator*
		If Turbine 1 Authorization switch is removed and Turbine Sequence in step 511, 512, 513 or 514, go to step 515.
	- Turbine 1 Start Order	*From Seq 600 or Switch on the Supervision*
	- No Turbine 1 Alarm or Trip condition activated	
	- Cool Down Sequence in Step X602 to X610	*Cold Box Cool Down Sequence*
X511	- Open PV-22242 at 100%	*Ramp 1%/s until 20% then open at 100%*
511 ↓	- PV-22242 at 100%	
	- ZSH-22242 active	*PV-22242 open status check*
X512	- Open EV-22432 - Open PV-22432	*PV-22432 Air supply / fast discharge valve* *Ramp 0.5%/s*
512 ↓	- ST-22433 > 200Hz	
X513	- Stop Ramping and Fix opening of PV-22432 at the current value	*Stabilization*
513 ↓	- Timer 10 sec	
X514	- Start Control loops: - SIC-22432 - TIC-22332 - Ramp TIC-22332 set point - When TT-22432 < 70K, start Control loop - EIC-22436	*Speed Control Loop* *Ramp speed Set Point (up and down) 50Hz/s* *Discharge Temperature Control Loop* *Ramp = -5 K/min from Current to Nominal* *Efficiency Control Loop (stopped whenever Turbine inlet temperature is higher than 70K or other process values outside of Table Range)*

At this step, the turbine is in nominal mode. The next steps will stop the Turbine.

JLAB:
At X514, if EIC224X6 is OFF; what is the ramp rate (X atm/s) to go back PIC224X6 set point of 5.0 atm?
ALATUS:
We can agree on 0.02 Atm/sec

8.1.2 Turbine 1 - Stop

Turbine 1 Sequence - Stop		
514 ↓	Turbine 1 Stop Order Or Not Turbine 1 Authorization from step 511, 512, 513 or 514	
X515	- Stop Control loops: - SIC-22432 - TIC-22332 - EIC-22436 Close PV-22432	 *Ramp 5%/sec*
515 ↓	- PV-22432 at 0%	
X516	- Close EV-22432 - Close PV-22242 - Close PV-22245	 *Ramp 5%/s* *Ramp 5%/s*
516 ↓	PV-22242 = 0% ZSL-22242 Activated And PV-22245 = 0% ZSL-22245Activated	 *PV-22242 close status check* *PV-22245 close status check*
X510	- Stop Control loops: - SIC-22432 - TIC-22332 - EIC-22436 - Close PV-22432, PV-22242 & PV-22245 - Close EV-22432	 *Close at 0% with no Ramp* *PV-22432 Air supply / fast discharge valve*

8.1.3 Turbine 1 – Trip

Turbine 1 Sequence – Trip		
511, 512, 513, 514, 515, 516 ↓	- Cold Box General Trip - Turbine 1 Trip	
X510	- Stop Control loops: - SIC-22432 - TIC-22332 - EIC-22436 - Close PV-22432, PV-22242 & PV-22245 - Close EV-22432	 *Close at 0% with no Ramp* *PV-22432 Air supply / fast discharge valve*

8.2 SEQUENCE 520 - TURBINE 2

8.2.1 Turbine 2 - Start

Turbine 2 Sequence - Start		
	- Turbine 2 Authorization	*Switch on the Supervision to be activated by the operator* *If Turbine 2 Authorization switch is removed and Turbine Sequence in step 521, 522, 523 or 524, go to step 525.*
520 ↓	- Turbine 2 Start Order	*From Seq 600 or Switch on the Supervision*
	- No Turbine 2 Alarm or Trip condition activated	
	- Cool down Sequence in Step X603 to X610	*Cold Box Cool Down Sequence*
X521	- Open PV-22358	
521 ↓	- ZSH-22358	
X522	- Open EV-22452 - Open PV-22452	*PV-22452 Air supply / fast discharge valve* *Ramp 0.5%/s*
522 ↓	- ST-22453 > 200Hz	
X523	- Stop Ramping and Fix opening of PV-22452 at the current value	*Stabilization*
523 ↓	- Timer 10 sec	
X524	- Start Control loops: - SIC-22452 - TIC-22352 - Ramp TIC-22352 set point - When TT-22452 < 45K, start Control loop - EIC-22456	*Speed Control Loop* *Ramp speed Set Point (up and down) 50Hz/s* *Discharge Temperature Control Loop* *Ramp = -5 K/min from Current to Nominal* *Efficiency Control Loop (stopped whenever Turbine inlet temperature is higher than 45K or other process values outside of Table Range)*

At this step, the turbine is in nominal mode. The next steps will stop the Turbine

8.2.2 Turbine 2 - Stop

Turbine 2 Sequence - Stop

524 ↓	Turbine 2 Stop Order Or Not Turbine 2 Authorization from step 521, 522, 523 or 524	
X525	- Stop Control loops: - SIC-22452 - TIC-22352 - EIC-22456 Close PV-22452	*Ramp 5%/sec*
525 ↓	- PV-22452 at 0%	
X526	- Close EV-22452 - Close PV-22358	
526 ↓	ZSL-22358	
X520	- Stop Control loops: - SIC-22452 - TIC-22352 - EIC-22456 - Close PV-22452 & PV-22358 - Close EV-22452	*Close at 0% with no Ramp* *PV-22452 Air supply / fast discharge valve*

8.2.3 Turbine 2 – Trip

Turbine 2 Sequence – Trip

521, 522, 523, 524, 525, 526 ↓	- Cold Box General Trip - Turbine 2 Trip	
X520	- Stop Control loops: - SIC-22452 - TIC-22352 - EIC-22456 - Close PV-22452 & PV-22358 - Close EV-22452	*Close at 0% with no Ramp* *PV-22452 Air supply / fast discharge valve*

8.3 SEQUENCE 530 - TURBINE 3

8.3.1 Turbine 3 - Start

Turbine 3 Sequence - Start		
530 ↓	- Turbine 3 Authorization - Turbine 3 Start Order - No Turbine 3 Alarm or Trip condition activated - Cool down Sequence in Step X604 to X610	*Switch on the Supervision to be activated by the operator* *If Turbine 3 Authorization switch is removed and Turbine Sequence in step 531, 532, 533 or 534, go to step 535.* *From Seq 600 or Switch on the Supervision* *Cold Box Cool Down Sequence*
X531	- Open PV-22378	
531 ↓	- ZSH-22378	
X532	- Open EV-22472 - Open PV-22472	*PV-22472 Air supply / fast discharge valve* *Ramp 0.5%/s*
532 ↓	- ST-22473 > 200Hz	
X533	- Stop Ramping and Fix opening of PV-22472 at the current value	*Stabilization*
533 ↓	- Timer 10 sec	
X534	- Start Control loops: - SIC-22472 - TIC-22372 - Ramp TIC-22372 set point If TT-22472 – TT-22372 ≥ 50K Then hold Ramp on TIC-22372 set point. - When TT-22472 < 25K, start Control loop - EIC-22476	*Speed Control Loop* *Ramp speed Set Point (up and down) 50Hz/s* *Discharge Temperature Control Loop* *Ramp = -5 K/min from Current to Nominal* *Avoid the risk of having a too high Temperature difference on HX-9.* *Efficiency Control Loop (stopped whenever Turbine inlet temperature is higher than 25K or other process values outside of Table Range)*

At this step, the turbine is in nominal mode. The next steps will stop the Turbine

8.3.2 Turbine 3 - Stop

Turbine 3 Sequence - Stop

534 ↓	Turbine 3 Stop Order Or Not Turbine 3 Authorization from step 531, 532, 533 or 534	
X535	- Stop Control loops: - SIC-22472 - TIC-22372 - EIC-22476 Close PV-22472	*Ramp 5%/sec*
535 ↓	- PV-22472 at 0%	
X536	- Close EV-22472 - Close PV-22378	
536 ↓	ZSL-22378	
X530	- Stop Control loops: - SIC-22472 - TIC-22372 - EIC-22476 - Close PV-22472 & PV-22378 - Close EV-22472	*Close at 0% with no Ramp* *PV-22472 Air supply / fast discharge valve*

8.3.3 Turbine 3 – Trip

Turbine 3 Sequence – Trip

531, 532, 533, 534, 535, 536 ↓	- Cold Box General Trip - Turbine 3 Trip	
X530	- Stop Control loops: - SIC-22472 - TIC-22372 - EIC-22476 - Close PV-22472 & PV-22378 - Close EV-22472	*Close at 0% with no Ramp* *PV-22472 Air supply / fast discharge valve*

8.4 SEQUENCE 540 - TURBINE 4

8.4.1 Turbine 4 - Start

The Turbines 4 is a Joules Thomson Turbine. As such, it is installed in line with the HP Line.

When the Turbine 4 is stopped, the HP Joules Thomson flow is controlled by Turbine 4 by-pass control loop TIC-22485.

This control loop is not stopped when Turbine 4 is in operation.

However, PV-22485 needs to have a lower opening % compared to PV-22482, the reason being that the flow through Turbine 4 shall be maximized.

Therefore, TIC-22466 set point is set at a higher value than TIC-22485 set point:

- TIC-22466 SP = 18.5K
- TIC-22485 SP = 18K

Turbine 4 Sequence - Start

	- Turbine 4 Authorization	*Switch on the Supervision to be activated by the operator* *If Turbine 4 Authorization switch is removed and Turbine Sequence in step 541, 542, 543 or 544, go to step 545.*
540 ↓	- Turbine 4 Start Order	*From Seq 600 or Switch on the Supervision*
	- No Turbine 4 Alarm or Trip condition activated	
	- Cold Box Cool Down Sequence in Step X610	*Cold Box Cool Down Sequence*
X541	- Open PV-22388	
541 ↓	- ZSH-22388	
X542	- Open EV-22482 - Open PV-22482	*PV-22472 Air supply / fast discharge valve* *Ramp 0.2%/s (slower than other turbines)*
542 ↓	- ST-22483 > 200Hz	

Note: The cool down of Turbine 4 is a tricky transient phase for the Cold box since it will force warm flow toward the LHe stored in the Subcooler and the Dewar. It must be done very slowly so as to limit the flow of LHe vaporized, and thus limiting the perturbation for the Cold Box.

X543	- Stop Ramping and Fix opening of PV-22482 at the current value	*Stabilization*
543 ↓	- Timer 10 sec And - TT-22382 <10K	*Turbine 4 circuits cold enough to allow more flow through the Turbine*

X544	- Start Control loops: - SIC-22482 - TIC-22466 - Ramp TIC-22466 set point - EIC-22486	 *Speed Control Loop* *Ramp speed Set Point (up and down) 50Hz/s* *20K Adsorber Outlet Temperature Control Loop* *Ramp = +/- 0.5 K/min from Current to Nominal* *Efficiency Control Loop (stopped whenever Turbine inlet temperature is higher than 7K)*

At this step, the turbine is in nominal mode. The next steps will stop the Turbine.

8.4.2 Turbine 4 - Stop

Turbine 4 Sequence - Stop

544 ↓	Turbine 4 Stop Order Or Not Turbine 4 Authorization from step 541, 542, 543 or 544	
X545	- Record PT-22482 - If PV-22485 < 50% Hold TIC-22485 and Ramp PV-22485 at 50% Then restart TIC-22485 (when valve opened) - Stop Control loops: - SIC-22482 - TIC-22466 - EIC-22486 - Close PV-22482	*Ramp 5%/sec* *(refer to Section 4.6.3)* *This is to anticipate the closing of Turbine 4 inlet valve and minimize the impact on the Joules Thomson flow.* *TIC-22485 remains active* *Ramp 5%/sec*
	PV-22482 and PV-22485 are ramped at the same time: *PV-22482 to 0% and PV-22485 to a fixed value.*	
545 ↓	- PV-22482 at 0%	
X546	- Close EV-22482 - Close PV-22388	
546 ↓	ZSL-22388	
X540	- Stop Control loops: - SIC-22482 - TIC-22466 - EIC-22486 - Close PV-22482 - Close EV-22482	 *PV-22482 Air supply / fast discharge valve*

8.4.3 Turbine 4 - Trip/Emergency Stop

When Turbine 4 is tripped, as when it is stopped, the by-pass valve PV-22485 shall be forced open to a certain value so as to allow HP flow towards the JT valve.

The controller TIC-22485 is already activated (not stopped during Turbine 4 operation), but forcing opening the valve will allow a faster reaction of the system.

2 different Turbine 4 Trips are to be considered however:

- Turbine 4 Trip only: The Trip is not due to a general Cold Box Trip or Emergency Stop.
- Turbine 4 Trip from Cold Box Trip or Emergency Stop.

The difference between the 2 cases is that:

- After a Turbine 4 Trip, the controller TIC-22485 acting on PV-22485 remains active.
- After a Cold Box Trip, the controller TIC-22485 acting on PV-22485 is stopped.

Turbine 4 Sequence – Trip (Turbine 4 Trip only)

541, 542, 543, 544, 545, 546 ↓	- Turbine 4 Trip - Not Cold Box Trip nor Emergency Stop	See Section 4.6.3 conclusion (page-35) which says PV-22485 to jump open to 50%. Should we jump open to 50% value similar to STOP sequence in X545?
X547	- Record PT-22482 - Hold TIC-22485, and Open PV-22485 at $20.745 \times Ln[0.008366 \times (14.115 \times PT22482 + 90.925)] + 49.41$ Then restart TIC-22485 (when valve opened)	*No Ramp* *This is to anticipate the closing of Turbine 4 inlet valve and minimize the impact on the Joules Thomson flow.* *TIC-22485 remains active*
	- Stop Control loops: - SIC-22482 - TIC-22382 - EIC-22486 Close PV-22482 & PV-22388	*Close at 0% with no Ramp*
	PV-22482 and PV-22485 are actuated at the same time: *PV-22482 closed at 0% and PV-22485 opened to a fixed value.*	
547 ↓	~~- PV-22485 at 50%~~	Since, all the actions are taken at X547, this transition condition may not require any more.
X540	- Stop Control loops: - SIC-22482 - TIC-22382 - EIC-22486	
	- Close PV-22482 & PV-22388	*Close at 0% with no Ramp*
	- Close EV-22482	*PV-22482 Air supply / fast discharge valve*

Air solenoid should be closed with PV22482 to ensure inlet valve is closed before closing outlet valve.

Turbine 4 Sequence – Trip (Cold Box Trip or Emergency Stop)

541, 542, 543, 544, 545, 546 ↓ - Cold Box General Trip / Emergency Stop

X540	- Stop Control loops: - SIC-22482 - TIC-22382 - EIC-22486	
	- Close PV-22482 & PV-22388	*Close at 0% with no Ramp*
	- Close EV-22482	*PV-22482 Air supply / fast discharge valve*

9. MANUAL OPERATION - COLD BOX PREPARATION BEFORE COOL DOWN

The Cold Box preparation is **a manual operation** that is performed from the Supervision system as well as from the Upper Cold Box platform and the Turbines area.

9.1 COLD BOX PREPARATION - PRE REQUISITS

- All the utilities are available (compressed air, water, electricity).

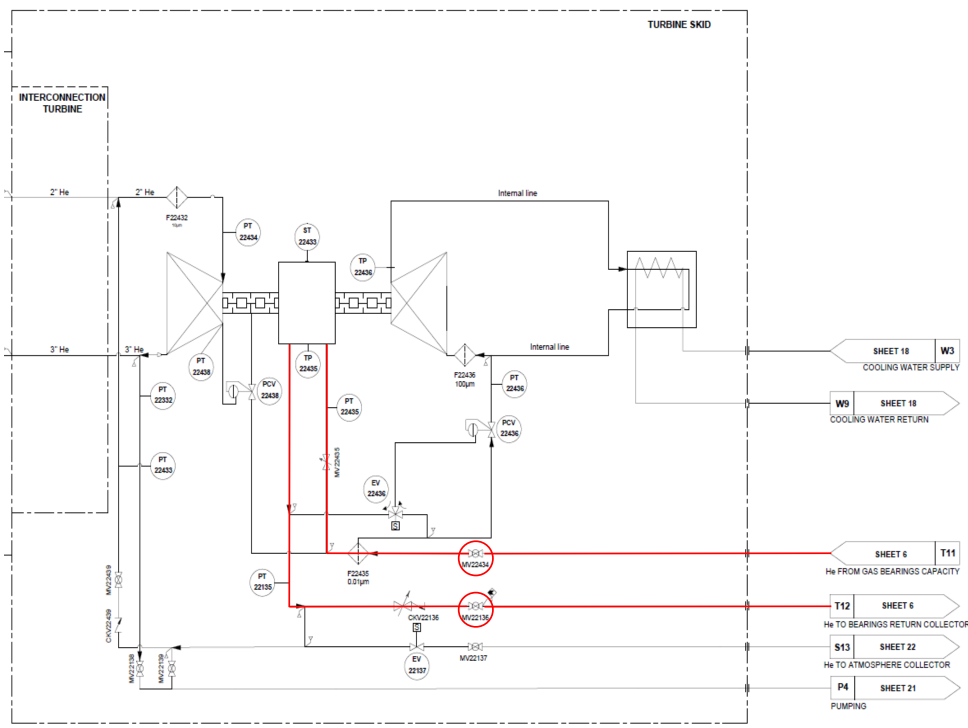
- The compression station is in nominal operation.

- Automatic valves are in manual mode and in their failure position (control loop associated).

- Control loops in Manual mode (Stopped).

- No fault is displayed or in progress.

- Turbines bearings valves open:



9.2 COLD BOX PREPARATION – MANUAL OPERATIONS

9.2.1 Start Turbine Bearings pressure Control Loop and all 4 Brake pressure Control Loops – From control system supervision

- Open PV-22405 in manual progressively so as not to disturb MCS HP control loop.
- When PT-22405 = 11 Atm, turn ON PIC-22405.
- Turn ON PIC-22436, PIC-22456, PIC-22476, PIC-22486.

9.2.2 Connect Adsorbers to the HP Line

- Connect the 80K adsorber to be used during Cool Box Cool Down
  - Open the outlet valve PV-22420A or PV-22420B
  - Open the inlet valve PV-22415A or PV-22415B

Opening ramp = 0.5%/s
Closing ramp = 10%/s

- Connect the 20K adsorber
  - Open the outlet valve PV-22466
  - Open the inlet valve PV-22461

9.2.3 Connect HP Cold end to HP Line

- Open T4 by-pass valve at 100%

9.2.4 Connection of the Cold Box to the MCS – From Upper Cold Box Platform

- Connect LPL line to the MCS
  - Use MV-22101 to equalize pressures between Cold Box and MCS
  - Open MV-22100
  - Close MV-22101.
- Connect LPR line to the MCS
  - Use MV-22201 to equalize pressures between Cold Box and MCS
  - Open MV-22200
  - Close MV-22201.
- Prepare Cool Down Line
  - Check that the Manual Valve between the Vaporizer and the MCS LP Line is open
  - Open PV-22110 to equalize pressure between Cool Down Line and MCS
  - If PT-22190 < 1.1 atm, then close PV-22110.
- Connect HP line to the MCS
  - Use MV-22401 or MV-22407 to pressurize the Cold Box HP line if PT-22393 ≠ PT-22400
  - ~~Open PV-22402 (Let PV-22400 closed, this valve will open during cool down with the HP Flow repartition regulator DTIC-22400)~~
  - Close MV-22401 or MV-22407.

Opening of PV-22402 is performed at step X601, no need to open PV-22402 manually.

10. SEQUENCE 600 – COLD BOX COOL DOWN

10.1 COLD BOX COOL-DOWN - PRE-REQUISITS

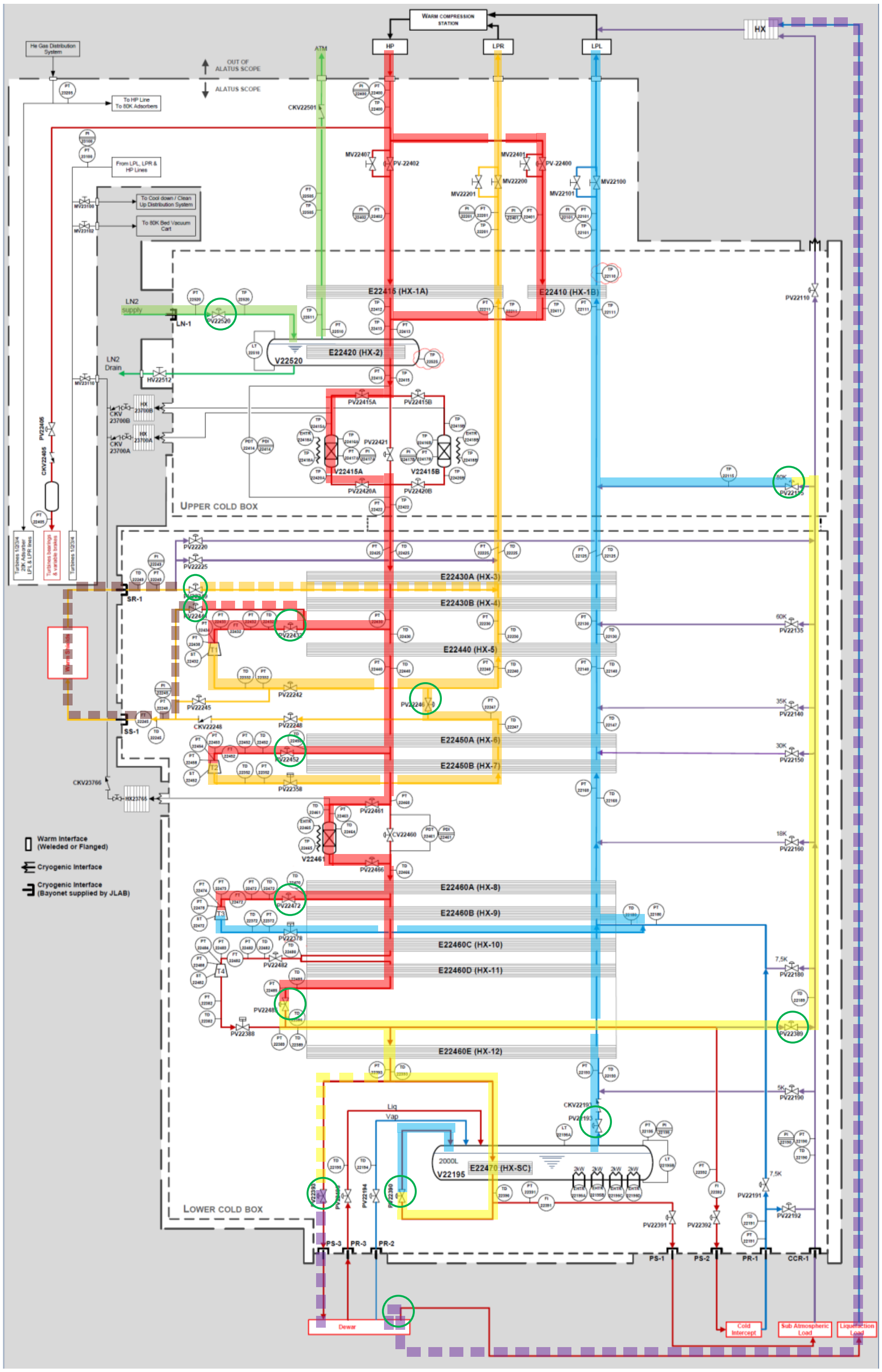
- MCS is running in nominal operation.
- Cold Box is pressurized and connected:
    - ZSH -22100 & ZSH -22200
    - PV-22400 @ 100% & PV-22402 @ 100%.
- Cold Box vacuum in Upper and Lower Cold Boxes OK
    - PT-23610 < 10-3 mbar.
    - PT-23630 < 10-3 mbar.
- Adsorbers are connected or by-pass line open:
    - PV-22415A & PV-22420A @100%, or PV-22415B & PV-22420B @100%, or PV-22421 @100%.
    - PV-22461 & PV22466 @100%, or PV-22460 @100%.

A check is necessary to ensure that beds are regenerated before connection.

Else, cool-down can be done using adsorber by-pass.

- LN2 is available

10.2 COLD BOX COOL-DOWN - PFD



10.3 COLD BOX COOL DOWN – START

During the first step of the cool down, the cold power is mainly brought by the first three turbines and by the liquid nitrogen through HX1A.

Important Note:
During this 1st part of the cool down, a small amount of LN2 is used to minimize temperature difference between:

- *HX2 HP stream (Warm) and HX2 LN2 stream (Cold)*
- *HX1A HP and LPR streams (Warm) and HX1A GN2 stream (Cold)*

LN2 control loop is not started, and the control system will only open LN2 supply valve at a small opening so as not to have Liquid level in the LN2 phase separator.

During the beginning of the cool down, only the HP flow sharing control on HX-1B is started.

Cool Down from 300K to 120K

Cold Box Preparation and Flow Circulation

600 ↓	- **COLD BOX COOL DOWN START** order - ~~MCS is running in nominal operation.~~ - Cold Box is pressurized and LPR and LPL Lines are connected: - ZSH -22100 & ZSH -22200 - |PT-22400 – PT-22402| < 200 mbar. - PT-23610 < 10-3 mbar. - PT-23630 < 10-3 mbar. - 80K Adsorbers or by pass valves are connected - PV-22415A & PV-22420A @100% - or PV-22415B and PV-22420B @100% - or PV-22421 @100% - 20K Adsorber or by pass valves are connected - PV-22461 & PV22466 @100% - or PV-22460 @100% - PV-22246 (Failed Open) open at 100% - PIC-22405 ON and Bearings pressure OK	to be checked by operator, no such signal for condition check by PLC *HP Line pressurized and ready for connection* *Vacuum in Upper and Lower Cold Boxes OK* *PT-22405 > 11 atm*
X601	- Start "Transient Modes Cool down line logic" - Open cold end by pass PV-22389 at 10% - Open PV-22402 @ 100% - Open PV-22485 @100% (Turbine 4 by-pass) - Open PV-22193 @100% (Subcooler outlet Valve) - Open PV-22190 (Subcooler to Cool Down Line) - Start Timer 2 min	*(see section 5)* *Will start a small flow through HP Line* *Ramp 1%/s* *Ramp 1%/s* *Ramp 1%/s* *Ramp 1%/s*
601 ↓	- End of Timer 2 min	

Subcooler Connection

X602	- Start TIC-22400 - Start PIC-22193 Set SP = 1.05 atm - Start Cold end by-pass control loop TIC-22389 with a minimum output (minimum opening) at 10%. - Open PV-22390 at 20% - Close PV-22390 if PT-22195 > 1.5 Atm - Start Timer 2 min	*Initial Output 0% (PV-22400 closed)* *Set point 1.05 atm* *Refer to section 4.7* *Opening Ramp 0.2%/s* *Closing Ramp 1%/s*
602 ↓	- End of Timer 2 min	

During testing, an interlock on PV-22390 became active and force the opening to 5%. Once 2 min timer is over, the X602 become in-active and cool down sequence never tried to open the valve PV-22390 up to 20%
Do we need to repeat this action (i mean -> continue ramp PV-22390 till 20% and close if PT22195> 1.5 atm) till X608?

TURBINES 1, 2, 3 START

X603	- If Turbine 1 Authorized, Start Turbine 1 sequence	*Turbine 1 Authorization is a variable that can be activated from a the HMI by operator*
603 ↓	- Turbine 1 in nominal mode Or - Turbine 1 not Authorized	
X604	- If Turbine 2 Authorized, Start Turbine 2 sequence	*Turbine 2 Authorization is a variable that can be activated from a the HMI by operator*
604 ↓	- Turbine 2 in nominal mode Or - Turbine 2 not Authorized	
X605	- If Turbine 3 Authorized, Start Turbine 3 sequence	*Turbine 3 Authorization is a variable that can be activated from a the HMI by operator*
605 ↓	- Turbine 3 in nominal mode Or - Turbine 3 not Authorized	

At this step (X605), the system will start LN2 supply and Helium circulation in the Cold Box via the Cool down line and the Subcooler.

LN2 PRE COOLING START

X606	- If LN2 pre-cooling authorized, Start LN2 preliminary supply: **If** TT-22520 > 120K TDT-22520A > - 25K TDT-22520B > - 25K → Open PV-22520 at TDT-22520A_SP **If** TT-22520 < 120K TDT-22520A > - 25K TDT-22520B > - 25K → Open PV-22520 at TDT-22520B_SP **Else** → Close PV-22520 - Ramp Maximum Opening of TIC-22389 at 80%	*LN2 pre-cooling Authorization is a variable that can be activated from a the HMI by operator* TDT-22520A = TT-22525 – TT-22412 TDT-22520B = TT-22511 – TT-22412 TDT-22520A_SP = 20% (to be adjusted) *Opening Ramp 1%/s* TDT-22520B_SP = 5% (to be adjusted, the valve shall just be cracked open at this stage to maintain the supply line cold) *Opening Ramp 1%/s* *Closing Ramp 5%/s* *Ramp 2%/s* *Opening value to be adjustable from HMI if needed to be reduced.*

Note: PV-22520 opening values shall be adjustable parameters from HMI.

The next step of the cool down happens when the HP temperature downstream HX-1A reaches 120K. At this step, LN2 can be used in normal conditions.

At this step, the cold end-by pass position shall also be continuously adjusted son that the flow in the cool down line is limited while temperature in the cold box decreases.

COOL DOWN FINAL

606 ↓	- TT-22412 < 115K	*Alarm implemented if TT-22412 > 120K and LT-22510>25%*
X607	- Start LN2 Control Loop LIC-22520	*→ Set Point (LN2 level) forced at 0% and then ramped by 2% / min until the set point value is 70%*

When the 20K adsorber reaches its nominal temperature around 18K, the JT flow control based on PV-22485 (Turbine 4 by-pass) is started:

607 ↓	- TT-22466 < 19K	*20K Adsorber at its nominal temperature*
X608	- Set TIC-22485 output at PV-22485 value	
	- then Start TIC-22485	*Set Point = TT-22466 then Ramp 0.05 K/min to 18K (Refer to section 4.6)*
	- Start PIC-22485	*Set Point = PT-22393 then Ramp 0.05 atm/s to 3.0atm (Refer to section 4.8.4)* *→ PV-22485 will close slowly*
	- Close PV-22190 (Subcooler Outlet to Cool Down Line)	*Ramp 1%/s*
	- Stop TIC-22389.	
	- Set PV-22389 min opening at 0% and Close PV-22389	*Ramp 1%/s*

TIC-22485 acting on PIC-22485, it is important that the output is initially set at PV-22485 current value to avoid a fast closing of the valve.

608 ↓	- TT-22193 < 10K	*Subcooler almost at LHe temperature*
X609	- Switch ON Superconductive level probe LT-22195A Action for operator	*Pop-Up window (or equivalent) asking the Operator to switch on the AMI probe transmitter.*
	- Start LIC-22390	*Set Point = LT-22195A then ramp 0.1 %/min (Refer section 4.~~10.2)~~* ..section 4.10.4) up to 50%.
	- Start PIC-22390	*Set Point: PT-22393 = 2.8 atm*
	- Start LIC-22195B	*Set Point 90% (see section 4.10.3)*

At this step, the only remaining condition for the Cold box to be in nominal step is to have the Dewar connection sequence also in nominal step.

609 ↓	- Dewar connection sequence in Step X654	*Nominal step*
X610	Cold Box in Nominal Step	

This step corresponds to the nominal step for the Cold Box.
At this step, Turbine 4 sequence can start or stop upon request of the operator.

10.4 COLD BOX COOL DOWN - STOP

The Cold Box stop sequence stops the Turbines, the LN2 pre-cooling, and isolate the Cold box from its cold interfaces.

Cold Box Cool Down - Stop

600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610 ↓	- Cold Box Stop Order	
X620	- Reset Cold box Start order - Set "Cold Box in Nominal mode" variable at 0 - Turbine 4 Stop order	
620 ↓	- Turbine 4 Sequence in step 540	
X621	- Turbine 3 Stop order - 4.5K Supply Stop order - Cold Intercepts Stop order - Stop PIC-22390 and LIC-22390 - Close PV-22390 at 0% - LHe Dewar connection Stop order	 *No Ramp* *Will activate step X658*
621 ↓	- Turbine 3 Sequence in step 530 - 4.5K Supply Sequence in step 900 - LHe Dewar Sequence in step 650	
X622	- Stop TIC-22400 - Close PV-22400 at 0% - Open PV-22402 at 100% - Turbine 2 Stop order - Warm Shields Stop order - Stop TIC-22485 and PIC-22485 - Open PV-22485 at 30%	 *Ramp 1%/sec* *Ramp 1%/sec* *Ramp 5%/s*
622 ↓	- Turbine 2 Sequence in step 520	
X623	- Turbine 1 Stop order - Stop LIC-22520 and close PV-22520	 No ramp
623 ↓	- Turbine 1 Sequence in step 510, - PV-22520 closed	

X624	- Close 80K Adsorbers Valves - Open PV-22421 - Close PV-22402 at ~~100%~~ Should be 0% - Set 80K Adsorber that was connected “Offline” - Close 20K Adsorber Valves - Open PV-22460 - Set 20K Adsorber “Offline” - Open PV-22389 at 20%	*Closing Ramp 10%/sec* *No Ramp* *Ramp 1%/sec* *See section 16.1* *Closing Ramp 10%/sec* *No Ramp* *Ramp 0.5%/sec*

At this step, the cold box is stopped and isolated from its cold interfaces.

The warm shields and cold intercepts may still be in their 30 minutes timing to allow cold gas expansion towards the Cool Down line.

The Cold by-pass PV-22389 is opened to depressurize the HP Line.

624 ↓	- Cold Intercepts Sequence in step 800 - Warm Shields Sequence in step 700	
X600	- Stop TIC-22485, PIC-22485 and Close PV-22485 - Stop TIC-22400 - Close PV-22400 - Close PV-22402 - Stop LIC-22520 and close PV-22520 - Close PV-22421 - Close PV-22415A / PV-22415B - Close PV-22420A / PV-22420B - Stop TIC-22418A/B and stop EHTR-22418A/B - Close PV-22460 - Close PV-22461 / PV-22466 - Stop TIC-22465 and stop EHTR-22465 - Stop PIC-22193 and Close PV-22193 - Stop PIC-22390, LIC-22390 and close PV-22390 - Stop LIC-22195B and Stop EH-22195 - Stop TIC-22389 and Close PV-22389 - Stop PIC-22405 and close PV-22405 - Stop PIC-22436 and close PV-22436 - Stop PIC-22456 and close PV-22456 - Stop PIC-22476 and close PV-22476 - Stop PIC-22486 and close PV-22486 - Stop “Transient Modes Cool down line logic” - Stop "Sub Atmospheric Recovery Cool Down Line Logic"	

All Cold Box control loops are stopped and all automatic valves are in their failure position

The Cold Box can be warmed –up manually.

Note: The operator may also want to leave the cold box in cold conditions (for a quick restart operation). In this case, he will open manually all required valves to allow gas expansion in internal lines toward the cool down line (refer to associated Manual operation procedure).

Note: All actions in step X600 shall be latched so that valves can be opened by the operator when Cold Box Cool Down sequence is not started.

10.5 COLD BOX COOL DOWN – TRIP / EMERGENCY STOP

The Cold Box TRIP / Emergency Stop can either be launched by:

- A Cold Box Trip order (refer to the Alarm, Interlock and Trip list)
- The activation of an Emergency switch on the system.

The Cold Box TRIP / Emergency Stop will:

- Force all auxiliary sequences in their initial step (Except the Vacuum Sequence).
- Stop and reset all the control loops,
- Turn all Cold Boxes actuators in their failure position (Except Vacuum skids actuators).

Cold Box Cool Down – Trip / Stop

600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610, 620, 621, 622, 623, 624 - Cold Box General Trip / Emergency Stop

↓

X600	- Stop TIC-22485, PIC-22485 and Close PV-22485 - Stop TIC-22400 - Close PV-22400 - Close PV-22402 - Stop LIC-22520 and close PV-22520 - Close PV-22421 - Close PV-22415A / PV-22415B - Close PV-22420A / PV-22420B - Stop TIC-22418A/B and stop EHTR-22418A/B - Close PV-22460 - Close PV-22461 / PV-22466 - Stop TIC-22465 and stop EHTR-22465 - Stop PIC-22193 and Close PV-22193 - Stop PIC-22390, LIC-22390 and close PV-22390 - Stop LIC-22195B and Stop EH-22195 - Stop TIC-22389 and Close PV-22389 - Stop PIC-22405 and close PV-22405 - Stop PIC-22436 and close PV-22436 - Stop PIC-22456 and close PV-22456 - Stop PIC-22476 and close PV-22476 - Stop PIC-22486 and close PV-22486 - Stop “Transient Modes Cool down line logic” - Stop "Sub Atmospheric Recovery Cool Down Line Logic"	

Note: All actions in step X600 shall be latched so that valves can be opened by the operator when Cold Box Cool Down sequence is not started.

11. SEQUENCE 650 - LHE DEWAR CONNECTION MANAGEMENT

This sequence controls the connection of the Dewar with the cold box during the Cold Box Cool Down.

This sequence monitors the temperature difference between the Dewar and the Cold Box to connect the Dewar at the right time. It also adapts the opening of the subcooler during the cool down, depending on the opening condition of the Dewar. This will ensure that not too much flow is sent in the Cold Box.

11.1 LHE DEWAR CONNECTION MANAGEMENT – START

LHE DEWAR CONNECTION

650 ↓	- “LHe Dewar connection” start order And - Sequence 600 in either of steps X603 to X610.	*Operator Order from HMI* *And* *Cool down sequence in appropriate step*

The subcooler is already connected in the Cold Box in Step X602.

The Dewar is slowly connected to the cold-box. Indeed, the CB and LHe storage can be at cryogenic temperature while the connection line is warm. (A few hours without gas circulation can warm the line up to ambient temperature).

X651	- Close PV-22393, PV-22194 and PV-22195 if: - PT-22100 > 1.2 atm - Close PV-22393 if: - PT-31000 >1.6 atm - Close PV-22195 at 5% if: - TT-22195 < 80K **<u>Else:</u>** - Open Dewar Vapor return valve PV-22194 at 100% - Open Dewar LHe return valve PV-22195 at 100% - Open Dewar supply valve PV-22393 at 20%	*Ramp 5 %/s* *Ramp 5 %/s* *Ramp 5 %/s* *Opening Ramp 0.05%/s* *Opening Ramp 0.05%/s* *Opening Ramp 0.01%/s*

The conditions on PT-22100 and PT-31000 will help avoiding a fast vaporization of LHe during the connection.

Note: The temperature of the Dewar is regarded all along the sequence and drives the opening of PV-22195

- *If the Dewar is warm, PV-22195 can be opened to help cold gas circulation in the Dewar*
- *If the Dewar is cold, this valve does not require to be opened to more than 5%. The small opening allows maintaining the valve cold and limits the transfer of LHe (if any) to the Subcooler.*
- *If the Dewar is cold, the sequence will move down to the following Steps. These precautions prevents any issue until the sequence reaches the appropriate step.*

651 ↓	- PV-22393 opening >15% - PT-31000 < 1.3 atm - PV-22194 at 100%	*LHe Dewar is connected* *LHe Dewar is depressurized*
X652	- Start Dewar pressure control loop PIC-22194 - PV-22195 closed at 5% if: else freeze in place - TT-22195 < 80K - Continue Opening Dewar supply valve PV-22393 at 20%	*Set Point = PT-31000 then Ramp 0.05 atm/min to 1.5 atm* *Ramp 5 %/s* *Opening Ramp 0.01%/s*
652 ↓	- TT-22466 < 19K	*Same condition that transition 607 in Cold Box cool down sequence*
X653	- Start PIC-22393 *(Turbine 4 Discharge pressure using Dewar supply valve – Refer Section 4.8.3)*	*Set Point = PT-22393 then Ramp 0.05 atm/min to 3.25 atm*
653 ↓	- TT-22194 < 6K - LT-31000 > 10% - All Set points ramped to their nominal values.	*Dewar is at Liquid Helium Temperature* *Enough Level in the Dewar to start Subcooler level main Control loop*
X654	- Start Dewar level control LIC-31000 - Set a minimum opening of PV-22195 at 5% - If LT-31000 > 25% then Start LIC-22195A - Initial Set Point = LT-22195A - Then Ramp Set Point to 70%	*(Refer section 4.10.5)* *Ramp 0.1 %/min*

Step X654 is the nominal step of this sequence.

11.2 LHE DEWAR CONNECTION MANAGEMENT – STOP

LHE DEWAR CONNECTION STOP

651, 652, 653, 654, ↓	- "LHe Dewar connection" stop order	From Cold Box Cool Down sequence – Step X621
X655	- Stop LIC-22195A and Close PV-22195 - Stop LIC-31000 and Stop Dewar Heaters - Start PIC-31020	Ramp 5%/s Set Point = PT-3100 then ramp at 0.001 atm/min to 1.2 atm
655 ↓	- PV-22195 closed	
X656	- Stop PIC-22393 and close PV-22393	Ramp 0.5%/s
656 ↓	- PV-22393 closed - PV-22195 closed	
X650	- Stop PIC-22194 and closed PV-22194 - Stop PIC-22393 and close PV-22393 - Stop LIC-22195A and Close PV-22195 - Stop LIC-31000 and Stop Dewar Heaters	

11.3 LHE DEWAR CONNECTION MANAGEMENT – TRIP / EMERGENCY STOP

LHE DEWAR CONNECTION STOP

651, 652, 653, 654, 655, 656, ↓	- Cold Box General Trip / Emergency Stop	
X650	- Stop PIC-22194 and closed PV-22194 - Stop PIC-22393 and close PV-22393 - Stop LIC-22195A and Close PV-22195 - Stop LIC-31000 and Stop Dewar Heaters	

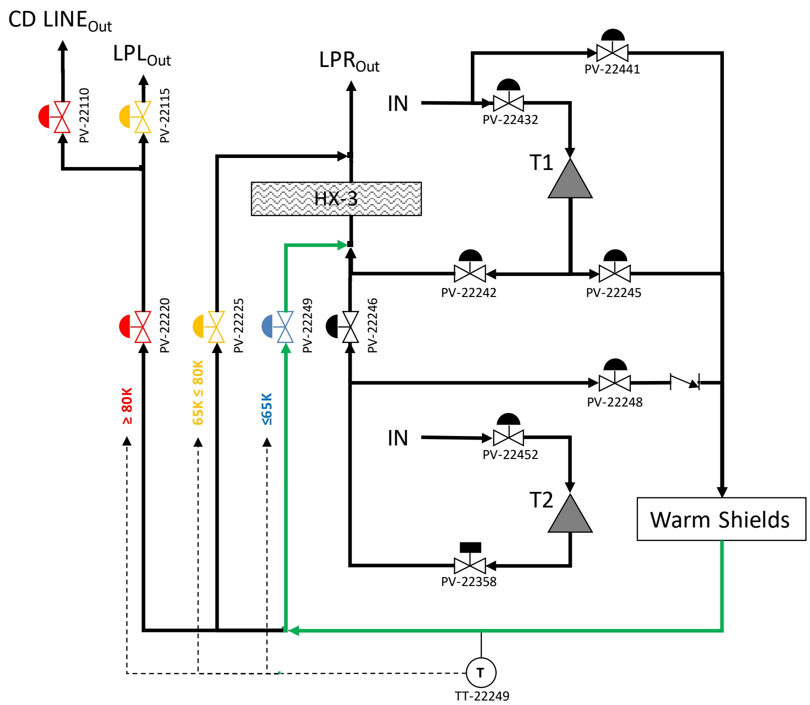
12. SEQUENCE 700 - WARM SHIELDS

12.1 WARM SHIELDS - FLOW RETURN LOGIC

The temperature returned from the warm Shields will vary:

- During shields cool down, it will go from 300K down to the nominal temperature ~50K.
- During shields warm-up, temperature will rise up again.

Therefore, the return line is equipped with three valves allowing the distribution of the gas at the appropriated temperature level in the cold box. The logic will act during the warm shields cool down and warm-up sequences.



Valve	Opening Speed	Closing Speed	Opening Condition
PV-22110	5%/sec	10%/sec	• PV-22220 Opened • PV-22115 Closed
PV-22115	2%/sec	10%/sec	• PV-22220 Opened • Not opening condition for PV22135 & PV22140 & PV22150 & PV22160 & PV22180 & PV22190
PV-22220	5%/sec	10%/sec	• TT-22249 > 80K
PV-22225	5%/sec	10%/sec	• 80K ≥ TT-22249 > 65K
PV-22249	5%/sec	10%/sec	• TT-22249 ≤ 65K

When the logic is lost for one valve, the valve starts to close only when the following valve opening reaches 50%.

12.2 WARM SHIELDS - START

Note: Warm Shields sequence can be started at any step of the cold box cool down sequence, but it shall not be started while the Cold Intercepts are also in Cool Down sequence. A permissive in the initial transition of the Warm Shields Cool Down prevents this sequence to start if the Cold Intercepts cool down sequence is active.

Warm Shields – Start to Nominal

700 ↓	- Cold Box Cool Down sequence in step X602 to X610 And - Cold Shields sequence in Step X800 - 4.5K Supply in step X900 - Warm Shields Start Order	Cold Shields not Started 4.5K Supply not started Switch available on the supervision
X701	- Start Flow Return Logic	*Return flow distribution as per section 12.1*
701 ↓	- PV-22220 > 50% - Or PV-22225 >50% - Or PV-22249 >50%	*Either 1 of the 3 shield return valve should be open > 50%*
X702	- Start DPIC-22441	*Ramp PIC-22441 set point from 0 atm to 2.5 atm at a speed of 0.01 atm/sec*
702 ↓	- TT-22249 ≤ 90K - Turbine 1 in Nominal operation (step X514)	
X703	- Stop DPIC-22441 - Close PV-22441	*Ramp 5%/s*
703 ↓	- PV-22441 at 0% And - PT-22245 ≤ PT-22332	*To avoid Turbine 1 Trip*
X704	- Open PV-22245 at 100% - Start DPIC-22242	*Ramp 2%/s* *Ramp PIC-22242 set point from 0 atm to 1 atm at a speed of 0.01 atm/sec*

This step is the Nominal Step for the Warm Shields

When ZSH22245 is ON, then Start DPIC-22242

If Turbine 1 stops, the sequence needs to go back to step X702 to supply the Warm Shields with PV-22441:

AND ↓	- Turbine 1 not in Nominal operation (step X514) - or PV-22245 at 0%	
X702	- Start PIC-22441	*Ramp PIC-22441 set point from 0 atm to 2.5 atm at a speed of 0.01 atm/sec*

12.3 WARM SHIELDS - STOP

Warm Shields - Stop

701, 702
703, 704
↓ - Warm Shields Stop Order

X705	- Stop DPIC-22441 - Close PV-22441 - Stop DPIC-22242 - If Sequence 510 not in Step X500 Open PV-22242 - Close PV-22245 and PV-22248 - Close PV-22249 & PV-22225 - Open PV-22220 - Start Timer 30 minutes	 *Ramp 5%/s* *Ramp 5%/s* *Ramp 5%/s* Ramp 5%/s *Ramp 5%/s* *Allow gas expansion in Shields return line.*

If sequence is in X514 - T1 Nominal state

Close PV-22245 only if PV-22242 is fully open to 100% and ZSH22242 is ON.
This will prevent T1 trip.

705
↓ - End of Timer 30 minutes

X700	- Close PV-22220 - Stop DPIC-22441 - Close PV-22441 - Stop DPIC-22242 - If Sequence 510 not in Step X500 Open PV-22242 - Open PV-22246 - Close PV-22245 and PV-22248 - Stop Flow Return Logic - Close PV-22249 & PV-22225	 *Just in case it is not already fully open*

Not useful as it is covered in X705

Step 700 corresponds to the initial step for the Warm Shields.

Step 705 is a “Normal Stop” step before returning to initial step. It allows opening PV-22220 during 30 minutes to allow gas expansion exhaust in the shields return line.

12.4 WARM SHIELDS – TRIP / EMERGENCY STOP

During a General Cold Box trip or an Emergency Stop, the sequence would go directly back to step 700.

Warm Shields – Trip / Emergency Stop

701, 702, 703, 704, 705 ↓ - Cold Box General Trip / Emergency Stop

X700	- Close PV-22220 - Stop DPIC-22441 - Close PV-22441 - Stop DPIC-22242 - If Sequence 510 not in Step X500 Open PV-22242 - Open PV-22246 - Close PV-22245 and PV-22248 - Stop Flow Return Logic - Close PV-22249 & PV-22225	

Not required as - warm shield is only possible with Cold Box General Trip which trips the Turbine 1 as well.

13. SEQUENCE 800 - COLD INTERCEPTS

13.1 COLD INTERCEPTS - START

Note: Cold Shields sequence can only be started when Cold Box is in Nominal Mode.

The Cold Shields can be cooled down simultaneously with the Warm Shields only if warm shields return temperature is below 70K.

In this mode, the Cool down Line is also in Nominal Mode. The gas returning from the Cold Shields will be returned at the appropriate level of Temperature, in the Cold Box.

Cold Intercepts – Start		
800 ↓	- Cold Box Cool Down sequence in step 608, 609 or 610 and PT-22393 < 4atm - TT-22249 < 80K & PV-22220 closed - Cold Shields Start Order - Cool Down Line logic active	*Cold Box Cold end pressure shall be controlled and low enough to allow cold intercept opening* *When TT-22249 <80K (in steps 702 to 704 of Warm Shields), and PV-22220 is closed, it shall be possible to start cold intercept cool-down*
X801	- Open PV-22192 at 20%	*Ramp 1%/s*
801 ↓	- PV-22192 at 20% - PT-22191 < 1.4 atm	
X802	- Start Cold Shields Temperature control TIC-22392 - Start Turbine 4 discharge pressure auxiliary control PIC-22392 with initial output at 100%	*See section 4.12.3* *See section 4.8.5*
802 ↓	- TT-22191 < 10K	
X803	- Open PV-22191 at 20%	*Ramp 0.5%/s*
803 ↓	- PV-22191 at 20%	
X804	- Close PV-22192 at 0%	*Ramp 2%/s*
804 ↓	- PV-22192 at 0%	
X805	- Start Cold Shields Pressure control PIC-22191	*See section 4.12.2*

This step is the Nominal Step for the Cold Shields

13.2 COLD INTERCEPTS - STOP

Cold Intercepts - Stop		
801, 802 803, 804 805 ↓	- Cold Shields Stop Order	*From the Operator on HMI or from Cold Box Stop Sequence*
X806	- Stop Cold Shields Temperature Regulation TIC-22392 - Stop Turbine 4 discharge pressure auxiliary control PIC-22392 - Close PV-22392 at 0% - Stop Cold Shields Pressure Regulation PIC-22191 - Close PV-22191 at 0% - Open PV-22192 at 30% - Timer 30 min	*Ramp 5%/s* *Ramp 0.5%/s* *Ramp 0.5%/s*
807 ↓	- End of Timer 30 minutes	
X800	- Stop Cold Shields Temperature Regulation TIC-22392 - Stop Turbine 4 discharge pressure auxiliary control PIC-22392 - Close PV-22392 at 0% - Stop Cold Shields Pressure Regulation PIC-22191 - Close PV-22191 at 0% - Open PV-22192 at 0% Close?	

Step 800 corresponds to the initial step for the Cold Shields.

Step 806 is a "Normal Stop" step before returning to initial step. It allows opening PV-22192 during 30 minutes to allow gas expansion exhaust in the shields return line.

13.3 COLD INTERCEPTS – TRIP / EMERGENCY STOP

During a General Cold Box trip or an Emergency Stop, the sequence would go directly back to step 800.

Cold Intercepts – Trip / Emergency Stop

801, 802 803, 804 805, 806 ↓	- Cold Box General Trip / Emergency Stop	
X800	- Stop Cold Shields Temperature Regulation TIC-22392 - Stop Turbine 4 discharge pressure auxiliary control PIC-22392 - Close PV-22392 at 0% - Stop Cold Shields Pressure Regulation PIC-22191 - Close PV-22191 at 0% - Open PV-22192 at 0%	

Close?

14. SEQUENCE 900 - 4.5K SUPPLY

Note: 4.5K Supply sequence can only be started when Cold Box is in Nominal Mode. The 4.5K Supply will not be cooled down simultaneously with the Warm Shields.

In this mode, the Cool down Line is also in Nominal Mode. The gas returning from the 2K Cold Box cool down will be returned at the appropriate level of Temperature, in the Cold Box.

14.1 4.5K SUPPLY - START

4.5K Supply – Start

900 ↓	- Cold Box Cool Down sequence in step 608, 609 or 610 and PT-22393 < 4atm - TT-22249 < 80K & PV-22220 closed - 4.5K Supply Start Order	*Cold Box Cold end pressure shall be controlled and low enough to allow cold 4.5K supply line to open* *When TT22249 <80K (in steps 702 to 704 of Warm Shields), and PV-22220 is closed, it shall be possible to start cold intercept cool-down*
X901	- Open PV-22391 at 100% - Start Cool Down Line Logic for Sub Atmospheric Recovery -Stop "Transient Modes Cool Down Line Logic"	*Ramp 0.5%/s* *Refer to Section 5*
901 ↓	- PV-22391 at 100%	
902	- Start Turbine 4 discharge pressure auxiliary control PIC-22391 with initial output at 100% and Set Point at 2.7 atm	See Section 4.8.7

This step is the Nominal Step for the 4.5K Supply

14.2 4.5K SUPPLY - STOP

4.5K Supply - Stop

901, 902 ↓	- 4.5K Supply Stop Order OR - Cold Box stop Order	
X905	- Stop Turbine 4 discharge pressure auxiliary control PIC-22391 - Close PV-22391	*Ramp 5%/s*
905 ↓	- PV-22391 closed	
X900	- Stop Turbine 4 discharge pressure auxiliary control PIC-22391 - Close PV-22391 at 0% - Stop Cool Down Line Logic for Sub Atmospheric Recovery	

14.3 4.5K SUPPLY – TRIP / EMERGENCY STOP

4.5K Supply – Trip / Emergency Stop

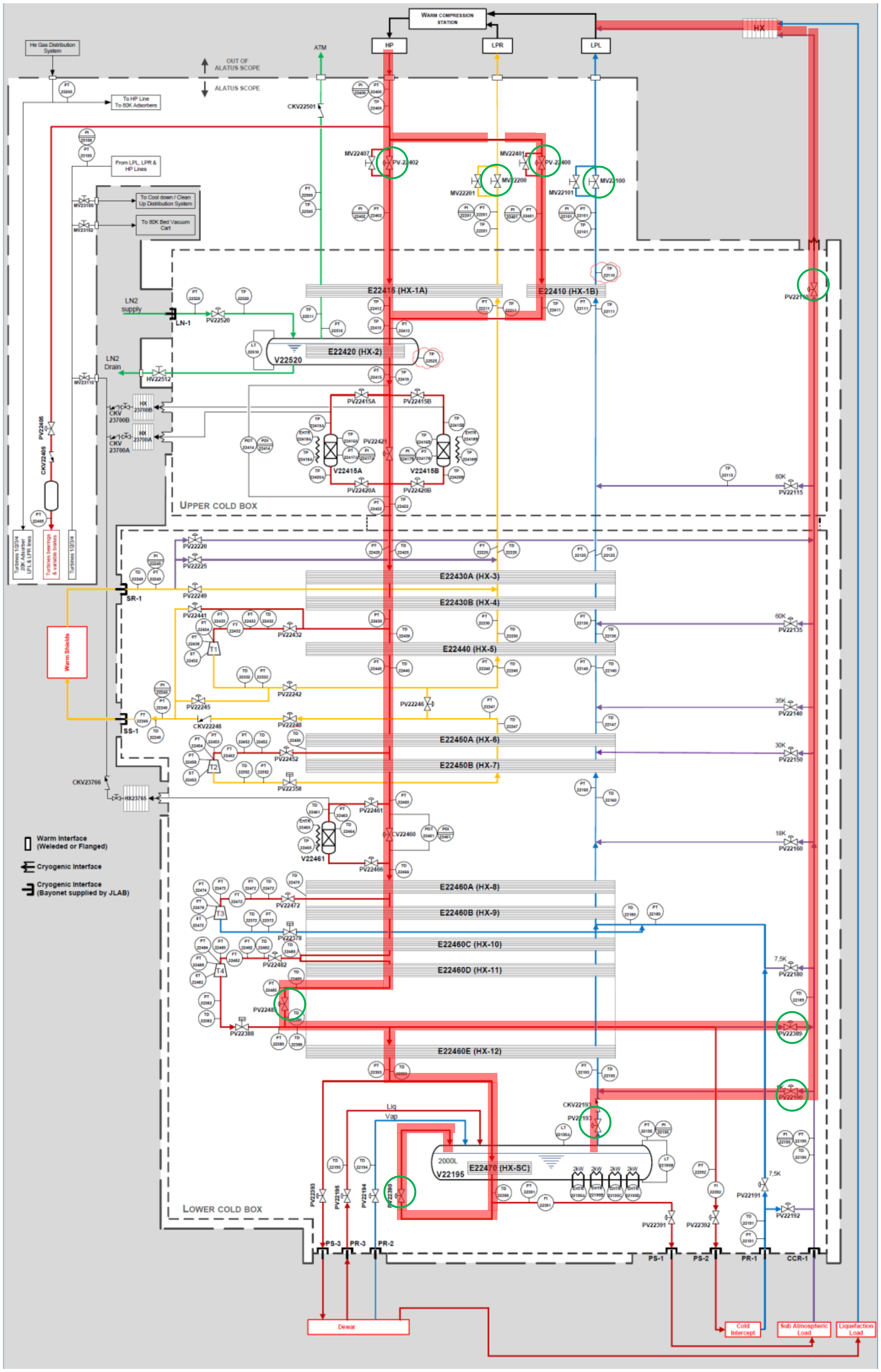
901, 902 ↓	- Cold Box General Trip / Emergency Stop	
X900	- Stop Turbine 4 discharge pressure auxiliary control PIC-22391 - Close PV-22391 at 0%	

15. MANUAL OPERATION - WARM-UP

15.1 WARM-UP - PRE REQUISITS

- All the utilities are available (compressed air, water, electricity).
- The compression station is in nominal operation.
- Cold Box stopped sequence completed → Step X600
- Automatic valves are in manual mode and in their failure position (control loop associated).
- All Control loops Stopped.
- No fault is displayed or in progress.
- Turbines bearings valves open.

15.2 WARM-UP - DIAGRAM



15.3 WARM-UP – PROCEDURE

Only the Turbines bearing pressure control loop shall be maintained during this sequence to protect the turbines against any mistaken opening of inlet or outlet valves while Cold Box lines are under pressure.

WARM-UP Manual Procedure

↓
- Check that Turbines Inlet and Outlet valves are closed.
- Check that Turbines bearings are operating properly.
- Check that MV-22200 & MV-22100 are open (ZSH-22200 & ZSH-22100 active).

Step 1	Adsorbers Depressurization, Warm-Up and Regeneration
1	For each adsorber that was used and is cold and under pressure, follow the procedures described in sections: 16.2.1 – Adsorber depressurization 16.2.2 – Adsorber warm-up 16.2.3 – Adsorber depressurization before pumping 16.2.4 – Adsorber pumping 16.2.5 – Adsorber filling

↓ 80K and 20K Adsorbers are warm, clean, and filled with Helium at 1 atm.

Step 2	LN2 Phase Separator Draining
2	If LN2 is remaining in LN2 phase separator, it must be drained before starting the Warm-up: - Drain LN2 using HV-22512

↓ - LN2 Phase separator fully drained

Step 3	Emptying LHe phase separator
3	If LHe is remaining in the Subcooler, it must be evacuated before starting the warm-up: - Close MV-22100 LPL Outlet Valve - Open PV-22110 Cool Down Line to 300K - Open PV-22190 LPL to Cool Down Line - Vaporize LHe from subcooler using EH-22195 (This will avoid sub cooling the Heat Exchangers and freezing the LPL outlet Line)

↓ - LHe Subcooler fully empty

Note: Step 1, 2 and 3 can be performed simultaneously.

Step 4	Preparation for Warm-Up
4	- Open following valves: - PV-22400 & PV-22402 at 100% — HX1a & HX1B HP Valves - PV-22421 at 100% — 80K Adsorbers by-pass - PV-22460 at 100% — 20K Adsorbers by-pass - PV-22485 at 100% — Turbine 4 by-pass - PV-22193 at 100% — Sub-Cooler outlet - PV-22191 at 100% — LPL to Cool Down Line - PV-22110 at 100% — Cool Down Line to 300K - Leave Open LPR and LPL inlet valves to allow gas expansion - MV-22100 — LPL Outlet Valve - MV-22200 — LPR Outlet Valve - Close 80K and 20K Adsorbers: - PV-22415 A/B, PV-22420 A/B — 80K Adsorbers in & out - PV-22461 and PV-22466 — 20K Adsorbers in & out

↓ All valves in position and MCS still running

Step 5	Warm Up Cold Box internals
5	Open progressively (not more than 5% steps every 10 sec to avoid Compression Station issues) - PV-22390 up to 50% — Sub-Cooler inlet - PV-22389 up to 80% — Cool Down by-pass Note: Position of PV-22390 and PV-22389 to be adjusted according to: - The Flow available from the compression station - The capacity of the Atmospheric Exchanger recovering gas from the Cool Down Line along the Continuous Warm-Up

↓ Warm up complete:

TT-22393, TT-22189 and TT-22193 > 280K.

Step 6	Stop Warm-Up and Isolate Cold Box
6	Close PV-22390 and PV22389 progressively (not more than 5% steps every 10 sec to avoid Compression Station issues) Close all valves opened in Step 3

↓ All Valves Closed.

Warm-Up is completed.

16. MANUAL OPERATION - ADSORBERS

16.1 ADSORBERS: STATE

Adsorbers operation is Manual.
The following logic is a proposal intended to help the operation team.
It may or may not be implemented by JLAB.

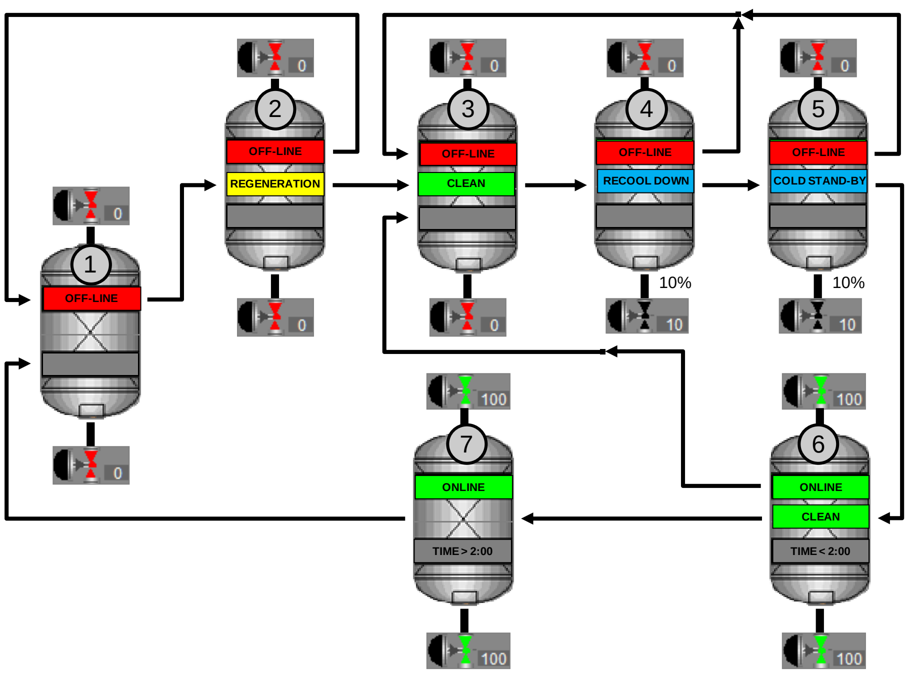
Adsorber	80K	20K
Composition	He + 5 ppm N_2+ 1 ppm O_2	He + 23 ppm Ne
Pressure	18 atm	18 atm
Temperature	80 K	18 K
Flow	1292 g/s	712 g/s
Operating Time	30 Days	Production of 20,000L of LHe

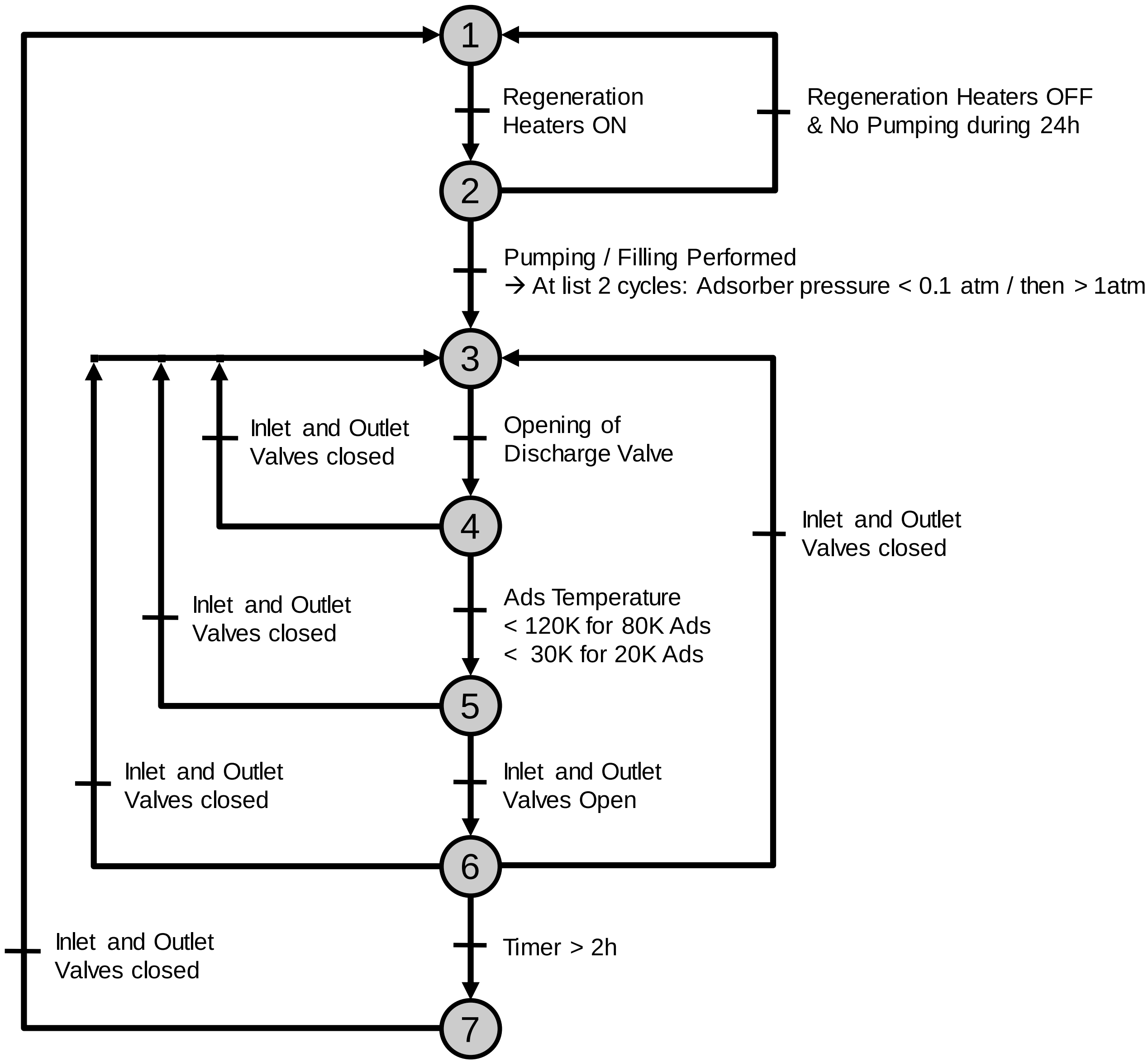
NOTE: The exact operating time can be adapted if the system is used at partial load or with an impurity content lower than the design values.

The adsorbers can be in different states depending on their temperature, the position of their inlet and outlet valves, the operation of the regeneration Heater, the duration spent online…

Adsorber State is "detected" by the program and displayed to inform the Operating Team.

The logic to switch from one state to the following one is as follows:




1
Regeneration
Heaters ON
Regeneration Heaters OFF
& No Pumping during 24h
2
Pumping / Filling Performed
→ At list 2 cycles: Adsorber pressure < 0.1 atm / then > 1atm
3
Inlet and Outlet
Valves closed
Opening of
Discharge Valve
4
Inlet and Outlet
Valves closed
Inlet and Outlet
Valves closed
Ads Temperature
< 120K for 80K Ads
< 30K for 20K Ads
5
Inlet and Outlet
Valves closed
Inlet and Outlet
Valves Open
6
Inlet and Outlet
Valves closed
Timer > 2h
7

16.2 ADSORBERS: REGENERATION MANUAL SEQUENCE

Step 1: Isolation

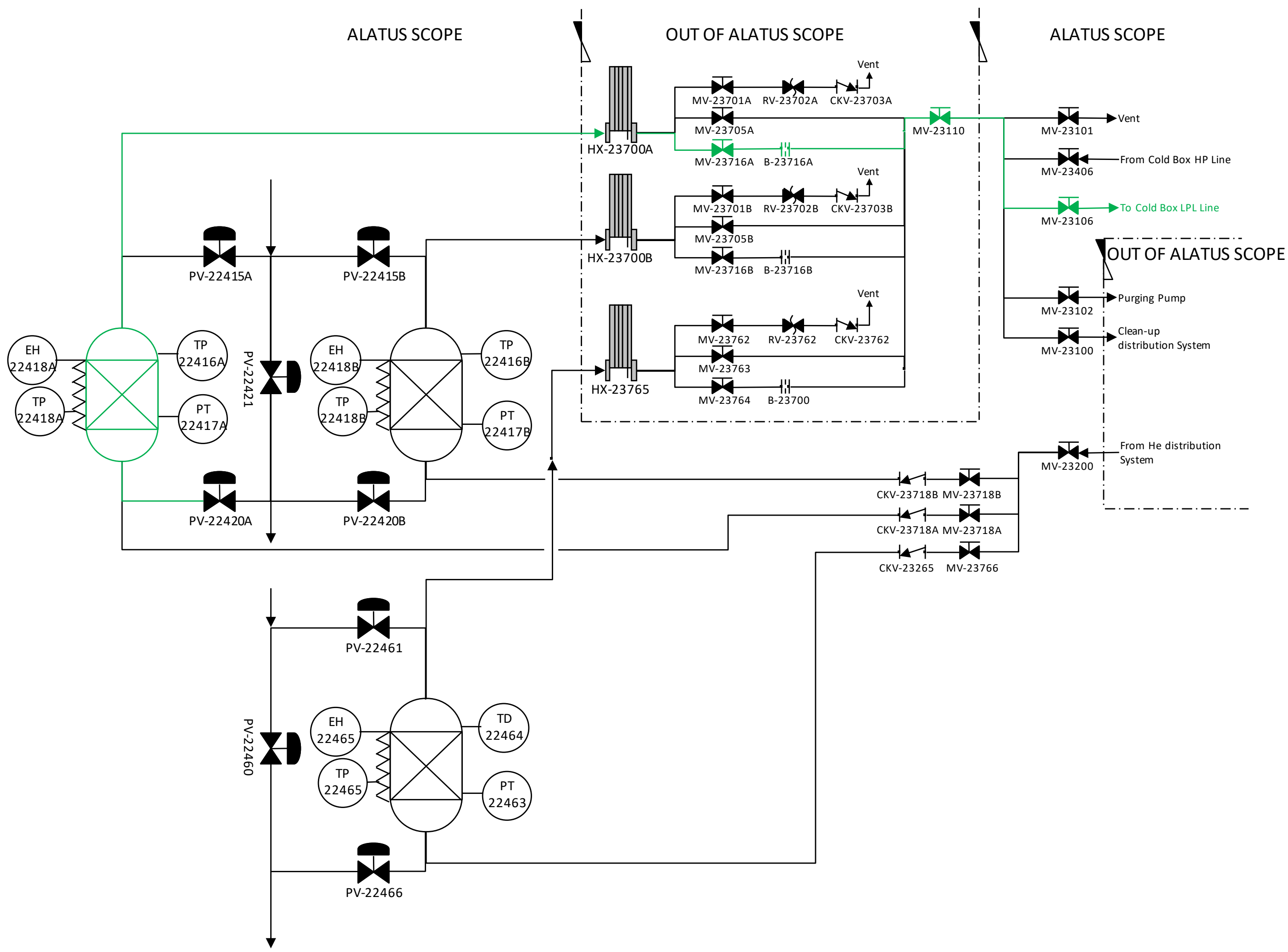
Step 2: Depressurization

Step 3: Warm-up

Step 4: Purging

Step 5: Filling/Connection

16.2.1 Adsorber depressurization



In order to limit the waste of He, adsorbers can be depressurized in the Cold Box LPL Line toward the Compression station.

→ This is allowed only if adsorber temperature is:

- Below 90K for 80K adsorbers
- Below 25K for 20K adsorber.

If temperature is higher, then it is depressurized via the clean-up distribution system to the atmosphere.

After having isolated the adsorber from the cycle (inlet and outlet process valves closed), the adsorber is depressurized by the operator to the low pressure circuit.

Note: The depressurization of the Adsorber must be smooth, using the depressurization line equipped with the orifice (JLAB scope). This is important to avoid increasing the pressure on the LPL line to the MCS, as well as the risk of fluidization of the Adsorber bed.

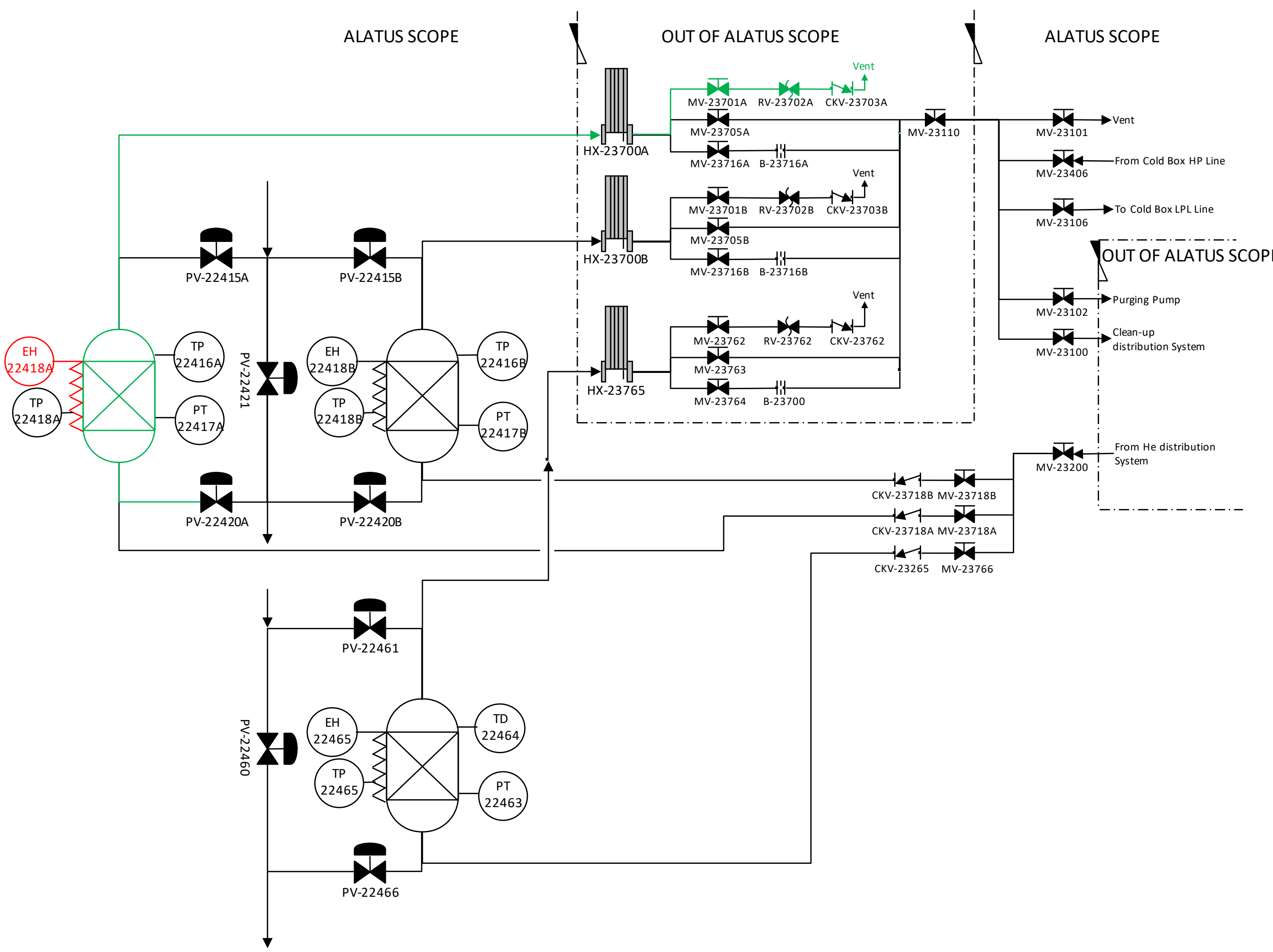
When the pressure inside the adsorbers and in the regeneration circuit is below 1,20 atm then depressurization is finished.

16.2.2 Adsorber warm-up

The adsorber is depressurized and ready for warm-up.

The electrical heater control loop shall be started from the supervision.

The pressure in the circuit will increase due to helium thermal expansion AND impurities desorption.



The operator shall open the vent valve to the atmosphere to continuously release the pressure.

The warm-up is considered completed when the internal adsorber temperature reaches:

- 200K for 80K adsorbers.
- 120K for 20K adsorber

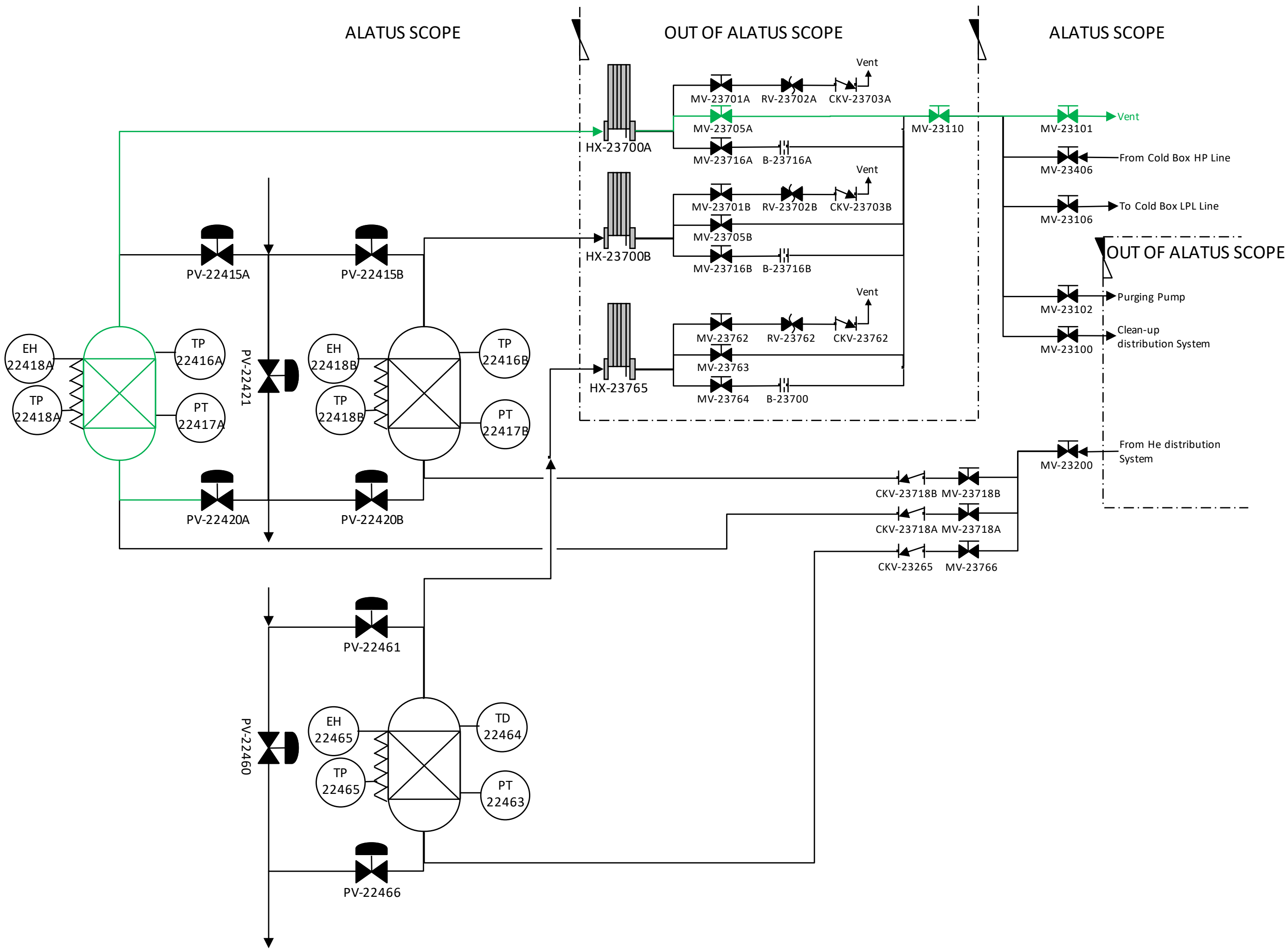
Note: Adsorber wall temperature shall be limited to 100°C (373K) to avoid insulation damage.

16.2.3 Adsorber depressurization before pumping

Regeneration Heater is stopped.

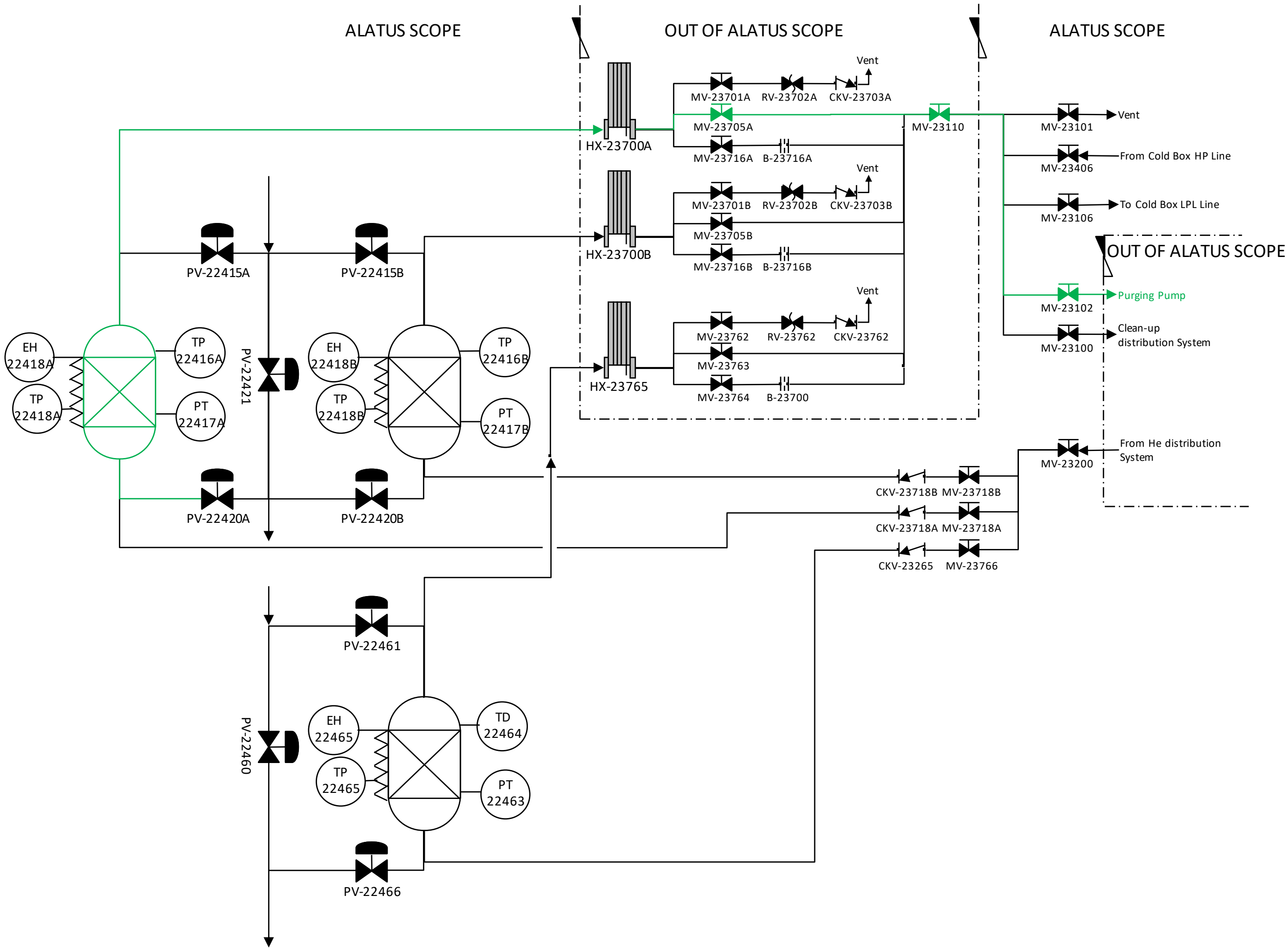
The pressure in the adsorber may be higher than 1 atm depending on the setting pressure of RV-23702A in this example. RV-23702A is 44 PSIG (4.03 Bara)

The pressure shall be decreased down to atmospheric pressure before pumping.



16.2.4 Adsorber pumping

Adsorber is depressurized, the purging pump is started.

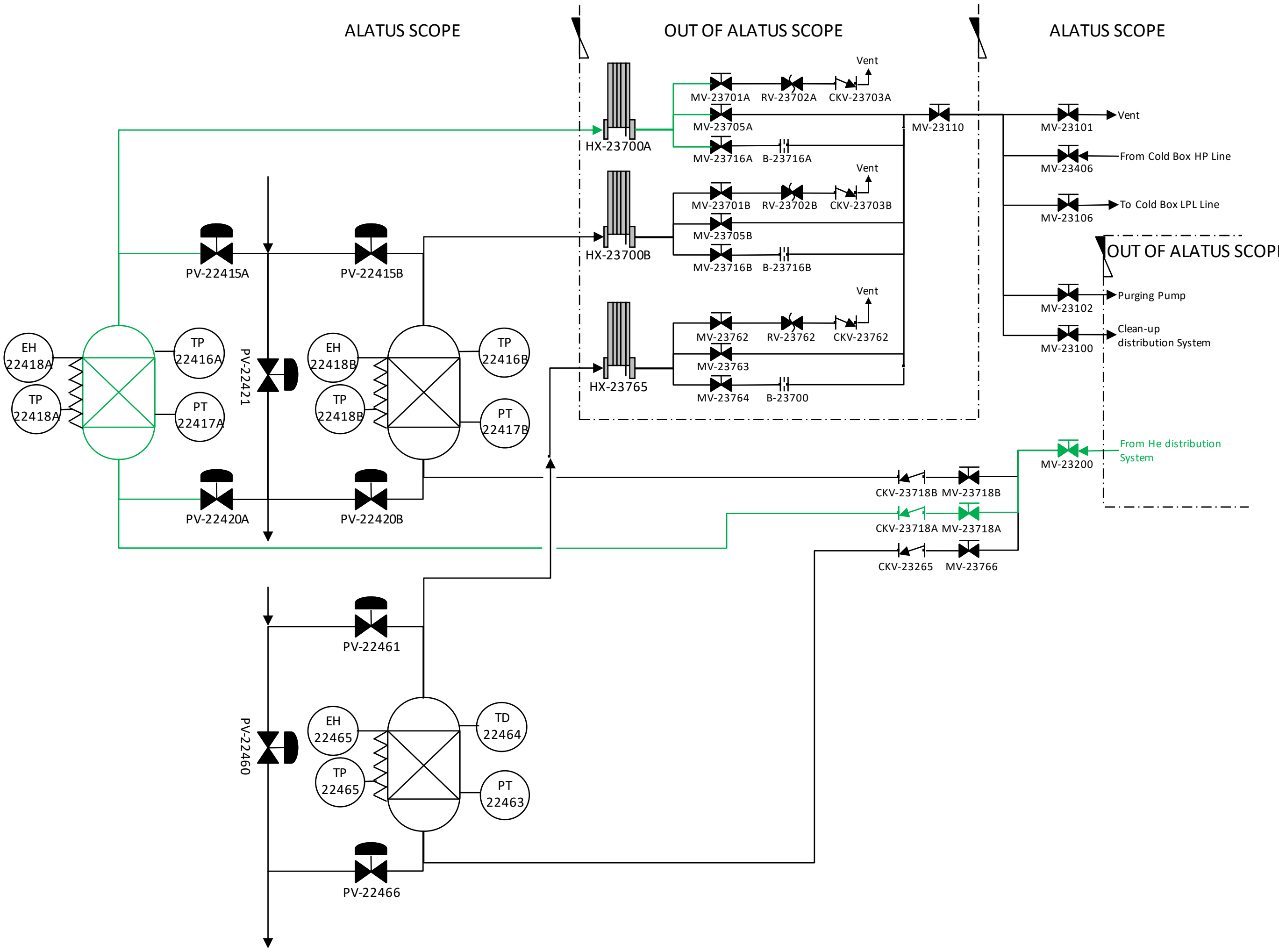


The valve to be used on the Atmospheric Heater manifold is the the unrestricted one to limit the pressure drop between the pump and the adsorber.

The pumping operation is intended to remove all impurities remaining in the adsorber.

The pressure in the adsorber at the end of the pumping phase shall be lower than 50mbar (less than 10 mbar at pump suction).

16.2.5 Adsorber filling



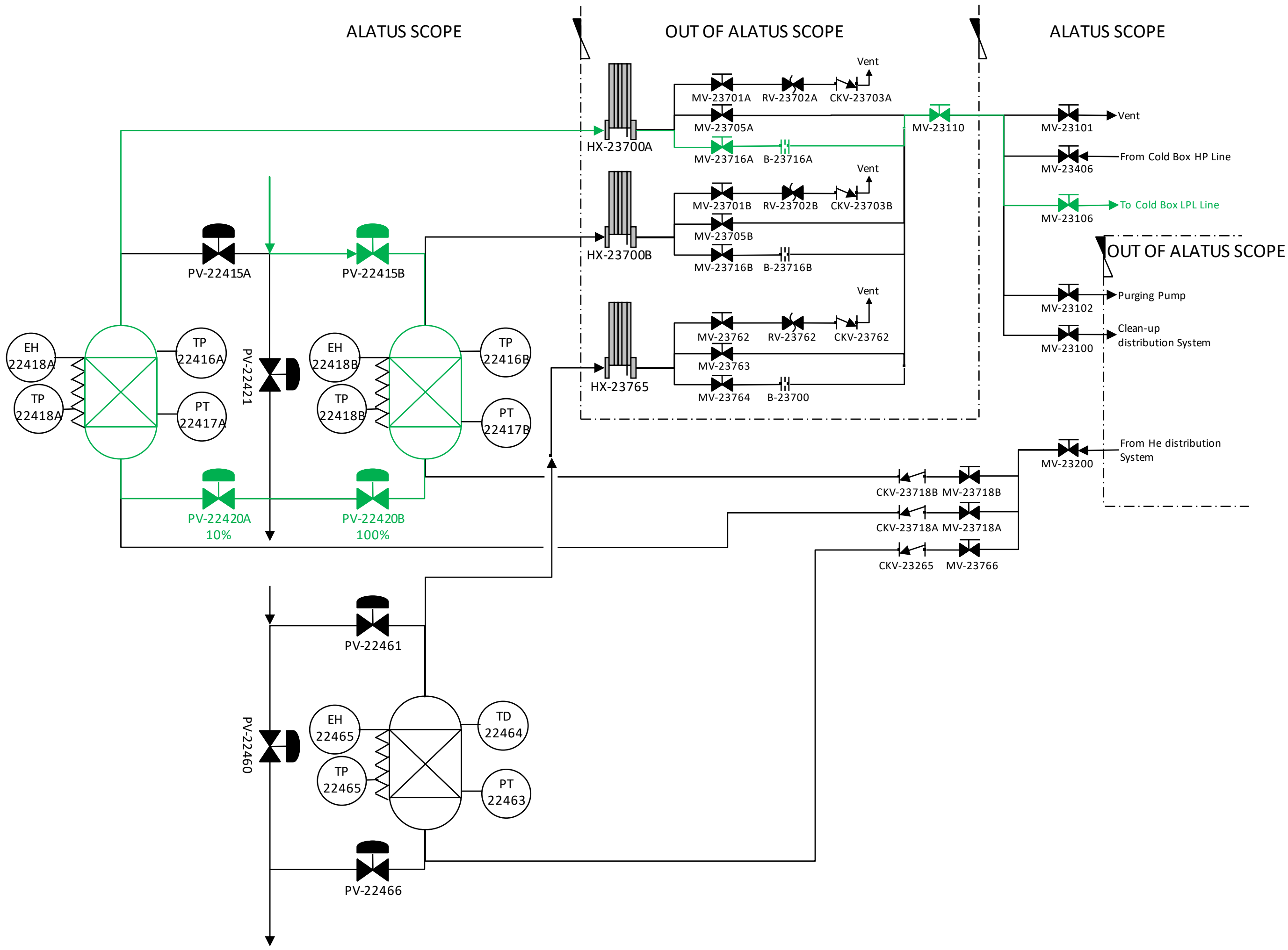
The valve to the purge pump is closed.

The filling operation is intended to fill the adsorber up to 1 atm using the 3 atm He distribution System (JLAB Scope).

Pumping + Filling cycle shall be repeated 3 times to complete the regeneration of the adsorber.

16.2.6 Adsorber re-cool down

The re-cool down of the adsorber after the regeneration is done using cold pure helium from the online adsorber (for the 80K adsorber) or from the by-pass line (for the 20K adsorber).



The discharge valve of the adsorber is open at 10%.

The cold Helium used to re-cool the adsorber is sent back to the Cold Box LPL line via the atmospheric Heater. The valve to be used on the atmospheric Heater manifold is the one associated with the restriction orifice, to help limiting the cool down flow, and maintain the pressure in the adsorber.

The re-cool down operation is completed when the temperature of the adsorber inlet temperature is as close as 2K from the outlet temperature.

JLAB: I am just double checking if we really want this way which has a potential to trip entire cold box on a faulty sensor.
I fully agree on turbine trips on sensor failure for protection.
ALATUS: Noted

17. APPENDIXE 1 – ALARMS & TRIPS LIST

General Note: The failure of a sensor associated to a trip shall trigger the Trip.

HAZOP node	Alarm / Trip Name	Type	Phase (if specified)	Sensor	Condition	Action	Message	Reset Conditions
General	-	Alarm		All	Sensor signal out of range during 2sec	Turn sensor display in red	Sensor out of range	Sensor signal back in range during 2sec
General	-	Alarm		Valves Position feedback (HART)	HART feedback position differs from Valve Position Set Point by more than 2%	Turn Valve position display in red	Valve Position discrepancy	
Utilities		Trip		PSL-23500	PSL-23500 during more than 2sec	Cold Box Cool Down Sequence 600 Trip	Air Instrument Failure on Upper Cold Box	Operator Reset and Not PSL-23500
Utilities		Trip		PSL-23550	PSL-23550 during more than 2sec	Cold Box Cool Down Sequence 600 Trip	Air Instrument Failure on Lower Cold Box	Operator Reset and Not PSL-23550
WARM LINES - PRESSURE								
#15	PT-22101HiHi	Alarm	Cold Box Cool Down Sequence NOT in Initial Step X600	PT-22101	PT-22101 > 1.3 atm		LPL Pressure High	PT-22101 < 1.2 atm
#8	PT-22201LoLo	Alarm	Cold Box Cool Down Sequence NOT in Initial Step X600	PT-22201	PT-22201 < 1.05 atm		LPR Pressure Low	PT22201 > 1.2 atm
#1	PT-22401HiHi	Alarm		PT-22401 PT-22413	PT-22401 – PT-22413 > 0.3 atm		HX-1B HP pressure drop High	PT22401 - PT22413 < 0.2 atm
#1	PT-22402HiHi	Alarm		PT-22402 PT-22413	PT22402 - PT22413 > 0.3 atm		HX-1A HP pressure drop High	PT22402 - PT22413 < 0.2 atm
#1	PT-22400AHiHi	Alarm		PT-22400 PT-22401	PT22400 - PT22401 > 0.2 atm And PV-22400 at 100%		HP inlet filters pressure drop High Or PV-22400 fails to stay Open	PT22400 - PT22401 < 0.15 atm Or PV-22400 not at 100%
#1	PT-22400BHiHi	Alarm		PT-22400 PT-22402	PT22400 - PT22402 > 0.2 atm And PV-22402 at 100%		HP inlet filters pressure drop High Or PV-22402 fails to stay Open	PT22400 - PT22402 < 0.15 atm Or PV-22402 not at 100%
WARM LINES - COLD EMBRITTLEMENT								
#1	TT-22505LoLo	Alarm		TT-22505	TT-22505 < 240 K		GN2 outlet temperature Low	TT-22505 > 250 K
#1	TT-22201LoLo	Alarm		TT-22201	TT-22201 < 240 K		LPR outlet temperature Low	TT-22201 > 250 K
#1	TT-22101LoLo	Alarm		TT-22101	TT-22101 < 240 K		LPL outlet temperature Low	TT-22101 > 250 K
ADSORBERS								
#3 #4	PDT-22414AHiHi	Alarm		PDT-22414	PV-22415A & PV-22420A open And PDT-22414 > 1.5 atm		80K Adsorber A pressure drop High	PV-22415A Or PV-22420A closed Or PDT-22414 < 1.0 atm
#3 #4	PDT-22414BHiHi	Alarm		PDT-22414	PV-22415B & PV-22420B open And PDT-22414 > 1.5 atm		80K Adsorber B pressure drop High	PV-22415B Or PV-22420B closed Or PDT-22414 < 1.0 atm
#3 #4	PDT-22461HiHi	Alarm		PDT-22461	PV-22461 & PV-22466 open And PDT-22461 > 1.5 atm		20K Adsorber pressure drop High	PV-22461 Or PV-22466 closed Or PDT-22461 < 1.0 atm

HAZOP node	Alarm / Trip Name	Type	Phase (if specified)	Sensor	Condition	Action	Message	Reset Conditions
HX DELTA TEMPERATURES								
#1	TDT-22400NHiHi	Alarm		TT-22505 & TT-22400	|TT-22400-TT-22505|>30K and LT-22510 > 25%		High Temperature difference on HX-1A Warm End N2 Stream	|TT-22400-TT-22505|<25K Or LT-22510 < 25%
#1	TDT-22400NTripHi	Trip		TT-22505 & TT-22400	|TT-22400-TT-22505|>50K and LT-22510 > 25%	Cold Box Cool Down Sequence 600 Trip	Too High Temperature difference on HX-1A Warm End N2 Stream	Operator Reset and Or |TT-22400-TT-22505|<40K Or LT-22510 < 25%
#1	TDT-22400MHiHi	Alarm		TT-22201 & TT-22400	|TT-22400-TT-22201|>30K and Or Turbine 1 Sequence not in step X510 Or Turbine 2 Sequence not in step X520 Or Warm Shields Sequence not in step X700		High Temperature difference on HX-1A Warm End LPR Stream	|TT-22400-TT-22201|<25K Or And Turbine 1 Sequence in step X510 And Turbine 2 Sequence in step X520 And Warm Shields Sequence in step X700
#1	TDT-22400MTripHi	Trip		TT-22201 & TT-22400	|TT-22400-TT-22201|>50K and Or Turbine 1 Sequence not in step X510 Or Turbine 2 Sequence not in step X520 Or Warm Shields Sequence not in step X700	Cold Box Cool Down Sequence 600 Trip	Too High Temperature difference on HX-1A Warm End LPR Stream	Operator Reset and |TT-22400-TT-22201|<40K Or And Turbine 1 Sequence in step X510 And Turbine 2 Sequence in step X520 And Warm Shields Sequence in step X700
#1	TDT-22400LHiHi	Alarm		TT-22101 & TT-22400	|TT-22400-TT-22101|>30K and Or Turbine 3 Sequence not in step X530 Or PV-22193 >0%, Or PV-22115>0% Or PV-22135 >0%, Or PV-22140>0% Or PV-22150 >0%, Or PV-22160 >0% Or PV-22180 >0%, Or PV-22190>0%		High Temperature difference on HX-1B Warm End LPL Stream	|TT-22400-TT-22101|<25K Or And Turbine 3 Sequence in step X530 And PV-22193=0%, And PV-22115=0% And PV-22135=0%, And PV-22140=0% And PV-22150=0%, And PV-22160=0% And PV-22180=0%, And PV-22190=0%
#1	TDT-22400LTripHi	Trip		TT-22101 & TT-22400	|TT-22400-TT-22101|>50K and Or Turbine 3 Sequence not in step X530 Or PV-22193 >0%, Or PV-22115>0% Or PV-22135 >0%, Or PV-22140>0% Or PV-22150 >0%, Or PV-22160 >0% Or PV-22180 >0%, Or PV-22190>0%	Cold Box Cool Down Sequence 600 Trip	Too High Temperature difference on HX-1B Warm End LPL Stream	Operator Reset And Or |TT-22400-TT-22101|<40K Or And Turbine 3 Sequence in step X530 And PV-22193=0%, And PV-22115=0% And PV-22135=0%, And PV-22140=0% And PV-22150=0%, And PV-22160=0% And PV-22180=0%, And PV-22190=0%
#1	TDT-22412NHiHi	Alarm		TT-22511 & TT-22412	|TT-22412-TT-22511|>30K and LT-22510 > 25%		High Temperature difference on HX-1A Cold End N2 Stream	|TT-22412-TT-22511|<25K Or LT-22510 < 25%
#1	TDT-22412NTripHi	Trip		TT-22511 & TT-22412	|TT-22412-TT-22511|>50K and LT-22510 > 25%	Cold Box Cool Down Sequence 600 Trip	Too High Temperature difference on HX-1A Cold End N2 Stream	Operator Reset and Or |TT-22412-TT-22511|<40K Or LT-22510 < 25%

HAZOP node	Alarm / Trip Name	Type	Phase (if specified)	Sensor	Condition	Action	Message	Reset Conditions
#1	TDT-22412MHiHi	Alarm		TT-22211 & TT-22412	|TT-22412-TT-22211|>30K and Or Turbine 1 Sequence not in step X510 Or Turbine 2 Sequence not in step X520 Or Warm Shields Sequence not in step X700		High Temperature difference on HX-1A Cold End LPR Stream	|TT-22412-TT-22211|<25K Or And Turbine 1 Sequence in step X510 And Turbine 2 Sequence in step X520 And Warm Shields Sequence in step X700
#1	TDT-22412MTripHi	Trip		TT-22211 & TT-22412	|TT-22412-TT-22211|>50K and Or Turbine 1 Sequence not in step X510 Or Turbine 2 Sequence not in step X520 Or Warm Shields Sequence not in step X700	Cold Box Cool Down Sequence 600 Trip	Too High Temperature difference on HX-1A Cold End LPR Stream	Operator Reset And Or |TT-22412-TT-22211|<40K Or And Turbine 1 Sequence in step X510 And Turbine 2 Sequence in step X520 And Warm Shields Sequence in step X700
#1	TDT-22411LHiHi	Alarm		TT-22111 & TT-22411	|TT-22411-TT-22111|>30K and Or Turbine 3 Sequence not in step X530 Or PV-22193 >0%, Or PV-22115>0% Or PV-22135 >0%, Or PV-22140>0% Or PV-22150 >0%, Or PV-22160 >0% Or PV-22180 >0%, Or PV-22190>0%		High Temperature difference on HX-1B Cold End LPL Stream	|TT-22411-TT-22111|<25K Or And Turbine 3 Sequence in step X530 And PV-22193=0%, And PV-22115=0% And PV-22135=0%, And PV-22140=0% And PV-22150=0%, And PV-22160=0% And PV-22180=0%, And PV-22190=0%
#1	TDT-22411LTripHi	Trip		TT-22111 & TT-22411	|TT-22411-TT-22111|>50K and Or Turbine 3 Sequence not in step X530 Or PV-22193 >0%, Or PV-22115>0% Or PV-22135 >0%, Or PV-22140>0% Or PV-22150 >0%, Or PV-22160 >0% Or PV-22180 >0%, Or PV-22190>0%	Cold Box Cool Down Sequence 600 Trip	Too High Temperature difference on HX-1B Cold End LPL Stream	Operator Reset And Or |TT-22111-TT-22111|<40K Or And Turbine 3 Sequence in step X530 And PV-22193=0%, And PV-22115=0% And PV-22135=0%, And PV-22140=0% And PV-22150=0%, And PV-22160=0% And PV-22180=0%, And PV-22190=0%
#1	TT-22413HiHi	Alarm		TT-22413 & LT-22510	TT-22413 > 120K and LT-22510 > 25%		High Temperature difference on HX-2	TT-22413 < 110K or LT-22510 < 20%
#1	TT-22413TripHi	Trip		TT-22413 & LT-22510	TT-22413 > 130K and LT-22510 > 25%	Cold Box Cool Down Sequence 600 Trip	High Temperature difference on HX-2	Operator Reset And Or TT-22413 < 110K Or LT-22510 < 20%
#13	TDT-22393HiHi	Alarm		TT-22393 & TT-22193	|TT-22393-TT-22193| > 30K		High Temperature difference on HX-12 Cold End	(TT-22393-TT-22193) < 25K
#13	TDT-22393TripHi	Trip		TT-22393 & TT-22193	|TT-22393-TT-22193| > 50K	Cold Box Cool Down Sequence 600 Trip	Too High Temperature difference on HX-12 Cold End	Operator Reset and (TT-22393-TT-22193) < 25K

HAZOP node	Alarm / Trip Name	Type	Phase (if specified)	Sensor	Condition	Action	Message	Reset Conditions
LN2 PHASE SEPARATOR								
#1	LT-22510LoLo	Alarm	LIC-22520 ON for more than 1h	LT-22510	LT-22510 < 50%		LN2 Level Low	LT-22510 > 60%
COLD BOX COLD END								
#14	TT-22390HiHi	Alarm	Cold Box Cool Down Sequence in Nominal Step X610	TT-22390	TT-22390 > 6K		Temperature to 4.5K Supply High	TT-22390 < 5K
#13	PT-22391LoLo	Alarm	Cold Box Cool Down Sequence in Nominal Step X610	PT-22391	PT-22391 < 2.8 Atm		Pressure in 4.5K supply line Low	PT-22391 > 3 Atm
#13	PT-22392LoLo	Alarm	Cold Box Cool Down Sequence in Nominal Step X610	PT-22392	PT-22392 < 2.8 Atm		Pressure in Cold Intercept supply line Low	PT-22392 > 3 Atm
#13	PT-22393LoLo	Alarm	Cold Box Cool Down Sequence in Nominal Step X610	PT-22393	PT-22393 < 2.8 Atm		Pressure in Dewar supply line Low	PT-22393 > 3 Atm
LHE SUBCOOLER								
#13	LT-22195ALoLo	Alarm	Cold Box Cool Down Sequence in Nominal Step X610	LT-22195A	LT-22195A < 15%		Level in LHe subcooler Low	LT-22195A > 25%
#14	LT-22195AErr	Alarm		LT-22195A & LT-22195B	LT-22195B > 5% and LT-22195A < 90%		Discrepancy between LT-22195A and LT-22195B	LT-22195A > 95% OR LT-22195B<5% During 1 minute
#13 & #14	PT-22195HiHi	Alarm	Cold Box Cool Down Sequence in Nominal Step X610	PT-22195	PT-22195 > 1.5 atm		Pressure in Subcooler High	PT-22195 < 1.3 atm
Dewar								
LT-31000LoLo Alarm:				LT-31000	LT-31000 < 10% AND X654		Level in Dewar Low	LT-31000 > 25% or NOT X654
PT-31005HiHi Alarm:				PT-31005	PT-31005 > 1.7 bar AND X654		Pressure in Dewar High	PT-31005< 1.5bar or NOT X654

HAZOP node	Alarm / Trip Name	Type	Phase (if specified)	Sensor	Condition	Action	Message	Reset Conditions
Turbine 1								
#6	PT-22432HiHi	Alarm		PT-22432	PT-22432 > 19.01 atm		Turbine 1 inlet pressure high	PT-22432 < 18 atm
#6	PT-22432TripHi	Trip		PT-22432	PT-22432 > 19.46 atm	Turbine 1 Trip	Turbine 1 inlet pressure too high	Operator Reset and PT-22432 < 18 atm
#6	PT-22332LoLo	Alarm	Turbine 1 sequence not in step X510	PT-22332	PT-22332 < 1.11 atm		Turbine 1 discharge pressure low	PT-22332 > 1.2 atm
#6	PT-22332TripLo	Trip	Turbine 1 sequence not in step X510	PT-22332	PT-22332 < 1.04 atm	Turbine 1 Trip	Turbine 1 discharge pressure too low	Operator Reset and PT-22332 > 1.2 atm
#6	PT-22332HiHi	Alarm		PT-22332	PT-22332 > 4.32 atm		Turbine 1 discharge pressure high	PT-22332 < 4 atm
#6	PT-22332TripHi	Trip		PT-22332	PT-22332 > 4.50 atm	Turbine 1 Trip	Turbine 1 discharge pressure high	Operator Reset and PT-22332 < 4 atm
#6	PT-22X35LoLo	Alarm		PT-22435 & PT-22135	$\frac{\mathrm{PT}-22435-8.35}{\mathrm{PT}-22135} < 2.15$		Turbine 1 Bearing Pressure difference low	$\frac{\mathrm{PT}-22435-8.35}{\mathrm{PT}-22135} > 2.15$
#6	PT-22X35TripLo	Trip		PT-22435 & PT-22135	$\frac{\mathrm{PT}-22435-7.85}{\mathrm{PT}-22135} < 2.15$	Turbine 1 Trip	Turbine 1 Bearing Pressure difference too low	Operator Reset and $\frac{\mathrm{PT}-22435-8.35}{\mathrm{PT}-22135} > 2.15$
#6	PT-22X3XLoLo	Alarm		PT-22436	PT-22436 – PT-22332 < - 0.60atm		Turbine 1 brake pressure low	PT-22436 – PT-22332 > - 0.60atm
#6	PT-22X3XTripLo	Trip		PT-22436	PT-22436 – PT-22332 < - 0.84atm	Turbine 1 Trip	Turbine 1 brake pressure too low	Operator Reset and PT-22436 – PT-22332 > - 0.60atm
#6	PT-22X3XHiHi	Alarm		PT-22436	PT-22436 – PT-22332 > 3.10atm		Turbine 1 brake pressure high	PT-22436 – PT-22332 < 3.10atm
#6	PT-22X3XTripHi	Trip		PT-22436	PT-22436 – PT-22332 > 3.24atm	Turbine 1 Trip	Turbine 1 brake pressure high	Operator Reset and PT-22436 – PT-22332 < 3.10atm
#6		Turbine 1 Wheel Pressure Formula: $\mathrm{PT}-22438 > \mathrm{K} \times \mathrm{PT}-22432 \times \left(\frac{PT-22432}{PT-22332}\right)^{\sigma-1}$ with $\sigma = 0.52$						
#6	T1_KHiHi	Alarm		PT-22438	K > 1.20		Turbine 1 wheel pressure high	K < 1.20
#6	T1_KTripHi	Trip		PT-22438	K > 1.25	Turbine 1 Trip	Turbine 1 wheel pressure too high	Operator Reset and K < 1.20
#6	PDT-2243XHiHi	Alarm		PT-22433 & PT-22434	PT-22433 - PT-22434 > 1.5 atm		Turbine 1 inlet filter pressure drop High	PT-22433 - PT-22434 < 0.2 atm
#6	PDT-2243XTripHi	Trip		PT-22433 & PT-22434	PT-22433 - PT-22434 > 2.5 atm	Turbine 1 Trip	Turbine 1 inlet filter pressure drop too High	Operator Reset and PT-22433 - PT-22434 < 0.2 atm

HAZOP node	Alarm / Trip Name	Type	Phase (if specified)	Sensor	Condition	Action	Message	Reset Conditions
#6	TT-22332LoLo	Alarm		TT-22332	TT-22332 < 30 K		Turbine 1 discharge temperature low	TT-22332 > 32 K
#6	TT-22332TripLo	Trip		TT-22332	TT-22332 < 25 K	Turbine 1 Trip	Turbine 1 discharge temperature too low	Operator Reset and TT-22332 > 32 K
#6	TT-22436HiHi	Alarm		TT-22436	TT-22436 > 370 K		Turbine 1 brake temperature high	TT-22436 < 365 K
#6	TT-22436TripHi	Trip		TT-22436	TT-22436 > 375 K	Turbine 1 Trip	Turbine 1 brake temperature too High	Operator Reset and TT-22436 < 365 K
#6	TT-22435LoLo	Alarm		TT-22435	TT-22435 < 275 K		Turbine 1 bearings temperature Low	TT-22435 > 280 K
#6	TT-22435TripLo	Trip		TT-22435	TT-22435 < 270 K	Turbine 1 Trip	Turbine 1 bearings temperature too Low	Operator Reset and TT-22435 > 280 K
#6	ST-22433TripLo	Trip	Turbine 1 sequence not in step X510	ST-22433	ST-22433 < 30 Hz during 5sec And PV-22432 > 10%	Turbine 1 Trip	Turbine 1 no speed	Operator Reset and PV-22432 closed
#6	ST-22433HiHi	Alarm		ST-22433	ST-22433 > 2246 Hz		Turbine 1 speed High	ST-22433 < 2230 Hz
#6	ST-22433TripHi	Trip		ST-22433	ST-22433 > 2311 Hz	Turbine 1 Trip	Turbine 1 speed too High	Operator Reset and ST-22433 < 2230 Hz
#6	ST-22433CrCr	Alarm		ST-22433	ST-22433 > 900 Hz & ST-22433 < 1000 Hz During 120sec		Turbine 1 in Critical speed Zone 1	ST-22433 < 900 Hz or ST-22433 > 1000 Hz
#6	ST-22433TripCr	Trip		ST-22433	ST-22433 > 900 Hz & ST-22433 < 1000 Hz During 180sec	Turbine 1 Trip	Turbine 1 in Critical speed Zone 1	Operator Reset and ST-22433 < 900 Hz or ST-22433 > 1000 Hz
#8	PT-22332TripVH	Trip		d(PT-22332) / dt	$\frac{d(PT-22332/dt)}{PT-22332} > 14\ \%/s$	Turbine 1 Trip	T1 discharge pressure Variation too High	Operator Reset
#8	ST-22433TripVH	Trip		d(ST-22433) / dt	d(ST-22433/dt) > 200 Hz/s	Turbine 1 Trip	T1 speed Variation too High	Operator Reset
#8	PV-22432TripLo	Trip	Turbine 1 sequence not in step X510	PV-22432	PV-22432 closed during 180s (Valve Position feedback < 3%)	Turbine 1 Trip	T1 inlet valve closed	Operator Reset
#6	PV-22242TripLo	Trip		ZSH-22242, ZSH-22245	Not ZSH-22242 And Not ZSH-22245 During - 180s in Steps X511 and X516 - 5s in any other step	Turbine 1 Trip	T1 Outlet valves opening issue	Operator Reset

HAZOP node	Alarm / Trip Name	Type	Phase (if specified)	Sensor	Condition	Action	Message	Reset Conditions
Turbine 2								
#7	PT-22452HiHi	Alarm		PT-22452	PT-22452 > 18.9 atm		Turbine 2 inlet pressure high	PT-22452 < 18.5 atm
#7	PT-22452TripHi	Trip		PT-22452	PT-22452 > 19.35 atm	Turbine 2 Trip	Turbine 2 inlet pressure too high	Operator Reset and PT-22452 < 18.5 atm
#7	PT-22352LoLo	Alarm	Turbine 2 sequence not in step X520	PT-22352	PT-22352 < 1.19 atm		Turbine 2 discharge pressure low	PT-22352 > 1.2 atm
#7	PT-22352TripLo	Trip	Turbine 2 sequence not in step X520	PT-22352	PT-22352 < 1.12 atm	Turbine 2 Trip	Turbine 2 discharge pressure too low	Operator Reset and PT-22352 > 1.2 atm
#7	PT-22352HiHi	Alarm		PT-22352	PT-22352 > 3.12 atm		Turbine 2 discharge pressure high	PT-22322 < 3 atm
#7	PT-22352TripHi	Trip		PT-22352	PT-22352 > 3.25 atm	Turbine 2 Trip	Turbine 2 discharge pressure high	Operator Reset and PT-22322 < 3 atm
#7	PDT-22X55LoLo	Alarm		PT-22455 & PT-22155	$\frac{\mathrm{PT}-22455-7.5}{\mathrm{PT}-22155} < 2.0$		Turbine 2 Bearing Pressure difference low	$\frac{\mathrm{PT}-22455-7.5}{\mathrm{PT}-22155} > 2.0$
#7	PDT-22X55TripLo	Trip		PT-22455 & PT-22155	$\frac{\mathrm{PT}-22455-7.25}{\mathrm{PT}-22155} < 2.0$	Turbine 2 Trip	Turbine 2 Bearing Pressure difference too low	Operator Reset and $\frac{\mathrm{PT}-22455-7.5}{\mathrm{PT}-22155} > 2.0$
#7	PDT-22X5XLoLo	Alarm		PT-22456	PT-22456 – PT-22352 < - 0.88atm		Turbine 2 brake pressure low	PT-22456 – PT-22352 > - 0.88atm
#7	PDT-22X5XTripLo	Trip		PT-22456	PT-22456 – PT-22352 < - 1.0atm	Turbine 2 Trip	Turbine 2 brake pressure too low	Operator Reset and PT-22456 – PT-22352 > - 0.88atm
#7	PDT-22X5XHiHi	Alarm		PT-22456	PT-22456 – PT-22352 > 3.65atm		Turbine 2 brake pressure high	PT-22456 – PT-22352 < 3.65atm
#7	PDT-22X5XTripHi	Trip		PT-22456	PT-22456 – PT-22352 > 3.76atm	Turbine 2 Trip	Turbine 2 brake pressure high	Operator Reset and PT-22456 – PT-22352 < 3.65atm
#7		Turbine 2 Wheel Pressure Formula: $\mathrm{PT}-22458 > \mathrm{K} \times \mathrm{PT}-22452 \times \left(\frac{PT-22452}{PT-22352}\right)^{\sigma-1}$ with $\sigma = 0.53$						
#7	T2_HiHi	Alarm		PT-22458	K > 1.20		Turbine 2 wheel pressure high	K < 1.20
#7	T2_TripHi	Trip		PT-22458	K > 1.25	Turbine 2 Trip	Turbine 2 wheel pressure too high	Operator Reset and K < 1.20
#7	PDT-2245XHiHi	Alarm		PT-22453 & PT-22454	PT-22453 - PT-22454 > 1.5 atm		Turbine 2 inlet filter pressure drop High	PT-22453 - PT-22454 < 0.2 atm
#7	PDT-2245XTripHi	Trip		PT-22453 & PT-22454	PT-22453 - PT-22454 > 2.5 atm	Turbine 2 Trip	Turbine 2 inlet filter pressure drop too High	Operator Reset and PT-22453 - PT-22454 < 0.2 atm

HAZOP node	Alarm / Trip Name	Type	Phase (if specified)	Sensor	Condition	Action	Message	Reset Conditions
#7	TT-22352LoLo	Alarm		TT-22352	TT-22352 < 11 K		Turbine 2 discharge temperature Low	TT-22352 > 12 K
#7	TT-22352TripLo	Trip		TT-22352	TT-22352 < 10 K	Turbine 2 Trip	Turbine 2 discharge temperature too Llow	Operator Reset and TT-22352 > 12 K
#7	TT-22456HiHi	Alarm		TT-22456	TT-22456 > 370 K		Turbine 2 brake temperature High	TT-22456 < 365 K
#7	TT-22456TripHi	Trip		TT-22456	TT-22456 > 375 K	Turbine 2 Trip	Turbine 2 brake temperature too high	Operator Reset and TT-22456 < 365 K
#7	TT-22455LoLo	Alarm		TT-22455	TT-22455 < 275 K		Turbine 2 bearings temperature Low	TT-22455 > 280 K
#7	TT-22455TripLo	Trip		TT-22455	TT-22455 < 270 K	Turbine 2 Trip	Turbine 2 bearings temperature too Low	Operator Reset and TT-22455 > 280 K
#7	ST-22453TripLo	Trip	Turbine 2 sequence not in step X520	ST-22453	ST-22453 < 30 Hz during 5secANDPV-22452 > 10%	Turbine 2 Trip	Turbine 2 no speed	Operator Reset and PV-22452 closed
#7	ST-22453HiHi	Alarm		ST-22453	ST-22453 > 2030 Hz		Turbine 2 speed High	ST-22453 < 1990 Hz
#7	ST-22453TripHi	Trip		ST-22453	ST-22453 > 2060 Hz	Turbine 2 Trip	Turbine 2 speed too High	Operator Reset and ST-22453 < 1990 Hz
#7	ST-22453CrCr	Alarm		ST-22453	ST-22453 > 900 Hz & ST-22453 < 1075 Hz During 120sec		Turbine 2 in Critical speed Zone 1	ST-22453 < 900 Hz or ST-22453 > 1075 Hz
#7	ST-22453TripCr	Trip		ST-22453	ST-22453 > 900 Hz & ST-22453 < 1075 Hz During 180sec	Turbine 2 Trip	Turbine 2 in Critical speed Zone 1	Operator Reset and ST-22453 < 900 Hz or ST-22453 > 1075 Hz
#8	PT-22352TripVH	Trip		d(PT-22352) / dt	$\frac{d(PT-22352/dt)}{PT-22352} > 18\ \%/s$	Turbine 2 Trip	T2 discharge pressure Variation High	Operator Reset
#7	ST-22453TripVH	Trip		d(ST-22453) / dt	d(ST-22453/dt) > 200 Hz/s	Turbine 2 Trip	T2 speed Variation too High	Operator Reset
#7	PV-22452TripLo	Trip	Turbine 2 sequence not in step X520	PV-22452	PV-22452 closed during 180s (Valve Position feedback < 3%)	Turbine 2 Trip	T2 inlet valve closed	Operator Reset
#7	PV-22358TripLo	Trip		ZSH-22358	Not ZSH-22358 during - 180s in Steps X521 and X526 - 5s in any other step	Turbine 2 Trip	T2 Outlet valve opening issue	Operator Reset

HAZOP node	Alarm / Trip Name	Type	Phase (if specified)	Sensor	Condition	Action	Message	Reset Conditions
Turbine 3								
#11	PT-22472HiHi	Alarm		PT-22472	PT-22472 > 18.9 atm		Turbine 3 inlet pressure high	PT-22472 < 18.5 atm
#11	PT-22472TripHi	Trip		PT-22472	PT-22472 > 19.35 atm	Turbine 3 Trip	Turbine 3 inlet pressure too high	Operator Reset and PT-22472 < 18.5 atm
#11	PT-22372LoLo	Alarm	Turbine 3 sequence not in step X530	PT-22372	PT-22372 < 0.94 atm		Turbine 3 discharge pressure low	PT-22372 > 1.1 atm
#11	PT-22372TripLo	Trip	Turbine 3 sequence not in step X530	PT-22372	PT-22372 < 0.88 atm	Turbine 3 Trip	Turbine 3 discharge pressure too low	Operator Reset and PT-22372 > 1.1 atm
#15	PT-22372HiHi	Alarm		PT-22372	PT-22372 > 1.50 atm		Turbine 3 discharge pressure High	PT-22372 < 1.5 atm
#15	PT-22372TripHi	Trip		PT-22372	PT-22372 > 1.56 atm	Turbine 3 Trip	Turbine 3 discharge pressure too High	Operator Reset and PT-22372 < 1.5 atm
#11	PDT-22X75LoLo	Alarm		PT-22475 & PT-22175	$\frac{PT-22475-6.5}{PT-22175} < 2$		Turbine 3 Bearing Pressure difference low	$\frac{PT-22475-6.5}{PT-22175} > 2$
#11	PDT-22X75TripLo	Trip		PT-22475 & PT-22175	$\frac{PT-22475-6}{PT-22175} < 2$	Turbine 3 Trip	Turbine 3 Bearing Pressure difference too low	Operator Reset and $\frac{PT-22475-6.5}{PT-22175} > 2$
#11	PDT-22X7XLoLo	Alarm		PT-22476	PT-22476 – PT-22372< 1.0 atm		Turbine 3 brake pressure low	PT-22476 – PT-22372> 1.0 atm
#11	PDT-22X7XTripLo	Trip		PT-22476	PT-22476 – PT-22372< 0.87 atm	Turbine 3 Trip	Turbine 3 brake pressure too low	Operator Reset and PT-22476 – PT-22372> 1.0 atm
#11	PDT-22X7XHiHi	Alarm		PT-22476	PT-22476 – PT-22372> 4.98 atm		Turbine 3 brake pressure high	PT-22476 – PT-22372< 4.98 atm
#11	PDT-22X7XTripHi	Trip		PT-22476	PT-22476 – PT-22372> 5.11 atm	Turbine 3 Trip	Turbine 3 brake pressure high	Operator Reset and PT-22476 – PT-22372< 4.98 atm
#11		Turbine 3 Wheel Pressure Formula: $PT-22478 > K \times PT-22472 \times \left(\frac{PT-22472}{PT-22372}\right)^{\sigma-1}$ with $\sigma = 0.48$						
#11	T3_KHiHi	Alarm		PT-22478	K > 1.20		Turbine 3 wheel pressure high	K < 1.20
#11	T3_KTripHi	Trip		PT-22478	K > 1.25	Turbine 3 Trip	Turbine 3 wheel pressure too high	Operator Reset and K < 1.20
#11	PT-2247XHiHi	Alarm		PT-22473 & PT-22474	PT-22473 - PT-22474 > 1.5 atm		Turbine 3 inlet filter pressure drop High	PT-22473 - PT-22474 < 0.2 atm
#11	PT-2247XTripHi	Trip		PT-22473 & PT-22474	PT-22473 - PT-22474 > 2.5 atm	Turbine 3 Trip	Turbine 3 inlet filter pressure drop too High	Operator Reset and PT-22473 - PT-22474 < 0.2 atm

HAZOP node	Alarm / Trip Name	Type	Phase (if specified)	Sensor	Condition	Action	Message	Reset Conditions
#14	TT-22372LoLo	Alarm		TT-22372	TT-22372 < 5.5K		Turbine 3 Discharge Temperature Low	TT-22372 > 5.5K
#14	TT-22372TripLo	Trip		TT-22372	TT-22372 < 5.0K	Turbine 3 Trip	Turbine 3 Discharge Temperature Too Low	Operator Reset and TT-22372 > 5.5K
#11	TT-22476HiHi	Alarm		TT-22476	TT-22476 > 370 K		Turbine 3 brake temperature high	TT-22476 < 365 K
#11	TT-22476TripHi	Trip		TT-22476	TT-22476 > 375 K	Turbine 3 Trip	Turbine 3 brake temperature too high	Operator Reset and TT-22476 < 365 K
#11	TT-22475LoLo	Alarm		TT-22475	TT-22475 < 275 K		Turbine 3 bearings temperature low	TT-22475 > 280 K
#11	TT-22475TripLo	Trip		TT-22475	TT-22475 < 270 K	Turbine 3 Trip	Turbine 3 bearings temperature too low	Operator Reset and TT-22475 > 280 K
#11	ST-22473TripLo	Trip	Turbine 3 sequence not in step X530	ST-22473	ST-22473 < 30 Hz during 5secANDPV-22472 > 10%	Turbine 3 Trip	Turbine 3 no speed	Operator Reset and PV-22472 closed
#11	ST-22473HiHi	Alarm		ST-22473	ST-22473 > 1456 Hz		Turbine 3 speed high	ST-22473 < 1450 Hz
#11	ST-22473TripHi	Trip		ST-22473	ST-22473 > 1498 Hz	Turbine 3 Trip	Turbine 3 speed too high	Operator Reset and ST-22473 < 1450 Hz
#11	ST-22473CrCr	Alarm		ST-22473	ST-22473 > 760 Hz & ST-22473 < 840 Hz During 120sec		Turbine 3 in Critical speed Zone 1	ST-22473 < 760 Hz or ST-22473 > 840 Hz
#11	ST-22473TripCr	Trip		ST-22473	ST-22473 > 760 Hz & ST-22473 < 840 Hz During 180sec	Turbine 3 Trip	Turbine 3 in Critical speed Zone 1	Operator Reset and ST-22473 < 760 Hz or ST-22473 > 840 Hz
#15	PT-22372TripVH	Trip		d(PT-22372) / dt	$\frac{d(PT-22372/dt)}{PT-22372} > 30\ \%/s$	Turbine 3 Trip	T3 discharge pressure Variation High	Operator Reset
#11	ST-22473TripVH	Trip		d(ST-22473) / dt	d(ST-22473/dt) > 200 Hz/s	Turbine 3 Trip	T3 speed Variation too High	Operator Reset
#11	PV-22472TripLo	Trip	Turbine 3 sequence not in step X530	PV-22472	PV-22472 closed during 180s (Valve Position feedback < 3%)	Turbine 3 Trip	T3 inlet valve closed	Operator Reset
#11	PV-22378TripLo	Trip		ZSH-22378	Not ZSH-22378 during - 180s in Steps X531 and X536 - 5s in any other step	Turbine 3 Trip	T3 Outlet valve opening issue	Operator Reset

HAZOP node	Alarm / Trip Name	Type	Phase (if specified)	Sensor	Condition	Action	Message	Reset Conditions
Turbine 4								
#12	PT-22482HiHi	Alarm		PT-22482	PT-22482 > 18.9 atm		Turbine 4 inlet pressure high	PT-22482 < 18.5 atm
#12	PT-22482TripHi	Trip		PT-22482	PT-22482 > 19.35 atm	Turbine 4 Trip	Turbine 4 inlet pressure too high	Operator Reset and PT-22482 < 18.5 atm
#13	PT-22382LoLo	Alarm	Turbine 4 sequence not in step X540	PT-22382	PT-22382 < 2.76 atm		Turbine 4 discharge pressure low	PT-22382 > 2.8 atm
#13	PT-22382TripLo	Trip	Turbine 4 sequence not in step X540	PT-22382	PT-22382 < 2.6 atm	Turbine 4 Trip	Turbine 4 discharge pressure too low	Operator Reset and PT-22382 > 2.8 atm
#13	PT-22382HiHi	Alarm		PT-22382	PT-22382 > 3.9 atm		Turbine 4 discharge pressure High	PT-22382 < 3.7 atm
#13	PT-22382TripHi	Trip		PT-22382	PT-22382 > 4.06 atm	Turbine 4 Trip	Turbine 4 discharge pressure too High	Operator Reset and PT-22382 < 3.7 atm
#12	PDT-22X85LoLo	Alarm		PT-22485 & PT-22185	$\frac{\mathrm{PT}-22485-4.6}{\mathrm{PT}-22185} < 2.13$		Turbine 4 Bearing Pressure difference low	$\frac{\mathrm{PT}-22485-4.55}{\mathrm{PT}-22185} > 2.1$
#12	PDT-22X85TripLo	Trip		PT-22485 & PT-22185	$\frac{\mathrm{PT}-22485-4.4}{\mathrm{PT}-22185} < 2.13$	Turbine 4 Trip	Turbine 4 Bearing Pressure difference too low	Operator Reset and $\frac{\mathrm{PT}-22485-4.55}{\mathrm{PT}-22185} > 2.1$
#12	PDT-22X8XLoLo	Alarm		PT-22486	PT-22486 – PT-22382< -0.06 atm		Turbine 4 brake pressure low	PT-22486 – PT-22382> -0.06 atm
#12	PDT-22X8XTripLo	Trip		PT-22486	PT-22486 – PT-22382< -0.19 atm	Turbine 4 Trip	Turbine 4 brake pressure too low	Operator Reset and PT-22486 – PT-22382> -0.06 atm
#12	PDT-22X8XHiHi	Alarm		PT-22486	PT-22486 – PT-22382> 2.74 atm		Turbine 4 brake pressure high	PT-22486 – PT-22382< 2.74 atm
#12	PDT-22X8XTripHi	Trip		PT-22486	PT-22486 – PT-22382> 2.87 atm	Turbine 4 Trip	Turbine 4 brake pressure high	Operator Reset and PT-22486 – PT-22382< 2.74 atm
#12		Turbine 4 Wheel Pressure Formula: $\mathrm{PT}-22488 > \mathrm{K} \times \mathrm{PT}-22482 \times \left(\frac{PT-22482}{PT-22382}\right)^{\sigma-1}$ with $\sigma = 0.53$						
#12	T4_KHiHi	Alarm		PT-22488	K > 1.20		Turbine 4 wheel pressure high	K < 1.20
#12	T4_KTripHi	Trip		PT-22488	K > 1.25	Turbine 4 Trip	Turbine 4 wheel pressure too high	Operator Reset and K < 1.20
#12	PT-2248XHiHi	Alarm		PT-22483 & PT-22484	PT-22483 - PT-22484 > 1.5 atm		Turbine 4 inlet filter pressure drop High	PT-22483 - PT-22484 < 0.2 atm
#12	PT-2248XTripHi	Trip		PT-22483 & PT-22484	PT-22483 - PT-22484 > 2.5 atm	Turbine 4 Trip	Turbine 4 inlet filter pressure drop too High	Operator Reset and PT-22483 - PT-22484 < 0.2 atm

HAZOP node	Alarm / Trip Name	Type	Phase (if specified)	Sensor	Condition	Action	Message	Reset Conditions
#14	TT-22382LoLo	Alarm		TT-22382	TT-22382 < 5.0K		Turbine 4 Discharge Temperature Low	TT-22382 > 5.2 K
#14	TT-22382TripLo	Trip		TT-22382	TT-22382 < 4.5K	Turbine 4 Trip	Turbine 4 Discharge Temperature Too Low	Operator Reset and TT-22382 > 5.2 K
#12	TT-22486HiHi	Alarm		TT-22486	TT-22486 > 370 K		Turbine 4 brake temperature high	TT-22486 < 365 K
#12	TT-22486TripHi	Trip		TT-22486	TT-22486 > 375 K	Turbine 4 Trip	Turbine 4 brake temperature too high	Operator Reset and TT-22486 < 365 K
#12	TT-22485LoLo	Alarm		TT-22485	TT-22485 < 275 K		Turbine 4 bearings temperature low	TT-22485 > 280 K
#12	TT-22485TripLo	Trip		TT-22485	TT-22485 < 270 K	Turbine 4 Trip	Turbine 4 bearings temperature too low	Operator Reset and TT-22485 > 280 K
#12	ST-22483TripLo	Trip	Turbine 4 sequence not in step X540	ST-22483	ST-22483 < 30 Hz during 5secANDPV-22482 > 10%	Turbine 4 Trip	Turbine 4 no speed	Operator Reset and PV-22482 closed
#12	ST-22483HiHi	Alarm		ST-22483	ST-22483 > 1232 Hz		Turbine 4 speed high	ST-22483 < 1210 Hz
#12	ST-22483TripHi	Trip		ST-22483	ST-22483 > 1268 Hz	Turbine 4 Trip	Turbine 4 speed too high	Operator Reset and ST-22483 < 1210 Hz
#13	ST-22483CSCS	Alarm		ST-22483	ST-22483 > 600 Hz & ST-22483 < 750 Hz During 240sec		Turbine 4 in Critical speed Zone 1	ST-22483 < 600 Hz or ST-22483 > 750 Hz
#13	ST-22483TripCS	Trip		ST-22483	ST-22483 > 600 Hz & ST-22483 < 750 Hz During 360sec	Turbine 4 Trip	Turbine 4 in Critical speed Zone 1	Operator Reset and ST-22483 < 600 Hz or ST-22483 > 750 Hz
#13	PT-22382TripVH	Trip		d(PT-22382) / dt	$\frac{d(PT-22382/dt)}{PT-22382} > 11\ \%/s$	Turbine 4 Trip	T4 discharge pressure Variation High	Operator Reset
#12	ST-22483TripVH	Trip		d(ST-22483) / dt	d(ST-22483/dt) > 200 Hz/s	Turbine 4 Trip	T4 speed Variation too High	Operator Reset
#12	PV-22482TripLo	Trip	Turbine 4 sequence not in step X540	PV-22482	PV-22482 closed during 180s (Valve Position feedback < 3%)	Turbine 4 Trip	T4 inlet valve closed	Operator Reset
#12	PV-22388TripLo	Trip		ZSH-22388	Not ZSH-22388 during - 180s in Steps X541 and X546 - 5s in any other step	Turbine 4 Trip	T4 Outlet valve opening issue	Operator Reset

AND PT23610<0.33 mbar

Alarm / Trip Name	Type	Phase (if specified)	Sensor	Interlocked equipment (if any)	Condition	Action	Message	Reset Conditions
UCB VACUUM SKID								
DPT-23610TripVH	Trip		PT-23610	PV-23611	ΔPT-23610 > 100 mTorr / min (~ 0.133 mbar / min)	Vacuum sequence Trip	System Vacuum failure on UCB	Operator Reset
PT-23610TripVH	Trip		PT-23610	PV-23611	DP-23610 running and PT-23610 > 250 mTorr (~ 0.33 mbar)	Vacuum sequence Trip	System Vacuum failure on UCB	Operator Reset
PV-23611ErEr	Alarm		ZSL-23611 & ZSH-23611	PV-23611	ZSL-23611 & ZSH-23611 off simultaneously during 1 min		Vacuum Gate Valve not fully open/closed on UCB	ZSL-23611 or ZSH-23611 Operator Reset
PV-23611TripEr	Trip		ZSL-23611 & ZSH-23611	PV-23611	ZSL-23611 & ZSH-23611 simultaneously	Vacuum sequence Trip	Vacuum Gate Valve end switched failure on UCB	Operator Reset
PV-23611TripLo	Trip		ZSH-23611	PV-23611	PV-23611 open order and not ZSH-23611 after 4sec	Vacuum sequence Trip	Vacuum Gate Valve opening failure on UCB	Operator Reset
PV-23611TripHi	Trip		ZSL-23611	PV-23611	PV-23611 close order and not ZSL-23611 after 4sec	Vacuum sequence Trip	Vacuum Gate Valve closing failure on UCB	Operator Reset
TSH-23610TripHi	Trip		TSH-23610	EH-23610	TSH-23610 (Temperature over 46˚C +/-3˚C)	Vacuum sequence Trip	Diffusion Pump over heating on UCB	Operator Reset
FSL-23418TripLo	Trip		FSL-23418	EH-23610	FSL-23418	Vacuum sequence Trip	Cooling water flow on Vacuum skid too low on UCB	Operator Reset
VP-23610TripLo	Trip		VP-23610 breaker	VP-23610	VP-23610 breaker stops the pump	Vacuum sequence Trip	Primary Pump breaker failure on UCB	Operator Reset
DP-23610TripLo	Trip		DP-23610 breaker	DP-23610	DP-23610 breaker stops the pump	Vacuum sequence Trip	Diffusion Pump breaker failure on UCB	Operator Reset

- E-stop from VP, DP controller and E-stop from skid generates a trip.
- This trip shutdown all the vacuum valves and pumps.

AND PT23630<0.33 mbar

LCB VACUUM SKID								
DPT-23630TripVH	Trip		PT-23630	PV-23631	ΔPT-23630 > 100 mTorr / min (~ 0.133 mbar / min)	Vacuum sequence Trip	System Vacuum failure on LCB	Operator Reset
PT-23630TripVH	Trip		PT-23630	PV-23631	DP-23630 running and PT-23630 > 250 mTorr (~ 0.33 mbar)	Vacuum sequence Trip	System Vacuum failure on LCB	Operator Reset
PV-23631ErEr	Alarm		ZSL-23631 & ZSH-23631	PV-23631	ZSL-23631 & ZSH-23631 off simultaneously during 1 min		Vacuum Gate Valve not fully open/closed on UCB	ZSL-23631 or ZSH-23631 Operator Reset
PV-23631TripEr	Trip		ZSL-23631 & ZSH-23631	PV-23631	ZSL-23631 & ZSH-23631 simultaneously	Vacuum sequence Trip	Vacuum Gate Valve end switched failure on LCB	Operator Reset
PV-23631TripLo	Trip		ZSH-23631	PV-23631	PV-23631 open order and not ZSH-23631 after 4sec	Vacuum sequence Trip	Vacuum Gate Valve opening failure on LCB	Operator Reset
PV-23631TripHi	Trip		ZSL-23631	PV-23631	PV-23631 close order and not ZSL-23631 after 4sec	Vacuum sequence Trip	Vacuum Gate Valve closing failure on LCB	Operator Reset
TSH-23630TripHi	Trip		TSH-23630	EH-23630	TSH-23630 (Temperature over 46˚C +/-3˚C)	Vacuum sequence Trip	Diffusion Pump over heating on LCB	Operator Reset
FSL-23438TripLo	Trip		FSL-23428	EH-23630	FSL-23428	Vacuum sequence Trip	Cooling water flow on Vacuum skid too low on LCB	Operator Reset
VP-23630TripLo	Trip		VP-23630 breaker	VP-23630	VP-23630 breaker stops the pump	Vacuum sequence Trip	Primary Pump failure on LCB	Operator Reset
DP-23630TripLo	Trip		DP-23630 breaker	DP-23630	DP-23630 breaker stops the pump	Vacuum sequence Trip	Diffusion Pump breaker failure on LCB	Operator Reset

- E-stop from VP, DP controller and E-stop from skid generates a trip.
- This trip shutdown all the vacuum valves and pumps.

18. APPENDIXE 2 – TRIPS ON PRESSURE AND SPEED VARIATION MEASUREMENT

18.1 DISCHARGE PRESSURE VARIATION HIGH

Turbines Trip protection on discharge pressure variation must be programmed as follows:

1. Measure of the discharge pressure at t0
2. Save the measurement
3. Measure the discharge pressure at t0 + 200ms
4. Compare the two discharge pressure measurements: P(t0) - P(t0+100ms)
5. Trip the Turbine sequence if the difference is higher than 1/5th of the value given in the Trip table.

   → For instance, 14 %/s (trip value) shall be coded as 2.8 %/200ms.

This logic shall continuously run when Turbine sequence is started.

Each comparison cycle lasts 100ms.

18.2 SPEED VARIATION HIGH

Turbines Trip protection on speed variation must be programmed as follows:

1. Measure of the speed at t0
2. Save the measurement
3. Measure the speed at t0 + 200ms
4. Save the measurement
5. Compare the two speed measurements: S(t0) - S(t0+100ms)
6. Trip the Turbine sequence if the difference is higher than 1/5th of the value given in the Trip table.

   → For instance, 200 Hz/s (trip value) shall be coded as 40 Hz/200ms.

This logic shall continuously run when Turbine sequence is started.

Each comparison cycle lasts 100ms.

General Note: Interlock shall override auto and manual mode/action.

19. APPENDIXE 2 – INTERLOCKS TO AVOID TRIP SITUATIONS

HAZOP node	Type	Phase (if specified)	Sensor	Interlocked equipment	Condition	Action	Reset Conditions	Fallback position	Comments
General	Interlock		Any sensor linked to a control loop	**Actuator linked to the control loop**	Sensor signal out of range during 2sec	Turn off the control loop and switch the actuator in its failure position	Sensor signal back in range during 2sec Operator action required to restart the Control loop.	Controller remains off with actuator in its failure position.	
WARM INLET VALVES									
#1	Temporary Interlock		TT-22413, TT-22511	**PV-22400**	TT-22413-TT-22511>40K During 10 min	Force Maximum opening of PV-22400 at 10%	TT-22413 - TT-22511 < 20K Ramp Max Opening to TIC-22400-A output (1%/sec)	Maximum opening of PV-22400 back at its value before Interlock	High Temperature difference at LN2 Level
#1	Temporary Interlock		TT-22411, TT-22511	**PV-22400**	TT-22411-TT-22511>40K During 10 min	Force Maximum opening of PV-22400 at 10%	TT-22411 - TT-22511 < 20K Ramp Max Opening to TIC-22400-A output (1%/sec)	Maximum opening of PV-22400 back at its value before Interlock	
#1	Temporary Interlock		TT-22413, TT-22511	**PV-22402**	TT-22413-TT-22511>40K During 10 min	Force Maximum opening of PV-22402 at 10%	TT-22413 - TT-22511 < 20K Ramp Max Opening at 100% (1%/sec)	Maximum opening of PV-22402 back at its value before Interlock	High Temperature difference at LN2 Level
#1	Temporary Interlock		TT-22412, TT-22511	**PV-22402**	TT-22412-TT22511>40K During 10 min	Force Maximum opening of PV-22402 at 10%	TT-22412 - TT-22511 < 20K Ramp Max Opening at 100% (1%/sec)	Maximum opening of PV-22402 back at its value before Interlock	
LN2 PHASE SEPARATOR									
#2	Temporary Interlock		LT-22510	**PV-22520**	LT-22510 > 90%	Force Maximum opening of PV-22520 at 10%	LT-22510 < 80% Ramp Max Opening at 100% (1%/sec)	Maximum opening of PV-22520 back at its value before Interlock	High level in the LN2 phase separator
#2	Temporary Interlock		PT-22510	**PV-22520**	PT-22510 > 3 Atm	Force Maximum opening of PV-22520 at 0%	PT-22510 < 2 Atm Ramp Max Opening at 100% (1%/sec)	Maximum opening of PV-22520 back at its value before Interlock	High pressure in the LN2 phase separator
COOL DOWN LINE VALVES									
#15	Temporary Interlock		PT-22190 PT-21000	**PV-22110**	PT-22190 > 3 atm And PT-22190 - PT-21000 > 0.3 atm	Force Minimum opening of PV-22110 at 15%	PT-22190 < 1.5 atm Or PT-22190 - PT-21000 < 0.1 atm	Minimum opening of PV-22110 back at its value before Interlock	This will open PV-22110 if all other Cool Down Line valves are closed
#15	Temporary Interlock		TT-22411 - TT-22111	**PV-22115**	TT-22411 - TT-22111 > 35K	Force Maximum opening of PV-22115 at 0%	TT-22411 - TT-22111 < 20K Ramp Max Opening at 100% (1%/sec)	Maximum opening of PV-22115 back at its value before Interlock	This will open PV-22110 if all other Cool Down Line valves are closed
#15	Temporary Interlock		TT-22440-TT-22140	**PV-22140**	TT-22440 - TT-22140 > 35K	Force Maximum opening of PV-22140 at 0%	TT-22440 - TT-22140 < 20K Ramp Max Opening at 100% (1%/sec)	Maximum opening of PV-22140 back at its value before Interlock	This will open PV-22110 if all other Cool Down Line valves are closed
#15	Temporary Interlock		TT-22466 - TT-22160	**PV-22160**	TT-22466 - TT-22160 > 35K	Force Maximum opening of PV-22160 at 0%	TT-22466 - TT-22160 < 20K Ramp Max Opening at 100% (1%/sec)	Maximum opening of PV-22160 back at its value before Interlock	This will open PV-22110 if all other Cool Down Line valves are closed

Interlock set point is reduced to 1.5 atm similar to 20K bed bypass valve interlock. (Device range for PDT-22414 is 2 bar)

HAZOP node	Type	Phase (if specified)	Sensor	Interlocked equipment	Condition	Action	Reset Conditions	Fallback position	Comments
80K ADSORBERS									
#1	Interlock	Not X600	PV-22415A, PV-22420A, PV-22415B, PV-22420B	**PV-22421**	PV-22415A closed Or PV-22420A closed; And PV-22415B closed Or PV-22420B closed;	Force Minimum opening of PV-22421 at 100%	[PV-22415A & PV-22420A opened] OR [PV-22415B & PV-22420B opened] AND Operator action required to reset the interlock. Ramp Min Opening at 0% (1%/sec)	Minimum opening of PV-22421 back at its value before Interlock	One of Adsorbers valve abnormally closed
#1	Interlock		PDT-22414	**PV-22421**	PDT-22414 > 2atm	Force Minimum opening of PV-22421 at 100%	PDT-22414 < 1atm AND Operator action required to reset the interlock. Ramp Min Opening at 0% (1%/sec)	Minimum opening of PV-22421 back at its value before Interlock	High pressure drop across Adsorbers
#3 #4	Interlock	Cold Box Cool Down Sequence in Nominal Step X610 And Adsorber A connected	TT-22415A	**PV-22421**	TT-22415A > 100K And PV-22415A at 100% And PV-22420A at 100%	Force Minimum opening of PV-22421 at 100%	Adsorber A or B Online AND Operator action required to reset the interlock. Ramp Min Opening at 0% (1%/sec)	Minimum opening of PV-22421 back at its value before Interlock	Adsorber warming up: Risk of impurity release
#3 #4	Interlock	Cold Box Cool Down Sequence in Nominal Step X610 And Adsorber B connected	TT-22415B	**PV-22421**	TT-22415B > 100K And PV-22415B at 100% And PV-22420B at 100%	Force Minimum opening of PV-22421 at 100%	Adsorber A or B Online AND Operator action required to reset the interlock. Ramp Min Opening at 0% (1%/sec)	Minimum opening of PV-22421 back at its value before Interlock	Adsorber warming up: Risk of impurity release
#3 #4	Interlock	Cold Box Cool Down Sequence in Nominal Step X610 And Adsorber A connected	TT-22415A	**PV-22420A**	TT-22415A > 100K And PV-22415A at 100% And PV-22420A at 100%	Force Maximum opening of PV-22420A at 0%	80K Adsorber A in Regeneration state AND Operator action required to reset the interlock. Set Max Opening at 100%	Maximum opening of PV-22420A back at its value before Interlock	Adsorber warming up: Risk of impurity release
#3 #4	Interlock		TT-22418A*	**EH-22418A**	TT-22418A > 400K	Force Heater EH-22418A stopped Stop TIC-22418A	TT-22418A < 350K AND Operator action required to reset the interlock.	TIC-22418A remains off and EH-22418A stopped	Heater Temperature High See section 4.4.1
#3 #4	Interlock		PT-22417A	**EH-22418A**	PT-22417A > 9 atm	Force Heater EH-22418A stopped Stop TIC-22418A	PT-22417A < 8 atm AND Operator action required to reset the interlock.	TIC-22418A remains off and EH-22418A stopped	High pressure in Adsorber
#3 #4	Interlock		TT-22418B*	**EH-22418B**	TT-22418B > 400K	Force Heater EH-22418B stopped Stop TIC-22418B	TT-22418B < 350K AND Operator action required to reset the interlock.	TIC-22418B remains off and EH-22418A stopped	Heater Temperature High See section 4.4.1
#3 #4	Interlock		PT-22417B	**EH-22418B**	PT-22417B > 9 atm	Force Heater EH-22418B stopped Stop TIC-22418B	PT-22417B < 8 atm AND Operator action required to reset the interlock.	TIC-22418B remains off and EH-22418A stopped	High pressure in Adsorber

*TT-22418 A = Max [TT-22418-AA1 / TT-22418-AA2 / TT-22418-AB1 / TT-22418-AB2]
*TT-22418 B = Max [TT-22418-BA1 / TT-22418-BA2 / TT-22418-BB1 / TT-22418-BB2]

We need to remove this interlock as we did for Bed B.
Re-cooldown of Beds are manual operation by opening the outlet valve PV22420A/B to ~10%. If we implement on Interlock action to override manual mode; manual re-cooldown will not be possible.

HAZOP node	Type	Phase (if specified)	Sensor	Interlocked equipment	Condition	Action	Reset Conditions	Fallback position	Comments
20K ADSORBER									
#9	Interlock	Not X600	PV-22461, PV-22466	**PV-22460**	PV-22461 closed Or PV-22466 closed	Force Minimum Opening of PV-22460 at 100%	[PV-22461 & PV-22466 opened] AND Operator action required to reset the interlock. Ramp Min Opening at 0% (1%/sec)	Minimum opening of PV-22460 back at its value before Interlock	One of Adsorbers valve abnormally closed
#9	Interlock	Not X600	PDT-22461	**PV-22460**	PDT-22461 > 1.5 atm	Force Minimum Opening of PV-22460 at 100%	PDT-22461 < 1 atm AND Operator action required to reset the interlock. Ramp Min Opening at 0% (1%/sec)	Minimum opening of PV-22460 back at its value before Interlock	High pressure drop across Adsorbers
#9	Interlock	Cold Box Cool Down Sequence in Nominal Step X610 And 20K Adsorber connected	TT-22464	**PV-22460**	TT-22464 > 23K And PV-22461 opened And PV-22466 opened	Force Minimum Opening of PV-22460 at 100%	TT-22464 < 21 K AND Operator action required to reset the interlock. Ramp Min Opening at 0% (1%/sec)	Minimum opening of PV-22460 back at its value before Interlock	Adsorber warming up: Risk of impurity release
#9	Interlock	Cold Box Cool Down Sequence in Nominal Step X610 And 20K Adsorber connected	TT-22464	**PV-22466**	TT-22464 > 23K And PV-22461 opened And PV-22466 opened	Force Maximum opening of PV-22466 at 0%	20K Adsorber in Regeneration State AND Operator action required to reset the interlock. Set Max Opening at 100%	Maximum opening of PV-22466 back at its value before Interlock	Adsorber warming up: Risk of impurity release
#9	Interlock		TT-22465*	**EH-22465**	TT-22465 > 400K	Force Heater EH-22465 stopped Stop TIC-22465	TT-22465 < 350 K AND Operator action required to reset the interlock.	TIC-22465 remains off and EH-22465 stopped	Heater Temperature High See section 4.4.1
#9	Interlock		PT-22463	**EH-22465**	PT-22463 > 9 atm	Force Heater EH-22465 stopped Stop TIC-22465	PT-22463 < 8 atm AND Operator action required to reset the interlock.	TIC-22465 remains off and EH-22465 stopped	High pressure in Adsorber

*TT-22465 = Max [TT-22465-A1 / TT-22465-A2 / TT-22465-A3 / TT-22465-B1 / TT-22465-B2 / TT-22465-B3]

JLAB: Text similar to "Maximum opening of PV-22400 back at its value before Interlock" in page 120 - is it also

ALATUS:

Yes (or it gives the hand back to the controller which acts on a max opening if any)

Actuators associated with a PID Controller:

- Actuators with ON/OFF logic:

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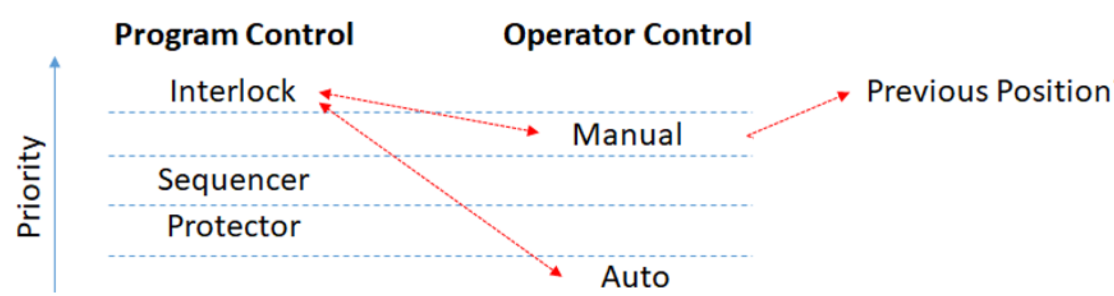

HAZOP node	Type	Phase (if specified)	Sensor	Interlocked equipment	Condition	Action	Reset Conditions	Fallback position	Comments
Cold End and LHe SUBCOOLER									
#12	Temporary Interlock	Turbine 4 sequence not in step X540	PT-22382	**PV-22485**	PT-22382 > 3.6 atm	Force Maximum & Minimum opening of PV-22485 at 5% (by-pass T4)	PT-22382 < 3.3 atm Ramp Min Opening at TIC-22485 output (1%/sec) Ramp Max Opening at 100% (1%/sec)	Maximum & Minimum opening of PV-22485 back at their values before Interlock	
#13	Temporary Interlock		TT-22393-TT-22193	**PV-22390**	IF (TT-22393-TT-22193) > 45K	Force PV-22390 Maximum Opening at 5%	(TT-22393-TT-22193) < 30K Ramp Max Opening at PIC-22390 output (1%/sec)	Maximum opening of PV-22390 back at its value before Interlock	Limit HP flow in HX-12 if Cold DT High to avoid Cold Box Trip
#13	Temporary Interlock		LT-22195A & LT-22195B	**PV-22390**	LT-22195A > 90% & LT-22195B > 50% during more than 1 min	Force PV-22390 Maximum Opening at 5%	LT-22195A < 85% for more than 1 min Ramp Max Opening at PIC-22390 output (1%/sec)	Maximum opening of PV-22390 back at its value before Interlock	Limit LHe transfer in Subcooler if Level gets high
#14	Temporary Interlock		PT-22195	**PV22390**	PT-22195 > 1.5 atm during more than 5sec	Force PV-22390 Maximum Opening at 5%	PT-22195 < 1.3 atm Ramp Max Opening at PIC-22390 output (1%/sec)	Maximum opening of PV-22390 back at its value before Interlock	Pressure High in Subcooler
#15	Temporary Interlock		LT-22195, TT-22193	**PV-22193**	LT-22195 > 10% And TT-22193 > 40K	Force PV-22193 Maximum Opening at 5%	LT-22195 < 10% Or TT-22193 < 30K Ramp Max Opening at 100%(1%/sec)	Maximum opening of PV-22193 back at its value before Interlock	Limit cold Flow in Warm Hx
#14	Interlock		TT-22195A	**EH-22195**	TT-22195A > 330K	Force Heater EH-22195 stopped Stop LIC-22195B	TT-22195A < 320K . AND Operator action required to reset the interlock.	LIC-22195B remains off and EH-22195 stopped	Heater overheating
#14	Interlock		TT-22195B	**EH-22195**	TT-22195B > 330K	Force Heater EH-22195 stopped Stop LIC-22195B	TT-22195B < 320K AND Operator action required to reset the interlock.	LIC-22195B remains off and EH-22195 stopped	Heater overheating
#14	Interlock		TT-22195C	**EH-22195**	TT-22195C > 330K	Force Heater EH-22195 stopped Stop LIC-22195B	TT-22195C < 320K AND Operator action required to reset the interlock.	LIC-22195B remains off and EH-22195 stopped	Heater overheating
#14	Interlock		TT-22195D	**EH-22195**	TT-22195D > 330K	Force Heater EH-22195 stopped Stop LIC-22195B	TT-22195D < 320K AND Operator action required to reset the interlock.	LIC-22195B remains off and EH-22195 stopped	Heater overheating
#14	Interlock		LT-22195A	**EH-22195**	LT-22195A < 10% during more than 1 min	Force Heater EH-22195 stopped Stop LIC-22195B	LT-22195A > 15% for more than 1 min AND Operator action required to reset the interlock.	LIC-22195B remains off and EH-22195 stopped	Allow Heaters only if they are in Liquid He
#14	Interlock		PT-22195	**EH-22195**	PT-22195 > 1.5 atm during more than 5sec	Force Heater EH-22195 stopped Stop LIC-22195B	PT-22195 < 1.3 atm AND Operator action required to reset the interlock.	LIC-22195B remains off and EH-22195 stopped	Pressure High in Subcooler

HAZOP node	Type	Phase (if specified)	Sensor	Interlocked equipment	Condition	Action	Reset Conditions	Fallback position	Comments
DEWAR									
#13	Temporary Interlock		TT-22393-TT-22193	**PV-22393**	IF (TT-22393-TT-22193) > 45K	Force PV-22393 Maximum Opening at 5%	(TT-22393-TT-22193) < 30K Ramp Max Opening at 100%(1%/sec)	Maximum opening of PV-22393 back at its value before Interlock	Limit HP flow in HX-12 if Cold DT High to avoid Cold Box Trip
#13	Temporary Interlock		TT-22393-TT-22194	**PV-22393**	IF |TT-22393-TT-22194| > 45K	Force PV-22393 Maximum Opening at 5%	|TT-22393-TT-22194| < 30K Ramp Max Opening at 100%(1%/sec)	Maximum opening of PV-22393 back at its value before Interlock	Limit HP flow to the Dewar if the Dewar is much colder or warmer than Cold Box (Dewar Connection)
#14	Temporary Interlock		TT-22194	**PV-22194**	TT-22194 > 7K And TT-22193 < 7K	Force PV-22194 Maximum Opening at 10%	TT-22194 < 6K Ramp Max Opening at 100%(1%/sec)	Maximum opening of PV-22194 back at its value before Interlock	Limit warm Flow from Dewar into the Cold Subcooler
#14	Temporary Interlock		PV-22193, TT-22193, TT-22194	**PV-22194**	PV-22193 > 10%, And TT-22193 > 80K, And TT-22194 < 10K	Force PV-22194 Maximum Opening at 10%	TT-22193 < 80K Or TT-22194 > 10K Ramp Max Opening at 100%(1%/sec)	Maximum opening of PV-22194 back at its value before Interlock	Prevent cold flow from Dewar to Warm HX12 (Subcooler being also warm)
#14	Temporary Interlock		PV-22193, TT-22193, TT-22195	**PV-22195**	PV-22193 > 10% And TT-22193 > 80K And TT-22195 < 10K	Force PV-22195 Maximum Opening at 5%	TT-22193 < 80K Or TT-22195 > 10K Ramp Max Opening at 100%(1%/sec)	Maximum opening of PV-22195 back at its value before Interlock	Prevent cold flow from Dewar to Warm HX12 (Subcooler being also warm)
#14	Temporary Interlock	Cold Box Cool Down Sequence in Nominal Step X610	TT-22195	**PV-22195**	TT-22195 > 7K and PV-22195 >10%	Force PV-22195 Maximum Opening at 10%	TT-22195 < 6K Ramp Max Opening at 100%(1%/sec)	Maximum opening of PV-22195 back at its value before Interlock	Limit warm Flow back in Cold Subcooler
#13	Temporary Interlock		LT-22195A & LT-22195B	**PV-22195**	LT-22195A > 90% & LT-22195B > 50% during more than 1 min	Force PV-22195 Maximum Opening at 5%	LT-22195A < 85% for more than 1 min Ramp Max Opening at 100%(1%/sec)	Maximum opening of PV-22195 back at its value before Interlock	Limit LHe transfer in Subcooler if Level gets high

JLAB:
GENERAL: Some of the interlock action requires valves maximum opening go to an intermediate values (Example 10% or 5% etc.). If the valve is at 0%, we wouldn't want an Interlock to open it to 10% in that case. Ex: PV22400/402, PV22520, PV22390, PV22193 and Dewar interlocks.
If valve % opening tries to go beyond the interlocked value X% (Example 10%) in above cases, interlock will override and prevent exceeding the interlocked value.
ALATUS:
"If valve % opening tries to go beyond the interlocked value X% (Example 10%) in above cases, interlock will override and prevent exceeding the interlocked value." is indeed the expected way the interlock shall be coded.

HAZOP node	Type	Phase (if specified)	Sensor	Interlocked equipment	Condition	Action	Reset Conditions	Fallback position	Comments
TURBINES									
#6	Temporary Interlock	Turbine 1 sequence in step X510	ST-22433 PT-22135	**EV-22137**	IF ST-22433 > 30 Hz* And PT-22135 > 2.15 Atm	Force EV-22137 Open whatever the valve state (Auto or Manu)	ST-22433 < 30 Hz Or PT-22135 < 2.15 Atm Release EV-22437 opening action	Close EV-22137 Set the valve in the mode (Manual or Auto) it was in before the interlock	• During Turbine warm-up, the bearing discharge pressure is increased to force warm-up flow. This interlock protects the Turbines in case the speed becomes high. • During Turbine Trip, if Discharge Bearing pressure increases, the EV must be opened during the turbine deceleration time
#7	Temporary Interlock	Turbine 2 sequence in step X520	ST-22453 PT-22155	**EV-22157**	IF ST-22453 > 30 Hz* And PT-22155 > 1.92 Atm	Force EV-22157 Open whatever the valve state (Auto or Manu)	ST-22453 < 30 Hz Or PT-22155 < 1.92 Atm Release EV-22457 opening action	Close EV-22157 Set the valve in the mode (Manual or Auto) it was in before the interlock	• During Turbine warm-up, the bearing discharge pressure is increased to force warm-up flow. This interlock protects the Turbines in case the speed becomes high. • During Turbine Trip, if Discharge Bearing pressure increases, the EV must be opened during the turbine deceleration time
#11	Temporary Interlock	Turbine 3 sequence in step X530	ST-22473 PT-22175	**EV-22177**	IF ST-22473 > 30 Hz* And PT-22175 > 1.92 Atm	Force EV-22177 Open whatever the valve state (Auto or Manu)	ST-22473 < 30 Hz Or PT-22175 < 1.92 Atm Release EV-22477 opening action	Close EV-22177 Set the valve in the mode (Manual or Auto) it was in before the interlock	• During Turbine warm-up, the bearing discharge pressure is increased to force warm-up flow. This interlock protects the Turbines in case the speed becomes high. • During Turbine Trip, if Discharge Bearing pressure increases, the EV must be opened during the turbine deceleration time
#12	Temporary Interlock	Turbine 4 sequence in step X540	ST-22483 PT-22185	**EV-22187**	IF ST-22483 > 30 Hz* And PT-22185 > 1.88 Atm	Force EV-22187 Open whatever the valve state (Auto or Manu)	ST-22483 < 30 Hz Or PT-22185 < 1.88 Atm Release EV-22487 opening action	Close EV-22187 Set the valve in the mode (Manual or Auto) it was in before the interlock	• During Turbine warm-up, the bearing discharge pressure is increased to force warm-up flow. This interlock protects the Turbines in case the speed becomes high. • During Turbine Trip, if Discharge Bearing pressure increases, the EV must be opened during the turbine deceleration time

* The Speed value shall be adjusted for each Turbine. Some Turbines may have a stand-by speed higher than 30Hz.

Type	Phase (if specified)	Sensor	Interlocked equipment (if any)	Condition	Action	Reset Conditions	Fallback position	Comments
Vacuum Skid - UCB								
Temporary Interlock		PT-23610 PT-23615	PV-23611	PT-23615 - PT-23610 > ~~100mtorr (~0.133 mbar)~~ 1000 mtorr (~ 1.33 mbar)	Force PV-23611 closed whatever the valve state (Auto or Manu)	PT-23615 - PT-23610 < 50mtorr (~0.066mbar) Release PV-23611 closing action	Set PV-23611 in the mode (Manual or Auto) it was in before the interlock. If in Manu, leave it closed	Avoid risk of back filling of the Vacuum Enclosure
Temporary Interlock		PT-23610 PT-23618	PV-23616	PT-23618 - PT-23610 > ~~100mtorr (~0.133 mbar)~~ 1000 mtorr (~ 1.33 mbar)	Force PV-23616 closed whatever the valve state (Auto or Manu)	PT-23618 - PT-23610 < 50mtorr (~0.0665mbar) Release PV-23616 closing action	Set PV-23616 in the mode (Manual or Auto) it was in before the interlock. If in Manu, leave it closed	Avoid risk of back filling of the Vacuum Enclosure
Interlock		TSH-23610	EH-23610 PV-23611	TSH-23610 (Temperature over 46˚C +/-3˚C)	Force EH-23610 OFF whatever the Heater state (Auto or Manu) and force PV-23611 closed	Not TSH-23610 Release EH-23610 Interlock action. Operator action required to restart the Diffusion Pump.	Set EH-23610 in the mode (Manual or Auto) it was in before the interlock. If in Manu, leave it OFF	Diffusion Pump Heater protection
Interlock		FSL-23418	EH-23610 PV-23611	FSL-23418	Force EH-23610 OFF whatever the Heater state (Auto or Manu) and force PV-23611 closed	Not FSL-23418 Release EH-23610 Interlock action. Operator action required to restart the Diffusion Pump.	Set EH-23610 in the mode (Manual or Auto) it was in before the interlock. If in Manu, leave it OFF	Diffusion Pump Heater protection
Vacuum Skid - LCB								
Temporary Interlock		PT-23630 PT-23635	PV-23631	PT-23635 - PT-23630 > ~~100mtorr (~0.133 mbar)~~ 1000 mtorr (~ 1.33 mbar)	Force PV-23631 closed whatever the valve state (Auto or Manu)	PT-23635 - PT-23630 < 50mtorr (~0.0665mbar) Release PV-23631 closing action	Set PV-23631 in the mode (Manual or Auto) it was in before the interlock. If in Manu, leave it closed	Avoid risk of back filling of the Vacuum Enclosure
Temporary Interlock		PT-23630 PT-23638	PV-23636	PT-23638 - PT-23630 > ~~100mtorr (~0.133 mbar)~~ 1000 mtorr (~ 1.33 mbar)	Force PV-23636 closed whatever the valve state (Auto or Manu)	PT-23638 - PT-23630 < 50mtorr (~0.0665mbar) Release PV-23636 closing action	Set PV-23636 in the mode (Manual or Auto) it was in before the interlock. If in Manu, leave it closed	Avoid risk of back filling of the Vacuum Enclosure
Interlock		TSH-23630	EH-23630 PV-23631	TSH-23630 (Temperature over 46˚C +/-3˚C)	Force EH-23630 OFF whatever the Heater state (Auto or Manu) and force PV-23631 closed	Not TSH-23630 Release EH-23630 Interlock action. Operator action required to restart the Diffusion Pump.	Set EH-23630 in the mode (Manual or Auto) it was in before the interlock. If in Manu, leave it OFF	Diffusion Pump Heater protection
Interlock		FSL-23428	EH-23630 PV-23631	FSL-23428	Force EH-23630 OFF whatever the Heater state (Auto or Manu) and force PV-23631 closed	Not FSL-23428 Release EH-23630 Interlock action. Operator action required to restart the Diffusion Pump.	Set EH-23630 in the mode (Manual or Auto) it was in before the interlock. If in Manu, leave it OFF	Diffusion Pump Heater protection

Dewar Heater Interlocks (EHTR-31000)
- Interlock2.24 turns the dewar heater off if the level < 10% for one minute. Reset if level >15% for 1 minute AND operator reset
- Interlock2.25 turns the dewar heater off if the pressure > 1.7 for 5 seconds. Reset if pressure < 1.5 AND operator reset

Turbine instrumentation ranges may be added. Refer C1303 ED 300 (B)

20. APPENDIXE 3 – INSTRUMENTATION RANGES AND CALIBRATION TABLE

- Pressure Transmitters

Tag	Process Range	Manufacturer	Model	Signal Range	Range Supplier	Input Signal	Program conversion	Display
PT-22100	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22101	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22111	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22125	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22130	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22140	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22160	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22180	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22190	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22191	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22193	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22195	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22200	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22201	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22211	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22225	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22230	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22240	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22245	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22247	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22249	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22389	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22391	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22392	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22393	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm

Tag	Process Range	Manufacturer	Model	Signal Range	Range Supplier	Input Signal	Program conversion	Display
PT-22400	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22401	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22402	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22405	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22413	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22415	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22417A	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22417B	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22422	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22425	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22430	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22432	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22440	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22452	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22460	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22463	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22472	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22482	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22485	0-23 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm
PT-22505	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22510	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT-22520	0-11 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-250PSIA	4-20 mA	0-250 PSIA	0-100%	0-100%	0-17 atm
PT -23100	0-2 atm	GE UNIK	5000 PTX50C2-TB-A1-CA-HO-PF-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm

- Differential Pressure Transmitters

Tag	Process Range	Manufacturer	Model	Signal Range	Range Supplier	Input Signal	Program conversion	Display
PDT-22461	0-2 Atm	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE Pressure Range: 0-2 atm, Wet/wet differential	4-20 mA	0-2 Atm (0-2026 mbar)	0-100%	0-100%	0-2026 mbar
FT-22245	0-45 mbar	Endress+Hauser	PMD55-AA21BD67DGBHAJA2A+N3PB	4-20 mA	0-100 mbar	0-45%	0-100%	0-45 mbar
FT-22391	0-30 mbar	Endress+Hauser	PMD55-AA21BD67DGBHAJA2A+N3PB	4-20 mA	0-100 mbar	0-30%	0-100%	0-30 mbar
FT-22392	0-30 mbar	Endress+Hauser	PMD55-AA21BD67DGBHAJA2A+N3PB	4-20 mA	0-100 mbar	0-30%	0-100%	0-30 mbar
FT-22432	0-30 mbar	Endress+Hauser	PMD55-AA21BD67DGBHAJA2A+N3PB	4-20 mA	0-100 mbar	0-30%	0-100%	0-30 mbar
FT-22452	0-20 mbar	Endress+Hauser	PMD55-AA21BD67DGBHAJA2A+N3PB	4-20 mA	0-100 mbar	0-30%	0-100%	0-20 mbar
FT-22472	0-30 mbar	Endress+Hauser	PMD55-AA21BD67DGBHAJA2A+N3PB	4-20 mA	0-100 mbar	0-30%	0-100%	0-30 mbar
FT-22482	0-30 mbar	Endress+Hauser	PMD55-AA21BD67DGBHAJA2A+N3PB	4-20 mA	0-100 mbar	0-30%	0-100%	0-30 mbar
PDT-22195C	0-30 mbar	Endress+Hauser	PMD55-AA21BD67DGBHAJA2A+N3PB	4-20 mA	0-100 mbar	0-30%	0-100%	0-30 mbar
PDT-22510	0-0.2 Atm.	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE Pressure Range: 0 to 5 psi Wet/wet differential	4-20 mA	0-5 psi (0-344.738 mbar)	0-56%	0-100%	0-190 mbar
PDT-22414	0-2000 mbar	GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE Pressure Range: 0 to 2000 mbar Wet/wet differential	4-20 mA	0-2000 mbar	0-100%	0-100%	0-2000 mbar

- Superconductive Probes Transmitters

Tag	Process Range	Manufacturer	Model	Signal Range	Range Supplier	Input Signal	Program conversion	Display
LT-22195A	4.5-450 K	American Magnetics	Model 1700 He Only	4-20 mA	0-100%	0-100%	0-100%	0-100%
LT-22195B	4.5-450 K	American Magnetics	Model 1700 He Only	4-20 mA	0-100%	0-100%	0-100%	0-100%
PT -22487		GE UNIK	5000 PTX50G2-TB-A1-CA-HO-PE-500PSIA	4-20 mA	0-500 PSIA	0-100%	0-100%	0-34 atm

Information:

LT -31000	4-20 mA	0-100%	0-100%	0-100%
PDT-31005	4-20mA	0-50 inH2O (calibration)		0-124.54 mbar
PT-31005	4-20 mA	0-100 PSIA		0- 6.8947 bara
TCG31091	4-20 mA	???		
PDT22190 (FT22190)	4-20 mA	0-25inH2O		0 - 62.272 mbar

- Vacuum Gauges

Tag	Process Range	Manufacturer	Model	Signal Range	Range Supplier	Input Signal	Program conversion	Display
PT-23610	0-2 Atm	Televac	CC-10 (Part No. 2-7980-031)	0 V to 10 V linear/logarithmic	1E-09 to 1E03 Torr 0.5V/decade setting	4V-10V	1.33E(2V-17) mbar	1.33E-09 to 1.33E03 mbar
PT-23615	0-45 mbar	Granville-Phillips	275912-EU	0 V to 10 V	1.3E-3 to 1.33E3 mbar	0.375V-5.659V	*	1.3E-3 to 1.33E3 mbar
PT-23618	0-30 mbar	Granville-Phillips	275912-EU	0 V to 10 V	1.3E-3 to 1.33E3 mbar	0.375V-5.659V	*	1.3E-3 to 1.33E3 mbar
PT-23630	0-30 mbar	Televac	CC-10 (Part No. 2-7980-031)	0 V to 10 V linear/logarithmic	1E-09 to 1E03 Torr 0.5V/decade setting	4V-10V	1.33E(2V-17) mbar	1.33E-09 to 1.33E03 mbar
PT-23635	0-30 mbar	Granville-Phillips	275912-EU	0 V to 10 V	1.3E-3 to 1.33E3 mbar	0.375V-5.659V	*	1.3E-3 to 1.33E3 mbar
PT-23638	0-20 mbar	Granville-Phillips	275912-EU	0 V to 10 V	1.3E-3 to 1.33E3 mbar	0.375V-5.659V	*	1.3E-3 to 1.33E3 mbar

*Equations for calculating Pressure Versus Analog Output Voltage for the Granville-Phillips 275912-EU vacuum gauge:

Segment	Output Voltage	Equation where y = Pressure and x = Voltage	Coefficients
1	0.375 to 2.842 V	$y_{Torr} = a + bx + cx^2 + dx^3 + ex^4 + fx^5$ $y_{Pa} = (a + bx + cx^2 + dx^3 + ex^4 + fx^5) \times 133.3$ $y_{mbar} = (a + bx + cx^2 + dx^3 + ex^4 + fx^5) \times 1.333$	a −0.02585 b 0.03767 c 0.04563 d 0.1151 e −0.04158 f 0.008737
2	2.842 to 4.945 V	$y_{Torr} = \frac{a + cx + ex^2}{1 + bx + dx^2 + fx^3}$ $y_{Pa} = \left(\frac{a + cx + ex^2}{1 + bx + dx^2 + fx^3}\right) \times 133.3$ $y_{mbar} = \left(\frac{a + cx + ex^2}{1 + bx + dx^2 + fx^3}\right) \times 1.333$	a 0.1031 b −0.3986 c −0.02322 d 0.07438 e 0.07229 f −0.006866
3	4.94 to 5.659 V	$y_{Torr} = \frac{a + cx}{1 + bx + dx^2}$ $y_{Pa} = \left(\frac{a + cx}{1 + bx + dx^2}\right) \times 133.3$ $y_{mbar} = \left(\frac{a + cx}{1 + bx + dx^2}\right) \times 1.333$	a 100.624 b −0.37679 c −20.5623 d 0.0348656

21. APPENDIXE 3 – VENTURI FLOW CALCULATION

21.1 VENTURI FLOW CALCULATION - INTRODUCTION

All flow are obtained by means of venturi tubes (pressure differential devices) and calculated according to ISO 5167.

The Venturi elements are defined in the Data Sheet document C1303 DS 460 (2). The following equation is used to calculate the mass flow going through the flow element.

$$Q_m = \frac{C}{\sqrt{1-\beta^4}}.\varepsilon.\frac{\pi.d^2}{4}.\sqrt{200.\Delta P.\rho}$$ With: $Q_m[kg/s],\ d[m],\ \Delta P[mbar],\ \rho[kg/m3]$

The correction factor $k = \frac{C}{\sqrt{1-\beta^4}}.\varepsilon.\frac{\pi.d^2}{4}.\sqrt{200}$ is calculated for the design case and is considered constant. The formula is simplified:

$$Q_m = k\sqrt{\Delta P.\rho}$$

For flowmeters operating in cold temperatures (Turbine 4 inlet - FT-22482 / Cold Intercepts supply – FT-22392 / 4.5K supply – FT-22391), helium density will be calculated using two different ways:

- In higher temperature conditions (T>7K), when the Helium behaves like a perfect gas, we use the following equation:

  $\rho = P\ /\ RT$ With: $P[kPa],\ T[K],\ \ R = 8.314\ /\ 4.003 = 2.077\ J/kg.K$

- In lower temperature conditions (T<7K), density tables are provided for each flowmeter. The density shall be taken from this table based on Pressure and Temperature information.
  The density is calculated from tabulated values from Hepack thermodynamic library to be implemented in the program. The density value shall then be calculated from Pressure and Temperature:
  - · Pi, Pj, Ti, Tj and the associated density: ρii, ρij, ρji, ρjj can all be found in the input chart.
  - · P and T are measured parameter: Pi < P < Pj and Ti < T< Tj

	T_i	T	T_j
P_i	ρ_{ii}		ρ_{ij}
P		ρ	
P_j	ρ_{ji}		ρ_{jj}

$$\rho = \frac{1}{T}.\left(\frac{Pj-P}{Pj-Pi}.\frac{Tj-T}{Tj-Ti}.\rho ii.Ti + \frac{Pj-P}{Pj-Pi}.\frac{T-Ti}{Tj-Ti}.\rho ij.Tj + \frac{P-Pi}{Pj-Pi}.\frac{Tj-T}{Tj-Ti}.\rho ji.Ti + \frac{P-Pi}{Pj-Pi}.\frac{T-Ti}{Tj-Ti}.\rho jj.Tj\right)$$

Regular bi-polar interpolation has been implemented - same as in turbine H and S.

21.2 VENTURI FLOW CALCULATION - PARAMETERS

The following Table provides the coefficients to be used for each Flowmeter, as well as examples of calculation which gives an indication of the inaccuracy that can be expected from the calculation only (the inaccuracy coming from the measurement loop is indicated in Flowmeters Data Sheet document C1303 DS 460 (2)).

	C	β	d	ε	k	Pin	Tin	$\rho_{Process}$	P_{Calcul}	ρ_{Table}	ΔP	$Qm_{Process}$	Qm_{Calcul}	$Error_{Calcul}$	Qm_{Table}	$Error_{Table}$
FT-22245	1	0.414	34.3 mm	1	0.0133	3.7 bara	37.4 K	4.7 kg/m3	4.8 kg/m3	NA	45 mbar	190.5 g/s	194.3 g/s	2.0%	NA	NA
FT-22432	1	0.402	33.3 mm	1	0.0125	18.1 bara	55.5 K	15.0 kg/m3	15.7 kg/m3	NA	30 mbar	261.4 g/s	270.4 g/s	3.4%	NA	NA
FT-22452	1	0.422	34.9 mm	1	0.0138	18.0 bara	29.9 K	27.6 kg/m3	28.9 kg/m3	NA	20 mbar	318.6 g/s	331.3 g/s	4.0%	NA	NA
FT-22472	1	0.348	28.8 mm	1	0.0093	17.9 bara	16.5 K	53.1 kg/m3	52.2 kg/m3	NA	30 mbar	367.5 g/s	367.0 g/s	0.1%	NA	NA
FT-22482	1	0.400	21.9 mm	1	0.0054	17.9 bara	6.9 K	139.3 kg/m3	124.7 kg/m3	139.4 kg/m3	30 mbar	344.3 g/s	330.0 g/s	4.2%	348.9 g/s	1.3%
FT-22391	1	0.310	17.0 mm	1	0.0032	3.3 bara	4.6 K	129.9 kg/m3	34.9 kg/m3	128.9 kg/m3	30 mbar	200.0 g/s	104.2 g/s	47.9%	200.1 g/s	0.1%
FT-22392	1	0.194	8.3 mm	1	0.0008	3.0 bara	5.4 K	94.8 kg/m3	26.6 kg/m3	94.7 kg/m3	30 mbar	40.6 g/s	21.5 g/s	47.0%	40.6 g/s	0.0%

Based on the process tables provided in the next section, the program calculates the following densities:

FT-22482	6.8	6.9	6.7
17.5	139.6 kg/m3		140.7 kg/m3
17.9		139.4 kg/m3	
18.0	140.6 kg/m3		141.6 kg/m3

FT-22392	5.3	5.4	5.5
2.9	102.7 kg/m3		78.7 kg/m3
3		94.7 kg/m3	
3.1	106.6 kg/m3		91.4 kg/m3

FT-22391	4.5	4.6	4.7
3.2	130.4 kg/m3		126.5 kg/m3
3.3		128.9 kg/m3	
3.4	131.3 kg/m3		127.5 kg/m3

	C	β	d (m)	ε	k	Pin (bara)	Tin (K)	ρ process (kg/m3)	ρ calcul (kg/m3)	ΔP (mbar)	Qmprocess (g/s)	Qmcal (g/s)	Error %
FT22190	0.995	0.42254	0.04572	0.996	0.023384838	1.25	30	2.00005197	2.00609854	9.127327	99.91	100.07	0.151046
									Refer p-131				

21.3 VENTURI FLOW CALCULATION - PARAMETERS

21.3.1 FT-22482 – Density Tabulation

FT-22482																						
Density (kg/m3)		TT-22482 (K)																				
		5	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7
PT-22482 (atm)	4	124.5	122.2	119.7	117.0	113.9	110.4	106.4	101.6	95.9	89.3	82.0	75.0	68.6	63.2	58.7	54.8	51.6	48.8	46.4	44.3	42.5
	4.5	127.0	125.0	122.9	120.5	117.9	115.1	112.0	108.5	104.5	100.0	94.9	89.3	83.5	77.8	72.5	67.7	63.6	59.9	56.7	53.8	51.3
	5	129.2	127.4	125.5	123.4	121.2	118.8	116.2	113.3	110.2	106.8	102.9	98.7	94.1	89.3	84.4	79.6	75.1	70.9	67.1	63.7	60.6
	5.5	131.2	129.5	127.8	125.9	123.9	121.8	119.5	117.1	114.4	111.6	108.5	105.2	101.5	97.6	93.5	89.2	85.0	80.8	76.9	73.2	69.8
	6	133.0	131.4	129.8	128.1	126.3	124.3	122.3	120.2	117.9	115.4	112.8	110.0	106.9	103.7	100.3	96.7	92.9	89.1	85.4	81.7	78.2
	6.5	134.6	133.2	131.6	130.0	128.4	126.6	124.7	122.8	120.7	118.6	116.2	113.8	111.2	108.4	105.5	102.4	99.2	95.9	92.5	89.0	85.7
	7	136.2	134.8	133.3	131.8	130.3	128.6	126.9	125.1	123.2	121.3	119.2	117.0	114.7	112.3	109.7	107.0	104.2	101.3	98.2	95.1	92.0
	7.5	137.6	136.3	134.9	133.5	132.0	130.5	128.9	127.2	125.5	123.6	121.7	119.8	117.7	115.5	113.2	110.8	108.3	105.7	103.0	100.2	97.4
	8	138.9	137.7	136.4	135.0	133.6	132.2	130.7	129.1	127.5	125.8	124.0	122.2	120.3	118.3	116.2	114.0	111.8	109.4	107.0	104.5	101.9
	8.5	140.2	139.0	137.7	136.4	135.1	133.7	132.3	130.8	129.3	127.7	126.1	124.4	122.6	120.7	118.8	116.8	114.8	112.6	110.4	108.1	105.8
	9	141.3	140.2	139.0	137.8	136.5	135.2	133.8	132.4	131.0	129.5	128.0	126.3	124.7	123.0	121.2	119.3	117.4	115.4	113.4	111.3	109.1
	9.5	142.5	141.4	140.2	139.1	137.8	136.6	135.3	134.0	132.6	131.1	129.7	128.2	126.6	125.0	123.3	121.6	119.8	118.0	116.1	114.1	112.1
	10	143.6	142.5	141.4	140.3	139.1	137.9	136.6	135.4	134.0	132.7	131.3	129.8	128.4	126.8	125.3	123.6	122.0	120.2	118.5	116.6	114.8
	10.5	144.6	143.6	142.5	141.4	140.3	139.1	137.9	136.7	135.4	134.1	132.8	131.4	130.0	128.5	127.1	125.5	123.9	122.3	120.6	118.9	117.2
	11	145.6	144.6	143.6	142.5	141.4	140.3	139.1	138.0	136.7	135.5	134.2	132.9	131.5	130.1	128.7	127.3	125.8	124.2	122.6	121.0	119.3
	11.5	146.6	145.6	144.6	143.6	142.5	141.4	140.3	139.2	138.0	136.8	135.5	134.3	133.0	131.6	130.3	128.9	127.4	126.0	124.5	122.9	121.4
	12	147.5	146.5	145.6	144.6	143.5	142.5	141.4	140.3	139.2	138.0	136.8	135.6	134.3	133.1	131.8	130.4	129.0	127.6	126.2	124.7	123.2
	12.5	148.4	147.5	146.5	145.5	144.5	143.5	142.5	141.4	140.3	139.2	138.0	136.8	135.6	134.4	133.1	131.8	130.5	129.2	127.8	126.4	124.9
	13	149.2	148.3	147.4	146.5	145.5	144.5	143.5	142.4	141.4	140.3	139.2	138.0	136.9	135.7	134.5	133.2	131.9	130.6	129.3	128.0	126.6
	13.5	150.1	149.2	148.3	147.4	146.4	145.5	144.5	143.5	142.4	141.4	140.3	139.2	138.0	136.9	135.7	134.5	133.3	132.0	130.7	129.4	128.1
	14	150.9	150.0	149.2	148.3	147.3	146.4	145.4	144.4	143.4	142.4	141.3	140.3	139.2	138.0	136.9	135.7	134.5	133.3	132.1	130.8	129.6
	14.5	151.7	150.8	150.0	149.1	148.2	147.3	146.3	145.4	144.4	143.4	142.4	141.3	140.2	139.2	138.0	136.9	135.8	134.6	133.4	132.2	130.9
	15	152.4	151.6	150.8	149.9	149.0	148.1	147.2	146.3	145.3	144.3	143.3	142.3	141.3	140.2	139.1	138.0	136.9	135.8	134.6	133.4	132.2
	15.5	153.2	152.4	151.6	150.7	149.9	149.0	148.1	147.2	146.2	145.3	144.3	143.3	142.3	141.2	140.2	139.1	138.0	136.9	135.8	134.6	133.5
	16	153.9	153.1	152.3	151.5	150.7	149.8	148.9	148.0	147.1	146.2	145.2	144.2	143.2	142.2	141.2	140.2	139.1	138.0	136.9	135.8	134.7
	16.5	154.6	153.9	153.1	152.3	151.4	150.6	149.7	148.8	147.9	147.0	146.1	145.1	144.2	143.2	142.2	141.2	140.1	139.1	138.0	136.9	135.8
	17	155.3	154.6	153.8	153.0	152.2	151.4	150.5	149.6	148.8	147.9	147.0	146.0	145.1	144.1	143.1	142.1	141.1	140.1	139.1	138.0	136.9
	17.5	156.0	155.3	154.5	153.7	152.9	152.1	151.3	150.4	149.6	148.7	147.8	146.9	146.0	145.0	144.1	143.1	142.1	141.1	140.1	139.0	138.0
	18	156.7	155.9	155.2	154.4	153.6	152.8	152.0	151.2	150.3	149.5	148.6	147.7	146.8	145.9	145.0	144.0	143.0	142.0	141.0	140.0	139.0
	18.5	157.3	156.6	155.9	155.1	154.3	153.6	152.8	151.9	151.1	150.3	149.4	148.5	147.6	146.7	145.8	144.9	143.9	143.0	142.0	141.0	140.0
	19	158.0	157.2	156.5	155.8	155.0	154.3	153.5	152.7	151.8	151.0	150.2	149.3	148.4	147.6	146.7	145.7	144.8	143.9	142.9	141.9	141.0
	19.5	158.6	157.9	157.2	156.4	155.7	154.9	154.2	153.4	152.6	151.8	150.9	150.1	149.2	148.4	147.5	146.6	145.7	144.7	143.8	142.8	141.9
	20	159.2	158.5	157.8	157.1	156.3	155.6	154.8	154.1	153.3	152.5	151.7	150.8	150.0	149.1	148.3	147.4	146.5	145.6	144.7	143.7	142.8

21.3.2 FT-22391 – Density Tabulation

FT-22391																						
Density (kg/m3)		TT-22391 (K)																				
		4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6	6.1	6.2
PT-22391 (atm)	2.5	132.9	131.2	129.3	127.3	125.1	122.6	119.8	116.6	112.8	107.9	100.9	86.5	54.8	44.7	39.8	36.5	34.1	32.1	30.5	29.2	28.0
	2.6	133.3	131.6	129.8	127.8	125.7	123.3	120.6	117.6	114.0	109.6	103.6	94.0	70.2	51.7	44.3	40.0	36.9	34.6	32.7	31.1	29.8
	2.7	133.7	132.0	130.2	128.3	126.2	123.9	121.3	118.4	115.1	111.0	105.8	98.2	83.7	61.3	50.0	44.0	40.1	37.3	35.0	33.2	31.7
	2.8	134.1	132.4	130.7	128.8	126.8	124.5	122.0	119.3	116.1	112.3	107.6	101.2	91.0	72.5	57.0	48.8	43.8	40.3	37.6	35.4	33.7
	2.9	134.4	132.8	131.1	129.3	127.3	125.1	122.7	120.0	117.0	113.4	109.1	103.6	95.5	81.9	65.2	54.4	47.9	43.6	40.4	37.9	35.8
	3	134.8	133.2	131.5	129.7	127.8	125.7	123.3	120.8	117.9	114.5	110.5	105.5	98.8	88.5	73.5	60.8	52.7	47.3	43.4	40.5	38.1
	3.1	135.1	133.6	131.9	130.2	128.3	126.2	123.9	121.5	118.7	115.5	111.8	107.2	101.4	93.0	80.8	67.6	57.9	51.4	46.7	43.3	40.5
	3.2	135.5	134.0	132.3	130.6	128.7	126.7	124.5	122.1	119.4	116.4	112.9	108.7	103.5	96.5	86.5	74.1	63.5	55.8	50.4	46.3	43.1
	3.3	135.8	134.3	132.7	131.0	129.2	127.2	125.1	122.8	120.2	117.3	114.0	110.1	105.3	99.2	90.9	80.0	69.1	60.5	54.2	49.6	45.9
	3.4	136.1	134.7	133.1	131.4	129.6	127.7	125.6	123.4	120.9	118.1	115.0	111.3	106.9	101.5	94.3	85.0	74.5	65.4	58.3	53.0	48.9
	3.5	136.5	135.0	133.5	131.8	130.1	128.2	126.2	124.0	121.6	118.9	115.9	112.4	108.4	103.4	97.2	89.0	79.4	70.1	62.5	56.6	52.0
	3.6	136.8	135.4	133.8	132.2	130.5	128.7	126.7	124.5	122.2	119.6	116.7	113.5	109.7	105.1	99.5	92.4	83.8	74.7	66.8	60.3	55.2
	3.7	137.1	135.7	134.2	132.6	130.9	129.1	127.2	125.1	122.8	120.3	117.5	114.4	110.8	106.6	101.6	95.2	87.5	79.0	70.9	64.1	58.6
	3.8	137.4	136.0	134.5	133.0	131.3	129.6	127.7	125.6	123.4	121.0	118.3	115.3	111.9	108.0	103.3	97.7	90.7	82.8	74.9	67.8	61.9
	3.9	137.7	136.3	134.9	133.4	131.7	130.0	128.1	126.1	124.0	121.6	119.0	116.2	113.0	109.3	104.9	99.7	93.5	86.2	78.6	71.5	65.3
	4	138.0	136.7	135.2	133.7	132.1	130.4	128.6	126.6	124.5	122.2	119.7	117.0	113.9	110.4	106.4	101.6	95.9	89.3	82.0	75.0	68.6

21.3.3 FT-22392 – Density Tabulation

FT-22392																														
Density (kg/m3)		TT-22392(K)																												
		4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7
PT-22392 (atm)	2.5	132.9	131.2	129.3	127.3	125.1	122.6	119.8	116.6	112.8	107.9	100.9	86.5	54.8	44.7	39.8	36.5	34.1	32.1	30.5	29.2	28.0	26.9	26.0	25.1	24.3	23.6	23.0	22.4	21.8
	2.6	133.3	131.6	129.8	127.8	125.7	123.3	120.6	117.6	114.0	109.6	103.6	94.0	70.2	51.7	44.3	40.0	36.9	34.6	32.7	31.1	29.8	28.6	27.5	26.6	25.7	24.9	24.2	23.5	22.9
	2.7	133.7	132.0	130.2	128.3	126.2	123.9	121.3	118.4	115.1	111.0	105.8	98.2	83.7	61.3	50.0	44.0	40.1	37.3	35.0	33.2	31.7	30.3	29.1	28.1	27.1	26.3	25.5	24.8	24.1
	2.8	134.1	132.4	130.7	128.8	126.8	124.5	122.0	119.3	116.1	112.3	107.6	101.2	91.0	72.5	57.0	48.8	43.8	40.3	37.6	35.4	33.7	32.1	30.8	29.6	28.6	27.7	26.8	26.0	25.3
	2.9	134.4	132.8	131.1	129.3	127.3	125.1	122.7	120.0	117.0	113.4	109.1	103.6	95.5	81.9	65.2	54.4	47.9	43.6	40.4	37.9	35.8	34.1	32.6	31.3	30.1	29.1	28.1	27.3	26.5
	3	134.8	133.2	131.5	129.7	127.8	125.7	123.3	120.8	117.9	114.5	110.5	105.5	98.8	88.5	73.5	60.8	52.7	47.3	43.4	40.5	38.1	36.1	34.5	33.0	31.7	30.6	29.6	28.6	27.8
	3.1	135.1	133.6	131.9	130.2	128.3	126.2	123.9	121.5	118.7	115.5	111.8	107.2	101.4	93.0	80.8	67.6	57.9	51.4	46.7	43.3	40.5	38.3	36.4	34.8	33.4	32.1	31.0	30.0	29.1
	3.2	135.5	134.0	132.3	130.6	128.7	126.7	124.5	122.1	119.4	116.4	112.9	108.7	103.5	96.5	86.5	74.1	63.5	55.8	50.4	46.3	43.1	40.6	38.5	36.7	35.1	33.7	32.5	31.4	30.4
	3.3	135.8	134.3	132.7	131.0	129.2	127.2	125.1	122.8	120.2	117.3	114.0	110.1	105.3	99.2	90.9	80.0	69.1	60.5	54.2	49.6	45.9	43.0	40.7	38.6	36.9	35.4	34.0	32.8	31.8
	3.4	136.1	134.7	133.1	131.4	129.6	127.7	125.6	123.4	120.9	118.1	115.0	111.3	106.9	101.5	94.3	85.0	74.5	65.4	58.3	53.0	48.9	45.6	42.9	40.7	38.8	37.1	35.7	34.3	33.2
	3.5	136.5	135.0	133.5	131.8	130.1	128.2	126.2	124.0	121.6	118.9	115.9	112.4	108.4	103.4	97.2	89.0	79.4	70.1	62.5	56.6	52.0	48.3	45.3	42.8	40.7	38.9	37.3	35.9	34.6
	3.6	136.8	135.4	133.8	132.2	130.5	128.7	126.7	124.5	122.2	119.6	116.7	113.5	109.7	105.1	99.5	92.4	83.8	74.7	66.8	60.3	55.2	51.2	47.8	45.1	42.8	40.8	39.0	37.5	36.1
	3.7	137.1	135.7	134.2	132.6	130.9	129.1	127.2	125.1	122.8	120.3	117.5	114.4	110.8	106.6	101.6	95.2	87.5	79.0	70.9	64.1	58.6	54.1	50.4	47.4	44.9	42.7	40.8	39.1	37.6
	3.8	137.4	136.0	134.5	133.0	131.3	129.6	127.7	125.6	123.4	121.0	118.3	115.3	111.9	108.0	103.3	97.7	90.7	82.8	74.9	67.8	61.9	57.1	53.1	49.8	47.1	44.7	42.6	40.8	39.2
	3.9	137.7	136.3	134.9	133.4	131.7	130.0	128.1	126.1	124.0	121.6	119.0	116.2	113.0	109.3	104.9	99.7	93.5	86.2	78.6	71.5	65.3	60.2	55.9	52.3	49.3	46.7	44.5	42.6	40.8
	4	138.0	136.7	135.2	133.7	132.1	130.4	128.6	126.6	124.5	122.2	119.7	117.0	113.9	110.4	106.4	101.6	95.9	89.3	82.0	75.0	68.6	63.2	58.7	54.8	51.6	48.8	46.4	44.3	42.5

22. APPENDIXE 4 – CONTROL LOOPS PID VALUES

Control Loops PID values are very preliminary, based on JLAB CHL2 and Air Liquide experience.

22.1 CONTROL LOOPS PID - ALLEN BRADLEY PLC EQUATION:

$$\mathrm{M(n)} = \mathrm{KP} \times \mathrm{E(n)} + \mathrm{KI} * \sum_i [\mathrm{E(i)} \times \mathrm{dT(i)}] + \mathrm{KD} \times \frac{\mathrm{E(n)} - \mathrm{E(n-1)}}{\mathrm{dT(n)}} + \mathrm{Mr}$$

Taking first differential yields

$$del\mathrm{M(n)} = \mathrm{KP} \times [\mathrm{E(n)} - \mathrm{E(n-1)}] + \mathrm{KI} \times \mathrm{E(n)} \times \mathrm{dT(n)} + \mathrm{KD} \times \left[\frac{\mathrm{E(n)} - \mathrm{E(n-1)}}{\mathrm{dT(n)}} - \frac{\mathrm{E(n-1)} - \mathrm{E(n-2)}}{\mathrm{dT(n-1)}}\right]$$

$$dm = \mathrm{kp} \times \mathrm{de} + \mathrm{ki} \times \mathrm{e} \times \mathrm{dt} + \mathrm{kd} \times \left(\frac{de}{dt} - \frac{dep}{dtp}\right)$$

- If dm > Max change, then dm = Max Change.
- If dm < Min Change, then dm = 0

Positive gains are for a Reverse-acting PID loop, Negative gains are for a Direct-acting one.

Function	Description	Tag
Delta time		dt
Previous delta time		dtp
		derr
	Previous delta error	dep
Current error	process value minus set point	e
Previous process value		VAL
Delta error	Current error minus previous error	de
Previous error	Previous error	err
Proportional component	KP times delta error	p
Integral component	KI times current error times delta time	i
Derivative component		d
	Sum of proportional, integral and derivative components	Dm
Sample Time	Time between executions of the pid loop. Shown as “ST”	Mdt

22.2 CONTROL LOOPS PID - HP LINE LINE AND ADSORBERS

Control Loop	Action	Gp	Gi	Gd
PIC-22405	Indirect	8.0	0.2	0
TIC-22400	Direct	-3.0	-0.01	0
TIC-22418A	Indirect	1.5	0.01	0
TIC-22418B	Indirect	1.5	0.01	0
TIC-22465	Indirect	1.5	0.01	0
LIC-22520	Indirect	5.0	0.5	0

22.3 CONTROL LOOPS PID - TURBINES

Control Loop	Action	Gp	Gi	Gd
SIC-22432	Indirect	5.0	0.01	0
TIC-22332	Direct	-1.5	-0.005	0
SIC-22452	Indirect	5.0	0.01	0
TIC-22352	Direct	-1.5	-0.005	0
SIC-22472	Indirect	5.0	0.01	0
TIC-22372	Direct	-1.5	-0.005	0
SIC-22482	Indirect	5.0	0.01	0
TIC-22466	Indirect	1.5	0.005	0
PIC-22436	Indirect	3.0	0.2	0
EIC-22436	Direct	-0.5	-0.005	0
PIC-22456	Indirect	3.0	0.2	0
EIC-22456	Direct	-0.5	-0.005	0
PIC-22476	Indirect	3.0	0.2	0
EIC-22476	Direct	-0.5	-0.005	0
PIC-22486	Indirect	3.0	0.2	0
EIC-22486	Direct	-0.5	-0.005	0

22.4 CONTROL LOOPS PID – COLD END

Control Loop	Action	Gp	Gi	Gd
TIC-22485	Indirect	3.0	0.01	0
TIC-22389	Direct	-0.5	-0.005	0
PIC-22393	Direct	-3.0	-0.2	0
PIC-22485	Indirect	3.0	0.005	0
PIC-22392	Direct	-3.0	-0.005	0
PIC-22390	Direct	-15.0	-0.5	0
PIC-22391	Direct	-3.0	-0.005	0
PIC-22193	Direct	-20.0	-2.0	0
PIC-22194	Direct	-2.0	-0.1	0
LIC-22195A	Indirect	2.0	0.02	0
LIC-22195B	Direct	-0.2	-0.02	0
LIC-22390	Indirect	0.5	0.02	0
LIC-31000	Direct	-0.2	-0.02	0

22.5 CONTROL LOOPS PID – WARM AND COLD SHIELDS

Control Loop	Action	Gp	Gi	Gd
DPIC-22241	Indirect	0.5	0.01	0
DPIC-22242	Direct	-0.5	-0.01	0
PIC-22191	Direct	-3.0	-0.1	0
TIC-22392	Direct	-1.5	-0.05	0