Base Load Power Hub (BLPH)

Relief, Vent and Blowdown Report

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Table of contents

1 INTRODUCTION 6
1.1 PROJECT OVERVIEW 6
1.1.1 Project Location 6
1.1.2 Project Concept 7
2 DOCUMENT SCOPE 9
2.1 REFERENCES 9
2.2 DEFINITIONS AND ABBREVIATIONS 12
3 PSV CALCULATION METHODOLOGY 13
3.1 GENERAL 13
3.2 PSV RELIEF SIZING 13
3.2.1 Fire case 13
3.2.2 Blocked outlet 16
3.2.3 Control valve failure 16
3.2.4 Check valve leakage or Failure 16
3.2.5 Determination of PSV orifice size 17
3.3 PSV CALCULATION SUMMARY 18
4 BLOWDOWN SYSTEM 19
4.1 BASIS AND METHODOLOGY 19
4.2 SYSTEM VOLUMES 20
4.3 BLOWDOWN CALCULATION results SUMMARY 22
4.3.1 Emergency case (FIRE) 22
4.3.2 Low Temperature Depressurization case 25
5 VENT NETWORK SIZING 27
5.1 DESIGN CRITERIA 27
5.1.1 Linea upstream of PSVs 27
5.1.2 Lines downstream of Relieving Devices 27
5.1.3 Hydrogen Vent Knock-out Drum 27
5.2 Vent Network Design Data 27
5.3 Vent Network Simulation Model 27
5.4 Definition of the Main Relief Loads 28

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5.5 RESULTS 29
5.5.1 Vent Network Back Pressures 29
5.5.2 Vent Network Line Sizing 29

6 APPENDICES 30

6.1 APPENDIX 01 – PSV CALCULATION SHEETS 31

6.2 APPENDIX 02 –INTERNAL PRESSURE, OUTER AND INNER VESSEL WALL TEMPERATURE DURING AUTOMATIC DEPRESSURIZATION 40

6.3 APPENDIX 03 –DUCTILE RUPTURE CRITERION 41

6.4 APPENDIX 04 –VENT NETWORK DESIGN (pressure(barg)/massflow(kg/h)/size(inches)) – governing scenario 44

6.5 APPENDIX 05 - VENT NETWORK DESIGN (mach/velocity(m/s)/rho*v2(pascal)) – governing scenario 45

6.6 APPENDIX 06 – VENT NETWORK DESIGN (pressure(barg)/massflow(kg/h)/size(inches)) – PSVs OPEN CASE 46

6.7 APPENDIX 7 – VENT NETWORK DESIGN (mach/velocity(m/s)/rho*v2(pascal)) – PSVs OPEN CASE 47

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List of Figures

Figure 1 HOLLANDSE KUST NOORD WIND PARK Location Map 6
Figure 2 - Wind Park Details 7
Figure 3 – BLPH Concept 7
Figure 4 – General procedure for optimizing design of the depressuring 15
Figure 5 – Main Vessel V-25001A to F and surrounding piping system (schematic) 20
Figure 6 – System characteristics 22
Figure 7 – System Stefan-Boltzmann Fire Model 23
Figure 8 –Results summary 23
Figure 9 –Simultaneous cumulative blowdown flowrate (Emergency Fire Case) 24
Figure 10 – System characteristics 25
Figure 11 – Results summary 26

List of Tables

Table 1 - Definitions 12
Table 2 - Abbreviations 12
Table 3 – API Std 526 Designation orifices 17
Table 4 – PSV calculation summary 18
Table 5 – Blowdown sizing and verification basis 19
Table 6 – Major inventory system as per above figure 20
Table 7 – Blowdown sizing and verification basis 21
Table 8 – Blowdown sizing results summary (EMERGENCY CASE-FIRE) (15 min depressurization) 22
Table 9 – Main Relief Loads 28
Table 10 – Network back pressures 29

1 INTRODUCTION

1.1 PROJECT OVERVIEW

Crosswind, a Shell and Eneco joint venture, was awarded the tender to develop the offshore Hollandse Kust Noord (HKN) wind farm, located 18.5km off the coast of Netherlands near the town of Egmond aan Zee. The consortium plans to have HKN operational in 2023 with an installed capacity of 759MW generating at least 3.3TWh per year. This is sufficient renewable power to supply more than 1 million Dutch households with green electricity.

Offshore wind farms produce intermittent electricity and balancing these dips and peaks and integrating this electricity into the national energy system requires new technologies. For this reason, the offshore wind farm will include several new technologies that could be implemented at full-scale in the future. The new technologies being explored include a floating solar park, a short-duration battery storage as well as long-term storage via green hydrogen produced by water electrolysis and subsequently consumed in a fuel cell. The combination of these individual measures, herein referred to as the Base Load Power Hub (BLPH) will ensure a continuous power supply regardless of the wind situation.

1.1.1 Project Location

The Hollandse Kust Noord (HKN) wind farm is located 18.5km off the coast of the Netherlands near the town of Egmond aan Zee.

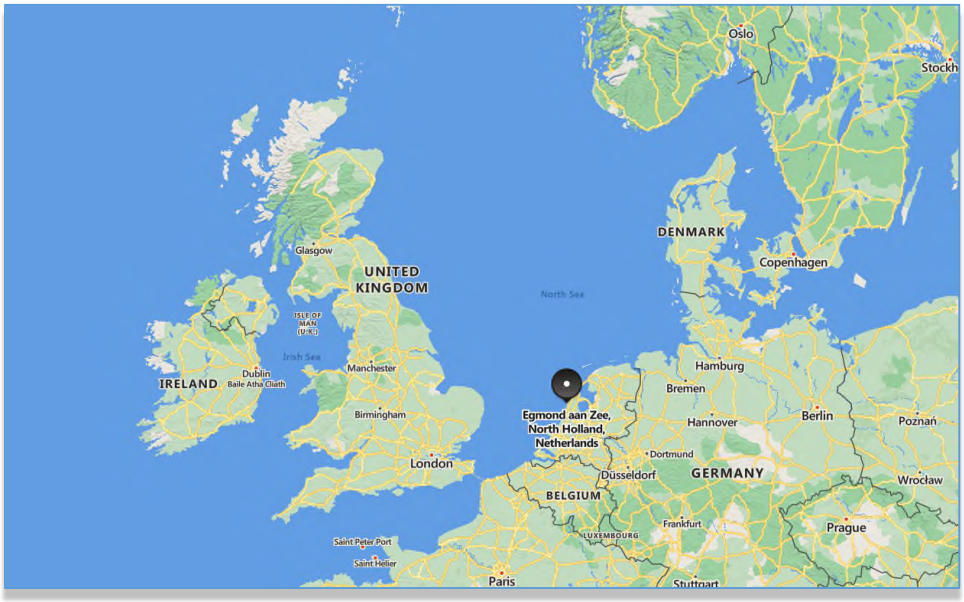


Figure 1 HOLLANDSE KUST NOORD WIND PARK Location Map

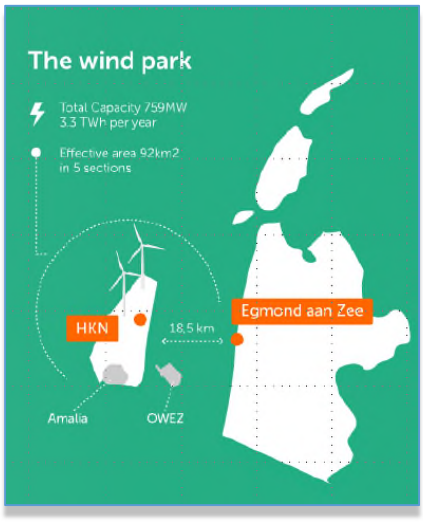


Figure 2 - Wind Park Details

The wind farm will consist of No. 69 x 11.5MW wind turbine generators each to be installed on a dedicated monopile structure. A 70th monopile located on coordinates E 590719.1, N 5841602.3 is reserved for installing the platform accommodating the BLPH. The monopile structure was designed and installed by Van Oord Offshore Wind (VooW) and therefore not part of the BLPH scope.

1.1.2 Project Concept

All components included in the BLPH will be integrated onshore on a topsides and installed in an offshore location within the boundaries of the HKN wind farm. At its simplest, the BLPH will store energy during periods of high electricity generation from renewable sources (a wind turbine generator and the floating solar PV farm) and release it during periods of low generation. In practice. It is expected that the energy stored will supplement generation from renewable sources to ensure that at least 1.0MW of power is exported to the electrical grid regardless of wind/solar availability.

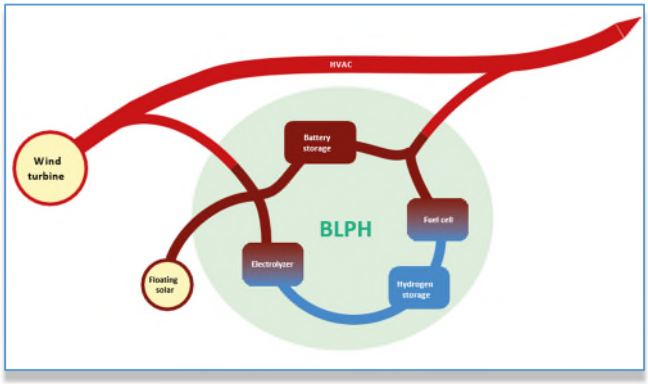


Figure 3 – BLPH Concept

Electricity in the BLPH will be stored in the form of electrons in a battery energy storage system (BESS) as well as converted into green hydrogen via water electrolysis. When the power output from the connecting wind turbine drops to below 1 MWe, the BLPH will return its stored energy to supplement the remaining power output. This will be by discharging the BESS, while stored hydrogen will be converted back into electricity using a fuel cell to extend the discharge duration.

The purpose of the BLPH is to function as a testbed for the integration of energy storage technologies with renewable generation. It is expected that equipment installed on the BLPH will operate as Normally Unmanned Installation for at least two (2) years with no or minimal maintenance and it will have its own independent control room with the ability to communicate with Crosswind's control room.

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2 DOCUMENT SCOPE

This document presents the basis, methodology and results of the relief, depressurization and vent network analysis for the BLPH offshore project.

The main scope of this analysis consists of:

A. summarize the findings of PSV calculations

B. to size the restriction orifices adequate to conduct the depressurization function intended/needed

C. to determine the peak blowdown flow rate establishing the relief load for the venting system

D. as well as, to establish the lowest fluid/metal temperature experienced during depressurization which would be used to determine the appropriate material specification for the relief/blowdown piping systems

E. to obtain the applicable backpressures and other conditions of the tailpipe/relief header during the relieving / depressurization scenarios based on the depressurization/blowdown study performed on the equipment and piping included in the BLPH Project

All references as provided in the reference list apply to the review of this document.

2.1 REFERENCES

Project Documents

Ref. [1] Basic Design Engineering Package - Document No: K559-2254-PM-PLN-003, REV.02

Ref. [2] Heat And Mass Balance - Document No: 123A90-DDL-PR-BL-80002, REV.01

Ref. [3] Equipment Sizing Philosophy and Calculations – Document No: 123A90-DDL-PR-CA-80033, REV.02

Ref. [4] BLPH PROCESS FLOW SCHEME ELECTROLYSER AND HYDROGEN DRYING PACKAGE – Document No: 123A90-DDL-PR-DG-80003, REV.03

Ref. [5] BLPH PROCESS FLOW SCHEME HYDROGEN STORAGE – Document No: 123A90-DDL-PR-DG-80004, REV.02

Ref. [6] BLPH PROCESS FLOW SCHEME FUEL CELL PACKAGE – Document No: 123A90-DDL-PR-DG-80005, REV.02

Ref. [7] BLPH UTILITY FLOW DIAGRAM WATER TREATMENT PLANT – Document No: 123A90-DDL-PR-UFD-80006, REV.03

Ref. [8] BLPH UTILITY FLOW DIAGRAM INSTRUMENT AIR AND NITROGEN SYSTEMS – Document No: 123A90-DDL-PR-UFD-80007, REV.03

Ref. [9] BLPH UTILITY FLOW DIAGRAM VENT SYSTEMS – Document No: 123A90-DDL-PR-UFD-80008, REV.03

Ref. [10] BLPH PIPING AND INSTRUMENTATION DIAGRAM GENERAL NOTES – Document No: 123A90-DDL-PR-PID-80009, REV.03

Ref. [11] BLPH PIPING AND INSTRUMENTATION DIAGRAM PIPING SYMBOLOGY – Document No: 123A90-DDL-PR-PID-80010, REV.02

Ref. [12] BLPH PIPING AND INSTRUMENTATION DIAGRAM ELECTROLYSER PACKAGE – Document No: 123A90-DDL-PR-PID-80011, REV.04

Ref. [13] BLPH PIPING AND INSTRUMENTATION DIAGRAM FUEL CELL PACKAGE – Document No: 123A90-DDL-PR-PID-80012, REV.04

Ref. [14] BLPH PIPING AND INSTRUMENTATION DIAGRAM HYDROGEN STORAGE VESSELS HEADER (INLET) – Document No: 123A90-DDL-PR-PID-80013, REV.02

Ref. [15] BLPH PIPING AND INSTRUMENTATION DIAGRAM HYDROGEN STORAGE VESSELS HEADER (OUTLET) – Document No: 123A90-DDL-PR-PID-80014, REV.03

Ref. [16] BLPH PIPING AND INSTRUMENTATION DIAGRAM HYDROGEN STORAGE VESSEL A – Document No: 123A90-DDL-PR-PID-80015, REV.03

Ref. [17] BLPH PIPING AND INSTRUMENTATION DIAGRAM HYDROGEN STORAGE VESSEL B – Document No: 123A90-DDL-PR-PID-80016, REV.03

Ref. [18] BLPH PIPING AND INSTRUMENTATION DIAGRAM HYDROGEN STORAGE VESSEL C – Document No: 123A90-DDL-PR-PID-80017, REV.03

Ref. [19] BLPH PIPING AND INSTRUMENTATION DIAGRAM HYDROGEN STORAGE VESSEL D – Document No: 123A90-DDL-PR-PID-80018, REV.03

Ref. [20] BLPH PIPING AND INSTRUMENTATION DIAGRAM HYDROGEN STORAGE VESSEL E – Document No: 123A90-DDL-PR-PID-80019, REV.03

Ref. [21] BLPH PIPING AND INSTRUMENTATION DIAGRAM HYDROGEN STORAGE VESSEL F – Document No: 123A90-DDL-PR-PID-80020, REV.03

Ref. [22] BLPH PIPING AND INSTRUMENTATION DIAGRAM SEA-WATER INTAKE SYSTEM SHEET 1 – Document No: 123A90-DDL-PR-PID-80021, REV.04

Ref. [23] BLPH PIPING AND INSTRUMENTATION DIAGRAM SEA-WATER INTAKE SYSTEM SHEET 2 – Document No: 123A90-DDL-PR-PID-80022, REV.03

Ref. [24] BLPH PIPING AND INSTRUMENTATION DIAGRAM WATER TREATMENT PLANT SHEET 1 – Document No: 123A90-DDL-PR-PID-80023, REV.02

Ref. [25] BLPH PIPING AND INSTRUMENTATION DIAGRAM WATER TREATMENT PLANT SHEET 2 – Document No: 123A90-DDL-PR-PID-80024, REV.03

Ref. [26] BLPH PIPING AND INSTRUMENTATION DIAGRAM WATER DISPOSAL SHEET 1 – Document No: 123A90-DDL-PR-PID-80025, REV.05

Ref. [27] BLPH PIPING AND INSTRUMENTATION DIAGRAM WATER DISPOSAL SHEET 2 – Document No: 123A90-DDL-PR-PID-80026, REV.04

Ref. [28] BLPH PIPING AND INSTRUMENTATION DIAGRAM INSTRUMENT AIR PACKAGE – Document No: 123A90-DDL-PR-PID-80027, REV.03

Ref. [29] BLPH PIPING AND INSTRUMENTATION DIAGRAM HYDROGEN VENT HEADER – Document No: 123A90-DDL-PR-PID-80028, REV.03

Ref. [30] BLPH PIPING AND INSTRUMENTATION DIAGRAM HYDROGEN VENT DRUM – Document No: 123A90-DDL-PR-PID-80029, REV.04

Ref. [31] BLPH PIPING AND INSTRUMENTATION DIAGRAM Instrument air distribution header – Document No: 123A90-DDL-PR-PID-80041, REV.05

Ref. [32] BLPH PIPING AND INSTRUMENTATION DIAGRAM instrumentation SYMBOLOGY – Document No: 123A90-DDL-PR-PID-80042, REV.02

Ref. [33] BLPH PIPING AND INSTRUMENTATION DIAGRAM - OPEN DRAIN SYSTEM – Document No: 123A90-DDL-PR-PID-80043, REV.01

Ref. [34] PIPE MATERIAL CLASS – Document No: 123A90-DDL-PP-SP-70000, REV.02

Ref. [35] Batch of ISOMETRIC DRAWINGs, REV.02

International Codes and Standards

For a list of external, Industry and/or Vendor Standards as well as for a list of Shell DEPs that shall be applied to the project, reference shall be made to Section 10 of Ref. [1].

In addition to the above, also the following have to be taken into account:

Ref. [36] "ON THE ADEQUACY OF API 521 RELIEF-VALVE SIZING METHOD FOR GAS-FILLED PRESSURE VESSELS EXPOSED TO FIRE" – Article published on Safety 2018, 4, 11; doi:10.3390/safety4010011

Ref. [37] "GUIDELINES FOR THE PROTECTION OF PRESSURISED SYSTEMS EXPOSED TO FIRE" – Scandpower Risk Management AS – Rep.N° 27.207.291/R1 – Version 2 – 31 March 2004

Ref. [38] "CRANE TECHNICAL PAPER No.410M" – 1982

Vendor Documents

Ref. [39] INSTRUMENTS DATA SHEETS (INCLUDING SIZING CALCULATION SHEETS) - PRESSURE SAFETY VALVES – Document No: 1724000518-IN-DS-00004. REV.05

2.2 DEFINITIONS AND ABBREVIATIONS

DEFINITIONS

COMPANY or Client (CPY):	Crosswind
CONTRACTOR (CTR):	ROSETTI MARINO S.p.A.
PROJECT:	HOLLANDSE KUST NOORD WIND PARK Project

Table 1 - Definitions

ABBREVIATIONS

BD	blowdown
BDV	blowdown valve
BESS	battery energy storage system
BFD	block flow diagram
BLPH	base load power hub
c.a.	corrosion allowance
CPI	company provided item
CS	carbon steel
CV	control valve
ΔP	pressure drop
DEP	Design Engineering Practice
D/S	downstream
FC	fuel cell
FEED	front-end engineering design
H&MB	heat and material balance
KOD	knock out drum
IA	instrument air
ID	internal diameter
ISBN	international standard book number
JT	Joule-Thomson
LP	low pressure
Ma	Mach number
MSm^3/d	millions of standard cubic meters per day (@ 1 atm and 15°C)
MW	molecular weight
N.A.	not applicable
OD	outside diameter
P&ID	piping & instrumentation diagram
PFD	process flow diagram
PSV	pressure safety relief valve
RO	restriction orifice
SDV	shut down valve
SS	stainless steel
TL/TL	tangent line to tangent line
THK	thickness
UFD	utility flow diagram
U/S	upstream

Table 2 - Abbreviations

3 PSV CALCULATION METHODOLOGY

3.1 GENERAL

There are several causes of overpressure related to process equipment or lines. They are either the result of an accumulation of liquid and/or gas (blocked outlet case, gas blow-by, control valve failure), the result of a fire (wetted or unwetted), the back flow due to check valve failure or tube rupture.

Within the limits of this project not all the above-mentioned cases are applicable for the following reasons:

- the gas coming out from the Electrolyser package A-20000 is normally dry and technically pure (99.9%mol H2) according to ISO 14687-2019 Type I, Grade E, Cat.3
- the gas is then transferred through pipes inside the pressure vessels V-25001A/B/C/D/E/F where is temporarily accumulated and stored, in order to be consumed on demand by the FC package A-80000

In particular, calculations are based on equations provided in *Sizing, Selection, and Installation of Pressure-Relieving Devices, Part I* (API STD 520 Part I) and Pressure-relieving & Depressuring Systems (API STD 521).

PSV orifices have been selected in accordance with Flanged Steel Pressure-Relief Valves (API STD 526). As per good engineering practice, the number and orifice size as well as the final data of PSVs shall be confirmed by the nominated VENDOR.

3.2 PSV RELIEF SIZING

Relief system loads and resulting sizes are determined in accordance with API STD 520 – Part I, API STD 521, DEP 80.45.10.10-Gen. and DEP 80.45.10.11-Gen.

The PSVs sizing activity is performed using the Aspen HYSYS (V12.1) Pressure Relief sub-flowsheet anywhere applicable and in addition, for those PSVs valves that are involved in the unwetted fire cases (such as 25-PSV-001A to F) the dynamic tool of HYSYS (named "Depressuring") has been utilized in order to better simulate the behavior of fluid and the vessel under the contemporary effect of fire attack and PSV action in dynamic mode.

3.2.1 Fire case

In general, if the relief temperatures in case of fire found using the methodologies explained below are greater than 500°C, the mechanical integrity of CS piping or of the CS vessels cannot be ensured. Usually, if such conditions were established, the smallest PSV is commonly retained whatever the relief rate.

3.2.1.1 Unwetted vessel fire case

The required capacity of the PSV corresponds to the thermal expansion of the gas contained in the vessel due to fire after the internal pressure has risen from the operating to the relieving value. Moreover, it is assumed that the amount of heat absorbed by a vessel exposed to an open fire does not take credit from the fire-fighting system. Assuming that the Jet-Fire scenario may be the possible event, API STD 521 (section 4.4.13.4) states that due to the localized nature of heating (whereby the bulk fluid temperature might not increase appreciably), a relief device (i.e. overpressure protection device) might not prevent vessel failure from jet fire impingement and protection against jet fires focuses on prevention of leaks through proper

maintenance and/or mitigation systems such as external insulation, depressuring systems, isolation of leaks, equipment and/or flange orientation and minimization and emergency response. On the other hands, unlike pool fire, a jet fire can, in essence, be "turned off" through isolation and depressurization of the jet fire source. Moreover, multiple studies show that in many cases, the installation of a PRV offers little or no protection therefore it provides an unfounded sense of security. Often and in many cases the vessel wall is weakened by high temperatures, before the PRV relieving pressure is reached. Thus, a transient thermomechanical response analysis has been carried out to accurately determine vessel rupture time. In general, it is demonstrated worldwide that only vessels with relatively thick walls may get a benefit from the presence of a PRV, while for most cases no appreciable increase in the vessel survival time beyond the onset of relief is observed.

Therefore, as mentioned before, we recommend that extreme caution should be taken, if and when designing relief systems for gas-filled vessels, and we propose the following recommendations:

- Never base relief valve sizing for gas-filled vessels on API 521 equations–except maybe for early phase studies. For detailed design and actual installation purposes, always base relief valve sizing on dynamic simulations with rigorous modelling of the heat transfer process in order to avoid grossly oversized PRVs
- Carefully consider if the vessel survival time actually benefits from an installed PRV by performing thermomechanical calculations of the vessel rupture time and taking the chosen material properties into account
- If the vessel rupture time is not significantly prolonged by the presence of a PRV, consider alternative means for protecting the vessel, such as e.g., insulation, fireproofing or even better, blowdown activated by fusible plugs or equivalent detection, deluge systems.

In case of protection against jet fire, never rely on a PRV; always consider alternative means of protection even if in conjunction with PRV (Ref. [37]). In particular for this project a blowdown system has been foreseen as an alternative means of protection against jet fire attack; however, additional protection (i.e.: fireproofing on vessel saddles) can be provided to furtherly reduce the risk of collapse.

3.2.1.1.1 Fire Heat Flux Modelling

The net heat flux (global) is calculated based on the Stefan–Boltzmann fire equation, being more appropriate to mimicking the jet-fire attack. The general formula is as follows:

$$Q_{fire} = \alpha_s \cdot \sigma \cdot \left(\varepsilon_f \cdot T_f^4 - \varepsilon_s \cdot T_s^4\right) + h_f \cdot \left(T_f - T_s\right)$$

Where:

- Q_{fire}: heat absorbed by a segment (W/m^2)
- σ: Stefan–Boltzmann constant, 5.67×10^{-8} ($W/m^2\ K^4$)
- T_f: flame temperature (K)
- T_{amb}: ambient temperature (K)
- h_f: flame convective heat transfer coefficient ($W/m^2\ K$)
- α_s: surface absorptivity
- ε_s: surface emissivity
- ε_f: flame emissivity
- T_s: segment temperature (K) (time dependent)

The above values are shown for 25PSV001A to F along APPENDIX 01 – PSV CALCULATION SHEETS

3.2.1.1.2 Methodology for failure criterion

A failure criterion for the material applied in the process vessels is established according to the appendix C of Scandpower guideline (Ref. [37]). See Appendix 03 for further information.

Based on the dynamic study of the P(time), T(time) and the failure criterion it can be decided whether parts of the process equipment will rupture or not. It is worth to note that T(time) will vary for the different elements of the process segment. For the purposes of this report the main vessel failure has been taken into account having the most exposed surface to any potential jet-fire. Moreover, the main objective and recommendation is to prevent a small fire from escalating to a large fire. In general, the following flowchart has been taken into account for both depressurization and PSV dynamic study:

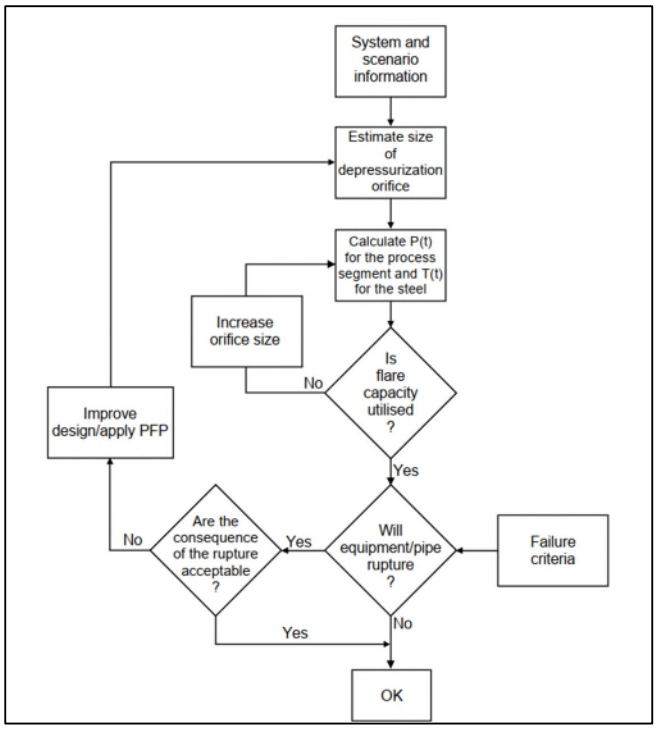


Figure 4 – General procedure for optimizing design of the depressuring

As demonstrated through the verification carried-out in APPENDIX 6.3 the pressure vessels V-25001AtoF will not reach the burst pressure of ductile rupture within 15 minutes.

3.2.1.2 Wetted vessel fire case

It is not covered in this specific project as there is no liquid normally inside the large hydrogen vessels. On the contrary, if one assumes either the presence of liquid water, where normally there isn't liquid water, and an accidental fire scenario simultaneously, this will lead to admit a "double jeopardy" event; the American Petroleum Institute's Standard API521 indicates that designing a relief system for double jeopardy is not

required on the grounds that simultaneous failures impacting relief sizing are unlikely to be credible scenarios.

The above considerations can be replicated for unwetted/wetted piping systems.

3.2.2 Blocked outlet

For a vessel or a line handling only gas, the required capacity of the PSV is the gas flow rate. API STD 520 Part I §5.6 is used for PSV orifice area calculation.

3.2.3 Control valve failure

Control valve failure occurs when an upstream control valve becomes fully open. When a control valve fails in the fully open position (100% opening), the downstream side process must be considered for protection with a PSV (or rupture disk) because it may not be designed to handle the additional flow and pressure level. Calculation routines take into account control valve CV calculation and cover a gas break-through situation, which is one of the most frequent scenarios encountered. In general, the relief load calculations for control valve failure are applicable to all Relieving Phase Methods and for this particular project only gas phase has been considered applicable.

3.2.4 Check valve leakage or Failure

Calculation of reverse flow through failed check valves have been considered. Check valve leakage or failure may affect the nitrogen network in terms of overpressure. Thus the relevant valve 64-PSV-001 has been sized to mitigate the effects of a remote back flow from hydrogen systems to which it is directly connected.

The potential flowrate is estimated according to the modified Darcy equation as per CRANE methodology (Ref. [38]).

3.2.5 Determination of PSV orifice size

According to API Std 526 Flanged Steel Pressure Relief Valves and the required calculated orifice area (defined by above calculation methods), a standard PSV orifice area is selected.

The following standard orifice sizes are summarized in the table below:

Designation	Effective Orifice Area (in^2)
D	0.110
E	0.196
F	0.307
G	0.503
H	0.785
J	1.287
K	1.838
L	2.853
M	3.600
N	4.340
P	6.38
Q	11.05
R	16.0
T	26.0

Table 3 – API Std 526 Designation orifices

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3.3 PSV CALCULATION SUMMARY

The following table summarizes applicable scenarios and sizing results of each PSV, the detailed calculation are shown through the Appendix 01 Section.6.1:

PSV TAG	PID n°	Type	Set P (barg)	Case	Calc. load (kg/h)	Rated Flow (kg/h)	Vendor Rated Flow (kg/h) Ref. [39]	PSV size
25-PSV-001A to F (*)	123A90-DDL-PR-PID-80015 to PID-80020	Conventional	40	Fire	627	1067	1016.22	1E2 300lbX150lb
80-PSV-001	123A90-DDL-PR-PID-80012	Conventional	10	Bloc.disch	106	185		1D2 150lbX150lb
				CV fail	2679	3095	2921.12	3K4 150lbX150lb
64-PSV-001	123A90-DDL-PR-PID-80027	Conventional	10	Bloc.disch	61.4	690.4	662.424	1D2 150lbX150lb
				Reverse flow (H2 from vessel)	23.8	185		1D2 150lbX150lb

Table 4 – PSV calculation summary

(*) The PSV set pressure is reached only after 4.4 minutes and after that time the PSV valve starts to discharge at a pressure slightly above the set pressure value (~44 bara) as shown along the below APPENDIX 01 – PSV CALCULATION SHEETS.

See APPENDIX 01 – PSV CALCULATION SHEETS

4 BLOWDOWN SYSTEM

4.1 BASIS AND METHODOLOGY

The blowdown simulations are performed using the Aspen HYSYS (V12.1) BLOWDOWN™ TOOL (by Imperial college of London). The individual blowdown system volume (piping & equipment volume) has been modelled in HYSYS BLOWDOWN™ TOOL. It is worth to note that the largest part of the volumes is constituted by the large pressure vessels V-25001A to F, while a very minor part of the gas inventory is enclosed within the surrounding piping system.

Two blowdown cases have been performed:

a) Emergency Fire Blowdown: the system is depressurized under the emergency fire case of each isolated section to 7.0 barg (or 50% of the design pressure whichever is the lowest) for restriction orifice sizing purposes. In addition, the same failure criterion has been applied as described in the above para.3.2.1.1.2

b) Low Temperature depressurization case: the system is depressurized to 0 barg with the assumption that it has attained the minimum ambient temperature -8.4 °C and normal operating pressure of 30 barg of the isolated section. Basically, after the induced shutdown (say for the maintenance case), the system is allowed to cool down from the initial temperature (25°C) to the minimum ambient temperature (-8.4°C). The new pressure is calculated by the simulation with the above-mentioned blowdown tool.

The blowdown sizing and verification basis for the 25-BDV-005/007/010/013/016/019 are as follows:

BLOWDOWN	INITIAL PRESS.	INTIAL TEMP.	LIQUID LEVEL	INPUT PARAMETERS	FINAL PRESSURE AND BD TIME
Emergency fire	30 barg	Normal operating (25°C)	0.00	Fire type: Detailed- Stefan Boltzman Ambient medium: Air Ambient Temperature: 10.5˚C Ambient Fluid Speed: ~10 m/s Back Pressure:0.835barg	7 barg or 50% of vessel design pressure (20barg) whichever is more stringent within 15 minutes (900 sec)
Low Temperature depressurization case	30 barg (~28 barg is reached after the isochoric cooldown)	Lowest (-8.4°C)	0.00	Fire type: NONE Ambient medium: Air Amb. Temperature: -8.4˚C Amb. Fluid Speed: ~10 m/s Back Pressure:0barg	0 barg and BD time as per calculation

Table 5 – Blowdown sizing and verification basis

The thickness of vessels V-25001A to F has been considered 44mm thick (it is worth to note that shell thickness variation may affect the blowdown calculation, since the mass of steel (and its thickness) contributes to the heat flux transfer phenomenon and to the relevant capacity of energy flux absorption).

4.2 SYSTEM VOLUMES

At the present stage of the project the system volume consists approximately of the following arrangement for each large pressure vessel V-25001A to F:

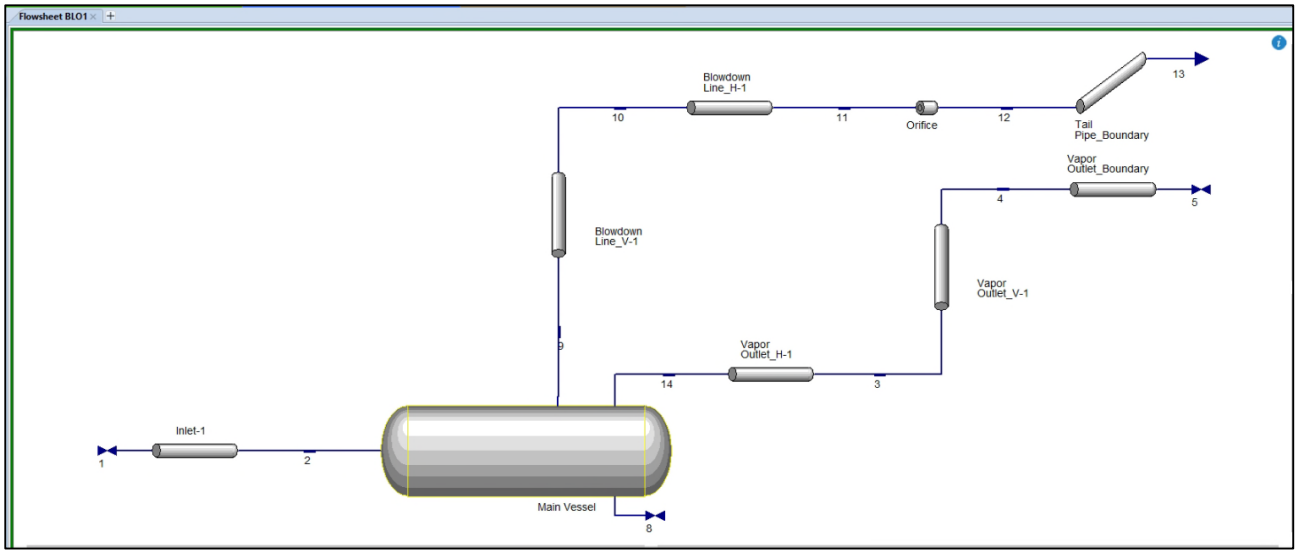


Figure 5 – Main Vessel V-25001A to F and surrounding piping system (schematic)

With the following geometry:

	INVENTORY	ND (inches)	Schedule thickness	Eq. Length (m)	Volume (m^3)
BD-V-25001A	INLET-1	1″	STD	10	0.005576
	BLOWDOWN V-1	4″	STD	2	0.016430
	BLOWDOWN H-1	4″	STD	5	0.041070
	VAPOUR OUTLET H-1	1″	STD	10	0.005576
	VAPOUR OUTLET V-1	1″	STD	10	0.005576
	VAPOUR OUTLET BOUNDARY	1″	STD	10	0.005576
	TAIL PIPE BOUNDARY	4″	STD	20	1.459
	MAIN VESSEL	Ø2800mm X Lt-t 15500mm			101.2
					102.738804

Table 6 – Major inventory system as per above figure

The above-listed table valid for a single Vessel (V-25001A) has been replicated a further 5 times to account for all the vessels V-25001 from A to F and the system are named BD-V-25001A to F.

Moreover, the same system above has been utilized to simulate the above-mentioned *Low Temperature Depressurization Case*.

Instead, the (negligeable) volume of the outlet manifold has been approximated as follows:

INVENTORY	ND (inches)	Schedule thickness	Length (m)	Volume (m^3)
1"-HY-026-03HSS-N	1"	STD	10	0.005576
1"-HY-132-03HSS-N	1"	STD	10	0.005576
1"-HY-133-03HSS-N	1"	STD	10	0.005576
1"-HY-134-03HSS-N	1"	STD	10	0.005576
1"-HY-135-03HSS-N	1"	STD	10	0.005576
1"-HY-136-03HSS-N	1"	STD	10	0.005576
1"1/2-HY-148-03HSS-N	1"1/2	STD	10	0.013160
				0.046616

Table 7 – Blowdown sizing and verification basis

The system listed in Table 7 is named BD-DISCHARGE MANIFOLD.

As said, all the above inventory has been depressurized simultaneously for the **Emergency case,** instead for the **Low Temperature Depressurization Case** just one vessel has been depressurized mostly for sake of simplicity, being all the vessels V-25001 identical from A to F and not being a governing case in terms of peak flowrate.

4.3 BLOWDOWN CALCULATION RESULTS SUMMARY

This section details the results of the above-described depressurization cases.

4.3.1 Emergency case (FIRE)

In particular, the main findings obtained from the emergency case have been listed in the following table. The calculated orifice diameters allow to reduce the pressure down to 7 barg in 15 minutes (the most stringent condition).

SYSTEM	BD VALVE TAG	TOTAL VOL. (m^3)	RO Ø (mm)	Peak Flow (kg/h)	Peak Flow +10% (kg/h)	Final P (barg)
BD-V-25001A	25-BDV-005	~102.74	19	1861	2047	7
BD-V-25001B	25-BDV-007	~102.74	19	1861	2047	
BD-V-25001C	25-BDV-010	~102.74	19	1861	2047	
BD-V-25001D	25-BDV-013	~102.74	19	1861	2047	
BD-V-25001E	25-BDV-016	~102.74	19	1861	2047	
BD-V-25001F	25-BDV-019	~102.74	19	1861	2047	
BD-DISCH.MANIFOLD	25-BDV-022	~4.66E-002	5	108	119	0

*Table 8 – Blowdown sizing results summary (**EMERGENCY CASE-FIRE**) (**15 min** depressurization)*

Moreover, here under the typical execution valid for each pressure vessel V-25001:

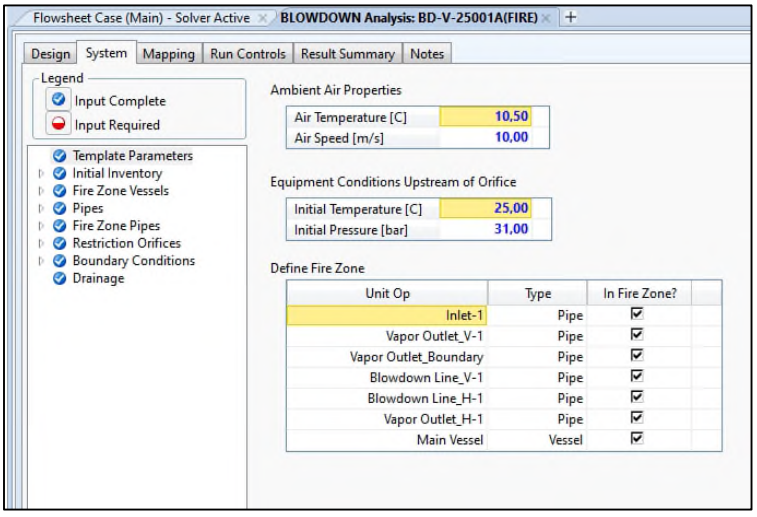


Figure 6 – System characteristics

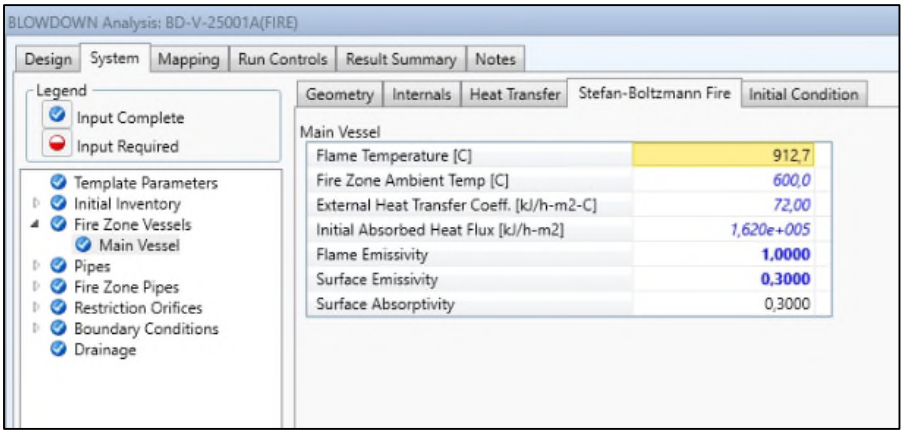


Figure 7 – System Stefan-Boltzmann Fire Model

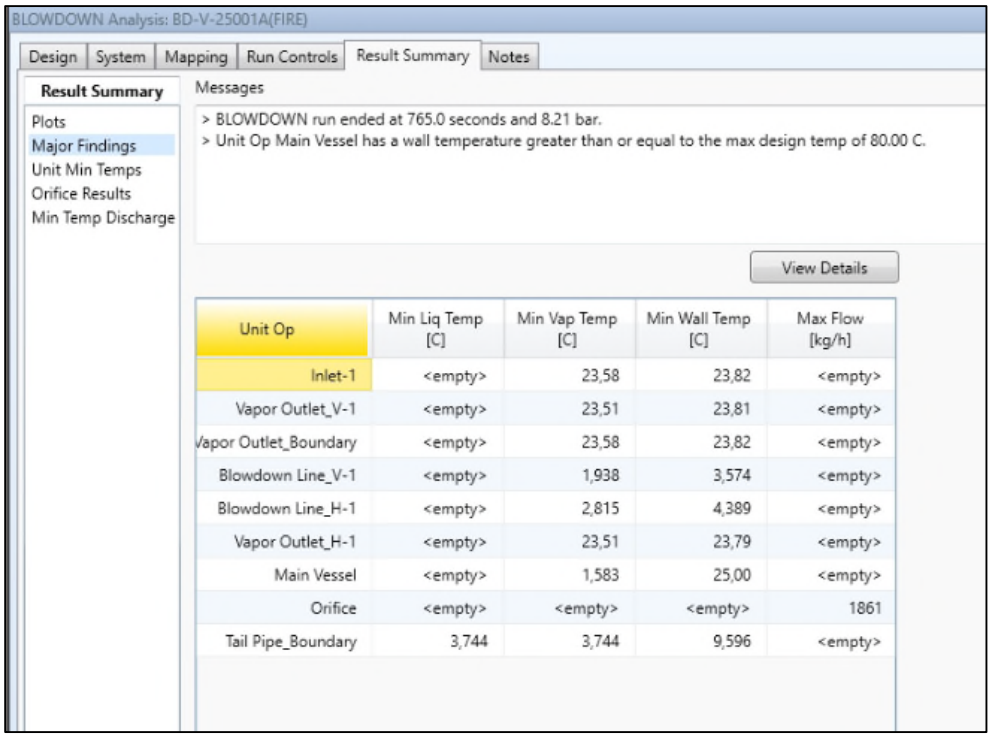


Figure 8 –Results summary

During blowdown simulation, the Pressure (time) and Temperature (time) functions have been recorded as shown through the APPENDIX 02 –INTERNAL PRESSURE, OUTER AND INNER VESSEL WALL TEMPERATURE DURING AUTOMATIC DEPRESSURIZATION.

As demonstrated through the verification carried-out in APPENDIX 03 –DUCTILE RUPTURE CRITERION the pressure vessels V-25001AtoF will not reach the burst pressure of ductile rupture within the required 15 minutes.

Furthermore, the whole simultaneous blowdown flowrate has been furtherly calculated with Hysys tool "Staggered Blowdown" with *orifice opening time set to 0 sec* and the obtained results are shown in the following curve:

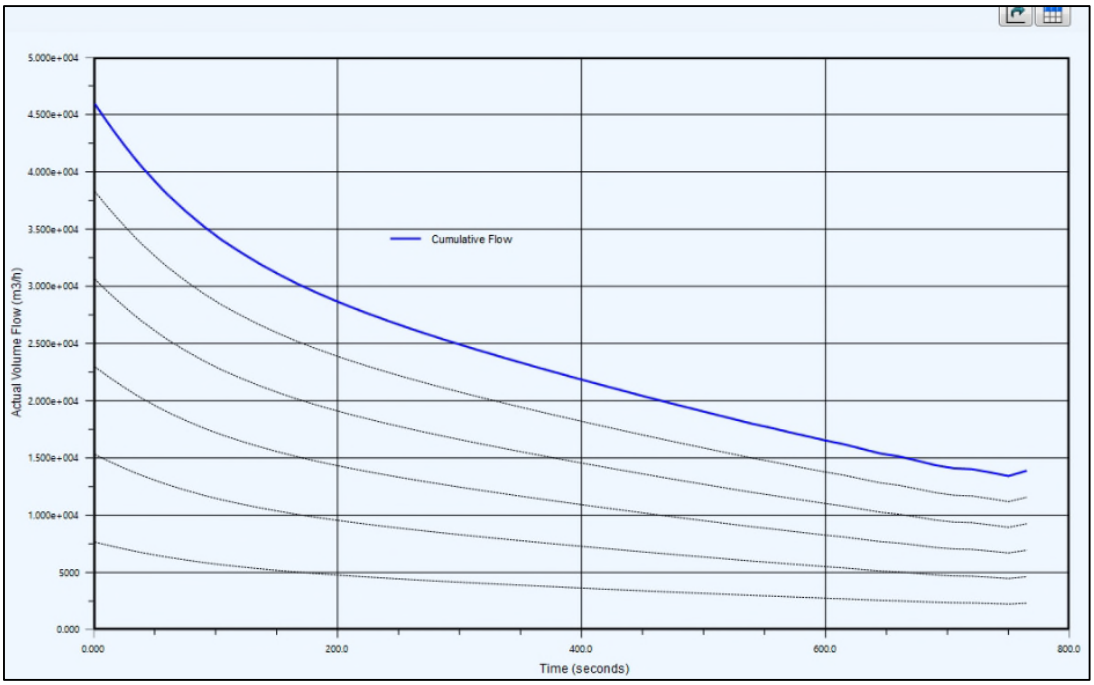


Figure 9 –Simultaneous cumulative blowdown flowrate (Emergency Fire Case)

4.3.2 Low Temperature Depressurization case

As mentioned above, here under the main results obtained in case of Low Temperature Depressurization using the same orifices designed as per the above section 4.3.1.

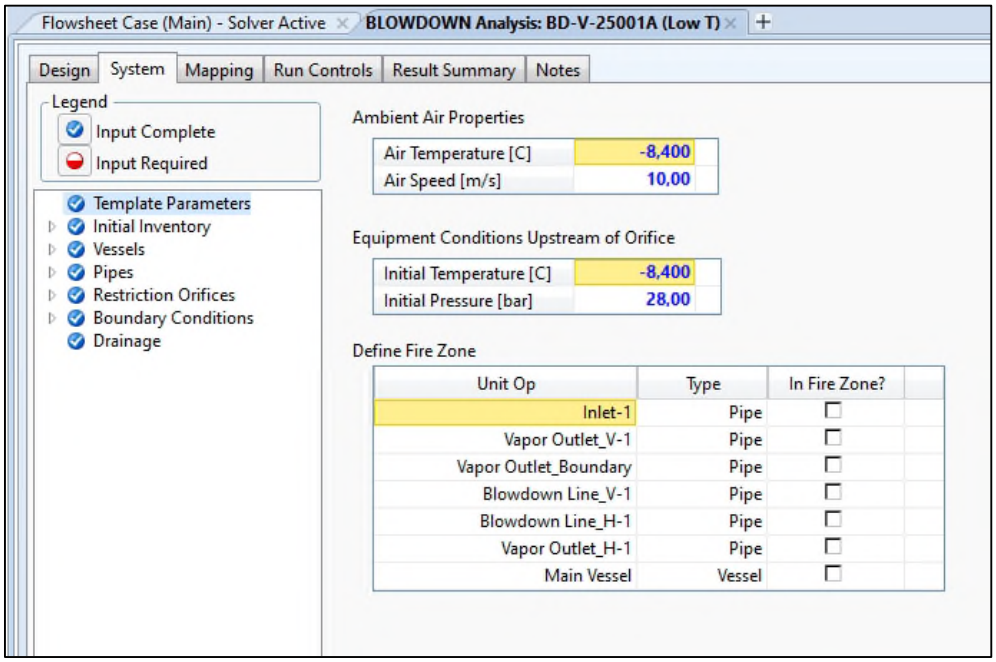
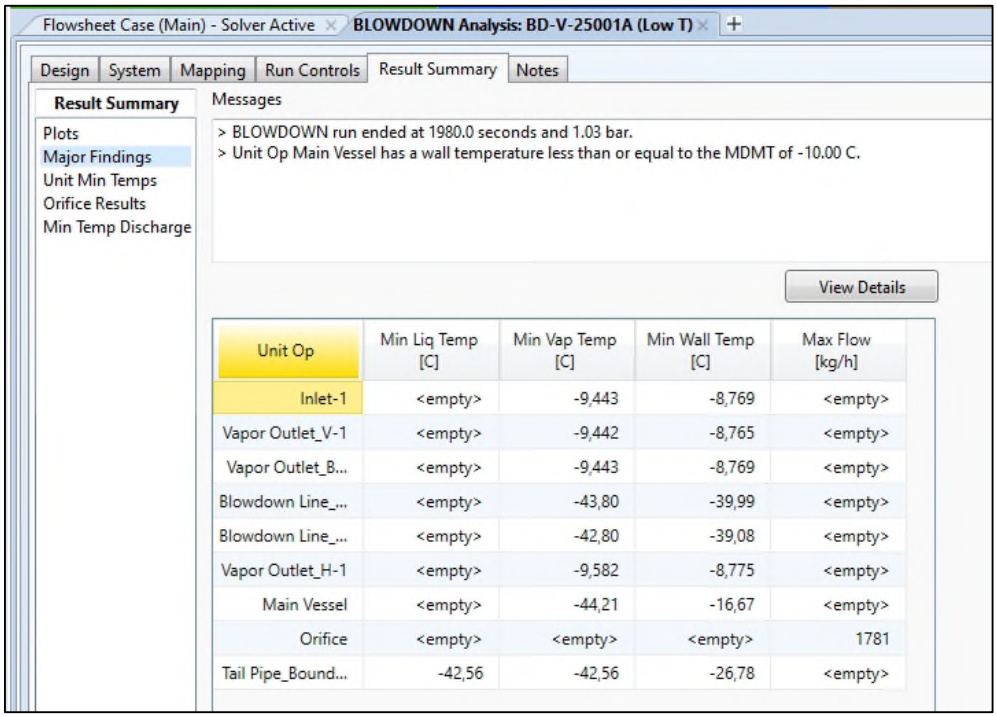


Figure 10 – System characteristics



Unit Op	Min Liq Temp [C]	Min Vap Temp [C]	Min Wall Temp [C]	Max Flow [kg/h]
Inlet-1	<empty>	-9,443	-8,769	<empty>
Vapor Outlet_V-1	<empty>	-9,442	-8,765	<empty>
Vapor Outlet_B...	<empty>	-9,443	-8,769	<empty>
Blowdown Line_...	<empty>	-43,80	-39,99	<empty>
Blowdown Line_...	<empty>	-42,80	-39,08	<empty>
Vapor Outlet_H-1	<empty>	-9,582	-8,775	<empty>
Main Vessel	<empty>	-44,21	-16,67	<empty>
Orifice	<empty>	<empty>	<empty>	1781
Tail Pipe_Bound...	-42,56	-42,56	-26,78	<empty>

Figure 11 – Results summary

Thus, the lowest Wall Temperature in the main vessel is almost -17°C, instead the minimum wall temperature U/S the orifice will be -40 °C and D/S the orifice will be around -27°C. The total time to reach the residual pressure of 1.03 bar is 1980 seconds.

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5 VENT NETWORK SIZING

The Vent system consists of:

- A H2 Vent Main Header relief routing to the hydrogen Vent KO Drum V-43001 prior to the disposal to atmosphere via hydrogen (cold) vent Q-43004.

5.1 DESIGN CRITERIA

5.1.1 Linea upstream of PSVs

The design criteria for sizing lines upstream PSVs is based by limiting the total pressure drop from the vessel to be protected up to the PSV at 3% of PSV set pressure.

5.1.2 Lines downstream of Relieving Devices

The design criteria for sizing the above-mentioned Hydrogen network is based on DEP 80.45.10.10 and DEP 31.38.01.11. by limiting the **ρv^2<200000 Pa (intermittent) as per section 2.2.6 of DEP 31.38.01.11 and Mach number no greater than 0.7 as per good engineering practices.**

The sizing is done for the line downstream of each device with the built-up back pressure for the corresponding occurrence and not with the maximum built-up pressure for the maximum flowrate to the vent. The same is applied for the headers and sub-headers.

5.1.3 Hydrogen Vent Knock-out Drum

This vessel is sized for the vent service; the sizing criteria is as per Equipment Sizing Philosophy and Calculation (Ref. [3]), thus it will be treated in that separated document.

5.2 VENT NETWORK DESIGN DATA

All flow rates and relief conditions have been taken as per PSV Sizing (see the above section 3) and Depressurization calculation (see the above section 4). Lengths and routing of each gas discharge line are taken as per the current layout and 3D model.

5.3 VENT NETWORK SIMULATION MODEL

Aspen Flare System Analyzer version 12.1 has been used for vent network sizing and pressure drop calculation. Piping diameter, class and length are incorporated into the simulation model and are in accordance with Piping Material Classes.

The vent network is built taking into account the main scenarios and assuming the overall geometry, as per ISOMETRIC DRAWINGs. It shall be sized to accommodate the most stringent of the sizing scenarios.

5.4 DEFINITION OF THE MAIN RELIEF LOADS

The scenarios considered for vent system sizing occur separately and are summarized in the following table:

Relieving Device	Service	Calculated Relief PEAK Flowrate (kg/h)	Relief Pressure (barg)	Relief Temperature (°C) (at peak flowrate)	Scenario
25-PSV-001A	H2 Storage Vessel Protection	627	48.4(*)	213.6	Fire
25-PSV-001B	H2 Storage Vessel Protection	627	48.4(*)	213.6	Fire
25-PSV-001C	H2 Storage Vessel Protection	627	48.4(*)	213.6	Fire
25-PSV-001D	H2 Storage Vessel Protection	627	48.4(*)	213.6	Fire
25-PSV-001E	H2 Storage Vessel Protection	627	48.4(*)	213.6	Fire
25-PSV-001F	H2 Storage Vessel Protection	627	48.4(*)	213.6	Fire
80-PSV-001	FC feed line	2679	11	25	CV failure
64-PSV-001	Nitrogen system protection	61.4	11	AMB	Bloc.disch
25-BDV-005	Emergency depressurizzation	2047	30	25	Fire
25-BDV-007	Emergency depressurizzation	2047	30	25	Fire
25-BDV-010	Emergency depressurizzation	2047	30	25	Fire
25-BDV-013	Emergency depressurizzation	2047	30	25	Fire
25-BDV-016	Emergency depressurizzation	2047	30	25	Fire
25-BDV-019	Emergency depressurizzation	2047	30	25	Fire
25-BDV-022	Emergency depressurizzation	119	30	25	Fire

Table 9 – Main Relief Loads

(*): *during the dynamic simulation with orifice "E" the PSV set pressure is reached after about 4.8 minutes.*

The worst-case scenario (GOVERNING CASE for Blowdown network) is supposed to be the simultaneous discharge of all 7 (seven) blowdown valves listed in the above Table 9, even though, depending on the fire attack scenario, it may happen that only some of the PSVs will discharge through the network.

Even though a simultaneous discharge of PSV and blowdown cannot be considered a credible case, one of the above PSVs (25-PSV-001) has been activated for blowdown network simulation but only for sizing purposes (as mentioned above, starting from 30 barg and 25°C the set pressure of PSV is reached after 4.8 minutes).

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A further case has been simulated where all 25PSV001 from A to F are discharging during fire (FIRE SCENARIO WITH PSVs OPEN). But it is not the governing case.

5.5 RESULTS

5.5.1 Vent Network Back Pressures

Relieving Device	SCENARIO	Max Pressure in H2 KOD (barg)	Max Pressure in Vent Header (barg)	Max Pressure at Relieving Device (barg)
25BDV010/007/005/013/016/019/022 25PSV001C	Governing case	0.65	See APPENDIX 6.4	See APPENDIX 6.4
25PSV001AtoF	Fire scenario with PSVs open	0.25	See APPENDIX 6.6	See APPENDIX 6.6

Table 10 – Network back pressures

Thus, H2 Vent KOD maximum operating pressure is 0.6 barg.

For PSV's Vendor response and calculations, reference shall be made to Ref. [39].

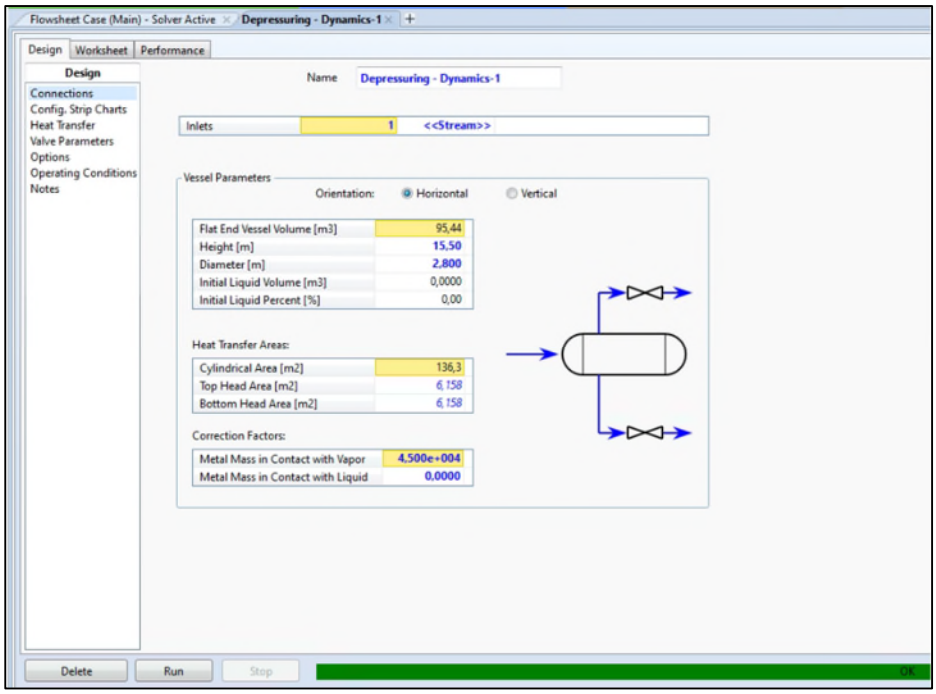
5.5.2 Vent Network Line Sizing

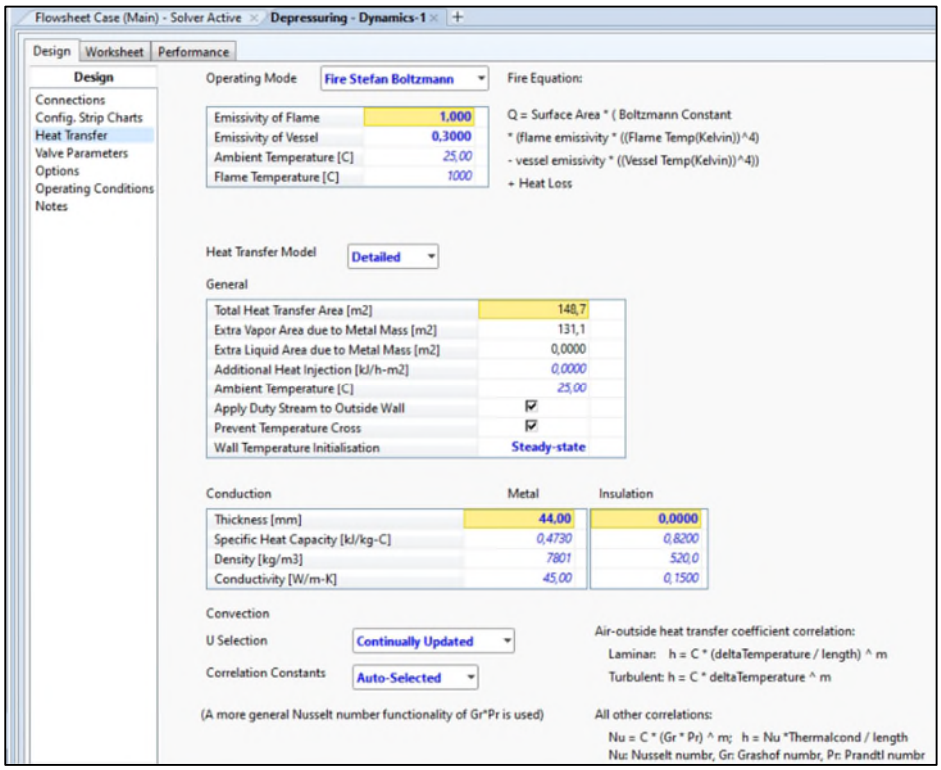
See APPENDIX 6.4 and APPENDIX 6.6

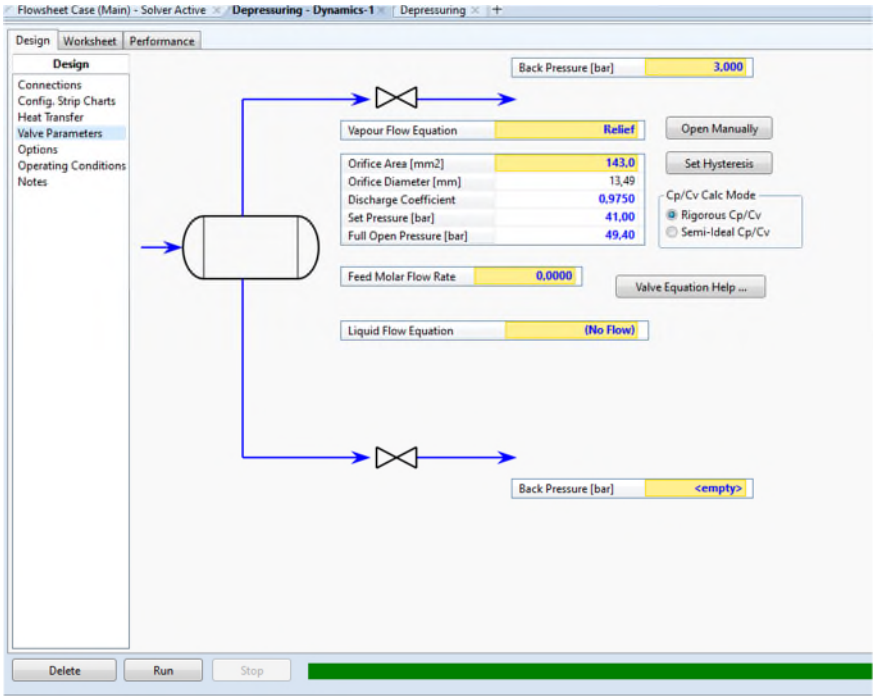
6 APPENDICES

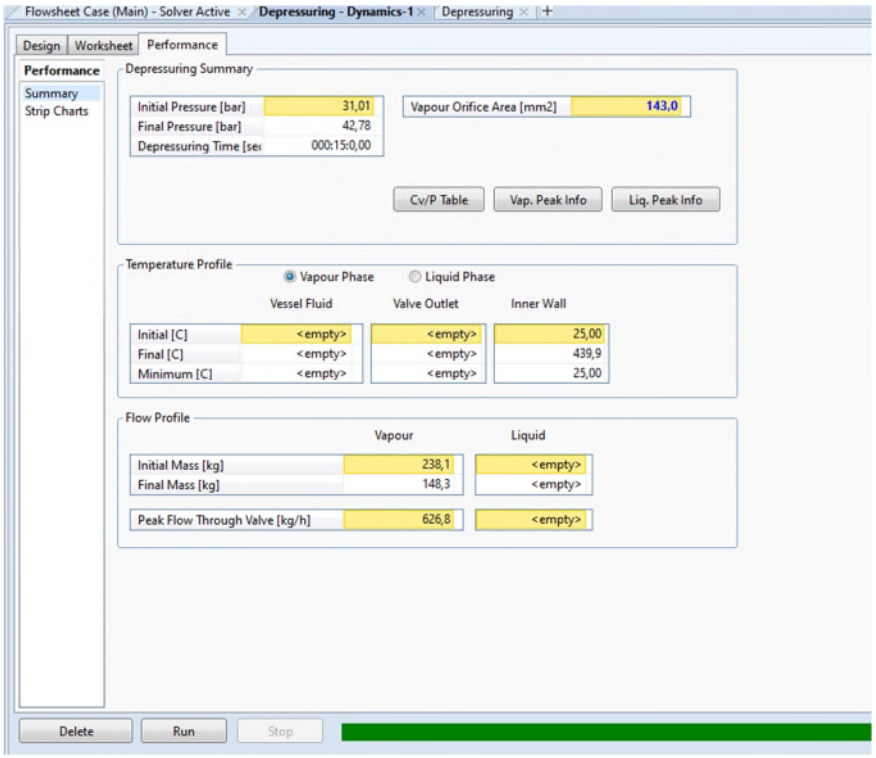
6.1 APPENDIX 01 – PSV CALCULATION SHEETS

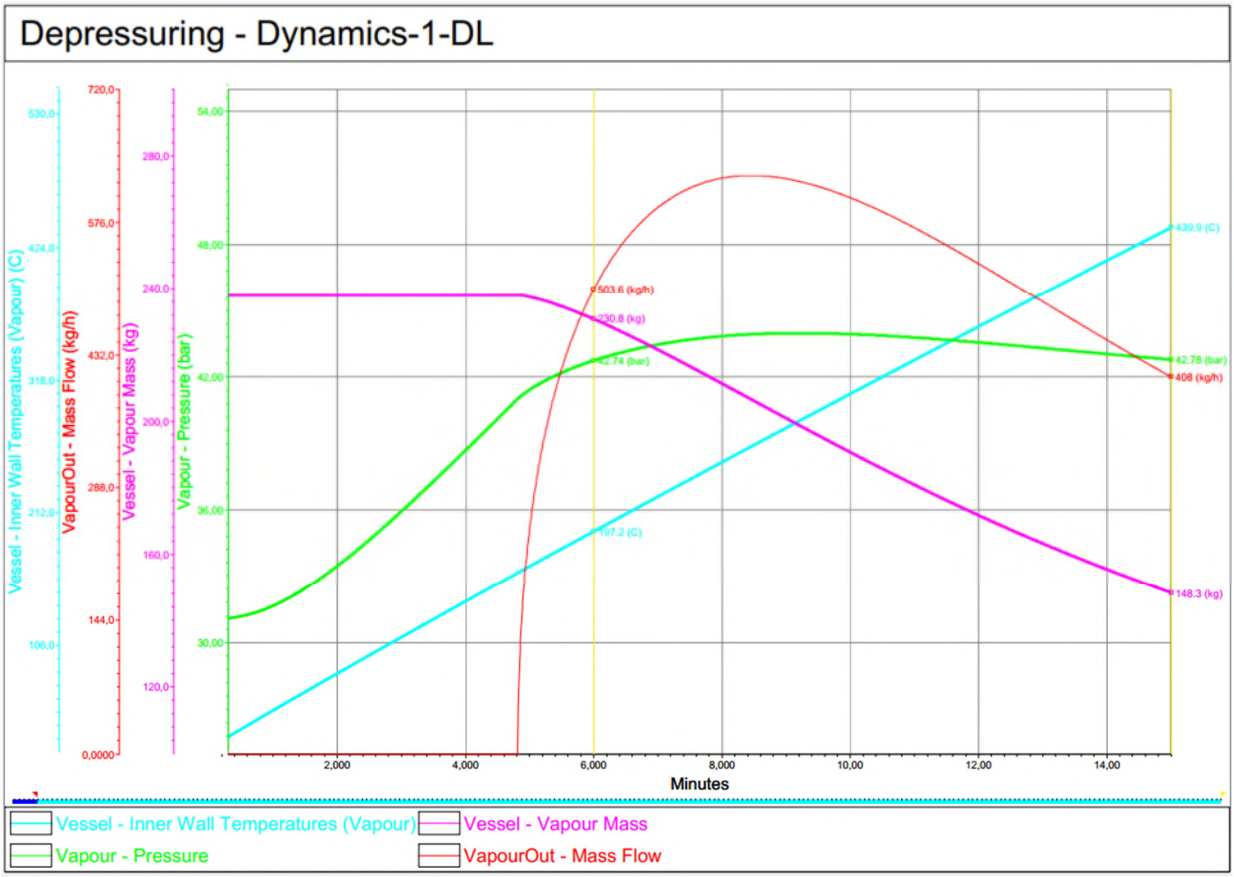
Valid for 25-PSV-001A to F





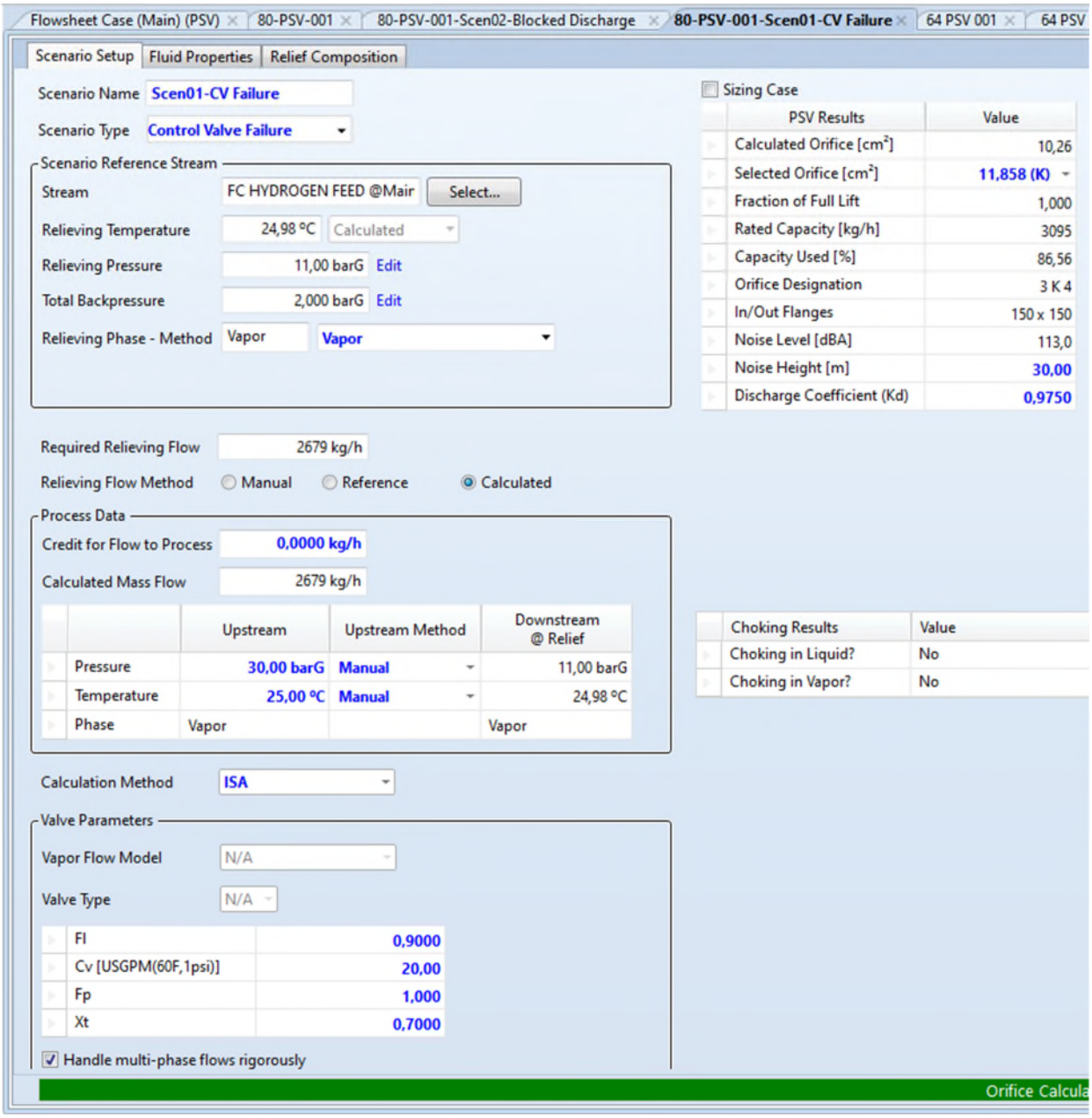

Flowsheet Case (Main) - Solver Active
Depressuring - Dynamics-1
Depressuring
Design
Worksheet
Performance
Connections
Config. Strip Charts
Heat Transfer
Valve Parameters
Options
Operating Conditions
Notes
Back Pressure [bar] 3,000
Vapour Flow Equation Relief
Open Manually
Orifice Area [mm2] 143,0
Orifice Diameter [mm] 13,49
Discharge Coefficient 0,9750
Set Pressure [bar] 41,00
Full Open Pressure [bar] 49,40
Set Hysteresis
Cp/Cv Calc Mode
Rigorous Cp/Cv
Semi-Ideal Cp/Cv
Feed Molar Flow Rate 0,0000
Valve Equation Help ...
Liquid Flow Equation (No Flow)
Back Pressure [bar] <empty>
Delete
Run
Stop


Flowsheet Case (Main) - Solver Active
Depressuring - Dynamics-1
Depressuring
Design
Worksheet
Performance
Performance
Summary
Strip Charts
Depressuring Summary
Initial Pressure [bar] 31,01
Final Pressure [bar] 42,78
Depressuring Time [se 000:15:0,00
Vapour Orifice Area [mm2] 143,0
Cv/P Table
Vap. Peak Info
Liq. Peak Info
Temperature Profile
Vapour Phase
Liquid Phase
Vessel Fluid
Valve Outlet
Inner Wall
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Run
Stop

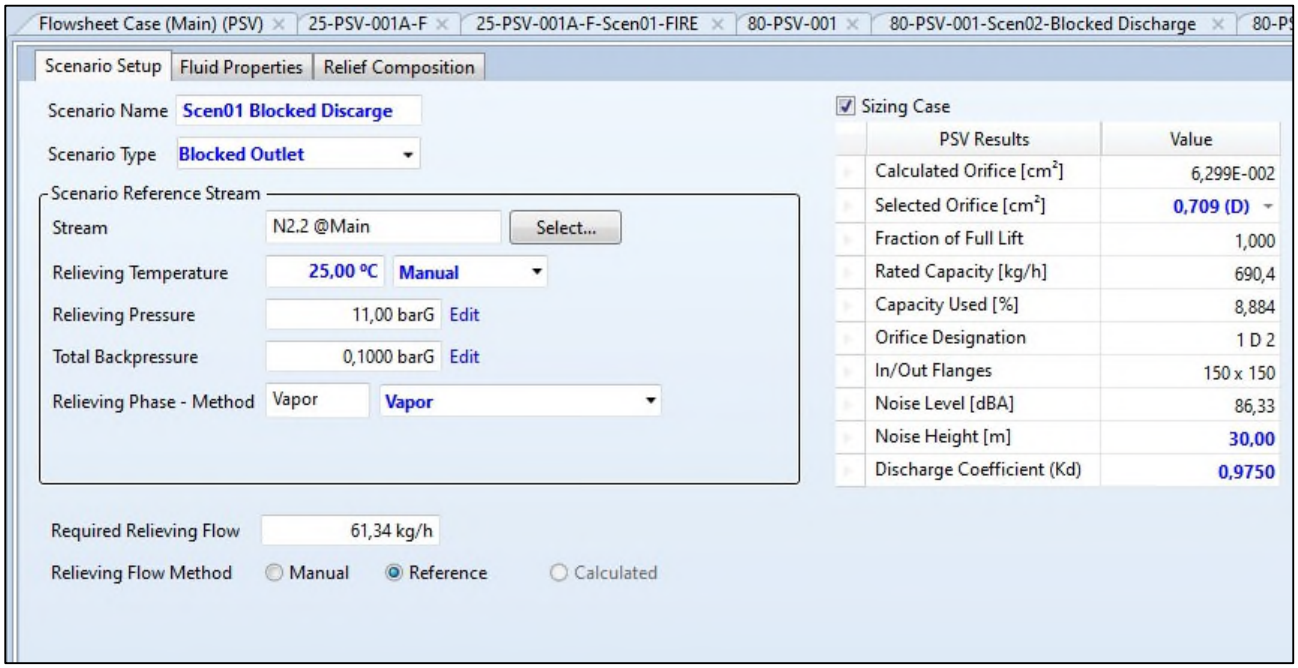


AS PER BELOW APPENDIX 03 –DUCTILE RUPTURE CRITERION WILL NOT REACH THE BURST DUCTILE RUPTURE PRESSURE.

*Valid for **80-PSV-001**(Control valve failure)*



*Valid for **64-PSV-001**(Blocked discharge)*



*Valid for **64-PSV-001**(Reverse flow from hydrogen circuit)*

*(FLOWRATE ESTIMATE **64-PSV-001**)*

1. CASE DESCRIPTION

Nitrogen circuit shall be protected also against any check valve failure/leakage and against any consequent overpressure should occur due to H2 back flow.

2.BASIS AND ASSUMPTIONS

A. API std 521 2020 guideline para.4.4.9.3.3

B. Modified Darcy equation is utilized according to *CRANE "Flow of fluids" 410M sect.4-13:*

Modified Darcy Formula

$$W = 1.265 Y d^2 \sqrt{\frac{\Delta p}{K V_1}} \quad \ldots\ldots$$

where V1 is the specific volume (Liters/kg) at upstream conditions P1 and T1.

3.CALCULATION

STEP 1 - INPUT DATA and SYSTEM CONFIGURATION

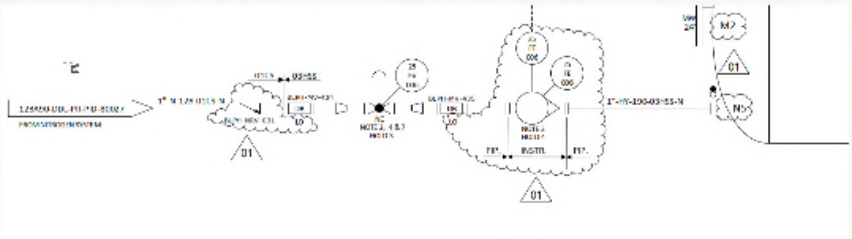


Fig.01 System configuration

Assuming reverse flow through the above system between the vessel nozzle and the 64-PSV-001 one can estimate the following:

STEP 2 - DP calculation

$P_0 := 31\ \text{bar}$ — Stagnant vessel pressure

$P_1 := 11\ \text{bar}$ — Relief pressure of 64PSV001

$\Delta P := P_0 - P_1 = 20\ \text{bar}$ — Differential pressure

STEP 3 - Geometry and calculation of Ktot

$L := 120\%\ 33\ \text{m} = 39.6\ \text{m}$ — Pipe length from the farthest vessel up to 64PSV001 (+20% for uncertaineties)

$D := 33.4\ \text{mm} - 2 \cdot 4.55\ \text{mm} = 24.3\ \text{mm}$ — Pipe internal diameter as per piping class 01CS

$f := 0.02$ — Friction factor assuming turbulent flow in commercial steel pipe

$K_p := f \cdot \frac{L}{D} = 32.59$ — Straight pipe

$K_1 := 340\ f = 6.8 \qquad n_1 := 1$ — Globe control valve (fully open)

$K_2 := 0.5$ $n_2 := 1$ Entrance from vessel

$K_3 := 0.5$ $n_3 := 1$ Entrance from header

$K_4 := 0.4$ $n_4 := 1$ Entrance to PSV inlet line

$K_5 := 30\ f = 0.6$ $n_5 := 6$ 90° elbow

$K_{tot} := K_p + K_1 \cdot n_1 + K_2 \cdot n_2 + K_3 \cdot n_3 + K_4 \cdot n_4 + K_5 \cdot n_5 = 44.39$ Valid for the entire system

STEP 4 - DP/P0

$\frac{\Delta P}{P_0} = 0.645$

STEP 5 - CRANE chart

From the followin chart (Net Expansion Factor Y fro Compressible Flow) taken from the same Crane handbook one obtains:

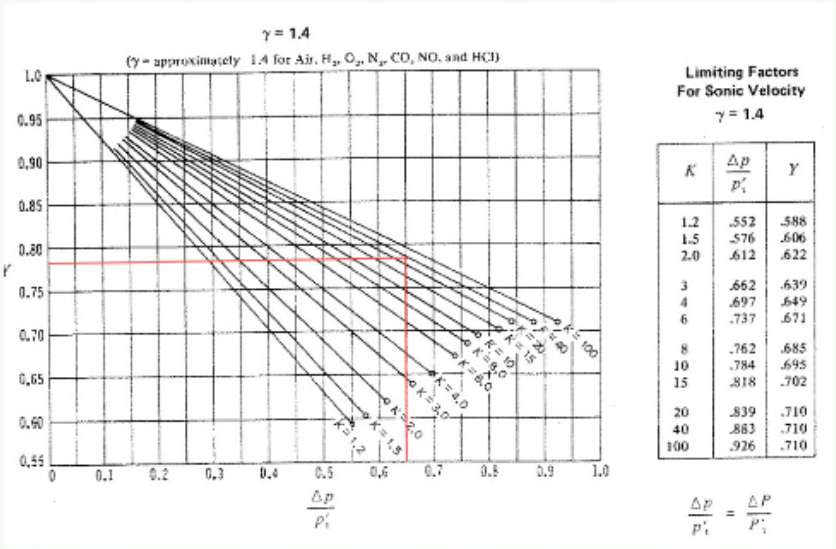


Fig.02 Net expansion factor Y for compressible flow through pipe to a larger flow area

The maximum DP/P for K=~45 is roughly 0.888 as one can obtain from the above table. Thus, being the $\frac{\Delta P}{P_0} = 0.645$ (less than 0.888) then the flow results to be SUB-SONIC and the flowrate is determined as per the following step.

STEP 6 - Specific volume V1 of fluid at upstream condition

$T_1 := 20\ °C$ $P_1 := 31\ bar$ $MW := 2.016\ \frac{gm}{mol}$

$$V1 := \frac{R \cdot T_1}{P_1 \cdot MW} = 390\ \frac{l}{kg}$$

STEP 7 - Flowrate calculation

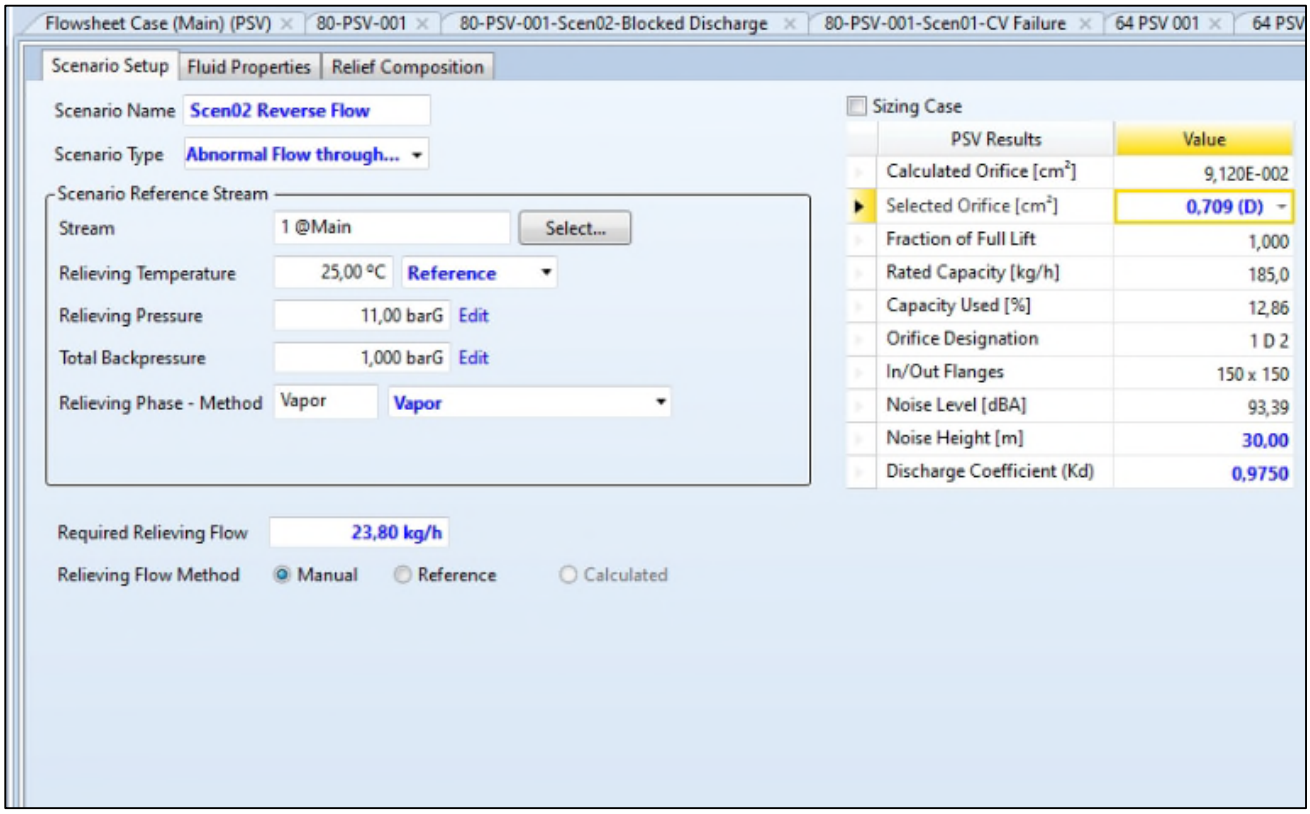
$Y := 0.78$ From the above chart (instead 0.71 is the max in SONIC CONDITIONs), thus the calculated flow rate of hydrogen is as follows:

$$W := \left(1.265 \cdot Y \cdot \left(\frac{D}{mm}\right)^2 \cdot \sqrt{\frac{\frac{\Delta P}{bar}}{K_{tot} \cdot \frac{V1}{\left(\frac{l}{kg}\right)}}}\right) \cdot \frac{kg}{hr} = 19.8\ \frac{kg}{hr}$$

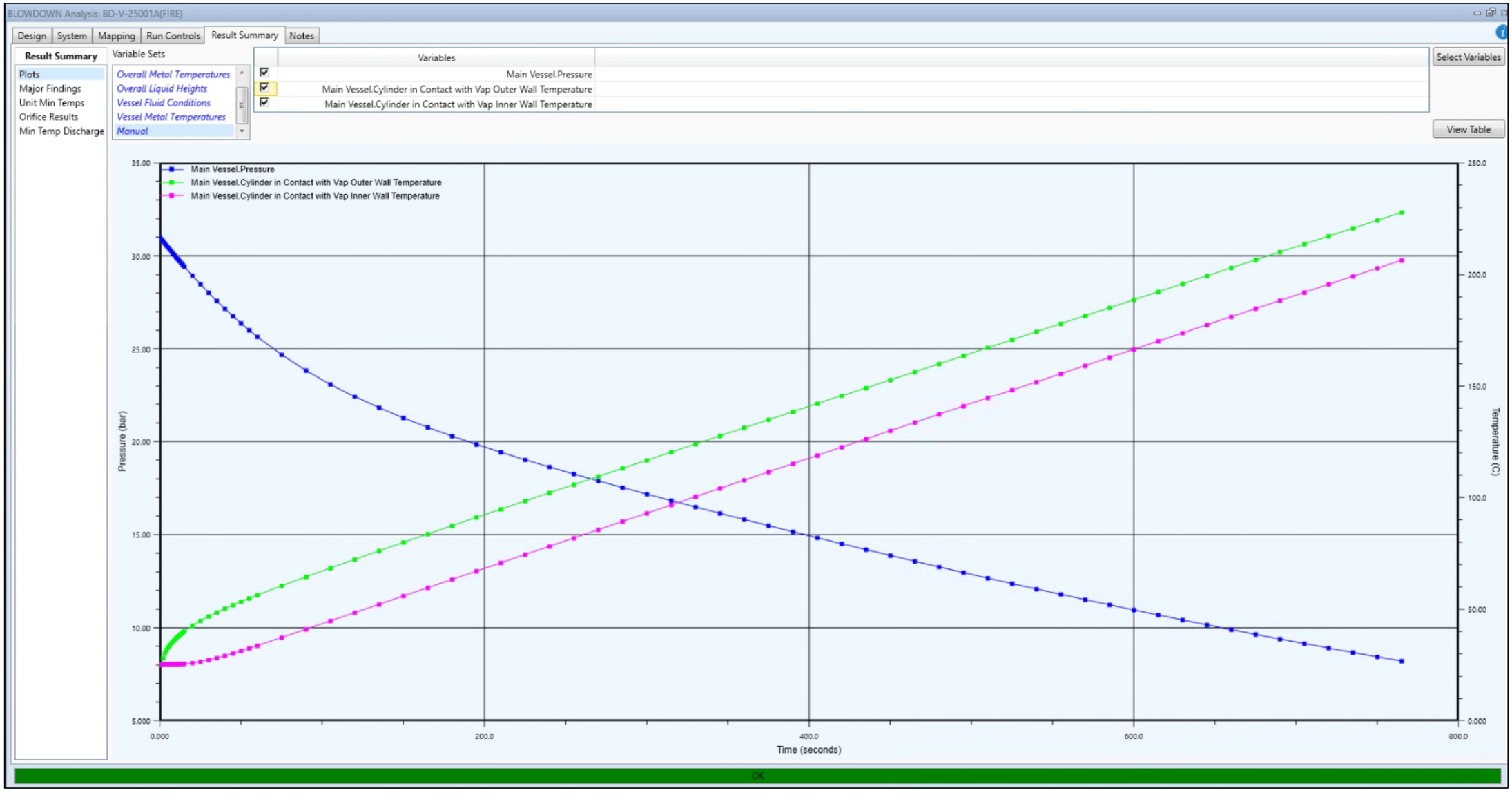
To account for uncertaineties and assumptions one can consider a +20% overdesign margin, as follows:

$120\%\ W = 23.8\ \frac{kg}{hr}$ DESIGN FLOWRATE FOR BACKFLOW FROM VESSEL TO NITROGEN CIRCUIT

(PSV SIZING ***64-PSV-001***)



6.2 APPENDIX 02 –INTERNAL PRESSURE, OUTER AND INNER VESSEL WALL TEMPERATURE DURING AUTOMATIC DEPRESSURIZATION



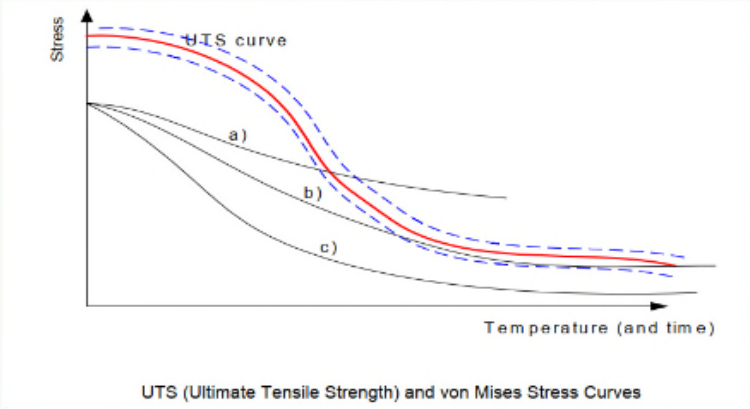
The maximum wall temperature is 236 °C after 765 seconds coupled with the final pressure of 7 barg. As per the below calculation APPENDIX 03 –DUCTILE RUPTURE CRITERION the system does not reach the DUCTILE RUPTURE bursting pressure (according to Scandpower guidelines (Ref. [37])).

6.3 APPENDIX 03 –DUCTILE RUPTURE CRITERION

Ductile Burst calculation

1. MATERIAL DATA

The figure below illustrates the qualitative characteristic behaviour of process vessel in terms of applied stress (von Mises stress) compared to the allowed stress (tensile strength) during fire loading and depressurization.



UTS (Ultimate Tensile Strength) and von Mises Stress Curves

The thick red curve is the actual ultimate tensile strength (UTS) as function of temperature and indirectly of time for the material data given here below. The dashed blue lines reflect the uncertainties in this data. The lines marked (a), (b) and (c) can be regarded as the actual von Mises for three different pressure profiles for a specific vessel or component involved in the process.
System (c) is a system where the influence of the uncertainty of the UTS with respect to the conclusion of time to rupture is smaller than for system (b) and so forth.

2.BASIS AND ASSUMPTIONS

- No connected piping components have been analysed but only the vessel/buffer
- As final verification, a FEM analysis should be considered for the most severe process elements

$A_p := \frac{\pi}{4} \cdot (D^2 - d^2) = 0.393\ m^2$ area of the vessel cross section

$q := \frac{Weight}{l} = 37.3\ \frac{kN}{m}$ assumed distributed uniform load along vessel axis

$R_1 := q \cdot l \cdot \frac{(l - 2 \cdot a)}{2\,b} = 326.3\ kN$ Vertical Reaction at vessel saddle

$M_1 := R_1 \cdot \left(\frac{R_1}{2 \cdot q} - a\right) = 367\ kN \cdot m$ max bending moment along the vessel

$W_s := \pi \cdot \frac{(D^4 - d^4)}{32 \cdot D} = 0.275\ m^3$ vessel elastic section modulus

$\sigma_a := \frac{F_a}{A_p} + \frac{M_1}{W_s} = 1.62\ MPa$ LONGITUDINAL STRESS due to external load (self-weight)

STEP 3-CALCULATION OF INTERNAL PRESSURE AT DUCTILE RUPTURE [Ref.01]

$$f_{uT}(T) := \begin{cases} \text{if } T \le 375 \\ \quad 414 \\ \text{else if } T > 375 \\ \quad (914.067 - 1.256 \cdot T) \end{cases} \quad MPa$$

Ultimate strength at elevate temperature
CARBON STEEL ASTM A516 GR.60

$p_{UTS}(T) := 2 \cdot \frac{t}{D - t} \cdot f_{uT}(T)$

$p_{refM}(T) := \left(\frac{2}{\sqrt{3}}\right)^{1+n} \cdot \left(\frac{1}{2}\right)^{n} \cdot p_{UTS}(T)$

$p_{refT}(T) := \left(\frac{1}{2}\right)^{n} \cdot p_{UTS}(T)$

$k_L(T) := \left(\frac{2}{3}\right) \cdot \left(1 - 2 \cdot t \cdot \frac{e^{-n}}{D - t}\right) \cdot e^{-n} \cdot \left(\frac{\sigma_a}{f_{uT}(T)}\right)$

$k_N := 1 + \left(\frac{1}{3}\right) \cdot \left(1 - 2 \cdot t \cdot \frac{e^{-n}}{D - t}\right)^2$

$k_Q(T) := \left(\frac{4}{3}\right) \cdot \left(\frac{\sigma_a}{f_{uT}(T)}\right)^2 \cdot e^{-2n} - \left(\frac{p_{refM}(T)}{p_{UTS}(T)}\right)^2$

$k_M(T) := k_L(T)^2 - k_N \cdot k_Q(T)$

$p_{ref}(T) := \frac{1}{2} \cdot (p_{refM}(T) + p_{refT}(T))$

$p_{iT}(T) := p_{ref}(T)$

$p_{iM}(T) := \frac{\left(k_L(T) + k_M(T)^{0.5}\right)}{k_N} \cdot p_{UTS}(T)$

$$p_{iRa}(T) := \min\left(\frac{1}{2}\left(p_{iM}(T) + p_{iT}(T)\right), p_{iM}(T)\right)$$

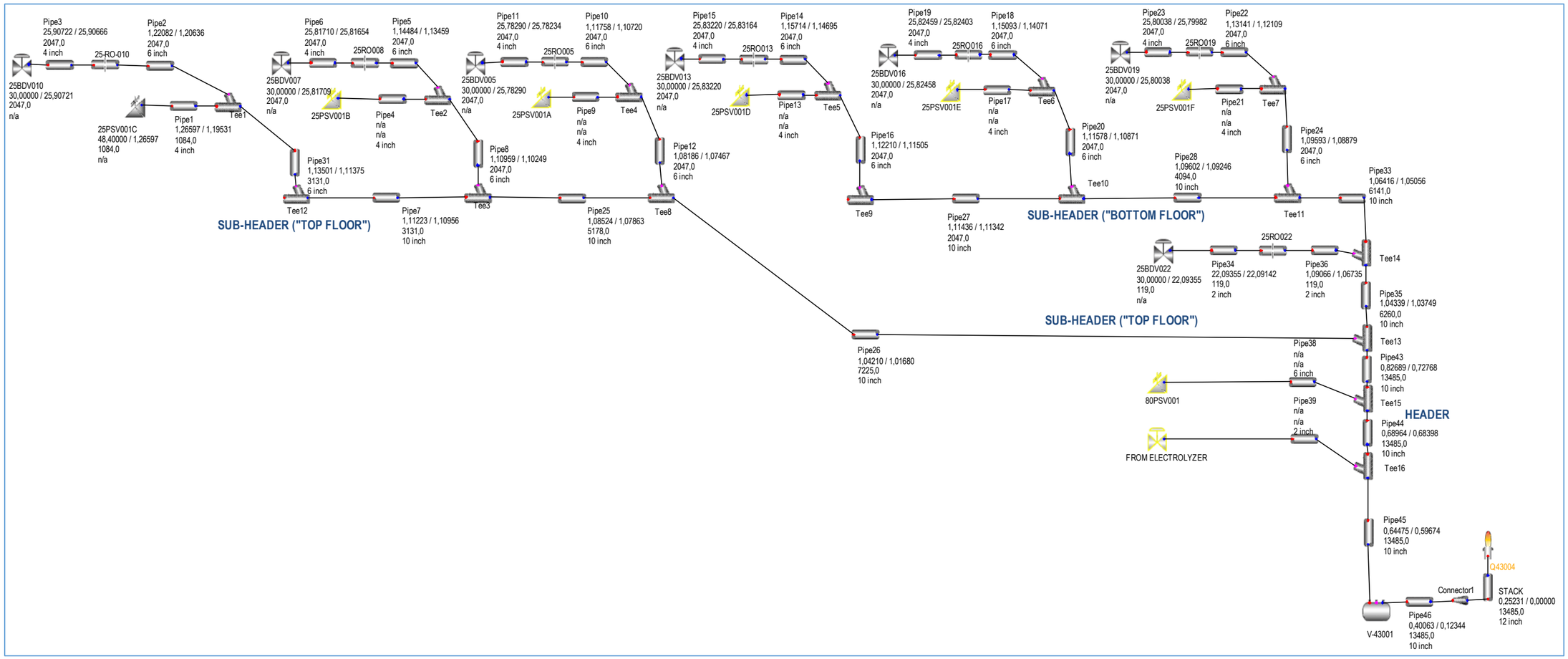
$p_{iRa}(230) = 122.3\ bar$ PRESSURE FOR DUCTILE RUPTURE @230°C

$p_{iRa}(450) = 103.1\ bar$ PRESSURE FOR DUCTILE RUPTURE @450°C

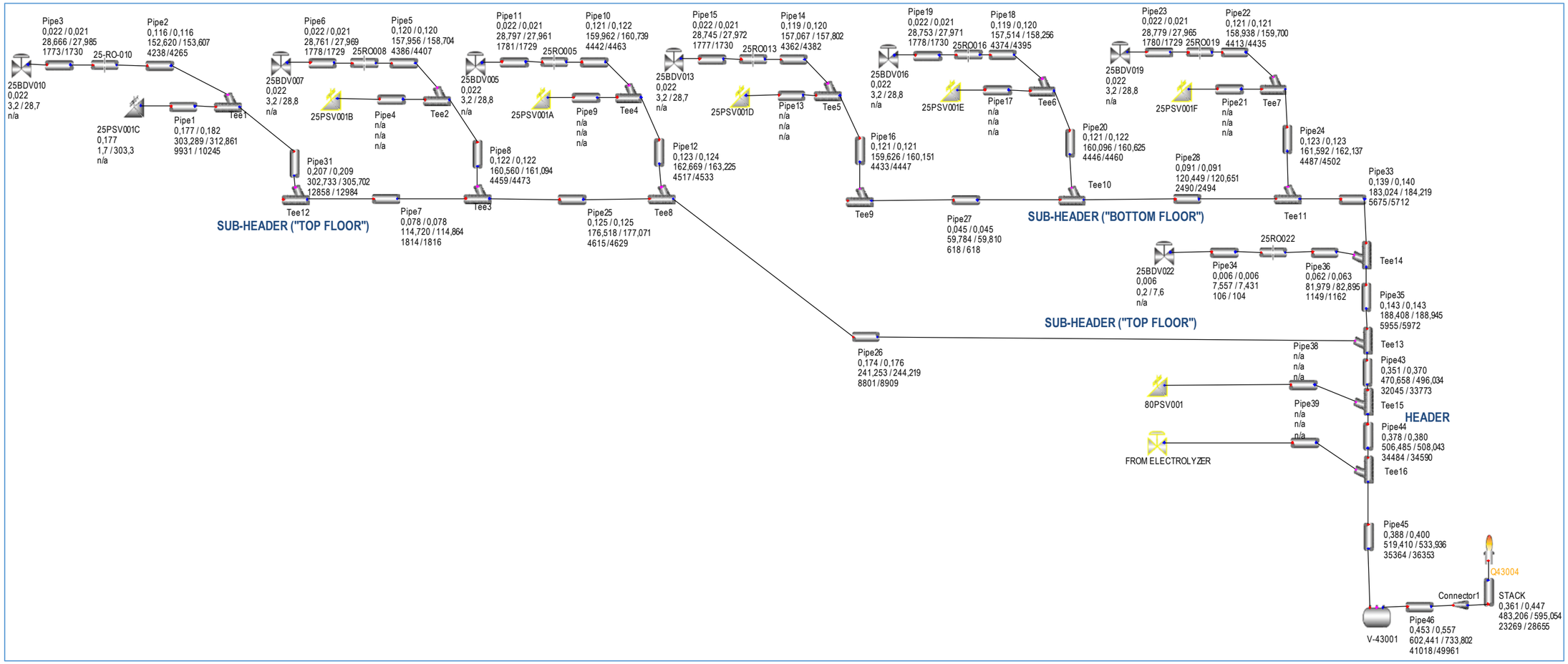
$p_{iRa}(525) = 75.3\ bar$ PRESSURE FOR DUCTILE RUPTURE @525°C

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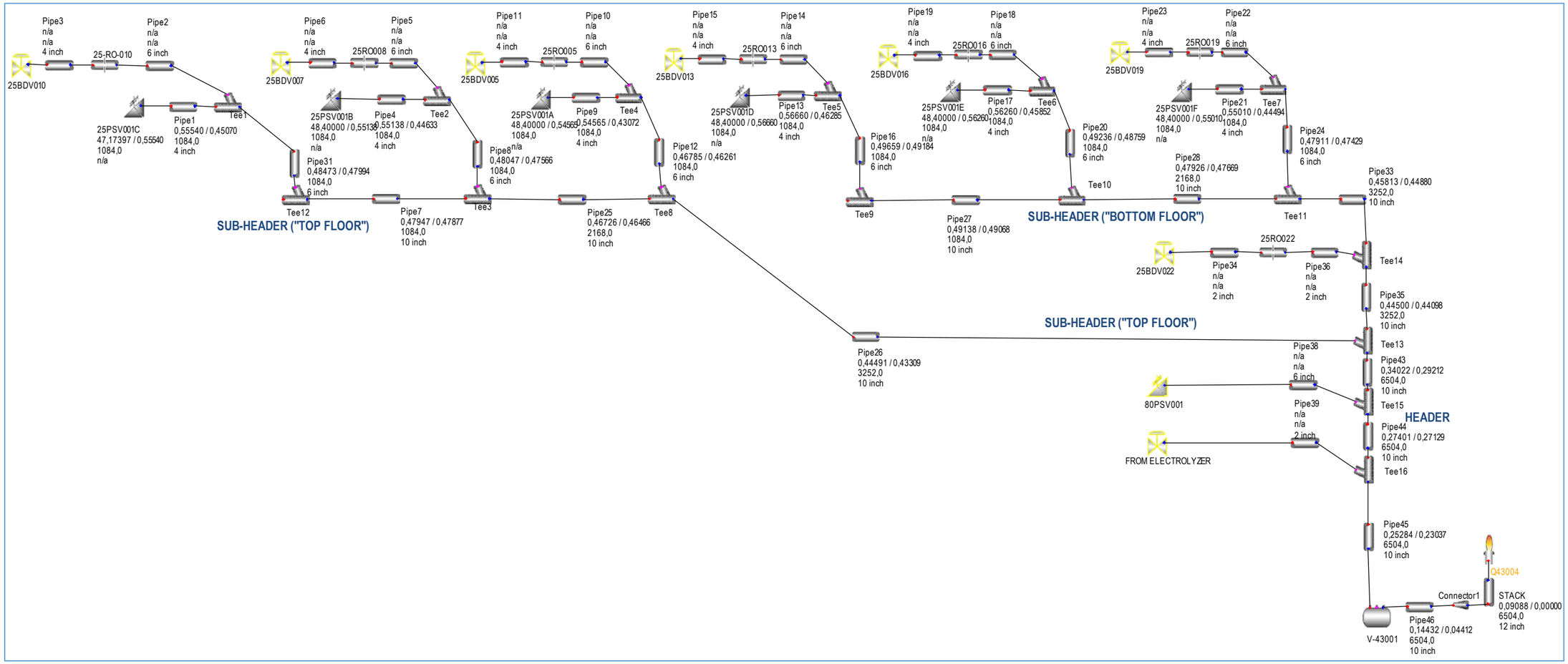
6.4 APPENDIX 04 –VENT NETWORK DESIGN (PRESSURE(BARG)/MASSFLOW(KG/H)/SIZE(INCHES)) – GOVERNING SCENARIO



6.5 APPENDIX 05 - VENT NETWORK DESIGN (MACH/VELOCITY(M/S)/RHO*V2(PASCAL)) – GOVERNING SCENARIO



6.6 APPENDIX 06 – VENT NETWORK DESIGN (PRESSURE(BARG)/MASSFLOW(KG/H)/SIZE(INCHES)) – PSVs OPEN CASE



6.7 APPENDIX 7 – VENT NETWORK DESIGN (MACH/VELOCITY(M/S)/RHO*V2(PASCAL)) – PSVs OPEN CASE

