APPLICATION OF THE SIMPLE ANALYTICAL APPROACH TO CALCULATE PRESSURE DROP IN LIQUID NITROGEN TWO PHASE FLOW OVER LARGE DISTANCES USING HOSES

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Abstract

In order to repair/replace passing shutdown cooling (SDC) isolation valves, three ice plugs are required in the SDC rooms 13 m below the ground level (elevation 87.7 m) to provide the necessary isolation. The results in this paper show that 1½" corrugated hoses can provide adequate LN2 from the tanker at ground level (elevation 100 m) to the SDC rooms 120 m from the tanker using the existing ¾" containment penetration of the feeder freezing system to maintain these three ice plugs. The calculations also show that if ¾" hoses are used exclusively, the pressure drop is significant enough to prevent any LN2 supply to the SDC rooms.

1. Introduction

Analysis of the feeder/pipe freezing system is required so that recommendations can be made to provide adequate supply of liquid nitrogen (LN2) in the shutdown cooling (SDC) rooms at elevation 87.7 m. The bounding case required for SDC system is the ability to provide simultaneous ice plugs on 2", 8" and 10" pipe lines in SDC system.

The experimental data on LN2 consumption is limited. Reference [1] provides a limited resource for such data for pipe sizes 1½ ", 3", 3½" and 4" as shown in Table 1.

From Table 1, it is obvious that the maximum LN2 consumption is for a 3" Sch 80 pipe ice plug when a 24" long 1/8" thick Aluminium freeze jacket is used. Following assumptions are made to calculate the bounding mass flow rate assuming jacket length is 24":

1. The maximum LN2 consumption rate for 3" sch 80 pipe ice plug will be used for calculating the LN2 consumption for pipes smaller than 3".

2. For pipes greater than 3", the consumption will be prorated by the ratio of the square of pipe cross-sectional area to that of 3" sch. 80.

Based on the above assumptions, following LN2 consumptions are calculated:

LN2 consumption for a 2" pipe = 0.535 kg/min

LN2 consumption for a 8" pipe = $((8.625-2\times0.594)/(3.5-2\times0.3))^2 \times 0.535 = 3.518$ kg/min

LN2 consumption for a 10" pipe = $((10.75-2\times0.719)/(3.5-2\times0.3))^2 \times 0.535 = 5.516$ kg/min

Total LN2 consumption for 2", 8" and 10" pipe ice plugs = $9.569 \approx 9.6$ kg/min

Hence the bounding case is the concurrent ice plugs for SDC system and the bounding LN2 consumption is 9.6 kg/min.

Table 1: Experimental Data for LN2 Consumption (Reference [1])

Pipe Size & Material	Jacket Length (in)	Jacket Type/ Material	Position of the pipe with D_2O	Water Temp K	Rate of LN2 Consumption (kg/min)	Time to form ice plug @ D_2O flow of 0.6 kg/min
1½ " Sch 80, A106B	6	Single-walled	Downward	327.6	0.138	21
1½ " Sch 80, A106B	12	Single-walled	Downward	327.6	0.232	13
1½ " Sch 80, A106B	24	1/8" thick Al	Downward	327.6	0.365	11
3" Sch 80, A106B	10	1/16" thick SS double Walled	Downward	327.6	0.328	30
3" Sch 80, A106B	24	1/8" thick Al	Downward	327.6	0.535	21
3½ " Sch 80, A106B	6	Single-walled	Downward	327.6	0.236	42
3½ " Sch 80, A106B	12	Single-walled	Downward	327.6	0.442	30
4" Sch 80, A106B	10	1/16" thick SS double Walled	Downward	327.6	0.402	41

2. Calculation for Hose Sizes

2.1 Assumptions

The calculations produced in this document are for the steady-state conditions in the LN2 supply hoses. Following are the main assumptions:

1. Nitrogen conditions assumed are 50 psig saturated (345 kPa (g) = 446 kPa (a), -293.4 °F (-180.8 °C = 92.36 K) [2].

2. Environment is assumed at a room temperature of 32 °C = 305 K

3. Target mass flow rate at the distribution header should at least be 50% liquid to account for adequate margins, with pressure considerably above the atmospheric pressure.

4. LN2 hoses are assumed to be smooth but corrugated hoses are shown to be equivalent for the purposes of this calculation. It is further assumed that there is no abrupt change in the direction of the flow from the tanker to the distribution header. This assumption can lead to under estimation of the pressure drop. In order to account for the uncertainties in the hose surface roughness and change in flow direction, a multiplication factor of 1.3 is used to estimate the pressure drop. [3]

5. Only radial heat transfer to the environment is assumed.

6. The temperature inside the hose insulation is assumed to be the same as that of liquid nitrogen; i.e., there is no resistance offered by the hose material. This assumption neglects the resistance of the hose material and results into over-estimation of the heat losses to the environment. The heat gained from the environment evaporates the LN2 in the hose.

7. The vapor produced in the LN2 does not add to the resistance to heat transfer, and therefore results into over-estimation of the heat transfer.

8. The temperature on the outside the insulation is assumed to be the same as that of the environment. This assumption neglects the natural convection resistance of the room and results in an over estimation of the heat losses to the environment.

9. The thermal conductivity of the insulation (silicon rubber sponge) is conservatively assumed to be 0.542 Btu/hr-ft^2-°F/in = 0.078 W/m-K [3].

10. Insulation is assumed to be 1½” thick for 1½” diameter hose and ¾” thick for ¾” diameter hose [5].

11. If pressure at any point decreases below atmospheric, it is assumed that all LN2 flashes into vapor.

2.2 Methodology

LN2 pipe sizing is based on pressure drop and heat gain considerations. Heat transfer into a saturated cryogenic liquid such as LN2, causes a portion of the liquid to evaporate whereas the pressure drop causes the liquid to flash into vapor to attain the new state.

The methodology presented here is not iterative with only one boundary condition fixed at the inlet at the tanker. The boundary condition at the other end where the freezing jackets are located is not defined. The outlet of freezing jackets is open to atmosphere. The aim is to check different configurations and assess the best possible configuration with least pressure drop.

A two-phase flow condition must then be considered when determining the required hose size. The total pressure drop for two-phase flow consists of three parts [3]; the frictional, gravitational and acceleration pressure drops, so that,

$$\left(\frac{dp}{dz}\right)_{2P} = \left(\frac{dp_F}{dz}\right) + \left(\frac{dp_G}{dz}\right) + \left(\frac{dp_A}{dz}\right)$$

where p is the pressure and z is the distance along the pipe.

Gravitational pressure drop becomes significant only when the vertical flow is the dominant term. Though there are vertical sections of the pipe/hoses expected, this term is neglected for the calculations providing LN2 to the SDC rooms. But this term is included for the pressure drop calculation in case of providing LN2 to the feeders and is applied to a vertical section of the hose inside the containment as follows [3]:

$$\left(\frac{dp_G}{dz}\right) = g\sin\theta\left(\alpha\rho_G + (1-\alpha)\rho_L\right)$$

where g = acceleration due to gravity = 9.8 m/s^2

$$\alpha = \text{void fraction} = \frac{1}{1+\frac{1-x}{x}\frac{\rho_G}{\rho_L}}$$

θ = angle to horizontal = 90°

The acceleration pressure drop is often negligible for two-phase flow of cryogenic fluids. [3].

The following method is used to calculate the pressure drop and heat transfer at each discreet point.

Step 1 Calculate the liquid and vapor densities based on the pressure in the previous discreet point in the hose.

Step 2 Calculate the mass of liquid and mass of vapor based on the quality in the previous discreet point as follows (The total mass flow rate is assumed to be 9.6/60 = 0.16 kg/s):

$$M_G = 0.16\,x$$

$$M_L = 0.16\,(1\text{-}x)$$

Where subscripts L and G stand for liquid and vapor phase and x is the vapor mass fraction or quality.

Step 3 Calculate the Reynolds number for each phase as follows:

$$\text{Re}_L = \frac{M_L D}{A\mu_L}$$

$$\text{Re}_G = \frac{M_G D}{A\mu_G}$$

where

D = Internal diameter of the hose;

A = Cross-sectional area of the hose

μ = Dynamic viscosity

Step 4 Calculate the frictional pressure drop for each phase as follows [3]:

$$\left(\frac{dp_F}{dz}\right)_L = \frac{2k_L(\mathrm{Re}_L)^{-n}\rho_L}{D}\left(\frac{M_L}{A\rho_L}\right)^2$$

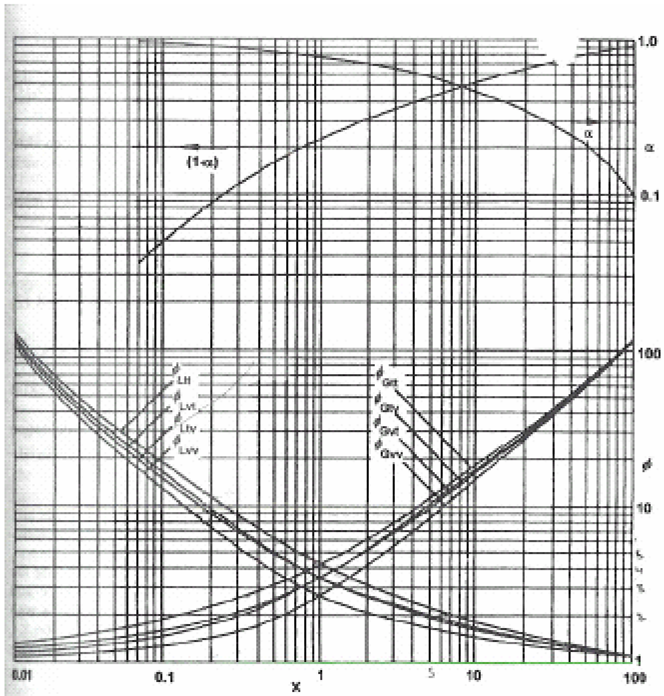
$$\left(\frac{dp_F}{dz}\right)_G = \frac{2k_G(\mathrm{Re}_G)^{-m}\rho_G}{D}\left(\frac{M_G}{A\rho_G}\right)^2$$

where

k_L, k_G, m and n are empirically defined in reference [3] as follows:
$k_L = k_G = 0.046$ for both phases in turbulent region.
m = n = 0.2 for both phases in turbulent region.
ρ = density.
Step 5 Calculate *X* from:

$$X = \left[\left(\frac{dp_F}{dz}\right)_L \Big/ \left(\frac{dp_F}{dz}\right)_G\right]^{0.5}$$

Step 6 Use Fig. C8.5 in reference [3] (shown below) to determine the 2-phase multiplication factor ϕ_L.



Step 7 Calculate the 2-phase frictional pressure drop as follows:

$$\left(\frac{dp_F}{dz}\right) = \phi_L^2 \left(\frac{dp_F}{dz}\right)_L$$

Step 8 Update the pressure by subtracting the pressure drop from the pressure in the previous discreet point. If the pressure is above atmospheric pressure, continue the subsequent calculations; else assume all LN2 vaporized, and terminate calculations.

Step 9 Calculate the new saturation temperature, *T*, liquid and vapor enthalpies, h_f and h_g at the new pressure.

Step 10 Calculate the rate of heat gain from the environment as follows:

$$Q_{gained}^{rate} = \frac{2\pi\Delta T}{\ln(r_2/r_1)/k}$$

For 1½" hose, OD of the hose = 2.1"; so r_1 = 1.05" and OD of hose + insulation = 5.1"; so r_2 = 2.55".

For ¾" hose, OD of the hose = 1.1"; so r_1 = 0.55" and OD of hose + insulation = 3.1"; so r_2 = 1.55".

k = Thermal conductivity = 0.542 Btu/hr-ft^2-°F/in = 0.078 W/m-K.

Step 11 Calculate the rate of vapor generated due to the rate of heat gain.

$$m_{vap-gen}^{rate} = \frac{Q_{gained}^{rate}}{h_g - h_f}$$

Step 12 Update the quality due to vapor generated because of heat transfer as well as the vapor generated due to the pressure drop as follows:

Quality = Increase in vapor mass fraction due to heat transfer +Increase in vapor mass fraction due to pressure drop

$$x = \frac{m_{vap-gen}^{rate} + M_G^{prev}}{M_L^{prev} + M_G^{prev}} + \frac{h_f^{prev} - h_f^{curr}}{h_g^{curr} - h_f^{curr}}$$

where super-script *prev* stands for the previous discreet point and *curr* stands for the curret discreet point.

3. Results

The following three cases have been run with the above methodology using MS Excel.

Case 1: Bounding scenario with a hose of ¾" diameter from the distribution header downstream of the tanker to the distribution header in the SDC rooms.

Case 2: Bounding scenario with a hose of 1½" diameter from the distribution header downstream of the tanker to the distribution header in the SDC rooms.

Case 3: 30 m of ¾" diameter hose is estimated from the distribution header downstream of the tanker to the containment penetration. 1½" diameter hose is used from the containment penetration to the distribution header in the SDC rooms.

3.1 Case 1

This is the bounding case with the ¾" diameter hose. Figure 1 and 2 show that the pressure drop is substantial and increases exponentially with the increase in the quality of fluid flowing through the hoses. After 65 m (~210 ft) the pressure drops below atmospheric and there is no driving force left for the liquid to flow. The overall pressure drop over 65 m of length is 355 kPa (d) (50 psid).

3.2 Case 2

This is the bounding case with 1½" diameter hose. It neglects the fact that the containment penetration size is ¾". Figures 3 and 4 show that the quality increases to 50% after 117 m (~384 ft) of length. Until then, the overall pressure drop is 26 kPa (~4 psi) and there is enough driving force to push 50% of liquid nitrogen into the freezing jackets.

3.3 Case 3

This case takes into account the fact that both the containment penetration and the nozzle at the tanker are ¾" in size and are joined by ¾" hose of 100ft (~30m) It is assumed that following the containment penetration, 86m of 1½" diameter hoses are used up to the distribution header in the SDC rooms. For such a scenario, Figures 5 and 6 show that the quality increases to 50% after 116 m

(~380 ft), but the pressure drop is approximately 100 kPa (d) (14.5 psid). Still there is enough driving force to push 50% of LN2 into the freezing jackets.

4. Conclusion

It is concluded that LN2 can be delivered to form 3 ice plugs in the SDC rooms on NPS 2,8 and 10 pipes for maintenance on the SDC valves,

5. References

[1] K. Saari, Handbook of Pipe Freezing Technology, Atomic Energy of Canada Limited, 1979.

[2] R.T. Jacobsen, S.G. Penoncello & E.W. Lemmon, Thermodynamic Properties of Cryogenic Fluids, Plenum Press New York, 1997.

[3] Cryogenic Piping System*, Ch. 8 of Piping Handbook*, edited by M. L. Nayyar, 7th Ed., McGraw-Hill.

[4] N.E. Todreas & M. S. Kazimi, *Nuclear Systems I*, Hempshire Pub. Corp., 1990.

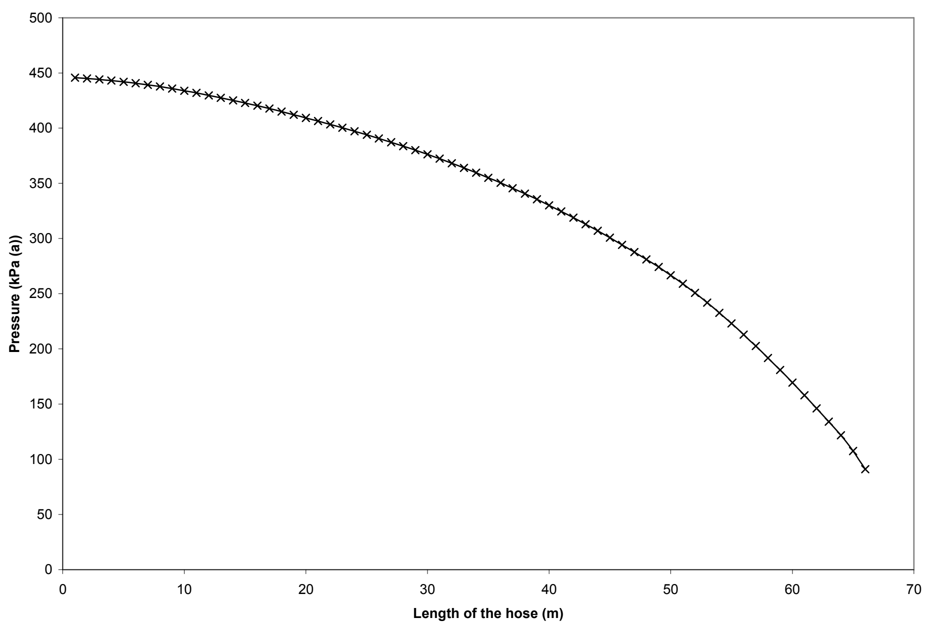


Figure 1: Case 1, Pressure profile through the length of the hose

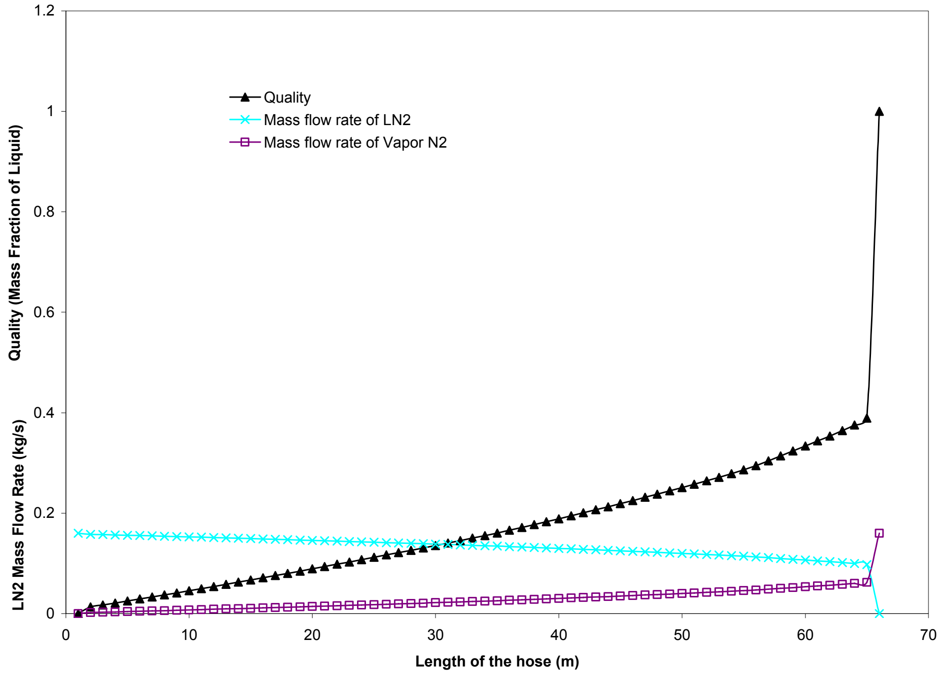


Figure 2: Case 1, Quality, Liquid and Vapor Nitrogen profile through the length of the hose

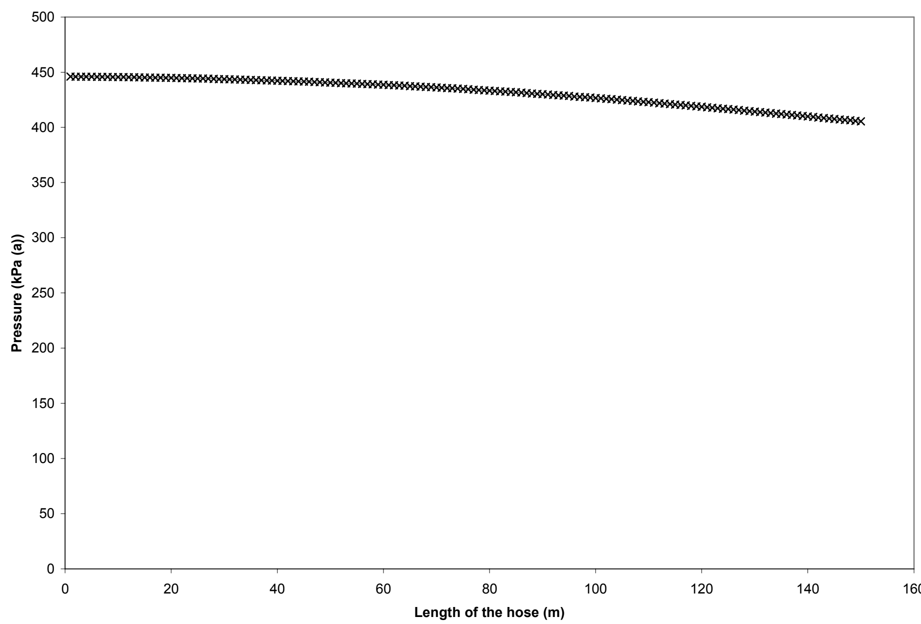


Figure 3: Case 2, Pressure profile through the length of the hose

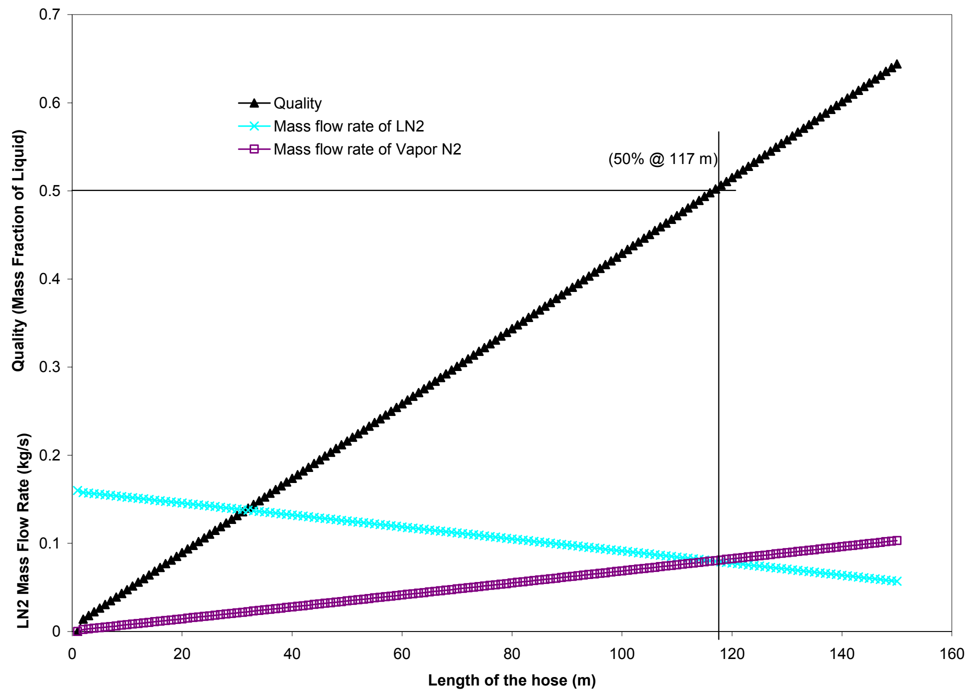


Figure 4: Case 2, Quality, Liquid and Vapor Nitrogen profile through the length of the hose

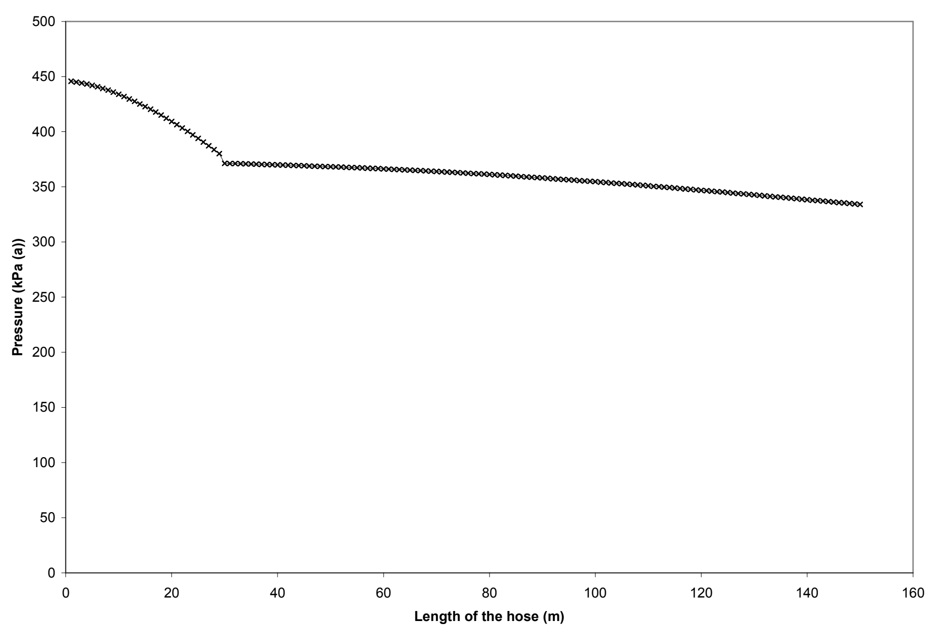


Figure 5: Case 3, Pressure profile through the length of the hose

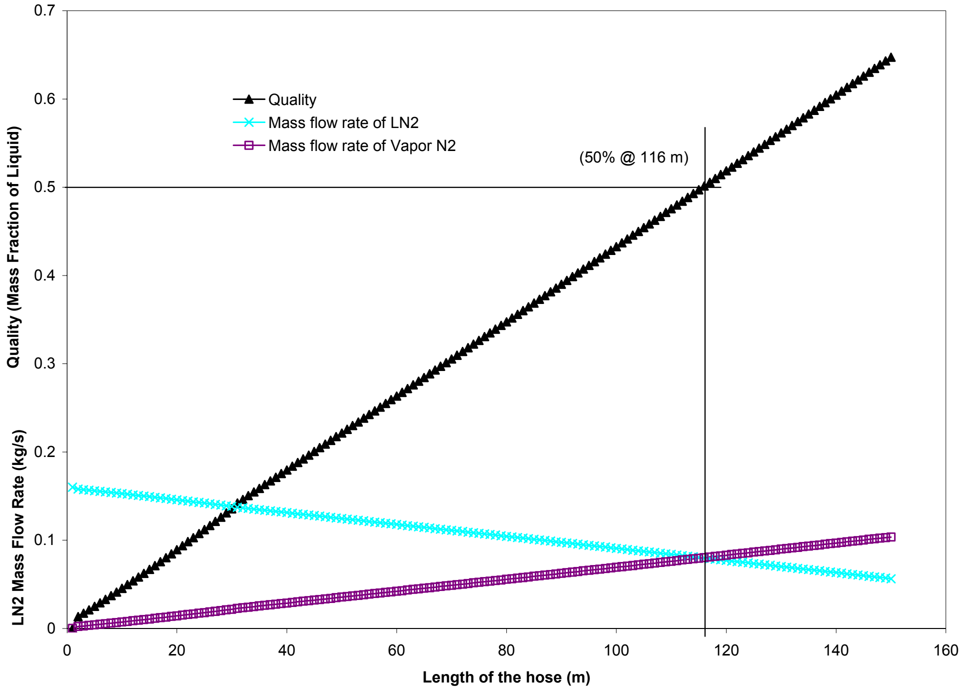


Figure 6: Case 3, Quality, Liquid and Vapor Nitrogen profile through the length of the hose