Appendix B:
Safe Venting Report

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SAFE VENTING REPORT

Summary: Justification of vent Stack Height.
The height of the vent stack is 40' to ensure that any released hydrogen that is ignited does not cause injury to the public. This explained in summary format in section "1 Summary". This release event is rare and only occurs if multiple level of protection fail. The justification of the acceptable heat level are highlighted in section "3.3 Assessment criteria for radiation heat." In section "4 Results" the worst case scenario shows that the vent stack needs to be 40ft high to avoid injury to the public in the rare event that the released H2 ignites; graph on image # 4-4 shows the calculation results.

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1 Summary

This report investigated the potential consequences of a failure-related release of hydrogen from the low and high pressure vent stack of hydrogen refueling station type CP and to the define the secure release location for these vent stacks.

Based on the very small mass of hydrogen released in the explosion endangered area and the free dispersion in open air, no danger from explosion pressure from a delayed ignition of the hydrogen-air-mixture is to be expected.

The calculation of the radiation heat in case of immediate ignition did **not** result in unacceptable danger for humans in the area of the hydrogen refueling station and the surrounding area if the height of the low and high pressure vent stack is at least 12 meters and the release direction is located at an angle (60° to horizontal).

Result of having a height of 40' high is acceptable amount of heat from ignited hydrogen release.

Negative impacts from the radiation heat on the cryogenic LH2 storage tank as well as the container roof are not expected.

Detailed results are summarized in chapter 4.

2 Documents

[1] Internal information from Mr. Schäfer (Linde Gas) dated 10/13/2015: design data for dispersion calculation LH2 refueling station

[2] Determination and calculation for “incidence development scenarios” [Störfallablaufszenarien] according to measure 3 of the “Störfallverwaltungsvorschrift”; research and development project 204 09 428 of the federal ministry for environment, environmental protection and reactor safety, expert area plant safety, incident prevention, treatment of hazardous material, October 1999

[3] API Standard 521: Pressure Relieving and Depressuring Systems; 5th Edition; Januar 2007

[4] UK HSE (Health and Safety Executive): Methods of approximation and determination of human vulnerability for offshore major accident hazard assessment.

3 Description of the investigate scenarios

While releasing gaseous hydrogen at ambient or elevated temperature often results in immediate ignition at the opening of the vent stack based on the low minimum ignition energy. During the release of cryogenic hydrogen generally no ignition is reported yet. The hydrogen is mixed with ambient air, diluted quickly and warmed-up. Despite that as part of a conservative approach also with the release of cryogenic hydrogen an immediate ignition of the gas is assumed.

Based on the above, incident related release of hydrogen via the low and high pressure vent stack after activation of safety valves is investigated. The assumed release scenarios are further described in chapter 3.1.

Based on the elevated pressure in the high pressure vent stack a pulsing gas release and atmospheric release in the nearby area as turbulent open jet stream is to be expected.

Depending on the timing of the presumed ignition of the forming hydrogen-air-mixtures, the following effects are possible:

- immediate ignition of the released hydrogen („Jet Fire“) or
- delayed ignition of an ignitable hydrogen-air-mixture („Vapour Cloud Explosion“)

For the release scenarios described in chapter 3.1, the distances until falling below the lower explosion limits, the mass in the explosion endangered area and the possible implications in case of an explosion or a fire respectively have been calculated with the software Phast® (version 6.7; Det Norske Veritas). For this, the following models have been used:

- Chamberlain model for the evaluation of implications in case of immediate ignition
- TNO multi-energy model for the evaluation of implications in case of delayed ignition

3.1 Gas release scenarios

3.1.1 Low pressure vent stack (LP stack)

The incident-related hydrogen release to be expected by safety valve activation in the area of the cryogenic LH2 storage tank is released to atmosphere via the LP stack. The following cases have been defined as significant and were used for investigating the related impact:

- Case 1.1: hydrogen release via SV 1/2 at the cryogenic LH2 storage tank in case of failure of the vacuum insulation; the amount relates to the release capacity of the safety valve (600 kg/h)
- Case 1.2: hydrogen release via SV 1/2 at the cryogenic LH2 storage tank in case of failure of the vacuum insulation caused by an external fire; the amount relates to the release capacity of the safety valve (1600 kg/h)
- Case 1.3: hydrogen release via SV 1/2 or SV 5.122 in case of a back flow from the HP buffer storage via leaking check valves and the H2 cryo pump 3.0; the amount relates to the maximum calculated leakage (10 kg/h)

3.1.2 High pressure vent stack (HP stack)

The incident-related hydrogen release to be expected by safety valve activation in the area of the H2 cryo pump 3.0 as well as the HP buffer storage is released to atmosphere via the HP stack. The following cases have been defined as significant and were used for investigating the related impact:

- Case 2.1: hydrogen release via a safety valve of the HP buffer storage; the amount relates to the release capacity of the safety valve (5820 kg/h), the activation of the safety valve is limited to a time frame of below 5 seconds [3].

3.1.3 Detailed information on the release scenarios

A summary of the detailed information on the described release scenarios is shown in table 3-1.

Table 3-1: detailed information on the release scenarios for the LP and HP stack

	LP stack			**HP stack**
	Case 1.1	**Case 1.2**	**Case 1.3**	**Case 2.1**
Amount released [kg/h]	600	1600	10	5820
Release velocity [m/s]	72	180	5.7	500 [1)]
Release temperature [°C]	-250	-251	9	9
Release height [m]	12			12
Release direction	60° to horizontal			60° to horizontal

Remark: 1) The release velocity is limited by the software to 500 m/s

3.2 Ambient conditions

The general ambient conditions have been taken into account as the following:

- Ambient temperature = 10 °C
- Relative humidity = 70 %.
- Sun irradiation = 0.65 kW/m²

The implication of the investigated scenarios have been calculated for different weather conditions The following weather conditions have been taken into account based on wind velocity and weather stability according to Pasquil:

- Category 1.5 / F: wind velocity 1.5 m/s, stable weather (unfavorable, nightly weather situation)
- Category 5 / D: wind velocity 5 m/s, neutral weather (midday weather situation)
- Category 9 / D: wind velocity 9 m/s, neutral weather (unfavorable weather situation for the calculation of heat radiation)

For the calculation of heat radiation caused by immediate ignition of the released hydrogen, a sun irradiation of 0.65 kW/m² has been taken into account.

3.3 Assessment criteria for radiation heat

According to [2] the following values can be used when assessing radiation heat (Table 3-2):

Table 3-2: assessment criteria for critical heat radiation for different objects

To be protected object	Radiation intensity [kW/m2]
Limit for negative impact	1.6
Sensitive building: hospitals, retirement facilities, schools, residential areas	2
Public roads	4.5
Limit for potential to pass on fire	8.0
Storage tank (not cooled)	10
Factory building: control room, workshop	12.6
Storage tank (cooled)	37.8

Further assessment criteria in terms of the impact of radiation heat towards humans can be found in [3]:

- 1.58 kW/m²: Maximum radiant heat intensity at any location where personnel with appropriate clothing can be continuously exposed
- 2.9 kW/m²: Time to pain threshold for 30 sec
- 4.73 kW/m²: Maximum radiant heat intensity in areas where emergency actions lasting 2 min to 3 min can be required by personnel without shielding but with appropriate clothing
  Acceptable Heat Scenario
- 6.31 kW/m²: Maximum radiant heat intensity in areas where emergency actions lasting up to 30 s can be required by personnel without shielding but with appropriate clothing
  Not acceptable Heat Scenario
- 9.46 kW/m²: Maximum radiant heat intensity at any location where urgent emergency action by personnel is required. When personnel enter or work in an area with the potential for radiant heat intensity greater than 6.31 kW/m2, then radiation shielding and/or special protective apparel (e.g. a fire approach suit) should be considered.

Based on the above information two assessment criteria for radiation heat are defined. Therefore the release scenarios have been categorized according to the hazardous incident law into – reasonably excludable and reasonably excludable sources of hazards:

- 1.58 kW/m² for scenarios resulting from reasonably not to be excluded sources of hazards ("likely incident")
- 2.9 kW/m² for scenarios resulting from reasonably to be excluded sources of hazards ("incident happens despite reasonable exclusion")

Based on the above the release scenarios discussed in chapter 3.1 are ranked and evaluated as follows (table 3-3).

Table 3-3: assessment criteria for the investigated release scenarios

Release scenario	Reasonably not excludable source of hazard	Reasonably excludable source of hazard	Assessment criteria for radiation heat
Case 1.1	---	X	2.9 kW/m²
Case 1.2	---	X	4.73 kW/m² (see remark 1)
Case 1.3	X	---	1.58 kW/m²
Case 2.1	X	---	8.4 kW/m² (see remark 2)

Remark 1: the scenario is evaluated based on liquid hydrogen tank outer jacket subjected to an external. According to tank sheath 120 minutes fire-resistance, it is assumed the release happens after an emergency evacuation on site and may be only fire service response personal are on site. According to [3] negative impact for starts after 2 to 3 minutes for personnel without shielding but with appropriate clothing at a maximum radiant heat intensity 4.73 kW/m².

Remark 2: based on the release time of below 5 sec the release scenario Case 2.1 is evaluated on the basis of the radiation heat amount. According to [4] negative impact (pain) starts at a radiation heat amount of 85 $[kW/m^2]^{4/3}*s$. At a release time of 5 seconds this translates into heat radiation of 8.4 kW/m².

4 Results

4.1 Consequences in case of an immediate ignition of the released hydrogen

The calculation of the radiation heat for LP and HP vent stacks shows that the evaluation criteria according to table 3-3 are met.

A summary of the maximum calculated radiation heat for the investigated release scenarios and the investigated weather conditions is shown in table 4-1.

Table 4-1: Maximum calculated radiation heat on [near] ground level for the investigated release scenarios

Release scenario	Maximum radiation heat [near] ground level [kW/m²]		
	Category 1.5 / F	**Category 5 / D**	**Category 9 / D**
Case 1.1	1.9	2.5	3.3
Case 1.2	2.3	3.4	4.4
Case 1.3	0.8	0.8	0.8
Case 2.1	3.2	4.6	5.8

Based on the results above **no** prohibitive threat towards humans in the area of the hydrogen refueling station is expected assuming that:

- the height of the low and high pressure vent stack is at least 12 m
- and that the release direction is at an angle (60° from the horizontal).

Furthermore, the radiation heat at the container roof has been calculated. The maximum radiation heat results from release scenario Case 2.1 and amounts to 6.4 kW/m² at the at the container roof (refer to image 4-5).

Worst Case scenario heat radiation

Detailed results over the course of the calculated radiation heat near ground level dependent on the distance to the location of the release is depicted in images 4-1 to 4-4. The following legend is used:

- Blue shape: Category 1.5 / F (unfavorable, night weather situation)
- Green shape: Category 5 / D (typical, mid-day weather situation)
- Red shape: Category 9 / D (unfavorable weather situation for the calculation of the heat radiation)

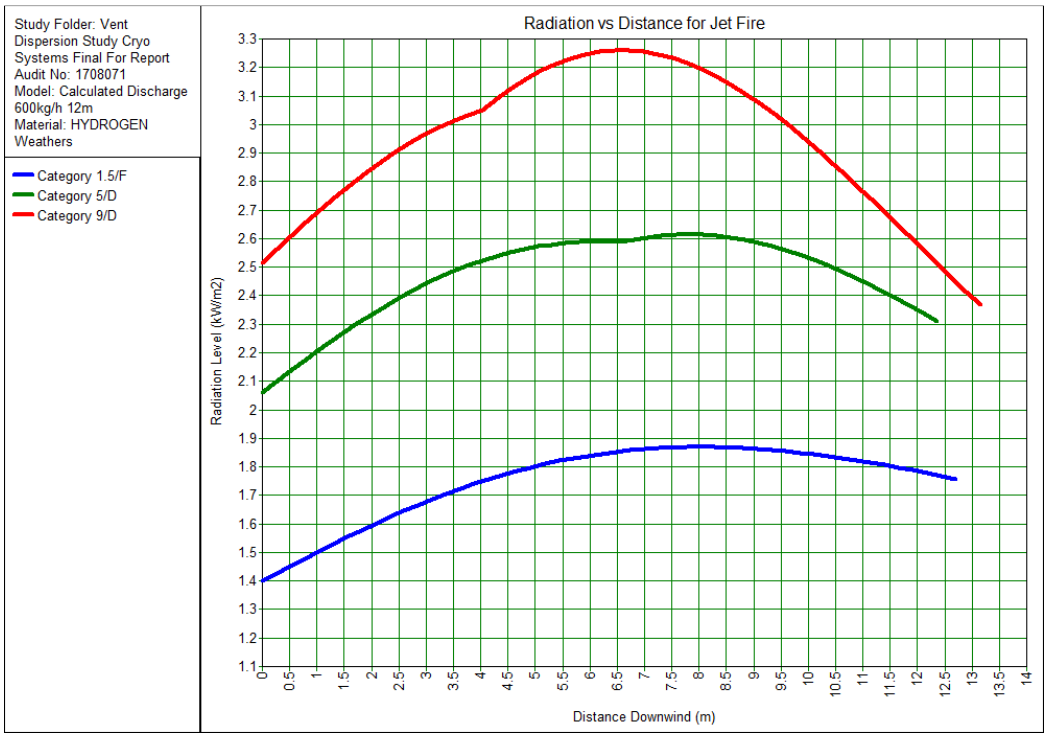


Image 4-1: calculated radiation heat near ground level for LP stack, Case 1.1

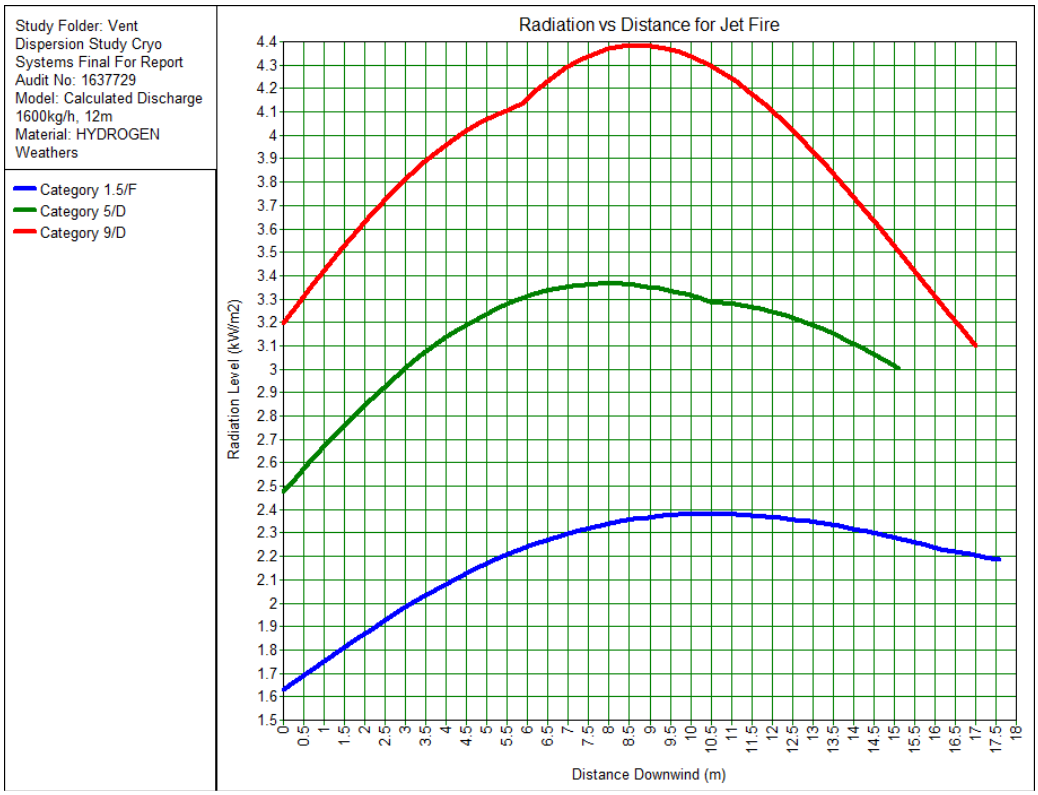


Image 4-2: calculated radiation heat near ground level for LP stack, Case 1.2

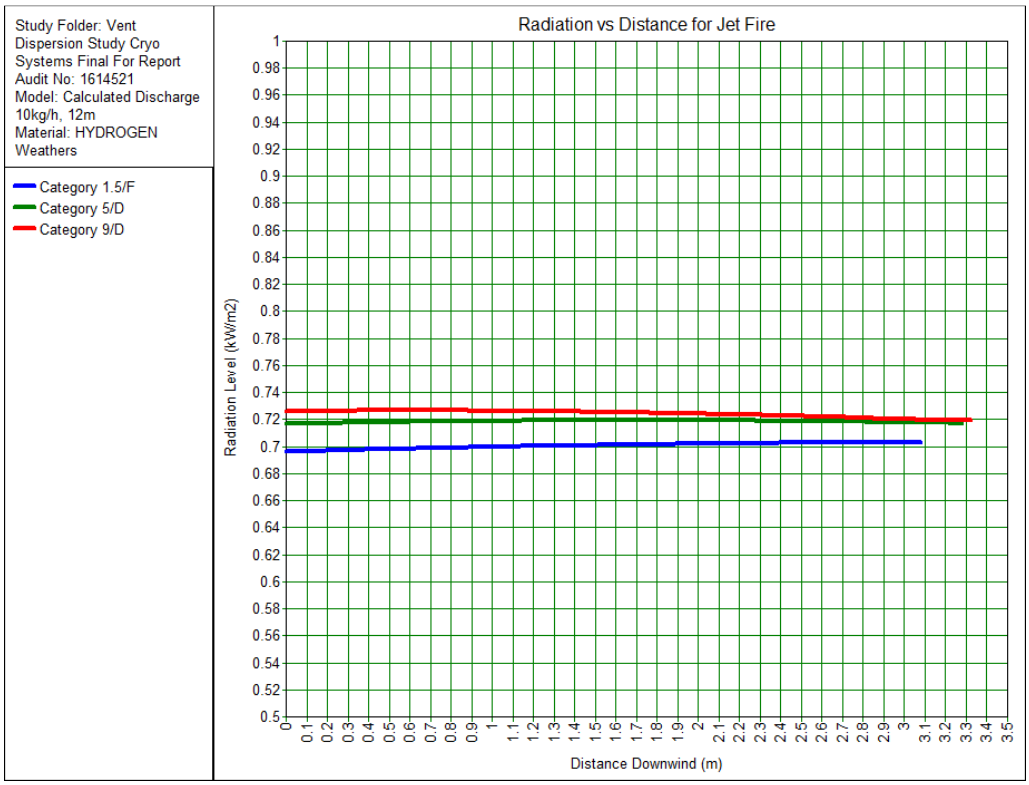
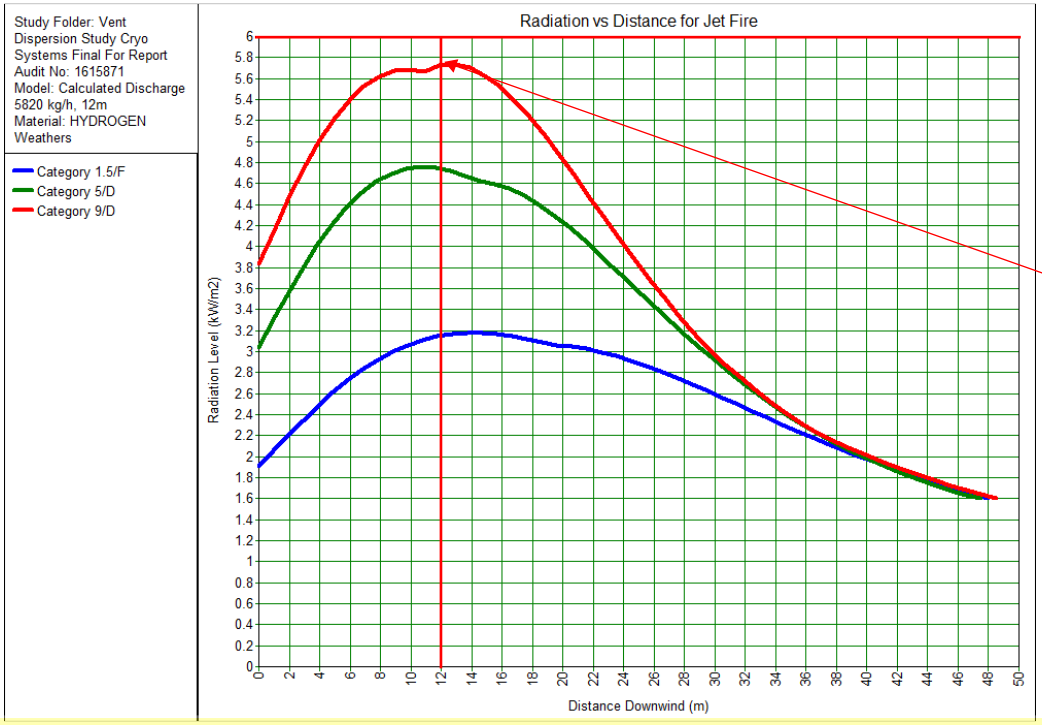


Image 4-3: calculated radiation heat near ground level for LP stack, Case 1.3



At 12m (40ft) high. The heat radiation is acceptable to avoid injury to the public (below 6.31 kw/m2).

Image 4-4: calculated radiation heat near ground level for HP stack, Case 2.1

Worst Case Scenario Heat Radiation

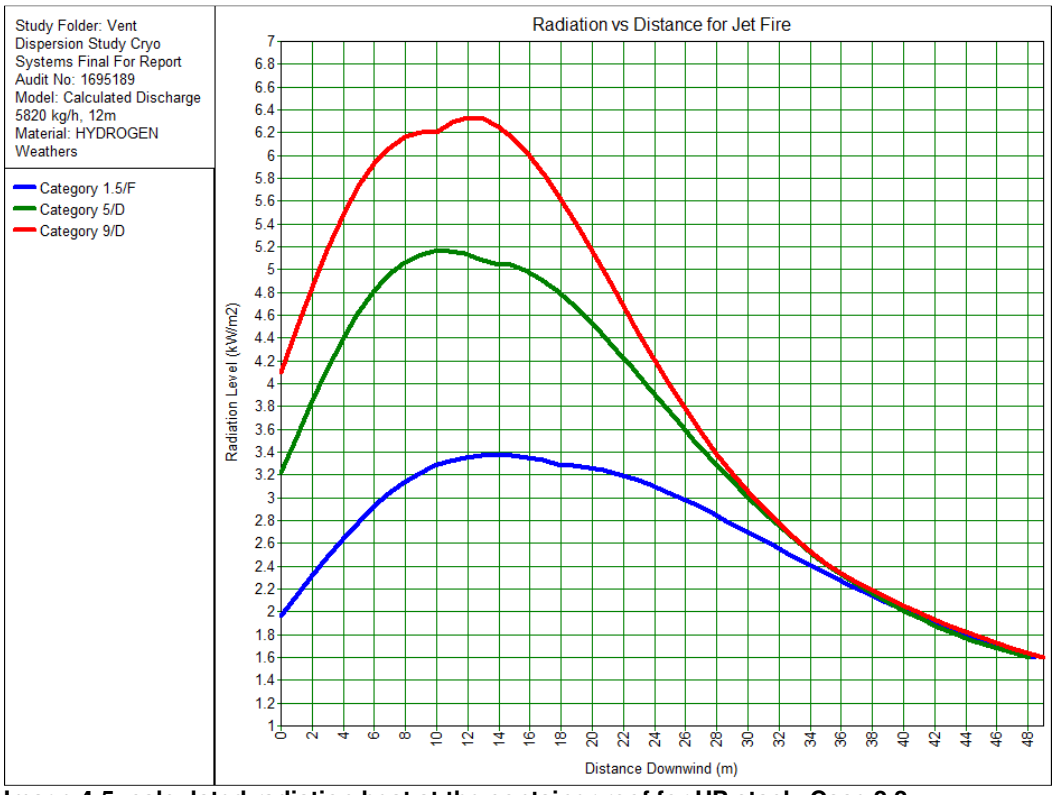


Image 4-5: calculated radiation heat at the container roof for HP stack, Case 2.2

4.2 Impact in case of delayed ignition of the released hydrogen

Based on the described release scenarios in chapter 3.1 the lower ignition distance as well as the mass in the explosion endangered area for the least favorable weather condition (category 1.5 / F) have been calculated (see table 4-2). The lower ignition distance is the distance where the lower explosion limit of 4 volume percent is reached or falling below that limit.

Table 4-2: lower ignition distance and mass in the explosion endangered area for the investigated release scenarios considering the least favorable weather conditions (category 1.5 / F)

Release scenario	Lower ignition distance	Mass in the explosion endangered area/zone
Case 1.1	18 m	710 g
Case 1.2	26 m	1790 g
Case 1.3	2 m	2 g
Case 2.1	17 m	4450 g

For release scenarios – Case 1.1, Case 1.2. and Case 1.3. – the explosion pressure impact in case of a delayed ignition has been calculated. Based on the free dispersion in open area (no or limited blockage in the area of the lower ignition distance) a blockage value [Verdämmungsgrad] of 1 and 2 has been assumed. Blockage value 1 means no blockage; blockage value 2 takes smaller blockage into account, i.e. blockage related fencing, hedges etc..

The calculated explosion pressure in relation to the distance to the source of ignition is shown in images 4-6 to 4-8 (red graph – blockage value 1; blue graph – blockage value 2).

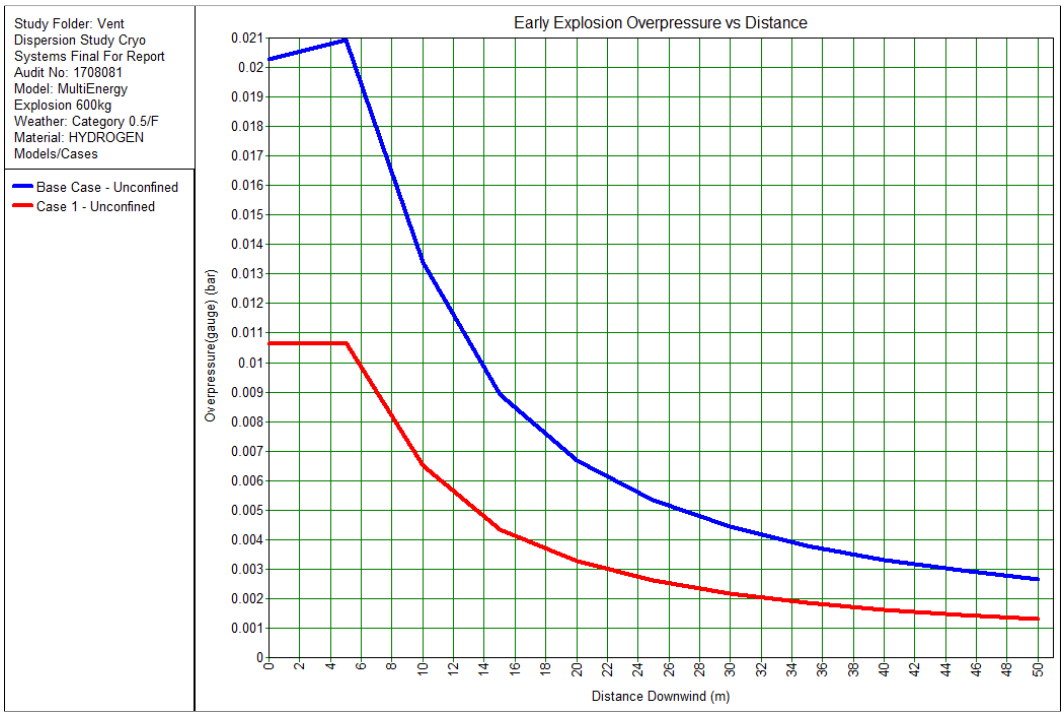


Image 4-6: calculated explosion pressure for the case "delayed ignition" (release scenario Case 1.1)

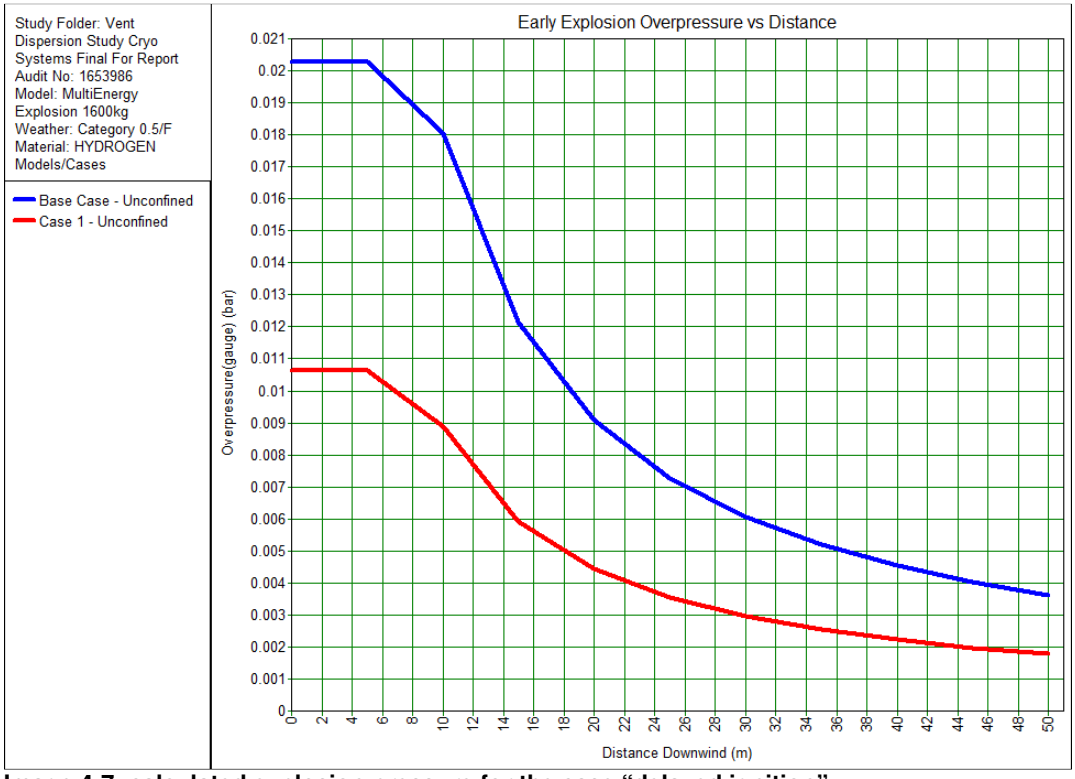


Image 4-7: calculated explosion pressure for the case "delayed ignition" (release scenario Case 1.2)

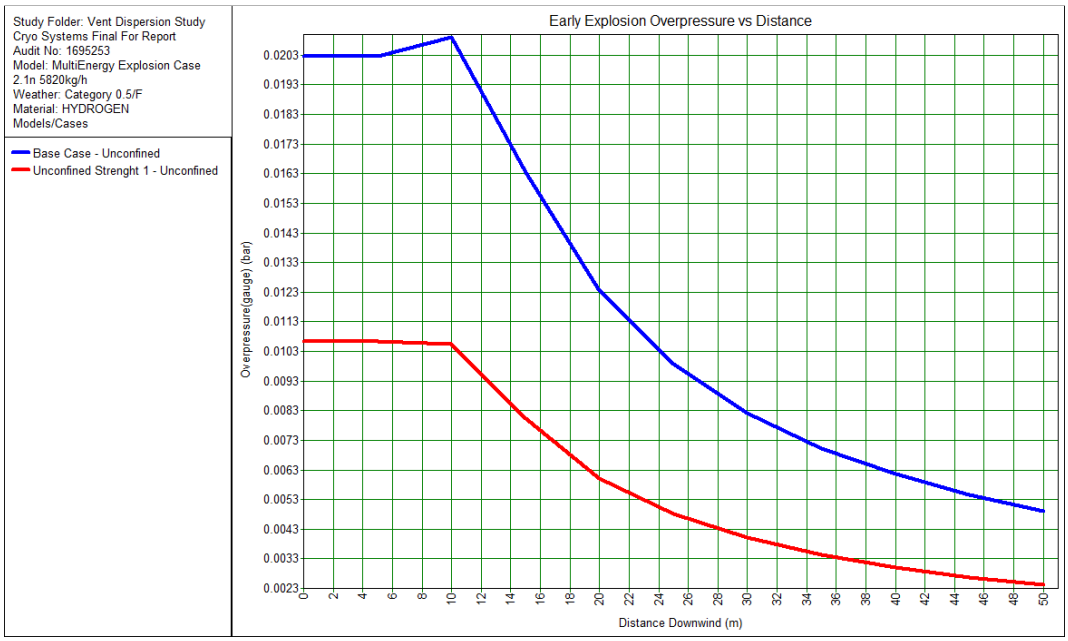


Image 4-8: calculated explosion pressure for the case "delayed ignition" (release scenario Case 2.1)

The maximum explosion pressure directly at the source of ignition is between 10 and 20 mbar depending on the blockage value. According to [7] 10% of glass panels break at an over pressure of 10 mbar and 75% of glass panels at 30 mbar; damage to humans only occur at higher explosion overpressure values. E.g. the lower limit for rupturing the eardrum is 175 mbar [2].

Therefore delayed ignition of the hydrogen-air-mixture does not result in an unacceptable danger from explosion overpressure.